Investigating the feasibility and logistics of decentralized urine treatment for resource recovery

Dissertation submitted in partial fulfilment of the requirements for the degree

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Declaration

I, *Tinashe Chipako*, hereby declare that the work on which this dissertation/thesis is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university. This thesis/dissertation has been submitted to the Turnitin module and I confirm that my supervisor has seen my report and any concerns revealed by such have been resolved with my supervisor

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Abstract

Background

Phosphorous levels around the world are decreasing rapidly, as urbanization increases. This is significant as phosphorus is a resource that is required by all living organisms and is a key ingredient in many fertilizers. Similar to the peak oil phenomenon, phosphorus will soon experience a peak in its production, and it is predicted that within the next century, naturally occurring phosphorous will be completely depleted. Moreover, methods of nitrogen production such as the Haber-Bosch process contribute largely towards global energy expenditure and greenhouse gas emissions. Considering this, researchers have aimed to investigate methods of recovering phosphorus and nitrogen to help cope with the increasing global demand and promote environmental sustainability. Urine has been identified as a potential source of recoverable phosphorus and nitrogen.

Urine accounts for approximately 1% of the total volume of domestic wastewater. Conversely, urine accounts for 80%, 60% and 63% of the nitrogen, phosphorus and potassium in domestic wastewater, respectively. Moreover, wastewater treatment plants specifically target the removal of nitrogen and phosphorus. This is because these substances can cause a toxic environment in surface water, which can have a negative effect on aquatic organisms. This research aimed to evaluate a novel mode of resource recovery, through the assessment of a decentralized approach to urine treatment.

Methodology

Two methodological approaches were adopted to evaluate this system. In the first, a thorough review of literature was conducted to assess current innovations pertaining to urine treatment technologies. Public perceptions regarding the collection and recycling of urine were also researched. This culminated in the creation of design charts depicting treatment sequences for fresh and hydrolyzed urine, aimed at maximum resource recovery. These charts were entirely based on values from published literature and basic calculations.

Secondly, geographic information systems (GIS) were used to assess the transportation and logistics of a decentralized urine treatment system, using the City of Cape Town as an illustrative case study. In this model, existing urinals at frequently visited shopping centres are theoretically replaced with waterless nutrient recovery urinals. Within these urinals, urea hydrolysis is prevented from occurring in an attached urine collection container. This minimizes nitrogen losses and allows for a solid, phosphorous based fertilizer to form. The collected urine is retrieved from individual buildings and transported to a resource recovery facility (RRF) by truck. The collected urine is filtered to remove the solid fertilizer, while the remaining liquid is concentrated to produce a liquid fertilizer. Finally, the recovered material is then sold as fertilizers to wholesalers.

The implication of transportation and logistics was also assessed through four scenarios of decentralization. In scenario one, one RRF was used. In scenarios two, three and four; two, four and eight RRFs were used, respectively. The economic and environmental implications of each scenario were then evaluated through standard engineering economics and potential greenhouse gas (GHG) emissions.

Ideal treatment sequence

It was deduced that the most promising treatment sequence for maximum resource recovery, based on nutrient recovery rates and operating conditions, incorporated a combination of alkaline stabilization and volume reduction. Calcium hydroxide and reverse osmosis (RO) were the chosen mediums for stabilization and volume reduction. If this sequence is used, almost all urine constituents can be recovered. Moreover, a liquid fertilizer with a 3.3 – 0 - 0.8 NPK rating, and 11 grams of calcium phosphate, per litre of urine treated, can theoretically be produced. This was the chosen treatment sequence for the decentralized urine transportation system.

Decentralized urine transportation treatment

It was found that the main contributor to GHG emissions in the decentralized system was the truck. Driving distance decreased as the number of RRFs increased, which led to a decrease in the GHG emissions because of fuel consumption. However, warehouse rental costs were a large contributor to operating expenditure (OPEX) and increased proportionately as the degree of decentralization increased. Therefore, a globally optimal solution incorporating the minimum cost, minimum GHG emissions and shortest travel distance was not possible. From a financial perspective, increased decentralization was not appealing, meaning the use of one RRF was the most favourable scenario.

Weight limitations of the truck were found to influence the travel route designations within the model road network. However, transportation had a small effect on the systems monetary cost, as it only accounted for 2% to 6% of the total OPEX across all design scenarios. This is likely due to the geographical configuration of Cape Town. Similar studies in larger areas with more dispersed collection locations may yield different results.

It was found that a positive net present value was achieved if the recovered fertilizer was capable of being sold at prices in line with commercially available liquid fertilizers, with similar nitrogen content. However, it is likely overly optimistic to believe the recovered liquid fertilizer could break into the South African fertilizer market and immediately compete with established products. Although, it was shown that the liquid fertilizer produced would only need to be sold at R22.75/L to equate the total system expenditure to the total income, over a five-year period.

Conclusion and Outlook

It was determined that the decentralized approach to urine treatment, investigated in this research, exhibited several advantages over biological nutrient removal at conventional wastewater treatment plants. These advantages included lower GHG emissions and energy expenditure for a similar operating cost. This study ultimately shows that the collection of source-separated urine for the purposes of resource recovery holds significant potential from a monetary and an environmental perspective. Furthermore, the combination of transportation planning and waste management could play an important role in future studies aiming to improve decentralized sanitation systems.

Acknowledgements

This dissertation would not have been possible without the help of various individuals.

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All calculation errors or misinterpretations in this body of work are entirely my own, and I take full responsibility for these shortcomings.

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List of acronyms, abbreviations and symbols

BNR	Biological nutrient removal
CAPEX	Capital expenditure
EFC	Eutectic freeze concentration
FAO UN	Food and Agricultural Organization of the United Nations
GHG	Greenhouse gas
GIS	Geographic information systems
HAP	Hydroxyapatite
MAP	Magnesium ammonium phosphate
MLE AS	Modified Ludzack-Ettinger activated sludge
NPC	Net present cost
NPV	Net present value
NRU	Nutrient recovery urinal
OIV	International Organization of Vine and Wine
OPEX	Operating expenditure
PAD	Packaging and distribution
RO	Reverse osmosis
RRF	Resource recovery facility
SAWIS	South African Wine Industry
UCT	University of Cape Town
UDT	Urine diverting toilet
UDDT	Urine diverting dry toilet
UF	University of Florida
V&A	Victoria & Alfred Waterfront
WWT	Wastewater treatment
WWTP	Wastewater treatment plant

ha	Hectare
g	Grams
kg	Kilogram
kWh	Kilowatt hours
kL	Kilolitres

L	Litres
m	Meter
mg	milligrams
R	South African rand
Al^{3+}	Aluminium
Ca^{2+}	Calcium
$CaCO_3$	Calcium carbonate
Ca-P	Calcium phosphate
$Ca(OH)_2$	Calcium hydroxide
Cl^-	Chlorine
CO_2	Carbon dioxide
Fe^{2+}	Iron
$H_2\ SO_4^{2-}$	Sulphuric acid
Mg^{2+}	Magnesium
MgCl	Magnesium chloride
MgO	Magnesium oxide
N	Nitrogen
N_2O	Nitrous oxide
Na^+	Sodium
Na(OH)	Sodium hydroxide
NH^3	Ammonia
NH^3-N	Nitrogen bound in ammonia
NH_4^+	Ammonium
NH_4^+-N	Nitrogen bound in ammonium
K^+	Potassium
P	Phosphorous
PO_4^{3-}	Phosphate
PO_4^{3-}-P	Phosphorus bound in Phosphate
SO_4^{2-}	Sulphate
Urea-N	Nitrogen bound in urea

1 Introduction

1.1 The proposed project

This dissertation investigates a decentralized urine collection and treatment system that emphasises maximum recovery of resources from the human urine. Additionally, different technologies that could be used to recover valuable products such as fertilizer from human urine are reviewed and used to develop guidelines and design charts for maximum resource recovery.

1.2 Background/ motivation

1.2.1 Phosphorous and nitrogen production

Naturally occurring phosphorus is depleting at a rapid rate, as the global population continues to grow (Cordell et al., 2009). This non-renewable resource is important for the growth of all living organisms, and is one of the most prominent constituents found within modern day fertilizers (Spångberg et al., 2014). Phosphorus cannot exist in gaseous form, so its natural movement is restricted to land and water, in liquid and solid phase. Moreover, vegetation can only absorb soluble phosphorous through soil. In the phosphorous cycle, plant life would typically receive the phosphorous they require for growth from the decomposition of dead plant matter. This cycle has been disrupted by mass harvesting and global transportation of crops by humans. As a result, plants require a constant application of phosphorous, from fertilizers, to replenish what has been removed (Cordell et al., 2009).

The effects of urbanization on phosphorous production between the years 1800 and 2000 are displayed in **Figure 1-1**. The global need for phosphorous steeply increased as populations increased in the 20th century. This is significant, as it is predicted that phosphorous production will peak by the year 2030 (Cordell et al., 2009). Considering this, many researchers have aimed to investigate methods of recovering phosphorus to help cope with the increasing global demand.

Moreover, nitrogen production is primarily facilitated through the Haber-Bosch process. This process accounts for over 99% of global ammonia production, and 75% of that is used as fertilizer (Smil, 2011). However, this process accounts for 1% of the world’s total energy consumption and has led to pollution that has cost the European Union alone, hundreds of billions of euros (Sutton et al., 2011).

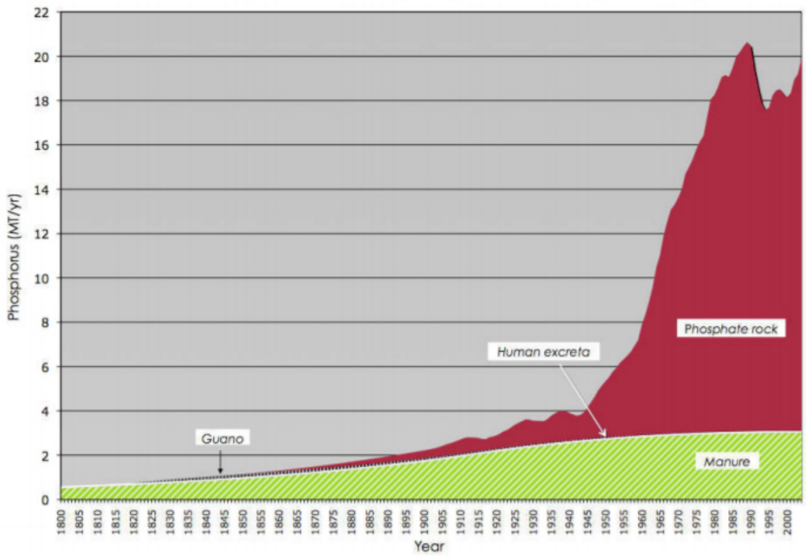

Figure 1-1: Global phosphorous sources and production between 1800-2000 (Cordell et al., 2009).

1.2.2 Centralized wastewater treatment

Conventional wastewater treatment is specifically geared towards the removal of nitrogen and phosphorus from wastewater streams (Wilsenach & van Loosdrecht, 2003). This is because the presence of these materials can lead to algal growth in a process known as eutrophication. This phenomenon induces an anoxic environment in water, which can have harmful effects on aquatic organisms (Spångberg et al., 2014). The current philosophy pertaining to human waste is typically centred around treatment and disposal of these resources, as opposed to recovery and reuse (Andersson et al., 2016). As a result, a shift in objectives for researchers has seen the promotion of studies pertaining to sustainability and resource recovery from wastewater. Policy changes around the world have also seen sustainable wastewater treatment initiatives prioritized. For example, it has recently become obligatory, as per the German sewage sludge ordinance, for wastewater treatment facilities to recover phosphorus from sewage sludge. Phosphorous recovery at wastewater treatment plants has also been made mandatory in Sweden, Switzerland and Austria (Günther et al., 2018).

Urine has been identified as a potential source of recoverable phosphorus and nitrogen. Previous research indicates that urine accounts for approximately 1% of the total volume of domestic wastewater streams (Spångberg et al., 2014). Conversely, urine contains roughly 60% and 80% of the total phosphorus and nitrogen within domestic wastewater (Spångberg et al., 2014). This becomes significant, as the total phosphorus that could be recovered from urine is estimated to be roughly 22% of the current global phosphorus demand (Barbosa et al., 2016). A shift in infrastructure and philosophy could see urine being removed from waste streams before its constituents are required to be removed and disposed of at treatment plants. Furthermore, this could allow for recycling of source-separated urine through decentralized treatment systems.

1.2.3 Decentralized wastewater treatment

Decentralization of wastewater treatment is not a novel concept. The main differences between central and decentralized wastewater treatment systems are the distance that the waste travels, the quantity treated and the treatment methods employed (Casey, 2013). Centralized wastewater management systems typically have waste travelling large distances within sewage networks and incorporate bulk treatment methods for a large population. Decentralized systems characteristically treat waste closer to the point of waste production and can be flexible towards the most appropriate method of treatment for the area being serviced (Casey, 2013). An additional benefit to decentralized wastewater treatment is the ability to apply its methodologies to smaller communities that may not be serviced by centralized facilities, due to distance or monetary reasons (Tooke, 2015). Moreover, smaller treatment loads mean that failure of the system or malfunctioning of crucial process steps are not as catastrophic as they would be in a centralized wastewater treatment system.

Studies have shown that decentralizing the treatment of urine offers lower greenhouse gas (GHG) emissions, energy expenditure, and operating costs, in comparison to centralized wastewater treatment of equal quantities of urine (Tervahauta et al., 2013, Shi et al., 2018). In addition to this, the treatment of urine to recover nutrients potentially holds many financial benefits if sold commercially (Kavvada et al., 2017, Yetilmezsoy et al., 2017). Furthermore, a decrease in the influent nutrient load at wastewater treatment facilities would likely allow for monetary savings regarding biological nutrient removal (Spångberg et al., 2014). The treatment of waste products to produce materials of value (known as upcycling) (Bridgens et al., 2018) is the driving force of this research.

1.2.4 Significance of research

This research directly relates to five of the seventeen sustainable development goals set out by the United Nations; numbers two, six, eleven, thirteen and fourteen as seen in **Figure 1-2**. This is because it is envisioned that this research could aid in mitigating world hunger, by increasing fertilizer supplies through nutrient recovery, and provide an alternate waste removal system which also conserves water. From a South African perspective, this is significant as it is estimated that over 60% of the rivers in South Africa which act as potable water sources are being overexploited, and approximately one third of the country's main rivers are in good condition (Donnenfeld et al., 2018).

The proposed system would also promote sustainable infrastructure and communities that recycle materials that are typically seen as waste products. Additionally, decentralized collection of urine could reduce water pollution and decrease the greenhouse gas emissions created from nitrogen and phosphorus removal processes at conventional wastewater treatment facilities.

Figure 1-2: Sustainable development goals outlined by the United Nations (Fullman & Fortunati, 2017, UN, 2015).

1.3 Problem statement

Many benefits can potentially be achieved by separating solid and liquid waste collection for decentralized urine treatment. Barriers which prevent this from occurring include the transportation logistics of urine from where it originates, the economic feasibility of implementing decentralized treatment, and the selection of appropriate urine treatment technologies.

Methods for treating urine to recover phosphorus and nitrogen do exist. However, design guidelines outlining urine treatment methodologies for maximum resource recovery, based on nutrient recovery rates, are limited.

1.4 Research objectives

This study had two main objectives. These objectives were to determine if a decentralized approach for urine treatment is financially and environmentally feasible, and to determine the urine treatment methods that would be most conducive to maximum resource recovery.

The research objectives were thus broken down into the following tasks:

1. An in-depth review of literature pertaining to previously iterated urine treatment techniques, public perception regarding urine reuse, and transportation of urine-based fertilizers.
2. A quantitative compilation of resource recovery potential based on urine treatment techniques from literature. This compilation will culminate in the creation of design charts depicting process sequences for maximum recovery of resources from urine.

3. The design of a basic decentralized approach to urine collection, for resource recovery, within the City of Cape Town. Evaluating the effects of transportation and logistics of source-separated urine formed the main modelling portion of this objective. Subsequently, an evaluation of the monetary and environmental implications of this decentralized system, in comparison to conventional wastewater treatment was required.

1.5 Scope and limitations

This dissertation was entirely a desktop study. Detailed software modelling and a thorough review of literature were conducted, but no experimental work was done. The applicability of the findings was only determined through literature and heuristic calculations.

A focus was placed on urinals as the main urine collection medium, as it was assumed that urinals would offer an efficient manner of urine collection, in the event of any real-life implementation. Therefore, urine diverting pedestals (toilets) were not considered. Subsequently, female urine contributions were not included in any calculations because female urinals and alternate urine collecting technology available for women is limited.

1.6 Dissertation structure

A total of 7 Chapters were incorporated in this dissertation. Chapter 1 presents the introduction and the motivations behind this research. The research problem, objectives and scope and limitations are also given Chapter 1. In Chapter 2, a review of literature from previous research pertaining to urine collection, treatment and transportation was conducted. The methodology followed for this research is outlined in Chapter 3. It is here that the research hypotheses and key questions are posed. Chapters 4 and 5 are the main results and discussions sections. Methodologies for maximum recovery of resources from urine using previously published research are presented in Chapter 4. Chapter 5 presents a transportation model for a decentralized approach to urine treatment. The proposed decentralized approach is accompanied by an economic and environmental analysis. In Chapter 6, the research conclusions are presented, and recommendations for future research are made. A complete list of references used to inform the direction of this research is provided in Chapter 7. Finally, all raw data and calculations used in this study are presented in the appendices.

2 Literature review

This Chapter contains a review of already known and previously published literature pertaining to the problem statement and research objectives outlined in sections 1.3 and 1.4.

A brief review of conventional wastewater treatment is outlined in section 2.1. This is followed by an overview of urine diverting technologies and examples of where urine diverting technology has been implemented, in section 2.2. The applications of transportation planning and geospatial analysis for decentralized collection of urine are presented in section 2.3. A review of urine treatment methodology and the factors influencing the conditions of collected urine is provided in section 2.4. Finally, a summary of the key findings from the review of literature is provided in section 2.5.

2.1 Conventional wastewater treatment and sustainability

Central wastewater treatment (WWT) is typically the main form of wastewater management in urban environments. In this scenario, all built infrastructure is connected to a sewage network that transports the blackwater produced (solid and liquid wastewater) to a central wastewater treatment plant (WWTP) (Wilsenach & van Loosdrecht, 2003). The removal of micronutrients from wastewater is facilitated through some form of biological nutrient removal (BNR).

Biological Nutrient Removal most notably deals with the removal of nitrogen and phosphorus from waste streams, and can be quite energy intensive (Wilsenach & van Loosdrecht, 2003). Additionally, processes involved in BNR are known to release large amounts of greenhouse gas (GHG) as by-products (Kyung et al., 2015). These include, but are not limited to, methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) (Parravicini et al., 2016).

Biological Nutrient Removal of nitrogen has often been given preference over phosphorous removal. A widely used BNR configuration that focuses primarily on nitrogen removal is known as the Modified Ludzack-Ettinger activated sludge (MLE AS) system (EPA, 2007). Nitrification, denitrification and activated sludge solid removal are the main removal processes incorporated in this configuration, occurring in the anoxic and aerobic compartments of the design (Ni et al., 2016). This WWTP configuration can remove up to 80% of total influent nitrogen (EPA, 2007). A basic representation of the MLE AS configuration is displayed in **Figure 2-1**.

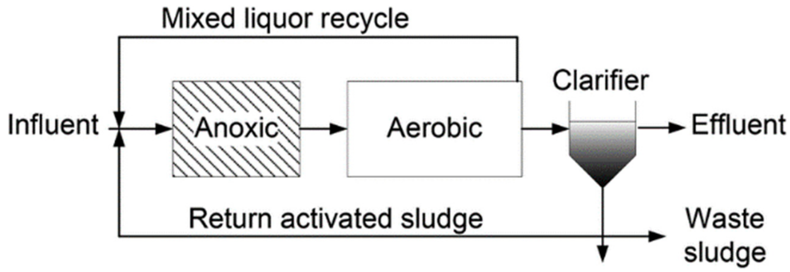

Figure 2-1: Modified Ludzack-Ettinger system configuration (Ni et al., 2016).

Given that urine contributes approximately 80% of the nitrogen quantity of wastewater (Spångberg et al., 2014), using the MLE AS configuration as a direct comparison to urine source-separation is considered appropriate. Moreover, the inclusion of urine collection for the purposes of resource recovery would undoubtedly have a significant effect on the way we approach WWT.

2.2 Urine collection technology

If the collection of source-separated urine is considered for implementation, sophisticated methods of urine collection are required. This section reviews previously researched urine collection apparatus, and their levels of public acceptance, where applicable. This will serve as a platform to identify potential implementation choices for use in different environments.

2.2.1 Source-separating toilets

There are typically two forms of source-separating toilets; urine diverting toilets (UDTs) and urine diverting dry toilets (UDDTs) (von Münch & Winker, 2011). Much like conventional household toilets, both consist of a pedestal and a cistern, but do not function in the same manner as conventional toilets. There are two compartments in these toilets, one for urine collection and one for solid waste collection, as can be seen in **Figure 2-2**. Urine diverting dry toilets are completely waterless and can be used to collect solid waste and urine for composting and alternate forms of nutrient recovery (Lienert & Larsen, 2010). However, the urine collection segment in UDTs are waterless, while the waste collection segment is water-based. In terms of water consumption, UDDTs, UDTs and conventional toilets use approximately 0, 2 and 10 litres per flush respectively (von Münch & Winker, 2011).

With regards to resource recovery, it is generally advised that solid and liquid waste be completely separated to avoid cross contamination. Pathogens in faeces are not destroyed as easily as those found in urine, thus typical urine treatment methods will not suffice if cross contamination occurs (von Münch & Winker, 2011, Jönsson et al., 1997).

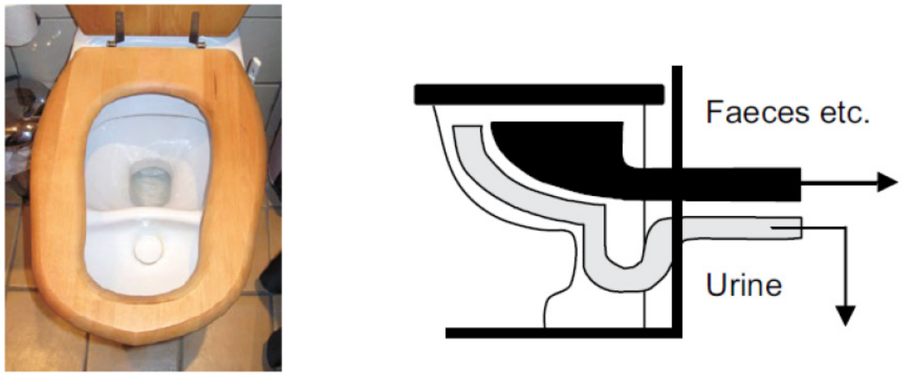

Figure 2-2: Urine diverting pedestal (left) (von Münch & Winker, 2011) and urine diverting mechanism (right) (Rossi et al., 2009).

Urine diverting toilets have previously been targeted as a means for urine collection for nitrogen recovery (Kavvada et al., 2017). However, an issue regarding the installation of urine diverting toilets is that the implementation of a two-pipe system (one for solid waste and one for liquid waste) would be required. This would likely require a detailed overhaul of the plumbing network in existing buildings, which could be complicated and expensive.

2.2.2 Waterless urinals

Waterless urinals offer a simple solution for water conservation and urine collection, alike. However, widespread access to urinals is primarily available to males. This is due to the lack of sophistication regarding current female urinal models. Female urinals require more privacy than male urinals, and also require users to adopt changes in their bathroom routines (von Münch & Dahm, 2009).

Conventional urinals use up to 4 litres of water per flush, whereas waterless versions use no water (von Münch & Dahm, 2009). Urine is composed of approximately 96% water (Sakthivel & Chariar, 2013) so no flushing is necessary to remove the waste stream, unlike solid waste. However, waterless urinals are not without their flaws. Issues such as unpleasant odours in certain designs and negative public perceptions do exist. Odours can be dealt with by applying membranes or sealant liquids to the pipes which lead from urinal drains (Sakthivel & Chariar, 2013). An example of one such membrane can be seen in **Figure 2-3**. These allow the one-way movement of urine to drainage pipes while preventing unpleasant smells from escaping (von Münch & Dahm, 2009).

Figure 2-3: Plastic membrane used to control urinal pipe odour (Sakthivel & Chariar, 2013).

In addition, spontaneous precipitation caused by urine tends to occur in the sewage pipes connected to conventional waterless urinals. These solid precipitates are known to cause blockages by excessive pipe scaling (Udert et al., 2003a). However, this scale is rich in phosphorus and other nutrients and could potentially be used as a fertilizer instead, if urine is not allowed to enter drainage pipes (Udert et al., 2003b).

Considering the nutrient recovery potential from the precipitated solids in urinal pipes, a novel nutrient recovery urinal (NRU) was constructed and tested at the University of Cape Town (UCT) (Flanagan & Randall, 2018) in South Africa. The design of the urinal can be seen in **Figure 2-4**. Urine was collected in the attached container with the intention of maximum nutrient recovery. This was achieved by placing calcium hydroxide within the collection container before urine was allowed to enter. Doing this prevented malodour and caused phosphorous precipitation. The urinal fulfilled its initial purpose of recovering almost all the phosphorus from the collected urine. Detailed theory behind the effect of calcium hydroxide addition to urine is discussed further in section 2.4.4.

Despite the success of this prototype model, it was assumed that the makeshift nature of the urinal design would deter users if the NRU were to be widely manufactured. It was recommended that making the NRU resemble a conventional urinal is paramount to the overall success and acceptance of the system (Flanagan & Randall, 2018).

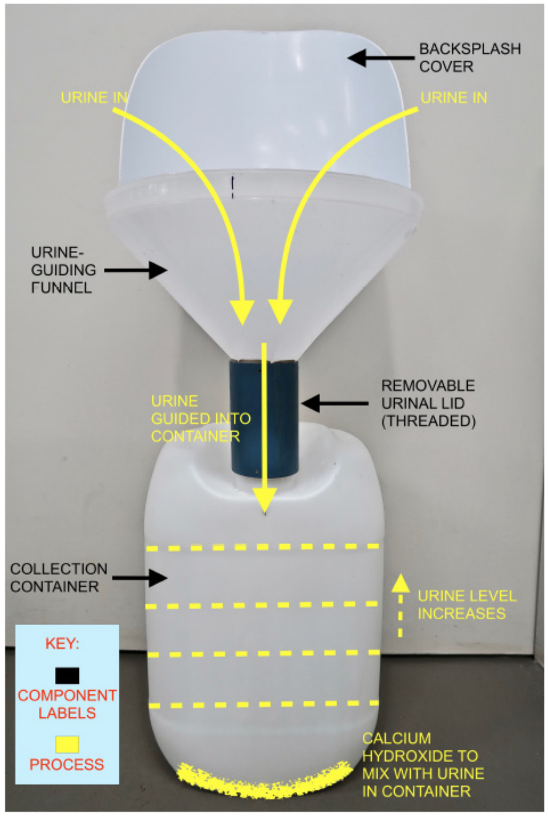

Figure 2-4: Novel nutrient recovery urinal (Flanagan & Randall, 2018).

2.2.3 Public perception and case studies

Considering that an estimated 2.3 billion people around the globe cannot access proper sanitation makes the need for innovative technologies even greater (WHO & UNICEF, 2017). However, public acceptance of any novel waste management system is required for it to succeed. Despite potentially being anecdotal in nature, scenarios of real-life implementations of urine diverting systems and public opinion has been investigated in this section. Perceptions regarding resource recovery have also been considered in this context.

2.2.3.1 Urine diverting technology in developing countries

The use of urine diverting technology as a means of waste management, at the very least, has been socially accepted and successfully implemented in developing countries such as Bangladesh (Pramanik et al., 2011), Ethiopia (Kassa et al., 2010), and Nepal (Etter et al., 2011). Moreover, in the cases of Bangladesh and Ethiopia, resource recovery from UDDTs was found to be accepted for crop fertilization.

Widespread success has not been consistent in all cases for urine diversion implementation though. In South Africa, UDDTs were installed in the eThekwini municipality for a nine-year period, between

2002 and 2011 (Etter et al., 2015). These UDDTs were installed to target the sanitation needs of approximately 75 000 households in the eThekwini municipality. Within the first three years of the system's implementation, 78% of the user base reported overall satisfaction with the system. However, after nine years of operation, under 30% of residents were still satisfied (Roma et al., 2013). Improper use, poor hygienic upkeep and vandalism of the installed UDDT units significantly decreased user satisfaction. It was suggested that this dissatisfaction was mostly due to smell and general hygiene. The households that utilized the system in the eThekwini community were provided with equipment to safely dispose of faecal matter and were left responsible for the maintenance of the UDDTs to promote a sense of ownership of toilets. However, regular and adequate maintenance of the toilets was proven to be a significant factor in this scenario.

When the benefits of resource recovery from urine were discussed with the household who utilised the installed UDDTs in the eThekwini community, the user acceptance increased from 30% to 40% (Etter et al., 2015). This was due to financial incentives, such as payment for households that participated in urine collection and recycling. Approximately 95% of households that participated in urine collection stated that this new source of income had significant effects on their household budget. Similarly, UDDT systems were implemented in Arba Minch, Ethiopia (Kassa et al., 2010). Although residents were initially sceptical, support of urine recycling grew once the fertilization capabilities of urine were shown. Many people in this Ethiopian study were not averse to consuming food that was grown using urine derived fertilizers. This provides encouraging signs that recycling of urine may not be met with resistance if the benefits are explained to those utilizing urine diverting systems.

Furthermore, a survey conducted at UCT found that 96% of 507 survey participants were willing to use urine diverting technology once it was revealed that the technology offered a method of water conservation (Chipako & Randall, 2019). In addition to this, results from Chipako & Randall (2019) indicated that 79% of respondents claimed that they were willing to eat food grown using urine derived fertilizer. This gives an indication that the social acceptance of a nutrient recovery systems would not be unreasonable.

Urine collection and recycling is not always accepted, though. In Efutu, Ghana, a census was conducted on over 400 households. It was found that 84% of respondents believed all forms of excrement are fundamentally waste products (Mariwah & Drangert, 2011). This was due to a combination of cultural and hygienic reasons. The majority of those interviewed reportedly would not even entertain the idea of waste reuse. Physical examples of novel system benefits may be the most practical method of changing opinions regarding urine reuse, but increased efforts are still required to convince people.

2.2.3.2 Urine diverting technology in developed countries

Urine diverting Technology has been successfully and indefinitely implemented in developed countries with high levels of acceptance. These countries include Germany, Switzerland and Austria, among several others (Lienert & Larsen, 2010). Moreover, a survey originating from the University of Florida (UF) in the United States of America (Ishii & Boyer, 2016) indicated that 84% of the 570 respondents were willing to use urine diverting technology for nutrient recovery.

In 2006, the German Organization for Technical Cooperation Headquarters (GTZ) in Eschborn, Germany installed waterless urinals and UDTs to conserve water and collect urine for subsequent resource recovery (Blume & Winker, 2011). Most users did not find there to be a difference in the appearance of the systems when compared to conventional urinals and toilets. However, issues pertaining to odour and cleanliness did arise regarding the waterless urinals and the UDTs. Over 60% and 50% of users were unhappy with the odour produced from the urinals, and the cleanliness of the UDTs, respectfully. However, it was suggested that these complaints could be alleviated with more intensive maintenance and better training of cleaning staff.

2.3 Decentralization of urine collection

Additional barriers to the implementation of decentralized urine treatment are the logistics and transportation of large volumes of urine to treatment facilities. Methods of transporting urine from commercial and residential areas, in a non-invasive manner, are pivotal for the success of source-separating technologies. To accomplish this, basic principles of economics, transportation planning and logistics must be considered.

In transportation planning, arguably the most pivotal aspect of any proposed system is the identification of supply and demand locations in a transportation network. In economics, supply and demand are represented by the ability to provide a product, and the rate at which that product is desired, respectively (Whelan & Msefer, 1996). Likewise, regarding transportation planning; supply and demand refers to the capacity of transportation modes and infrastructure, and the materials requiring transport (Sabharwal, 2013). Determination of these two parameters allows for cost-efficient routing and appropriate transportation mode designation. In terms of decentralized urine management, collected urine is the demand and treatment facilities, as well as transportation, are the supply. If the location of the demand is identified first, as would be the case in site specific wastewater management, the supply would then need to be catered to this demand (Sabharwal, 2013). Computer software can be used to optimize supply locations and expand supply where necessary (Kavvada et al., 2017).

Urine is produced in liquid form; thus, bulk transportation is limited by weight and volume. To model a methodology for the logistics of a decentralized system, it is useful to liken urine as being part of a supply chain. Distribution of goods from the location of production to retail outlets plays a pivotal role in any economic supply chain. This phenomenon is referred to as last-mile logistics and plays a complimentary role alongside transportation planning (Ewedairo et al., 2015), as seen in **Figure 2-5**. However, this requires geospatial analysis, to accurately depict the characteristics of the infrastructure within any given study area. Geospatial analysis is a form of analytics that incorporates known geographical information to help in understanding patterns in human behaviour (Ewedairo et al., 2015). This form of analysis finds significant applications for mobility and is typically done using databases known as geographic information systems (GIS) (Ewedairo et al., 2015).

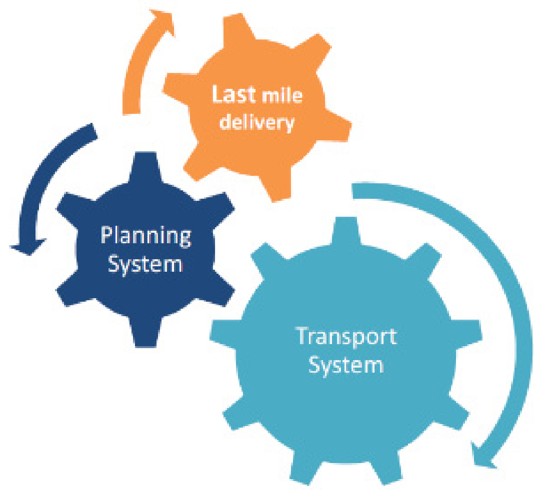

Figure 2-5: Inter connecting relationship between transportation, planning and last-mile logistics (Ewedairo et al., 2015).

GIS has previously been used to model last-mile delivery and optimize supply chains for sustainability related research. These studies incorporate upcycling of resources, whereby waste products are transported from demand sources to recycling facilities. Hendrickson et al. (2015) used spatial analysis to model the last-mile logistics of recycling batteries from electric vehicles. Similarly, Jenkins et al. (2008) used geospatial planning to analyse the supply chain potential and optimum location for biofuel production facilities.

Research regarding the logistics of decentralized urine collection systems are limited but have been previously explored. In a study conducted by Kavvada et al. (2017), the planning of transportation methods for nitrogen recovered from source-separated urine from households was investigated. Geospatial and last-mile logistics modelling was considered for a hypothetical system implemented in the City of San Francisco, United States of America. It was determined that decentralizing urine treatment was desirable as it offered a lower operating cost, lower unit energy expenditure and lower

GHG emissions when compared to centralized wastewater management (Kavvada et al., 2017). It also displayed the potential to earn a profit, but this was only the case when the potential sale of the nitrogen fertilizers produced was taken into consideration.

2.4 Nutrient recovery techniques

Once urine is collected and transported to a treatment facility, useful products can be manufactured and recovered. The upcycling of nutrients found within urine presents an opportunity to create value from waste as fertilizers (Barbosa et al., 2016). Various treatment techniques have been tested in attempts to maximise nutrient recovery from urine. Several human urine treatment techniques were reviewed in this section and compared based on their pH requirements, operating temperatures and projected nutrient recovery capabilities. The driving force behind this research is the notion that value can be created from waste, as seen in **Figure 2-6**.

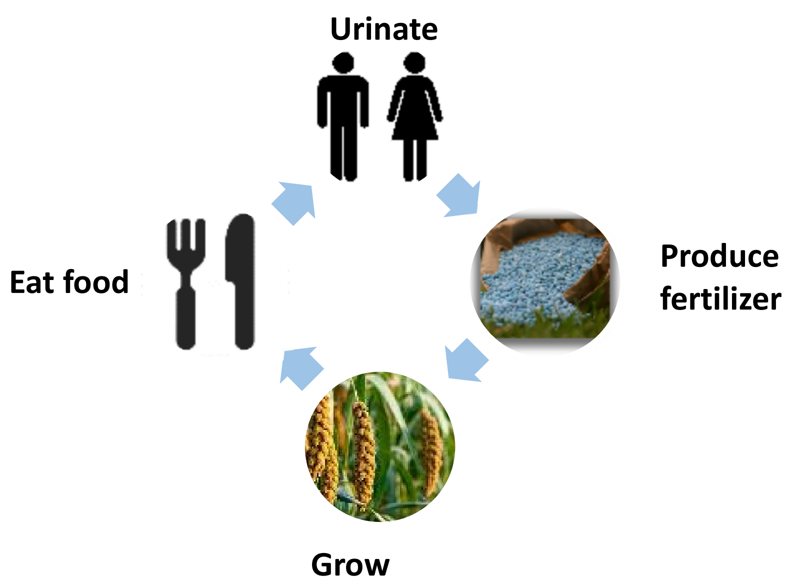

Figure 2-6: The premise of nutrient recovery from urine.

The exact monetary costs and energy consumption of each nutrient recovery procedure were not considered for this study because of differences in scale and implementation of the literature considered. However, Maurer et al. (2003) gives detailed energy consumption calculations for different urine treatment technologies.

2.4.1 Urine chemistry

Precipitation of phosphorus-based solids in urine can occur spontaneously when the pH of the solution increases. This occurs because magnesium (Mg^{2+}) and calcium ions (Ca^{2+}), which appear naturally in urine, can react with phosphate (PO_4^{3-}) ions to form solids (Etter et al., 2014). The most prominently precipitated magnesium and calcium based compounds are struvite (magnesium ammonium phosphate, $MgNH_4PO_4{\cdot}6H_2O$) and HAP (hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$) (Udert et al., 2003a). In the absence of ammonium, potassium struvite (Struvite- K, $KMgPO_46H_2O$) can also precipitate (Wilsenach et al., 2007).

This spontaneous precipitation reaction happens due to an increase in pH as a result of an increase in ammonium ions (NH_4^+) within solution. This increase in ammonium occurs as a result of urea hydrolysis, whereby urea ($NH_2(CO)NH_2$) is decomposed to become ammonia (NH_3) and ammonium (Udert et al., 2003b). Approximately 85% of the nitrogen in urine is initially only available in urea, with 5% being available in ammonium and ammonia (Senecal & Vinnerås, 2017). Urea hydrolysis is catalysed by an enzyme called urease, which is released by microorganisms that are naturally present within urine. The complete conversion of urea to ammonia and ammonium (complete hydrolysis) can occur in urine within 72 hours of urine production (Udert et al., 2003a). In this dissertation, urine samples that have undergone hydrolysis and those that have not, are referred to as hydrolyzed and fresh urine, respectfully.

The chemical changes that occur during urea hydrolysis are detailed in **Equation 2-1**. Urease induced hydrolysis is typically referred to as enzymatic hydrolysis, but chemically induced hydrolysis can also occur. Chemical hydrolysis can occur if fresh urine is exposed to high temperatures (above 50°C) or a steep increase in the pH value (above 13) (Randall et al., 2016).

$$\mathrm{NH_2(CO)NH_2} + \mathrm{2H_2O} \rightarrow \mathrm{NH_3} + \mathrm{NH_4^+} + \mathrm{HCO_3^-}$$ **Equation 2-1** (Udert et al., 2003a).

Fresh urine usually has a pH between 6 and 7. After urine has hydrolyzed, the pH of the urine rises to a value of approximately 9.25. This number is significant, as it is also the buffer pH that dictates which compound, between ammonia and ammonium will be most abundant in water-based solutions (Leyva-Ramos et al., 2004). This relationship between ammonia and ammonium in aqueous solutions (such as urine) can be seen in **Equation 2-2** and **Figure 2-7**, respectively. The curve shown in **Figure 2-7** may change in different solutions due to differences in composition, leading to varying interactions between ions in solutions (Leyva-Ramos et al., 2004).

$$\mathrm{NH_4^+} \leftrightarrow \mathrm{NH_{3(aq)}} + \mathrm{H^+}$$ **Equation 2-2** (Leyva-Ramos et al., 2004).

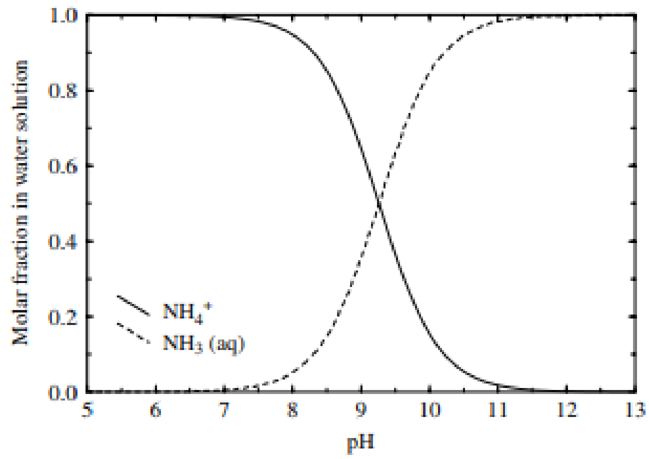

Figure 2-7: Speciation graph of ammonia in water-based solutions (Leyva-Ramos et al., 2004).

If the nitrogen present in urine is in the form of ammonium or ammonia, it can be volatilised in the presence of air and lost as ammonia gas. Therefore, if maximum resource recovery is considered, ammonia volatilization should be prevented, as it could result in a significant loss of irretrievable nitrogen. Pahore et al. (2012) states that up to 33% of the original nitrogen content of urine can be lost due to ammonia volatilization.

Spontaneous struvite precipitation typically begins to occur at pH values between 7 and 8, with HAP following at slightly higher pH values (Udert et al., 2003a, Tilley et al., 2008). Due to the quantity of magnesium and calcium (the solutes) in fresh urine being higher than the quantity at equilibrium, after hydrolysis has occurred, urine is deemed to be supersaturated when it is fresh (Galbraith & Schneider, 2009). Moreover, it was also found that struvite precipitation occurs at a lower supersaturation than calcium based phosphates (Udert et al., 2003a). This is further explained by the low solubility products of struvite (4.33×10^{-14}) and HAP (2.91×10^{-58}) (Bell et al., 1978, Bhuiyan, 2007).

The limiting factor for spontaneous precipitation in hydrolyzed urine is the magnesium or calcium which is required to form phosphate based precipitates. Barbosa et al. (2016) states that approximately 30% of phosphorus within urine is recoverable during spontaneous struvite and HAP precipitation. This value was confirmed by Etter et al. (2014) and Liu et al. (2008) where it was found that 31% and 30% was recoverable. However, the extent of spontaneous precipitation is also dependent on the composition of urine. To recover all the phosphorus from urine, additional magnesium or calcium needs to be added (Barbosa et al., 2016).

2.4.2 Magnesium dosing

High phosphorus recovery from urine is not difficult to achieve as it is widely documented that close to 100% of the phosphorus in urine is recoverable from several different urine samples (Liu et al., 2013, Wilsenach et al., 2007, Flanagan & Randall, 2018, Etter et al., 2015). Divalent or trivalent ions such as magnesium, calcium, sodium, iron and aluminium can be dosed to urine to achieve this. However, sodium, iron and aluminium ions, are not preferred as they are not as beneficial to plant growth as magnesium and calcium ions and can even be toxic in some cases (Mossor-Pietraszewska, 2001, Prinzenberg et al., 2010). Similar to spontaneous precipitation, the induction of phosphorous precipitation through magnesium dosing is primarily governed by pH, requiring a pH of between 8 and 10.5 for maximum phosphorous removal (Liu et al., 2013, Barbosa et al., 2016, Dai et al., 2014). Furthermore, temperature seemingly does not play a significant role, as 99% of phosphorous can be removed from urine through magnesium dosing at room temperature (Dai et al., 2014).

Barbosa et al. (2016) explored chemical precipitation from urine using various magnesium sources, namely magnesium oxide (MgO), magnesium chloride ($MgCl_2$), and magnesium hydroxide ($Mg(OH)_2$). It was demonstrated that magnesium oxide was the most favourable magnesium source. However, It was found that the Mg to P molar ratio should be 2:1 for maximum phosphorus recovery (Barbosa et al., 2016). If this condition is met, and the pH is not altered from the optimal range for struvite precipitation, the magnesium source is not important. In fresh urine, the Mg to P molar ratio is typically around 1:5 (Udert et al., 2003a).

Dosing with magnesium has an additional limiting factor in that only 3 to 5% of the nitrogen present in urine is recovered as struvite crystals when magnesium is dosed (Etter et al., 2015). Similar to phosphorus, ammonia recovery by struvite precipitation is dependent on the urine composition. The Mg to N to P molar ratio in fresh urine is typically 1:79:5 (Udert et al., 2003a), whereas, the Mg to N to P molar ratio in struvite is 1.2:1:1 (Barbosa et al., 2016) . To recover the maximum amount of nitrogen, using this method (up to 95%), magnesium and phosphorus would need to be added to urine to establish a near equal molar balance between the three nutrients (Barbosa et al., 2016). This is undesirable as it would increase the cost of the nutrient recovery process since additional sources of magnesium and phosphorus would be required.

2.4.3 Urea stabilization

Although maximum recovery of phosphorus from urine by chemical dosing is relatively simple, the same cannot be said for nitrogen. This is because nitrogen can be lost due to ammonia volatilization after urea hydrolysis has occurred. A high initial pH of fresh urine (above 11) has been known to inhibit enzymatic urea hydrolysis (Randall et al., 2016). This inhibition is likely due to the inactivation of urease-producing microorganisms in urine at highly alkaline pH ranges (Höglund et al., 1998). It has also been confirmed that urea stabilization (the prevention of urea hydrolysis) can be achieved by adding a strong base to fresh urine, before hydrolysis begins (Randall et al., 2016). Moreover, with regards to bases, calcium hydroxide may be ideal for the purposes of stabilization as it allows for a long period of urease inhibition (over 27 days). This is due to the lower solubility calcium hydroxide has over other bases such as sodium hydroxide (Na(OH)) and limestone (Boncz et al., 2016, Randall et al., 2016).

The urea hydrolysing capabilities of urease can also be stunted by decreasing the solution pH to a value below 5 (Aguilar, 2011, Boncz et al., 2016). In addition, Hellström et al. (1999) showed that sulphuric acid (H_2SO_4) can inhibit urease for up to 100 days. However, acid dosing on a large scale would likely require dosing equipment and pumping, which would increase the costs of the process. Acids can also be dangerous to handle if the user is not properly trained (Randall et al., 2016). Furthermore, because acids are typically available in liquid form, transportation may be difficult if large volumes are required to be moved.

Urine stabilization can also refer to the conversion of volatile ammonia into nitrates and ammonium ions (Udert & Wächter, 2012, Oosterhuis & van Loosdrecht, 2009). However, when referring to the concept of 'stabilization', this dissertation will focus on stabilization of urine before it has undergone hydrolysis, i.e. maintaining nitrogen in urine as urea.

2.4.4 Calcium dosing

The addition of calcium hydroxide to urine is useful as it has applications in urea stabilization as well as chemical phosphorous precipitation (Pradhan et al., 2017). Moreover, calcium phosphate solids are less sensitive to heat than struvite, as struvite is known to decompose when exposed to temperatures higher than 60°C (Sarkar, 1991).

Adding calcium hydroxide to fresh urine and hydrolyzed urine has different effects on the solutions. Randall et al. (2016) investigated the potential of stabilizing fresh urine with the addition of calcium hydroxide. It was found that 96% of the phosphorus in urine was recovered from the urine as amorphous calcium phosphate, which is a precursor to HAP. This was accomplished at a temperature of 25°C and within a pH range of 11 to 13 (Randall et al., 2016). Calcium carbonate ($CaCO_3$) and calcium oxide (CaO) were also tested, as calcium sources. The addition of CaO is exothermic, and would result in an increase in solution temperature, which could potentially lead to a loss of urea through chemical decomposition. Calcium carbonate has a low saturation pH of 7 and would not inhibit hydrolysis since the threshold pH was found to be 11. Calcium hydroxide proved to be a better option than both sources of calcium and yielded the best results for the purposes of stabilization and precipitation (Randall et al., 2016). The theory regarding urea stabilization by calcium hydroxide addition was tested on a waterless urinal at the University of Cape Town, using the equipment shown in **Figure 2-4**, where a phosphorous recovery rate of 98% was achieved (Flanagan & Randall, 2018).

Furthermore, chemical precipitation in hydrolyzed urine by calcium hydroxide addition was tested by Pradhan et al (2017). Although 99% of phosphorus was removed from the urine, the most prominent precipitate was found to be calcium carbonate ($CaCO_3$). This was due to the calcium hydroxide reacting with the carbonate ions formed during urea hydrolysis as well as the absorption of CO_2 from the air (Pradhan et al., 2017). In addition, the increase in urine pH, due to the high alkalinity of calcium hydroxide, increased the NH_3 concentration. This was found to be beneficial for ammonia recovery in a process known as ammonia stripping, which is discussed in section 2.4.5.1.

A dosage of 10 g/L of fresh urine was recommended, as this ensured that the urine was always saturated with calcium hydroxide, regardless of the urine composition (Randall et al., 2016). However, Pradhan et al. (2017) suggested a dosage of 22 g/L for hydrolyzed urine to maintain a high pH (of 12.5) for maximum NH_3 production. This is because the urine samples used in the work done by Pradhan et al. (2017) had already hydrolyzed and was already at a high pH of 9.25 before testing was done, meaning more alkalinity was required to maintain a high pH for ammonia stripping.

2.4.5 Nitrogen recovery

Nutrient recovery techniques aimed specifically towards nitrogen recovery were researched for an overall evaluation of resource recovery from urine. In literature where nitrogen recovery from hydrolyzed urine samples was conducted, it is understood that nitrogen loss due to hydrolysis had likely occurred during storage, prior to testing. However, the recovery percentages quoted in this review are in reference to the nitrogen present in the urine solutions used in each study, regardless of the state of urine.

2.4.5.1 Ammonia stripping

A well-established method of recovering nitrogen from urine is ammonia stripping. In this process ammonia volatilization is induced, and the ammonia gas produced is recovered (Başakçilardan-Kabakci et al., 2007). Once stripped from solution, a common method of reclaiming the ammonia as a product involves exposing the ammonia gas to an acidic solution. This is widely achieved using sulphuric acid (H_2SO_4) (Pradhan et al., 2017), but can also be done using acetic acid (Dhillonn & Perry, 1962). The ammonia together with air and a sulphuric acid solution results in the formation of ammonium sulphate ($(NH_4)_2SO_4$) (Başakçilardan-Kabakci et al., 2007).

Urea hydrolysis is a prerequisite for maximum nitrogen recovery using this treatment method, as the presence of ammonia is required. Solution pH and temperature are the governing factors for this recovery technology. Studies done by Liu et al. (2014) and Gulyas et al. (2014) showed that operating air stripping equipment at high temperatures (above 50°) accelerates the stripping of ammonia from urine solutions. Pradhan et al. (2017) ,Başakçilardan-Kabakci et al. (2007) and Liu et al. (2014) showed that a high pH can also accelerate the expulsion of ammonia gas. Calcium hydroxide (Pradhan et al., 2017) and sodium hydroxide (Liu et al., 2014) have previously been used to increase ammonia stripping efficiencies. Likewise, the pH of urine can also be increased by introducing an electric current to the solution (Tarpeh et al., 2018, Luther et al., 2015, Christiaens et al., 2017). When using an electric current to induce the release of ammonia gas, hydroxide ions are created around the cathode of the cell which increases the pH of the solution and causes the production of ammonia gas. This process is known as electrochemical stripping.

2.4.5.2 Adsorption

Adsorption is a process whereby atoms or ions attach to the surface of one another. With regards to nitrogen, an electronegative surface can be used to adsorb ammonium ions. Urea can also be adsorbed by intermolecular forces onto a suitable surface. Van der Waal forces are typically the forces driving urea adsorption (Shintre, 1943). A well-established ammonia adsorption process regarding urine is selective cation exchange. There are several suitable surfaces that are capable of adsorbing ammonium ions, as the primary requirement for a cation adsorption surface is a high electronegativity (Allar Emek & Beler Baykal, 2015, Schumacher et al., 2011). Granular materials known as zeolites (aluminium silicate-based materials) are used in cation exchange processes due to their natural abundance in the environment (Tarpeh et al., 2017, Beler-Baykal et al., 2011). Recovery of phosphate ions (PO_4^-) is also possible, through another form of adsorption, known as anion exchange. Up to 97% of phosphorus can be removed from fresh and hydrolyzed urine using hybrid anion exchange resins and hydrated ferric oxide (Sendrowski & Boyer, 2013).

Moreover, activated carbon adsorption can be accomplished with both fresh and hydrolyzed urine; urea nitrogen and ammonium nitrogen can both be adsorbed onto a suitable activated carbon surface. Activated carbon can be derived from various sources of high carbon content, such as coconut shells (Pillai et al., 2014), wood sawdust (Mazlan, 2016) and charcoal.

2.4.6 Volume reduction

Physical water removal can recover all the resources in urine as a concentrated final product. This is significant, as water comprises approximately 96% of the volume of urine (Sakthivel & Chariar, 2013). As a result, the remainder of the urine, after water removal, would be rich in nutrients and can potentially be used as a liquid fertilizer (Udert & Wächter, 2012). Potable water recovery from urine is also possible, and is of particular interest regarding interplanetary space travel where renewable water sources are scarce (Schmidt, 2007). This presents additional benefits to a system that focuses on maximum resource recovery from urine.

2.4.6.1 Evaporation

Evaporation is the least complex urine volume reduction method. A heat source is required to raise the temperature of water and produce water vapour. What is left behind is a concentrated solution or mixed solid product (Antonini et al., 2011). Evaporation can also be followed by distillation to collect water vapour for water reclamation (Derese & Verliefde, 2016, Udert & Wächter, 2012).

However, unless conducted in a sealed environment or reclaimed by ammonia stripping, up to 93% of the nitrogen bound in ammonia can be lost due to volatilization (Bethune et al., 2014, Etter et al., 2015). This would be applicable for evaporation of hydrolyzed urine conducted under atmospheric pressure (Bethune et al., 2014). Ek et al. (2006) evaporated hydrolyzed urine in a vacuum, which prevented volatilization by lowering the temperature required for evaporation to 30°C. Moreover, in this study by Ek et al. (2006), 95% of the nitrogen in urine was recovered, with a water removal rate of 95%, by vacuum evaporation. Similarly, Derese & Verliefde (2016) found that membrane distillation can recover up to 95% of the nitrogen in urine with a water removal rate of over 75%.

2.4.6.2 Reverse Osmosis

During reverse osmosis (RO), the regular osmosis process (in which materials move from a high hydrostatic pressure to a low one) is reversed through the addition of external pressure (Rao, 2011). RO treatment is the most prominent desalination technique around the globe, as it is responsible for an estimated 74% of global desalination procedures (Oatley-Radcliffe, 2017). When applied to urine, only water molecules can generally pass through the RO membrane. A highly concentrated brine consisting of salts and nutrients is produced which could be used as a liquid fertilizer (Ek et al., 2006).

Thörneby et al. (1999) showed that an 80% volume reduction rate can be achieved when treating hydrolyzed swine urine with RO. A roughly 95% ammonium nitrogen recovery rate was achieved in this study. Likewise, in a study which included volume reduction of hydrolyzed human urine by evaporation and RO, Ek et al. (2006) showed that 95% nitrogen recovery was achievable in both cases. Moreover, RO volume reduction rates of 80% were recorded in this study. Evaporation was found to be over double the cost of RO and required over three times the energy input of RO per m^3 of urine treated (Ek et al., 2006). This was likely dependant on scale of the process and the source of energy used, but unfortunately the researchers did not include this information.

2.4.6.3 Freeze concentration

Two freezing techniques were reviewed as a means for volume reduction for urine: freeze thaw and eutectic freeze crystallization (EFC). Freeze thaw treatment involves the freezing and subsequent thawing of the ice produced. Once the solution temperature is lowered to sub-zero, it becomes difficult for anything other than water particles to be incorporated into the crystal lattice of ice (Gulyas et al., 2004). In the case of urine, the separation of ions and salts would occur as the solution is thawed. In a freeze thaw experiment conducted by Lind et al. (2001), 80% of the nutrients in hydrolyzed urine were reportedly recovered with a 75% reduction in volume.

Eutectic freeze crystallization is similar to freeze thawing, with the only difference being that the solution is cooled to the eutectic point where salt(s) can form. The eutectic point of any solution can be defined as the lowest melting temperature of any given combination of the solutions constituents (Randall & Nathoo, 2015). When applied to hydrolyzed urine, up to 99% of the nitrogen bound in urine could be theoretically recovered at a temperature of -30°C (Randall & Nathoo, 2018). An estimated 95% water recovery is possible when using EFC for urine treatment (Schmidt & Alleman, 2006). However, due to the low temperature requirements of EFC and considering that most of the energy is required for ice formation, EFC works best when the stream is already significantly concentrated. As a result, Randall & Nathoo (2015) suggested that volume reduction of wastewaters could be achieved using RO as a pre-treatment step, followed by EFC.

2.4.6.4 Factors influencing volume reduction

Temperature plays a key role in the success of each volume reduction process, with the only exception being RO. Typically, distillation and evaporation methods require temperatures between 40 and 85°C to successfully concentrate urine (Derese & Verliefde, 2016, Antonini et al., 2011, Udert & Wächter, 2012), whereas freezing processes require temperatures between -6°C and -30°C (Gulyas et al., 2004, Lind et al., 2001, Randall & Nathoo, 2018). Conversely, RO of urine can be conducted at near room temperature with no adverse effect on water removal or nutrient concentration (Ek et al., 2006, Thörneby et al., 1999).

However, there is a gap in knowledge regarding volume reduction for fresh urine. Research on freezing treatment and RO for concentrating fresh urine is limited, so the efficiency of these methods is hard to predict with absolute certainty. Conversely, Boncz et al. (2016) showed that acid stabilization of fresh urine, as a pre-treatment step for evaporation, could prevent urea hydrolysis and retain 99% of nitrogen in solution. Acetic acid was used as the stabilizing agent in this study and complete evaporation was achieved, with no water recovery.

Similarly, Senecal & Vinnerås (2017) and Simha et al. (2018) demonstrated that base stabilization of fresh urine, using wood ash, as a pre-treatment for evaporation could minimise urea hydrolysis. Total nitrogen retention rates of 90% and 70% were recorded in these studies, with total solution volume reductions of 95% and 90%.

2.4.7 Alternative techniques

Alternative niche nutrient recovery techniques were considered for an overall evaluation of this field. Udert & Wächter (2012) investigated a method of complete nutrient recovery from hydrolyzed urine that incorporated a combination of ammonia stabilization by biological nitrification, and volume reduction by distillation. Nitrifying bacteria prevented volatilization by oxidising ammonia to nitrate in this study. Close to 100% of the nutrients bound in hydrolysed urine were retained in 3% of the original volume (Udert & Wächter, 2012). This treatment method has since been adopted by a company known as VUNA, to produce a liquid fertilizer that is currently commercially available in Switzerland (Etter et al., 2015). Although nitrification and distillation displayed positive results in this study, the treatment process is complex and requires highly specialized equipment and personnel. It was estimated that a nitrification plant, which focusses on urine, would require over 50 days to start up , as the bacteria is required to acclimatise to the high ammonia concentrations in hydrolyzed urine (Etter et al., 2015). Moreover, the nitrogen that was lost due to hydrolysis during storage was not taken into consideration when reporting the total nitrogen recovery in this study.

Precipitation of a urea based solid, known as isobutyraldehyde di-urea (IBDU), has been explored by Behrendt et al (2002). This was done by reacting urea and Isobutyric aldehyde (IBA) thus inducing precipitation. In this investigation, up to 75% of the nitrogen present in fresh urine was recovered after an acidic stabilization and evaporation pre-treatment step (Behrendt et al., 2002). The presence of urea is vital if formation of IBDU is desired, thus urea stabilization to prevent hydrolysis would be required as a pre-treatment step.

Microbial Fuel Cells (MFC) have also been used to recover nitrogen. Kuntke (2012) explored ammonium recovery from hydrolyzed urine using an MFC. Ammonia recovery rates of 11.4% were observed in this study. This low recovery rate was a result of the chemical oxygen demand (COD) of the solution limiting the amount of ammonium that could be moved from the anode chamber to the cathode chamber.

Moreover, the direct cultivation of plants using fresh and hydrolyzed urine has been tested (Latrou et al., 2015). Duckweed Lemna minor (an aquatic based plant) was observed to remove 84% and 58% of the urea and total ammonia in fresh and hydrolyzed urine, respectively.

2.4.8 Pathogen and micropollutant removal

Pathogens and microorganisms pose a threat towards the safe use of urine derived fertilizers; therefore, methods of disinfection are important. Urea stabilization offers a potential method of urine disinfection, by subjecting urine to extremely high or low pH values. Disinfection of wastewater streams using bases such as calcium hydroxide has been used previously in WWTPs to stabilize primary and secondary sewage sludge and destroy hazardous microorganisms (Farrell et al., 1974, Eriksen et al., 1996). Moreover, Peracetic acid (the product of combining hydrogen peroxide and acetic acid) has been used as a means for sewage effluent disinfection (Baldry & French, 1989, Gehr & Cochrane, 2002). Furthermore, the increase in urine pH, that occurs naturally after urea hydrolysis, has been known to destroy harmful pathogen in urine(von Münch & Winker, 2011).

The effect of pharmaceuticals on the environment is not yet completely understood, but their presence represents a potential health hazard (Lienert et al., 2007). When urine is used as a fertilizer, the uptake of pharmaceuticals in plant roots has been shown to occur through transpiration (Winker et al., 2010, Ternes et al., 2007). Biochar, an alternative to activated carbon, has been used previously by Solanki & Boyer (2017) to remove pharmaceuticals from synthetic urine by adsorption. Moreover, the removal of micronutrients by electrodialysis has been tested by Pronk et al. (2006). The removal process in this study was facilitated by membrane forward osmosis.

Despite research regarding pharmaceutical removal from urine, work done by de Boer et al. (2018) suggests that the risk of pharmaceutical uptake in plants is not a significant health issue. The effect of pharmaceutical uptake in plants fertilized using urine derived struvite was investigated in this study. It was estimated that a person would have to eat approximately 750 kgs worth of tomatoes, grown using urine-derived struvite per day, to have a detrimental effect on a person's health over time.

2.4.9 Summary of urine treatment techniques

In summary, several factors play an important role in the recovery of nutrients from urine. Among these factors, the pH and the state of urine (fresh or hydrolyzed) is crucial when considering maximum resource recovery. The mechanism of urea hydrolysis in fresh urine is controlled predominately by the pH of the solution. Allowing the pH to stay in the range of 6.5 to 11, results in enzymatic urea hydrolysis and can lead to significant losses of nitrogen as ammonia gas (Liu et al., 2008, Udert et al., 2003a, Randall et al., 2016). Conversely, increasing or decreasing the pH of urine to a value above or below this range can inhibit enzymatic urea hydrolysis (Boncz et al., 2016, Hellström et al., 1999, Aguilar, 2011). Preventing urea hydrolysis allows for the retention of almost all the nitrogen initially present in urine.

Increases in temperature can lead to chemical hydrolysis of fresh urine, but this would only be the case if the urine solution was above 50°C (Randall et al., 2016). Moreover, high temperatures have been known to increase the conversion of ammonium to ammonia gas, which can be useful for nitrogen recovery in the case of hydrolyzed urine. High recovery of nitrogen (comparable to fresh urine) would likely be possible if hydrolysis occurs in a sealed environment, and an appropriate method of ammonia recovery is employed. However, this would be difficult to achieve at a large scale, unless all the collected urine is immediately sealed after generation.

Phosphorous recovery can be achieved regardless of the state of urine and is only dependant on pH. Temperature seemingly does not play a large role in dictating phosphorous precipitation potential, as all reviewed research was reportedly conducted at room temperature. This indicates that low energy inputs, pertaining to the temperature for urine related precipitation reactions, are possible.

The method of nutrient recovery one chooses to adopt is dependent on the specific nutrient(s) that is desired (between nitrogen and phosphorus) and the resources which are available. For example, magnesium dosing to urine has been conducted as trials in several countries, such as Nepal (Etter et al., 2011) and South Africa (Grau et al., 2012). In both cases, hydrolyzed urine was collected from UDDTs and treated with locally sourced magnesium compounds.

A summary of the nutrient recovery potential, against pH requirements, for each of the abovementioned treatment methods is shown in **Figure 2-8**.

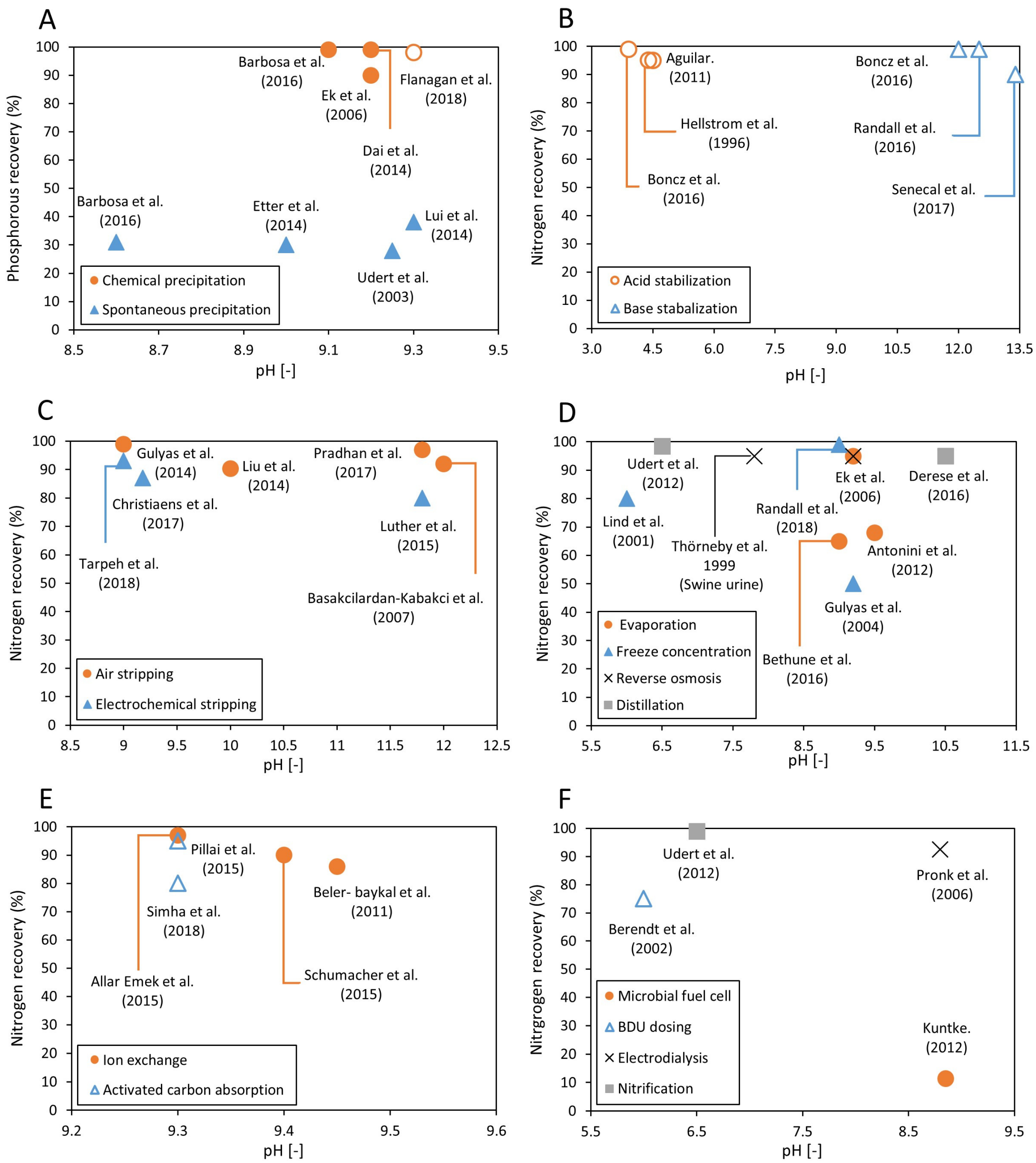

Figure 2-8: Summary of urine treatment methods from left to right: (A) phosphorus recovery from precipitation, (B) urea stabilization by base and acid addition, (C) nitrogen recovery from ammonia stripping, (D) nitrogen recovery from volume reduction, (E) nitrogen recovery from adsorption, and (F) alternate niche recovery techniques. All hallow markers indicate fresh urine was tested, and all solid markers indicated hydrolyzed urine was tested.

In cases where nitrogen recovery from hydrolyzed urine is stated, it is understood that urea hydrolysis and ammonia volatilization would have most likely occurred and caused a loss of nitrogen in the urine sample. However, the recovery percentages given in **Figure 2-8** are in reference to the nitrogen present in the solution used in each study, regardless of the state of urine.

2.5 Summary of literature

2.5.1 Public perception of source separation

The use of urine as fertilizers in developing countries holds great potential regarding supplementation of food security. Considering the resources required for central wastewater management, more universally available sanitation methods, that address the challenges faced in developing countries, are required. Moreover, results from pilot studies, pertaining to urine collection for resource recovery, indicate that societal resistance to these systems may not be as problematic as one might expect. There are encouraging signs that, despite scepticism regarding urine upcycling, the versatility of urine as a fertilizer source is not lost on individuals when they are made aware of the benefits. As stated by Kvarnström et al. (2006), on urine diversion, “The demonstration of good examples will facilitate the acceptance of new systems.”

2.5.2 Barriers to decentralized urine treatment

Aspects inhibiting the widespread implementation of urine collection for resource recovery are prevalent, despite the public displaying initial approval of the idea in some cases. Transportation planning is an important consideration regarding niche decentralized urine treatment, and GIS platforms provide a means for achieving this. Sophistication of existing technologies and pilot studies are still required to fill the gaps in knowledge which exist regarding decentralization with an emphasis on resource recovery in urban environments. In addition, previous literature suggests that decentralized urine treatment is potentially profitable if the usage and sale of urine derived fertilizers are widely accepted. This research aims to explore this notion further.

2.5.3 Urine treatment techniques

Nutrient recovery from urine could be important considering the ever-increasing global population and scarcity of resources. Previously tested treatment techniques tend to focus primarily on the recovery of phosphorus and nitrogen. This is because they are both arguably the most important constituents in modern day fertilizers (Spångberg et al., 2014). Moreover, published research of urine treatment processes that simultaneously aim to recover nitrogen and phosphorous are scarce.

Recovery of both nitrogen and phosphorous is limited because of certain factors. Such factors include: the pH and temperature of the urine, the quantity of divalent or trivalent ions required for solid precipitation and the occurrence of enzymatic urea hydrolysis. Although there are several different treatment techniques which yield varying recovery potentials, ultimately, the choice of treatment will depend on what nutrient(s) is desired as well as the associated cost. Maximum recovery of products from urine that results in zero waste have rarely been investigated and reported on. The information obtained from this literature review, in combination with the research objectives outlined in section 1.4, helped to provide a platform to form the methodology of this dissertation. This methodology is provided in the following chapter.

3 Research approach

This research aims to ascertain the feasibility of source-separated urine treatment for maximum recovery of resources. Urine treatment techniques and the logistics of a decentralized urine management and distribution system are investigated.

The following section describes the hypothesis and the key questions which were posed at the onset of this investigation. Two methods of investigation were employed to answer these questions. Previously researched methods of urine treatment were compared and design charts for urine treatment techniques, based on the complete upcycling of urine, were made. Following this, an economic feasibility assessment comparing four unique scenarios pertaining to the recovery of nutrients from source-separated urine was conducted. Both methods outlined utilized a quantitative research approach.

3.1 Hypothesis and key questions

The review of literature has shown that nutrient recovery from urine presents a promising solution to decreasing global phosphorous quantities, and a means for potentially increasing inorganic fertilizer supplies. Research pertaining to decentralized urine treatment offers little in terms of design guidelines which provide methods for maximum recovery of the nutrients present in urine. Furthermore, literature indicates that the implementation of decentralized urine treatment could be financially and environmentally feasible and accepted from a social perspective. Therefore, this dissertation presents two hypotheses:

1. **Urine stabilization by calcium hydroxide addition, together with reverse osmosis for volume reduction, is the most effective treatment scheme because it recovers all the nutrients in urine.**

2. **Decentralized urine treatment, which incorporates nutrient recovery in the form of fertilizer production, is profitable when large volumes of urine are collected and processed at a decentralized resource recovery facility. Moreover, this system produces lower GHG emissions and has a lower energy expenditure when compared with conventional WWT systems.**

3.1.1 Key questions

Following from the hypotheses presented and the information gathered during the review of literature, the following key questions were posed:

1. Which method(s) of urine treatment are best suited for maximum resource recovery, and what state of urine (fresh or hydrolyzed) is most conducive for achieving this?

2. If highly frequented locations such as shopping malls and universities are targeted for the installation of resource recovery systems, how would the urine be collected and what are the viable market avenues for the sale and use of urine derived fertilizers?

Detailed answers to questions one and two are discussed in Chapters 4 and 5 of this dissertation. The methodology employed for the creation of the urine treatment design charts and the decentralized urine treatment feasibility analysis can be found in sections 3.2 and 3.3.

3.2 Design charts methodology

The methodology for the creation of the urine design charts are presented in this section. Moreover, this methodology aimed to address the first research hypothesis outlined in section 3.1. A total of four treatment sequences were incorporated in the design chart creation. The determination of the most effective sequence of processes for maximum resource recovery consisted of the following steps:

- A thorough compilation and comparison of data obtained from literature pertaining to resource recovery from both fresh and hydrolyzed urine.

- The creation of design charts showcasing the effect of each individual process on the urine solution. The results of each process were assumed from previously published research, as outlined in the review of the literature.

3.2.1 Design chart descriptions

Flow process charts depicting an array of widely researched treatment techniques were created. Two sequences were included for both hydrolyzed and fresh urine. With regards to fresh urine, treatment sequences for both acid and base stabilization were included. In each scenario, a reduction of volume utilizing either RO or evaporation was investigated. In the case of hydrolyzed urine, nitrogen recovery by cation exchange and ammonia stripping was explored. Struvite precipitation through magnesium oxide addition was also considered for both hydrolyzed urine cases.

To account for the increase in nutrient concentration which would occur because of water removal, a mass balance of the influent and effluent water content of the urine solution was considered. It was assumed that pure water was produced in the permeate, leaving the salts as a concentrate. The NPK fertilizer characteristics of the effluent from each process sequence was also determined. Sample calculations for the obtaining the estimated final concentrations of each scenario can be found in Appendix A.

Several assumptions were employed to create a comparative analysis of each treatment scenario. These assumptions are given in **Table 3-1** .

Table 3-1: Numerical assumptions regarding urine treatment methods.

Description	Unit	Value	Source
Amount of $Ca(OH)_2$ dosed into fresh urine for urea stabilization	g/L of urine	10	Randall et al. (2016)
Amount of H_2SO_4 dosed into fresh urine for urea stabilization	g/L of urine	3	Hellström et al. (1999)
Amount of $Ca(OH)_2$ dosed into hydrolyzed urine for ammonia stripping	g/L of urine	22	Pradhan et al. (2017)
Urea decomposed to ammonium after $Ca(OH)_2$ or H_2SO_4 stabilization	%	0	Assumed
Urea decomposed to ammonium during urea hydrolysis	%	100	Assumed
Water removed during RO volume reduction	%	80	Ek et al. (2006)
Water removed during evaporation volume reduction	%	80	Assumed
Phosphorus recovery due to $Ca(OH)_2$ dosing	%	98	Flanagan & Randall (2018)
Phosphorus recovery due to calcium MgO dosing	%	99	Barbosa et al. (2016)
Nitrogen recovery due to ammonia stripping and absorption in hydrolyzed urine	%	99	Pradhan et al. (2017)
Nitrogen recovery due to cation exchange in hydrolyzed urine	%	97	Allar Emek & Beler Baykal (2015)
Density of urine	Kg/m^3	1 025	Pradella et al. (1988)
Density of liquid fertilizer	Kg/m^3	1 025	Assumed to be the same as urine density.

In addition to **Table 3-1**, it is acknowledged that a minor decrease in pH can occur during struvite precipitation, due to ammonium precipitation causing a decrease in alkalinity (Wilsenach et al., 2007). However, to standardise each treatment process for the creation of the design charts, it is assumed that no pH change occurs after each process other than in the cases of base or acid addition.

The actual composition of urine is not globally consistent, and depends on an individual’s diet, pharmaceutical intake, the physical activities they participate in, and the environment directly around them. To determine an approximate composition of urine, several sources of hydrolyzed and fresh urine were assessed. The composition of urine used to formulate the design charts is shown in **Table 3-2**.

Table 3-2: Composition of fresh and hydrolyzed human urine.

		Fresh Urine						Hydrolyzed Urine					
Source	**Unit**	**Randall et al. (2016)**	**Udert et al. (2003b)**	**Udert et al. (2003a)**	**Dai et al. (2014)**	**Luther et al. (2015)**	**Average**	**Pradhan et al. (2017)**	**Luther et al. (2015)**	**Dai et al. (2014)**	**Kuntke (2012)**	**Liu et al. (2013)**	**Average**
Mg	mg/L	57	95	77	36	59.8	65	0	0	0	0	0	0
PO_4^{3-}-P	mg/L	260	743	367	350	163	377	309	200	250	210	344	263
NH_4^+-N	mg/L	436	476	254	330	300	359	4 500	4 800	6 400	4 050	4 250	4 800
Urea- N	mg/L	5 420	7 564	5 810	7 400	5 500	6 339	0	-	0	0	0	0
Ca	mg/L	132	184	129	150	105.4	140	-	55.2	14	7.1	-	25
Na	mg/L	2 510	2 759	2 670	-	2 400	2 585	-	2 400	-	1 850	2 600	2 283
K	mg/L	469	2 189	2 170	-	1 900	1 682	1 700	1 900	-	1 490	2 000	1 773
Cl	mg/L	4 430	3 900	3 830	-	3 200	3 840	4 500	2 900	-	3 290	3 800	3 623
pH	mg/L	6.3	6.2	7.2	6.5	6.9	6.62	9.3	9.4	9.2	8.85	9.3	9.21

3.3 Decentralized urine treatment methodology

This section presents the methodology for the economic and environmental assessment of the proposed decentralized urine treatment system. Additionally, it serves to address the second hypothesis of this study, as outlined in section 3.1. To assess the feasibility of the proposed system, a decentralized transportation system was required to be modelled.

The assessment of the feasibility analysis consisted of the following steps:

1. Development of four separate design scenarios pertaining to the decentralized treatment of urine. The research approach taken to model these designs is outlined in sections 3.3.1 to 3.3.5.
2. An economic and environmental assessment for each scenario. The approach taken for this objective can be found in section 3.3.6.

3.3.1 System description

In the proposed decentralized system, conventional water-based urinals at shopping centres are retrofitted to become standalone NRUs, with 25 L capacity storage tanks at each urinal unit. An example of such a urinal unit is shown in **Figure 2-4**. In reality, the NRU model would need to be more aesthetically pleasing to have any long-term success, but for the sake of this investigation, any effect this may have was not taken into consideration. Shopping centres were selected as the most desirable urine collection locations for this investigation, as they are highly frequented, and it is assumed that urinals already exist in the male restrooms. Female oriented urinals are not at a high enough level of sophistication for widespread public usage and, furthermore, the NRU produced at the University of Cape Town was designed for male usage (Flanagan & Randall, 2018). Potential urine contributions by female users were, therefore, not considered for this research. However, Wilsenach & van Loosdrecht (2003) and Ekama et al. (2011) indicate that separating between 50 and 90% of urine from wastewater streams could potentially remove the need for biological nitrogen removal at conventional WWTPs. Therefore, assuming that approximately 50% of the population (males) participated in this system could still have significant impacts on the monetary cost, energy expenditure and GHG emissions of conventional WWTPs.

Urea hydrolysis is prevented in each container by calcium hydroxide dosing (Randall et al., 2016). Filled urinal containers are collected from each collection location once per week, by truck, and transported to a resource recovery facility (RRF). Once at the RRF, solid filtration of the collected urine occurs to separate the precipitated calcium phosphate (Ca-P) from the remaining liquid in solution. The solid filtration is done not only to recover the Ca-P solid fertilizer, but also to avoid clogging of the RO membranes. The separated Ca-P is dried, and the filtered liquid is subjected to volume reduction, by

RO, to concentrate the nutrients and separate the water content from the urine solution. This concentrated liquid has a high nitrogen content and is classified as an inorganic liquid fertilizer. Finally, the concentrated liquid and dried Ca-P is transported to a central packaging and distribution (PAD) facility where it is sold to wholesalers as fertilizers. A visual description of this system is shown in **Figure 3-1**.

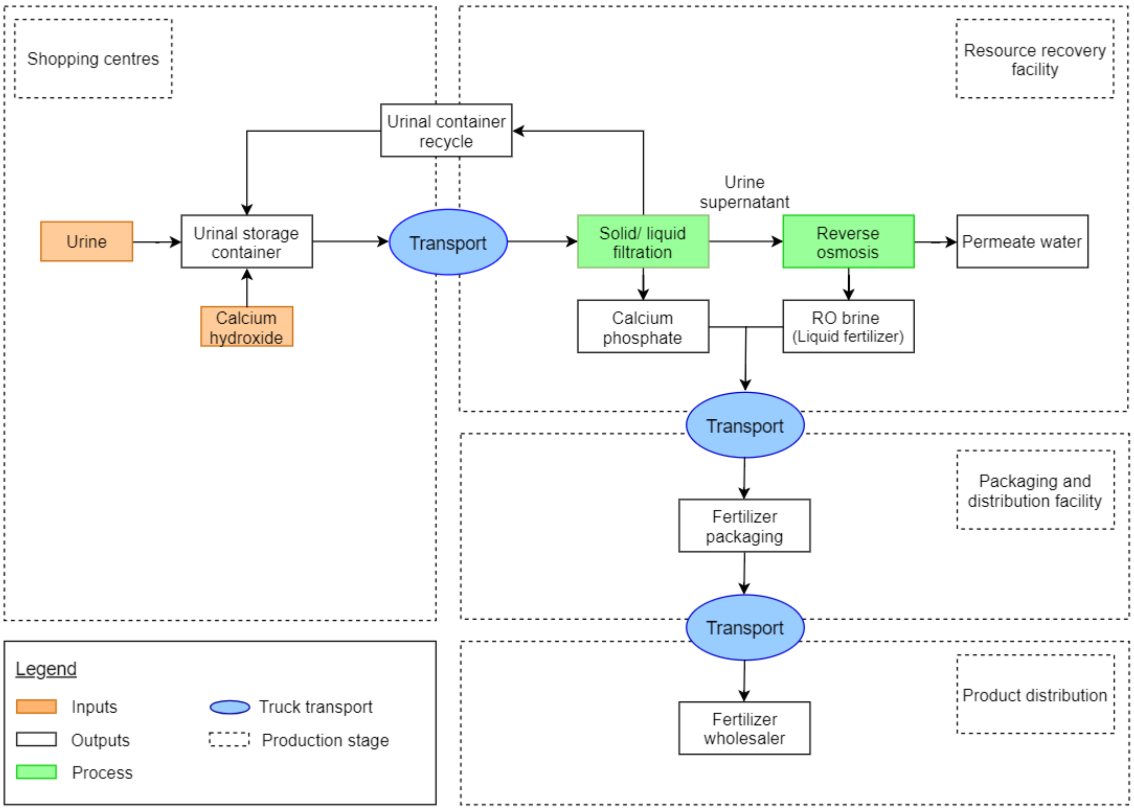

Figure 3-1: Process diagram of proposed source-separated urine treatment system.

3.3.2 Study area and collection location description

The City of Cape Town is a coastal city located near the southern-most part of South Africa, with an estimated surface area of 400 km^2 (StatsSA, 2018). This city was chosen as an illustrative case study to assess the potential impacts of decentralized urine treatment. Moreover, Cape Town was chosen as it is the second most populated city within South Africa, with a population density of 1530 people per km^2, and it also serves as the second most visited tourist destination in South Africa (StatsSA, 2018). The assumption was that the larger the population, the more urine could potentially be collected from highly frequented public locations. Additionally, the City of Cape Town experienced a drought in 2017 due to decreasing potable water levels in main supply dams (Donnenfeld et al., 2018). Using Cape Town as an illustrative example for the proposed system could display the potential for an alternate form of water conservation.

Furthermore, geospatial data for existing road networks, building locations and population density statistics are provided online by the City of Cape Town, for public use (CoCT, 2018b). These largely contributed to the feasibility of conducting a detailed last-mile logistics analysis.

The initial modelling step for this design involved identifying locations to be used as urine collection points. A total of eight collection locations were used; seven shopping malls and one university. An attempt was made to select locations within each of the Cape Town suburbs to evenly distribute the collection locations around the city. A map displaying the positions of the collection locations within the study area is shown in **Figure 3-2**.

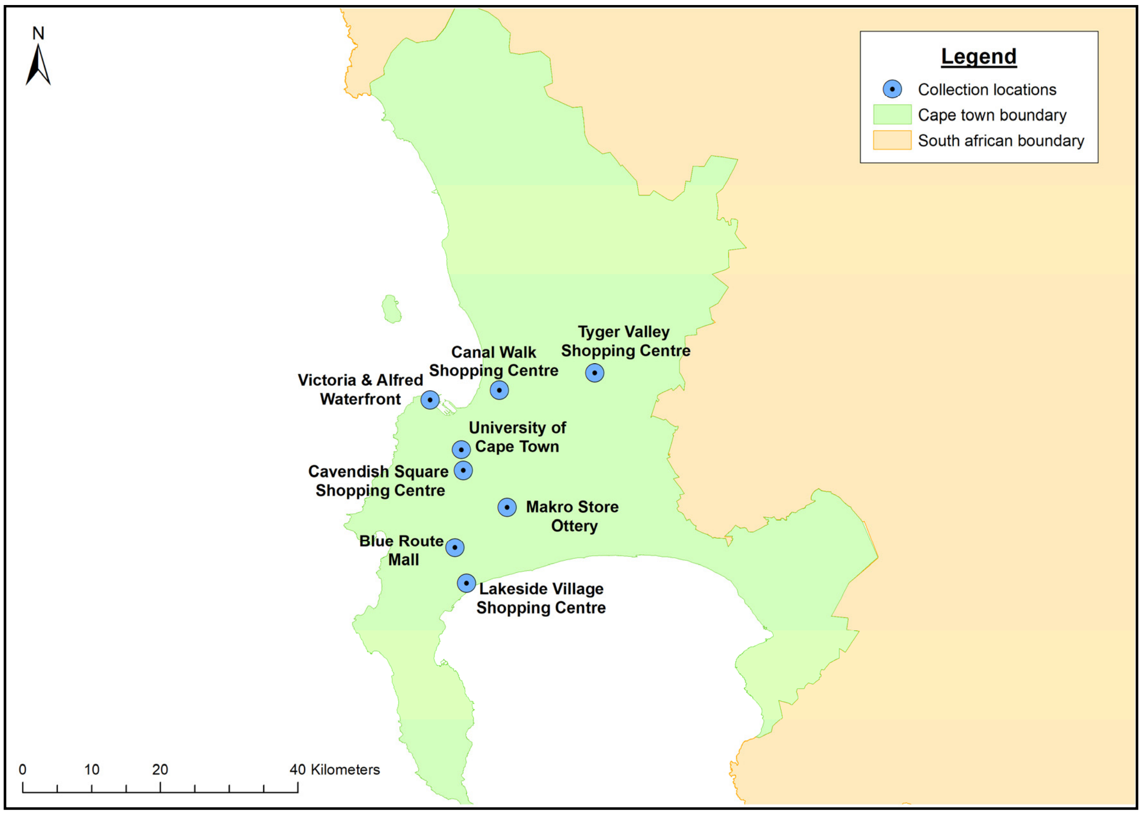

Figure 3-2: Study area in ArcGIS.

Research conducted by the Urban Studies Research Group (Prinsloo, 2013, Prinsloo, 2016) was used to uniformly estimate the average daily population frequency at each shopping mall, based on the retail area available at each location. The estimated retail area of each collection location is shown in **Table 3-3**. The population at the University of Cape Town (UCT) was sourced from the number of registered students and staff members, found from the official university website (UCT, 2017). It was assumed that each student and staff member visited the university at least once a day. In addition to this, it was assumed that the daily male population percentage within each location was 50%.

Table 3-3: Urine collection location details.

Collection locations	Retail area (m²)	Source
Blue Route Mall	55 500	BusinessTech.com (2018)
Canal Walk Shopping Centre	147 000	
Cavendish Square	45 000	
Lakeside Village Shopping Centre	7 500	
Makro Store Ottery	12 000	
Tyger Valley Shopping Centre	90 000	
Victoria & Alfred Waterfront	69 000	
University of Cape Town	N/A	N/A

Data detailing the number of urinals currently installed at each collection location is not publicly available. However, the approximate number of urinals required at each location was estimated based on the minimum required number of urinals in public spaces at peak demand, as per the South African National Standards (SANS, 2012). These requirements are based on the number of daily visitors at buildings designed for public use (SANS, 2012). Moreover, it would be difficult to obtain accurate data pertaining to the average usage of urinals per day per location. Therefore, it was assumed that each 25 L capacity NRU is filled every week prior to collection by truck.

3.3.3 Design scenarios

The proposed system was assessed based on four separate design scenarios. Each scenario incorporated either on-site or off-site solid filtration (or a combination of the two), followed by RO treatment. Each successive scenario featured an increase in the number of treatment facilities, whereas only one central PAD facility was utilized for all four scenarios. All the final treated fertilizer is packaged and transported to a wholesaler from the PAD facility in each scenario. The same quantity of urine is collected and treated in each scenario. The more RRFs added, the closer these facilities moved towards the collection locations (based on optimized placement), until an RRF is allocated to each location. In the final scenario, there were eight treatment facilities, and this can be likened to having the urine treated 'on-site'. In each scenario, urine collection containers from each location are collected once per week and replaced with an empty collection container (with an appropriate amount of calcium hydroxide powder inside).

In scenario one, there was only one RRF which all stabilized urinal containers are delivered to by truck. This central treatment facility also acted as the PAD facility, as both facilities were in the most central location, with respect to the collection locations, based on average distance. In scenarios two, three and four; two, four and eight RRFs were incorporated, respectively. The purpose of these scenarios was to determine the ideal level of decentralization required to minimize the GHG emissions, energy and cost amongst the chosen design scenarios. A summary of the chosen design scenarios is shown in **Table 3-4**.

Table 3-4: Summary of design scenarios descriptions

Design Scenario	Number of resource recovery facilities	Number of packaging and distribution facilities	Number of trucks
Scenario 1	1	1	1
Scenario 2	2	1	1
Scenario 3	4	1	1
Scenario 4	8	1	1

3.3.4 Resource recovery facility location optimization

With the coordinates of each collection location known, the optimal location of the RRF and PAD facilities needed to be calculated using geospatial analysis. Flowmap, a transportation planning software created by Utrecht University in the Netherlands, was used for these calculations.

GIS programmes are the most popular geospatial analysis platforms amongst designers and engineers and are designed to manage and display spatial data. Despite this, they do not incorporate the management and interpolation of pairs of data (De Jong & Van der Vaart, 2013). Essentially, GIS programmes can only choose optimal locations, based on an already existing location selection. The Flowmap software specializes in network analysis and interactions between all elements within a network (De Jong & Van der Vaart, 2013). Therefore, it was used to determine the most optimal location to service a demand, based on distance (using the existing Cape Town road network) and not established locations. Flowmap is a supplementary program intended to be used in tandem with GIS.

ArcGIS compatible files are typically referred to as ‘shapefiles’. The first step of the location optimization section required the acquisition of shape files for Cape Town as the study area, using ArcGIS (a GIS software package). The Cape Town road network and the chosen collection locations shape files were also necessary. All shapefiles were sourced online through the City of Cape Town’s open access database (CoCT, 2018b). Furthermore, the geographic coordinate system and projected coordinate systems used were the WGS 84 geodetic system and the WGS world Mercator. These shapefiles were then converted to Flowmap data files.

By choosing the number of required service locations (RRFs), the optimum location, along the Cape Town road network, which satisfied the demand, of each shopping mall was found. The locations of these RRFs were then optimized to minimize the overall average distance from each location to the RRF it was allocated to. This same methodology was used to determine the best locations for up to 8 different RRFs. Moreover, each shopping centre was allocated to its nearest RRF (spatial rationality)

(De Jong et al., 2005). To prevent the Flowmap software from assigning the service locations based on the highest market share, each collection location was given the same demand and supply weight within the Flowmap software. It is understood that the collection locations with higher visitor frequencies will contribute more to the urine supply, but this was not taken into consideration during the transportation modelling. This was done to maximize the overall network coverage of the service locations. The coordinates of the optimized collection locations were converted back into ArcGIS shapefiles to conduct the transportation network analysis. The layout of the Cape Town road network and collection locations used in Flowmap are displayed in **Figure 3-3**. A more detailed description of the procedure followed to determine the best allocation of treatment facilities, for minimum average distance, can be found in Appendix B.

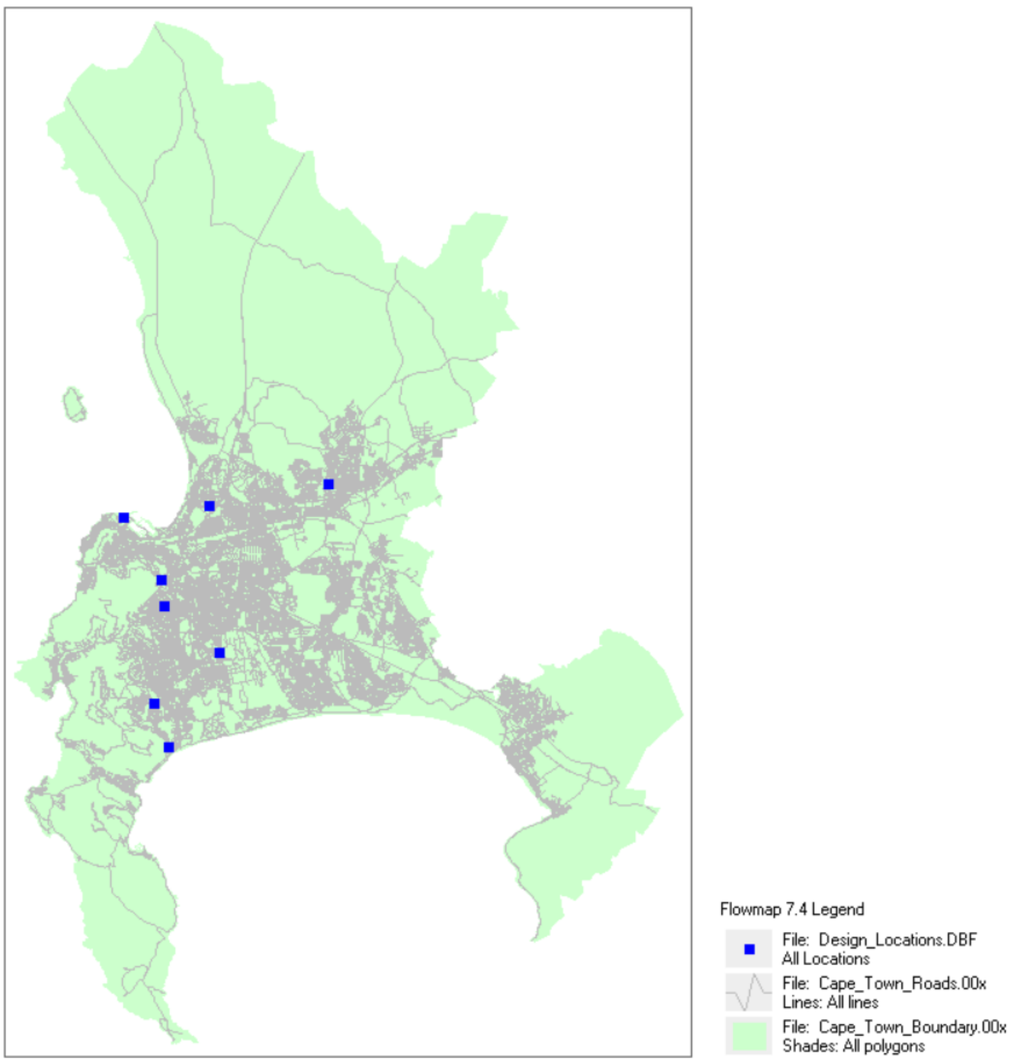

Figure 3-3: Study area layout in Flowmap.

3.3.5 Transportation network and last-mile logistics

With the supply and demand location information known, the last-mile logistics modelling could be conducted using the Cape Town road network.

Using the network analyst ArcGIS tool, the travel distances and routes travelled within each scenario were modelled using the travelling salesman problem (TSP). The TSP considers the shortest possible route that is required to be taken to reach all locations within a network (Mosheiov, 1994). An illustrative representation of a TSP can be seen in **Figure 3-4**.

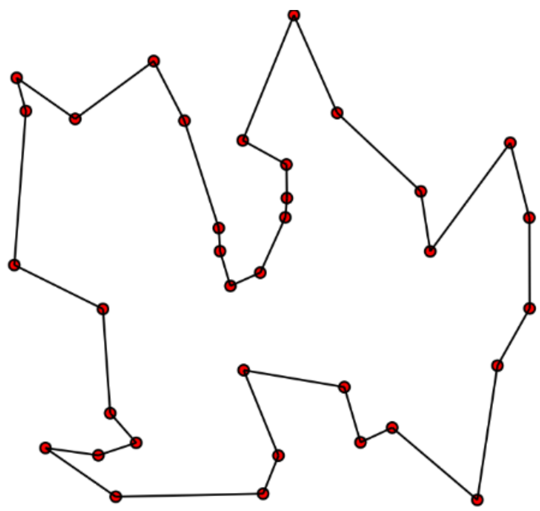

Figure 3-4: Travelling salesman problem solution (Kavvada et al., 2017).

With regards to proposed study area, the TSP was used to determine the minimum possible distance, within the Cape Town road network, that allowed a truck to visit each location at least once during collection. It was assumed that in each scenario, trips originated and ended at the PAD facility. This allowed for a detailed analysis on the financial and environmental effects of transportation on the proposed system. For simplicity, factors such as traffic jams and traffic lights were not considered, although it is acknowledged that their inclusion would be necessary in any real-life application of the proposed decentralized systems.

A 4-ton truck was chosen as the form of transportation. There were many limiting factors pertaining to the performance of the truck. Therefore, several assumptions were incorporated during the logistics and transportation modelling of the proposed system. These assumptions are shown in **Table 3-5**.

Table 3-5: Criteria used for last-mile logistics modelling.

Description	Unit	Value	Source
Average truck speed	km/hr	60	assumed
4-ton truck fuel consumption	km/L	6.7	Department of Agriculture and Forestry (DAFF, 2017)
8-ton truck fuel consumption	km/L	3.3	(DAFF, 2017)
14 -ton truck fuel consumption	km/L	2.5	(DAFF, 2017)
Calcium phosphate produced from calcium hydroxide dosing in fresh urine	g/Kg urine	11	Flanagan & Randall (2018)
Calcium phosphate density	kg/m^3	3 140	ChemicalBook (n.d.)
Urine produced per person	L/day	1.15	von Münch & Winker (2011)
Average urination frequency per person	Urinal visits/day	5	Rossi et al. (2009)
Urine produced per urinal usage	L/urinal usage	0.23	Assumed from average urination frequency.
Water used per flush in conventional waterborne urinals	L	4	von Münch & Dahm (2009)
Density of urine	Kg/m^3	1 025	Pradella et al. (1988)
Liquid fertilizer produced from RO	L/L urine	0.2	Ek et al. (2006)
Permeate water produced from RO	L/L urine	0.8	Ek et al. (2006)

3.3.6 Economic and environmental analysis

In the economic and environmental analysis, the results obtained from previous research at UCT (Flanagan & Randall, 2018) were scaled up to match the results from the transportation and logistics methodology outlined in sections 3.3.1 to 3.3.5. As such, the economic and environmental viability of the proposed decentralized system was assessed based on the following indicators (as will be explained in detail in the sections to follow):

- Capital expenditure (CAPEX).
- Operating expenditure (OPEX).
- Cost recovery of liquid and solid fertilizers.
- Net present cost (NPC)/Net present value (NPV) over an investment period of five years.
- Water usage and conservation.
- GHG emissions.

Sample calculations used to estimate all economic indicators can be found in Appendix B.

3.3.6.1 CAPEX estimations

The components which contributed to the CAPEX of each system were the provision of NRUs by retrofitting existing urinal installations, the trucks (assumed to be purchased once-off), the rental deposits for warehouse space and the RO units required for volume reduction. The monetary scaling of RO units was assumed to be linear in relation to the quantity of urine treated. Moreover, units of exact sizes for each scenario were assumed. The NRUs do not utilize any of the sewer connections within each building, thus retrofitting costs pertaining to existing piping networks were not considered for the financial feasibility of this study.

3.3.6.2 OPEX estimations

The components identified as contributors to the OPEX of the system included labour, energy requirements, calcium hydroxide for urine stabilization and rental expenses for treatment facilities and the packaging and distribution centres. The labour costs arose due to the need for truck drivers, warehouse workers and site managers. Each collection location included a site manager tasked with overseeing successful operation and maintenance of the urinal units on site, on a day to day basis. It is understood that labour costs could be decreased if automation of tasks such as filtration and RO unit operations were viable, but this was not considered for this investigation.

Furthermore, the rental space was calculated based on the function of each facility. Each RRF was expected to have the surface area required to store all the stabilized urine treated in the system per month, house the RO and filtration units and have adequate working space for warehouse employees. PAD facilities were expected to have the surface area required to store all fertilizer produced and have adequate working space. The Broll Property Group database was used to source Cape Town rental prices (Broll.com, 2018). Two daily employees were stationed at each RRF to conduct the RO and filtration processes and attend to the cleaning and maintenance of the machinery. Likewise, two daily employees were stationed at the PAD facility to collect and package the recovered fertilizer. Furthermore, for five days a week, eight hour working days were assumed for all employees, with the only exception being the truck drivers. Truck drivers were assumed to be paid an hourly wage that was consistent with the estimated weekly transportation time. Additionally, a urinal container loading/ offloading time of 15 minutes per stop was assumed when calculating the truck driver wage for the overall OPEX.

The operating and maintenance costs associated with an MLE AS system was compared to that of the proposed decentralized system for direct reference with centralized biological nutrient removal.

3.3.6.3 Cost recovery of liquid and solid fertilizers

The selling price of Ca-P fertilizer was assumed from recent market prices for urine derived granular fertilizers, which estimated the price to be R18 500 per ton of Ca-P (Herman, 2017). However, the selling price of liquid fertilizer was calculated differently. Ten commercially available liquid-based fertilizers were sourced and compared based on their nitrogen content. The commercial fertilizers chosen included both fertilizers for ornamental vegetation and vegetation intended for consumption. This was done because the best use of the urine derived liquid fertilizer and which vegetation it would be most effective on is yet to be tested. A least square regression analysis on liquid fertilizer selling prices versus nitrogen content, by weight, was done. This was done to determine an appropriate design selling price for the liquid fertilizer created in the proposed system.

Moreover, this analysis assumed that the urine derived liquid fertilizer could enter the South African market and be sold on par with commercially available fertilizers. The potential nitrogen content of the urine derived liquid fertilizer was calculated during the urine treatment design charts creation process and it’s chosen selling price was then extrapolated from the liquid fertilizer least square regression analysis. The cost recovery did not include packaging and delivery costs associated with the sale of the finished products.

3.3.6.4 NPV/NPC

The net present value or cost of installing and operating the entire system over a period of 5 years was determined to compare the monetary implications for each of the investigated scenarios. A 5-year investment period was used to assess each scenario over a long-term investment period. A discount rate of 10% was used for this evaluation.

3.3.6.5 Greenhouse gas estimations

GHG emissions were based on carbon dioxide (CO_2) production from the electricity requirement for RO and fuel consumption for trucks. Carbon dioxide makes up 97% of the GHG emissions from passenger vehicles. The remaining 3% is made up of methane, nitrous oxide and air conditioning refrigerant (EPA, 2018). These are not based on fuel consumption, but rather on the specific design of different vehicles. Thus, it is not easy to estimate these for the purposes of this model. The CO_2 emissions were directly compared to those emitted by an MLE AS configuration for biological nitrogen removal.

3.3.6.6 Water savings

The proposed system does not utilize a water-based flushing system. The potential impacts observed from converting to a waterless system were thus investigated. This included an estimation of the quantity of water saved per annum, as well as the water and sanitation and sewer system connection costs that would be applicable, as per the City of Cape Town tariffs (CoCT, 2018a). In 2017, City of Cape Town experienced a drought resulting from a water shortage (ref). As a result, the water tariffs imposed between then and the time of compiling this dissertation have been inconsistent. The tariffs used in the economic evaluation in this study represent the water, sanitation and sewer connection tariffs for commercial use on 1 December 2018 (CoCT, 2018a).

3.3.6.7 System calculation parameters

The expenses incorporated into the economic and environmental feasibility of this study are shown in **Table 3-6**.

Table 3-6: Assumed capital and operating costs.

Description	Unit	Value	Source
4-ton truck (once-off purchase)	R	554 931	Department of Agriculture and Forestry and Fisheries (DAFF, 2017)
8-ton truck (once-off purchase)	R	712 650	(DAFF, 2017)
14-ton truck (once-off purchase)	R	995 000	(DAFF, 2017)
4-ton truck maintenance	R/km	7.77	(DAFF, 2017)
8-ton truck maintenance	R/km	9.79	(DAFF, 2017)
14-ton truck maintenance	R/km	13.16	(DAFF, 2017)
Truck Fuel	R/L	16.85	Automobile association (AA.com, 2018)- Taken from price of fuel at 1 December 2018.
Industrial RO unit cost	10 R/m^3/day	100 000	(Nathoo, 2018)
Nutrient recovery urinal unit	R	800	Flanagan & Randall (2018)
Warehouse rental per m^2	R/ month	64	(Broll.com, 2018)
Warehouse space deposit	R/m^2	128	Assumed to be double the one month's rent.
Warehouse worker office and work space requirements per facility	m^2	50	Assumed
RO unit geometric footprint	m^2 per 10 m^3 urine treated per day	9	Nathoo (2018)
Truck driver wage	R/hr	82	Indeed.com (2018a)

Table 3-6: Assumed capital and operating costs (continued).

Description	Unit	Value	Source
Warehouse work wage	R/hr	60	Indeed.com (2018b)
Cleaning and maintenance wage	R/hr	60	Tyler (2017)
RRF site manager wage	R/hr	60	Assumed
RO energy consumption	kWh/m^3	2	Nathoo (2018)
Electricity	R/kWh	2.84	Eskom (2018)
Calcium hydroxide	R/kg	3.1	Alibaba.com (2018)
Calcium phosphate selling price	R/kg	18.5	Herman (2017)
Liquid fertilizer selling price	R/L	151.52	Assumed from least square regression
Water	R/m^3	43.13	CoCT (2018a)
Sewer connections	R/ m^3 flushed	34.83	CoCT (2018a)
BNR operating costs	R/m^3 wastewater	27.35	Environmental Protection Agency (EPA, 2007) – adjusted for inflation to 1 December 2018, at 2% per annum and converted to South African Rands at an exchange rate of \$1 to R14.43 as per exchange rate at 11 December 2018.
BNR energy consumption	kWh/kg N	2.3	Mulder (2003)
BNR GHG emissions	Kg CO_2/kg N	3	Falk et al. (2013)
Diesel GHG emissions	Kg CO_2/L fuel	2.7	Fruergaard et al. (2009)
Electricity GHG emissions	Kg CO_2/kWh	0.92	Guan (2006)

3.3.7 Sensitivity analysis

Potential variations in the factors which contribute to revenue and to expenses were considered. This was done to determine which aspects contributed the most to the financial feasibility of the proposed system and how any potential negative effects could be alleviated. The impacts experienced from varying the following aspects (of each scenario) were evaluated:

- Carrying capacity of the truck.
- Selling price of fertilizer product.

- Quantity of fertilizer sold.

With regards to the truck used, the financial and environmental impact observed from the use of a 4, 8 and 14-ton truck was measured. The liquid fertilizer selling price required to equate the total income to the total cost (break-even), when all the fertilizer that is produced is sold, was calculated. Likewise, the quantity of the fertilizer sold was varied based on the amount of liquid fertilizer sales required to break-even at the design fertilizer selling price. Moreover, estimated liquid fertilizer sales, sourced from local plant nurseries in Cape Town were considered during this sensitivity analysis. The break-even point for these estimated sales values were subsequently calculated.

All break-even points were calculated over a 5-year period, while taking inflation into account with a discount rate of 10%.

4 Results and discussion: treatment process design charts

The first of two results and discussion chapters is presented here. The aim of this chapter was to answer the first research question:

Which method(s) of urine treatment are best suited for maximum resource recovery, and what state of urine (fresh or hydrolyzed) is most conducive for achieving this?

This question was answered by conducting a thorough review of published literature and the creation of design charts which showed various treatment process sequences.

Design charts for the treatment and recovery of resources from fresh urine and hydrolyzed urine are given in sections 4.1 and 4.2. This culminates in an overall discussion and summary in section 4.3. The methodology used to evaluate the abovementioned research question is given in section 3.2 of Chapter 3. The observations from this chapter (Chapter 4) provide insight into previously published urine treatment processes which could lead to maximum resource recovery from urine.

Literature has shown that several treatment techniques have been employed to recover nitrogen and phosphorus at lab scale with high recovery rates. Four treatment scenarios are presented, but several different combinations of technologies could also be appropriate. Moreover, all values and assumptions used are completely derived from literature, as shown in **Table 3-1**. An emphasis was placed on nutrient recovery by phosphorous precipitation and volume reduction for the creation of these charts. This is because these techniques appear to be the methods most suited for maximum resource recovery from urine, based on reported recovery rates. Complete recycling of all the resources present in urine, with as little waste as possible, was the main objective of this study.

4.1 Fresh urine nutrient recovery

4.1.1 Base stabilization

Calcium hydroxide was chosen as the preferred base for alkaline urine stabilization because it can recover phosphorous and prevent enzymatic urea hydrolysis, as shown in **Figure 4-1**. Other bases such as sodium hydroxide can be used for urine stabilization, but the precipitation potential of other alternative bases in this context has not been widely investigated. Flanagan & Randall (2018) found that 11 g of Ca-P could be precipitated from 1 kg of urine, recovering 98% of the phosphorus present in urine. In addition, it is assumed that urine stabilization also allows for volume reduction without ammonia volatilization.

For every three calcium ions, two phosphate ions are required for calcium phosphate production (PubChem, 2018). Randall et al. (2016) suggested that 10 g/L of calcium hydroxide should be dosed to fresh urine for effective stabilization. Subsequently, all calcium that is not precipitated out as Ca-P will remain in the solution during further treatment.

After undergoing solid filtration and RO to separate the water from urine, the solution will be highly concentrated as shown in **Figure 4-1**. Evaporation and distillation were also considered as an alternative volume reduction technique. Solid fertilizers can be produced by urine evaporation (Antonini et al., 2011, Dutta & Vinnerås, 2016), but It was assumed that both RO and evaporation reduce the volume of urine to the same amount in this investigation, for comparative purposes. Furthermore, having the nutrient content in liquid form makes nutrients more accessible to plant roots (Cordell et al., 2009). **Table 4-1** displays the nutrient concentrations of the urine solution after each respective treatment process shown in **Figure 4-1**. Importantly, the phosphorous concentration would not increase after volume reduction due to the Ca-P precipitation induced by the addition of calcium hydroxide to fresh urine.

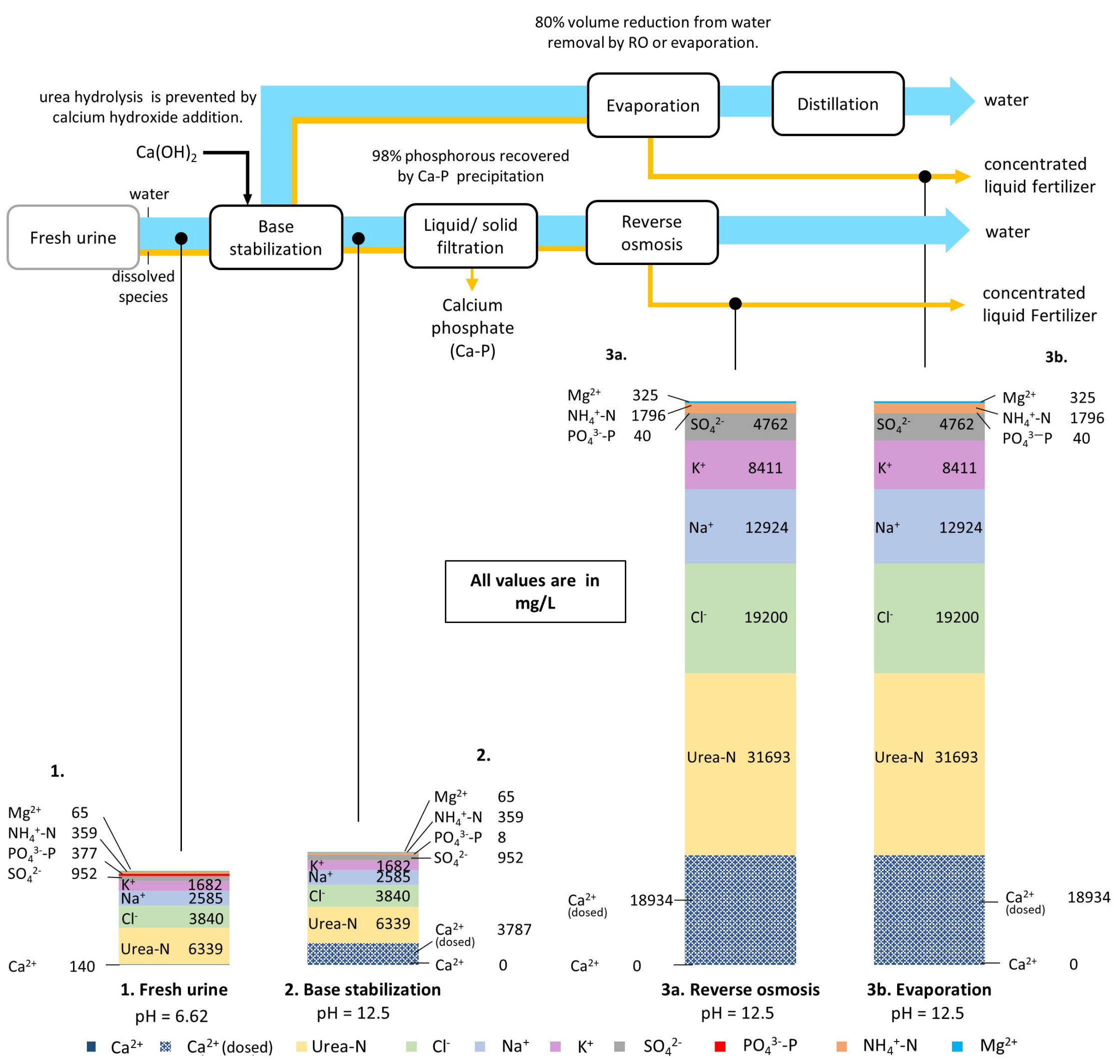

Figure 4-1: Fresh urine treatment options following base stabilization.

The size of the arrows in the **Figure 4-1**, **Figure 4-2**, **Figure 4-3** and **Figure 4-4** represent a mass flow of dissolved nutrients in urine and water. Moreover, the processes utilized are outlined by black borders: for example, in **Figure 4-1**: base stabilization, liquid/solid filtration, RO, evaporation and distillation.

Table 4-1: Nutrient concentrations in solution, following each respective treatment technique in **Figure 4-1**.

	Units	1. Fresh Urine	2. Base stabilization	3a. Reverse Osmosis	3b. Evaporation	Amount recovered as a Ca-P (%)	Amount recovered as liquid fertilizer (%)
Ca^{2+}	mg/L	140	0	0	0	100	0
Ca^{2+} (from $Ca(OH_2)$ dosing)	mg/L	0	3817	18 934	18 934	30	70
Urea-N	mg/L	6 339	6 339	31 693	31 694	0	100
Cl^-	mg/L	3 840	3 840	19 200	19 200	0	100
Na^+	mg/L	2 585	2 585	12 924	12 924	0	100
K^+	mg/L	1 682	1 682	8 411	8 411	0	100
SO_4^{2-}	mg/L	952	952	4 762	4 762	0	100
NH_4^+-N	mg/L	359	359	1 796	1 796	0	100
Mg^{2+}	mg/L	65	65	325	325	0	100
PO_4^{3-} -P	mg/L	377	8	40	40	98	2
pH	N/A	6.62	12.5	12.5	12.5	N/A	N/A

4.1.2 Acid stabilization

Acid stabilization was also explored as shown in **Figure 4-2**. Hellström et al. (1999) indicates that sulphuric acid and acetic acid are both applicable stabilizing agents. Sulphuric acid was the preferred acid in this study because it resulted in a lower pH for similar volumetric input. Research regarding phosphorous precipitation at low pH values is limited, and thus was not considered for the acid stabilization chart in **Figure 4-2**. Once stabilized by sulphuric acid, similar to stabilization with calcium hydroxide, water removal can be employed to reduce the volume and concentrate all the remaining components present in the urine. The dosed sulphuric acid would remain in the solution during the treatment processes that follow acid stabilization.

Table 4-2 displays the nutrient concentrations of the urine solution after each respective treatment process in **Figure 4-2**.

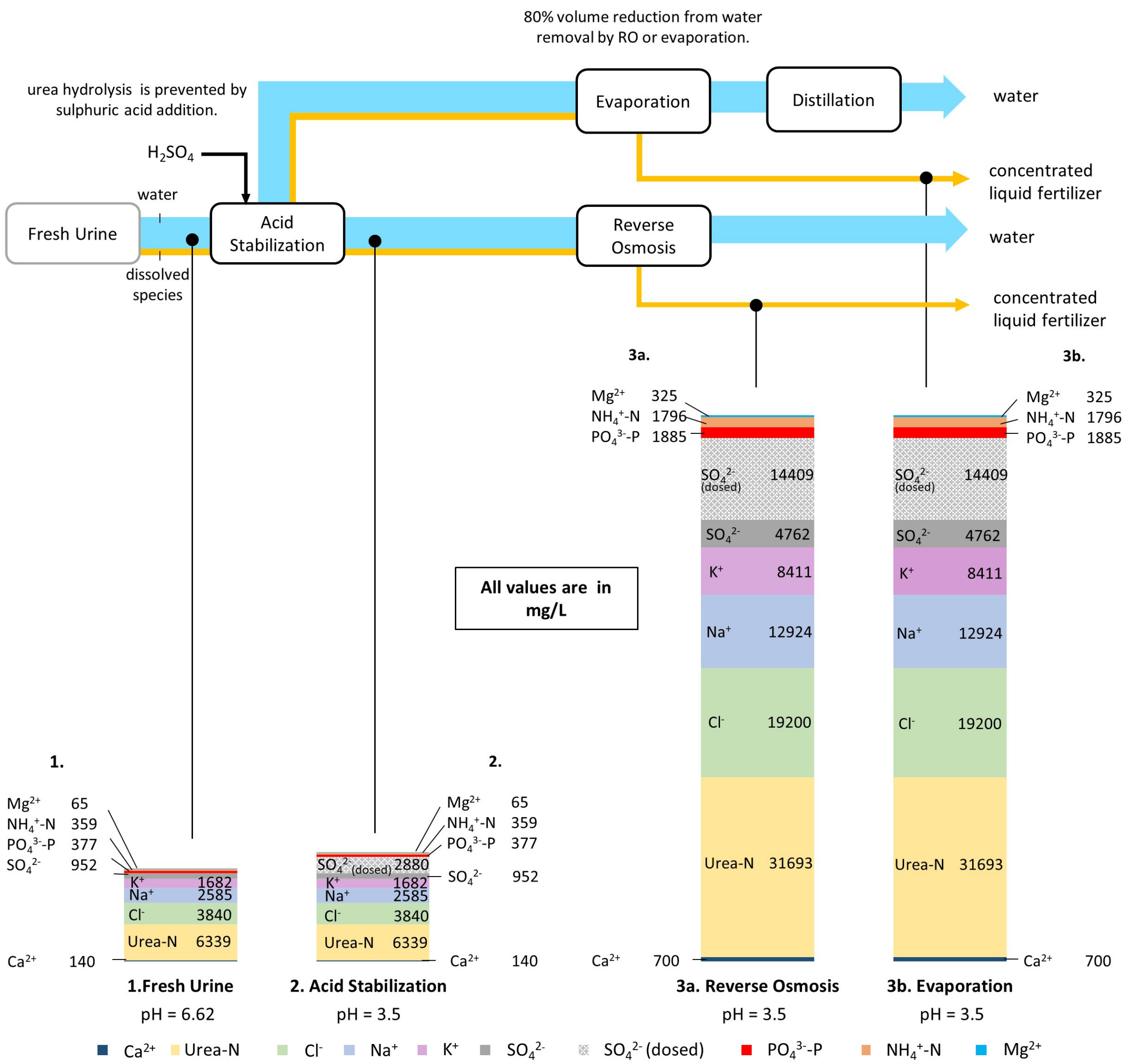

Figure 4-2: Fresh urine treatment options following acid stabilization.

Table 4-2: Nutrient concentrations in solution, following each respective treatment technique in **Figure 4-2**.

	Units	1. Fresh Urine	2. Acid Stabilization	3a. Reverse Osmosis	3b. Evaporation	Amount recovered as solid fertilizer (%)	Amount recovered as liquid fertilizer (%)
Ca^{2+}	mg/L	140	140	700	700	0	100
Urea-N	mg/L	6 339	6 339	31 694	31 694	0	100
Cl^-	mg/L	3 840	3 840	19 200	19 200	0	100
Na^+	mg/L	2 585	2 585	12 924	12 924	0	100
K^+	mg/L	1 682	1 682	8 411	8 411	0	100
SO_4^{2-}	mg/L	952	952	4 762	4 762	0	100
SO_4^{2-} (from H_2SO_4 dosing)	mg/L	0	2 880	14 409	14 409	0	100
NH_4^+-N	mg/L	359	359	1 796	1 796	0	100
Mg^{2+}	mg/L	65	65	325	325	0	100
PO_4^{3-} -P	mg/L	377	377	1 885	1 885	0	100
pH	N/A	6.25	3.5	3.5	3.5	N/A	N/A

4.1.3 Fresh urine discussion

Three volume reduction techniques were investigated when creating the fresh urine design charts: RO, freeze concentration and a combination of evaporation and distillation. Evaporation of urine at atmospheric pressure typically requires a temperature of between 40°C and 65°C (Antonini et al., 2011, Derese & Verliefde, 2016), but it is understood that subjecting fresh urine to temperatures above 50°C could cause chemical hydrolysis (Randall et al., 2016). Evaporation and distillation of urine within a vacuum reportedly allows for a decrease in the temperature required (30°C) (Ek et al., 2006), but may be difficult to facilitate on a large scale and would add to the total energy requirements. Senecal & Vinnerås (2017) and Boncz et al. (2016) have shown that evaporation of base and acid stabilized urine can occur at 35 and 45°C with limited urea hydrolysis occurring. However, in these studies the evaporation process reportedly took 46 days and 20 days to accomplish, respectively.

Freeze thaw experiments have been documented to have lower nitrogen recovery (up to 80%) (Lind et al., 2001) and high energy expenditure, in comparison to RO (95%) and evaporation (95%) (Ek et al., 2006), unless conducted in an environment with an already low temperature climate (Gulyas et al., 2004). Moreover, EFC of hydrolyzed urine requires a freezing temperature of -30°C for a nitrogen recovery rate of 99% (Randall & Nathoo, 2018). Reverse osmosis of wastewater (J. Rodríguez et al., 2002), urine (Ek et al., 2006, Thörneby et al., 1999) and salt water (Wimalawansa, 2013) can occur at room temperature with close to complete nutrient retention. For this reason, it appears that RO is the most effective water removal technique in terms of operating temperature and recovery rates.

Despite the employment of a stabilization pre-treatment step, concerns regarding the potential of scaling within the pores of RO membranes do exist (Lee & Lee, 2000). There is very limited published research regarding the use of RO to concentrate fresh urine. However, Ek et al. (2006) found that RO of hydrolyzed urine, with little scaling, was possible by subjecting the solution to a 5μm filter cartridge as a pre-treatment step. Therefore, it is assumed that scaling would not be a major problem for RO of fresh urine, provided maximum phosphorous precipitation and solid filtration is achieved prior to the RO step. Further research regarding the use of RO to concentrate fresh urine is required though.

Acid stabilization of fresh urine, with sulphuric acid, provides an option for urea stabilization. However, base stabilization (preferably using calcium hydroxide) was chosen as the most appealing method for urine stabilization, and subsequently, nutrient recovery from fresh urine. This is due to the benefits calcium hydroxide dosing presents such as phosphorous recovery and preventing enzymatic urea hydrolysis.

4.2 Hydrolyzed urine nutrient recovery

4.2.1 Struvite precipitation and ammonia stripping

Precipitation as a result of magnesium addition to urine is one of the most widely researched forms of phosphorus recovery from urine. Barbosa et al. (2016) states that struvite formation occurs in as quickly as 20 minutes after magnesium addition. Both **Figure 4-3** and **Figure 4-4** display a sequence of methods which indicate a means of recovering phosphorus from hydrolyzed urine using this precipitation method.

Barbosa et al. (2016) and Wilsenach et al. (2007) suggest that the magnesium source for chemical precipitation does not matter, as long as the Mg to P molar ratio in urine is roughly 2:1 after dosing. As a result, the recommended dosage of magnesium for maximum phosphorous recovery in urine is dependent on the concentrations of both magnesium and phosphorous in the urine sample prior to treatment.

In **Figure 4-3** and **Figure 4-4**, magnesium oxide was used as the chosen compound to illustrate induced precipitation, because it has a high magnesium content for a smaller mass, when compared to magnesium chloride and magnesium hydroxide (Barbosa et al., 2016, Wilsenach et al., 2007). Moreover, the addition of MgO leads to a slight pH increase, that can be beneficial if pH adjustment is required for struvite precipitation (Wilsenach et al., 2007). Minor nitrogen recovery can be achieved by struvite precipitation, as 3 to 5% of ammonium in hydrolyzed urine can be precipitated out of solution with struvite (Etter et al., 2015).

Stripping and absorption of ammonia can then be employed to recover the nitrogen remaining in the urine , as indicated by Pradhan et al. (2017) and shown in **Figure 4-3**. The acceleration of the stripping process can be facilitated by increasing the solution temperature or pH. Increasing the temperature will increase the energy consumption of the process though (Liu et al., 2014). Calcium hydroxide was used to increase the pH of the solution as shown in **Figure 4-3**. Pradhan et al. (2017) recommended that 22 g/L of calcium hydroxide is an adequate dosage for complete ammonia stripping from urine. Absorption of the stripped ammonia gas can then be facilitated by exposing the ammonia to sulphuric acid. **Table 4-3** displays the nutrient concentrations of the urine solution after each respective treatment stage.

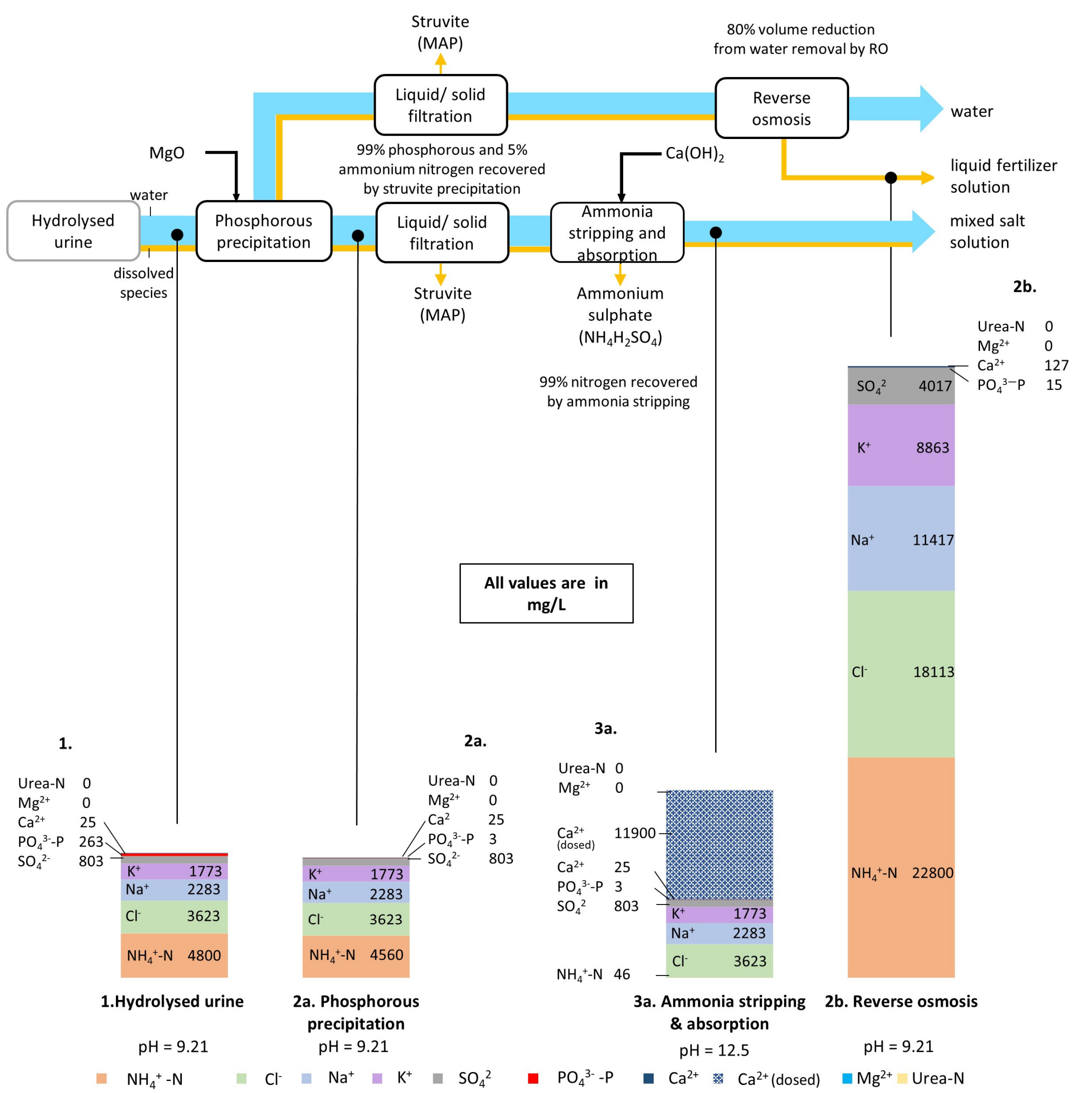

Figure 4-3: Hydrolyzed urine treatment options following phosphorous precipitation and ammonia stripping.

Table 4-3: Nutrient concentrations in solution, following each respective treatment technique in **Figure 4-3**. All nutrients that are not recovered in struvite and ammonium sulphate will remain in solution for any potential further treatment.

	Units	1. Hydrolyzed Urine	2a. Precipitation	3a. Ammonia Stripping & Absorption	2b. Reverse osmosis	Amount recovered as struvite (%)	Amount recovered as ammonium sulphate (%)
NH_4^+/NH_3-N	mg/L	4 800	4 560	45	22 800	5	94
Cl^-	mg/L	3 623	3 623	3 623	18 113	0	0
Na^+	mg/L	2 283	2 283	2 283	11 417	0	0
K^+	mg/L	1 773	1 773	1 773	8 863	0	0
SO_4^{2-}	mg/L	803	803	803	4 017	0	0
PO_4^{3-} -P	mg/L	263	3	3	15	99	0
Ca^{2+}	mg/L	25	25	25	127	0	0
Ca^{2+} (from $Ca(OH)_2$) dosing)	mg/L	0	0	11900	0	0	0
Mg^{2+}	mg/L	0	0	0	0	100	0
Urea-N	mg/L	0	0	0	0	0	0
pH	N/A	9.21	9.21	12.5	9.21	N/A	N/A

4.2.2 Struvite precipitation and cation exchange

Following struvite precipitation, cation exchange can be employed as an alternate method of ammonia recovery from urine, as shown in **Figure 4-4**. Tarpeh et al. (2017) suggests the use of a synthetic, silicon-based resin known as s Mac 3 to facilitate the adsorption of ammonium ions. However, multiple alternate zeolites or electronegative adsorption surfaces would be applicable. **Table 4-4** displays the nutrient concentrations of the urine solution after each respective treatment stage.

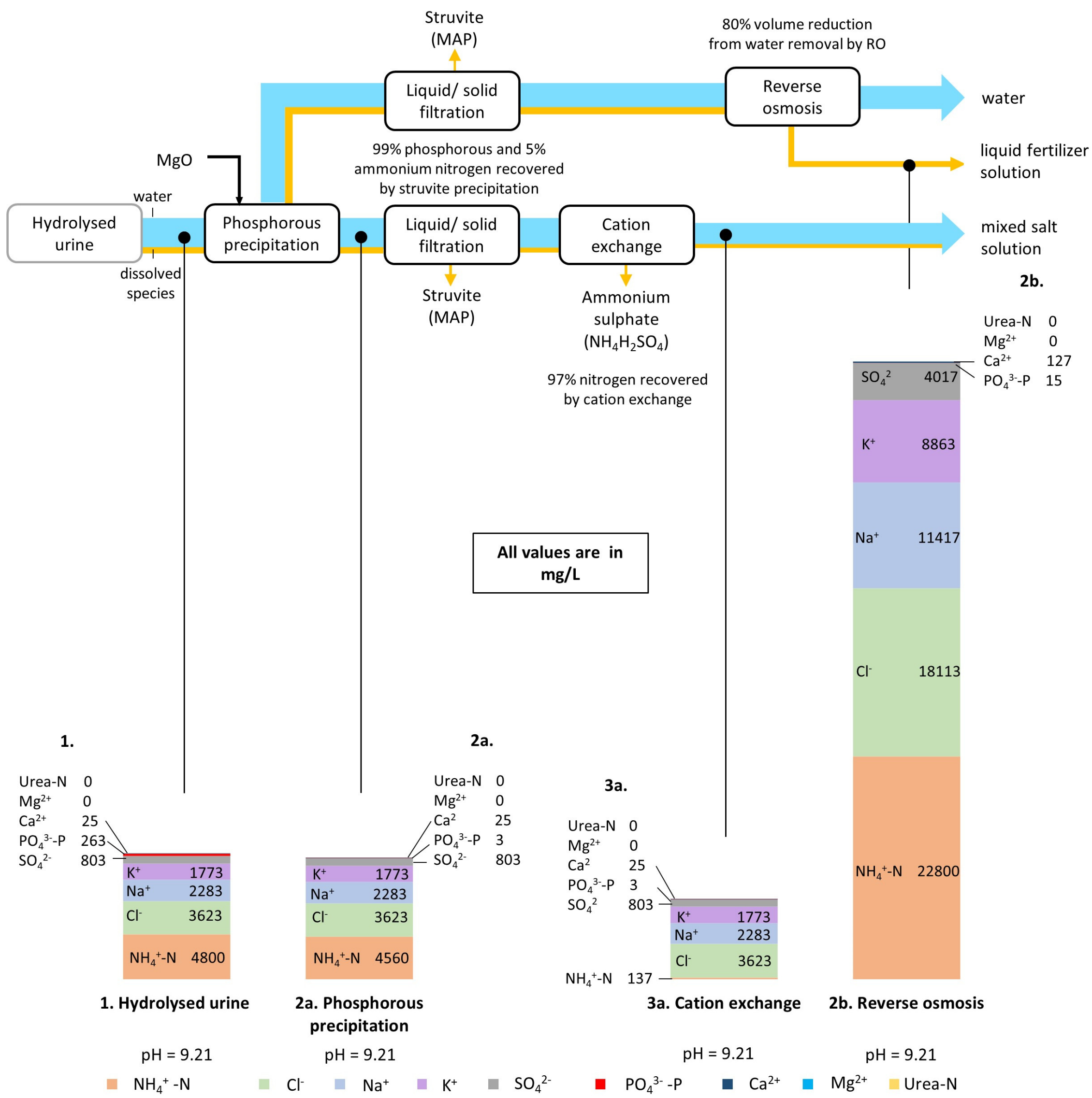

Figure 4-4: Hydrolyzed urine treatment options following phosphorous precipitation and cation exchange.

Table 4-4: Nutrient concentrations in solution, following each respective treatment technique in **Figure 4-4**. All nutrients that are not recovered in struvite and ammonium sulphate will remain in solution for any potential further treatment.

	Units	**1. Hydrolyzed Urine**	**2a. Precipitation**	**3a. Cation Exchange**	**2b. Reverse osmosis**	**Amount recovered in struvite (%)**	**Amount recovered in ammonium sulphate (%)**
NH_4^+/NH_3-N	mg/L	4 800	4 560	137	22 800	5	92
Cl^-	mg/L	3 623	3 623	3 623	18 113	0	0
Na^+	mg/L	2 283	2 283	2 283	11 417	0	0
K^+	mg/L	1 773	1 773	1 773	8 863	0	0
SO_4^{2-}	mg/L	803	803	803	4 017	0	0
PO_4^{3-}-P	mg/L	263	3	3	15	99	0
Ca^{2+}	mg/L	25	25	25	127	0	0
Mg^{2+}	mg/L	0	0	0	0	100	0
Urea-N	mg/L	0	0	0	0	0	0
pH	N/A	9.21	9.21	9.21	9.21	N/A	N/A

4.2.3 Hydrolyzed urine discussion

The most notable difference between the two sequences of hydrolyzed urine treatment presented are the methods of ammonia recovery. Research indicates that cation exchange yields slightly lower recovery percentages than that of ammonia stripping and absorption (refer to **Figure 2-8**). For this reason alone, ammonia stripping and absorption appears to be the more appealing ammonia recovery technique. In both cases, following nitrogen and phosphorous removal, a mixed salt solution with 0.2% potassium content would remain in solution that could be further concentrated. Methods of effectively recycling this mixed salt solution, while producing minimal waste, should be investigated further.

Volume reduction was considered as a means of concentrating urine after phosphorous precipitation has occurred for both hydrolyzed urine scenarios. This would be useful if separate ammonium reclamation is not desired. Evaporation and freezing techniques may not be suitable because of the high and low temperature requirements, which could have significant energy related prerequisites (Ek et al., 2006, Gulyas et al., 2004). Antonini et al. (2011) showed that solar evaporation of hydrolyzed urine could be an effective low energy form of volume reduction. However, complete volume reduction took 26 days to accomplish in this study, and a relatively low nitrogen recovery rate of 68% was accomplished.

Similar to fresh urine, RO was considered the most appropriate volume reduction technique for hydrolyzed urine. This is because RO offers high volume reduction and nutrient recovery at room temperature (Ek et al., 2006). Furthermore, it is assumed that due to the precipitation potential of hydrolyzed urine being maximised after magnesium dosing occurs, membrane scaling during RO would theoretically be limited, provided the solution is also filtered.

4.3 Discussion: treatment process design charts

4.3.1 Ideal treatment sequence

In response to the first research question; the design charts showed that resource recovery from fresh urine results in a greater potential for nitrogen recovery when compared to hydrolyzed urine. More specifically, a combination of urine stabilization using calcium hydroxide and volume reduction by RO is favourable. This is based on the quantity of nitrogen recoverable from each source, after a volume reduction: 33 g N/L and 23 g N/L from fresh and hydrolyzed urine respectively. Although, evaporation and distillation of urine in a vacuum is also viable with similar results (Ek et al., 2006), RO volume reduction is preferred as it can be accomplished at room temperatures with similar nitrogen recovery rates. However, if hydrolysis does occur in urine, then magnesium dosing, followed by ammonia stripping can be employed to retrieve almost all the phosphorous and nitrogen from urine.

Importantly, the removal of residual salts and pharmaceuticals from urine was not considered for the creation of the design charts. This is because it is assumed that pharmaceutical removal techniques, such as adsorption (Solanki & Boyer, 2017) or electrodialysis (Pronk et al., 2006), would be standard for each process sequence. Moreover, inactivation of harmful pathogens and microorganisms is assumed to be facilitated by urine stabilization, as both acidification (Baldry & French, 1989, Gehr & Cochrane, 2002) and alkalinisation (Farrell et al., 1974, Eriksen et al., 1996) have applications in sewage disinfection.

4.3.2 Fertilizer characterization

Fertilizers are typically categorised by their chemical makeup. More specifically the percentage of the fertilizer's weight that is contributed from nitrogen (N), phosphorous (P) and potassium (K). Taking this into consideration, the potential NPK values of the resulting liquid fertilizers after RO volume reduction for fresh urine and hydrolyzed urine are 3.3 - 0 - 0.8 and 2.2 - 0 - 0.9. These values are significant, as they allow for a direct comparison of the compositions of commercially available fertilizers and those of urine derived fertilizer.

Ammonia stripping of hydrolyzed urine can yield an ammonium sulphate fertilizer of 13% nitrogen content (Pradhan et al., 2017). Despite this, the total nitrogen content, by weight, which can be harvested from 1 m^3 of fresh urine (6.7 kg) outweighs that which can be retrieved from the same quantity of hydrolyzed urine (4.8 kg).

4.3.3 Large scale urine treatment in public locations

The treatment process employed, and the chosen method for urine collection are closely linked, such that the method of collection must allow for effective and appropriate treatment. In addition, the collection process must aid in recovering the maximum amount of urine while also being user friendly. Urea stabilization using acids is potentially viable, but the fact that sulphuric acid is primarily available in liquid form indicates that transportation and handling could present a potential health and safety hazard. This would be especially applicable for toilet users and untrained staff in public and commercial restrooms. Calcium hydroxide addition to fresh urine has many benefits, including decentralized urine collection systems (Randall et al., 2016). Literature indicates that phosphorus can be easily retrieved from urine with minimal smell in a decentralized urinal unit (Flanagan & Randall, 2018). In Chapter 5, the logistics of a decentralized urine collection system, and the implications of transporting calcium hydroxide stabilized urine for resource recovery is explored.

In summary, these design charts give a variation of approaches that can be employed for maximum recovery of resources from human urine with minimal waste. Further studies are required to optimize the economics of each system though.

5 Results and discussion: decentralized urine treatment

This chapter is the second of two results and discussion chapters and aims to answer the second research question:

If highly frequented locations such as shopping malls and universities are targeted for installation of nutrient recovery urinals, how would the urine be collected and what are the viable market avenues for the sale and use of urine derived fertilizers?

To investigate this question, a last-mile logistics analysis and an economic and environmental feasibility analysis were conducted on a decentralized urine resource recovery system. The City of Cape Town was used as the study area for this investigation. Section 5.1 details the transportation network and logistics analysis. These incorporated the allocation of resource recovery facilities using geospatial modelling software and the subsequent creation of network routes for urine collection. Following this, section 5.2 details a financial feasibility analysis on the capital and operating as well as the maintenance costs of such a system. This incorporated the CAPEX, OPEX, and NPV/NPC of the system. Moreover, the potential GHG emissions of the proposed system are given in section 5.2 and compared to an MLE AS WWTP. In section 5.2.6, a sensitivity analysis for the key parameters in the system was conducted.

5.1 Transportation network and last-mile logistics

5.1.1 Resource recovery facility location allocation

The optimum degree of decentralization was evaluated by the number of installed RRFs. A mapped representation of scenario one (one RRF) modelled using Flowmap, can be seen in **Figure 5-1**. It was found that the optimum location for one RRF was located adjacent to Cavendish Square Shopping Centre. The location of the RRF in scenario one was then transferred to ArcGIS, as shown in **Figure 5-2**, for route designation modelling.

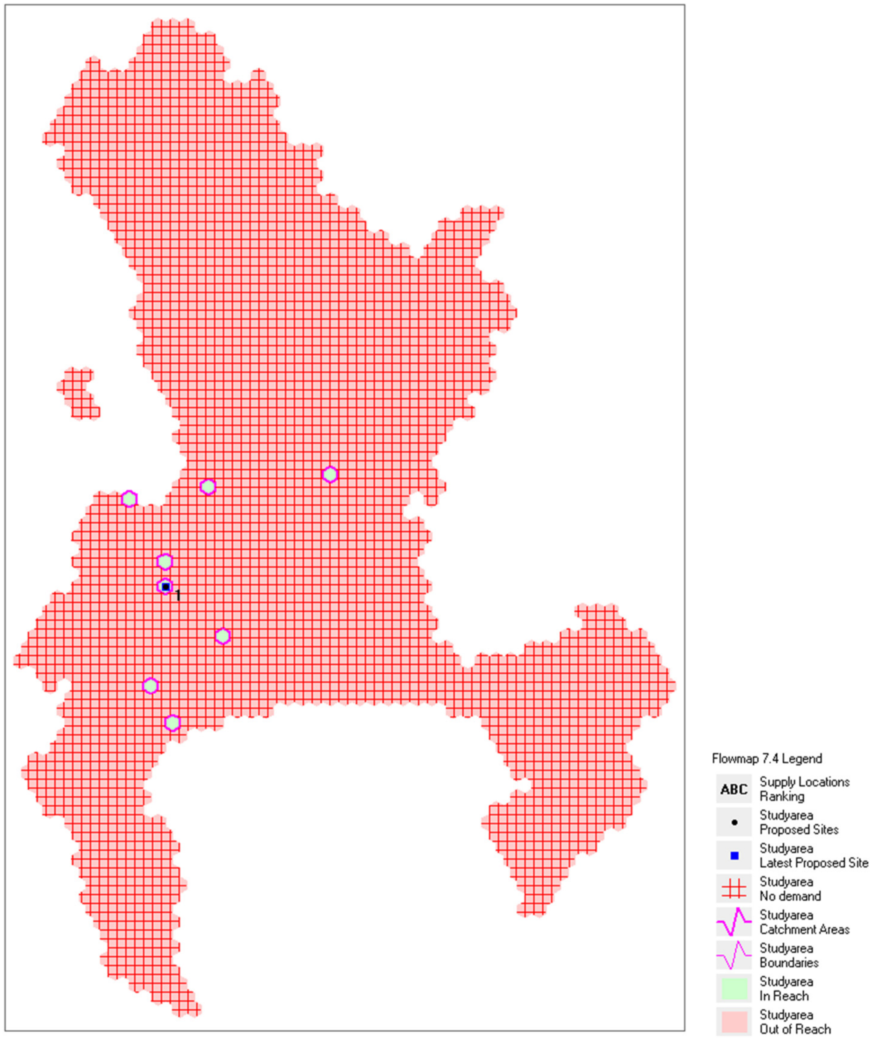

Figure 5-1: Optimum location for one RRF (scenario one) in Flowmap ("Study area in reach" refers to the collection locations, as seen by the eight "in reach" hexagons).

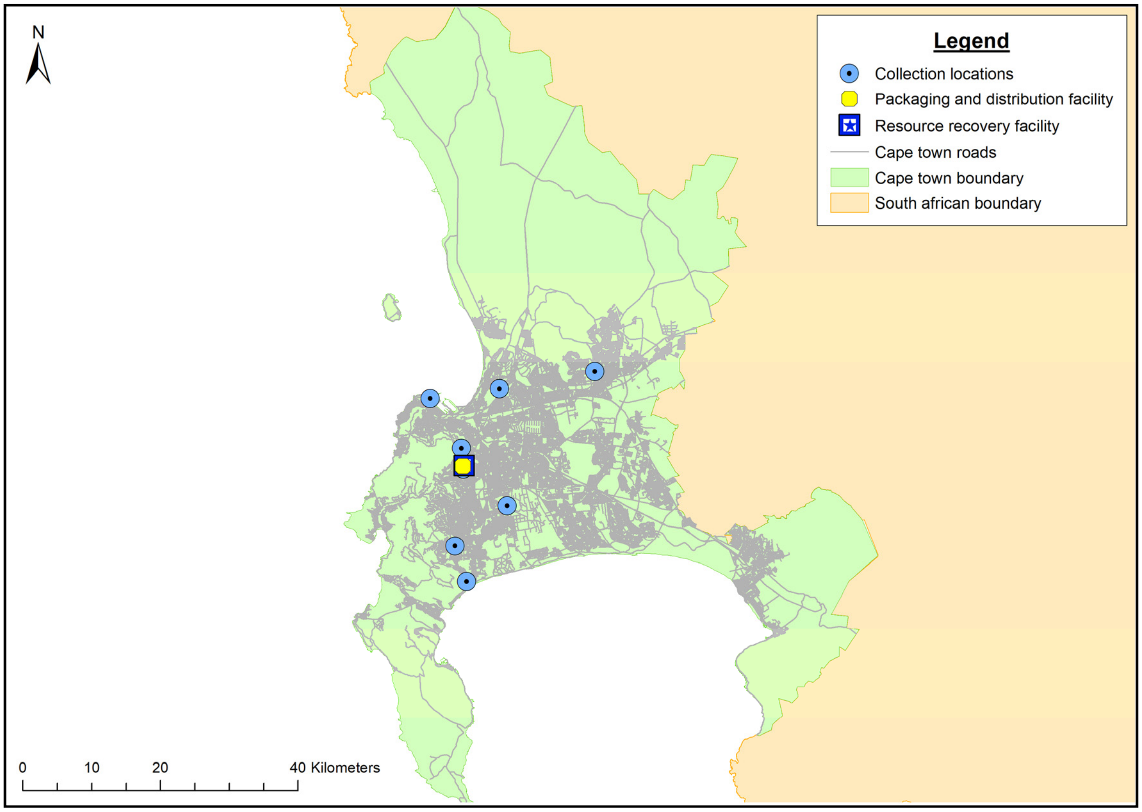

Figure 5-2: Optimum location for one RRF (scenario one) in ArcGIS. The RRF and the PAD facility are the same location in scenario one, as described in section 3.3.

The optimum locations for the treatment facilities in each scenario were determined using the methodology outlined in section 3.3.4. The location optimized RRFs, as well as the RRF allocated to each collection location is shown in **Figure 5-3**. As seen in **Figure 5-3**, scenarios one and two incorporated fully off-site treatment, scenario three included a combination of off-site and on-site treatment, and scenario four only incorporated on-site treatment. In scenarios where on-site treatment was employed, the truck was tasked with collecting the treated product, and not the stabilized urine.

The priority when allocating the location for each of these RRFs was to minimize the overall distance from the collection locations to the RRFs, while assuming spatial rationality (each location is allocated to its nearest RRF).

All scenarios were independent of one another. For example, the inclusion of two RRFs in scenario two did not consider the location of the one RRF used in scenario one. Each scenario essentially represented a hypothetical "greenfield" investigation.

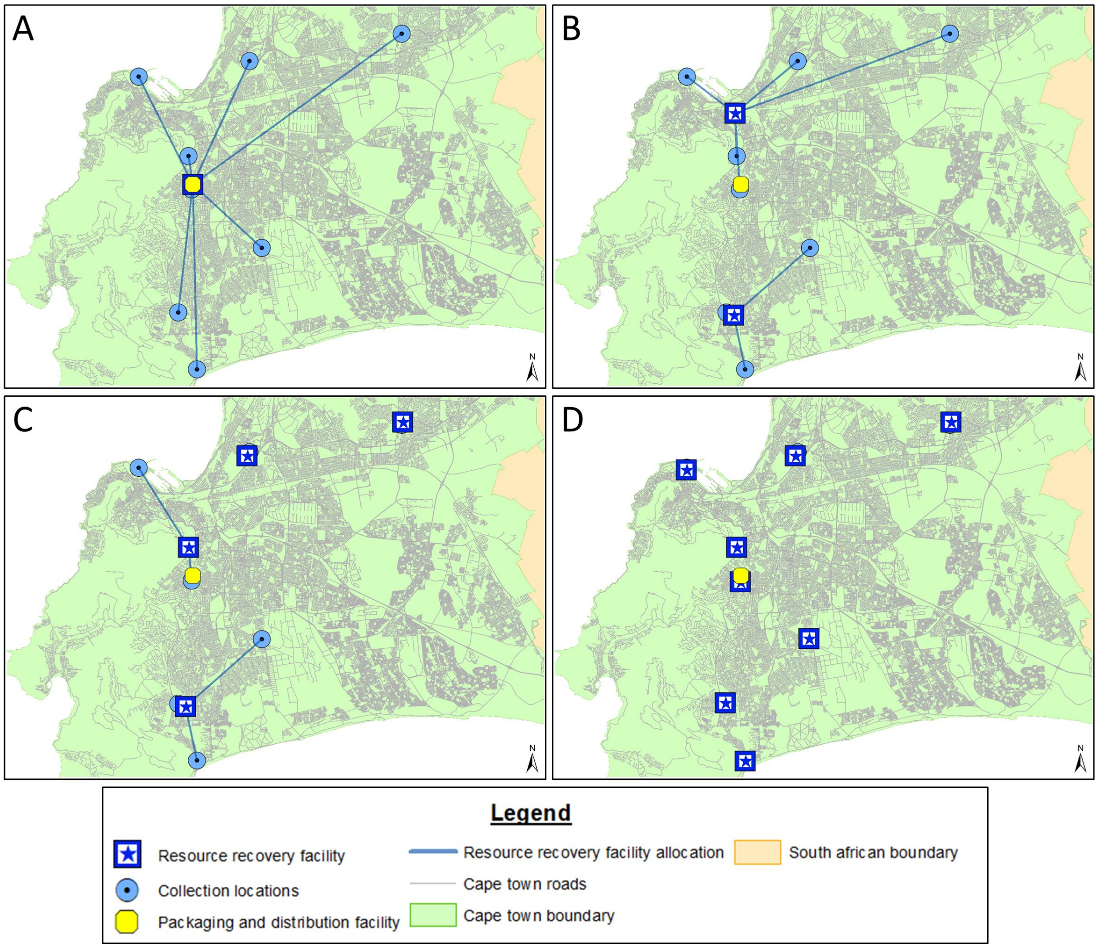

Figure 5-3: Configuration of each design scenario. In A, B, C and D, there are one, two, four and eight RRFs, respectively.

5.1.2 Transportation routing

The characteristics of each collection location were required for the travelling salesman problem (TSP) route optimization. The chosen transportation method envisioned for this simulation (a 4-ton truck) was weight restricted. Therefore, the quantity and weight of stabilized urine required for collection at each collection location was a key aspect to consider. The existing water-based urinals at each location were theoretically retrofitted to be the NRU displayed in **Figure 2-4**, so the quantity of Ca-P produced per kg of urine was scaled up in proportion to the quantity of collected urine. These characteristics are shown in **Table 5-1**. Moreover, it was assumed that each week the fertilizer produced from the previous week's urine was collected from the RRFs for delivery to the PAD facility. This added weight was taken into consideration when solving the TSP.

Table 5-1: Collection location characteristics.

Collection locations	Daily male population	NRUs retrofitted	Urine produced per week (L)	Urine produced per week (kg)	Ca-P produced per week (Kg)
Blue Route Mall	8 094	37	924	948	10
Canal Walk Shopping Centre	15 558	62	1 546	1 585	17
Cavendish Square	7 266	34	855	877	10
Lakeside Village Shopping Centre	1 710	16	393	402	4
Makro Store Ottery	2379	18	448	459	5
Tyger Valley Shopping Centre	13 125	54	1 344	1 377	15
Victoria & Alfred Waterfront	10 063	44	1 089	1 115	12
University of Cape Town	8 243	37	937	960	11
Total	**66 436**	**301**	**7 536**	**7 725**	**85**

The results of the TSP on the Cape Town road network are displayed in **Figure 5-4**. Moreover, the travel distances for each scenario are shown in **Table 5-2**. Each trip was modelled to start and end at the PAD facility for each design scenario.

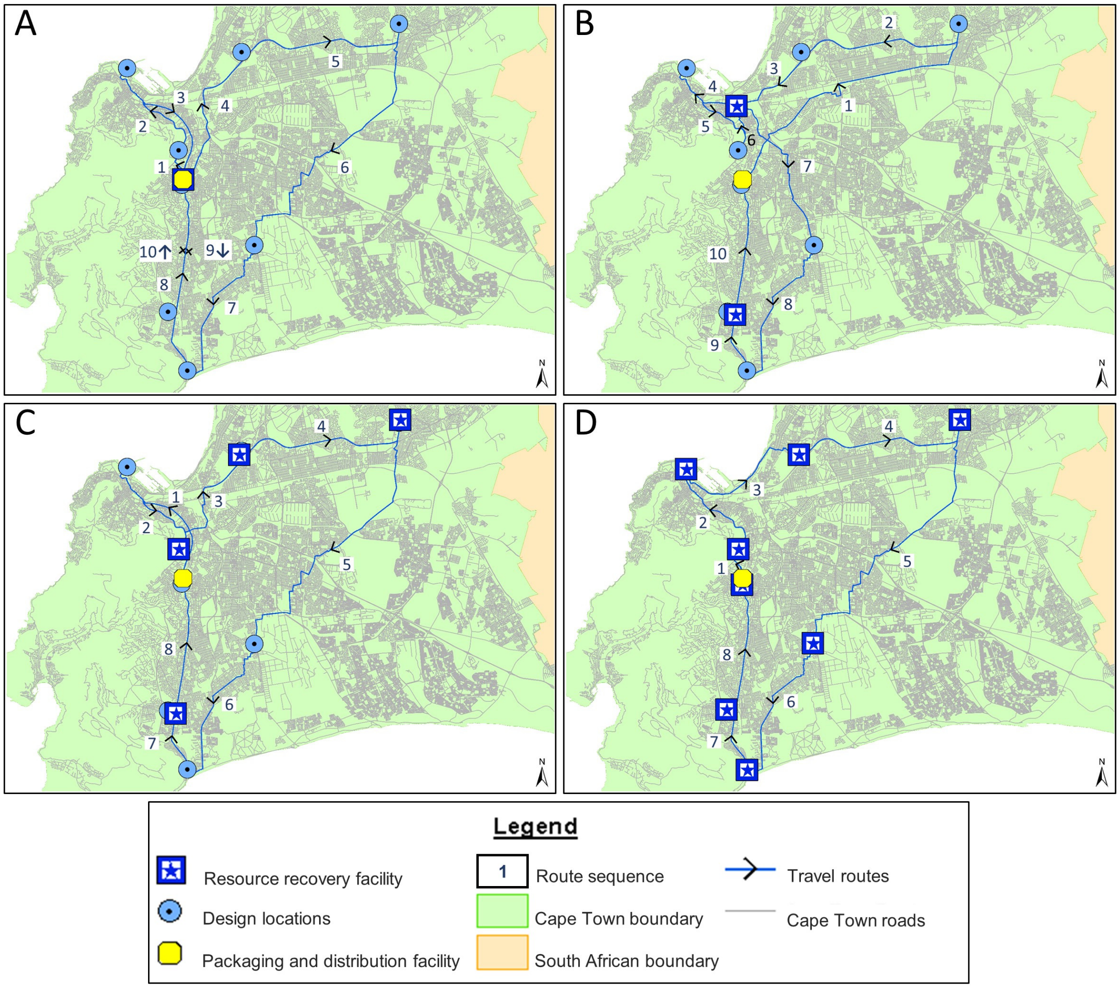

Figure 5-4: Travel routes for each scenario. A, B, C and D represent the inclusion of one, two, four and eight RRFs, respectively. In Figure 3A, the truck is at full capacity when approaching the second to last stop. It is thus required to offload its cargo before making the last collection. Arrows are provided for clarity.

A 4-ton truck, travelling at an average speed of 60 km/hr was employed in each of the four scenarios. Moreover, the travel time quoted in **Table 5-2** refers to the time that the truck spends on the road only. However, a loading time of 15 minutes per stop was assumed when calculating the truck driver wage in the economic feasibility model described in section 5.2.

Table 5-2: Travel route results for all scenarios utilizing a 4-ton truck.

Design scenario	Total travel distance (km)	Fuel consumption (L)	Total travel time (hrs)
1 Resource recovery facility	125.4	18.8	2.5
2 Resource recovery facilities	108.7	32.6	2.2
4 Resource recovery facilities	102.6	41.0	2.1
8 Resource recovery facilities	93.0	14.9	1.9

5.1.3 Discussion: transportation network and last-mile logistics

5.1.3.1 Resource recovery facility allocation

The positions of the RRFs were optimized for minimum average distance, to shorten the total travelling distance. In theory, this is ideal, as it decreases the total travel distance from the collection location to the RRFs, when spatial rationality is assumed. In reality, the locations of these optimized sites may not have space provisions for the warehouses and treatment facilities envisioned. Actual optimization of realistic sites would require industrial real estate data and site-specific trends. However, as this study deals with a hypothetical scenario, this form of data collection was not included.

5.1.3.2 Transportation restrictions

A single, 4-ton truck was used to model the collection logistics for each scenario. As seen in **Table 5-1**, a maximum of 7.5 m^3 of urine was produced per week for the entire study area. A 4-ton truck typically has a 20 m^3 carrying capacity (IsuzuTruck.com, 2018), therefore urine volume constraints would not apply for transportation. However, the maximum quantity of urine produced is heavier than what was capable of being carried in one trip, at 7.7 tons. Due to the chosen transportation mode being weight restricted, the travel routes were required to be optimized to cater to the truck's capabilities. One round trip was therefore not possible for the first and second design scenarios. This was because the truck could not carry all the urine allocated to each respective RRF without offloading the additional weight because of the collected urinal containers. In scenarios one and two, at least one RRF was required to be visited more than once, as displayed in **Figure 5-4**. This subsequently increased the overall travel distance and travel time. Conversely, if the carrying capacity were increased, by using an 8-ton truck, a 32 km and 1 km decrease is experienced in scenarios one and two, respectively.

However, the fuel consumption of an 8- ton truck, at 3.33 km/L, is double that of a 4-ton truck, at approximately 6.66 km/L (DAFF, 2016). This increase in fuel consumption would roughly translate to a 10 L and a 16 L fuel consumption increase for scenarios one and two, as well as a 25 kg CO_2 and 43 kg CO_2 increase in GHG emissions for scenarios one and two. This is despite the 8-ton truck having a shorter travel distance in both scenarios. Likewise, any increase in truck carrying capacity from 8-tons would have an increased negative effect, for the same reasons.

When using a 4-ton truck, scenarios three and four did not display problems pertaining to weight restrictions. This was due to the increase in RRFs, which offer increased opportunity to offload urine containers following collection. This indicates that for more than two RRFs, no benefit can be found from increasing the carrying capacity of the truck.

Interestingly, the travel distances for the 8-ton truck and the 4-ton truck increased and decreased, respectively, when increasing the number of RRFs from one to two. This is because an 8-ton truck did not have weight restrictions in the case of one RRF, but the total number of stops increased when two RRFs were employed. This changed the required travelling routes and increased the travelling distance. Conversely the 4-ton truck experienced a decrease in weight restriction, upon increasing the number of RRFs. Moreover, the 4-ton truck experienced the same route changes as the 8-ton truck and a decrease in travel distance.

5.1.3.3 Degree of decentralization

The difference in the travel distance, between successive design scenarios, decreased as the degree of decentralization increased. This is displayed in **Figure 5-5**. The reasoning for this is likely the fact that the same quantity of urine is being transported in each scenario, and weight restrictions only applied to scenarios one and two.

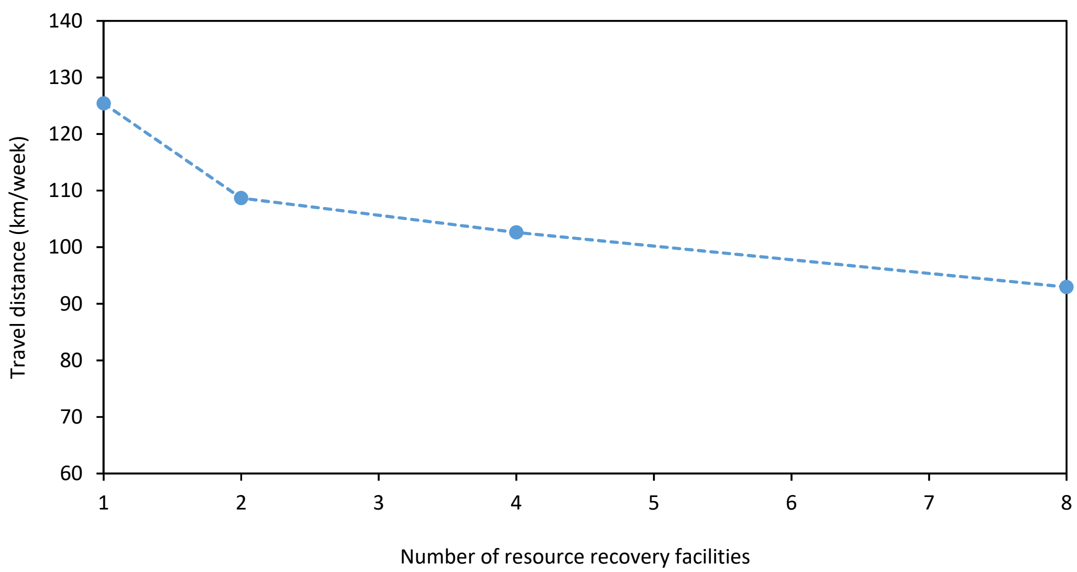

Figure 5-5: Travel distance vs number of RRFs (degree of decentralization), using a 4-ton truck.

Moreover, although the number of RRFs increased, the number of collection locations remained the same. An increase in the number of collection locations would likely increase the required travel distance, as new routes and increased weight restrictions would apply. As economic, environmental and time considerations are directly linked to travel distance, an increase in collection locations would require a revision of the mode of transport as well.

5.2 Economic and environmental assessment

The four design scenarios have been evaluated based on their respective implementation costs. The capital expenditure (CAPEX), operating expenditure (OPEX), projected fertilizer sales (recovered costs) and net present value/cost (NPV/NPC) were taken into considerations. The initial financial evaluations were done incorporating the use of a 4-ton truck. This assessment was conducted under the assumption that the full potential of the proposed system is realised, and all the produced fertilizer product is sold, creating a source of income.

For each design scenario, the same quantity of urine was treated to produce solid and liquid fertilizers. A summary of the potential products retrieved from the proposed system from one year of operation is shown in **Figure 5-6**.

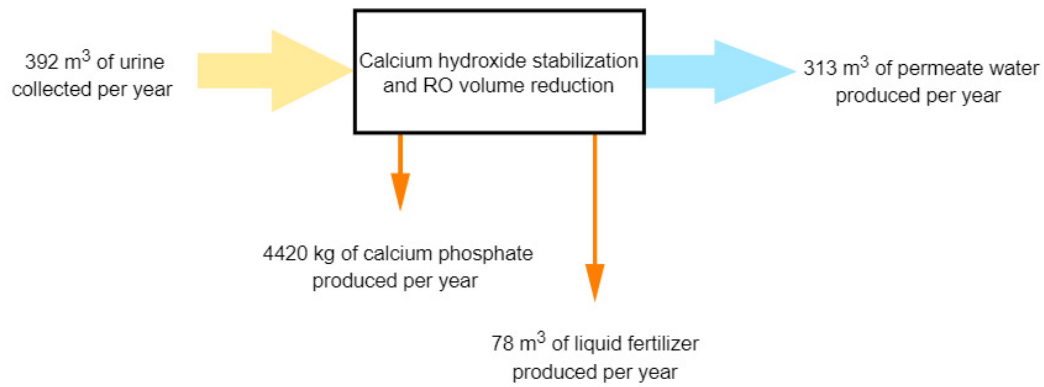

Figure 5-6: Mass balance for the inputs and outputs of urine treated for recovery of resources in the proposed system. The urine collected equates to approximately 1.7 million NRU uses per year across each of the eight collection locations.

5.2.1 CAPEX

The parameters used to determine the initial CAPEX of the project were the purchasing of NRUs, the deposit required for rental space, the RO unit(s) required and the truck costs. The CAPEX for each scenario is displayed in **Table 5-3**.

Table 5-3: CAPEX for each proposed design scenario.

	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
CAPEX	R millions	0.90	0.93	0.98	1.1

It was apparent that the higher the degree of decentralization, the higher the capital cost. This increase was caused by the increase in rental space required when the number of RRFs increased. An RRF with a surface area of 200 m^2 was required to provide enough working space for warehouse workers and store all the urinal containers and the RO unit(s) incorporated in the system. All RRFs were given an identical size. All other parameters remained unchanged for each scenario, including the surface area of the PAD facility, which was found to be 60 m^2 to store all produced fertilizer and offer enough working space for employees. With regards to scenarios one and four (one RRF and eight RRFs), the contribution of each factor to the overall CAPEX is given in **Figure 5-7**.

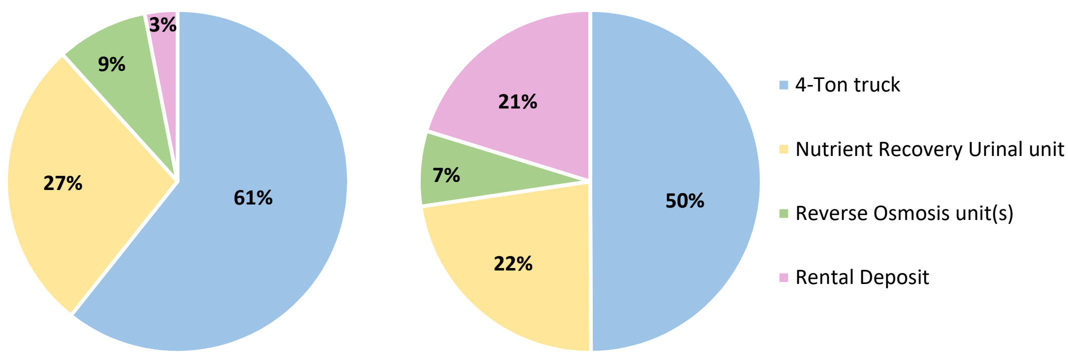

Figure 5-7 :CAPEX break-down for scenario one (left) and scenario four (right).

5.2.2 OPEX

Operating costs for scenarios one, two, three and four were found to be R1.6 million, R2.2 million, R2.8 million and R3.7 million per year, respectively. A break-down of these costs is displayed in **Figure 5-8**.

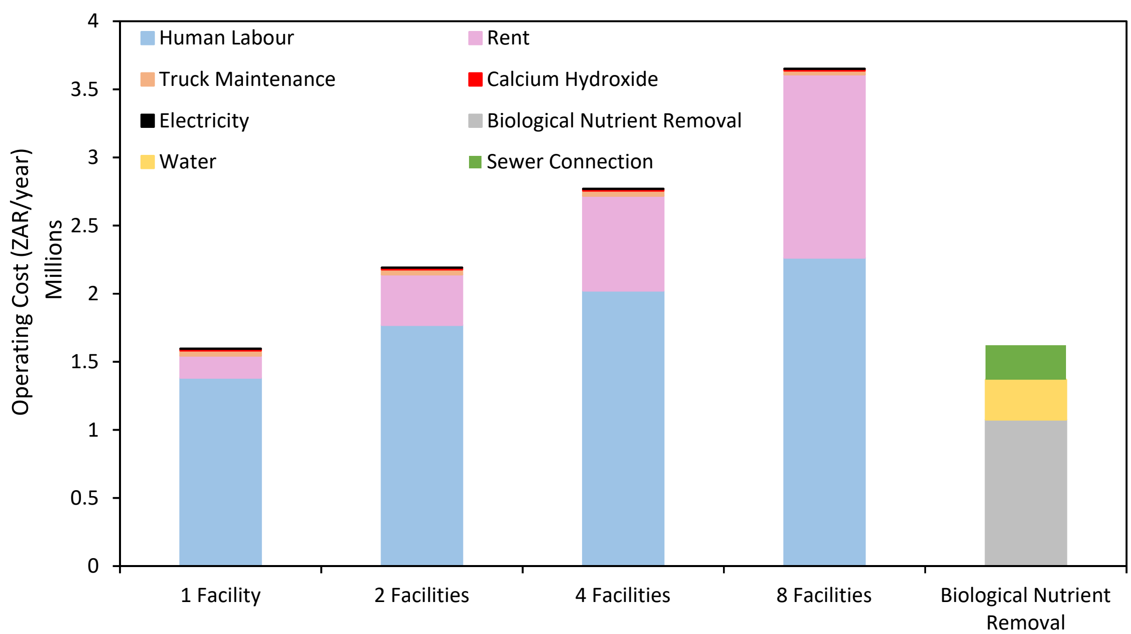

Figure 5-8: OPEX for each design scenario.

Human labour, rent and electricity were found to be the most significant components of the operating costs and increased as the number of RRFs increased. The BNR operating and maintenance values, included in **Figure 5-8,** incorporated all labour, electricity and processing expenses of an MLE AS system (EPA, 2007). Moreover, the BNR OPEX represents the equivalent amount of wastewater that would be treated in an MLE AS system, if the collected urine was not prevented from entering the sewerage.

The cost of the water that would be used per flush, equivalent to the quantity of urine collected in the proposed system, was considered when calculating the total cost of biological nutrient removal at WWTPs. Likewise, the cost of the sewer connections, equivalent to the urine collected by the system, was also considered. It was found that switching to a waterless urinal system would presumably lead to a decrease in flushes and promote water conservation. If any one of the design scenarios were to be implemented, approximately 6840 m^3 of water could be preserved per year, equating to roughly R294 000 and R251 000 worth of water and sewer connection expenses, respectively. Additionally, 313 m^3 of permeate water would be produced per year from urine treatment with RO. Literature indicates that RO treated wastewater (Lee & Lueptow, 2001) and urine (Yu et al., 2006) have applications in potable water production. Otherwise, this recovered water could also potentially find use in other industries. Considering the recent water shortage in the City of Cape Town, sustainable infrastructure that has applications in water conservation could aid in mitigating the effects of future water shortages.

5.2.3 Cost recovery

For cost recovery, it was assumed that the solid and liquid fertilizer produced in this system could break into the South African fertilizer market and be sold at prices which are competitive with established commercial fertilizers. In this case, the selling prices of the solid and liquid fertilizers would be R18.50/kg, and R151.52/L.

The nitrogen content for urine that is stabilized with calcium hydroxide and concentrated by RO was determined in Chapter 4. It was found that a liquid fertilizer, of 3.3% nitrogen (by weight), could potentially be produced from this combined treatment process. Approximately 78.4 m^3 of liquid fertilizer and 4420 kgs of Ca-P could potentially be retrieved by decentralizing urine treatment. Total fertilizer sales were found to be approximately R11.95 million per year. When considering the overall OPEX shown in section 5.2.2, it was found that the potential net income of the system (if all fertilizer is sold at the original design selling prices) would be approximately R10.32 million per year.

5.2.4 Greenhouse gas emissions and energy expenditure

The GHG emissions of the proposed decentralized system were calculated based on carbon dioxide emissions. This comparison is displayed in **Figure 5-9**. The truck fuel emissions were the main contributor to GHG emissions in the decentralized system. Therefore, as the number of RRFs increased, causing a decrease in the travelling distance, the carbon emissions of the system also decreased.

GHG emissions of a conventional MLE AS system are also provided. Considering urine contributes approximately 80% of the total nitrogen in wastewater (Spångberg et al., 2014), the mass of carbon emissions per mass of nitrogen removed in an MLE AS system was used as a direct comparison to the proposed system.

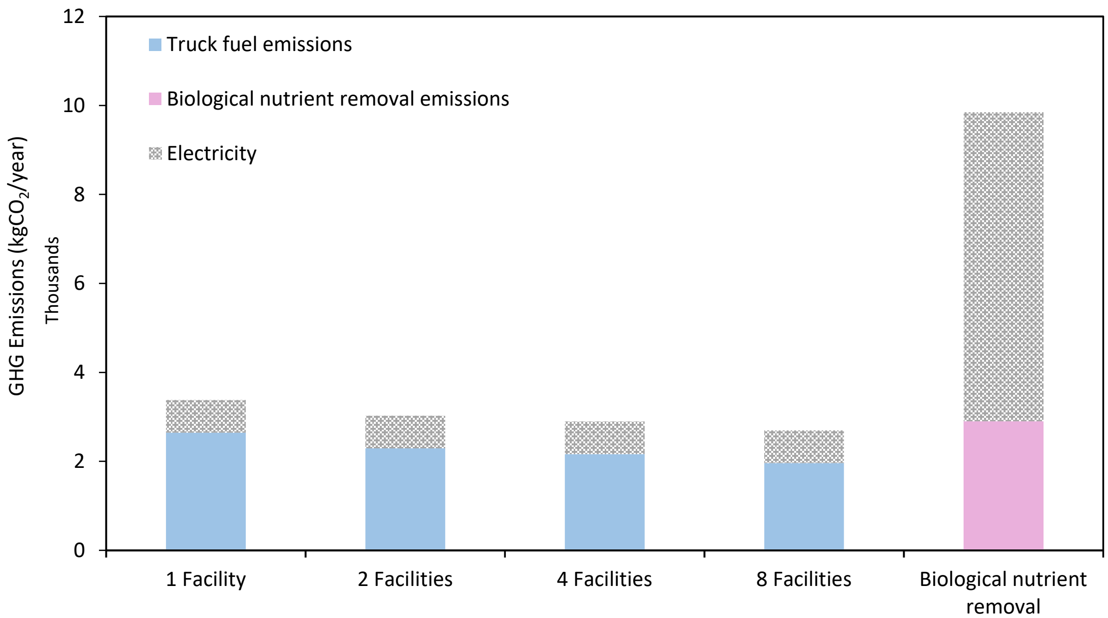

Figure 5-9: Greenhouse gas emissions for each design scenario.

Additionally, it was found that BNR energy expenditure for an equivalent mass of nitrogen in wastewater would be approximately 7550 kWh per year. This represented over a tenfold increase when compared to the 730 kWh per year energy expenditure for RO operation in the proposed decentralized system.

5.2.5 Net present value/ cost

The NPV of the system, considering maximum fertilizer sales, was evaluated over a 5-year investment period, at an interest rate of 10%. The comparison of the NPV for each scenario is illustrated in **Figure 5-10**.

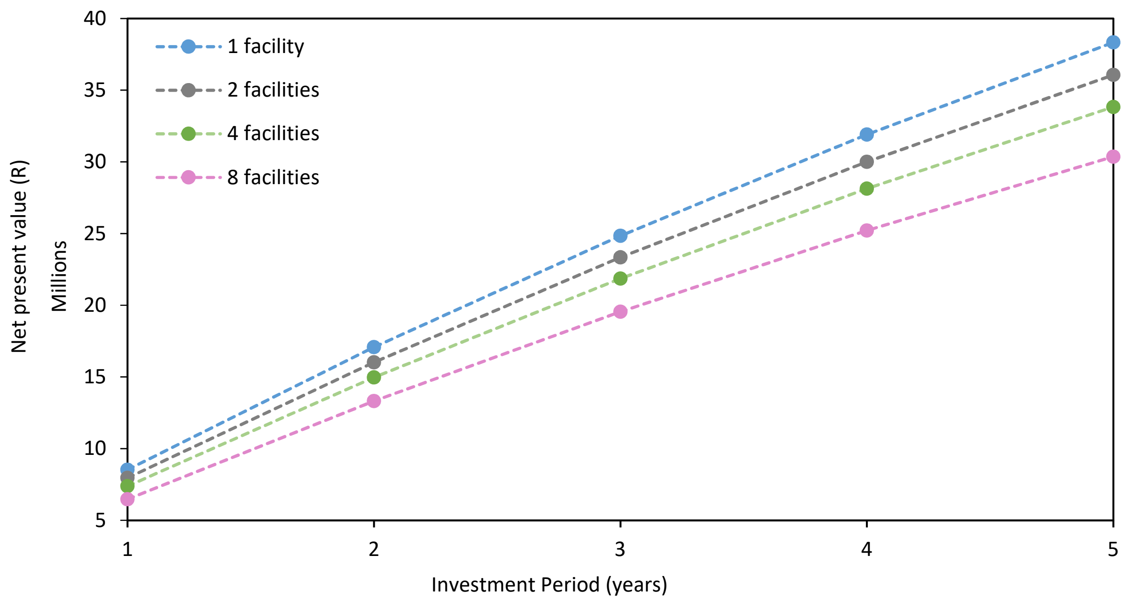

Figure 5-10: Net present value over a 5-year investment period.

A positive net present value is realized for each scenario at maximum sales, with scenario one exhibiting the highest NPV of R38.2 million over a 5-year period. Scenario four exhibits the worst, with an NPV of R30.3 million for the same period.

5.2.6 Sensitivity analysis

This economic feasibility assessment has thus far incorporated an empirical research approach, based on published literature and basic assumptions. Furthermore, the assumption that the urine derived liquid fertilizer would be sold at prices comparable to established fertilizers and be sold in its entirety, over a 5-year period, may not be realistic. The sensitivity of the proposed system to changes in the following parameters was assessed:

- The carrying capacity of the truck
- The selling price of the fertilizer product
- The quantity of fertilizer sold

5.2.6.1 Liquid fertilizer selling price

The selling price of the recovered fertilizer product used in this research contributed greatly to the overwhelmingly positive net present value achieved in the initial calculations. The effect of varying this selling price was investigated. More specifically, the selling price that resulted in a net present value of zero was calculated. This price was referred to as the 'break-even' selling price and is displayed in **Table 5-4** for each design scenario.

Table 5-4: Liquid fertilizer break- even selling price over an investment period of 5 years.

Design scenario	Unit	Break-even selling price
1 Resource recovery facility	R/L	22.75
2 Resource recovery facilities		30.36
4 Resource recovery facilities		37.86
8 Resource recovery facilities		49.52

It was found that even if the liquid fertilizer selling price were decreased by up to 85% (from R151.52/L to R22.75/L), the system is still capable of breaking even over an investment period of 5 years, if one RRF is installed.

In the initial model calculations, the Ca-P fertilizer accounted for just under 1% of the total income. Furthermore, granular, phosphorous based fertilizers derived from human urine are already commercially available in South Africa (Herman, 2017). Therefore, the ability of the recovered Ca-P to enter the South African fertilizer market at competitive prices was not questioned for this sensitivity analysis, but regulatory compliance would have to be investigated.

5.2.6.2 Liquid fertilizer sales

Another factor considered was the amount of liquid fertilizer sold. For this calculation, the quantity that was required to be sold to achieve a net present value of zero, at the design fertilizer selling price, was considered. It was found that for scenarios one, two, three and four, 15%, 20%, 25% and 33% of the liquid fertilizer would need to be sold to reach a break-even point at the chosen design selling price.

In addition, approximate sales figures for liquid fertilizers were sourced from five local plant nurseries in Cape Town. This was done to get an approximate estimate of the average quantity of liquid fertilizers sold per week. It was found that roughly two litres of a popular liquid fertilizer brand are sold every week by these nurseries. These approximate weekly sales values were applied to all the nurseries within Cape Town and evaluated over a five-year investment period to determine how the NPV was affected. The abovementioned parameters represent the sale of approximately 10% of the fertilizer produced from the collected urine. Moreover, it was found that at the design selling price, a net present cost is realised for all scenarios, as illustrated in **Figure 5-11**.

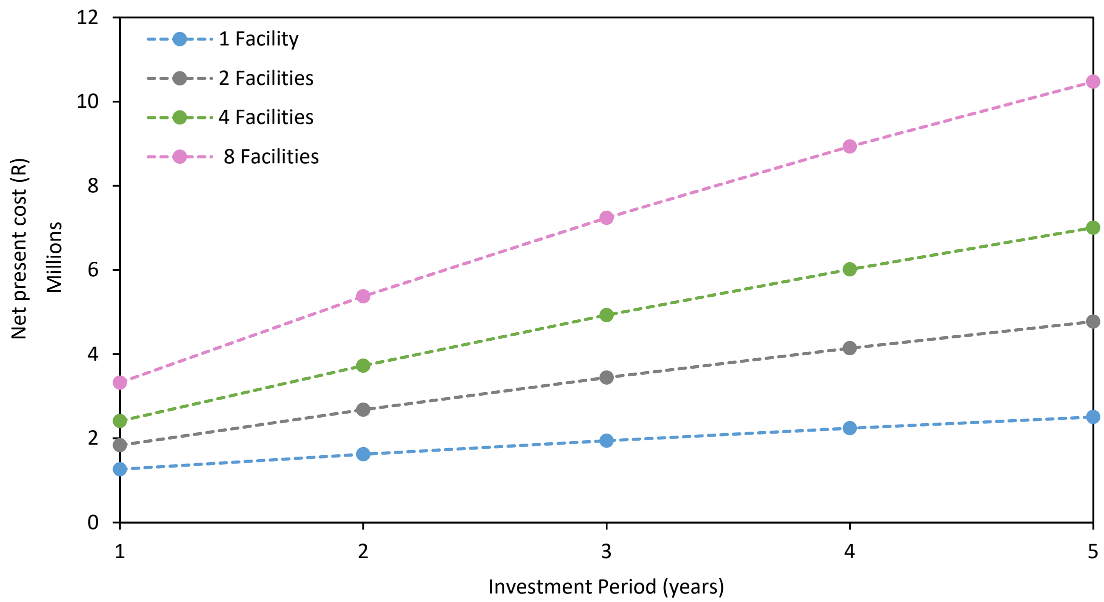

Figure 5-11: Net Present cost for realistic sales quantities.

However, if only this fraction of fertilizer is sold, the remaining 90% of liquid fertilizer would only need to be sold at a bulk value as low as R9.56/L over five years, to reach a break-even point, if one RRF is installed.

5.2.6.3 Truck carrying capacity

The effect that the mode of transport has was also considered. Trucks with higher carrying capacities would directly increase the CAPEX in each scenario. An approximately R158 000 increase and a R440 000 increase would be observed if an 8-ton truck or a 14-ton truck were utilized, respectively (DAFF, 2017). Likewise, the operating costs of increasing the carrying capacity of the truck were higher, as illustrated in **Figure 5-12**. For scenario one a 4-ton truck and an 8-ton truck would have a similar operating cost due to the larger distance travelled by the 4-ton truck. As the required travelling distance between the two trucks types converges, the 4-ton truck becomes less expensive option.

The operating costs for each carrying capacity, shown in **Figure 5-12**, includes truck maintenance, fuel consumption and driver wages.

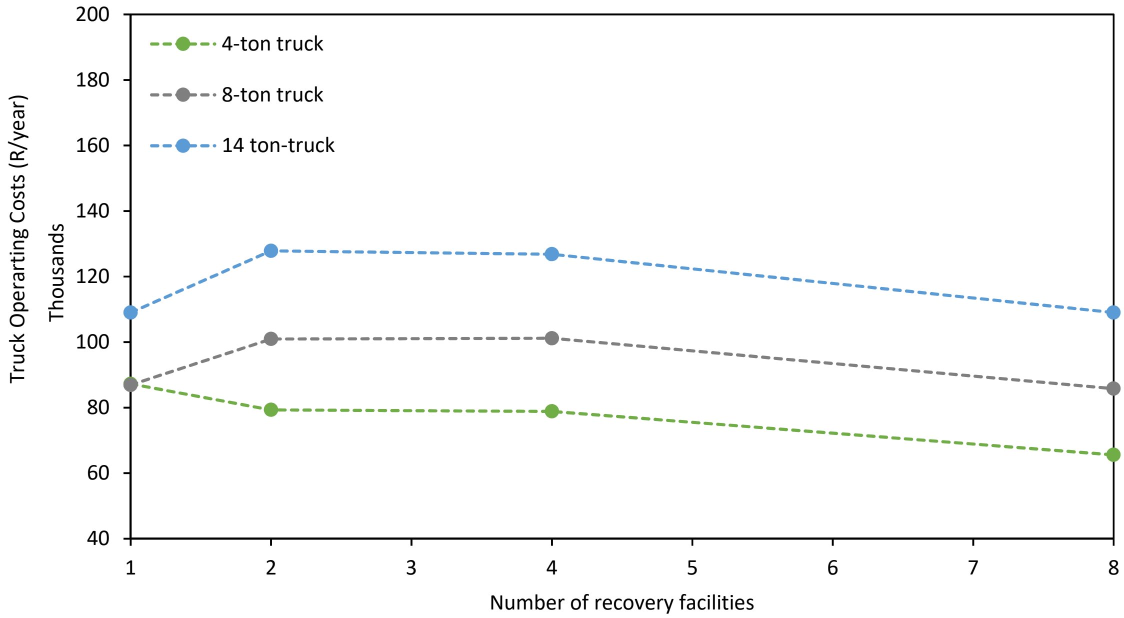

Figure 5-12: Vehicle operating costs vs number of recovery facilities.

5.2.7 Discussion: economic and environmental assessment

5.2.7.1 Scenario comparison

A shorter travel distance was observed as the level of decentralization increased. This subsequently resulted in a decrease in CO_2 emissions from the truck. Despite this, increasing the level of decentralization led to an increase in both CAPEX and OPEX. A point of diminishing returns was experienced as the number of RRFs increases. To that extent, a globally optimal solution which incorporated the minimum operating costs, minimum travel distance and the minimum GHG emissions was not found. Similar struggles to find a globally optimal solution for all abovementioned parameters were reported by Kavvada et al. (2017), where decentralized urine treatment by ion exchange was investigated.

The differences in operating costs arose mainly due to an increase in the amount of RRFs, which led to an increase in rental costs, and operating personnel. An argument could be made that rental costs would not have a significant contribution in the case of on-site treatment, provided that collection locations have pre-existing and vacant floor space. In this situation, discounted rental rates could be negotiated in exchange for provision of recovered fertilizer, if such a demand is applicable. For example, the urine produced by UCT alone would be capable of providing approximately 48% of the nitrogen requirements for its rugby fields on the main campus per year. However, such detailed knowledge of each specific collection location is difficult to estimate.

In response to the second research question; it was found that transporting source separated urine in a 4-ton truck (from highly frequented locations) offers an appealing method of facilitating decentralization of urine treatment. Moreover, from a financial perspective, it was deduced that scenario one, the implementation of one RRF, was the most appealing design scenario.

5.2.7.2 Alternate markets

In this research a niche method of resource recovery from urine was explored. The plant nursery market was interrogated as a means for distribution, because it was assumed that this is where the most appropriate sale opportunities would exist. However, it would be naïve to assume that urine derived liquid fertilizers would be capable of seamlessly entering the fertilizer market and competing with established, commercially available fertilizers.

Moreover, if the product is capable of being sold at competitive prices, the sales quantities could be low due to several factors, such as seasonal demand. Any decrease in sales would subsequently cause an increase in the break-even selling price required. If the realistic sales quantities are estimated to be 10% of the total producible liquid fertilizer (as shown in section 5.2.6.2), the cost of production per litre of liquid fertilizer sold would be 38% higher than the initial design selling price. From a financial perspective, scaling down fertilizer production to a point where a profit is made may be advisable. However, alternate markets could be explored for maximum product distribution, such as vineyards.

South Africa produces the seventh largest amount of wine globally, according to the International organization of Vine and Wine (OIV), and has multiple geographic wine regions (OIV, 2017). The Stellenbosch wine region, which Cape Town is situated within, constitutes roughly 16% of the total vineyard surface area in South Africa, according to the South African Wine industry (SAWIS) (SAWIS, 2017). The total quantity of fertilizer produced from the proposed system per year (78 m^3 of liquid fertilizer and 4420 kgs of Ca-P) could provide approximately 0.3%, 0.01% and 0.2% of the nitrogen, phosphorous and potassium required for the entire Stellenbosch region per year. Importantly, this is considering the potential contribution from only eight urine collection locations in Cape Town. Vineyards within and surrounding Cape Town thus offer potential for an alternative market to promote this liquid fertilizer as a bulk product. The Stellenbosch wine region annual NPK fertilizer demands were calculated based on the vineyard nutrient requirements outlined by the Food and Agriculture organization of the United Nations (FAOUN) (FAOUN, 2005).

To assess the full potential of the proposed system, the total amount of liquid and solid fertilizer that could be produced per year, if all Cape Town residents used the NRU, was evaluated. It was found that if all Cape Town residents (women included) urinated in an NRU once per week for one year, approximately 46%, 2% and 28% of the Stellenbosch wine region’s annual nitrogen, phosphorous and potassium requirements could be recovered as fertilizers. This is shown in **Figure 5-13**.

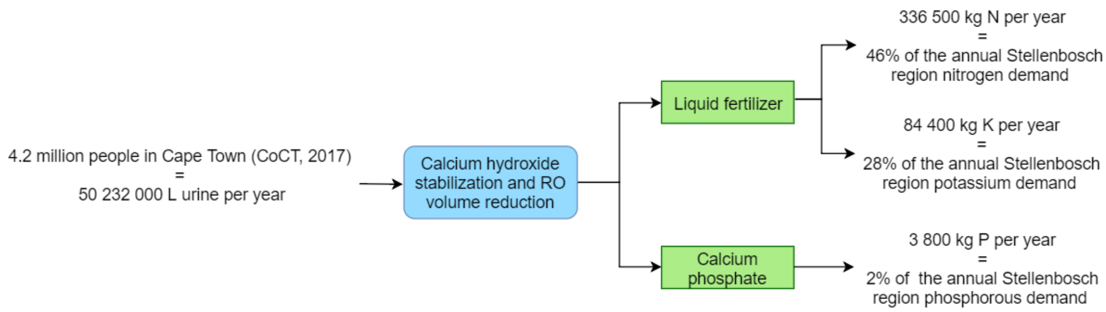

Figure 5-13: Potential nutrient recovery for widespread use of the NRU in the City of Cape Town. This assumes all Cape Town residents (CoCT, 2017) use an NRU once per week for one year. The annual Stellenbosch wine region N, P and K demands were found to be 763 000 kg N, 240 000 kg P and 303 000 kg K, respectively (SAWIS, 2017, FAOUN, 2005).

The prospect of supplying recovered fertilizers to vineyards is helped by the fact that urine derived liquid fertilizers, manufactured by VUNA (Etter et al., 2015), are already available and being successfully used to fertilize vineyards in France (Goutorbe, 2018)

5.2.7.3 Comparisons with conventional biological nutrient removal

The proposed decentralized system and conventional BNR exhibited a similar operating cost per annum for the incorporation of one RRF, as seen in **Figure 5-8**. However, lower GHG emissions and energy expenditure would be observed when comparing any of the chosen design scenarios to WWTPs. Furthermore, research indicates that urine source separation can increase the life span of WWTPs and treatment capacities by decreasing the influent nutrient load and the hydraulic load experienced (Wilsenach & van Loosdrecht, 2003).

To put this research into perspective, the effect that decentralized urine treatment would have on centralized WWTPs was estimated. Considering the average nutrient compositions in urine (**Table 3-2**) and that urine constitutes approximately 80% of the nitrogen in wastewater streams (Spångberg et al., 2014), the total nitrogen in the influent at a WWTP is approximately 84 mg N/L. An MLE AS configuration is capable of producing effluent quality with 10 mg N/L total nitrogen (EPA, 2007). By removing urine from wastewater streams, approximately 17 mg N/L total nitrogen would enter WWTPs.

Moreover, research suggests that urine source-separation and treatment may not be met with resistance. The notion of water conservation and water reclamation could be enough to persuade many people. This would especially be the case in previous, current and at-risk areas dealing with drought. Decreased total nitrogen influent concentrations and a decrease in hydraulic load, due to water conservation initiatives, would presumably have a significant effect on conventional BNR and WWT.

6 Conclusions and recommendations

In the final chapter of this dissertation, the methodologies followed, and the initial research questions and hypotheses are reviewed in section 6.1 and 6.3. This is done while considering the key findings outlined in Chapters 4 and 5. The degree of success, regarding the accomplishment of the initial research objectives, is assessed in section 6.2. Furthermore, the recommendations for future research in the field of urine source-separation and nutrient recovery is assessed in section 6.4.

6.1 Research overview

Two methodological approaches were adopted to address the research questions and hypotheses of this study. A thorough review of existing urine treatment literature was conducted to create design charts depicting urine treatment sequences for maximum nutrient recovery and limited waste. Following this, using the City of Cape Town as an illustrative case study, the impacts of a decentralized approach to urine treatment, by incorporating urine source-separation, was assessed. Geospatial analysis was used to optimize the locations of resource recovery facilities and the financial feasibility of this system was then assessed.

No experimental work was conducted in this study. Instead, the overall feasibility and potential outcomes of any real-life implementation was based solely on published literature pertaining to wastewater engineering and urine treatment. A sensitivity analysis was conducted to assess variations in the proposed system and account for uncertainty in the design parameters.

The methodology utilized in this study was deemed to be valid and furthermore, suitable for decision makers and future research opportunities.

6.2 Accomplishment of research objectives

The objectives of this research were to conduct:

1. An in-depth review of literature pertaining to previously iterated urine treatment techniques, public perception regarding urine reuse, and transportation of urine-based fertilizers.

2. A quantitative compilation of urine treatment techniques, based on resource recovery potential, from literature.

3. A design of a basic decentralized approach for resource recovery within the City of Cape Town. Evaluating the effects of transportation and logistics of source-separated urine formed the main modelling portion of this objective. Subsequently, an evaluation of the monetary and

environmental implications of this decentralized system, in comparison to conventional wastewater treatment was required.

The first two objectives were completed through both a qualitative and quantitative research approach, in Chapters 2 and 4, respectively. It was found that urine treatment and recovery of resources by precipitation and volume reduction arguably presents the most promising way to recover all nutrients from urine, leaving limited waste. The third objective was addressed in the Chapter 5, where a transportation network for the proposed decentralized urine treatment system was modelled using geospatial analysis on computer softwares. Basic engineering economics were used to assess the financial implications of the proposed system. Moreover, the decentralized system's potential for water conservation and GHG emissions was considered.

6.3 Research conclusions

The key finding as well as the overall conclusions can be found in the following sections. These findings were drawn in fulfilment of answering the two research questions posed at the onset of this research. The research questions were as follows:

1. Which method(s) of urine treatment are best suited for maximum resource recovery, and what state of urine (fresh or hydrolyzed) is most conducive for achieving this?

2. If highly frequented locations such as shopping malls and universities are targeted for installation of nutrient recovery urinals, how would the urine be collected and what are the viable market avenues for the sale and use of urine derived fertilizers?

6.3.1 Design charts assessment

As part of the review of literature, that ultimately culminated in the creation of the urine treatment design charts in Chapter 4, the first research question was addressed in response to the first hypothesis. The first hypothesis for this research was as follows:

Urine stabilization by calcium hydroxide addition, together with reverse osmosis for volume reduction, is the most effective treatment scheme because it recovers all the nutrients.

The main findings of this investigation in Chapter 4 were that:

- Due to urea hydrolysis, hydrolyzed urine cannot hold the same potential for nitrogen recovery as fresh urine, based solely on the quantity of nitrogen that can be recovered.

- Although both acid stabilization and base stabilization can prevent urea hydrolysis, acid presents a safety hazard for untrained personnel, decreasing its overall appeal if stabilization of urine in public spaces is to be considered.

- Reverse osmosis, evaporation and freeze concentration were considered as volume reduction methods for urine. Literature indicates that RO potentially offers a cheaper and less complex method of water removal for a similar nutrient concentration, when compared to evaporation and freeze concentration. Therefore, RO was the preferred volume reduction option.

It was thus concluded that a combination of calcium hydroxide dosing and RO volume reduction was the best process sequence for maximum recovery, as hypothesised. This treatment sequence can potentially produce a solid calcium phosphate fertilizer, as well as a liquid nitrogen-based fertilizer with a 3.3 - 0 - 0.8 NPK rating. Therefore, the nitrogen composition of this liquid fertilizer could potentially be comparable to that of commercially available liquid fertilizers.

6.3.2 Decentralized urine treatment assessment

The second research question was addressed in Chapter 5, in response to the second hypothesis. The second hypothesis for this research was as follows:

Decentralized urine treatment, which incorporates nutrient recovery in the form of fertilizer production, is profitable when large volumes of urine are collected and processed at a decentralized resource recovery facility. Moreover, this system produces lower GHG emissions and has a lower energy expenditure when compared with conventional WWT systems.

The main findings of this investigation in Chapter 5 were that:

- Weight limitations pertaining to the transportation of urine presented an issue and required several iterations to solve the travelling salesman problem for low levels of decentralization. Despite this, transportation and logistics only contributed between 2% and 6% of the OPEX across each design scenario. In small and densely populated areas, like Cape Town, short travel distances are experienced. This directly reduces the effect of routing from an economic perspective. Therefore, the level of success that can be experienced from such a system would likely be dependent on the geospatial configuration of the chosen area.

- Increasing the degree of decentralization, while the collection locations and urine collected remained constant, had an inversely proportionate effect on travel distance in this model. This was because the weight restrictions of the trucks decreased as the number of RRFs increased, which meant all collection locations were only required to be visited once per week. However, the difference in travel distance of successive degrees of decentralization appears to reduce.

- It was found that the most appealing scenario, from a financial perspective, incorporated the use of a 4-ton truck and one RRF (scenario one). Although the OPEX was found to be similar, the GHG emissions and energy expenditure for scenario one were more favourable than that of conventional WWT. Moreover, scenario one offered the added benefit of resource recovery from urine, while potentially decreasing hydraulic loads to WWTPs. However, a globally optimal solution which incorporated the minimum operating cost, minimum travel distance and minimum GHG emissions, amongst the design scenarios was not possible. This was because increasing the number of RRFs installed increased the OPEX but resulted in a decrease in GHG emissions due to a decrease in travel distance.

- A positive net present value was realised over an investment period of five years for each level of decentralization investigated. An NPV of R38.3 million was achieved for scenario one. When assessing the sensitivity of the proposed design, the selling price of liquid fertilizer required to break-even was as low as R22.75/L of fertilizer, if all recovered fertilizer is sold. Moreover, when selling at the chosen design selling price, only approximately 15% of the total producible liquid fertilizer would need to be sold to break even, for scenario one.

- It was assumed that plant nurseries would offer the most applicable medium for the sale of niche fertilizer products. However, the vineyards that surround the City of Cape Town could also potentially provide an avenue for bulk fertilizer distribution. It was found that the urine produced from the eight collection locations used in this study could potentially provide 0.3%, 0.01% and 0.2% of the nitrogen, phosphorous and potassium required for the Stellenbosch wine region per year.

Overall, the results of Chapter 5 agreed with the second research hypothesis. It is understood that a system of this nature would require a major overhaul to currently accepted WWT norms and hold additional capital and operating costs that cannot be predicted by a desktop study alone. The goal of this research was to display the potential that resource recovery from urine could have, by using a densely populated modern city.

It is hoped that further research will be undertaken to improve niche methods of resource recovery and continue to work towards the sustainability goals outlined by the United Nations (UN, 2015). Moreover, the amalgamation of geospatial analysis and source-separated urine treatment could prove to be a powerful tool for optimizing the feasibility of decentralized waste management at high resolution in the future.

6.4 Recommendations for future studies

The following recommendations for any future investigations were made.

- To increase the accuracy of travel time and travel distances, for transportation in future investigations into decentralized systems, the inclusion of traffic flow theory and site-specific transportation trends should be considered.

- Transportation and logistics were not found to be a major cost and only occupied a small fraction of the total OPEX. This is likely due to the City of Cape Town's geospatial configuration. Cape Town was used as a case study as information pertaining to its geospatial data is readily available online. However, taking South African cities as an example, the City of Cape Town encompasses only 17%, 24% and 58% of the surface area of Durban, Johannesburg and Pretoria, respectively (StatsSA, 2018). To fully understand if the results from this study are reproducible in the South African context, similar studies should to be conducted in larger locations. Increasing the coverage of this system would also help to deduce if economies of scale could be achieved.

- This research assumed that NRUs are installed at ground level or easy to access locations. The implications of implementing these devices in multi-story buildings is unknown. Previous studies have opted to collect urine in the basement of multi-story buildings (Etter et al., 2015). In the proposed system, this could present some problems. The plumbing of existing buildings would require an overhaul and there is a risk that urea hydrolysis, as well as scaling could occur within the urine collecting pipe system. An optimum solution for this requires further investigation.

- Methods of improving the urinal unit to make it more acceptable for female use is also required. Currently only half of the population would be capable of contributing to such a system if it existed.

- The complete implications of a change to a decentralized system using NRUs is unknown. Therefore, a trial period in which a limited number of NRUs are installed in a controlled environment is suggested. This exercise would be used to assess any shortcomings of the system that cannot be identified by a desktop study alone. Furthermore, experiments focusing on RO concentration of stabilized urine, as well as the testing of the fertilizer product on vegetation, are required.

- South African vineyards were used as an example to estimate the potential of the fertilizer products that can be formed from a decentralized urine collection and treatment system.

However, this approach to the applications of recovered fertilizer should also be broadened to alternate forms of agriculture for additional avenues of fertilizer distribution.

7 References

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Appendix A: Urine treatment design charts calculations

Herein lies the design calculations used to create the urine treatment sequence outcomes for the design charts displayed in Chapter 4. To estimate the composition of fresh and hydrolyzed urine, a thorough literature review was conducted, and average values were obtained. The sources, as well as the overall compositions are displayed in **Table A-1**.

Table A-1: Average Fresh and hydrolyzed urine composition.

		Fresh Urine						Hydrolyzed Urine					
Source	**Units**	**Randall et al. (2016)**	**Udert et al. (2003b)**	**Udert et al. (2003a)**	**Dai et al. (2014)**	**Luther et al. (2015)**	**Average**	**Pradhan et al. (2017)**	**Luther et al. (2015)**	**Dai et al. (2014)**	**Kuntke. (2012)**	**Liu et al. (2013)**	**Average**
Mg	mg/L	57	95	77	36	59.8	65	0	0	0	0	0	0
PO_4^{3-}	mg/L	797	2279	1125	1073	500	1155	947	613	767	644	1055	805
PO_4^{3}-P	mg/L	260	743	367	350	163	377	309	200	250	210	344	263
NH_4^+-N	mg/L	436	476	254	330	300	359	4500	4800	6400	4050	4250	4800
Urea- N	mg/L	5420	7564	5810	7400	5500	6339	0	-	0	0	0	0
Ca	mg/L	132	184	129	150	105.4	140	-	55.2	14	7.1	-	25
Na	mg/L	2510	2759	2670	-	2400	2585	-	2400	-	1850	2600	2283
K	mg/L	469	2189	2170	-	1900	1682	1700	1900	-	1490	2000	1773
Cl	mg/L	4430	3900	3830	-	3200	3840	4500	2900	-	3290	3800	3623
pH	mg/L	6..3	6.2	7.2	6.5	6.9	6.62	9.3	9.4	9.2	8.85	9.3	9.21

Moreover, to estimate how the urine solution is affected by different treatment methods, several assumptions were made. These assumptions are shown in **Table A-2**.

Table A-2: Urine treatment process chart assumption.

Description	Unit	Value	Source
Amount of $Ca(OH)_2$ dosed into fresh urine for urea stabilization	g/L of urine	10	Randall et al. (2016)
Amount of H_2SO_4 dosed into fresh urine for urea stabilization	g/L of urine	3	Hellström et al. (1999)
Amount of $Ca(OH)_2$ dosed into hydrolyzed urine for ammonia stripping	g/L of urine	22	Pradhan et al. (2017)
Urea decomposed to ammonium after $Ca(OH)_2$ stabilization	%	0	Assumed
Urea decomposed to ammonium during urea hydrolysis	%	100	Assumed
Water removed during RO volume reduction	%	80	Ek et al. (2006)
Water removed during evaporation volume reduction	%	80	Assumed
Phosphorus recovery due to calcium $Ca(OH)_2$ dosing	%	98	Flanagan & Randall (2018)
Phosphorus recovery due to calcium MgO dosing	%	99	Barbosa et al. (2016)
Nitrogen recovery due to ammonia stripping	%	99	Pradhan et al. (2017)
Nitrogen recovery due to cation exchange	%	97	(Allar Emek & Beler Baykal, 2015)
Density of urine	kg/m^3 urine	1025	Pradella et al. (1988)
Density of liquid fertilizer	kg/m^3 urine	1025	Assumed to be the same as urine

In sequences that incorporated dosing of an acid or a base into urine, the quantity and concentration of each element dosed was calculated using basic chemistry. An example of how base stabilization by calcium hydroxide dosing would affect the calcium concentration in a fresh urine solution can be seen in **Equation A-1**. An identical calculation procedure was used to determine the sulphuric acid dosage for acid stabilization, and the calcium hydroxide dosage for accelerating ammonia stripping.

Calcium hydroxide dosing for stabilization of fresh urine:

- 10 g/L of calcium hydroxide was dosed to fresh urine to inhibit urease and prevent urea hydrolysis.
- Calcium molar mass is 40.078 g/mol (PubChem, 2018b) and $Ca(OH)_2$ molar mass is 74.093 g/mol (PubChem, 2018a).

Calcium dosed $= \frac{10 \text{ g Ca(OH)}_2}{\text{L}} \text{ X } \frac{1 \text{ mol}}{74 \text{ g Ca(OH)}_2} \text{X} \frac{40\text{g Ca}}{\text{mol}}$

$\approx 5.409 \text{ g Ca/L}$

$\approx 5\ 409 \text{ mg Ca/L}$

$\therefore$ The calcium part of the calcium hydroxide dosed into fresh urine is 5 409 mg Ca/L

- Calcium phosphate is three parts calcium and two parts phosphate (Pubchem.com, 2018), so 1.5 mg Ca will precipitate out for every 1 mg PO_4^{3-}-P that is removed in Ca-P
- 140 mg Ca/L already exists in solution prior to dosing.
- Moreover, calcium is bound to phosphate, not just the phosphorous bound within. The average phosphate concentration for fresh urine was found to be 1 155 mg PO_4^{3-}/L, as per **Table A-1**.

Ca in solution after Ca-P precipitation $= \frac{140 \text{ mg Ca}}{\text{L}} + \frac{5409 \text{ mg Ca}}{\text{L}} - \frac{1.5 \text{ mg Ca}}{\text{mg PO}_4{}^{3-}} \text{ X } \frac{1155 \text{ mg PO}_4{}^{3-}}{\text{L}}$

$\approx 3\ 817 \text{ mg Ca/L}$ **Equation A-1**

$\therefore$The concentration of calcium in solution after calcium phosphate precipitation by calcium hydroxide dosing is 3 817 mg Ca/L.

In the cases where a volume reduction occurs, the solution concentrations following these processes was approximated through a mass balance. An example of the volume reduced nitrogen concentration experienced in a stabilized fresh urine sample, by RO is shown in **Equation A-2** and a summary of each nutrient in the same fresh urine sample is displayed in **Table A-3**. This process was repeated in all cases involving a reduction in volume for urine.

Volume reduced concentrations estimation:

- Approximately 80% of the water in fresh urine is assumed to be removed through RO and recovered as permeate water. Therefore, 20% of the influent urine volume is retained in the RO brine.
- For simplicity, it was assumed that pure water is produced, and all salts are retained in the brine.
- Total nitrogen composition content is measured through the addition of the nitrogen mass of ammonium and urea.

An assumed urine flow rate of 1 L/day is assumed in **Equation A-2.**

Total influent nitrogen $= \frac{6339 \text{ mg Urea N}}{\text{L urine}} + \frac{359 \text{ mg NH}^{4+} \text{ N}}{\text{L urine}} \approx 6700 \text{ mg N/L of urine}$

Nitrogen in volume reduction $\therefore \frac{6\,700 \text{ mg N}}{\text{L urine}} \text{ X } \frac{1 \text{ L urine/dayinfluent}}{0.2 \text{ L liquid fertilizer/day brine effluent}}$

$\approx$ 33 500 mg N/L liquid fertilizer **Equation A-2**

The flow rate assumed in **Table 3**, is identical to that which is shown in **Equation A-2**.

Table A-3: Concentrations of calcium hydroxide stabilized fresh urine after RO volume reduction.

	RO Influent		**Brine (liquid fertilizer)**	
	concentration (mg/L)	**Flux (mg/d)**	**concentration (mg/L)**	**Flux (mg/d)**
Mg	65	65	325	65
PO_4^{3-} -P (98% P removed in Ca-P precipitation)	8	8	40	8
NH_4^+-N	359	359	1 796	359
urea-N	6 339	6 339	31 694	6 339
Ca (from $Ca(OH)_2$ dosed)	3817	3817	18934	3817
Na	2 585	2 585	12 924	2 585
K	1 682	1 682	8 411	1 682
Cl	3 840	3 840	19 200	3 840
SO_4^{2-}	952	952	4 762	952

The NPK values for each sequence were estimated based on the volume reduced concentrations. The density of the volume reduced fertilizer was assumed to be identical to that of urine. Sample calculations for the NPK values of calcium hydroxide stabilized fresh urine following a RO volume reduction are shown in **Equation A-3.** Urine density was found to be 1025 g/L (Pradella et al, 1988). The liquid fertilizer density was assumed to be the same as the density of urine to estimate the weight fraction of the nitrogen, phosphorous and potassium.

Nitrogen composition $= \frac{33.5 \text{ g N}}{\text{L urine}} \text{ X } \frac{1 \text{ L urine}}{1025 \text{ g}} \text{ x } 100$

$\approx$ 3.3% Nitogen

Phosphorous composition $= \frac{0.04\ \text{g P}}{\text{L urine}} \text{X} \frac{\text{L urine}}{1025\ \text{g}}\ \text{x}\ 100$

$\approx 0\%$ Phosphorous

(377 g PO_4^{3-} phosphorous is precipitated out as Ca-P, as per **Table A-1**)

Potassium composition $= \frac{8.4\ \text{g K}}{\text{L urine}}\ \text{X}\ \frac{\text{L urine}}{1025\ \text{g}}\ \text{x}\ 100$

$\approx 0.8\%$ Potassium **Equation A-3**

$\therefore \text{N:P:K (weight \%)} = 3.3 - 0 - 0.8$

Appendix B: Decentralized urine treatment calculations

Herein lies the design calculations used to build the source-separated, decentralized urine treatment model presented in Chapter 5 of the main report. A complete list of basic assumptions and values used to model the transportation and financial implications of the proposed decentralized system are shown in **Table B-1**.

Table B-1: Decentralized urine treatment design parameters.

Description	Unit	Value	Source
Urinal container volume	L	25	Flanagan & Randall (2018)
14- ton fuel consumption	km/L	2.5	Department of Agriculture and forestry (DAFF, 2016)
14-ton truck	R	995 000	DAFF (2016)
14-ton truck maintenance	R/km	13.13	DAFF (2016)
4-ton fuel consumption	km/L	6.66	DAFF (2016)
4-ton truck	R	554 931	DAFF (2016)
4-ton truck maintenance	R/km	7.77	DAFF (2016)
8-ton fuel consumption	km/L	3.33	DAFF (2016)
8-ton truck	R	712 650	DAFF (2016)
8-ton truck maintenance	R/km	9.79	DAFF (2016)
BNR nitrogen GHG emissions	Kg CO_2/Kg N removed	3	Falk et al. (2013)
BNR operating costs	R/m^3 wastewater	27.35	EPA (2007)
BNR energy consumption	kWh/kg N	2.3	Mulder (2003)
Calcium hydroxide	R/kg	3.1	Alibaba.com (2018)
Calcium phosphate density	kg/m^3	3140	ChemicalBook (n.d.)
Calcium phosphate produced from calcium hydroxide dosing in fresh urine	g/kg urine	11	Flanagan & Randall (2018)
Calcium phosphate selling price	R/kg	18.5	Herman (2017)
Cleaning and maintenance wage	R/hr	60	Tyler (2017)
Density of urine	kg/m^3	1025	Pradella et al. (1988)
Density of liquid fertilizer	kg/m^3	1025	Assumed to be the same as urine density

Table B-1: Decentralized urine treatment design parameters (continued).

Description	Unit	Value	Source
Electricity GHG emissions	CO_2/kWh	0.94	Guan (2006)
Energy	R/kWh	2.84	Eskom (2018)
Fuel	R/L	14.4	AA.com (2018)
Fuel GHG emissions	Kg CO_2/L fuel	2.7	Fruergaard et al. (2009)
Industrial RO unit cost	R/10 m^3/day	100 000	Nathoo (2018)
Liquid fertilizer produced from RO	L/m^3 urine	200	Ek et al (2006)
Liquid fertilizer selling price	R/L	151.52	Assumed from least square regression
Nitrogen contribution to wastewater by urine	%	80	Spångberg et al. (2014)
Nutrient recovery urinal unit	R	800	Flanagan & Randall (2018)
Permeate water produced from RO	L/m^3 urine	800	Ek et al (2006)
RO energy consumption	kWh/m^3 urine	2	Nathoo (2018)
RRF site manager wage	R/hr	60	Assumed
Sewer connections	R/m^3 flushed	34.83	CoCT (2018a)
Truck average travel speed	km/hr	60	Assumed
Truck driver wage	R/hr	82	Indeed.com (2018)
Urine produced per person	L/day	1.15	von Münch & Winker (2011)
Average urinal usage per person	Usage /day	5	Rossi et al. (2009)
Urine produced per usage	L /urinal usage	0.23	Assumed from average urinal usage per day
Water used per flush in conventional waterborne urinals	L	4	von Münch & Dahm (2009)
Urine volumetric contribution to wastewater	% of total wastewater	1	Spångberg et al (2014)
Warehouse rental per m^2	R/ month	64	Broll.com, 2018
Warehouse space deposit	R/m^2	128	Assumed to be double the one month's rent

Table B-1: Decentralized urine treatment design parameters (continued).

Description	Unit	Value	Source
Warehouse work wage	R/hr	60	Indeed.com, (2018a)
Water supply	R/m^3	43.13	CoCT (2018a)

Transportation and last-mile logistics

Flowmap

As stated in the methodology (Chapter 3), obtaining the geospatial data containing the topographical information of Cape Town was the initial step in creating the transportation network model. Geospatial data included the land boundaries and road network. ArcGIS compatible data will herby be referred to as shapefiles. The WGS 1984 World Mercator and the GCS WGS 1984 systems were used as the projected coordinate system and geographic coordinates system, respectively. The coordinates of each collection location were required and are displayed in **Table B-5**. It was then possible to create a map detailing the study area, the road network, and the collection locations, which are shown in **Figure B-1.**

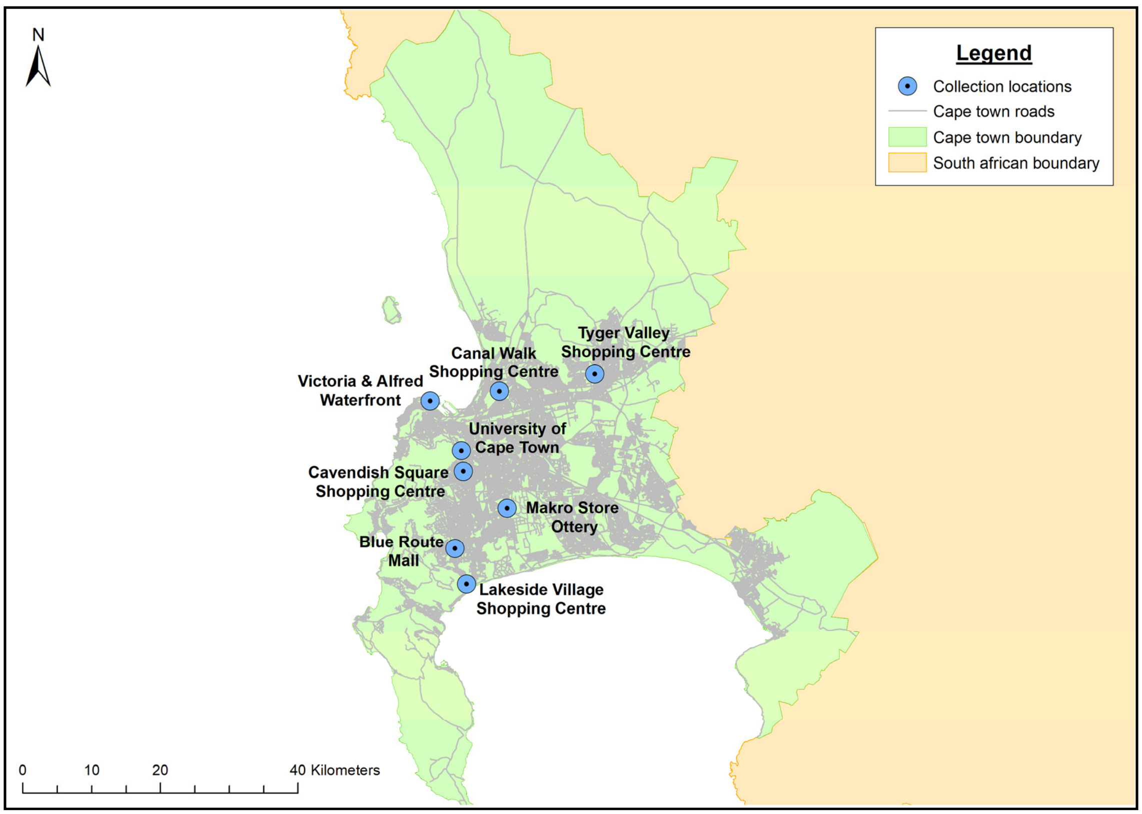


Figure B-1: Research study area.

These ArcGIS shapefiles were then converted to the Flowmap software file format to conduct the RRF location allocation for each scenario. The Flowmap software uses tessellations to map points on a given bounded surface. Hexagon shapes were used as the method of tessellation and the centroids of these hexagons represented all location within Cape Town as seen in **Figure B-2**. Moreover, the area within each hexagon is represented by these centroids, such that if a service location is allocated within a hexagon, its location will be that hexagon's respective centroid. Each hexagon is 2.6 km^2 in area and represents 0.1% of the total Cape Town metro surface area, offering a large degree of coverage for location optimization.

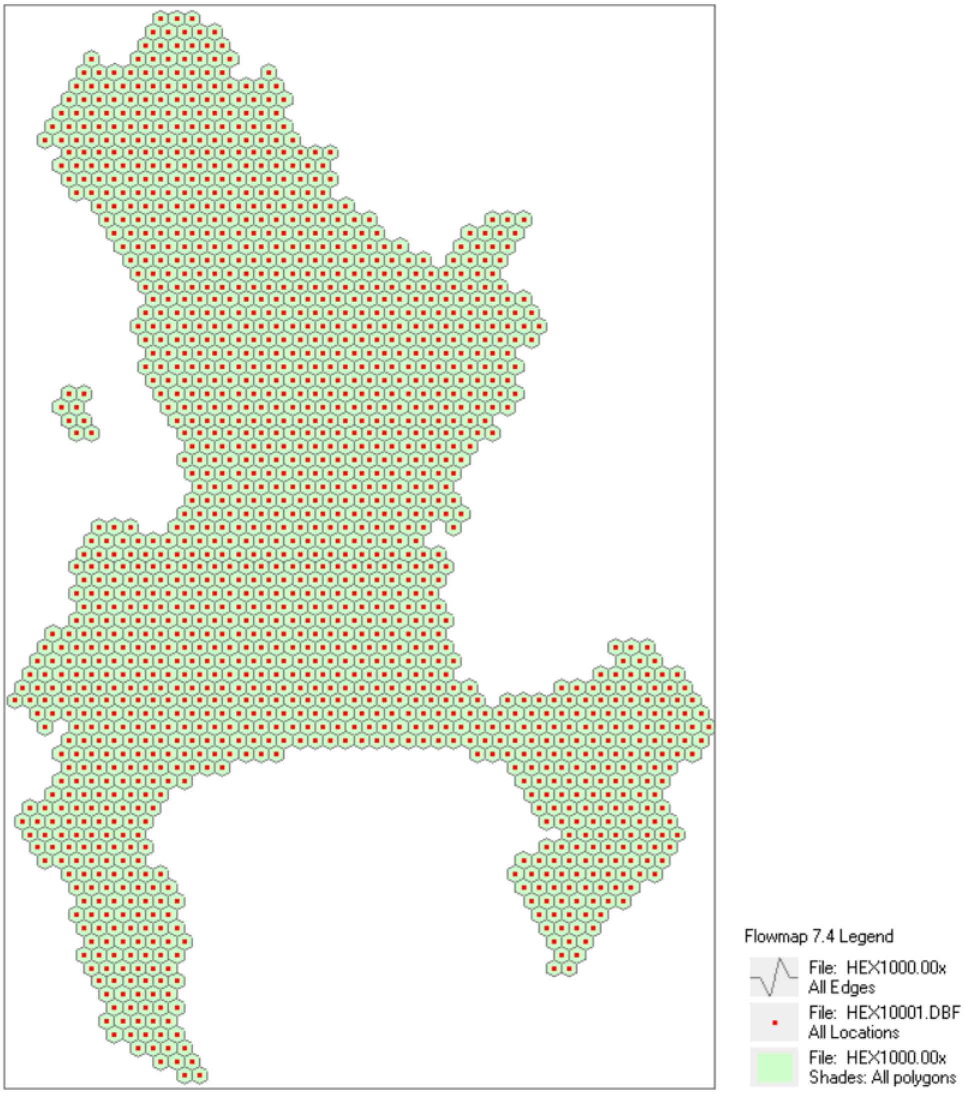


Figure B-2: Tessellated study area.

Before moving onto the allocation of RRFs, a network distance matrix was required to be created. This matrix was essential as it contained the distances between all possible combinations of locations within the road network. Distance, in meters, was used as the impedance attribute, and the average truck speed was assumed to be 60 km/hr. A screenshot of the modelling parameters used to create the distance matrix are shown in **Figure B-3**.

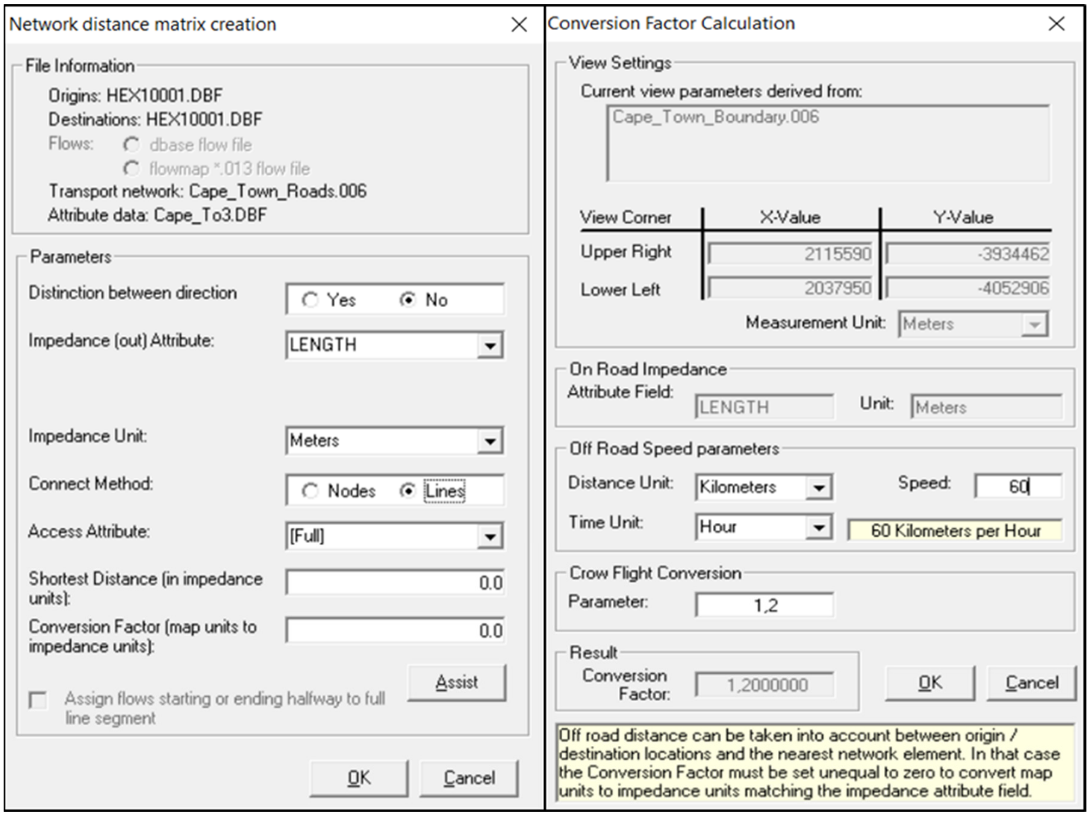
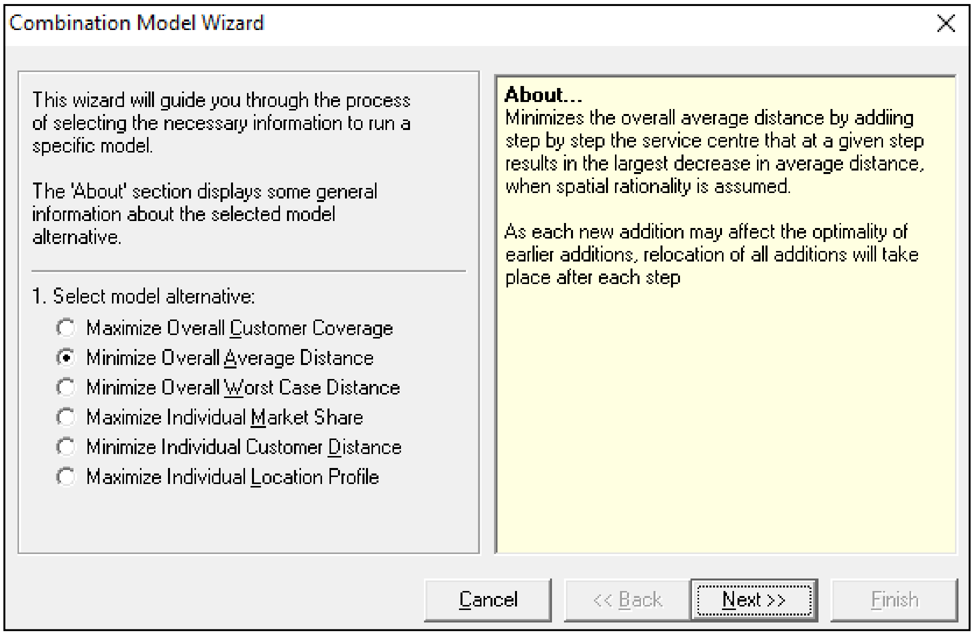


Figure B-3: Flowmap network distance matrix creation parameters.

The location allocation simulation was then conducted to determine the best location for each RRF in each of the four scenarios. This was done with the intention of minimising the average distance of each location to its respective RRF, while assuming spatial rationality. The expansion and relocation option in Flowmap was used to model the ideal locations for RRFs in each scenario. In scenario one, only one RRF is employed. In scenarios two, three and four; two, four and eight RRFs were incorporated, respectively. Each scenario included one central packaging and distribution (PAD) facility which all the final, treated fertilizer product is delivered to. The location of the PAD facility was the most central location amongst the collection locations, based on average distance, and thus was identical in each scenario. The expansion and relocation settings used in Flowmap are shown in **Figure B-4** below.



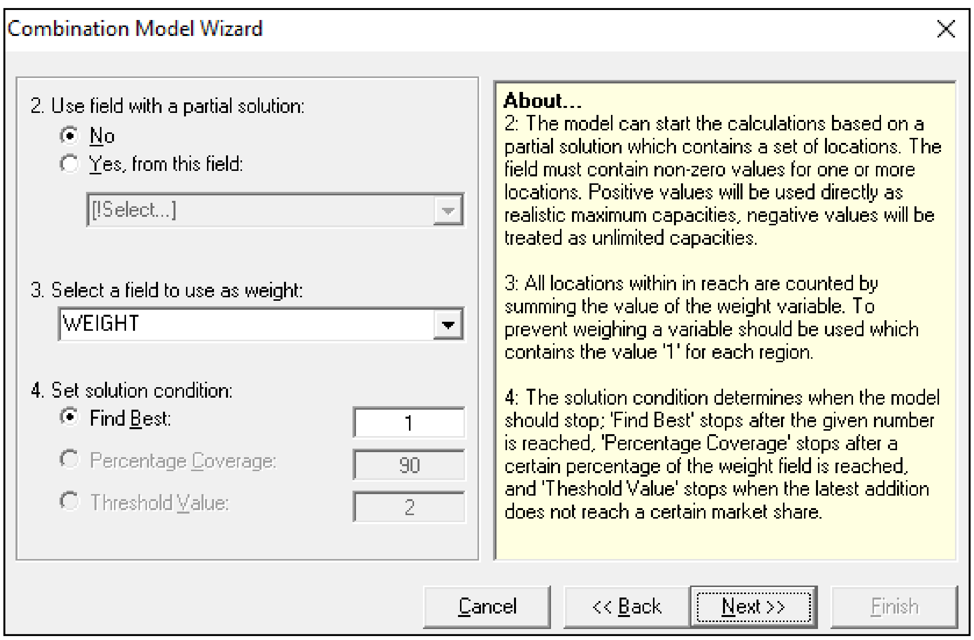


Figure B-4: Flowmap expansion and relocation model settings used to allocate optimal locations of RRFs based on minimum average distance. The set solution condition was set to either 1, 2, 4 or 8 to find the optimal locations in each scenario.

The allocation of RRFs for scenarios one and four (one RRF and eight RRFs) can be seen in **Figure B-5**. These newfound locations were then exported to ArcGIS for further analysis and transportation routing, as seen in **Figure 5-3** and **Figure 5-4** in Chapter 5 of the dissertation.

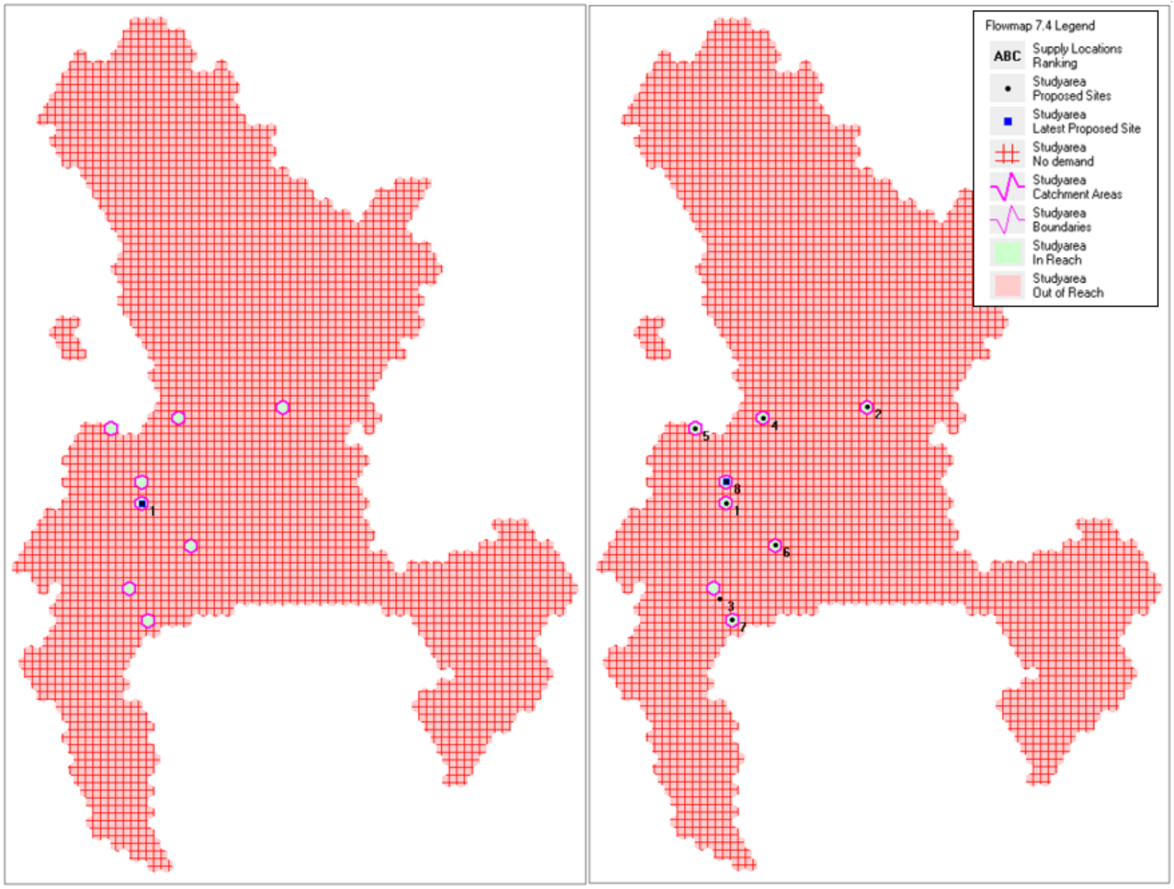


Figure B-5: RRF position allocation for one RRF (left) and eight RRFs (right). "Study area in reach" refers to the collection locations, as seen by the eight "in reach" hexagons. In scenario one, the RRF location also acted as the PAD facility location. The PAD facility was located in the same position for each scenario.

Collection location characteristics

As it is difficult to accurately estimate the number of daily visitors entering each shopping centre, the number of daily visitors was estimated from each location's retail area. Research conducted by the Urban Studies Research Group (Prinsloo, 2016 & Prinsloo, 2013) gives guidelines regarding the estimated number of monthly shopping centre visitors based on the category of the shopping centre, as seen in **Table B-3**. The retail area of each shopping centre was sourced from BusinessTech.com (2018). A sample calculation for the Victoria & Alfred Waterfront (V&A) shopping centre is shown in **Equation B-1**.

Table B-3: South African shopping mall visitor characteristics (Prinsloo, 2016 & Prinsloo, 2013).

Type of Centre	Retail area (m^2)	Average number of visitors (people/m^2/month)	Frequent visitors (% of total customer base)	Average visitor dwell time (minutes)
Neighbourhood Centres	5 000-12 000	17.1	80	32.5
Community centres	12 000- 25 000	18.3	65	70
Small Regional Centres	25 000- 50 000	15.5	62.5	95
Regional Centres	50 000- 100 000	14	62.5	120
Superregional Centres	>100 000	12.7	50	130

V&A daily male visitors $= \text{Retail area } (\text{m}^2) \text{ X } \frac{\text{people}}{\text{m}^2\text{.month}} \div \frac{\text{month}}{\text{30 days}} \text{ X } 50\% \text{ males x } \% \text{ frequent visitors}$

$$= 69\ 000 \text{ m}^2 \text{ X } \frac{14 \text{ people}}{\text{m}^2 \text{ x month}} \text{ X } \frac{1 \text{ male}}{2 \text{ people}} \text{ X } \frac{1 \text{ month}}{30 \text{ days}} \text{ X } 0.625 \text{ frequent visitors}$$

$$\approx 10\ 063 \text{ daily male visitors}$$ **Equation B-1**

These guidelines were used for all 7 shopping centres to uniformly estimate the number of daily visitors and were subsequently halved to give the number of daily male visitors. The estimated number of daily male visitors at the University of Cape Town included both the student and staff who were registered or employed at the University in 2018 (UCT, 2018), divided by two.

The number of urinals that required retrofitting were estimated from the minimum number of urinals required for public spaces at peak demand, as per the South African National Standards (SANS) (SANS, 2012). **Table B-4** summarizes these guidelines. A sample calculation for the urinals provided at the V&A shopping centre can be seen in **Equation B-2.**

Table B-4: Sanitary fixture to be installed for public use as per South African Building regulations (SANS, 2010).

For a population of up to-	Number of urinals
50	1
100	2
150	3
250	4
500	7
1 000	12
1 500	15
	For a population in excess of 1500 per day add 1 urinal pan for every 300 persons

It was assumed that each 25 L urinal container was filled every week. The quantity of urine that was transported was estimated from the number of urinals allocated to each collection location. A sample calculation for the volume and weight of the urine collected per week, at the V&A shopping centre can be seen in **Equation B-2**. Moreover, it was assumed that waterborne urinals are currently in use at all collection locations (status quo). Assuming that each urinal container is filled every week, a sample calculation for the water that would be required to flush the amount of urine collected, if a waterborne urinal system was in place, is shown in **Equation B-3**.

V&A urine collected per week $=15 \text{ urinals} + \frac{(\text{daily male visitor} - 1\,500)}{300}$

$$= 15 + \frac{10\,063 - 1\,500}{300}$$

$$\approx 44 \text{ Urinals x } 25 \text{ L per urinal container}$$

$$\approx 1\,089 \text{ L of urine collcected per week}$$

$$\therefore \frac{1\,089 \text{ L urine}}{\text{week}} \text{ x } \frac{1025 \text{ g}}{\text{L urine}} \text{ x } \frac{\text{kg}}{1000 \text{ g}}$$

$$\approx 1\,116 \text{ kg of urine collected per week}$$ **Equation B-2**

Approximately 0.23 L of urine are produced per urinal usage, assuming a person urinates 5 times per day (von Münch & Winker., 2011, Rossi et al., 2009). Moreover, it was assumed waterborne urinals use 4 L of water per flush von Münch & Dahm., 2009).

V&A water for waterborne urinals $= 44 \text{ urinals } \ \text{X} \frac{25 \text{ L}}{\text{urinal}} \ \text{X} \frac{1 \text{ urinal use}}{0.23 \text{ L}}$

$\approx 4733 \text{ urinal uses per week x } 4 \text{ L water used per flush}$

$\approx 18\,932 \text{ L water would be used on flushes per week in status quo}$ **Equation B-3**

A summary of the characteristics of each of the collection locations is seen in **Table B-5**. All values were calculated in an identical fashion to the sample calculations provided above.

Table B-5: Collection location characteristics.

Collection locations	Co-ordinates (Decimal degrees °)		Retail area (m²)	Mall classification	Daily male visitor population	Urinals containers required	Urine produced per week (L)	Urine produced per week (kg)	Estimated urinal usage frequency per week	Equivalent water used per week in status quo (L)
Blue Route Mall	34.0641° S	18.4528° E	55 500	Regional Centre	8 094	37	924	948	4 019	16 078
Canal Walk Shopping Centre	33.9577° S	18.4612° E	147 000	Super Regional Centre	15 558	62	1 546	1 585	6 724	26 895
Cavendish Square	33.9804° S	18.4638° E	45 000	Small Regional Centre	7 266	34	855	877	3 719	14 878
Lakeside Village Shopping Centre	34.1028° S	18.4681° E	7 500	Neighbourhood Centre	1 710	16	393	402	1 707	6 826
Makro Store Ottery	34.0202° S	18.5211° E	12 000	Community Centre	2 379	18	448	459	1 949	7 796
Tyger Valley Shopping Centre	33.9715° S	18.6021° E	90 000	Regional Centre	13 125	54	1 344	1 377	5 842	23 370
Victoria & Alfred Waterfront	33.8929° S	18.5112° E	69 000	Regional Centre	10 063	44	1 089	1 116	4 733	18 932
University of Cape Town	33.9036° S	18.4205° E	N/A	N/A	8 243	37	937	960	4 073	16 293
Total	**N/A**	**N/A**	**426 000**	**N/A**	**66 438**	**302**	**7 536**	**7 724**	**32 766**	**131 067**

ArcGIS

After finding the position of the optimized RRF locations, their coordinates were then converted into shapefiles. The ArcGIS network analyst tool was used to solve the travelling salesman problem (TSP) for each scenario. This required the creation of a network dataset, using the Cape Town road network. Similar to the parameters used to create the Flow map distance matrix, distance was used as the impedance attribute, and the average truck speed was assumed to be 60 km/hr.

The TSP analysis was done for a 4-ton truck, an 8-ton truck and a 14-ton truck. For direct comparison, the locations of each RRF, and the collection locations which are assigned to each RRF, all remained unchanged for each mode of transport analysed. For each scenario the TSP was solved considering the network analyst settings shown in **Figure B-6**. The travelling salesmen problem was solved with the most prominent restriction being that each trip had to originate and conclude at the PAD facility.

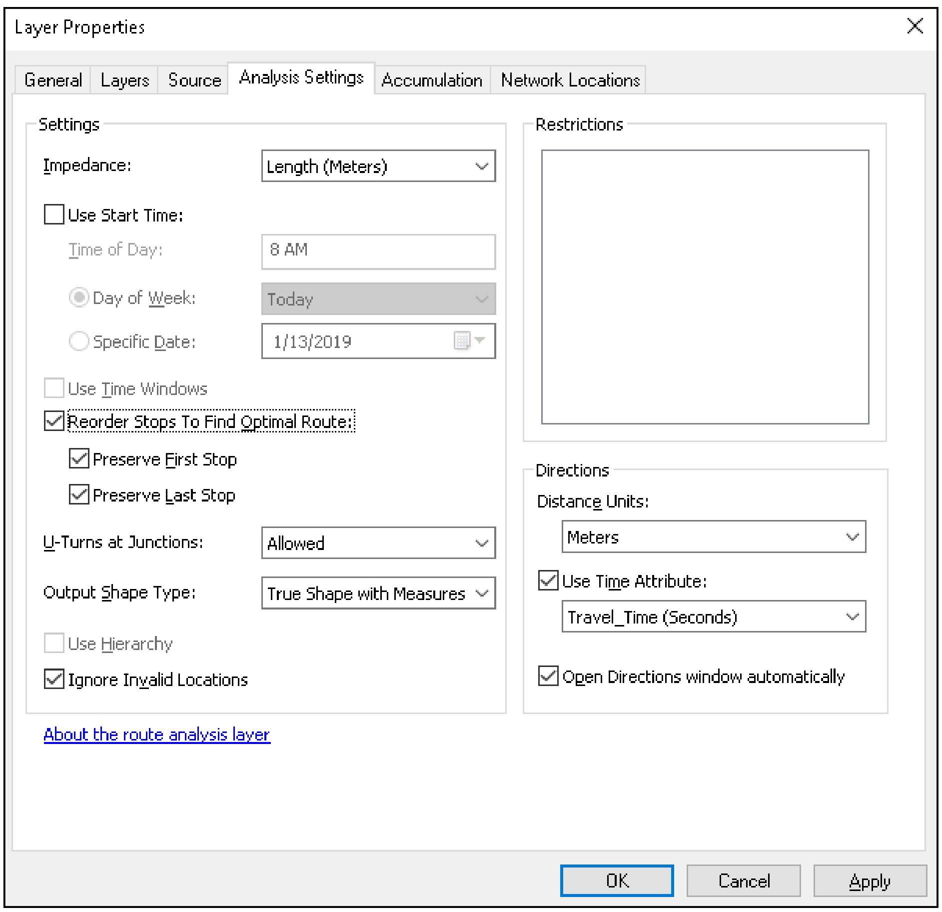


Figure B-6: Travelling salesman problem solution parameters.

Once the routes were created, the weight restrictions (pertaining to urine that required carrying and the truck carrying capacity) needed to be taken into consideration. Once the truck in question had reached its full carrying capacity, it was required to return to the RRF that is allocated to the collection location it has most recently visited. Moreover, once a truck had collected all the urine allocated to a specific RRF, delivering that urine to its respective RRF was prioritized over continuing collections from other collection locations.

Travelling salesman problem solution

The solution to the travelling salesman problem for the 4-ton truck is given below. An identical approach and methodology was followed when solving the TSP for an 8-ton truck and a 14-ton truck.

Scenario one

As seen in **Table B-6**, although the TSP solved the shortest route to visit all locations, the weight restrictions were not considered. Another simulation had to be done to incorporate these weight restrictions, show in **Table B-7**.

Table B-6: Scenario one TSP first iteration.

Stop name	Trip sequence	Cumulative length (m)	Cumulative travel time (s)	Cumulative stabilized urine weight (kg)	Cumulative treated fertilizer weight (kg)	Carriage weight when leaving each location (kg)	4- ton restriction IF confirmation
RRF/PAD Facility	1	0	0	0	0	0	OK
University of Cape Town	2	2891	209	960	0	960	OK
Victoria & Alfred Waterfront	3	12384	895	2076	0	2076	OK
Canal Walk Shopping Centre	4	25291	1827	3661	0	3661	OK
Tyger Valley Shopping Centre	5	39376	2844	5038	0	5038	NOT OK
Makro Store Ottery	6	63690	4601	N/A	N/A	N/A	N/A
Lakeside Village Shopping Centre	7	76861	5554				
Blue Route Mall	8	82057	5930				
Cavendish Square Shopping Centre	9	92564	6690				
RRF/PAD Facility	10	92961	6718				

At no point was treated fertilizer carried by the truck for scenario one, as the RRF and the PAD facility act as the same location.

Table B-7: Scenario one TSP second iteration, taking carriage weight into consideration.

Stop name	Trip sequence	Cumulative length (m)	Cumulative travel time (s)	Cumulative stabilized urine weight (kg)	Cumulative treated fertilizer weight (kg)	Carriage weight when leaving each location (kg)	4- ton restriction IF confirmation
RRF/PAD Facility	1	0	0	0	0	0	OK
University of Cape Town	2	2891	209	960	0	960	OK
Victoria & Alfred Waterfront	3	12384	895	2076	0	2076	OK
RRF	4	24237	1751	0	0	0	OK
Canal Walk Shopping Centre	5	37422	2703	1585	0	1585	OK
Tyger Valley Shopping Centre	6	51506	3720	2962	0	2962	OK
Makro Store Ottery	7	75821	5477	3422	0	3422	OK
Lakeside Village Shopping Centre	8	88991	6430	3824	0	3824	OK
RRF	9	103622	7488	0	0	0	OK
Blue Route Mall	10	114505	8275	948	0	948	OK
Cavendish Square	11	125012	9035	1824	0	1824	OK
RRF/PAD Facility	12	125409	9064	0	0	0	OK

Scenario two

Similar to scenario one, weight restrictions effected the initial TSP solution for scenario two as seen in **Table B-8**. The second iteration of the TSP for scenario two, considering weight is shown in **Table B-9**.

Table B-8: Scenario two TSP first iteration.

Stop name	Trip sequence	Cumulative length (m)	Cumulative travel time (s)	Cumulative stabilized urine weight (kg)	Cumulative treated fertilizer weight (kg)	Carriage weight when leaving each location (kg)	4- ton restriction IF confirmation
PAD facility	1	0	0	0	0	0	OK
Cavendish Square	2	397	29	877	0	877	OK
Tyger Valley Shopping Centre	3	24301	1755	2254	0	2254	OK
Canal Walk Shopping Centre	4	38386	2772	3839	0	3839	OK
Victoria & Alfred Waterfront	6	52405	3785	4955	0	4955	NOT OK
University of Cape Town	7	61899	4471	N/A	N/A	N/A	N/A
RRF 1	8	66071	4772				
Makro Store Ottery	9	79436	5738				
Lakeside Village Shopping Centre	10	92607	6691				
Blue Route Mall	11	97803	7067				
RRF 2	12	98531	7120				
PAD facility	13	108686	7854				

Note that each week the treated liquid fertilizer from the previous week's urine is collected at each RRF. This added weight was taken into consideration when optimizing the TSP for scenarios two, three and four.

Table B-9: Scenario two TSP second iteration, taking carriage weight into consideration.

Stop name	Trip sequence	Cumulative length (m)	Cumulative travel time (s)	Cumulative stabilized urine weight (kg)	Cumulative treated fertilizer weight (kg)	Carriage weight when leaving each location (kg)	4- ton restriction IF confirmation
PAD facility	1	0	0	0	0	0	OK
Cavendish Square	2	397	29	877	0	877	OK
Tyger Valley Shopping Centre	3	24301	1755	2254	0	2254	OK
Canal Walk Shopping Centre	4	38386	2772	3839	0	3839	OK
RRF 1	5	46216	3338	0	0	0	OK
Victoria & Alfred Waterfront	6	52405	3785	1116	0	1116	OK
University of Cape Town	7	61899	4471	2076	0	2076	OK
RRF 1	8	66071	4772	0	1183	1183	OK
Makro Store Ottery	9	79436	5738	459	1183	1643	OK
Lakeside Village Shopping Centre	10	92607	6691	862	1183	2045	OK
Blue Route Mall	11	97803	7067	1809	1183	2992	OK
RRF 2	12	98531	7120	0	1545	1545	OK
PAD facility	13	108686	7854	0		0	OK

Scenario three

In scenarios three and four, weight was not a limiting factor, and thus using a truck with a carrying capacity of over 4 tons did not display any advantage over the 4-ton truck. The TSP solutions for scenarios three and four are shown in **Table B-10** and **Table B-11**.

Table B-10: Scenario three TSP.

Stop name	Trip sequence	Cumulative length (m)	Cumulative travel time (s)	Cumulative stabilized urine weight (kg)	Cumulative treated fertilizer weight (kg)	Carriage weight when leaving each location (kg)	4- ton restriction IF confirmation
PAD facility	1	0	0	0	0	0	OK
Cavendish Square	2	397	29	877	0	877	OK
Victoria & Alfred Waterfront	3	12497	903	1993	0	1993	OK
University of Cape Town	4	21991	1589	2953	0	2953	OK
RRF 1	5	22119	1598	0	591	591	OK
Canal Walk Shopping Centre	6	33625	2429	1585	591	2176	OK
RRF 2	7	34168	2468	0	908	908	OK
Tyger Valley Shopping Centre	8	48502	3503	1377	908	2285	OK
RRF 3	9	48741	3520	0	1183	1183	OK
Makro Store Ottery	10	73074	5279	459	1183	1643	OK
Lakeside Village Shopping Centre	11	86244	6232	862	1183	2045	OK
Blue Route Mall	12	91440	6608	1809	1183	2992	OK
RRF 4	13	92317	6671	0	1545	1545	OK
PAD facility	14	102621	7416	0	0	0	OK

Scenario four

In scenario four, each collection location acted as an RRF, thus only the treated fertilizer was collected in each scenario.

Table B-11: Scenario four TSP.

Stop name	Trip sequence	Cumulative length (m)	Cumulative travel time (s)	Cumulative stabilized urine weight (kg)	Cumulative treated fertilizer weight (kg)	Carriage weight when leaving each location (kg)	4- ton restriction IF confirmation
PAD Facility	1	0	0	0	0	0	OK
University of Cape Town	2	2891	209	0	192	192	OK
Victoria & Alfred Waterfront	3	12384	895	0	415	415	OK
Canal Walk Shopping Centre	4	25291	1827	0	732	732	OK
Tyger Valley Shopping Centre	5	39376	2844	0	1008	1008	OK
Makro Store Ottery	6	63690	4601	0	1100	1100	OK
Lakeside Village Shopping Centre	7	76861	5554	0	1180	1180	OK
Blue Route Mall	8	82057	5930	0	1370	1370	OK
Cavendish Square	9	92564	6689	0	1545	1545	OK
PAD Facility	10	92961	6718	0	0	0	OK

A summary of the TSP routing results for each of the three modes of transport per week is shown in **Table B-12**. Furthermore, the TSP routes for the 8-ton and 14-ton truck can be seen in **Figure B-7**.

Table B-12: Summary of TSP analysis for each mode of urine collection transport.

	4-ton truck		
	Total travel distance (km)	**Fuel consumption (L)**	**Total travel time (hrs)**
1 Resource recovery facility	125.4	18.8	2.5
2 Resource recovery facilities	108.7	16.3	2.2
4 Resource recovery facilities	102.6	15.4	2.1
8 Resource recovery facilities	93.0	14.0	1.9
	8-ton truck		
	Total travel distance (km)	**Fuel consumption (L)**	**Total travel time (hrs)**
1 Resource recovery facility	93.0	27.9	1.9
2 Resource recovery facilities	107.6	32.3	2.2
4 Resource recovery facilities	102.6	30.8	2.1
8 Resource recovery facilities	93.0	27.9	1.9
	14-ton truck		
	Total travel distance (km)	**Fuel consumption (L)**	**Total travel time (hrs)**
1 Resource recovery facility	93.0	37.2	1.9
2 Resource recovery facilities	107.6	43.0	2.2
4 Resource recovery facilities	102.6	41.0	2.1
8 Resource recovery facilities	93.0	37.2	1.9

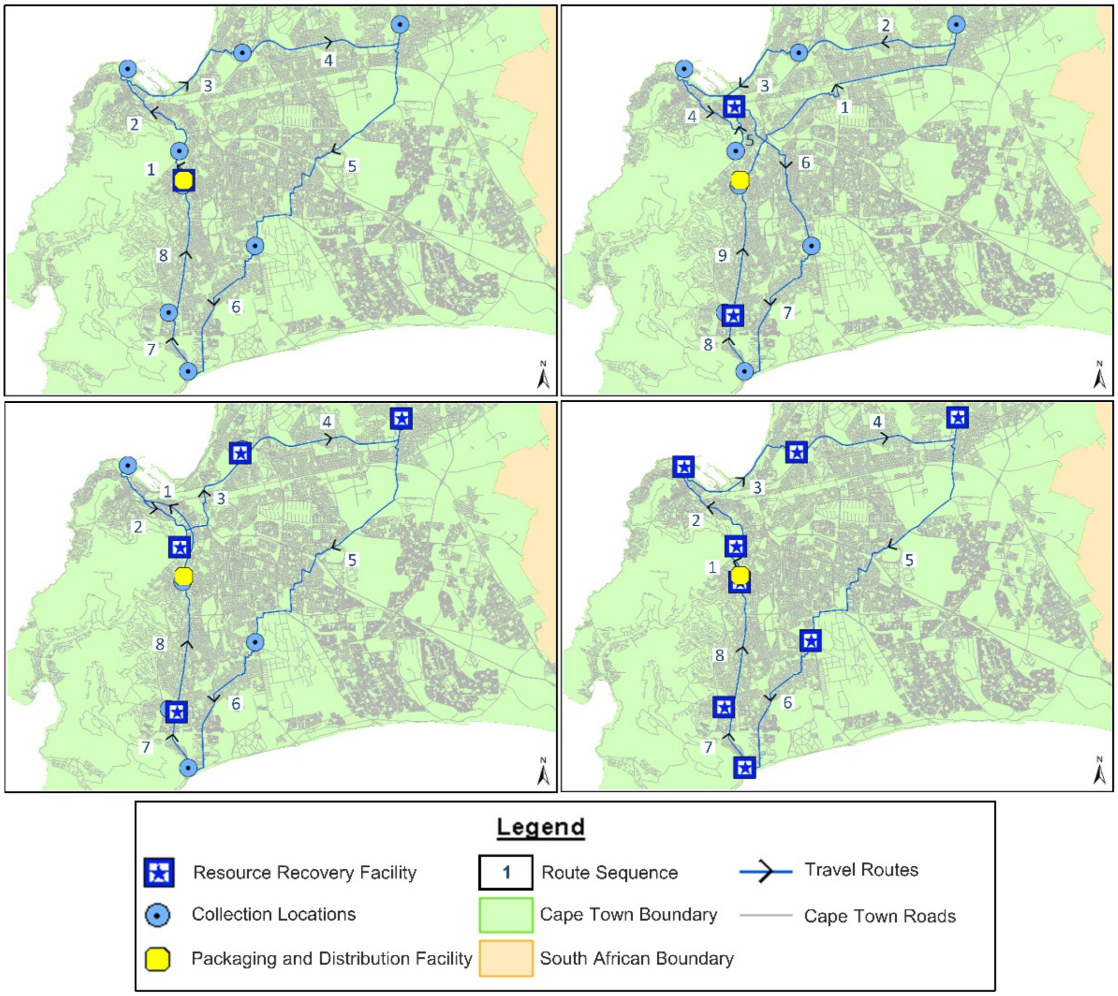


Figure B-7: Travelling salesmen problem solution for 8-ton and 14-ton truck.

All ArcGIS and Flowmap files used to determine the optimized RRF location allocation and to solve the travelling salesmen problem for each scenario are available within the following link:

https://drive.google.com/open?id=1qv3qSAw8KX91yCTPjU3hCpjQSqfY_adv

Economic feasibility calculations

The parameters outlined in **Table B-1** were used when deducing the prices displayed in this section.

CAPEX

The CAPEX of each scenario was calculated using the same parameters. Sample calculations for the CAPEX for scenario one (one resource recovery facility) can be seen in **Equation B-4.**

Capital expenditure

$$\begin{aligned} &= \text{4 ton truck (once off payment)} + \\ &\quad \text{Reverse osmosis unit (to treat 7.536 m}^3\text{ once per week)} + \\ &\quad \text{Nutrient recovery urinal units (x 302 units)} + \\ &\quad \text{Rental deposit (x1 warehouse: combined RRF and PAD facility)} \\ &= \text{R554 931} + \text{R75 363} + \text{R241 162} + \text{R26854 (x1)} \\ &= \text{R898 310} \end{aligned}$$

Equation B-4

The RRF sizes were made standard for each scenario, at 180 m^2 per warehouse. This was the warehouse size which allowed for storage of up to one month's worth of collected urine and allowed for adequate office and working space for warehouse employees. The total area was rounded up to 200 m^2 for each scenario, which equated to roughly R13 400. Likewise, the PAD facility required a 60 m^2 warehouse to store up to one month's worth of fertilizer and offer working space to employees and equated to R3 600 per month. The RRF and PAD facility were the same location in scenario one, so the extra costs associated with a PAD facility were not considered in scenario one. However, this extra cost was considered in all other scenarios. Rental prices were sourced from the broll.com (2008) real estate database for Cape Town properties, as shown in **Table B-1**.

Furthermore, because the same amount of urine was being treated in each scenario, the total cost of reverse osmosis was unchanged for each scenario. For example; 7.536 m^3 of urine was required to be treated per week, and it was assumed that all urine was treated in the same day. Thus, for scenario one (one RRF), a 7.536 m^3/d RO unit was required. For scenario two (two RRFs), two 3.768 m^3/d RO units were required. The same ideology was used for up to eight RO units (eight RRFs).

OPEX

Sample calculations for the OPEX for scenario one are shown in equation B-5.

Operating Expenditure $= \text{Fuel (for kms travelled)} + \text{Truck maintenance(for kms travelled)} + \text{Warehouse rental} + \text{RO electricity} + Ca(OH)_2 + \text{Driver Wage (for travel time)} + \text{Onsite managers} + \text{warehouse labour}$

$= R16\,499 + R50\,670 + R162\,373 + R3388 + R12158 + R22462 + R998\,400 + R361\,920$

$= R1\,627\,870 \text{ per year}$ **Equation B-5**

The comparative price of an MLE AS wastewater treatment plant configuration was estimated based on the equivalent amount of wastewater that would be treated with the urine that is being diverted from the sewerage in a decentralized system. The calculation for this value is shown in **Equation B-6**.

Modified Ludzack-Ettinger activated sludge equivalent estimation:

- Urine accounts for 1% of the volumetric composition of wastewater (Spångberg et al. 2014).
- Approximately 7 536 L of urine are collected per week across each collection location.

$$= 7\,536 \text{ L urine x } \frac{100 \text{ L wastewater}}{\text{L urine}}$$

$$\approx 753\,600 \text{ L of wastewater per week}$$

$$\therefore \frac{753.6 \text{ m}^3 \text{ wastewater}}{\text{week}} \text{ x } \frac{R27.35}{\text{m}^3 \text{ wastewater treated}} \text{ x } \frac{52 \text{ weeks}}{\text{year}}$$

$$\approx R1\,074\,817 \text{ per year for an MLE AS WWTP}$$ **Equation B-6**

Moreover, the OPEX for the water supply and sewer connections that would be incurred for centralized WWT were calculated as part of the MLE AS cost estimation, as shown in **Equation B-7** and **Equation B-8**. The total estimated cost of an MLE AS WWTP is also shown in **Equation B-9**.

- 131 067 L of water would be required for flushing per week (taken from **Table B-5**).
- 7 536 L of urine would be flushed per week, therefore total volume required for transport in sewers would be 138 603 L per week.

Water supply cost $= \frac{\text{131.067 kL water required}}{\text{week}} \text{ x } \frac{\text{R43.13}}{\text{kL of water supplied}}$

$\approx \frac{\text{R5 653}}{\text{week}} \text{ x } \frac{\text{52 weeks}}{\text{year}}$

$\approx$ R 294 000 per year **Equation B-7**

Sewer connection cost $= \frac{\text{138.603 kL flushed}}{\text{week}} \text{ x } \frac{\text{R34.83}}{\text{kL flushed for sewer connections}}$

$\approx \frac{\text{R4 828}}{\text{week}} \text{ x } \frac{\text{52 weeks}}{\text{year}}$

$\approx$ R 251 000 per year **Equation B-8**

Total MLE AS OPEX $\approx$ BNR operating costs + water supply costs + sewage connection costs

$\approx 1\,074\,817 + 294\,000 + 251\,032$ **Equation B-9**

$\approx$ R1 619 799.85 per year to treat the equivalent amount of urine that would be prevented from entering the sewage network in the poposed system

Fertilizer cost recovery

The cost of the liquid fertilizer for the base design was calculated using a least square regression analysis. The commercial liquid fertilizers used to form this analysis are displayed in **Table B-13** and **Figure B-8**, respectively. These fertilizer prices were sourced from online fertilizer stores and converted to a cost per litre of product.

Table B-13: Commercially available liquid fertilizers.

Product ID	N values (%)	Cost (R/L)	Vegetation type	Source
Product 1	1.3	74.5	Ornamental	Guzzle.com (n.d)
Product 2	3	172	all types	Faithful-tonature.com (n.d)
Product 3	3	130	Ornamental	Bidorbuy.com (n.d) (a)
Product 4	5	190	vines, vegetables etc	Bidorbuy.com (n.d) (b)
Product 5	5.3	198	Ornamental	Makro.com (n.d)
Product 6	6	280	Ornamental	Builder.com (n.d) (a)
Product 7	8	298	all types	Bidorbuy.com (n.d) (c)
Product 8	8	300	all types	Buiders.com (n.d) (b)
Product 9	9.25	310	Ornamental	Hydroponic.com (n.d)
Product 10	11	385	Ornamental	Bonsaitree.com (n.d)

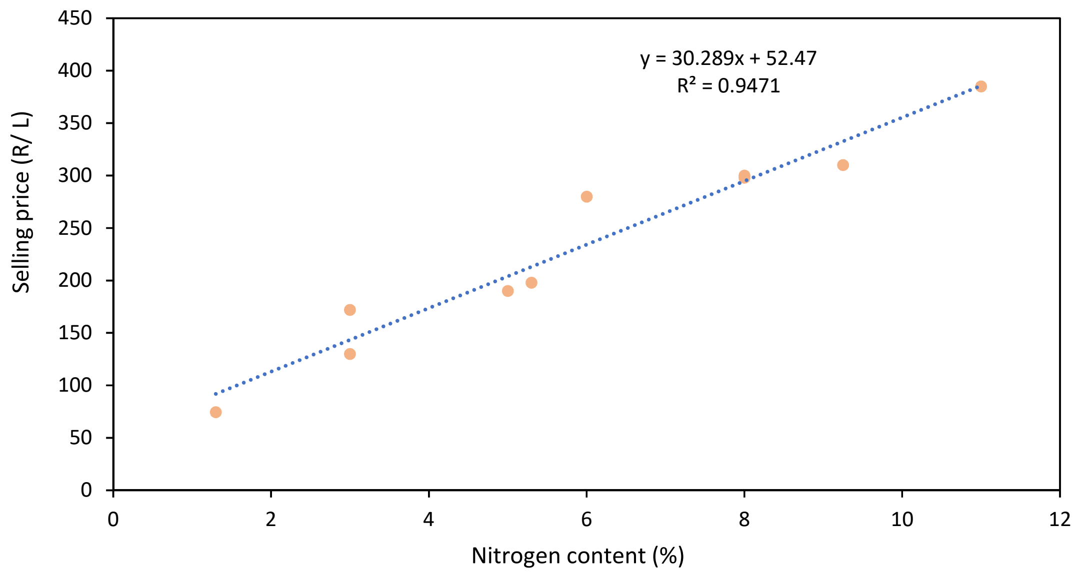


Figure B-8: Commercially available liquid fertilizers least square regression analysis.

From **Equation A-3**, it was found that the RO brine would produce a liquid fertilizer of 3.3% nitrogen content. An R value of 94.7% was deemed to suggest an adequate correlation between liquid fertilizer selling price and nitrogen content. The calculation for the liquid fertilizer design selling price is shown in **Equation B-10.** The selling was calculated from the slop of the linear regression graph shown in **Figure B-8**.

Liquid fertilizer design price $= 30.289 \text{ x liquid fertilizer nitrogen content (\%)} + 52.47$

$$= 30.289 \text{ x } 3.2 + 52.47$$

$$\approx \text{R151.52 per L of fertilizer}$$ **Equation B-10**

The quantity of liquid and solid (calcium phosphate) fertilizer provided from each collection locations was required for the estimation of the potential for cost recovery if the treated product were to be sold. This is shown in **Equation B-11**, **Equation B-12** and **Equation B-13**. Approximately 11g Ca-P per kg of urine (Flanagan & Randall, 2018) and 0.2 L liquid fertilizer per L of urine (Ek et al, 2006) are produced in the proposed system.

Solid fertilizer cost recovery $= \frac{7.536 \text{ m}^3 \text{ urine}}{\text{week}} \text{ x } \frac{1025 \text{ kg}}{\text{m}^3 \text{ urine}} \text{ x } \frac{11 \text{ g CaP}}{\text{kg urine}}$

$$= \frac{85 \text{ kg CaP}}{\text{week}} \text{ x } \frac{\text{R18.5}}{\text{kg CaP}} \text{ x } \frac{52 \text{ weeks}}{\text{year}}$$

$$= \text{R81 743 per year}$$ **Equation B-11**

Liquid fertilizer cost recovery $= \frac{7\ 536 \text{ L urine}}{\text{week}} \text{ x } \frac{0.2 \text{ L fertilizer}}{\text{L urine}}$

$$= \frac{1\ 507 \text{ L liquid fertilizer}}{\text{week}} \text{ x } \frac{\text{R151.52}}{\text{L liquid fertilizer}} \text{ x } \frac{52 \text{ weeks}}{\text{year}}$$

$$= \text{R11 875 797 per year}$$ **Equation B-12**

Total cost recovery $= \text{Liquid fertilizer} + \text{Solid fertilizer}$

$$= \text{R81 743} + \text{R11 875 797}$$

$$= \text{R11 957 541 per year}$$ **Equation B-13**

Greenhouse gas emissions and energy expenditure

Greenhouse gas emissions were calculated based on the truck and RO unit energy usage for the decentralized system. Emissions for conventional wastewater were calculated based on the CO_2 emissions from energy usage and nitrification/denitrification. The CO_2 was calculated per kg of nitrogen removed.

Scenario one energy expenditure $= \text{RO energy expenditure}$

$$= \frac{2 \text{ kWh}}{\text{m}^3 \text{ urine}} \text{ x } \frac{7.536\text{m}^3 \text{ urine}}{\text{week}} \text{ x } \frac{52 \text{ weeks}}{\text{year}}$$

$$= 784 \text{ kWh per year}$$ **Equation B-14**

BNR energy expenditure estimation

- 6.7 g N/L is the average total nitrogen concentration in fresh urine, as per **Equation A-1**.
- In 10 L of urine, there are 67 g N
- Urine contributes 1% of total wastewater volume (Spångberg et al. 2014), therefore there are 10 L of urine in 1000 L of wastewater.

$$\therefore \frac{67\text{g N}}{1000 \text{ L wastewater}}$$

$$= 0.067 \text{ g N/L}$$

- Urine contributes 80% of the nitrogen in wastewater (Spångberg et al. 2014).

$$\therefore \frac{0.067}{0.8}$$

$= 0.084 \text{ g N/L of wastewater}$

$\therefore$ influent wasterwater nitrogen concentration is 0.084 kg N/m^3

BNR energy expenditure $= \frac{0.084 \text{ kg N}}{\text{m}^3 \text{ wastewater}} \text{ x } \frac{753.6 \text{ m}^3 \text{ wastewater}}{\text{week}} \text{ x } \frac{2.3 \text{ kWh}}{\text{kg N removed}} \text{ x } \frac{52 \text{ weeks}}{\text{year}}$

$= \frac{145.6 \text{ kWh}}{\text{week}} \text{ x } \frac{52 \text{ weeks}}{\text{year}}$

$= 7548 \text{ kWh per year}$ **Equation B-15**

Scenario one GHG emissions $= \text{Truck } CO_2 \text{ emissions} + \text{ RO electricity emissions}$

$= \frac{2.7 \text{ kg } CO_2}{\text{L fuel used}} \text{ x } \frac{979.2 \text{ L truck fuel used}}{\text{week}} + \frac{0.94 \text{ kg } CO_2}{\text{kWh}} \text{ x } \frac{783 \text{ kWh}}{\text{year}}$

$= 3380 \text{ kg } CO_2 \text{ per year}$ **Equation B-16**

BNR GHG emissions $= \frac{3 \text{ kg } CO_2}{\text{kg N removed}} \text{ x } \frac{0.084 \text{ kg N}}{\text{m}^3 \text{ wastewater}} \text{ x } \frac{753.6 \text{ m}^3 \text{ wastewater}}{\text{week}}$

$= \frac{189.9 \text{ kg } CO_2}{\text{week}} \text{ x } \frac{52 \text{ weeks}}{\text{year}}$

$= 9846 \text{ kg } CO_2 \text{ per year}$ **Equation B-17**

Net present value/ Cost

For the calculation of the net present value, the cost recovery and OPEX of the system were assumed to be an annuity (The same value each year). The selling price and quantity sold was fixed and assumed to not change over the proposed 5-year investment period. A discount rate of 10% was assumed.

The system NPV/NPC was calculated with the following equation:

$$\text{NPC/NPV} = -\text{Co} + \frac{C_1}{1+r} + \frac{C_2}{(1+r)^2} + \cdots + \frac{C_T}{(1+r)^T}$$ **Equation B-18**

- NPV = Net present value
- C = The cash flow annuity
- Co =The initial investment
- T= The chosen time period
- r = The discount rate

For instances where the required annuity cash flow for a zero NPV was required, **Equation B-18** was rearranged to make the cash flow annuity the subject of the formula. This is seen in **Equation B-19.**

$$C = \frac{\text{Co x r}}{1-(1+r)^{-T}} + \text{OPEX for chosen time period} \qquad \textbf{Equation B-19}$$

A sample calculation for the NPV of Scenario one is displayed in **Equation B-20**. The annual cash flow annuity in each of the scenarios was taken as the OPEX subtracted from the cost recovery, to determine the estimated net income. From the OPEX (**Equation B-5)** and the total cost recovery (**Equation B-13)**, the cash flow annuity was found to be R10 329 670 per year. The CAPEX was shown in **Equation B-4** to be R89 8310.

Scenario one net present value $= \text{Capital expenditure} + \frac{\text{annual annuity}}{(1+r)^1} + \cdots \frac{\text{annual annuity}}{(1+r)^T}$

$$= -898\ 310 + \frac{10\ 341\ 916}{(1+0.1)^1} + \cdots \frac{10\ 341\ 916}{(1+0.1)^5}$$

$$= \text{R}38\ 259\ 267 \qquad \textbf{Equation B-20}$$

Sensitivity analysis

The sensitivity analyses in the main report was conducted by varying the variables that were thought to be pertinent in the base model. Once varied, the calculations presented above were redone taking the changes into account where applicable.

Liquid fertilizer selling price

The selling price to reach a break-even point was calculated by using the equation shown in **Equation B-19** (setting the NPV in **Equation 18** to zero) and solving for the required cash flow annuity over a 5-year period, at a 10% discount rate. The required selling price per L of liquid fertilizer to break even was then calculated. A sample calculation for scenario one, using a 4-ton truck is shown in **Equation B-21.**

Break-even point (price) $= \frac{\text{CAPEX x r}}{1+(1+r)^{-T}} + \text{OPEX for chosen time period}$

$$= \frac{873\ 379}{1-(1+0.1)^{-5}} + 1\ 615\ 624$$

$$= \text{R}1\ 864\ 842$$

$\therefore$ Fertilizer sales earnings per year required to break even over a 5 year investment period $=$ R1 846 019 for scenario one

Liquid fertilizer break-even price $= \text{Total fertilizer sales} - \text{Solid fertilizer sale}$

$$= \text{R1 846 842} \ - \text{R81 743}$$

$$= \frac{\text{R1 783 099 liquid fertilizer sales}}{\text{year}} \text{ x } \frac{\text{week}}{\text{1507 L liquid fertilizer}} \text{ x } \frac{\text{1 year}}{\text{52 weeks}}$$

$$= \text{R22.75/L liquid fertilizer for scenario one}$$ **Equation B-21**

Liquid fertilizer sales quantities and Cape Town nurseries

There are approximately 70 plant nurseries in Cape Town. This was found through a rough google maps survey of plant nurseries within the city. Moreover, 3 plant nurseries were contacted over the phone and 2 were approached in person. It was found that approximately 2 L of a popular brand of liquid fertilizer was sold at each of the 5 nurseries per week. The NPC for a scenario where only 2 L of the liquid fertilizer produced (realistic sales) in the proposed decentralized system is sold per week, at each of the 70 plant nurseries in Cape Town, was conducted. The NPC value was calculated using the same equation shown in **Equation B-20**, with the adjusted cash flow annuity from the sale of 2 L of liquid fertilizer at each nursery over a 5-year period. A discount rate of 10% was used for the NPC calculation.

The potential solid fertilizer cost recovery was found to be R81 743 per year in **Equation B-11**. The liquid fertilizer cost recovery from 2 L of fertilizer sales per plant nursery per week in a year was required to be calculated. Sample calculations for the cash flow annuity in scenario one for these ‘realistic’ values are shown in **Equation B-22**.

‘Realistic’ liquid fertilizer sales $= \frac{\text{2 L liquid fertilizer}}{\text{week}} \text{ x } \frac{\text{R151.52}}{\text{L liquid fertilizer}} \text{ x } \frac{\text{52 weeks}}{\text{year}} \text{ x 70 nurseries}$

$$= \text{R1 103 065.6 per year}$$ **Equation B-22**

$$\therefore \text{Total fertilizer sales for realistic sales}$$
$$\text{(solid and liquid fertilizer)is R1 184 808 per year}$$

From the OPEX (**Equation B-5**) and the realistic liquid fertilizer sales (**Equation B-22**), the cash flow annuity for ‘realistic’ sales was found to be approximately -R430 815. Sample calculations for the NPC in scenario one for these ‘realistic’ values are shown in **Equation B-23.** The CAPEX was shown in **Equation B-4** to be R89 8310.

Scenario one net present value $= \text{Capital expenditure} + \frac{\text{annual annuity}}{(1+r)^1} + \cdots \frac{\text{annual annuity}}{(1+r)^T}$

$$= -898\ 310 + \frac{-430\ 815}{(1+0.1)^1} + \cdots \frac{-430\ 815}{(1+0.1)^5}$$

$$= -\text{R}2\ 577\ 864 \qquad \textbf{Equation B-23}$$

$$\therefore \text{a net present cost of R2 577 864 was achieved for 'realistic' sales over a 5 year investment period in scenario one}$$

Truck carrying capacity

The transportation costs for the 4-ton truck, 8-ton truck and the 14-ton truck were evaluated based on the fuel (diesel) consumption, truck operating maintenance and driver wage. A sample calculation for the OPEX of scenario one, for the 4-ton truck is shown in **Equation B-24.** The sample calculation shown in **Equation B-24** was repeated for each scenario, as well as for each truck carrying capacity. The travel distance and travelling time for each truck per week are shown in **Table B-12**. Moreover, a 15-minute loading/offloading time was allocated for each stop in each scenario, in order to estimate the total driver wage per week (based on total travel time and loading/offloading times at collection points).

Scenario one 4-ton truck OPEX $= \text{driver wage} + \text{truck operating maintenance} + \text{fuel consumption}$

$$= \frac{5.3\ \text{travel hrs}}{\text{week}} \text{x} \frac{\text{R82}}{\text{hr}} + \frac{125.4\ \text{km}}{\text{week}} \text{x} \frac{\text{R6.26}}{\text{km}} + \frac{18.8\ \text{L fuel}}{\text{week}}\ \text{x} \frac{\text{R16.85}}{\text{L fuel}} \text{x} \frac{52\ \text{weeks}}{\text{year}}$$

$$= \text{R89 631 per year} \qquad \textbf{Equation B-24}$$

A summary of the answers from the sensitivity analysis is shown in **Table B-16**.

Alternate Markets Provision Estimation

To assess the potential of the proposed decentralized system, the estimated quantity of nutrients the recovered fertilizer could provide, as a fraction of the nutrient requirements of the Stellenbosch wine region was assessed. Sample calculations for the nitrogen produced by the system, in relation to what is required by the Stellenbosch wine region is displayed in **Equation B-25**. A summary of these calculations for all NPK nutrients is shown in **Table B-14**.

Stellenbosch wine region estimated provision:

- The size of the Stellenbosch wine region is estimated to be 15 252 hectares (OIV, 2017)
- Constituting 16% of the total vineyard area in South Africa (SAWIS, 2017)

- The nitrogen, phosphorous and potassium loading rates required per year for South African vineyards is approximately 50 kg N/ha, 15.7 kg P/ha and 19.8 kg K/ha, respectively (Food and Agriculture Organization of the United Nations, 2005 (FAO UN)).
- The liquid brine fertilizer has a 33.5 g N/L and 8.4 g K/L concentration, as per **Equation A-1**. Moreover, 0.377 g PO_4^{3-}-P precipitates out as calcium phosphate per L of urine treated.

Nitrogen required for Stellenbosch wine region

$$= \frac{50 \text{ kg N}}{\text{ha}} \text{ x } \frac{15\,252 \text{ ha}}{\text{Stellenbosch region}} \text{ x } \frac{1 \text{ ton}}{1\,000 \text{ kg}}$$

$$\approx 763 \text{ tons of nitrogen required per annum for fertilization of vineyards the Stellenbosch wine region}$$

Nitrogen produced per annum for decentralized system

$$= \frac{33.5 \text{ g N}}{\text{L liquid fertilizer}} \text{ x } \frac{1 \text{ ton}}{1\,000\,000 \text{ g}} \text{ x } \frac{1507 \text{ L liquid fertilizer}}{\text{week}} \text{ x } \frac{52 \text{ weeks}}{\text{year}}$$

$$\approx 2.63 \text{ tons of nitrogen per annum}$$

$$= \frac{2.63 \text{ tons N}}{763 \text{ tons N}} \text{ x } 100 \qquad = 0.34\%$$ **Equation B-25**

$$\therefore \text{ The proposed system can supply } 0.34\% \text{ of the total annual nitrogen requirements for the Stellenbosch wine region.}$$

Moreover, the potential of the proposed decentralized system was assessed, for a scenario where all Cape Town residents use an NRU once per week for a year. The cape Town population was found to consist of approximately 4.2 million people (CoCT, 2017). A sample calculation for the estimated nitrogen that could be recovered from collecting urine from all residents in Cape Town is shown in **Equation B-26**. It was assumed that each person contributed 0.23 L of urine in an NRU once per week (one urinal usage). A summary of these calculations for all NPK nutrients is shown in **Table B-14**.

Urine produced per year $=4\ 200\ 000 \text{ X } \frac{0.23 \text{ L urine}}{\text{person . week}} \text{ X } \frac{52 \text{ weeks}}{\text{year}}$

$= 50\ 232\ 00 \text{ L urine per year}$

Potential nitrogen supply from all Cape Town residents $= \frac{50\ 232\ 000 \text{ L urine}}{\text{year}} \text{ x } \frac{0.2 \text{ L liquid fertilizer}}{\text{L urine}} \text{ x } \frac{33.5 \text{ g N}}{\text{L liquid fertilizer}} \text{ x } \frac{1 \text{ ton}}{1\ 000000 \text{ g}}$

$= 336.5$ tons N per year could be provided from all Cape Town residents collectively.

$$\therefore \frac{336.5 \text{ tons}}{726.6 \text{ tons}} \text{ x } 100 = 46\% \quad \textbf{Equation B-26}$$

∴ If urine is collected from all Cape Town residents and treated to create fertilizers, 46% of the total annualnitrogen demand for the Stellenbosh wine region could be recovered.

Table B-14: nutrients produced by decentralized system and the estimated Cape Town population, compared to nutrient requirements of Stellenbosch vineyards

Description	Units	Nitrogen (N)	Phosphorous (P)	Potassium (K)
Required vineyard nutrient loading rates	Kg/ha	50	15.71	19.87
Stellenbosch wine region nutrient demand	ton	762.6	239.73	303.09
Fertilizer producible by decentralized system	tons	2.62	0.03	0.66
Fertilizer producible by decentralized system as a percentage of the annual Stellenbosch wine region nutrient demand	%	0.34	0.01	0.22
Fertilizer producible by collecting urine from all Cape Town residents	tons	336.5	3.8	84.4
Fertilizer producible by collecting urine from all Cape Town residents as a percentage of the annual Stellenbosch wine region nutrient demand	%	46	2	28

The potential of this system pertaining to the number of rugby fields that could potentially be fertilized was also found and is displayed in **Table B-15**.

Table B-15: Nitrogen recovery of system as a function of rugby fields that could be fertilized

Grass	Unit	Value	Source
Nitrogen required for common grass per year	Kg N/m^2	0.0195	Bigelow et al (2013)
Rugby field	m^2	10800	Australian Department of Sports and Regulation (DSR, n.d.)
Nitrogen required	kg	210.6	N/A
Nitrogen produced by system	Kg N/year	2625	Calculated
Rugby fields that can be fertilizer	Number of rugby fields per year	12.5	Calculated

A summary of the economic and environmental calculations for each of the results of the design scenarios is shown in **Table B-16**.

Table B-16: Summary of economic and environmental components for each design scenario

	CAPEX				
	Description	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
4-Ton truck (Once-off)	R	554931.00	554931.00	554931.00	554931.00
NRU units	R	241162.33	241162.33	241162.33	241162.33
RO Unit(s)	R	75363.23	75363.23	75363.23	75363.23
Floor space- Deposit	R	26854.00	61388.00	115096.00	222512.00
Total	R	898310.56	932844.56	986552.56	1093968.56
	OPEX				
	Description	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Fuel	R/year	16499.05	14298.88	13500.99	12230.13
Driver wage	R/year	22461.85	23160.55	25840.02	17551.27
Truck maintenance per week	R/year	50670.40	43913.42	41463.02	37560.08
On-site manager (at malls)	R/year	998400.00	998400.00	998400.00	998400.00
Calcium hydroxide	R/year	12158.15	12158.15	12158.15	12158.15
Warehouse workers	R/year	361920.00	748800.00	998400.00	1248000.00
Rent - floor space	R/year	162373.02	371183.26	695929.30	1345421.40
RO electricity	R/year	3388.13	3388.13	3388.13	3388.13
Total	R/year	1627870.61	2215302.37	2789079.61	3674709.16
	Cost Recovery				
	Description	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Ca-P design selling price	R/kg	18.5	18.5	18.5	18.5
Sales of Ca-P	R/year	81743.10	81743.10	81743.10	81743.10
Liquid fertilizer design selling price	R/L	151.52	151.52	151.52	151.52
Sales of liquid fertilizer	R/year	11875797.94	11875797.94	11875797.94	11875797.94
Total	R/year	11957541.05	11957541.05	11957541.05	11957541.05
	NPV/NPC				
	Description	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
NPV (4-ton truck)	R	38259267.45	35997904.90	33769129.74	30304480.97
NPC (Realistic sales -2 L liquid fertilizer sold at all Cape Town nurseries per week)	R	2577863.79	4839226.34	7068001.50	10532650.27

Table B-16: Summary of economic and environmental components for each design scenario (Continued)

	Sensitivity Analysis				
	Description	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Break even selling price for maximum liquid fertilizer sales	R/L	22.75	30.36	37.86	49.52
Amount of liquid fertilizer sales required to break even at design selling price	%	15.00	20.00	25.00	33.00
4-ton truck OPEX	R/year	89631.31	81372.84	80804.03	67341.48
8-ton truck OPEX	R/year	90468.43	105067.64	105084.33	89336.27
14-ton truck OPEX	R/year	113747.61	133316.04	132032.31	113747.61
	MLE AS WWTP				
	Description	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Water and sanitation costs	R/year	293950.67	293950.67	293950.67	293950.67
Sewer connection costs	R/year	251031.86	251031.86	251031.86	251031.86
Biological nutrient Removal	R/year	1074817.32	1074817.32	1074817.32	1074817.32
Total	R/year	1619799.85	1619799.85	1619799.85	1619799.85
	Electricity				
	Description	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
RO electricity usage	kWh/year	783.78	783.78	783.78	783.78
BNR electricity usage	kWh/year	7548.43	7548.43	7548.43	7548.43
	GHG emissions				
	Description	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Truck	Kg CO_2/year	2643.77	2291.21	2163.36	1959.72
RO electricity	Kg CO_2/year	736.75	736.75	736.75	736.75
Biological nutrient removal	Kg CO_2/year	2901.65	2901.65	2901.65	2901.65
Biological nutrient removal electricity	Kg CO_2/year	6944.56	6944.56	6944.56	6944.56

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Appendix C: Ethics Clearance

APPLICATION FO M

Plea. . Note:

Any person planning to undertake rasea In the Faculty of Ef1ilneanng and the Built Environment (EBE) at the Unlvaraily of Cape Town is raqulred to complete this form before collecllng or analysing data. The obJecllve of submitting this appllcatlon prtorto emba11dng on research ls to en,un, that the hlgh•t ethical ....-rd,in re•e.rch, cond•d 1.1nderthe auspices of the ESE Faculty, are met. Please ensura that you haWt read, and underatood the EBE Ethic• In RaNrch Handbook (avallable from the UCT EBE, Research Ethlca webalta) prior to complatlng thla application form: http:llwww.eba.ud,ac,za1abef.Jueareb{etblcs1

APPLICANT"S DETAILS		
Name of principal reaearcher, student oi' external applicant		Tlnaahe Chlpako
Department		Clvll Engineering
Preferred email addreu of applicant:		CHPTIN002Clmyuct.ac.za
If Student	Your Degraa: e.g., MSc, PhO, etc.	MSc Clvll Englneertng
	Credit Value of Research: e.g., 80/120/18013eO etc.	120 research credits, 60 couraework credltll
	Name of Supervlaor (If aupervlsed):	Dr Dyllon Randall
If this le a Atsearchconlract, Indicate the S!)URle of fundlng/&ponaorahlp		NIA
Project Tliie		Inveatlgating the featlblUty of raaouim recovery from urine and the loglsllc:l of transporting collected urine using geoepalfal analyais

I hereby undertaka to carry out my reaearch In ■uch a way that:

- there la no apparent legal objection to the nature or lha method of reaearch; and
- the research will not compromise staff or etudents or the other re1ponllb111t191 of the Unlveralty;
- the atated objective will be achieved, and the finding, will have a high degree of validity;
- llmltatlon1 and all8rnatlve lntarpratatlon1 wlll be considered;
- the findings could be subject to pear rav1aw and publldy available; and
- I will comply with the conventions of copyrtght and avoid any practice that would conatttut, plagiarism.

SIGNED BY	Full name	Signature	Date
Prlnclpal RHaarcher1 SbidantlExtllmal applicant	Tinaaha Chlpako		2018.()4/13

APPLICATION APPROVED BY	Full name	Signature	Date
Supervl■or (where applicable)		Signatures Removed	
HOD (or delegated nomlnH) Final authority for all applicants who have an8W8red NO to all queaflona In Sectlon1; and for all Undergraduatereaearch (Including Honours).		Signature Removed	
Chair : Faculty EIR Commlttea For applicants other than undergraduate llUdents who have anawared YES to any of the above quaatfona.		Signature Removed	