DOMESTIC WATER DEMAND FOR CONSUMERS WITH RAINWATER HARVESTING SYSTEMS

by

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DECLARATION

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ABSTRACT

The focus of the study is to theoretically assess tank-water demand and employ methods to establish the actual tank-water demand at selected houses in a case study area. This study also examines the influence of domestic rainwater harvesting systems when used in combination with a municipal water distribution system. The case study comprises of 410 low cost housing units in the Western Cape. The system demand patterns of low cost housing units are uncharacteristic, when compared with suburban system demand patterns, and cannot be defined by traditional models. Similarly, the use of rainwater harvesting systems in these areas follows an unconventional routine that is yet to be defined.

A stochastic end-use model for water demand is developed which produces temporal profiles for water supplied from both sources, namely the water distribution system and the rainwater harvesting system. The model approximates a daily system and tank-water demand pattern for a single domestic household, using @RISK software. The demand estimation methodology is clarified through application on a particular case study site where harvested rainwater is frequently utilized. Estimates of the parameter values are based on consumer surveys and previous studies on the case study area, where the household size was defined in the form of a probability distribution.

The results confirm the atypical system demand patterns in low cost housing units units. Although two clear peaks exist in the morning and in the evening, a relatively constant average flow is present throughout the day. A sensitivity analysis of all the model parameters verified that the household size has the most substantial influence on the tank-water demand pattern. The system and tank-water demand patterns were compared to published average daily water demand guidelines, which confirmed that increased water savings could be achieved when the rainwater source is accessible inside the household with minimal effort.

The stochastic demand profiles derived as part of this research agree with the metered system demand in the same area. The results of this study could be incorporated into the future development of national standards.

OPSOMMING

Die fokus van die studie is om die tenkwater-aanvraag teoreties te ontleed en metodes in werking te stel om die werklike tenkwater-aanvraag vas te stel by geselekteerde huise in 'n gevallestudie area. Hierdie studie ondersoek ook die invloed van plaaslike reënwater-herwinningstelsels wanneer dit gebruik word in kombinasie met 'n munisipale waterverspreidingstelsel. Die gevallestudie bestaan uit 410 laekoste behuisingseenhede in die Wes-Kaap. Die stelsel-aanvraagpatrone van laekoste behuisingseenhede is verskillend wanneer dit met voorstedelike stelsel-aanvraagpatrone vergelyk word en kan nie gedefinieer word deur tradisionele modelle nie. Soortgelyk volg die gebruik van reënwater-herwinningstelsels in hierdie areas 'n onkonvensionele roetine.

'n Stogastiese eindgebruikmodel vir water-aanvraag is ontwikkel, wat tydelike profiele genereer vir water wat van beide bronne verskaf word, naamlik die waterverspreidingstelsel en die reënwater-herwinningstelsel. Die model bepaal by benadering 'n daaglikse stelsel- en tenkwater-aanvraagpatroon vir 'n enkele plaaslike huishouding, deur @RISK sagteware. Die aanvraag-beramingstegnieke word verduidelik deur toepassing op 'n spesifieke gevallestudie, waar herwinde reënwater gereeld gebruik word. Die parameter waardeberamings is gebaseer op verbruikers-opnames en vorige studies oor die gevallestudie-gebied, waar die grootte van die huishoudings bepaal was in die vorm van 'n waarskynlikheidsverspreiding.

Die resultate bevestig die atipiese stesel aanvraagpatrone in laekoste behuisingseenhede eenhede. Alhoewel twee duidelike pieke in die oggend en die aand voorkom, is 'n relatiewe konstante vloei dwarsdeur die dag teenwoordig. 'n Sensitiwiteitsanalise van al die modelparameters bevestig dat die grootte van die huishouding die grootste beduidende invloed op tenkwater- aanvraagpatrone het. Die stelsel- en tenkwater-aanvraagpatrone was vergelyk met gepubliseerde gemiddelde daaglikse water-aanvraag riglyne wat bevestig dat meer waterbesparings bereik kan word waar die reënwaterbron binne die huishouding beskikbaar is met minimale moeite.

Die stogastiese aanvraagprofiele, wat as deel van hierdie navorsing afgelei was, stem saam met die gemeterde stelsel-aanvraagpatroon van dieselfde area. Die resultate van hierdie studie kan in die toekomstige ontwikkeling van nasionale standaarde opgeneem word.

ACKNOWLEDGEMENTS

I would like to thank the following people and institutions for their assistance and encouragement throughout the development and completion of my thesis:

- My sincere gratitude is due to my family, their constant support, understanding and patience throughout my entire study period. There are so many favours to be grateful for and for that, I am truly thankful.

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A	–	area
A_r	–	roof area
c	–	capita or person
C_a	–	capacity of the rainwater tank
c_r	–	roof runoff coefficient
D_t	–	demand during time interval
ℓ	–	litre
ℓ/c/day	–	litre per capita, per day
ℓ/day	–	litre per day
N	–	total number of days in a particular year
Q	–	flow rate
Q_A	–	water abstracted from the tank
Q_i	–	additional inflow into the tank
Q_O	–	overflow from the tank
Q_t	–	harvested rainwater during the time interval
R	–	rainfall
R_e	–	reliability of the tank to be able to supply the intended demand
R_v	–	volumetric reliability of rainwater in the system
t	–	time interval (day or month)
T	–	total monitoring/assessment time period
U	–	number of days in a year that the tank was unable to meet the demand
V	–	volume of water stored in the tank
V_t	–	cumulative volume of water stored in the tank at end of the time interval
V_{t-1}	–	volume of water stored in the tank at the end of the previous time interval
Y_t	–	water extracted from the tank

ABBREVIATIONS AND ACRONYMS

AADD	–	Average Annual Daily Demand
DWAF	–	Department of Water Affairs and Forestry
IPT	–	Internally Plumbed Tanks
LCH	–	Low Cost Housing
MAP	–	Mean Average Precipitation
NWA	–	National Water Act (No. 36 of 1998)
PPH	–	People Per Household
RHS	–	Rainwater Harvesting System(s)
RSA	–	Republic of South Africa
SANSA	–	South African National Space Agency
WDS	–	Water Distribution System(s)
WRC	–	Water Research Commission
WSA	–	Water Services Act (No. 108 of 1997)
YAS	–	Yield After Spillage
YBS	–	Yield Before Spillage

GLOSSARY

Some studies use different terms to characterize similar concepts. The terms defined in this section are used with the stated meaning in this thesis. The definitions are not comprehensive, but ensure consistency and clarity.

- Diurnal Pattern: A cycle that repeats itself over a 24 hour period.

- Domestic Water Consumption: The domestic water consumption denotes the metered or non-metered water flow rate that is used by consumers per time unit. The water consumption is obtained from values measured by a water meter.

- End-use: The term end-use in this report refers to an access point within the domestic property where water is released from the potable WDS to atmospheric pressure.

- Rainwater Harvesting System: The term rainwater harvesting system (RHS) denotes rainwater that is collected on rooftops and diverted to be stored in an above ground, partly underground or below ground storage tank. This thesis focuses only on the collection and storage of rainwater from individual household roof catchments. Rainwater applied directly to the end-use is not included, even if unintended, but rather rainwater stored prior to usage. Therefore, the disconnecting of gutters for irrigation is not included in the scope of this study, as the water is not stored before application.

- System-Demand: The volume of water required from the municipal WDS, per time unit, by domestic consumers for indoor and outdoor use is referred to as the system-demand. In this study, the term domestic denotes single family households.

- Tank-Demand: The tank-demand signifies the required volume of rainwater extracted from the tank, per time unit, in order to provide domestic consumers with an additional water source for indoor and outdoor use.

- Water Demand: The total volume of water necessary to supply consumers, within a certain period of time, is referred to as the water demand.

1. INTRODUCTION

1.1 Background

The term rainwater harvesting implies the collection, storage and use of rainwater for both domestic and agricultural purposes. Rooftop rainwater harvesting is a common method for collecting rainwater. The water is collected either by temporary facilities such as large storage drums, pots and containers or by permanent storage tanks. With the increase in the scarcity of water resources, rainwater harvesting systems (RHSs) have become an emerging practise (Thomas, 1998).

An escalating demand on water resources supplying urban areas, as a result of the growing urban population, the changing water use habits of these communities and the influence of climate change, has given rise to various challenges. The application of rainwater in domestic households can assist in reducing the demand on the municipal water distribution system (WDS) by allocating the harvested rainwater to non-potable end-uses. South Africa's water supply is primarily dependent on surface water resources (Still *et al.*, 2007) and therefore extensive potential exists for rainwater harvesting. On an international basis, household rainwater tanks are among the most broadly used water supply alternatives when implementing a variety of water development strategies.

A number of countries encourage the use of these systems, either through government subsidies or by introducing laws, which make the application of such systems mandatory. However, in South Africa RHS installations are limited, especially in urban areas where they are expensive compared to the price of potable water from the WDS. The most beneficial feature of an RHS is that it can be constructed at the demand node, in addition to having low maintenance requirements. Rainwater harvesting can greatly benefit people at the rural community level in South Africa (Houston & Still, 2002). The on-site advantage is reflected in unserviced areas where access to these systems is the only available source of water.

According to Kahinda *et al.* (2010), 96% of all rainwater tanks installed in South Africa are located in rural areas to provide an alternative source when the water supply is deficient. The limited use of RHSs in urban areas is due mainly to the initial cost of storage tanks, the unappealing aesthetics of the system and the fact that there are no design guidelines for the implementation of these systems in South Africa.

An additional reason for the infrequent domestic rainwater application in the Western Cape is the fact that the high-demand in the summer period corresponds with the dry season. In order for the RHS to have an impact on the system demand, the tanks are required to be as large as 20 kℓ (Jacobs *et al.*, 2011), which entails an increased initial expense as tanks larger than 5 kℓ on a domestic property are considered to be relatively large and unsuitable.

The employment of RHSs in South Africa as an additional water source has become more prevalent as it contributes to food security (Rockström, 2002) and amongst many other options, rainwater harvesting plays a role in widening water security as well as reducing environmental impacts (Domenech *et al.*, 2011; Thomas, 1998). Even in areas with reliable access to the municipal WDS, the presence of rainwater harvesting will still be beneficial as it could significantly lower the required system demand. A number of analytical methods, including modelling tools, have been used to predict the potential of RHSs taking into account proposed end-uses, connected catchment area and tank size.

Rainwater harvesting has a long tradition of over a thousand years (Helmreich & Horn, 2009) and it is a technology that could be used as the sole source (Kahinda *et al.*, 2008b) of water in areas where there is an unreliable or no water system available. Since the initiation of a reliable municipal WDS in urban areas of South Africa approximately 40 years ago, the application of these systems has become uncommon. However, in the last two decades the interest in RHSs has been renewed, as it is driven by environmental concerns (Herrmann & Schmida, 2000). Across most of South Africa, rainwater tanks have a relatively low yield, as well as being financially unfeasible for the homeowner in many cases; this depends on the cost of alternative water from the WDS. Current application of RHSs in South Africa is generally due to necessity, caused by drought or an inadequate water supply, with the implementation for water conservation or stormwater management being unusual (Jacobs *et al.*, 2011; Kahinda *et al.*, 2010). An estimate of the number of rainwater tanks used in South Africa is presented by Kahinda *et al.* (2010), as shown in Table 1-1.

In summary, the installation of RHSs is generally drought driven, or due to the unreliable water supply from municipal WDSs. Furthermore, these systems are relatively expensive, but have been reported to be financially feasible (Jacobs *et al.*, 2011) and economically viable as a backup water source.

Table 1-1: Rainwater Tanks in Existence across South Africa (Adapted from Kahinda et al., 2010)

Province	No. of Rainwater Tanks
Northern Province	1336
Mpumalanga	2592
Gauteng	1925
North West	3087
Free State	524
Kwazulu Natal	8275
Northern Cape	123
Eastern Cape	14599
Western Cape	1529

1.2 Problem Statement

The system demand patterns of LCH units are uncharacteristic, when compared with suburban system demand patterns, and cannot be defined by traditional models. In the same way, the use of RHSs in these areas follow an unconventional routine, as no information regarding water use habits was established during the literature review. When a household incorporates rainwater harvesting in an effort to meet the system demand, the harvested rainwater can be seen as a direct reduction in the system demand.

Rationally based models were implemented with the intention of estimating the water demand from two sources, namely the potable WDS and RHS. This study was performed to examine the influence of domestic RHSs on the system demand in the Western Cape, in terms of reliability. The main aim of this study is to theoretically assess tank-water demand and employ methods to establish the actual tank-water demand at selected houses in a case study area. The findings of this study explain tank-water demand, on average and for specific end-uses.

A computer based, stochastic end-use model was developed which generates temporal profiles for system and tank-water demand. The stochastic model was used to evaluate the effect of tank-water demand on the diurnal system demand pattern for low cost housing (LCH) units. Against this backdrop, large scale placement of rainwater tanks in South Africa could have an extensive influence on the system demand of these areas. In addition, it gives rise to future research and investigation on the technical and socio-economic effects of the employment of such a system in South Africa.

1.3 Research Motivation

The key motivation behind this study is to contribute to a better understanding and approximation of the impact rainwater application has on the system demand, which includes the future prospect of incorporating tank-water demand when deriving water demand guidelines. In many households, rainwater is highly valued as an appropriate water source for domestic practices such as cooking, cleaning, laundry, gardening and bathing. In places where the municipal WDS is unreliable, rainwater offers an alternative water source and the tank acts as a storage facility for water during dry periods.

On an international level, numerous cases exist where rainwater harvesting has successfully been carried out when employing rainwater tanks. In South Africa, a number of LCH areas acquired RHSs through government incentives. The residents have a great deal to gain from its use, because they gained the RHS as part of their new homes. The motivation for this research study was to more accurately explain the proposed reduction in system demand that the implementation of an RHS will allow, while taking into account the estimated system and tank-water demand over a period of time in a specific area.

The studies presented in recent years have put a substantial emphasis on the reductions in urban system demand achieved through implementing alternative water resources. One example of such a resource is rainwater harvesting at a household level, which could be used in various non-potable applications. The reduction in the system demand, accomplished by incorporating harvested rainwater as a water source for domestic use, is deemed credible by a number of studies (Thomas & Martinson, 2007.; Domenech *et al.*, 2011; Fewkes, 1999; Li *et al.*, 2010). However, the quantifications of the resulting reductions in system demand could in future be integrated into strategic planning for urban water supply systems.

1.4 Research Objectives

The objectives of this research project are to examine domestic households with on-site access to RHSs and theoretically evaluate the expected impact on the system demand. The following key objectives were included in this study:

- Conduct a literature review of previous studies done on worldwide and national use of harvested rainwater, domestic rainwater harvesting, effects on stormwater and sewer systems, potable water savings when using such a system (including real-time monitoring), and tank-water demand modelling as well as end-use frequencies and event volumes of water use.

- Incorporate information from a case study site. The selected site was in Kleinmond, which included 410 LCH units. The study on this particular site was intended to test the methodology for application on the system and tank-water demand estimation model and analysis. In addition, this case study site was employed to evaluate the implementation of an RHS on an area in the Western Cape as well its influence on the municipal WDS.

- Use consumer surveys from the case study site to investigate end-uses of the harvested rainwater, in addition to plotting the probability graph of the people per household (PPH). Establish the daily time range during which there is a probability that people will use the rainwater for different end-uses.

- Use the data achieved from surveys and previous studies on the case study area to construct a computer based stochastic end-use model that approximates a daily system and tank-water demand profile for a single household.

- Compare the modelled diurnal system and tank-water demand patterns to the average water demand from published guidelines. Conduct an analysis, using the results of the stochastic end-use model, to assess the effect of different tank sizes on the daily tank-water demand**.** In addition, this analysis uses the Kleinmond site to determine whether two smaller tanks on each side of the house are better than one tank, with the same total volume, along one side of the house.

- Discuss the effects and consequences of rainwater harvesting on the stormwater system, sewer system as well as WDS. Briefly address water quality as part of the investigation in addition to the legislation concerning harvested rainwater.

1.5 Scope and Limitations of Research

The study is focussed on the theoretical assessment of the system and tank-water demand patterns and any empirical data used in the modelling process was taken from a previous study or survey conducted on the case study site. The purpose of this investigation does not include data or analysis of the long-term economic viability of newly implemented domestic RHS.

There was a specific focus on the Western Cape, a winter-rainfall region in South Africa, where the seasons of supply and demand are dissociated. A theoretical volume of water captured in the rainwater tanks for every month of the year is computed using data from a credible weather website.

The study was limited to LCH in serviced, urban areas with RHSs. Only data from and assumptions regarding LCH areas, were applied to develop the stochastic end-use model. The justification behind this is that this type of property uses the alternative water source on a regular basis, resulting in a decreased use of the municipal WDS. Therefore, the application of RHSs would be amplified, resulting in a reduction in the system demand. The water leaks originating inside the household, which contribute to an increased system demand, were excluded in this study.

Information regarding the times at which the end-uses are used was unknown for the case study site; however, a diurnal system demand pattern exists which could act as a basis. The assumption was made that, on average, the tank-water demand would follow the same pattern as the system demand for each household in the case study area. The diurnal pattern by Steyn (2013) was used as a reference on which to base the time series.

The RHS included in this study refers to a permanently installed tank system with fixed roof areas. For the purpose of this study, it was assumed that the rainwater tanks are always in a working condition.

Assessment of the quality of the harvested rainwater was beyond the scope of this study. Therefore, it was briefly noted and not deliberated in detail. In addition, the legal implications regarding water rights to the harvested rainwater were not addressed in detail.

1.6 Application to Case Study Site

In contrast to generic models such as presented by Allen (2012), this research presents a site specific stochastic demand model. The model employed in this research requires weather and geographic data as inputs. A case study site was chosen for this purpose. The chosen site was a high density, low-income area comprising 410 LCH units that were constructed in Kleinmond, Western Cape. The selection of this area was motivated by the available information from the data loggers that were installed prior to this study as well as the fact that it has a reliable WDS in addition to the implemented RHS that was installed as a government incentive.

1.7 Chapter Overviews

Chapter 2 entails the literature review, which provides a background on water demand and the use thereof, in addition to an international and national interpretation of rainwater use.

In Chapter 3 the basic components that form the structure of an RHS and affect the performance of such a system, are inspected in great detail. The structural composition of certain components such as the roof type and size contribute largely to the performance and yield each rainwater tank can supply.

Chapter 4 defines the research approach to the modelling process and includes a description of the reliability software procedure used, which was formulated with the intention of fitting the criteria of the software in a user-friendly manner.

In Chapters 5 and 6, the case study site is characterized and the objectives of the chosen case study are defined. In addition, the data applicable to the Kleinmond site is recorded and described, since it is used as input values for the stochastic end-use model.

The actual modelling implementation is reviewed extensively in Chapter 7. The process performed to reach the research aims is explained and the use of the software is depicted. The methods clarified in this chapter may be used as a reference in the event that similar research procedures are executed in the future, as they form the very foundation of this study.

In Chapter 8, the results of the various methods employed to achieve the research objectives are illustrated and analysed. These results are then compared with the outcomes of investigations and analysis previously researched in the literature review. Furthermore, the chapter examines and interprets the results before deciding whether the models were implemented in the correct manner and evaluating the effectiveness of the testing method.

The final chapter draws a conclusion on the important aspects of the research project to attain an overview of the research concept and establish whether its aim was accomplished. In addition, it itemizes recommendations for future research in order to build on the research project investigated in this study.

2. LITERATURE REVIEW

2.1 Introduction

In life cycle assessments from numerous studies (Rahman *et al.*, 2010; Ghisi & Mengotti de Oliveira, 2007; Gardner *et al.*, 2010), it was concluded that RHSs were not financially viable for domestic households. A number of countries implement rainwater tanks on a large scale because this is a necessary option as a result of an inadequate water supply. The addition of rainwater tanks is accomplished either by introducing regulations making RHS mandatory or by motivating household owners to install rainwater tanks by means of financial incentives. A study done by Roebuck & Ashley (2006) in the United Kingdom evaluates numerous conditions where the financial efficiency of domestic RHSs was compared with that of relying solely on water from the potable WDS. Roebuck & Ashley (2006) concluded that the installation of a RHS is likely to lead to an overall financial deficit almost equal to the capital cost expenditure of such a system. Another study performed by Domenech *et al.* (2011) demonstrated that the financial benefits of installing a RHS are only realised after a minimum of 60 years, which causes home-owners to be discouraged from initiating these systems without any government inducement.

South Africa is not only a water scarce country, but according to Kahinda *et al.* (2007), 9.7 million (20%) people do not have access to adequate water supply in addition to the 16 million (33%) who lack proper sanitation services. Rainwater harvesting offers an alternative for South Africa to meet the Millennium Development Goals of halving the proportion of people without sustainable access to safe drinking water, in this case rainwater for non-potable end-uses, and basic sanitation (Kahinda *et al.*, 2007).

2.2 Water Demand Guidelines in South Africa

This study involves RHS in serviced residential areas, with a case study site in South Africa. Therefore, it makes sense to first present a brief review of South African guidelines for estimating the system demand in such areas. The knowledge regarding system demand would help to better understand the tank-water demand.

According to the Department of Water Affairs and Forestry (DWAF), the minimum water requirement to ensure a healthy lifestyle is 25 ℓ/c/day (DWAF, 2002). One of the standard guidelines used to determine the system demand for developed, domestic areas in South Africa is presented by CSIR (2003). This method has been shown to overestimate the demand, resulting in unnecessary expenditure (Jacobs *et al.*, 2004). A reduced AADD, supplied from the WDS, would be expected when a RHS is used in combination with the WDS. However, no guideline is available in South Africa for the combined use of a rainwater tank and WDS.

Gardens require water for irrigation, but this water need not be potable. Larger gardens normally require more water. The size of the garden varies significantly from one household to another and depends on the plot size. Some consumers tend to irrigate their gardens regularly, while others hardly irrigate at all. As a result, there is large variability and difficulty in predicting garden water demand.

Jacobs *et al.* (2004) updated the stand size-based guidelines and proposed the following equations for households in Cape Town, the winter rainfall region of South Africa:

$$Q_{high}(kl/stand/day) = (0.00110595 \times A) + 0.551$$

For $50m^2 \leq A < 1\,100m^2$

$$Q_{high}(kl/stand/day) = (0.00056253 \times A) + 1.148$$

For $1\,100m^2 \leq A < 2\,050m^2$

Equation 1: Upper Boundary of AADD Envelope (Jacobs *et al.*, 2004)

$$Q_{low}(kl/stand/day) = (0.0007 \times A) + 0.20$$

For $50m^2 \leq A < 1\,100m^2$

Equation 2: Lower Boundary of AADD Envelope (Jacobs *et al.*, 2004)

This guideline presented by Jacobs *et al.* (2004) is one of the few available AADD guidelines known in South Africa for suburbs, which include LCH units. Another update by Van Zyl *et al.* (2008) followed and also included the property value as an explanatory variable when analysing the effect of various socio-economic and climatic parameters on system demand.

The suggested new guideline by Van Zyl *et al.* (2008) and Jacobs *et al.* (2004) for system demand estimation, for LCH units, is presented alongside the CSIR (2003) guideline in Figure 2-1, where the most conservative boundary of each study was chosen and graphically exhibited.

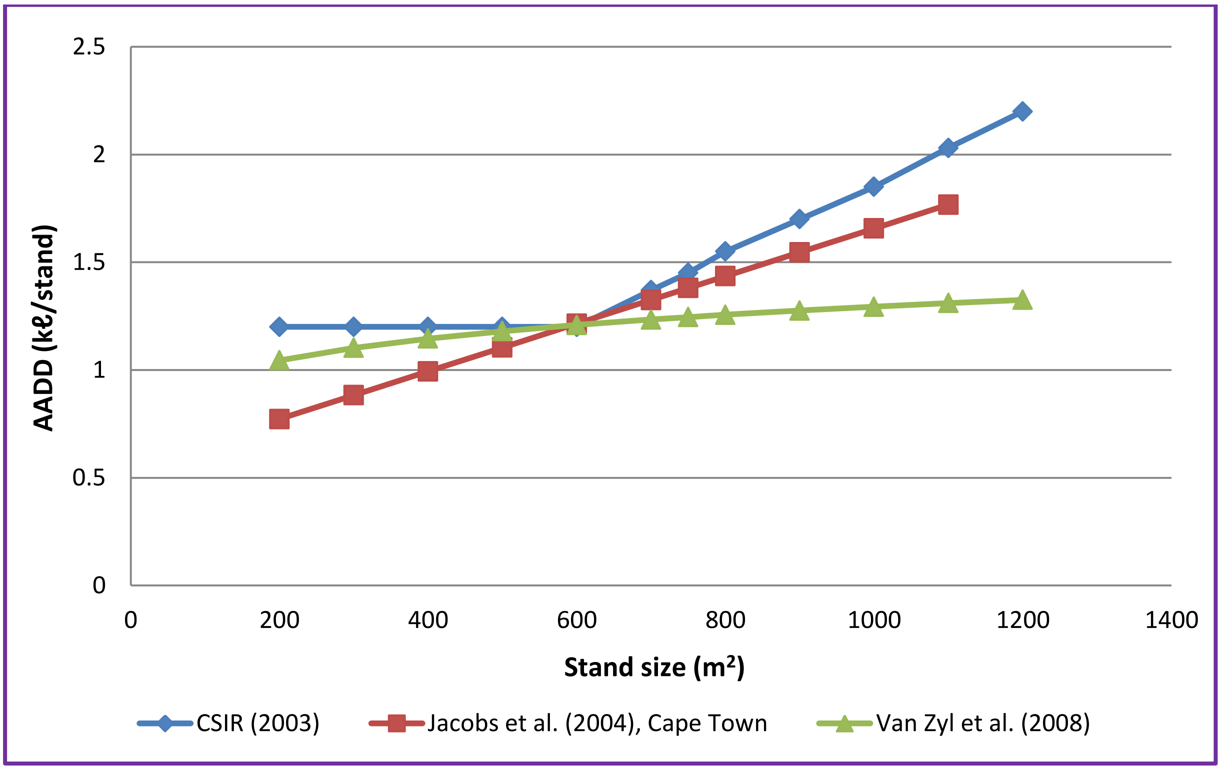


Figure 2-1: AADD Guideline as a Function of Stand Size and Stand Value

2.3 Water Use in South Africa

There is a noteworthy variation in water use for different types of buildings or areas, since it is largely dependent on the type of consumers. Previous research has been performed to estimate the breakdown of average water use in urban areas based on information from Rand Water, Durban Water and Waste and the Western Cape Metro published by DWAF. According to DWAF (2004b) in the Water Conservation and Water Demand Management Strategy, the domestic sector is the highest consumer of water across the country, using 30% of the total water consumption, as recognized in Figure 2-2.

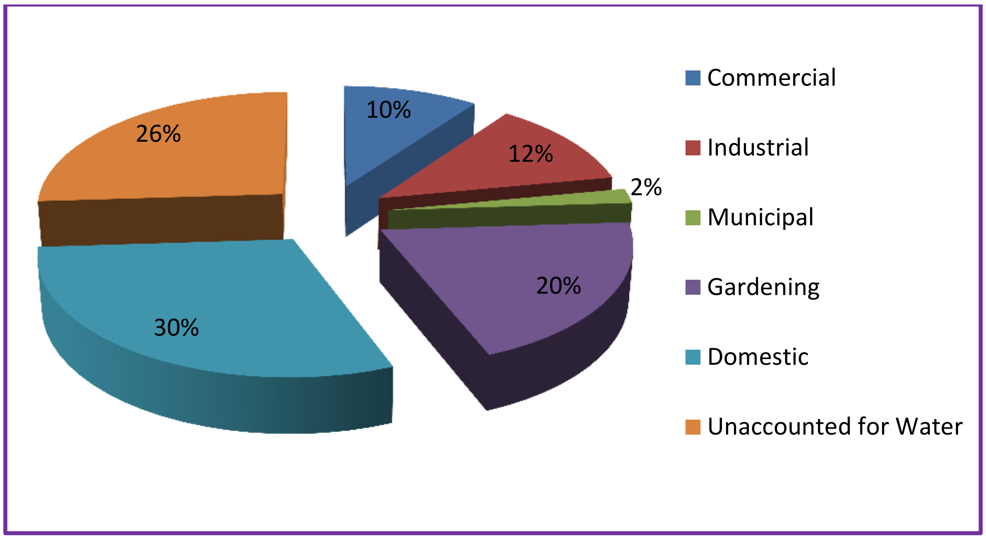


Figure 2-2: National Estimated Water Consumption for Urban Areas (DWAF, 2004b)

According to DWAF (2004a), 35% of domestic consumption in Cape Town is used for the purpose of garden irrigation, which is more than the water used for any of the other micro-components as portrayed in Figure 2-3. The diagram confirms that not all of the water consumed in a household needs to be of potable quality. The water used for toilet flushing (29%), laundry and dishwashing (13%) and gardening (35%) need not be potable. Hypothetically, about 64% of the water consumed within a typical South African household could be replaced by another water source such as rainwater.

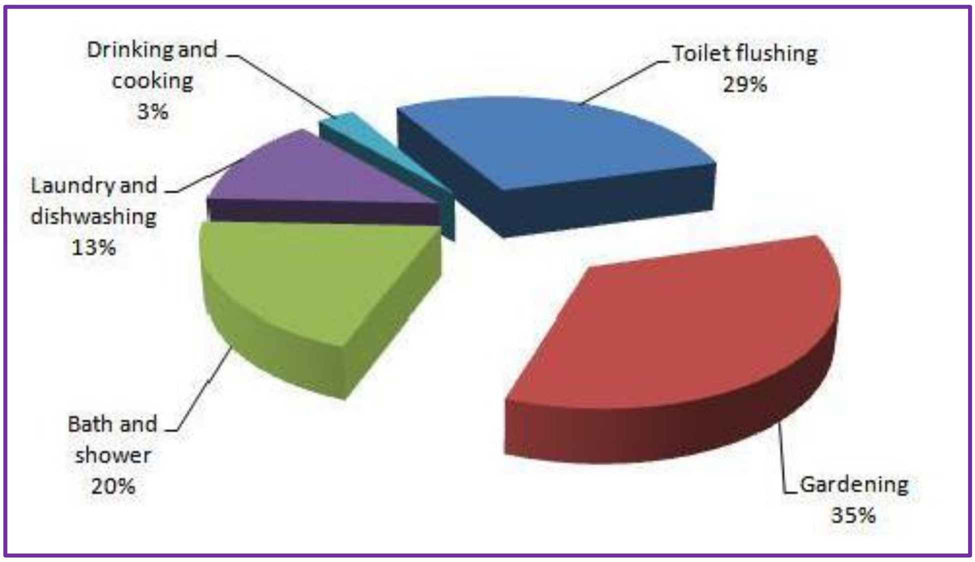


Figure 2-3: Typical Water Consumption in a Cape Town Domestic Household (DWAF, 2004a)

2.3.1 Household End-uses

The system demand comprises water used by consumers at various end-use points on a property. The end-uses found inside and outside a typical LCH unit are indicated in Figure 2-4. The quantification of these end-uses and their incorporation into the research topic are discussed later in this thesis. In addition, the system demand is largely dependent on the household size (Jacobs & Haarhoff, 2004b).

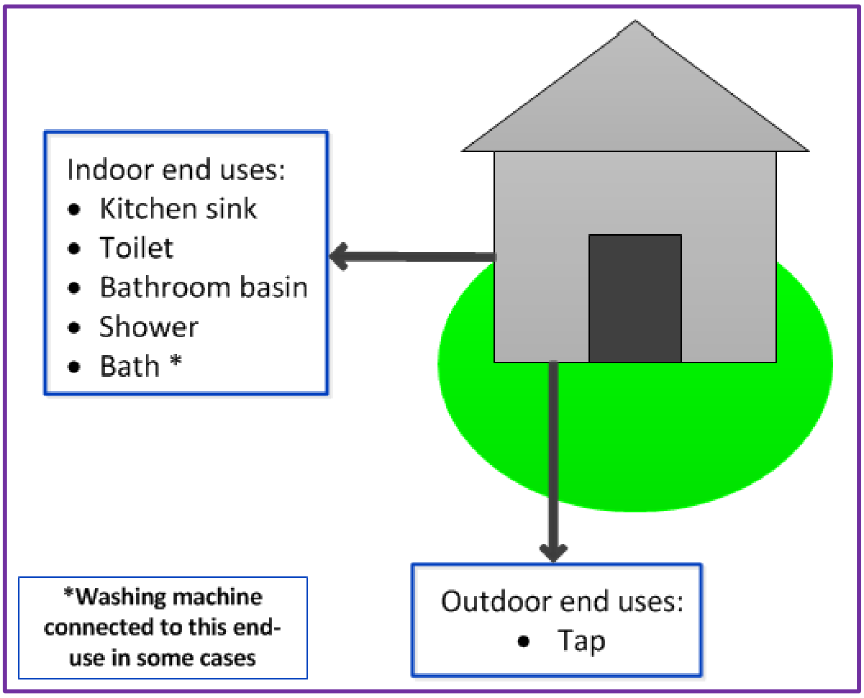


Figure 2-4: Household Plumbing of a LCH Unit

2.3.2 South African Water Demand Pattern

Research has also been done on the diurnal system demand for domestic areas in South Africa. Compion & Jacobs (2010) presented diurnal system demand patterns for small, medium and large domestic areas as well as for LCH units, as shown in Figure 2-5. The patterns clearly exhibit two peaks for domestic housing areas, contrasting the single, gradual peak, which transpires in the middle of the day for the LCH. The absence of the typical morning and evening peaks for the LCH could be as a result of the high unemployment rate present in these areas.

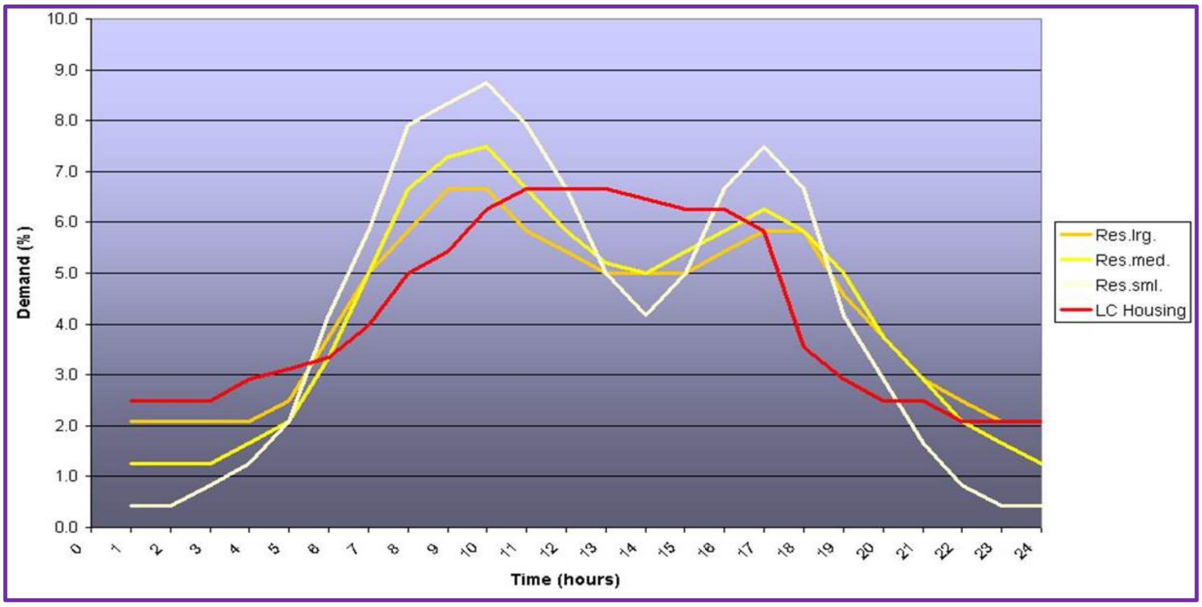


Figure 2-5: Diurnal System Demand Patterns (Compion & Jacobs, 2010)

2.3.3 AADD for Kleinmond LCH Area

Steyn (2013) analysed twenty LCH units with RHSs in Kleinmond, fitted with data loggers, to measure the actual municipal system demand of each household by means of an advanced web-based system. The objective of the study by Steyn was to construct a diurnal demand pattern and assess the peak flows. The resulting system demand pattern is shown in Figure 2-6.

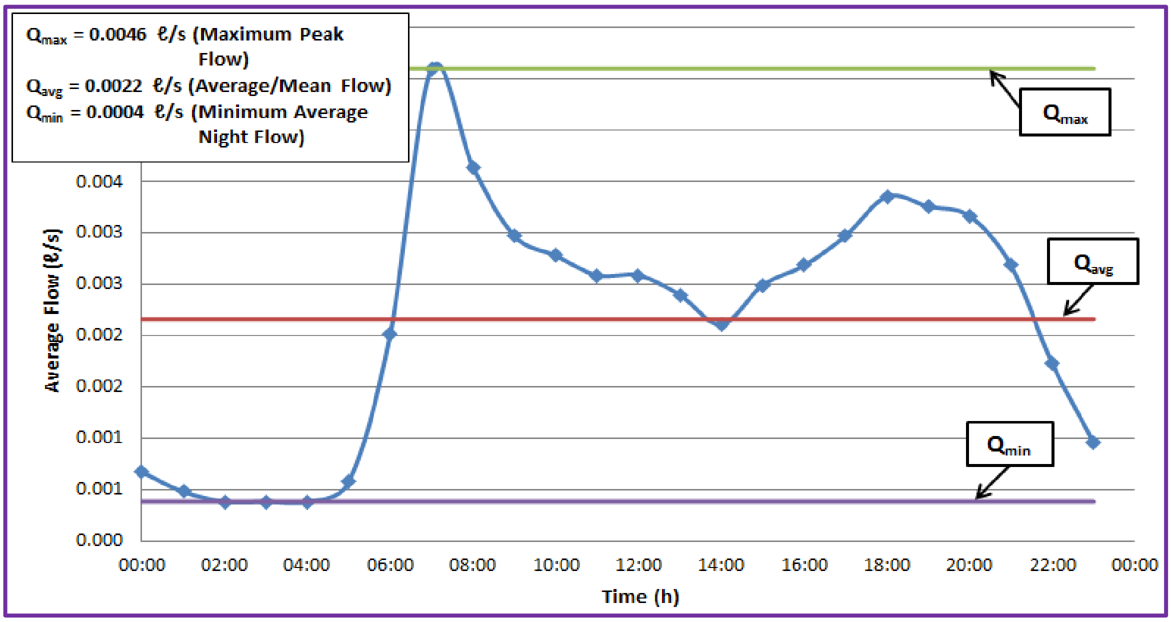


Figure 2-6: Average Flow of Kleinmond LCH Area (Steyn, 2013)

The impact of the tank-water demand on the diurnal system demand pattern was not evaluated by Steyn. The data used for the study runs over a 6 month period from 1 October 2012 to 31 March 2013. During this period, consisting of summer months, the water consumption is at its highest for winter rainfall areas. The total system demand over six months, for each house, was obtained by using the data from the meters as well as the approximated one year value. From this information, the AADD and the average monthly water usage for each house was estimated.

The average household size was 4 PPH and the calculated average consumption was 56.4 ℓ/c/day (Steyn, 2013). The average consumption of the houses was 187 ℓ/day (about 5.6 kℓ/month). The policy by DWAF (2002) specifies that the amount of free basic water is 6 kℓ/month (or 200 ℓ/day) per household. Based on this, very few households in the study by Steyn (2013) actually use more water than the allocated free volume.

The average flow graph illustrates that there are two unequivocal peaks, which exist during the 24 hour period. The first peak occurs between 06h00 and 09h00, which is expected since most residents wake up and start preparing for work and the second peak transpires between 18h00 and 21h00 (Steyn, 2013). The second peak is greater than the average flow across the entire day but it is still much less than the first peak. The average flow remains moderately constant during the day, which could be as a result of parents being at work and the children at school.

The diurnal pattern for system demand by Steyn (2013) is used as a basis for the time series demonstrating the likelihood that rainwater is used during the course of the day. The time series information, which is a fundamental input used for the stochastic model developed later in this thesis, is based on the assumption that the system and tank-water demand pattern would be identical.

2.3.4 Kleinmond AADD Compared to a South African Demand Pattern

In the past, studies have been done to determine the diurnal system demand patterns in domestic housing, but these studies were not specifically aimed at LCH. In order to examine the AADD of the Kleinmond site, the pattern developed by Steyn (2013) was discussed in contrast to the study done by Compion & Jacobs (2010). The flow rates for the Kleinmond LCH site were expressed as a percentage of the total flow rate, to be able to achieve a comparison with the LCH curve provided by Compion & Jacobs (2010). The juxtaposition is demonstrated in Figure 2-7.

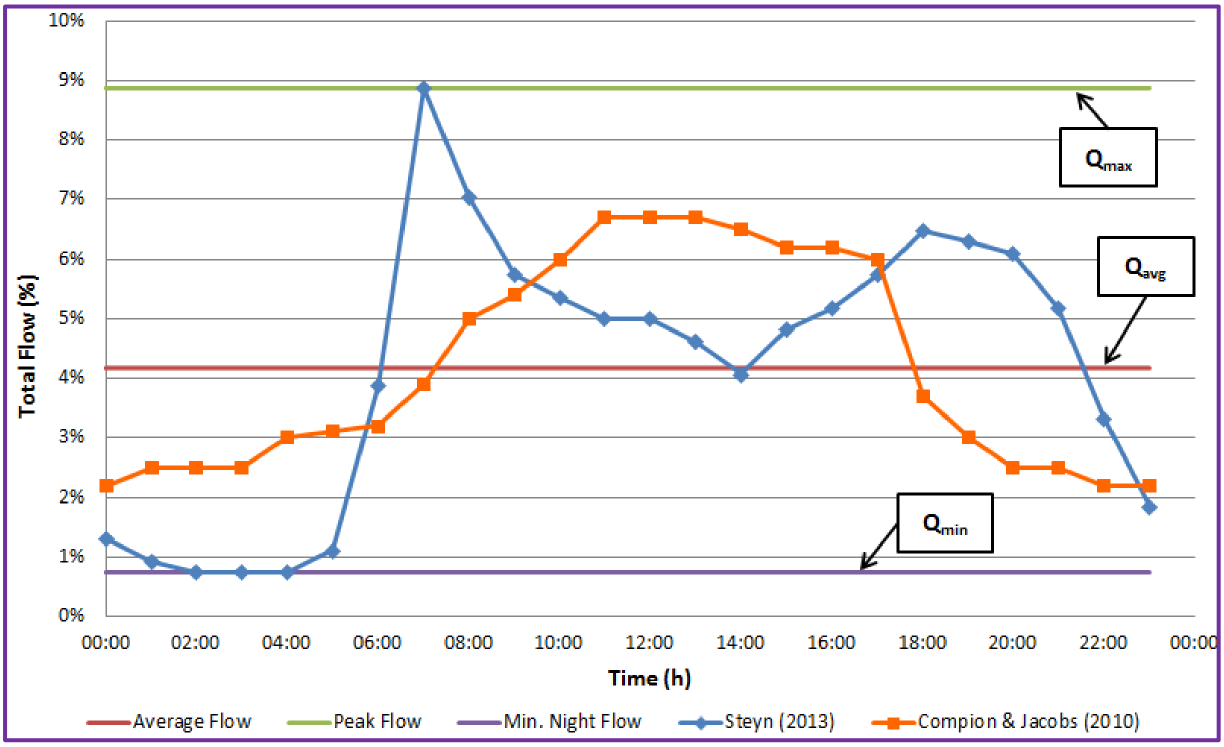


Figure 2-7: Average Flow of Kleinmond LCH Compared to a South African Pattern (Steyn, 2013)

The figure clarifies that the average flow rate from Compion & Jacobs (2010) does not represent the diurnal system demand pattern for Kleinmond. The graph derived by Compion & Jacobs (2010) was based on data from Gauteng and assumed that most LCH residents are at home during the day and therefore one peak exists throughout the course of the day. The consumer surveys conducted during this thesis, together with the system demand pattern, distinctly illustrate that this is not the case with the households in Kleinmond.

2.4 Worldwide Use of Rainwater Harvesting Systems

A research study done by Allen (2012) states that, a number of RHS guidelines have been developed for particular cities or areas around the world. These include, for example, the Texas Water Development Board (2005) in the USA and the Gold Coast City Council (2005) in Australia. These official documents comprise information regarding the functionality of RHSs, the basic design requirements and the methods employed when generating such a system.

The urban water consumption rate per person in Ireland is reported by Li *et al.* (2010) to be one of the highest in Europe.

Furthermore, the RHSs contribute to reducing the system demand and eliminate treatment costs for domestic usage since the rainwater acts as a potable water supply.

Özdemir *et al.* (2011) revealed that access to safe drinking water is limited in the Mekong Delta region of Vietnam, which results in harvested rainwater functioning as the primary drinking water source in households in the region. RHSs have recently been progressively promoted as an alternative or supplemental approach to municipal WDSs (Özdemir *et al.*, 2011). RHSs are the most common water source used for domestic events in the rural Delta region of Vietnam.

In Barcelona, Spain, the use of rainwater was treated as a risk in low precipitation areas, rather than a beneficial resource. The advancement to encourage use of RHSs through regulations and incentives was recently recognized in domestic areas, since it holds great potential for households to reduce the use of the municipal WDS. Domenech *et al.* (2011) reported that a single family in Barcelona could be supplied with enough water for toilet flushing and laundry by installing only a 6 kℓ rainwater tank. Users' reactions and their level of satisfaction regarding a RHS suggest that both regulations and subsidies are good strategies to advocate and expand rainwater harvesting technologies in domestic areas (Domenech *et al.*, 2011). From the study, it is evident that a large scale employment of RHSs across Barcelona would be beneficial.

In a similar study conducted by Furumai (2008) in Tokyo, RHSs were introduced on both small and large scales to meet the system demand in emergency cases. Initially, these systems were implemented out of a concern for the sustainability of urban water use in Tokyo. Rainwater harvesting for miscellaneous use such as toilet flushing and water-cooling is employed on an individual scale as well as on a large-scale (Furumai, 2008).

A domestic area in Sweden was considered by Villarreal & Dixon (2005), who generated a computer model to explore the water saving capability of such a RHS. Four scenarios for using rainwater were considered. The intention was to reduce the system demand and employ rainwater for low water quality demands. Villarreal & Dixon (2005) regarded the following domestic end-uses as low water quality demands: toilet flushing, laundry, car washing and garden irrigation. The model measured the performance of the RHS by its water saving proficiency, which proved to contribute extensively to drinking water savings. Likewise, in Brazil an economic analysis was executed by Ghisi & Mengotti de Oliveira (2007) on households with RHSs, in an effort to evaluate the benefits of using such a system.

A study performed by Fewkes (1999) in the United Kingdom, attempted to predict the amount of potable water that can be conserved when using an RHS for the flushing of toilets. Since the domestic sector uses 30% of the municipal WDS for toilet flushing, an internally plumbed RHS with a 2 kℓ rainwater tank was installed in a United Kingdom household. This household was monitored for 12 months in an effort to evaluate the performance of the RHS. The system was assessed according to the water saving efficiency, which is the measurement of how much potable water has been retained in comparison to the overall system demand.

Gardner *et al.* (2010) concentrated on the role and application of RHSs in the Australian urban domestic environment and showed that even 5 kℓ rainwater tanks can be very effective in providing non-potable water to residences in order to reduce the system demand. The succeeding water conservation is a result of government mandated Internally Plumbed Tanks (IPT) which enforce homeowners to accept some of the responsibility for their water supply.

2.5 Rainwater Harvesting in South Africa

The feasibility of installing a rainwater tank should be determined by considering the social impact as well as the installation costs (Allen, 2012). Kahinda *et al.* (2008a) included a set of suitability maps for rainwater harvesting in South Africa. The development of these maps includes the social impact of RHSs on the designated regions. In addition, they were constructed around aridity zones, rainfall, land cover, soil cover, ecological sensitivity and socio-economic aspects. The map presented in Figure 2-8 illustrates that most of the summer rainfall region of the country falls into either the moderate or high suitability zones (Kahinda *et al.*, 2008a).

Kahinda *et al.* (2008b) notes that the average annual rainfall for South Africa is 465 mm, which is strongly seasonal, highly irregular in occurrence, unevenly distributed and classifies South Africa as a semi-arid region. The rainfall attributes imply that adequate storage capacity is required to ensure that the water harvested is sufficient to act as a water source during the high demand period. However, this is not always possible because some households are limited by catchment area or insufficient storage capacity.

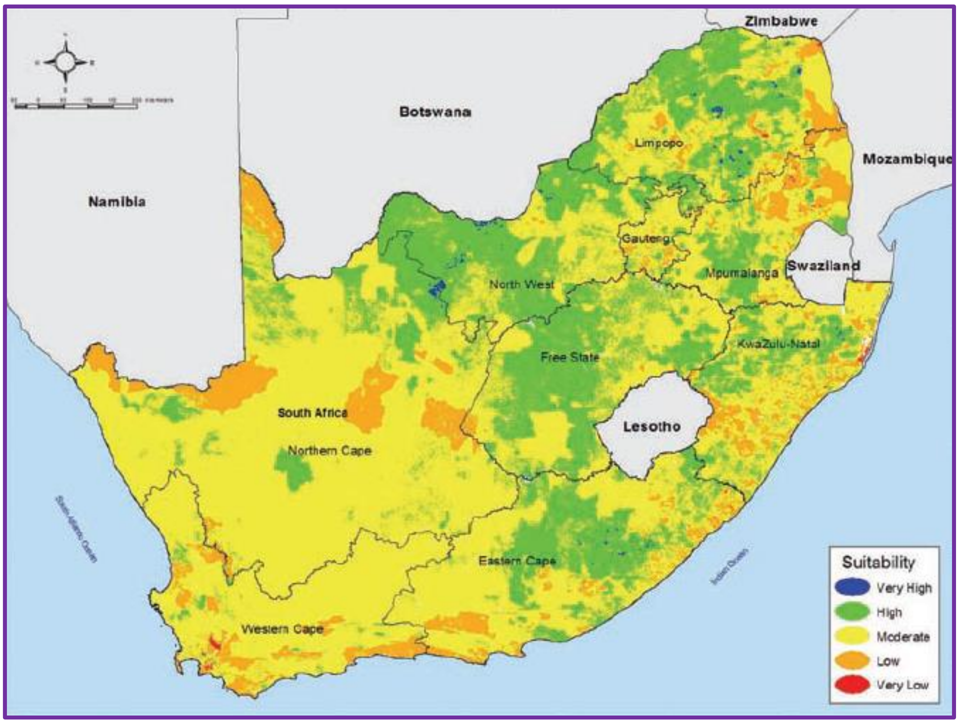


Figure 2-8: Rainwater Harvesting Suitability Map (Kahinda *et al.*, 2008a)

2.5.1 Domestic Rainwater Harvesting

Based on the literature review, the key uses of harvested rainwater are identified as:

1. A principal or additional source of potable water (Özdemir *et al.*, 2011), although the water quality has been found to be unsuitable for potable use without treatment (Houston & Still, 2002); and
2. A supplementary source of non-potable water, for example, washing laundry (Ghisi & Mengotti de Oliveira, 2007), garden irrigation (Domenech *et al.*, 2011), cleaning (Furumai, 2008) and toilet flushing (Fewkes, 1999).

Kahinda *et al.* (2008b) emphasized that domestic rainwater harvesting is currently the most widespread water resource management strategy in South Africa. However, the use of harvested rainwater as an alternative water source for selective domestic end-uses is a tool that has not advanced far enough toward its full potential in South Africa, especially in the Western Cape.

The lack of rainwater use in urban areas of South Africa is due to the high cost of the installation of such a tank, the fact that they are aesthetically unappealing, as well as the limited monetary savings they can offer (Allen, 2012; Jacobs *et al.*, 2011). The seasonal rainfall pattern that exists over most of South Africa requires a tank larger than the suitable 5 kℓ in order to capture enough water during the rainy season with the aim of providing a water supply during the dry season. For that reason, the initial expenditure is higher, with relatively small financial savings, making the installation of such a tank uneconomical for the individual home owner (Jacobs *et al.*, 2011; Kahinda *et al.*, 2008b).

The climatic environment in the Western Cape differs distinctly from that of the conditions across the rest of South Africa, as most of the Province experiences cool, wet winters and long, hot summers. Since most of the rainfall occurs during winter and given the high water demand during summer, water stored in the rainwater tanks will be consumed before it can act as a sustainable water source for the summer months. Despite the fact that the Western Cape is a winter rainfall region, up to 25% of the province's rainfall occurs during the summer months from October to March (Jacobs *et al.*, 2011) and a small area of the province receives year-round rainfall.

2.5.2 Application of Harvested Rainwater in Rural Areas

In rural areas, the use of rainwater tanks is a more common feature as it is a reliable water source and in some cases, it acts as the primary source of drinking water. The benefits related to RHSs are numerous, but predominantly significant for households located in these areas where the WDS is often unreliable. A dependable water supply requires finances, especially if it involves transporting water from a distant source, and therefore it is anticipated that the strongest interest in domestic RHSs will exist in developing regions.

Helmreich & Horn (2009) note that the main advantage of, a domestic RHS, is to provide water as close as possible to the household, reducing the need for long distance walks in order to collect water. The stored rainwater can be used for any domestic purpose, garden watering and small scale agricultural activities.

The role of RHSs in South Africa has a substantial influence on the rural communities with regard to household applications (Houston & Still, 2002), such as:

- A reduction in the time women and children spend on water collection;
- The existence of a backup supply in the event that there is a failure in the municipal WDS;
- A limitation in the presence of waterborne diseases by improving the water quality and availability, in view of the fact that people will be less reliant on public water sources; and
- The increased use of harvested rainwater results in the WDS being less likely to be over-exploited.

In certain areas, RHSs are frequently installed with no technical knowledge or external assistance, but simply as a method to acquire water when there is a lack thereof. Explicit guidelines relating to the employment and operation of RHSs for rural water supply are not yet available in South Africa. However, there are general regulations that consider the potable water usage. The DWAF (1997) provide the following general guidelines:

- The contamination of rainwater collection surfaces, which are generally house roofs, by animals and people should be prevented;
- Rainwater collection surfaces should be assembled from inert materials and well maintained and cleaned (particularly at the end of the dry season) to prevent contamination; and
- A 'first flush' system should be incorporated into the RHS in order to remove as much contamination as possible before the storage tank starts to replenish.

The employment of rainwater harvesting as an alternative water source can be substantially beneficial to the rural community in South Africa. Certain rural areas use these tanks as a result of government incentives in order to reduce the system demand. In the event that these areas lack reliable WDSs, the possibility does exist that they could obtain WDSs in the future. However, the effect of RHSs on the system demand in these areas has not been incorporated in this thesis.

2.5.3 Challenges of Rainwater Harvesting

Rainwater supply is completely dependent on one factor that is often unpredictable, namely, rain. The existence of rainfall is the only source that controls the accessibility and reliability of the RHS.

There are other influences that can affect the implementation of such a system, and they will be discussed in this section.

2.5.2.1 Tank size

The tank size plays a major role in the yield of an RHS. Sizing a rainwater tank can become rather complicated, as the required size is dependent on a number of factors. The most common method for determining the correct size for a rainwater tank is thus to execute a continuous simulation of the tank behaviour for a given rainfall record as discussed by Allen (2012). Installing a rainwater tank that is larger than 5 kℓ may be impractical and aesthetically unappealing. Generally, the tank sizes commonly used in South Africa vary between 2 and 5 kℓ (Jacobs *et al.*, 2011).

2.5.2.2 Rainwater Tank Yield Limitations

From the areas investigated in Jacobs *et al.* (2011), it became evident that high density domestic areas (such as low-cost developments) obtained no additional yield beyond a certain tank size. The lack of yield is the result of the relatively small catchment area of the houses, as this restricts the volume of rainwater that could potentially be stored. Additionally, it can be noted that for all the high density domestic areas, the tank size that will retain the most rainwater is larger than the tank size that is financially feasible. For that reason, it is more beneficial for households with a relatively large roof area to install a rainwater tank, than one with a small roof area.

2.5.2.3 Financial Implications

Most rural households live under a tight budget and do not have the required capital to buy the tanks needed to implement RHSs (Kahinda & Taigbenu, 2011). Once the acquisition of the system is accomplished, there is barely any maintenance or operational cost involved in the RHS. The cost of a domestic RHS depends on the on-site requirements, in other words, the rainwater tank size. A study conducted in Australia by Rahman *et al.* (2010), established that a typical homeowner would take approximately 30 years to salvage the cost of a rainwater tank without government subsidies. According to Jacobs *et al.* (2011), the financial benefits will only surface 69 years after the initial capital expenditure has been reimbursed.

For that reason, the financial constraints are the leading explanation as to why the potential of RHSs, without government incentives, are not yet recognized.

2.5.4 Water Quality

Despite the fact that rainwater comes from the sky, this does not imply that it is clean enough to be deemed as drinking rainwater. The water falling from the sky is one of the cleanest forms of water, but it becomes contaminated during the rainwater harvesting process. Contamination of rainwater is potentially caused by one or more of five main contributing factors (Jacobs *et al.*, 2011):

- The pollution of rainwater as it passes through the atmosphere;
- Contamination by dry particles, caused by atmospheric pollution, which have settled on the catchment area, specifically, rooftops;
- The rainwater initiating a chemical or physical reaction with the catchment area or any other component of the system;
- Any bird or animal faeces deposited onto the catchment area; and
- The pollution of the water as a result of the storage tank and conveyance system not being cleaned frequently, the water becoming stale in the tank due to age and insects falling into the tank.

In some cases the rainwater tank is referred to the as the “drinking water tank” which is in fact an inaccurate term. Appropriate treatment of the collected rainwater is essential to make the harvested rainwater suitable for drinking. A large contributing factor to poor rainwater quality originates from the first rain after a dry period. The water collects particles and debris from the rooftop and runs straight into the rainwater tank. This contamination could be reduced by installing a first flush diversion system, which diverts the first rain that falls during a rain event, allowing water containing roof debris to be washed away.

In the long term, an expansion of a simple, reliable way of household water treatment is necessary. There are other methods in which to improve the water quality, such as boiling, chemical disinfection or filtration, but these will not be investigated in this study.

2.5.5 Legislation Concerning Rainwater Harvesting Systems

In areas where a WDS is in place, the water is provided by a local municipality, and along with this service comes a financial obligation that may increase over time. In addition to this factor, water restrictions and drought procedures may be implemented from time to time, which induce consumers to make use of alternative water sources such as rainwater harvesting.

However, a brief overview of the current legal status of RHSs in South Africa, presented in a WRC report by Jacobs *et al.* (2011), suggests that there is yet to be a legislative framework that accommodates this practice. The National Water Act (NWA) and the National Water Services Act (WSA) (No. 108 of 1997) do not explicitly mention anything about rainwater use, but rather water use in general.

The legal aspects relating to rainwater harvesting in South Africa are confined to the NWA, as well as the WSA, which is inadequate in terms of defining the legal requirements for using such a system. The NWA, specifically section 21, states that a licence is essential for any water use and extracting water from a resource is regarded as a water use. One of the water uses, which is exempted from the registration process, is Schedule 1 use, which is provided in section 22 of the NWA. A Schedule 1 water use is defined in the NWA as a user who either obtains water from anywhere on their legal property, for reasonable domestic purposes in their own household, or stores and uses run-off water from their roof. Additionally, section 22 of the NWA stipulates the situations in which water can be consumed without a licence, specifically if the water use is accepted either under Schedule 1 or as an extension of an existing lawful use.

It is clear from section 22 of the NWA that taking water directly from any water resource to which that person has lawful access for domestic use is deemed legal, with no licence required. From this, it can be deduced that runoff water from a roof, which is stored in a tank, would fall within this category. Therefore, the use of a domestic RHS without a licence can be deemed legal in South Africa, unless the local municipality has by-laws enforcing the registration of such a system (Jacobs *et al.*, 2011).

2.5.6 Effect of Domestic Rainwater Harvesting on the Municipal WDS

From case studies in various publications (Thomas & Martinson, 2007.; Domenech *et al.*, 2011; Fewkes, 1999; Li *et al.*, 2010), harvested rainwater is capable of supplying at least 50% of the allocated system demand, provided that the rainwater is used for the appropriate end-uses, for example, toilet flushing. Jacobs *et al.* (2011) reported that extensive use of RHSs in low density, suburban areas could lead to the AADD being reduced by as much as 40%. The decreased AADD includes application of the RHS for indoor and outdoor household water requisites. However, only a 10% reduction in AADD was reported for high density, low income areas in Cape Town. The results of the various, above mentioned, theoretical studies postulate a significant impact on the WDS.

2.5.7 Effect of Domestic Rainwater Harvesting on Stormwater and Sewer Systems

The use of harvested rainwater is expected to reduce the stormwater discharge whilst the demand on the sewer systems might be amplified, as a result of rainwater being discarded inside the household. However, the devices used to quantify or estimate the volume of consumed harvested water entering the sewer system are expensive and will not be used in the investigation of domestic RHSs in this study.

Herrmann & Schmida (2000) identify that the practice of harvesting rainwater is an emergent tradition in Germany, where it has been encouraged by environmentally conscious people during the past 15 to 20 years. The idea was to reduce the need for potable water from the WDS and not to use potable water for flushing toilets but to substitute the water by collected roof runoff (Herrmann & Schmida, 2000). Until recently, the use of rainwater has only been considered as a manner in which to save water, with its hydraulic effect on the drainage system being recognized but quantitatively unknown. Despite the fact that this secondary effect of an RHS has not yet been investigated in Germany, there is a permanent financial incentive to detach the roof runoff water from the sewers as an approach designed to balance this effect.

It is apparent that domestic rainwater use in urban areas is likely to have an impact on the system demand. The application of domestic rainwater harvesting reduces stormwater runoff and recharges groundwater, which, in turn, delays the construction of new wastewater treatment plants.

However, the rise in stormwater inflows into sewers could lead to a reduced capacity of the entire sewer system, resulting in a negative effect on the performance of the system, including the wastewater treatment component. In the case of rural areas without service providers, there is a need to bestow guidelines on the construction, operation and maintenance of domestic RHSs (Kahinda *et al.*, 2008b).

2.6 Potable Water Savings When Using Rainwater Harvesting Systems

Each RHS is evaluated according to the volume of potable water that has been conserved in comparison to the overall system demand, since this gives an indication of how effective the system is and whether or not it is saving water. The studies presented in this section give an overview of the methods employed to predict the performance of an RHS.

Domestic RHSs are being employed as a preventive measure, to reduce the system demand, considering that it could supply almost 94% of the system demand in households (Li *et al.*, 2010). Domenech *et al.* (2011) also established that with an increase in the rainwater tank size, the tank could meet 62% of the household's irrigation requirements. Furumai (2008) recorded that 20% to 60% of the system demand is satisfied by using RHSs in multiple facilities in Tokyo. The potable water saving, when using the rainwater for toilet flushing and laundry, was reported by Ghisi & Mengotti de Oliveira (2007) to be 33% of the total water consumption. In a similar study conducted by Fewkes (1999), the employment of a RHS for toilet flushing was found to result in water saving of 57% of the annual system demand. Two Australian studies further investigated the potable water savings by using smart meters and reliability analysis, where their descriptions and results are examined in each sub-section.

2.6.1 Griffith University, Australia

A pilot study was done by Talebpour *et al.* (2011) in Australia on a newly constructed domestic area where the government authorized IPT connected to certain end-uses such as laundry, toilet flushing and irrigation. The rainwater tanks have two high-resolution smart meters attached to them, which measure the data every five seconds. The study by Talebpour *et al.* (2011) is motivated by the fact that on an annual basis, approximately 50 000 houses in Australia are being built with IPT. However, Talebpour *et al.* (2011) state that the evidence to substantiate the feasibility of potable water savings is based on unverified modelling procedures which lack practical field-based support.

For that reason, the pilot study aimed to design an experimental method to determine the tank-water demand from IPT across their supplied end-uses (Talebpour *et al.*, 2011).

Talebpour *et al.* (2011) investigated rainwater use at five households for the purpose of an experimental project for a full study of 50 households. Each housing site is connected to a 5 kℓ rainwater tank with a pump and a switch system. The examination period lasted only a few weeks, given that the data received was adequate to implement the analysis. The switch system is activated when there is a demand for water and uses sensors to check whether there is sufficient water in the tank. If inadequate water in the tank is detected, the water from the potable WDS flows to the appropriate end-use.

The results obtained by Talebpour *et al.* (2011) are displayed in Figure 2-9 where the end-use summary for the smart meter after the switch (Figure 2-9a), before the switch, exclusively the system demand (Figure 2-9b), and the tank-water demand (Figure 2-9c), which represents the difference between (a) and (b), are illustrated in the figure.

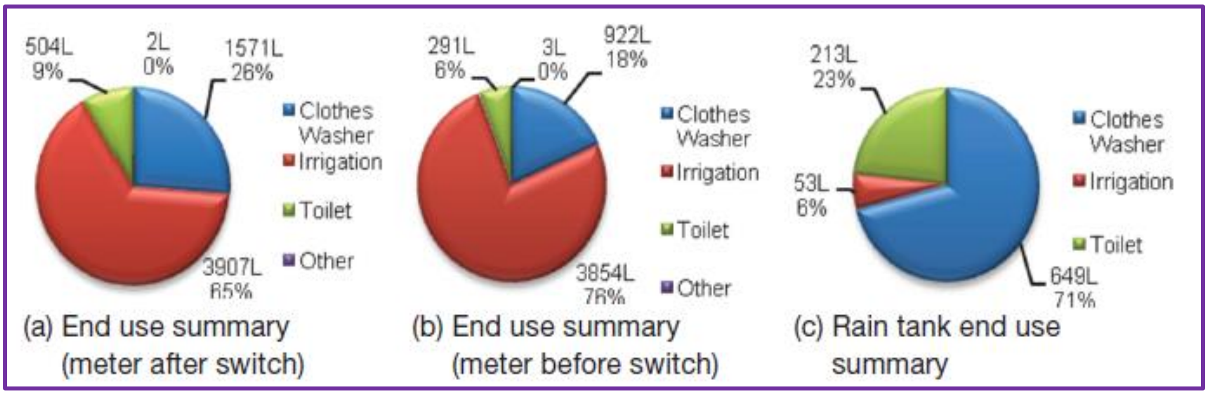


Figure 2-9: Selected Rainwater Tank End-Uses (Talebpour *et al.*, 2011)

As a concluding observation, the percentage of the system-demand supplied by the RHS, for each end-use, is demonstrated in Figure 2-10.

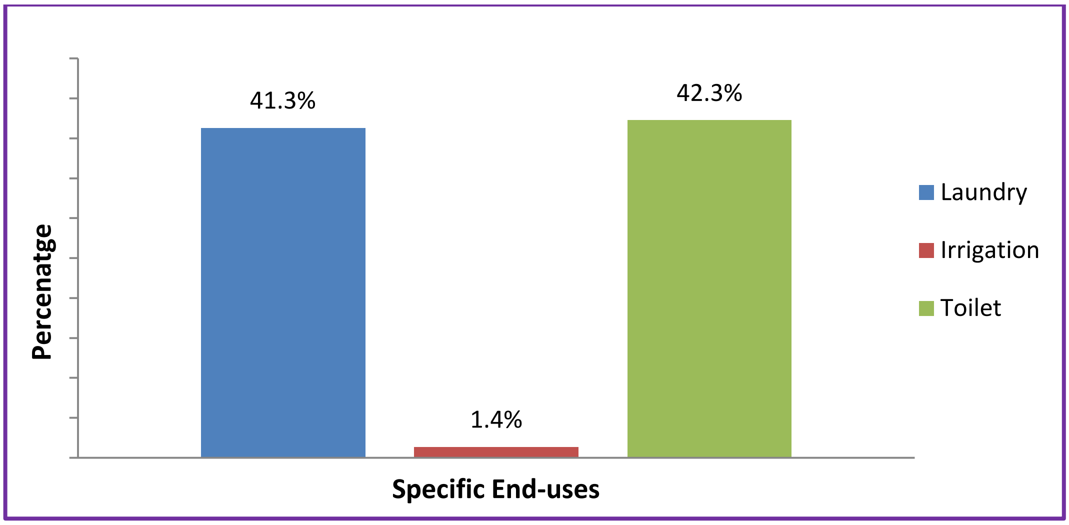


Figure 2-10: Percentage of System Demand Supplied by RHS (Adapted from Talebpour *et al.*, 2011)

2.6.2 Melbourne, Australia

Imteaz *et al.* (2011) conducted a study in Melbourne, Australia that made use of a daily water balance model to evaluate the reliability of domestic rainwater tanks when they are employed as a partial supply of the household system demand. The model uses daily rainfall data, roof area, rainfall loss, tank storage volume, tank overflow and tank-water demand in a spreadsheet to assess the reliability when a percentage of the system demand is delivered by the rainwater tank.

Reliability is defined as percentage of days in a year when the rainwater tank was able to supply the intended partial system demand for a particular condition (Imteaz *et al.*, 2011). The model calculated several reliability charts for the three climatic conditions (driest, average and wettest years) with relativity to the rainwater tank volume, the roof area, PPH and the percentage of the total system demand to be satisfied by tank-water demand.

The cumulative water storage equation is as follows:

$$V_t = V_{t-1} + Q_t - D_t$$

Equation 3: Cumulative Volume of Water Stored in Tanks (Imteaz *et al.*, 2011)

Where: V_t = cumulative volume of water stored in the tank at the end of the time interval (ℓ),

V_{t-1} = volume of water stored in the tank at the end of the previous time interval (ℓ),

Q_t = harvested rainwater during time interval (ℓ),

D_t = demand during time interval (ℓ) and

t = time interval (day).

The reliability is calculated with the subsequent equation:

$$R_e = \frac{P}{N} \times 100(N - U) \times 100$$

Equation 4: Reliability to Supply the Intended Demand (Imteaz *et al.*, 2011)

Where: R_e = reliability of the tank to be able to supply the intended demand (%),

P = percentage of total water demand to be fulfilled by the rainwater tank (%),

N = total number of days in a particular year (days), and

U = number of days in a year that the tank was unable to meet the demand (days).

The tank sizes that were used in the analysis ranged from 1 000 to 10 000 ℓ and the roof sizes that were inspected extended between 50 and 300m^2. With regard to the total system demand, two explicit scenarios were examined, namely, two-person household and four-person household with a typical AADD of 185 ℓ/person/day. The chosen percentages of the total system demand to be fulfilled by the tank-water demand were 60%, 70% and 80%.

An example of the relationship between the reliability, tank size and roof area of a two-person and four-person household, if 70% of the system demand is supplied by rainwater, is demonstrated in Figure 2-11 and Figure 2-12 respectively.

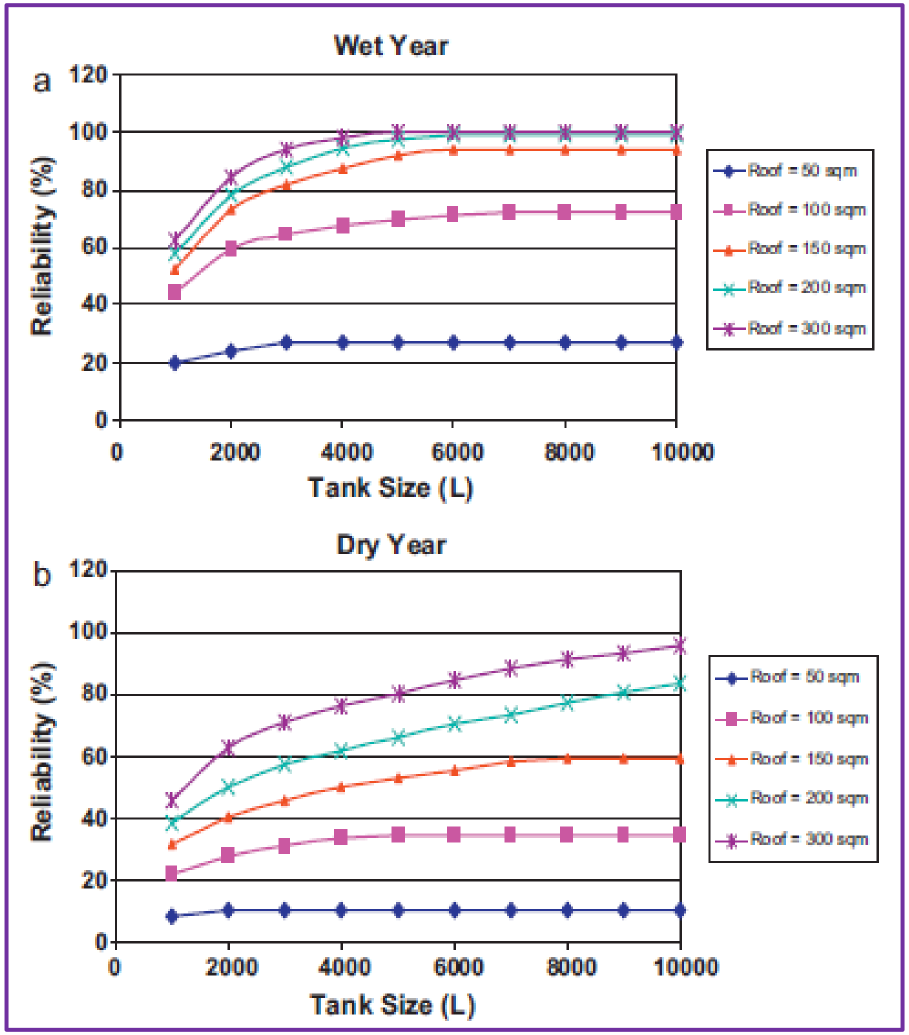


Figure 2-11: Reliability-Roof Area-Tank Size Relationships for two people (Imteaz *et al.*, 2011)

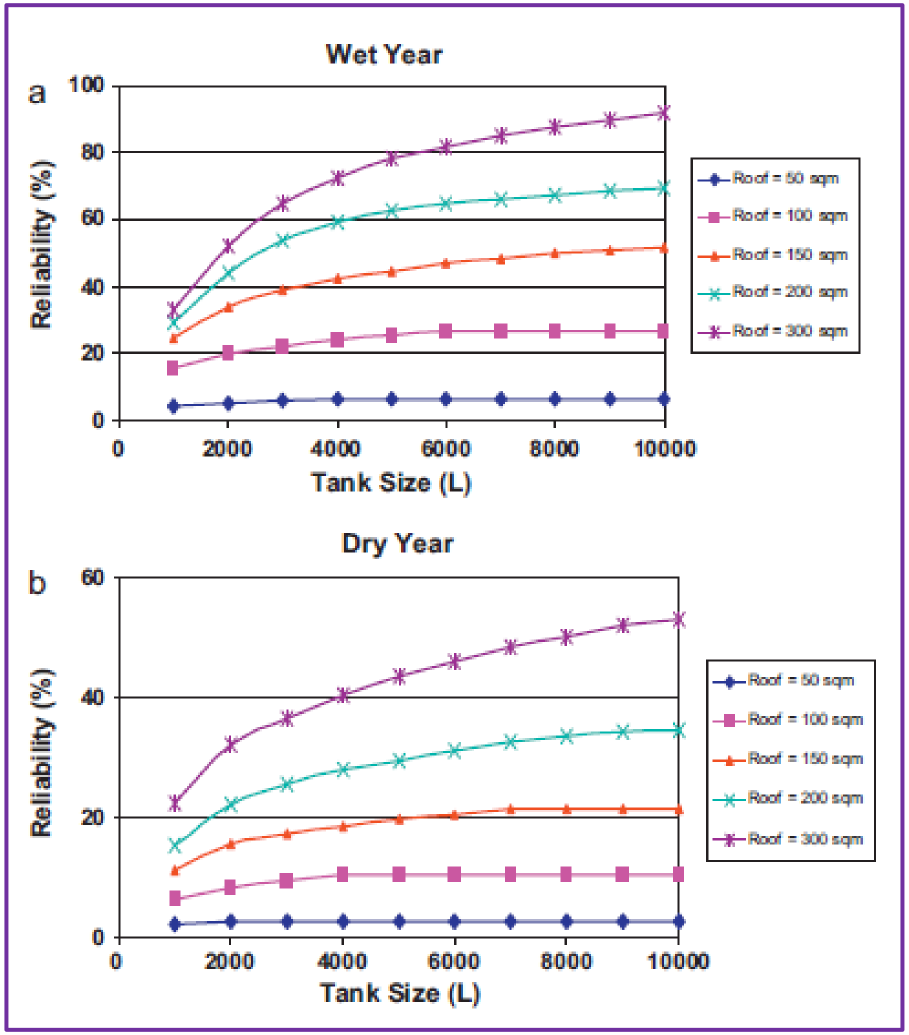


Figure 2-12: Reliability-Roof Area-Tank Size Relationships for four people (Imteaz *et al.*, 2011)

In brief, the four-person household scenario differs greatly from the two-person household, which can accomplish 100% reliability with a roof size of 150 to 300m^2 having a tank size within the required range. However, for the four-person household, a relatively small roof size of 50m^2 sustains a maximum reliability of only 10%, even in the wettest year, and the effect of the tank size becomes insignificant for a tank size beyond 3 000 ℓ. The reason for this is the higher system demand associated to a smaller roof area. The results of this study could vary under different climatic conditions or in general with different rainfall intensities and pattern (Imteaz *et al.*, 2011).

2.7 Models Available to Estimate Domestic Rainwater Demand

Models are implemented in order to evaluate the functioning of an RHS in order to predict how each will perform. A number of components are present in each model as they form the basis on which to build the analysis. These components are rainfall, which is dependent on climate and geographical position, as well as the roof size and condition, which determines the amount of rainwater collected. However, an increase in the complexity of a model requires more data, time, understanding and experience in order to use it effectively.

2.7.1 Roof Model

The reliability of a domestic RHS is projected using a model designed by Van der Zaag (2000). The reliability model, known as Roof, calculates the required storage capacity of a rainwater tank when the daily system demand and roof area are identified. Roof is a water balance model based on Equation 5, which involves a complete series of daily rainfall data for at least three consecutive years. When using the monthly rainfall data to calculate the storage requirements, it results in a severe underestimation of the required storage capacity (Van der Zaag, 2000).

Domestic rainwater harvesting reduces runoff by storing water in above ground tanks that could have contributed to catchment runoff. As a result, important parameters are compelled as inputs to balance the model. These parameters are daily rainfall records, daily tank-water demand, initial and final storage as well as the catchment characteristics (roof size and type) which vary along with the water requisites for the allocated study area.

The water balance equation for a domestic RHS is computed as follows:

$$\frac{dV}{dt} = Q_t + Q_i - Q_A - Q_O$$

$$For\ rooftop\ catchments: Q_t = c_r \times R \times A_r$$

Equation 5: Volume of Water Stored in the Rainwater Tank (Kahinda *et al.*, 2008b)

Where: V = volume of water stored in the tank (m^3),

Q_t = harvested rainwater during the time interval (m^3/d),

c_r = roof runoff coefficient,

R = rainfall (m/d),

A_r = roof area (m^2),

Q_i = additional inflow into the tank (m^3/d),

Q_A = water abstracted from the tank (m^3/d),

Q_O = overflow from the tank (m^3/d), and

t = time interval (day).

Kahinda *et al.* (2008b) conducted a reliability study of a domestic RHS and employed the roof model. The household roof size in their study was limited to between 20 and 40m^2 and the daily system demand predicted to be 125 ℓ/day. The percentage of the system demand satisfied by different rainwater tank sizes was estimated. Kahinda *et al.* (2008b) assessed three tank sizes, namely 1, 2.5 and 5m^3 and related them to the roof areas in an attempt to obtain a percentage of the system demand satisfied by the rainwater tank. Once this percentage is achieved, the reduction in daily system demand can be acquired.

2.7.2 South East Queensland, Australia

The region of South East Queensland in Australia has implemented water resource strategies, which include rebate programmes with the intention of reducing the consumer dependency on the potable WDSs. A rainwater monitoring study by Umapathi *et al.* (2013) revealed one such strategy that included a regulation enforcing the use of 5 kℓ IPT that is connected to the toilets, washing machine, cold water taps and at least one outdoor tap. The government is committed to using alternative water sources to enlarge the water storage in local dams for potable end-uses (Umapathi *et al.*, 2013).

The focus of the abovementioned study is on quantifying the actual amount of potable water savings realised when operating IPT in a household. Umapathi *et al.* (2013) employ a real-time monitoring approach using smart meters, which is different from the studies previously discussed (Domenech *et al.*, 2011; Furumai, 2008; Villarreal & Dixon, 2005; Imteaz *et al.*, 2011). The system and tank-water demand of the set of households were monitored and metered in order to determine the actual usage as well as estimating the volumetric reliability of the RHS. Even though this study was conducted in Australia, the technique exercised to estimate the water savings, volumetric reliability and impact on household system demand can be applied anywhere in the world.

The study by Umapathi *et al.* (2013) on system and tank-water demand patterns was done in four regions on the eastern coast of Australia and was conducted over a 12 month period between April and November 2011, which excluded the wet seasons. The regions are sub-tropical, which entails warm, wet summer months and cool, dry winter periods. A sum of 20 households with 5 kℓ IPT were chosen across the four regions and were each fitted with smart meters to monitor their tank-water demand.

The volumetric reliability for the household rainwater tanks was calculated as follows:

$$R_v = \frac{\sum_{t=1}^{T} Total\ Rainwater\ Supply}{\sum_{t=1}^{T} Total\ Main\ Water\ Supply\ +\ \sum_{t=1}^{T} Total\ Rainwater\ Supply}$$

Equation 6: Volumetric Reliability of the RHS (Umapathi *et al.*, 2013)

Where: R_v = volumetric reliability of rainwater in the system (%),

T = total monitoring/assessment time period (months), and

t = time interval (minutes).

The data acquired by Umapathi *et al.* (2013) from the smart meters was used to establish the average volumetric reliability of the individual RHSs, which was estimated to be 31%. Figure 2-13 illustrates the diurnal system and tank-water demand patterns achieved by Umapathi *et al.* (2013) as well as the municipal WDS pattern used for topping up the household rainwater tanks. From the figure, two clear peaks can be detected; the first peak occurs between 08h00 and 11h00 and the second peak between 18h00 and 20h00. The results of the study found that during the morning peak, 28% of the system demand was met by the rainwater source, compared to 10% during the evening.

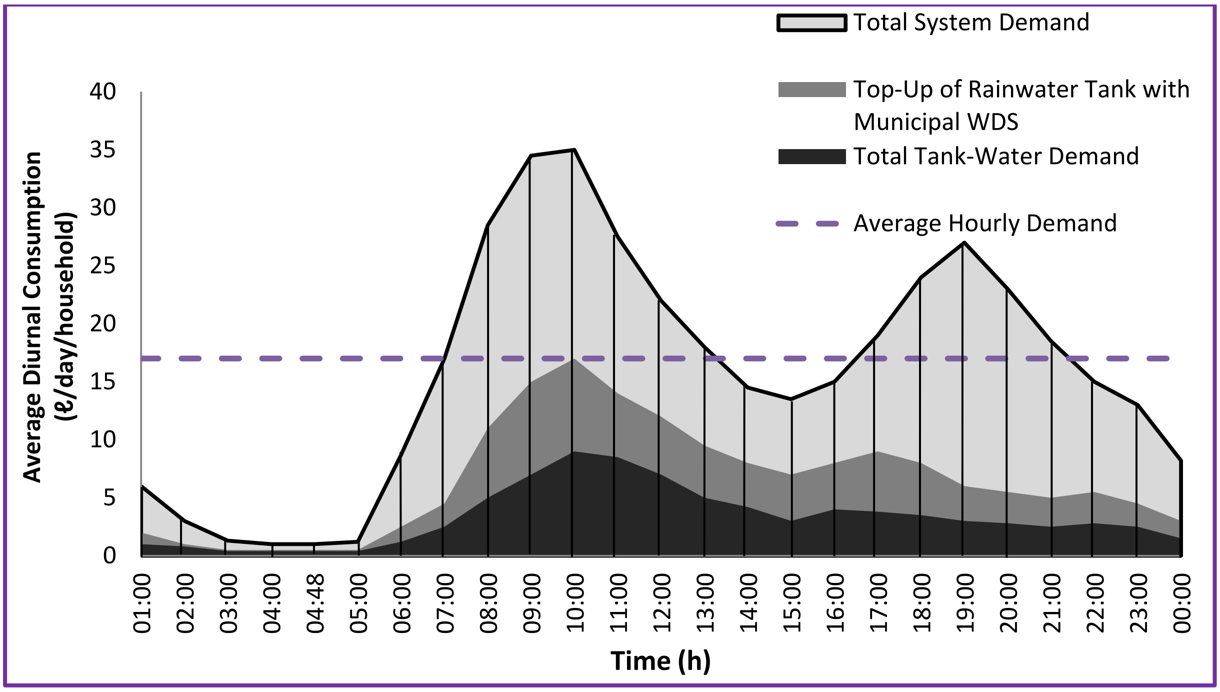
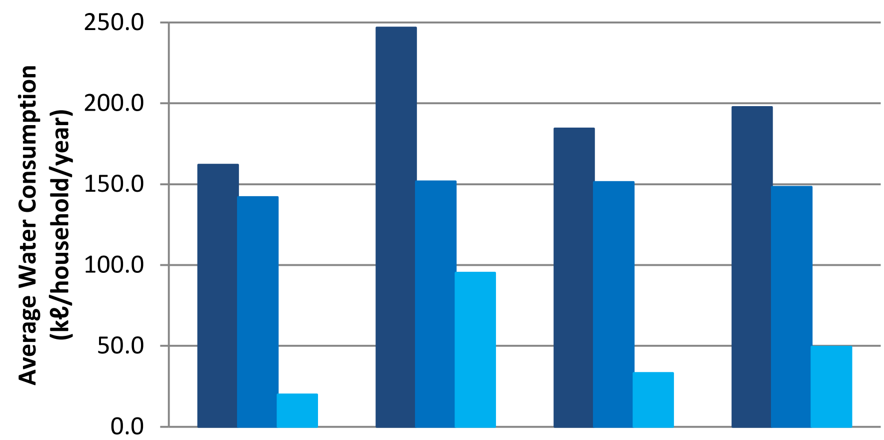


Figure 2-13: Average Diurnal Patterns for the 20 Households (Umapathi *et al.*, 2013)

Beal *et al.* (2012) conducted a similar study, on the same region in Australia, by performing a pairwise statistical analysis. The analysis compares households with IPT to randomly paired households without rainwater tanks of similar characteristics in an attempt to estimate potable water savings. In 2006, the local government issued rebate schemes as a way in which to encourage the installation of RHSs. The implementation of rainwater tanks is likely to have contributed to a reduced system demand in the South East Queensland area in the last 5 years (Beal *et al.*, 2012). The aim of their investigation was to develop a methodology, which evaluates the potable water savings when incorporating internally plumbed RHSs, and to act as an urban water management tool in order to reduce the dependence on WDSs.

Only households constructed after 2007 were considered in the statistical analysis by Beal *et al.* (2012), since these developments contain the mandated RHS connected to the toilet and washing machine. Over 1 100 data pairs comprising single, detached households, which consisted of fewer than 12 people, were examined over the 2008 analysis period. The results of the pairwise approach, presented by Beal *et al.* (2012), are displayed in Figure 2-14. The desktop analysis confirmed that the system demand in households with IPT was lower than that in households where these tanks were absent.



	Pine Rivers	Gold Coast	Redland	Combined Average
No Tank	162.0	246.9	184.5	197.8
IPT	142.0	151.7	151.4	148.3
WDS reductions	20.0	95.2	33.2	49.5

Figure 2-14: Average Water Use and Estimated Potable Water Savings in 2008 (Beal *et al.*, 2012)

The potable water savings achieved, according to the statistical analysis, were contrasted with approximations using measured end-use data and tank-water demand predictions by means of a specified model. The cross-check between these various methods is summarized in Table 2-1. The rainwater TANK model expressed in the table is an Excel-based, spreadsheet model which evaluates the ability of the rainwater tank to meet the water demand of the urban household. For the purpose of the study by Beal *et al.* (2012), TANK was used to provide a first approximation of the performance of rainwater tanks for comparison with the statistical desktop results.

Table 2-1: Summary of Potable Water Consumption Reductions (Beal *et al.*, 2012)

Region	Desktop study: Mean values	Desktop study: Median values	End-Use approach	TANK model, Internal only
	(kℓ/household/year)			
Pine Rivers Gold Coast Redland	20 95 33	28 52 41	43 to 46 (internal only)	49 54 46
Average reductions	50	40	44.5	50
Annual water savings	25%	-	22.5%	25%

The table displays the average water savings per household, ranging between 44.5 and 50 kℓ/year, provided that the rainwater tanks were connected to the washing machine and toilet. The combined data in Figure 2-14, together with the average reductions presented in Table 2-1, display that the annual potable water savings per household ranged between 22.5% and 25% for the South East Queensland region.

One of the key limitations of the pairwise investigation amply documented by Beal *et al.* (2012) was the fact that socio-demographic influences such as household size or family makeup were not incorporated into the analysis. This restriction gives rise to unbalanced pairs, for example, where a single person household with no rainwater tank could be matched with a six person household using an RHS, which results in misidentified comparisons of households with an unequal system demand.

The study by Beal *et al.* (2012) verified a substantial decline in the system demand at households with IPT. It is expected that these internally plumbed systems will reduce the annual system demand. However, Beal *et al.* (2012) confirm that the value of this attenuation is highly influenced by a range of factors such as the tank-water demand, rainfall, demographic factors (for example household size) and water efficient household appliances. In addition, improved water savings could be gained by regular use of the rainwater for outdoor applications, as this end-use drives the peak system demand (Beal *et al.*, 2012).

3. THE BASIC OPERATION OF RAINWATER HARVESTING SYSTEMS

3.1 Domestic Rainwater Harvesting System Components

A domestic RHS can vary in complexity, since the amount of water captured is a function of roof area and rainfall. The benefit of a domestic RHS is that the water is not transported but rather consumed at the point of the source, specifically, where it is harvested. In a broader sense, harvested rainwater acts as an umbrella term for a range of methodologies and techniques to collect and conserve various forms of runoff water. Regardless of the type of RHS or the use thereof, the principle of rainwater harvesting consists of three main components: the catchment, storage and cultivated area. The aim of this section is to discuss the components and functioning of domestic RHSs in the most basic manner.

Rooftop rainwater harvesting is most commonly used at household level for domestic purposes, as the source of water is close to the people who use it. As a result, it requires minimal energy to collect it, which is an added advantage. Additionally, the users of an RHS possess, maintain and control the system themselves without any reliance on the local government or community members.

Kahinda *et al.* (2008b) states that the most basic arrangement of RHSs has the following components:

- A catchment area: a simple structure where water is harvested such as a rooftop, path, road, rock or marginal land. For the purpose of this study, only roofs were considered as suitable catchment areas. The volume and quality of the rainwater gathered by the catchment area is dependent on the rainfall pattern, roof surface area, type of roofing material, which should not absorb the rain or pollute the run-off, and the surrounding environment.

- Conveyance system: is the arrangement that transfers the rainwater from the roof catchment area to the storage facility by connecting the roof gutters to the piping that transports the water to the storage tank. In some cases, the rainwater is filtered to remove particles and debris before it is stored and used.

- A storage facility: where the water harvested in the catchment area is stored. The storage can be either a reservoir or a tank (surface and subsurface). These tanks can be constructed above ground, partly underground or below ground, depending on the amount of space available. The storage system can be constructed as part of the building, or as a separate unit located away from the building.
- A targeted area: where the harvested water is used. The targeted use can be human beings, crops, plants or animals.
- The management is a non-physical component, which is however the key to the RHSs success.

The size of the storage tanks needs careful consideration and optimal design as it is usually the most expensive component of the RHS. As pointed out by Thomas & Martinson (2007), the rainwater tank should be constructed in such a way that it is watertight and durable in order to avoid contamination of the collected water. The factors influencing the tank size for particular applications are the amount of water that could be stored (a function of roof area and average rainfall), the volume of water likely to be used (a function of household size and frequency of use) and the time period when no rain transpires (drought period).

Additionally secondary components could also be incorporated into the RHS, such as first flush systems (diverts the first rainwater, containing roof debris, after a dry period), filtration systems (removing debris and contaminants before water enters the storage facility) and pressure pumps.
The first rainfall after a dry period may contain dust, debris, bird droppings or leaves, which are on the roof surface. In order to prevent these pollutants from entering the storage tank, the first rainwater containing the debris should be diverted or flushed. First flush devices that prevent the first 20 to 25 ℓ of roof runoff from being collected in the storage tanks are recommended (Thomas & Martinson, 2007). Installing screens at the tank inlet or at the start of the down-pipe prevents larger debris such as leaves or birds from entering the storage tank. Similarly, gravel-sand filters positioned at the inlet of the storage tank purifies the rainwater, to some extent, of pollutants.

3.2 Characteristics of Domestic Rainwater Harvesting

The installation of RHS can be done in both new and existing buildings where the harvested rainwater can be used for various applications that do not require potable water quality such as laundry, toilet flushing, garden irrigation and cleaning. As mentioned earlier, there is a substantial body of literature reporting that the tank-water demand could reduce the system demand and result in water savings of approximately 50% of the total household water consumption.

As systematically documented by Thomas & Martinson (2007), there are five ways in which domestic RHSs are typically used:

1. As the primary source of water in locations where there is little seasonality in rainfall or where all alternative water sources are impractical and/or socially unacceptable;
2. Acting as the main source of water by means of supplying at least 70% of the annual system demand, where alternatives can be used to substitute the rainwater during dry periods;
3. A wet-season only water source, where the benefit lies largely in the accessibility of the water for collection for a substantial part of each year;
4. Solely functioning as a potable water source, which provides 5 to 7 ℓ/c/day throughout the year; and
5. Operating as an emergency source of water in the event that all other sources fail, or for fire-fighting and other emergencies.

The application of harvested rainwater in urban and rural areas generate several benefits, including the provision of additional water, increasing the soil moisture levels for urban vegetation, raising the groundwater table through artificial recharge and alleviating urban flooding. In and around the household the collected rainwater can be used for toilet flushing, laundry and irrigation. Additionally, the rainwater can be used for drinking, bathing and showering with correct filtration and treatment. Generally, harvesting rainwater can have the following positive benefits (Smet, 2003):

- Rainwater is a free and moderately clean source of water that is provided at the point where it is needed;
- RHSs conserve water during times of abundance in order to use when it is scarce;
- It is owner-operated and managed which promotes self-sufficiency;
- RHSs offer potential savings on municipal water cost;

- The system has low running costs and its construction, operation and maintenance are not labour-intensive;
- With proper treatment, it can deliver water of a better quality fit for human consumption;
- Rainwater harvesting reduces stormwater runoff and is environmentally accommodating.

Conversely, there are also disadvantages to such a system, such as the limited storage supply and rainfall uncertainty. The rainwater is not a reliable water source given that there are dry periods and drought periods. Other disadvantages include (Houston & Still, 2002):

- Low storage capacity of the rainwater tank, which limits the use of harvested rainwater;
- Possible health risks from contamination of the rainwater if it is not treated prior to consumption as a drinking water source; and
- Leakages from the storage tank could cause the deterioration of load-bearing slopes.

The overall maintenance of the RHSs is usually limited to the annual cleaning of the storage tank, including the regular inspection and cleaning of gutters and down-pipes. The only maintenance of such a system comprises the removal of dirt, leaves and other accumulated material. A suitable time for cleaning is once a year, before the start of the major rainfall season. If the system includes a filter, inspection should occur regularly, since dirty filters will not be able to pass the water effectively and may become a source of contamination. Occasional washing of the filters will suffice if the filters are not self-cleansing. However, periodical inspection should still take place to ensure they are working correctly.

The cleaning of the storage tanks should be performed only once the sludge level approaches the outlet of the tank or when the water smells, and it must be limited to scooping or washing out any settled matter. The scrubbing of the tank walls and the entering of the tank itself is highly discouraged.

3.3 Rainwater Roof Run-off System

The use of an RHS implies that there is rainwater that can be harvested, which is not always the case as the system is dependent on the amount of rain that transpires in the local area. The potential volume of water likely to be captured by the roof area is computable using the formula by Thomas & Martinson (2007), demonstrated in Equation 7.

$$Q_t = c_r \times R \times A_r$$

Equation 7: Volume of Harvested Rainwater During a Time Interval (Thomas & Martinson, 2007)

Where: Q_t = harvested rainwater during the time interval (m^3),

c_r = roof runoff coefficient,

R = monthly or yearly rainfall (mm), and

A_r = roof area (m^2).

The harvested rainwater can be computed either on a monthly or yearly basis, depending on the available rainfall data used in the equation. The rainfall data plays a large role, not only in the volume of rainwater that is likely to be harvested, but also in the size of the rainwater tank. Since the rainfall varies geographically, a suitable tank size cannot be achieved without further analysis. There are models and desktop methods available in order to determine economically feasible tank sizes according to the location and roof size of the household in question.

A roof run-off coefficient is a variable employed to estimate the rainwater volume that is converted into run-off, which, in turn, enters the tank. It is essential to take cognisance of losses that occur due to the type of roof acting as the collection surface to capture the rainwater. These losses are particularly evident on flat roofs, as pooling takes place enabling the water to evaporate before it can be stored.

Fewkes & Warm (2000) have approximated values for these run-off coefficients, which are listed in Table 3-1. For the purpose of this study, the run-off coefficient for pitched, covered roofs, without a filtration system, circled in green, was used because this is the type of rooftop that was dealt with in the selected case study area.

Table 3-1: Roof Run-off Coefficients for Different Roof Types (Fewkes & Warm, 2000)

Roof run-off coefficients for different roofs (Fewkes & Warm, 2000)	
Roof/system type	Run-off coefficient
Pitched roof covered with tiles or slates (Total flow type)	0.90 - 1.00
Pitched roof covered with tiles or slates (Diverter flow type)	0.75 - 0.95
Flat roof covered with impervious membrane	0.00 - 0.50
Flat green roof	0.00 - 0.50

It is worth mentioning that the roof area applied in the calculation does not reflect the true area, but rather the projected area. The projection indicates the area that would be seen if the roof was viewed from above, not accounting for roof angle in any way as illustrated in Figure 3-1. From the figure, it can be deduced that a larger roof area will produce a bigger run-off volume. This aspect is often a disadvantage when the available roof area is not large enough to capture enough water to satisfy the demands of the consumers in the household, especially in areas with low annual rainfall.

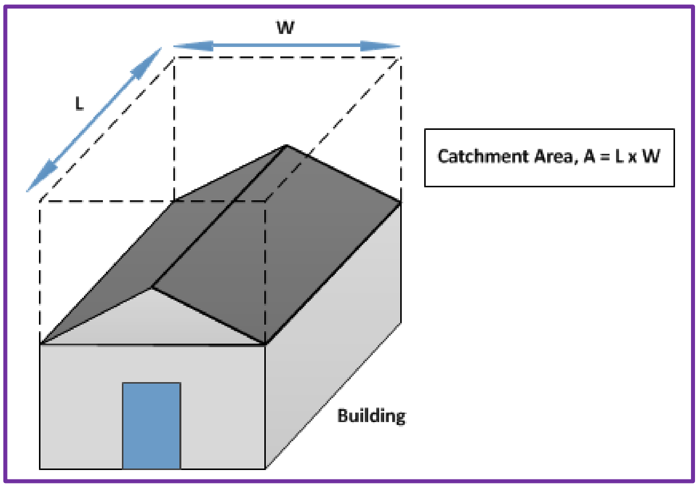


Figure 3-1: The Projected Roof Area Used in RHS Calculations (Roebuck & Ashley, 2006)

In addition, the following design elements can optimise the quantity of harvested water (Houston & Still, 2002):

- A sufficient gutter slope;
- Connecting the gutters securely to the roof;
- Adequate guttering and optimum storage location to enable rainwater to be collected from as much of the catchment area as possible;

- Suitably dimensioning the gutters and down pipes to accommodate the expected rainfall intensity;
- Splash plates to reduce rainfall losses; and
- Large enough storage tanks to retain the rainwater in order to last through long dry periods.

3.4 Reliability of the Supply

As previously discussed, the feasibility of RHSs in a particular area is highly dependent on the amount and intensity of rainfall. Since rainfall is usually irregularly distributed throughout the year, the harvested rainwater can only serve as an additional source of household water. Furthermore, the capability of an RHS is also a function of the volume and quality of water available from other sources, collection area, storage capacity, the household size, the daily system demand (per capita) and the affordability and financial benefit of such a system.

The research by Jacobs *et al.* (2011) stated that the Western Cape has a mean annual rainfall of 348 mm, which varies across the region, ranging from 100 mm in arid interiors and the west coast to almost 3 000 mm in some mountainous areas. The rainfall distribution implies that RHSs in the Western Cape would receive rainwater mostly in winter, with very little rainfall during summer months, which is the high water demand period. In the light of the above mentioned, the water stored in the tanks during the winter months will be consumed rapidly during the early stages of the summer period, resulting in the system being unable to act as an alternative water source throughout the dry summer months. The performance of an RHS is denoted in terms of reliability, which is defined as the total rainwater supply over the tank-water demand. The method used to compute the reliability is indicated in Equation 8.

$$R_v(\%) = \frac{Actual\ Supply}{Demand}$$

Equation 8: Volumetric Reliability of Rainwater in the System

4. *RESEARCH METHOD*

4.1 Introduction

The main concept of this study is the development of the computer based stochastic model, which produces the domestic flow profiles for system and tank-water demand. This reliability model does not assess the tank-water demand by means of a real-time monitoring approach, such as Fewkes (1999), Talebpour *et al.* (2011) and Umapathi *et al.* (2013) used, since there was no manner in which to physically measure the tank-water demand. However, there is a substantial body of literature (Domenech *et al.*, 2011; Furumai, 2008; Villarreal & Dixon, 2005; Beal *et al.*, 2012; Imteaz *et al.*, 2011) successful in their attempt to approximate the amount of potable water savings achieved by the installation of RHSs. This study is similar in its effort to model the effect of RHSs on the system demand without using empirical data.

A schematic of the model structure is presented in Table 4-1. The table displays three methods for assessing rainwater use as part of this research project. The three methods are described in more detail in this chapter - the corresponding sub-sections are listed in column two of the table. A step-by-step procedure was followed for Method 1, by employing a selected software package. The same software was also used for the other two methods, but the procedure was similar in all cases.

Table 4-1: Schematic Representation of the Model Structure

Method	Reference to Section	Demand Profile	Rainwater Source	Tank Size
1	4.4.1	To be determined (Model output)	Unlimited (Infinite rainfall)	Actual size (fixed)
2	4.4.2	To be determined (Model output)	Limited based on actual monthly rainfall	Actual size (fixed)
3	4.4.3	Fixed (Method 1 output: tank water demand)	Limited based on actual monthly rainfall	To be determined (Goal: supply tank water demand when using actual monthly rainfall)

4.2 Software Selection

The reliability software, @RISK was used to estimate the system and tank-water demand pattern of a domestic household. The @RISK software is a Microsoft Excel add-in using Monte Carlo simulation to perform risk analysis with the intention of evaluating models that contain uncertainty.

When creating a deterministic model all the values are fixed, which means that there are no variations in the results. In many research models there are variables that constantly change, specifically, uncertain values, such as the water quantity that people use during the summer and winter seasons, or the household size. The @RISK program enables the simulation of such models with the aim of observing a variety of scenarios that could occur, rather than a single resulting scenario.

The program allows the user to allocate probability distribution functions that directly replace a range of cells containing uncertain values in an excel spreadsheet. These probability functions represent a series of different possible values consistent with different scenarios. The @RISK software simulates the probabilistic model by selecting random variables and recording the resulting product. The end result of a simulation exhibits the range of possible outcomes for the assigned probabilities.

4.3 Model Approach

The design of any water system is dependent on the demand imposed upon it. In South Africa, it is unlikely that an RHS would be able to meet the total domestic system demand due to the country's classification as a semi-arid region, with a mean average precipitation (MAP) below the required average of such a region. However, an effective way of reducing the imposed system demand could be to use only the harvested rainwater for specific end-uses. This section describes the formation of the model in order to accomplish the indicated research objectives, and also outlines its incorporation into the reliability software.

Any @RISK computer model contains particular components that are necessary in order for a simulation to take place and these components contain elements specific to each different type of model. In this section, the elements present in the established stochastic model are discussed and a logic diagram of the general approach to the model is presented in Figure 4-1.

4.3.1 Known Inputs

These are the input values (deterministic components) that remain constant throughout the modelling process:

- The percentage of consumers using the RHS for the defined end-uses is acquired by Mannel (2013). As previously mentioned, an RHS in South Africa is unlikely to supply the total domestic system demand. In addition to this, employing rainwater for more than one end-use maximises drinking water savings and minimises spillage (Domenech *et al.*, 2011). In light of these considerations, only the most common end-uses for which the harvested rainwater is used, was focussed on and included in the model.

- The frequency of use and event volume for each end-use. Using the applicable literature and educated assessments, the frequency of use and event volume for each end-use can be categorized for an explicit domestic area. Additionally, these parameters relate the PPH to the system and tank-water demand inside the model.

- The time range during which the end-uses are most likely to take place. A diurnal pattern is required to find the times that there is likelihood that the rainwater will be used. This temporal pattern can be found from results of previous research or surveys done in the area under consideration.

With these known inputs, there is no need for any probability distributions. In the event that there is much uncertainty about a defined parameter and the only known information is that it lies within a distinct range of values, it is classified as an uncertain input. For this model, there is only one such input.

4.3.2 Uncertain Inputs

These input values involve uncertainty, which, in turn, require probability functions when being implemented into the software program:

A series of household sizes, from a specific study site, defined in the form of a probability distribution.

For any such uncertain input, @RISK compels the selection of a probability distribution that specifies the possible values and their likelihoods. The @RISK software has a list of probability distributions to decide from and it allows the user to fit the set of collected data to any one of its probability distributions that is the most suitable for the data range.

4.3.3 Logic Formulations

There are rational expressions that are required by Microsoft Excel in order to convert and calculate the outputs from the specified inputs. The logic formulations used in the stochastic model are demonstrated by Equation 9 and Equation 10.

$$Volume\ per\ End - Use\ [l/s] = \frac{(Frequency\ of\ Use) \times (Event\ Volume) \times (PPH) \times (Probable\ Peak\ Flow\ Fraction)}{3600 \times 24}$$

Equation 9: Volume of Water per End-use, per Time Interval

$$Total\ Volume\ per\ Time\ Interval\ [l/s] = \sum Volume\ per\ End - Use, At\ Every\ Specified\ Time\ Interval$$

Equation 10: Total Volume of Water, per Time Interval

4.3.4 Outputs

The intended achievable results, which are required for the aim of formulating the stochastic demand profiles for the daily system and tank-water demand patterns, are as follows:

- The total daily system demand per household; and
- The daily tank-water demand per household.

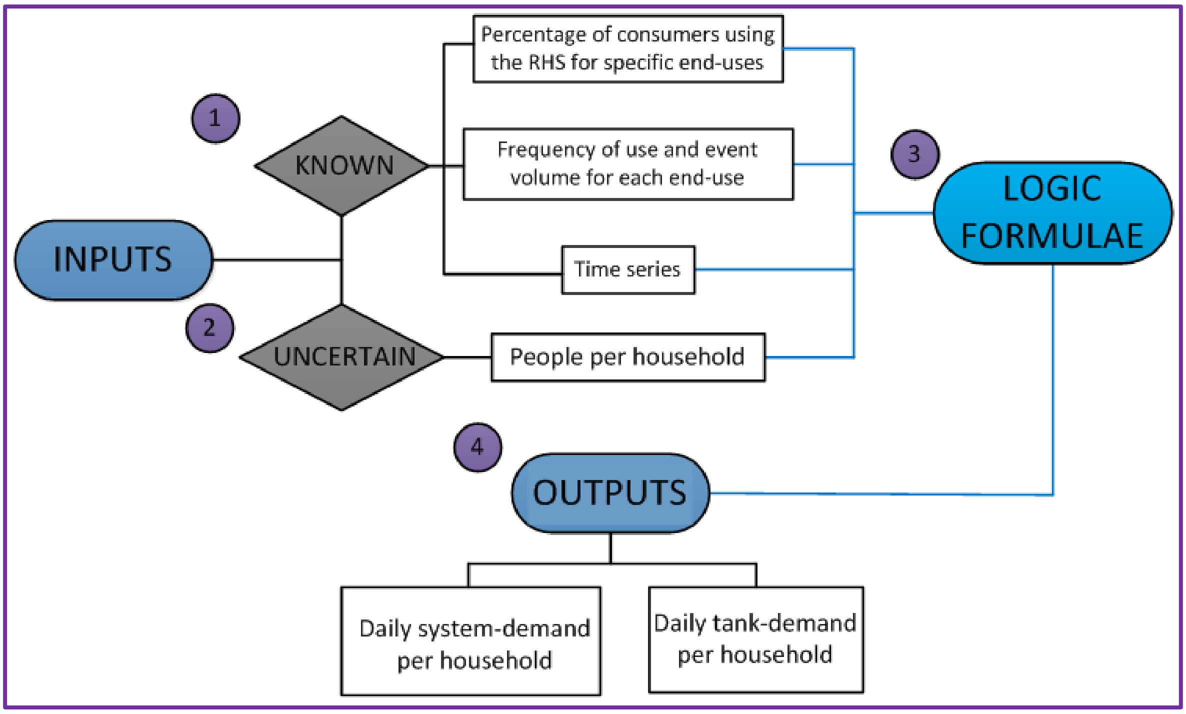


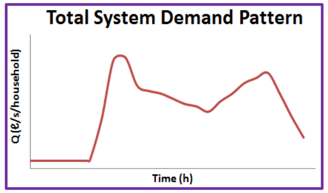
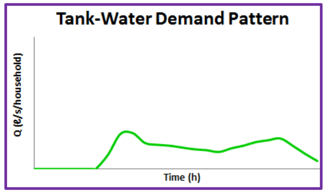
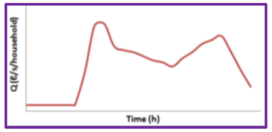
Figure 4-1: Logic Diagram of Research Methodology

The standard number of iterations for one simulation in @RISK is equivalent to 100 by default. However, the larger the number of iterations, the more accurate the results will be. Since the size of the Microsoft Excel workbook was quite large, the computation speed for one simulation of the model was prolonged. For this reason, the iterations were chosen to be 10 000, as this was the highest possible number of executions within reasonable computing time.

4.4 Model Structure

In this study, an analysis method is intended to model both the deterministic and probabilistic components of consumer system and tank-water demand. The step-by-step procedure employed to attain the required objectives is presented in Table 4-2. The procedure is based on the development of the model, for Method 1, in this study. Since all three methods (refer to Table 4-1) are based on the same concept, the same procedure applies in all cases.

Table 4-2: Breakdown of Procedure for Method 1

<table>
<tr><th colspan="6">Method 1: Breakdown of Procedure</th></tr>
<tr><td></td><td>Step 1</td><td>Step 2*</td><td>Step 3</td><td>Sensitivity Analysis</td><td>Comparative Analysis</td></tr>
<tr><td>Description</td><td>Derive water use pattern for all end-uses present in the household</td><td>Derive water use pattern for end-uses using the rainwater source</td><td>Reduced water use pattern by replacing the municipal WDS with a rainwater source</td><td rowspan="3">The input parameters of Step 2 are assigned distribution functions in order to establish how sensitive the tank-water demand model is to these selected parameters.</td><td rowspan="3">The results obtained in Step 1, 2 and 3 are compared to various previous studies, where the tank-water demand, system demand and water savings were developed in households with RHSs.</td></tr>
<tr><td>Water Use Pattern</td><td>
</td><td>
</td><td>
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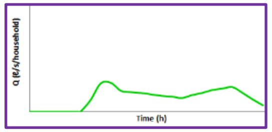
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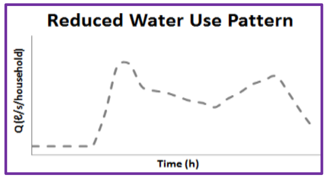
</td></tr>
<tr><td>Inputs</td><td>End-use information from literature</td><td>Literature and site survey questionnaires</td><td>N/A</td></tr>
<tr><td>Notes</td><td colspan="5">*Also refer to a worked example of Step 2 in Appendix A</td></tr>
</table>

4.4.1 Method 1 – Stochastic Demand Profiles

The objective of this method is the development of the stochastic end-use model with the intention of generating the domestic flow profiles for system and tank-water demand. The rainwater tank size is assumed to be unlimited for the purpose of this method in order to create a generic model that can be applied on any formal LCH site without geographic limitations. In other words, the model is independent of the rainfall in the area or the size of the tank.

The concept is implemented into @RISK in exactly the same way as the demonstration in Figure 4-1, in an attempt to achieve the expected output. However, this method is structured in three parts in order for each objective to be realised. The three sections of the stochastic demand model are defined as follows:

- The first endeavour was to create a stochastic end-use model of the total system demand for a specific area. The expected system demand for different areas in the urban sector varies and given that this is a theoretical model, the actual water consumption is unknown. Therefore, a system demand pattern is estimated using literature and data from the specified area. The end-uses are chosen in accordance with their applicability to the households present in the domestic area. For the intention of this study, the presence of swimming pools is ignored, in view of the fact that only formal LCH areas were investigated. This model formulates a diurnal pattern for the total system demand in order to act as a reference against which to compare the tank-water demand of the LCH area.

- The second process considers only the end-uses which consume the harvested rainwater, with the intention of producing a stochastic model of the total tank-water demand for any given area. The end-uses are determined by previous research done on the area of interest, or in the case of this study, consumer surveys are used to justify the chosen end-uses employed for the model. The result of this model is the construction of a diurnal tank-water demand pattern significant to the examined LCH area. From this tank-water demand pattern, the percentage of system demand likely to be met by harvested rainwater can be deduced and compared with previous studies.

- The final section is not the progression of a new model, but rather an adaptation of the previous one. A sensitivity analysis was done on the tank-water demand pattern in an effort to establish the degree to which the assigned inputs affect the output of the model. In the tank-water demand model, only one uncertain input exists and there are several known inputs. The approach to the sensitivity analysis was to allocate probability distributions to the deterministic components, which in turn transform them into uncertain inputs. This analysis was performed to evaluate the influence that the end-use frequencies and event volumes have on the designated output.

4.4.2 Method 2 – Rainwater Availability Analysis

Once Method 1 had been successfully completed, the possible rainwater availability of the tank, given a specific demand and supply, could be included in the model by means of a simple RHS mass balance equation. For the purpose of this method, the minimum data requirements for RHS performance models are necessitated. These prerequisites are listed as the following:

- Roof area and runoff coefficient;
- Average daily system demand;
- A historic rainfall record long enough to act as a reliable guide to future precipitation patterns; and
- Proposed tank size.

The method was formulated in light of the fact that there is an uncertainty as to whether there is water present in the tank at the time of use. A monthly water mass balance was done on an RHS in a particular area with the purpose of evaluating the difference in the tank-water demand, the yield and the water stored in the tank. The water demand information used in this model was obtained from the tank-water demand pattern produced in Method 1. An illustration of the sequence that an RHS undergoes when rainfall occurs is shown in Figure 4-2.

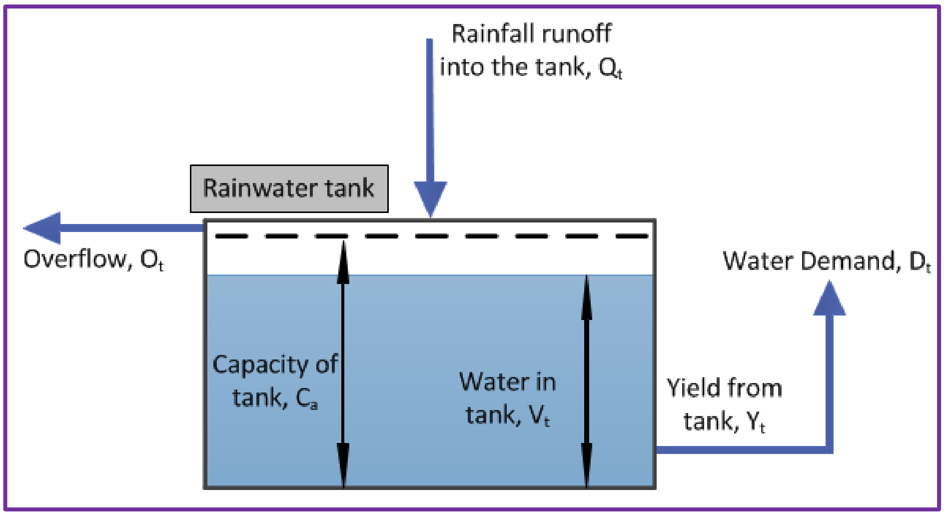

Figure 4-2: Graphical Representation of Rainwater Harvesting System Mass Balance

Together with the data prerequisites for RWH models and Figure 4-2, the mass balance used to compute the cumulative amount of water stored in the tank is presented in Equation 11. The rationale behind the RHS mass balance is based on the concept that the initial volume of the tank at a given time interval should be equivalent to the volume at the end of the previous time interval. That being said, the inflow is considered as a continuous supply with the demand taken from Method 1. When applying Equation 11, the theoretical performance of a specific inflow sequence, given a demand, can be determined. The yield of the system can however be determined based on two approaches developed by Fewkes & Butler (2000).

$$V_t = V_{t-1} + Q_t - D_t$$
$$Q_t = c_r \times R \times A_r$$

Equation 11: Mass Balance for a Rainwater Harvesting System (Allen, 2013; Imteaz *et al.*, 2011)

Where: V_t = cumulative volume of water stored in the tank during the time interval (m^3),

V_{t-1} = volume of water stored in the tank at the end of the previous time interval (m^3),

Q_t = harvested rainwater during time interval (m^3),

D_t = demand during time interval (m^3),

c_r = roof runoff coefficient,

R = rainfall (mm),

A_r = roof area (m^2), and

t = time interval.

- Yield After Spillage (YAS) and Yield Before Spillage (YBS):

The process exercised to calculate the potential yield of an RHS involves a mass balance equation verified by Fewkes & Butler (2000). The study used behavioural models to simulate the performance of RHSs, using two possible algorithms, namely, yield after spillage (YAS) and yield before spillage (YBS).

In the YAS algorithm, the spillage volume is subtracted from the inflow rainwater volume before the yield in the tank is computed, which allows only the volume that is needed (tank-water demand), or the volume that is existent in the tank, to be extracted as yield. Alternatively, in the YBS algorithm, the yield is subtracted after the inflow replenishes the tank and before the water overflows, which means that the tank capacity is overestimated since the method assumes there is enough water existent in the tank to meet the tank-water demand.

The two operating algorithms by Fewkes & Butler (2000) that could be adopted to calculate the yield and storage volume for YAS and YBS are revealed in Equation 12 and Equation 13.

YAS:

$$Y_t = Min(D_t\, ,\ V_{t-1})$$
$$V_t = Min(V_{t-1} + Q_t - Y_t\, , C_A)$$

Equation 12: Yield After Spillage (Fewkes & Butler, 2000)

YBS:

$$Y_t = Min(D_t\, ,\ V_{t-1} + Q_t)$$
$$V_t = Min(C_A\, , V_{t-1} + Q_t - Y_t)$$

Equation 13: Yield Before Spillage (Fewkes & Butler, 2000)

The choice between using the YAS or YBS algorithm is dependent on various factors, including the ratio of supply and demand. However, the findings by Fewkes & Butler (2000) postulate that the YAS algorithm provides a conservative estimate of the overall performance of an RHS, regardless of the allocated time interval.

4.4.3 Method 3 – Effect of Storage Size on the Tank-Water Demand

The approach behind the design of this model was to perform an analysis on the ability of different tank sizes to supply the required tank-water demand. The method studies the theoretical tank size that would inevitably be able to satisfy the expected tank-water demand for an entire year. A hypothetical situation is evaluated by this model in order to explore the effect that a large storage capacity would have on satisfying the system demand of a domestic household.

The standard roof area used in RHS mass balance calculations is the projected roof area as discussed in Chapter 3 of this study. However, LCH units are likely to have the rainwater tank situated adjacent to one side of the house, which results in only half of the projected roof area collecting the harvested rainwater. For that reason, the method was executed for three different variations of roof area namely, 50%, 100% and the area of the entire plot. The three cases predict the hypothetical tank sizes if the area contributing to the harvested rainwater is half of the roof area, the full roof area, and if the entire plot collected rainwater, although this would be impractical given the current technologies.

The generic model created by Allen (2012) investigated the simplification process of sizing a rainwater tank for optimal results. This model attempts to achieve this for a specific area under a required demand for one year. Allen (2012) used daily data from four rainfall stations for over 16 years for specific towns. In contrast, this model simulated the daily tank-water demand for one year in comparison to various tank sizes for one defined area. In addition, this analysis reaches a conclusion as to whether two smaller tanks on each side of the house are better than one tank, with the same total volume, along one side of the house.

4.5 Comparative Analysis

This section relates the established theoretical model to various previous studies that have acquired methods to estimate the tank-water demand pattern and potable water savings in households using RHSs. Before embarking on the evaluation of the tank-water demand profile, it is necessary to note that none of the comparative studies explicitly reflects the tank-water demand of LCH units, but rather general domestic households in the urban sector.

Although this model is not based on metered rainwater consumption, it can be compared to studies that include metered rainwater use, since the case study includes a metered diurnal system-demand pattern as well as informative surveys to accomplish the measurement of tank-demand in the most accurate way. The results of this research were compared to the following previous studies:

- Steyn (2013) – The study by Steyn (2013) was done on the real-time monitoring of water meters fitted with data loggers to quantify the actual system demand of each household. Since the flow rate is measured at the meter, the rainwater was not analysed in the study (Steyn, 2013). The impact of the tank-water demand model on the diurnal system demand pattern can be examined using the data available from this particular study.

- Van der Zaag (2000) – The Roof model is fundamentally a water balance model, which uses daily rainfall data to compute the theoretical percentage of the domestic system demand that could be satisfied by the tank-water demand. Closer analysis showed that this model does not directly incorporate the PPH in its calculation process, and therefore it can be set in contrast to the model used to estimate the tank-water demand at LCH units.

- Umapathi *et al.* (2013) – The focus of this particular study is quantifying the effect of a 5 kℓ IPT on the potable WDS in a household. The results of this study confirmed that more of the household system demand was met by the RHS during the morning, than in the evening. This Australian study can be compared with the domestic flow profiles attained by the stochastic demand model.

- Beal *et al.* (2012) – The study by Beal *et al.* (2012) executed a pairwise statistical analysis which compares households with IPT to those without rainwater tanks, in order to estimate the potable water savings. The limitation of the analysis by Beal *et al.* (2012) can be examined by comparing the results with the potable water savings achieved by the stochastic tank-water demand model. The contrast will explain the influence that household size has on the performance of an RHS.

5. DESCRIPTION OF THE CASE STUDY SITE – KLEINMOND

5.1 Overview

The town of Kleinmond was chosen as the one on which to base a case study, for the purpose of this research, due to its features that are applicable for this study. A section of the town consists of a formal LCH area where each unit uses an on-site RHS. In addition to this, the availability of data on which to perform the method of analysis is suitable and a comparison can be drawn with existing research that estimates the system demand when incorporating RHSs.

The Department of Science and Technology approached the Overstrand Municipality, in collaboration with the Council for Scientific Industrial Research (CSIR) to build formal LCH in an existing settlement area in Kleinmond. The desired outcome of the project by the CSIR was to develop a demonstration house, which is comfortable, durable, faster to build, easily extendable and less reliant on municipal services. CSIR (2010) specified that this project involved the construction of 410 housing units for consumers who had previously lived in informal dwellings.

The additional features include a solar geyser on top of the roof, a photo-voltaic panel above the front door as well as a water tank installed next to the house for harvested rainwater from the roof. The local authorities were responsible for tenure of the newly built houses in accordance with a waiting list, organized alongside the community, as the last set of houses was set for completion in March 2011. The houses were made available to their residents in October 2011 and were designed in order to encourage sustainable human settlements. The LCH units, along with their solar panels and rainwater tanks are represented in Figure 5-1.

Figure 5-1: Visual Observations at Kleinmond LCH Site

5.2 Purpose of the Case Study

The study on this particular site is intended to implement the methodology previously described when performing tank-water demand estimation and analysis. In addition, the study assessed the effect of the application of an RHS on an area in the Western Cape as well as the influence of this implementation on the municipal WDS. The examination of this area is motivated by the fact that it has a reliable WDS in addition to the RHS that was included as a government initiative.

Against this introductory perspective, the specific objectives of the case study are distinguished as follows:

- Identify and substantiate the typical uses of the harvested rainwater, the PPH using the rainwater, the daily time range when the water is most likely to be consumed and the volume of rainwater used for each end-use; and
- Compare the system and tank-water demand patterns of the LCH units in Kleinmond to the average system demand of domestic properties from various published AADD guidelines.

This basis allowed the investigation on the impact of tank-water demand on the system demand in serviced areas of Kleinmond on a limited scale.

5.3 Description of Study Area

The study area is located in the town of Kleinmond, which is situated approximately 120 km east of Cape Town and resides within the Overstrand municipal area, along the south coast of the Western Cape. Since this town is in the Western Cape, it also experiences dry, hot summers with winter rainfall and therefore a higher system demand is experienced in the summer months.

The houses have a roof area 44.5 m^2 in size with a 2 kℓ tank to harvest rainwater. The rainwater tank only collects water that runs off one side of the roof. Additionally, the harvested rainwater does not undergo a purification process and therefore can only be used for non-potable domestic purposes. A parallel study, in the same study area, is under way to develop an on-site microbial treatment system to provide potable water to the consumers (Khan & De Kwaadsteniet, 2014).

The design was optimised with the idea that it could easily be extended into a three bedroom house by the home owner (CSIR, 2010). A typical design of the LCH unit by De Villiers (2011) is demonstrated in Figure 5-2.

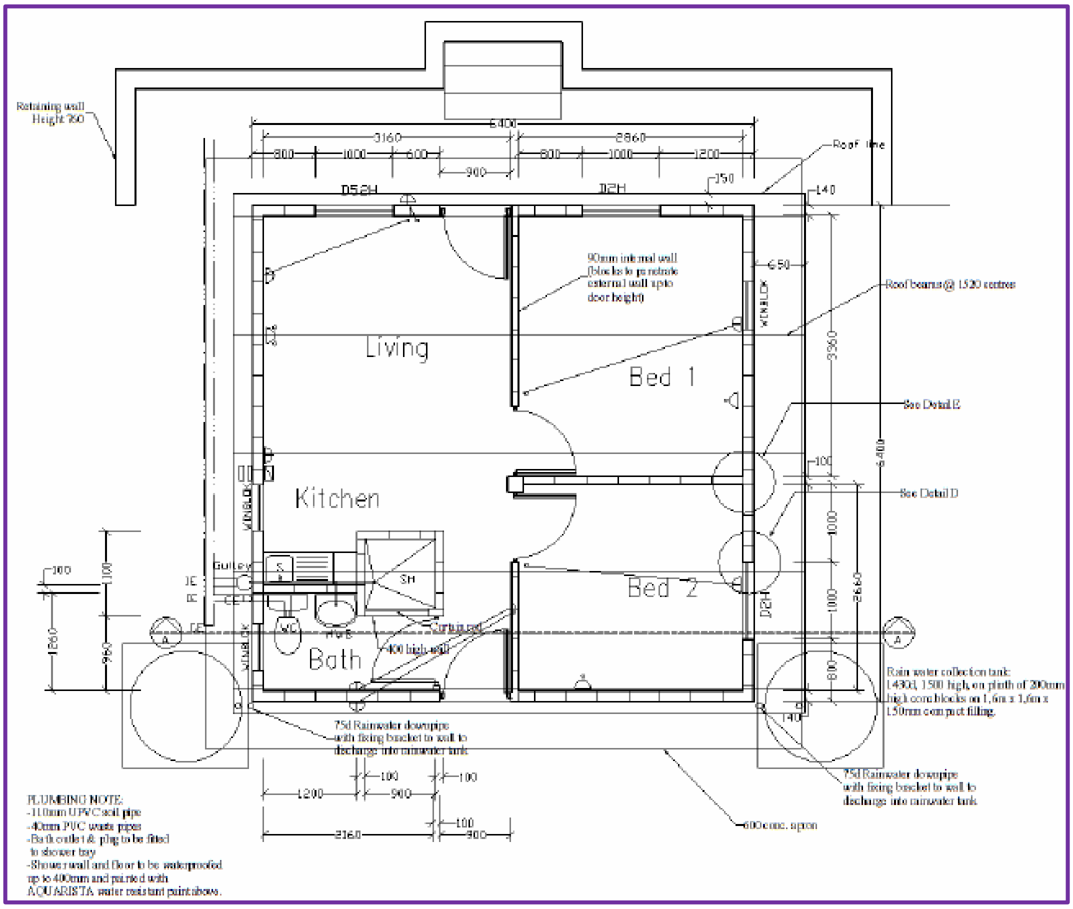

Figure 5-2: Typical design of a LCH Unit (De Villiers, 2011)

The implementation of these RHSs provide the residents with a supplementary water source in order to alleviate the potable WDS, allowing less system demand in addition to financial savings on their monthly water charges.

5.4 Consumer Perception

A key factor in the successful implementation of any water use scheme is the perception of the consumers and their adaptability to the existing or proposed technology. During the planning and designing of RHSs, the vital component is not only the technicality but also the importance of the social and cultural aspects of the water use.

A study by Domenech *et al.* (2011) included a survey of the public perception of the health risk associated with using harvested rainwater. The results obtained from the survey clarifies that the health risks were not a predominant concern to the residents, since the rainwater was used only for irrigation and toilet flushing.

Similarly, the RHSs installed in the case study site have had little public opposition, and substantial support exists for the use thereof for non-potable applications such as toilets, laundry washing and garden irrigation. Generally, the level of acceptability increases with the less personal use of the rainwater. For the purpose of this study, rainwater end-uses reaching close contact with the body will not be investigated, as it is a contentious issue and was not included in the scope of this thesis. The Kleinmond case study site considers the use of RHSs only for non-potable end-uses and for that reason, the operation of these systems do not in any way disadvantage consumers or give rise to any disapproval.

6. DATA ACQUISITION

6.1 Outline

The requirements for each method consist of different components and constraints relevant to the research hypothesis. The elements involving the design of each modelling process, as well as the indicated limitations, are described in this chapter. The main components of the RHS present in the case study site are summarized in Table 6-1.

Table 6-1: Components of the Domestic Rainwater Harvesting System for Kleinmond Case Study

Components of Domestic Rainwater Harvesting System for Kleinmond Case Study		
Component	**Value(s)**	**Comments**
Rainfall	Monthly rainfall data for Hermanus weather station	Hermanus is situated about 30km away from Kleinmond and data from its weather station will be applicable to this case study
Catchment Surface	Roof Area = 44.5m^2 Runoff Coefficient: 0.9	De Villiers (2011) Fewkes & Warm (2000)
First Flush Device	None	The use of first flush devices are limited in South Africa
Storage tank	Volume = 2000 ℓ. Initially assumed to be filled to capacity.	Direct RHS with top-up option using the municipal water distribution system

6.2 Weather Records

The minimum data requirement for any RHS performance model is a reliable historic rainfall record to act as a consistent guide. Despite the fact that the last houses were constructed (or occupied) in March 2011, the rainfall year under investigation was chosen from October 2011, since the occupants only moved into their residences on this date.

The monthly rainfall parameter is a vital input. In semi-arid regions such as the Western Cape, there is significant variation in rainfall depending, on the exact area of investigation. Practical consideration is necessary before selecting the appropriate rainfall station used in the development of the tank-water demand model.

The closest rainfall station to the case study site is the Kogelbaai rainfall station. However, the Kogelbaai station is situated in the mountainous region on the western (windward) side of the Hottentots Holland mountain range. This region will have notably different rainfall to Kleinmond on the eastern (leeward) side as illustrated in Figure 6-1. In the light of these observations, it was decided that the rainfall data provided by the South African National Space Agency (SANSA) for the Hermanus area, which is situated only 30km east of Kleinmond (see Figure 6-1), was employed in the model. The rainfall data used for the applicable model is abridged in Table 6-2.

Figure 6-1: Google Earth Image of Kleinmond and Selected Rainfall Station (Google Earth, 2013)

Table 6-2: Case Study Weather Information (SANSA, 2013)

Hermanus Data			
Latitude		34.4°	
Longitude		19.2°	
Month	**No. of Days per Month**	**No. of Rain Days**	**Average Monthly Rainfall (mm)**
2011			
October	31	4	24.6
November	30	11	31.8
December	31	8	16.0
2012			
January	31	4	11.2
February	29	4	11.4
March	31	5	23.1
April	30	7	58.9
May	31	10	46.7
June	30	10	18.5
July	31	14	80.8
August	31	15	109.5
September	30	13	81.3

6.3 Kleinmond Surveys

6.3.1 Social Survey

A social research study was done by Mannel (2012) on the consumer perceptions of the domestic RHSs at 67 houses in the Kleinmond LCH capacity. The survey comprised information about the different uses of the tank, the condition of the tank, maintenance or lack thereof, the frequency of use, whether the tank is filled with water from the municipal WDS, the PPH as well as various personal perceptions on the usage of the rainwater tanks. Only the material useful to this study was lifted from the data set and explicitly represented. The general condition of the rainwater tanks in the area is characterized in Figure 6-2 along with the common usage frequency of the system shown in Figure 6-3.

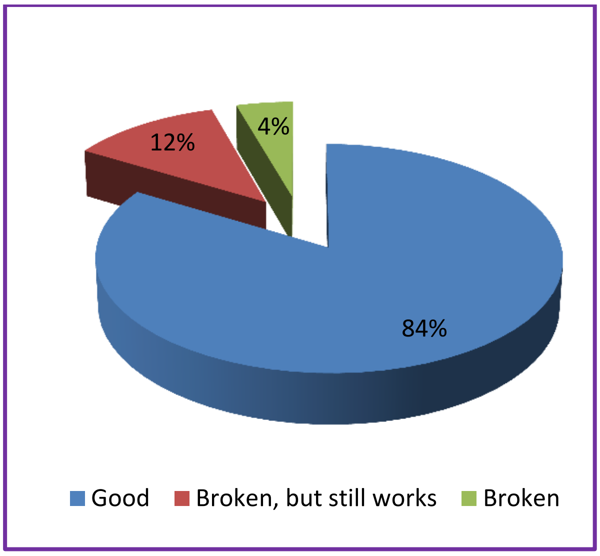

Figure 6-2: Overall Condition of the Rainwater Tanks

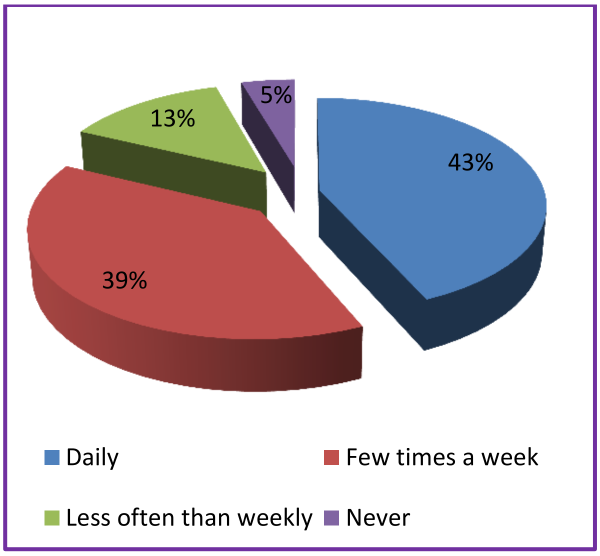

Figure 6-3: Overall Frequency of Use of the Rainwater Tanks

The overall condition of the rainwater tanks confirm that 84% of the RHSs in the study group were in working order. A majority of consumers make use of these systems either on a daily basis or a few times per week, resulting in a reduced usage of the municipal WDS. The percentage of users with broken rainwater tanks corresponds with the consumers who never make use of the harvested rainwater and therefore it can be assumed that all the tanks in working condition are actively being used.

Only the data obtained from households where the rainwater tanks were still in working condition was incorporated in the modelling process. The household size, which is indicated in Table 6-3, is an input value for the stochastic model discussed in a previous section of this thesis. The PPH parameter is defined in the model as the only uncertain variable with an assigned distribution fitting, since the value is not fixed for each household and the water consumption is dependent on household size.

Table 6-3: Household Size of Kleinmond LCH Units

Household Size			
House Reference no.	**Household Size (PPH)**	**House Reference no.**	**Household Size (PPH)**
1	5	35	2
2	3	36	3
3	3	37	4
4	6	38	3
5	3	39	4
6	4	40	4
7	5	41	5
8	5	42	6
9	3	43	6
10	5	44	3
11	2	45	4
12	4	46	3
13	5	47	3
14	4	48	5
15	1	49	4
16	2	50	3
17	3	51	4
18	8	52	2
19	3	53	3
20	3	54	3
21	4	55	5
22	3	56	3
23	6	57	6
24	5	58	4
25	4	60	4
27	4	61	1
28	5	62	2
29	6	63	5
30	4	64	3
31	3	65	9
32	4	66	2
34	3	67	5

The average household size in the Kleinmond LCH area is 3.8 PPH. Careful consideration is necessary in order to define the most suitable distribution function for this parameter, since the outcome of the model is largely dependent on this probabilistic component. Jacobs & Haarhoff (2004b) evaluated the practical application of a domestic end-use model and showed that the most influential parameter, when determining system demand, is the household size.

During the filtering of the data acquired from the survey, the percentage of consumers using the RHS for specific uses was recognized. The rainwater uses and consumer magnitudes are demonstrated in Figure 6-4. Alternatively, Figure 6-5 illustrates the proportion of households, using the RHS for each end-use, as a fraction of all the households included in the social study.

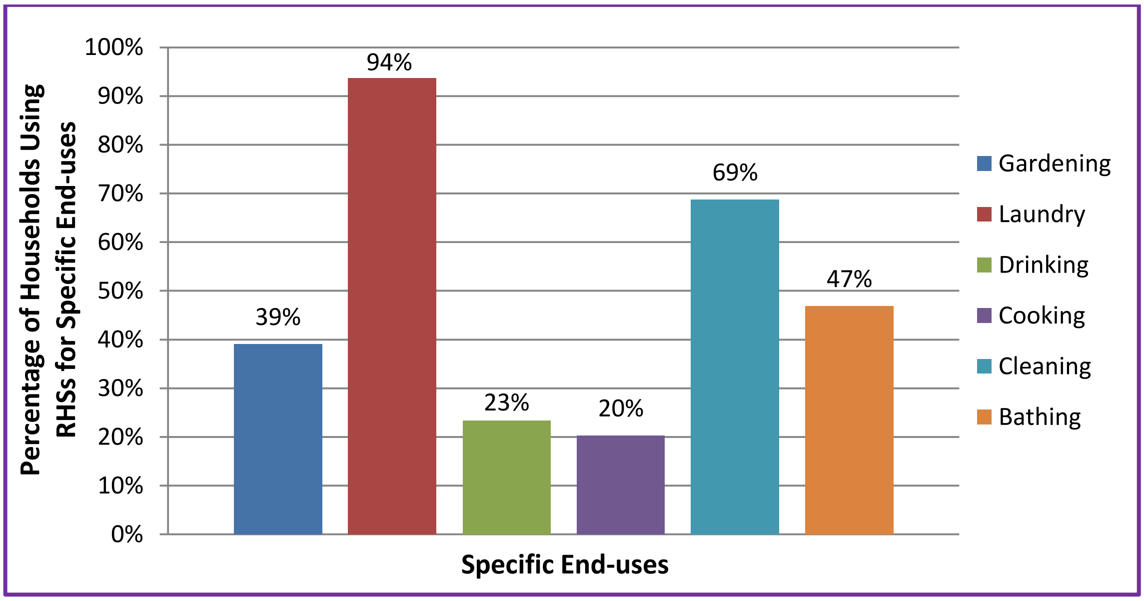

Figure 6-4: Households Using the Rainwater Harvesting System for Each Specific End-Use

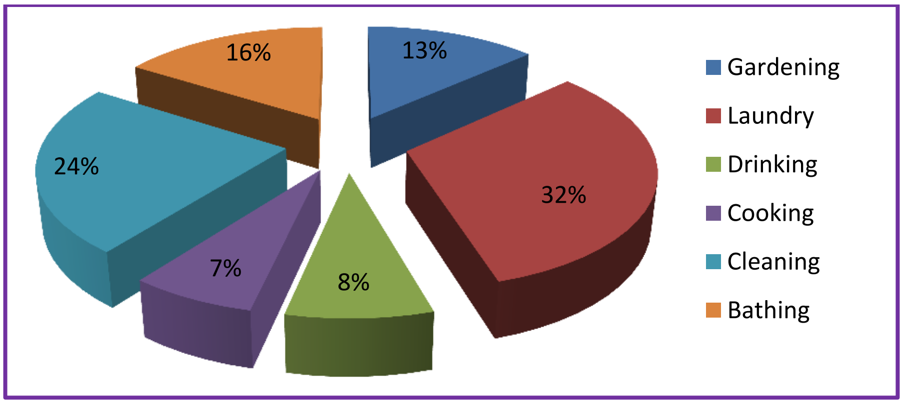

Figure 6-5: Overall Fraction of Households in Kleinmond Using Rainwater for Each End-Use

The Figure 6-4 illustrates that almost a quarter of the consumers use the rainwater as a drinking water source, which is undesirable since the water is not potable water quality. The results presented in Figure 6-5 will be used as a basis when the end-uses for the tank-water demand model are explained. The majority of the households included in the social study use the RHS for laundry and cleaning.

6.3.2 Technical Survey

The study, on the Kleinmond LCH units, was repeated for 20 houses where the system demand was logged using smart meters. This research was part of a parallel study on residential system demand performed by Jacobs *et al.* (2013). The water use information obtained from the consumer surveys is presented in Table 6-4, while the rainwater use frequencies and volumes are summarized in Table 6-5. Both tables provide insight into the water use habits of consumers living in the LCH units. For that reason, the rainwater end-uses that were exclusively addressed in the tank-water demand model were selected using the information provided by the surveys.

Figure 6-6 illustrates the percentage of households using rainwater for specific end-uses in the winter and summer months. During the winter months, the laundry and cleaning end-uses consume the most tank-water demand. However, throughout the summer months the laundry and gardening end-uses consume majority of the tank-water demand. As a result, the model used to conceptualise the tank-water demand profile for LCH units, integrates only three end-uses: laundry, cleaning and gardening. The social survey also illustrated the majority of the consumers in the study area use the rainwater for laundry and cleaning their households (see Figure 6-5). These two end-uses have been proved, by both surveys, to be responsible for consuming the most harvested rainwater.

The estimation of outdoor water demand is difficult to achieve, due to the large number of factors such as climate, garden size, soil type and water restrictions that influence its use. Alternatively, indoor water consumption is deemed easier to predict, as it comprises a more homogenous dataset with less variability of the parameters. For that reason, outdoor demand was not investigated in this thesis, except for the use of rainwater for gardening purposes.

Table 6-4: Consumer Survey Results of the System Demand Study

Household Size (PPH)	Rainwater Uses (when available)	Owner Modified House	Leaks and Maintenance	Clothes Washing	Bath/Shower Habits
5	Clothes washing, cleaning floors	Not home at time of visit			
3	Car washing, clothes washing	Home locked up at time of visit			
3	Washing hands, gardening	Removed bath	N/A	Washing machine	Cold shower not used; removed bath
4	Clothes washing, washing dishes, cooking, general cleaning	Removed bath	N/A	Washing machine	Cold shower used when ambient hot
2	Clothes washing	Not home at time of visit			
4	Clothes washing	Replaced bath with smaller bath	Owner fixed leaks	By hand with RW	Mostly used bath
1	Clothes washing, gardening	No	N/A	Washing machine	Cold shower used; bath for children
4	Clothes washing, cleaning floors	No	Owner fixed leaks	Washing machine	Cold shower used
6	Clothes washing, cleaning floors	No	Water meter leaking	Washing machine	Adults shower; children bath
5	Clothes washing, gardening	No	Water meter leaking; Municipality to replace meter	Washing machine	Cold shower used
3	Clothes washing, gardening, cleaning floors	Yes - very neat house	Owner fixed leaks	Washing machine	bath/shower at parents' home
3	Clothes washing, gardening	No	Owner suspects leak	By hand with RW	Cold shower used only when ambient hot
4	Clothes washing, gardening	No	N/A	By hand with RW	Only use shower for cleaning house
7	Clothes washing	Well-organised and secretive; could not confirm modification	Owner fixed leaks	Uncertain	Used shower and bath
2	Clothes washing, cleaning floors	No	N/A	By hand	Used plastic basin in bath
4	Clothes washing	Mentioned that there was something wrong with the water from the municipal supply - they prefered not to			Used bath; not shower
5	Clothes washing, gardening, cleaning floors, cleaning windows	No	Owner fixed leaks	By hand with RW	Used shower and bath
4	Clothes washing, gardening, cleaning floors, cleaning windows	No	Owner fixed leaks	By hand with RW	Used shower and bath
3	Clothes washing, cleaning floors, cleaning windows	No	N/A	Washing machine	Bath; only used shower for cleaning and washing machine
5	Clothes washing, gardening	Well-organised; removed bath (to make space for washing machine)	N/A	Washing machine	Shower used, but not often (washing machine is located under shower)

Table 6-5: Water Use Data of the System Demand Study

Water Use Data						
End-Use	**Frequency of Use (events/day)**		**Event Volume (ℓ)**	**Total Volume of Rainwater Used (ℓ/day/household)**		**General Comments**
	Winter	Summer		Winter	Summer	
Gardening	0.09	0.77	53.00	4.54	40.89	The recorded volume of water used in the tank-demand model for one laundry hand-washing event is 62 ℓ. Similarly, the volume of water used for per wash-cycle in a twin tub washing machine varies between 40 to 60 ℓ. For that reason, the difference between hand wash and washing machine event volumes do not vary significantly.
Laundry	0.27	0.26	112.11	30.49	29.60	
Dishes	0.01	0.01	0.25	0.00	0.00	
Cleaning	0.71	0.66	9.00	6.37	5.91	
Bathing	0.06	0.06	8.00	0.44	0.44	

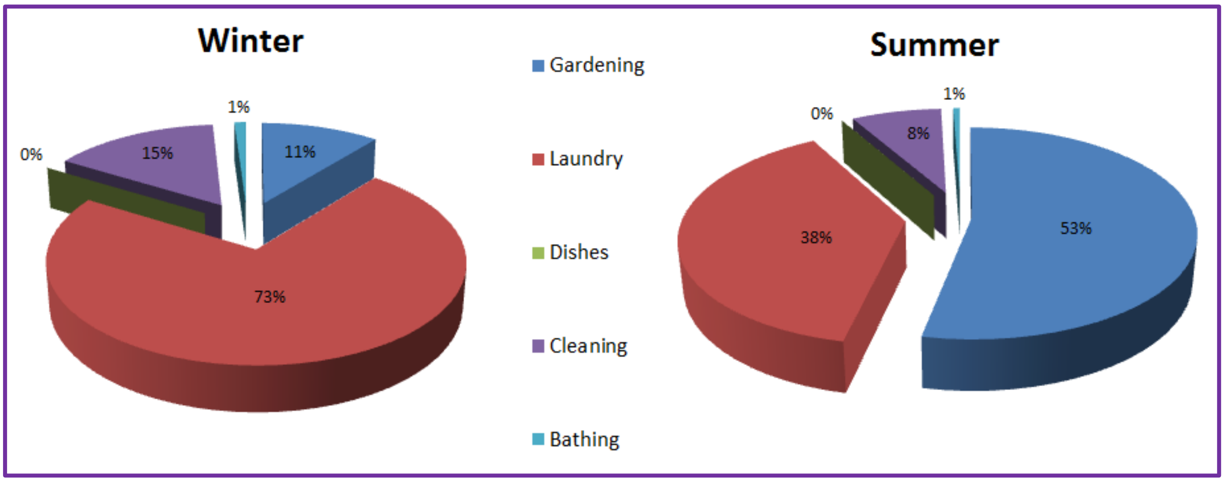

Figure 6-6: Summary of the Tank-Water Demand during the Winter and Summer Months

6.4 Water Demand Data

6.4.1 Times Series

A realistic indication of when, and if, water is being used within a household is required as an input parameter for the stochastic demand model. The information regarding the times at which rainwater is being used was unknown for the case study site. Since there is no way to accurately determine when water is most likely to be used during the course of the day, the diurnal pattern of system demand for the same study area (Steyn, 2013) was accepted as a basis for derivation.

The pattern by Steyn (2013) recorded water use between 00h00 and 04h00. During that time, there are end-uses being utilized inside the household, such as toilets and taps. It was considered highly unlikely that consumers would use rainwater from the tank, situated outside the house, during these hours. For that reason, the tank-water demand between 00h00 and 04h00 is assumed to be zero.

The diurnal pattern is used as a reference on which to base the probability that consumers will use water at specific time periods during the day. The pattern shows that the maximum flow during the day occurs in the morning, at 08h00. For the intention of creating the daily time series, probabilities in the form of percentages were linked to the values presented in the AADD graph. This time series is accomplished by eliminating the base flow; in other words, the leaks were excluded. Within households, it is estimated that water wastage due to leaks within the household can be as high as 20% of household consumption (Still *et al.*, 2007). The time series should depict only the water consumption and not the leakages that uninterruptedly occur during the course of each day.

It was necessary to establish the percentage of households using water during each time interval. In order to estimate this percentage, it was assumed that 100% of all households would use water during the peak time step (07h30-08h30). The actual flow rate per household during the peak time step, as recorded in this area by Steyn (2013), was 0.004 ℓ/s. The value is lower than the peak flow of 0.0046 ℓ/s, presented in Figure 2.6, because it excludes the base flow, as discussed above. As per Equation 14, the flow rate in the peak time step was divided by 1.0 to create a probable flow rate for the peak time step; this flow rate was 0.004 ℓ/s. This probable peak flow acts as a factor used to transform the flow rate at each time step to a corresponding percentage, which is proportional to the peak water use percentage assumed as 100%.

$$Probable\ Peak\ Flow\ (\ell/s)\ = \frac{Maximum\ Flow\ [07h30 - 08h30]}{1.0}$$

In other words,

$$\frac{0.004\ (\ell/s)}{1.0} = 0.004\ (\ell/s)$$

Equation 14: Probable Peak Flow Factor

The flow rate in each time step was subsequently divided by the probable peak flow, such as Equation 15, and multiplied by 100 in order to obtain the desired diurnal water use pattern (in terms of percentage).

The calculated values at each time step appear in Table 6-6 with the corresponding graph expressed in Figure 6-7.

As a result, at the peak time step (07h30-08h30):

$$\frac{0.004\ (\ell/\mathrm{s})}{0.004\ (\ell/\mathrm{s})} = 1.0$$

At each time step, for example,

$$06h00: \qquad \frac{0.0016\ (\ell/\mathrm{s})}{0.004\ (\ell/\mathrm{s})} = 0.40$$

Equation 15: Percentage Conversion for the Stochastic Model Time Series

Table 6-6: Probability of Daily Water Use

Likelihood of Rainwater Use				
Time (h)	**Time (days)**	**AADD by Steyn (2013) (ℓ/s)**	**AADD (ℓ/s) [Without Base Flow]**	**Percentage of Households Using Water During Each Time Interval**
0	0.000	0.0009	0.0000	0%
1	0.042	0.0008	0.0000	0%
2	0.083	0.0008	0.0000	0%
3	0.125	0.0007	0.0000	0%
4	0.167	0.0006	0.0000	0%
5	0.208	0.0006	0.0000	0%
6	0.250	0.0022	0.0016	40%
7	0.292	0.0045	0.0039	98%
8	0.333	0.0046	0.0040	100%
9	0.375	0.0035	0.0029	73%
10	0.417	0.0033	0.0027	68%
11	0.458	0.0032	0.0026	65%
12	0.500	0.0030	0.0024	60%
13	0.542	0.0028	0.0022	55%
14	0.583	0.0027	0.0021	53%
15	0.625	0.0025	0.0019	48%
16	0.667	0.0029	0.0023	58%
17	0.708	0.0032	0.0026	65%
18	0.750	0.0036	0.0030	75%
19	0.792	0.0038	0.0032	80%
20	0.833	0.0040	0.0034	85%
21	0.875	0.0032	0.0026	65%
22	0.917	0.0023	0.0017	43%
23	0.958	0.0015	0.0009	23%

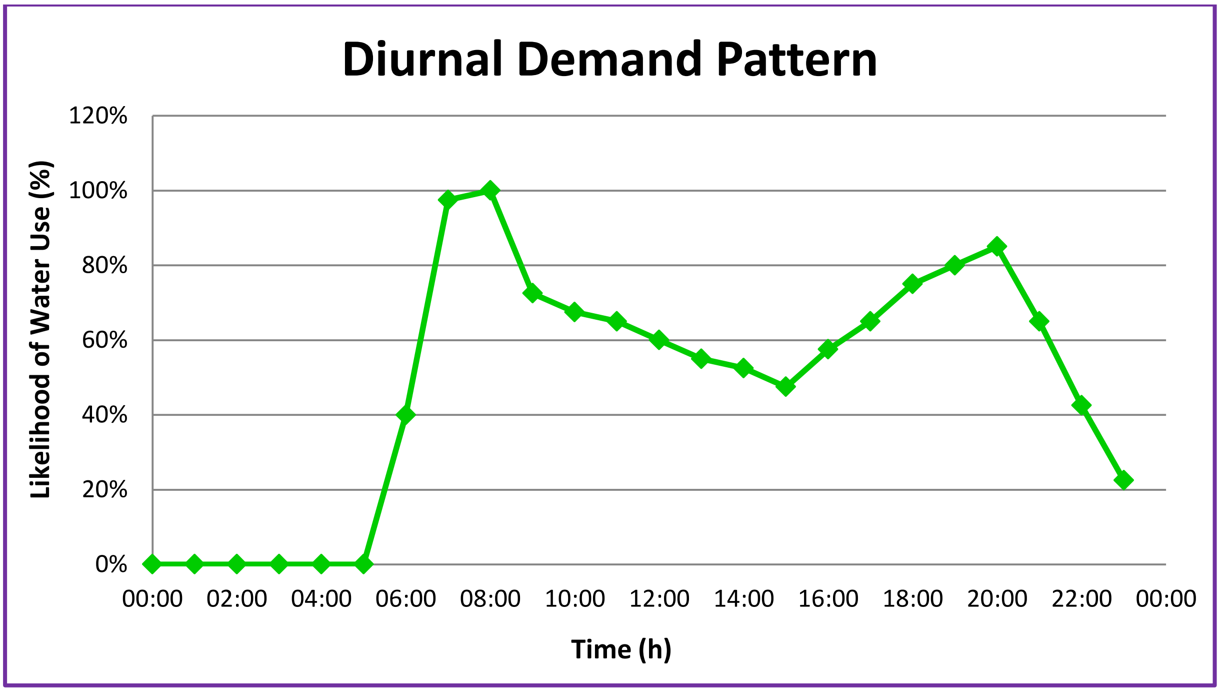

Figure 6-7: Time Series for the Likelihood of Water Use (Adapted from Steyn, 2013)

6.4.2 Frequency and Event Volume for Each End-Use

With the intention of gaining the objectives for the model developed in this study, accurately measured parameter values for the frequency and event volume of each individual end-use is essential. The frequencies of use and event volume parameters relate the PPH to the system and tank-water demand.

International research studies exist where the plumbing at each end-use in a household was monitored and measured by means of data loggers. In Table 6-7, four of these studies are exhibited and set in parallel to one another. These studies illustrate that a relatively wide range of input parameter values are necessary to describe domestic water consumption.

Table 6-7: Results from Previous Domestic End-Use Studies

	Results from Previous Domestic End-Use Studies (ℓ/c/day)			
End-use Category	Mayer & DeOreo (1999)	Loh & Coghlan (2003)	Roberts (2005)	Heinrich (2007)
Bath	4.4	-	3.2	5.5
Shower	43.9	51.0	49.1	44.9
Tap	41.3	24.0	27.0	22.7
Toilet (std)	70.0	33.0	30.4	31.3
Washing	56.8	42.0	40.4	39.9
Irrigation	381.6	180.0	57.4	13.9
Leaks	36.0	5.0	15.9	7.0

The application of end-use modelling has previously been investigated in South Africa by Jacobs & Haarhoff (2004a). The study achieved the distinctive water requirements and the frequency of use values for different end-uses by means of a desktop approach. The rounded off values of the study by Jacobs & Haarhoff (2004a), in addition to a similar method employed in the United Kingdom by Fidar, Memon & Butler (2010), are presented in Table 6-8.

Table 6-8: Frequency and Water Use Data Applicable to Case Study Site

	Frequency of Use (events/c/day)		Water Usage (ℓ/event)			
	Jacobs & Haarhoff (2004a)	Fidar, Memon & Butler (2010)	Jacobs & Haarhoff (2004a)			Fidar, Memon & Butler (2010)
End-use Category			low	Typical	High	
Kitchen sink	1.00	7.20	1	7	73	5
Bath	0.24	0.40	39	80	189	150
Shower	0.31	0.60	8	59	303	3
Bathroom sink	3.60	7.20	0	4	60	3
Toilet (std)	3.70	4.80	8	14	27	10
Washing Machine	0.30	0.31	60	114	200	92
Outside Tap	1.00	-	4	5	19	-

Using the data from Table 6-8 and educated estimates, the quantities for the stochastic system and tank-water demand model were assigned where each end-use value was justified according to its applicability to the case study site. These descriptions and associated parameters are confirmed in Table 6-9 and Table 6-10.

Table 6-9: System Demand End-Use Data Used in the Stochastic Model

Frequency and Water End-Use Data for Kleinmond Case Study		
Component	**Value(s)**	**Comments**
System Demand	Kitchen sink = 1.00 events/c/day Volume per event: 6.7 ℓ	The values for a typical kitchen sink event are used from Jacobs & Haarhoff (2004a).
	Shower = 0.31 events/c/day Volume per event: 59.1 ℓ	The shower and bath are combined in all the housing units where the bath is square shaped and approximately 1.0 x 1.0 x 0.8m^3 in size. Technically, there is either a bath or a shower and since the shower is the point at which the water supply exists, the bath end-use is discarded. A typical volume from Jacobs & Haarhoff (2004a) was chosen.
	Bathroom Basin = 3.60 events/c/day Volume per event: 3.8 ℓ	The values for a typical bathroom sink event are used from Jacobs & Haarhoff (2004a).
	Toilet = 3.70 events/c/day Volume per event: 9.0 ℓ	There is only one standard toilet present in all the households with one flush event being equivalent to 9 ℓ.
	Laundry - Hand wash = 0.143 events/c/day Volume per event: 62.0 ℓ	The paper by Rudin (2008) identifies the water requirement set by the City of Cape Town when doing laundry without a washing machine, which is limited to 4 times per week, for 4 people at 62 ℓ per wash.
	Outside Tap = 1.00 events/c/day Volume per event: 5.0 ℓ	The outside tap referred to in Jacobs & Haarhoff (2004a) is used since the garden is relatively small and does not require a large amount of irrigation.
	Leaks: 52.0 ℓ/d 0.0006 x 3600s x 24h	The minimum nightly flow is 0.0006 ℓ/s as computed by BP Steyn. This amount of water is the base flow that is always present in the municipal supply system as a result of leaks. Therefore, the use of rainwater has no effect on this value but since it is always present, it needs to be accounted for within the model.

Table 6-10: Tank-Water Demand End-Use Data Used in the Stochastic Model

Frequency and Water End-Use Data for Kleinmond Case Study		
Component	**Value(s)**	**Comments**
Tank-Water Demand	Laundry Usage: 0.143 events/c/day Volume per event: 62.0 ℓ	The paper by Rudin (2008) identifies the water requirement set by the City of Cape Town when doing laundry without a washing machine, which is limited to 4 times per week, for 4 people at 62 ℓ per wash.
	Cleaning Usage: 1.00 events/c/day Volume per event: 6.7 ℓ	The paper by Rudin (2008) states that general household cleaning should amount to at least 3 ℓ per event. In view of this, a typical volume for a kitchen sink event is used from Jacobs & Haarhoff (2004a) for the purpose of this model, as it is closest to the indicative value.
	Garden Irrigation: 1.00 events/c/day Volume per event: 5.0 ℓ	The outside tap referred to in Jacobs & Haarhoff (2004a) does not include gardening, but since the gardens are only approximately 7.5m^2, this event's values are used. (See Figure 5-1)

Most of the parameter values were acquired from Jacobs & Haarhoff (2004a) due to the fact that it is a South African end-use study. It is evident from the results reflected in Table 6-9 and Table 6-10 that the end-use data requires comprehensive examination relevant to the study site. For the Kleinmond LCH area, all the households have combined baths and showers and for that reason, it is not required to examine both end-uses. The people in the LCH units do not use washing machines, but rather hand wash their laundry and therefore the typical end-use information from an additional source was applied. In addition, the parameter values for the cleaning end-use is unconventional and rarely found in publications, therefore improvisation was required. Furthermore, the household gardens at the LCH units are fairly small and do not necessitate any considerable amount of water to survive (see Figure 5-1).

7. RAINWATER DEMAND MODEL

7.1 Introduction

A variety of components that comprise a modern day RHS improve its functionality and contribute to its low maintenance proficiencies, as discussed in Chapter 3. When predicting the performance of an RHS, it is essential to analyse some of these components and establish a method by which their behaviour can be simulated. The implementation of the research method is discussed in this section, with specific attention to the stochastic models.

The records received from the Kleinmond surveys led to the assumption that only the data from surveys with operational rainwater tanks will be examined. The reliability analysis can only be done if the tanks are assumed to be in a working condition, or else the rainwater cannot be used.

7.1.1 End-uses

The tank-water demand and the economic feasibility are determined by the end-uses given to rainwater, which are frequently limited to few purposes (Domenech *et al.* 2011). The Kleinmond LCH units do not use water from the municipal WDS for outdoor purposes because of the existing rainwater tank. As for the other two selected end-uses, it was considered fitting to assess the two most used indoor water demands as priority. Harvested rainwater is also very suitable for laundry, due to its low mineral content.

7.1.2 Initial Tank Condition

Previous studies assumed an empty tank as an initial condition when doing simulations, as it is considered the most likely scenario, since the tank would be unfilled after installation. However, these housing units remained empty after the completion of the project until the residents started occupying their households. That being said, the water in the tank accumulated over the months that the houses remained vacant and for that reason, the initial condition of the tank was assumed to be filled.

7.2 Reliability Analysis

7.2.1 Method 1 – Stochastic Demand Profiles

The input values for this model were described in Chapter 6, where the total system demand model included all the end-uses in the household and the tank-water demand model incorporated only laundry, cleaning and gardening end-uses. Only one component was modelled as an uncertain parameter, which is the household size. The PPH for the Kleinmond area covered a range of values acquired from the Mannel (2012) surveys, with a fixed minimum and maximum household size. The available information was processed by the software program and appropriate distributions were selected. Given the known data parameters, the triangle distribution was the best suited probability distribution for the PPH parameter.

To accomplish the system and tank-water demand profiles, the maximum flow rate at each time step was evaluated from the graphs generated by the stochastic model. The maximum water consumption would be the worst case scenario if all the consumers in the data range used water at any specific time. The simulation process used to gain the system demand profile follows a meticulous sequence which is graphically displayed in Figure 7-1. The same procedure is applied for the tank-water demand profile; however the input end-use data differs, as indicated in Table 7-1.

Table 7-1: Input End-Use Data for the Tank-Water Demand Model

Known Inputs			
	Laundry	Cleaning	Gardening
Frequency of Use (events/c/day)	0.143	1.0	1.0
Volume (ℓ/event)	62.0	6.7	5.0

The percentage of system demand likely to be met by harvested rainwater is computed using the successive data from the tank-water demand model. The potable water savings achieved by each end-use using harvested rainwater is quantifiable by means of Equation 16.

$$Water\ Savings\ (\%) = \frac{\sum Daily\ Rainwater\ Volume\ per\ End-Use}{\sum Total\ Daily\ Water\ Demand\ Volume}$$

Equation 16: Amount of Water Savings when Tank-Water Demand Substitutes the System Demand

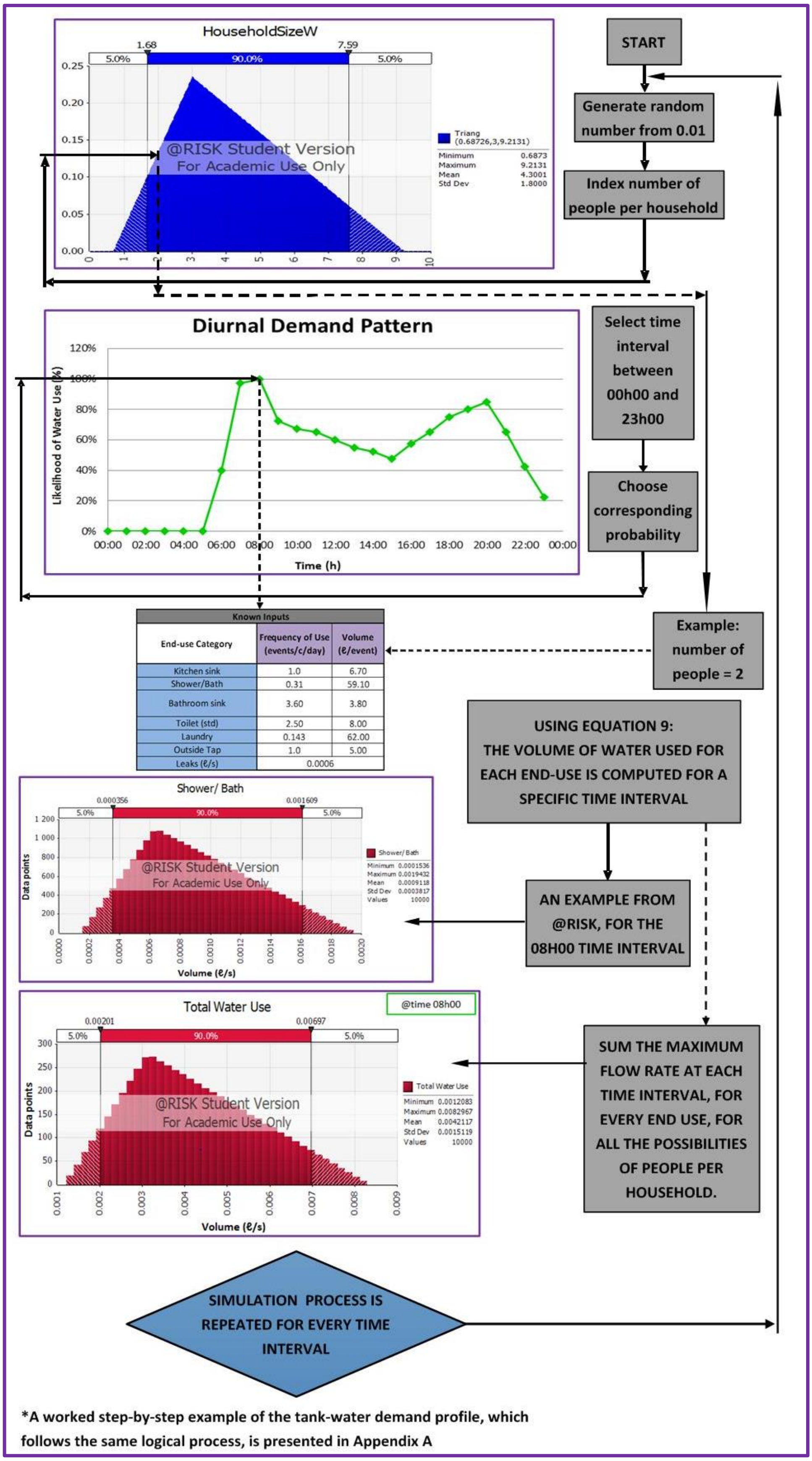

Figure 7-1: Simulation Process for the Stochastic Model

The last component of the stochastic model is the sensitivity analysis, where deterministic parameters are converted to probabilistic values by means of distribution functions. The chosen probability distributions, assigned to the frequency of use and event volume parameters, were implemented in order to evaluate the degree of significance with regard to the required output. The aim was to achieve a variation in end-use frequency and event volume with the intention of determining the effect that these parameters have on the tank-water demand model. These distinct distributions are shown in Figure 7-2 and Figure 7-3, respectively.

Since each end-use consists of only one data parameter, there are merely a certain number of distributions that fit the particular criterion. Also, log-normal distributions are generally used for water demand models, which result in a conventional graph skewed to the left, as the range of values are more congested before the peak due to the fact that the water volumes cannot be below zero. Conversely, the parameter under investigation is one data value and not a range of values. The aim of this technique is to obtain an evenly dispersed distribution of values.

The frequency of use parameter was fitted to a normal distribution. The rationale behind this was the attempt to achieve more variation in these variables. LCH units differ from conventional domestic households in the sense that unemployment is more likely, the habits of the consumers are unpredictable, and informal housing could be in existence on the premises. These socio-economic factors play a large role in everyday water use. For that reason, a wider variation in the frequency of use parameter is required in order to depict the effect that these factors have on the tank-water demand.

The event volume parameter was fitted to a triangle distribution given that less variation in these values is compelled. The selected distribution for the event volume parameter is motivated by the fact that measured research was performed to derive these values and, as a result, hardly any fluctuation is necessary.

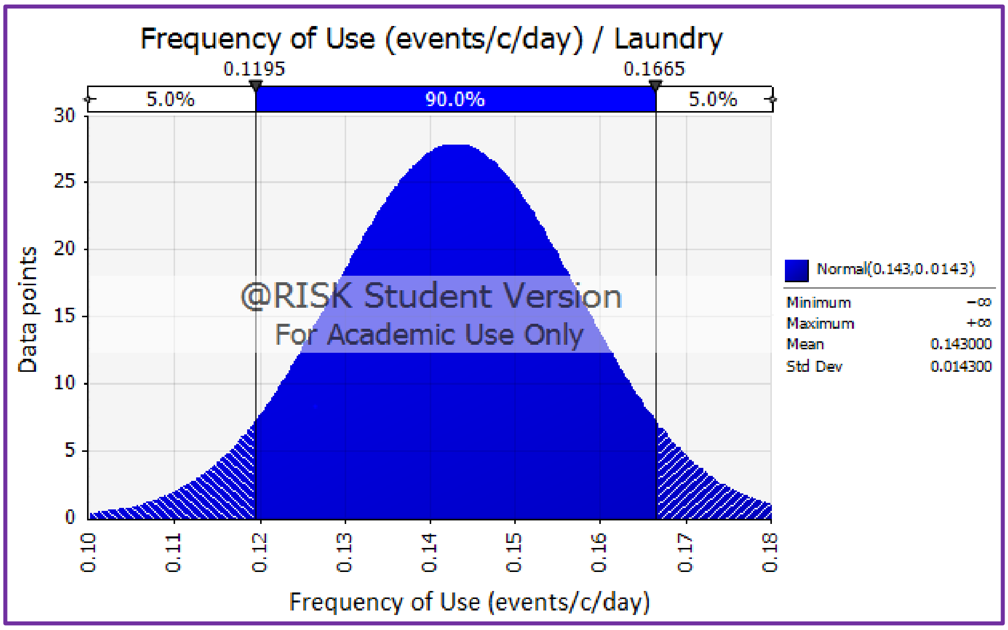

Figure 7-2: Example of Probability Distribution for Frequency of Use Parameter

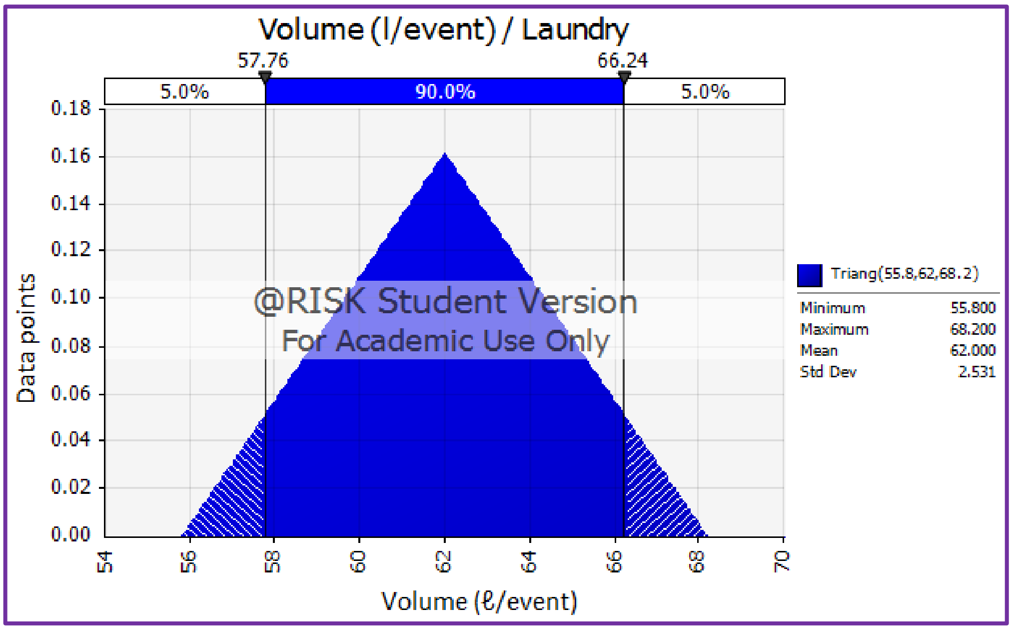

Figure 7-3: Example of Probability Distribution for Event Volume Parameter

7.2.2 Method 2 – Rainwater Availability Analysis

A monthly water mass balance was done on the RHSs in the Kleinmond area in Microsoft Excel, since the daily system and tank-water demand profiles had successfully been achieved.

It is imperative to note that the households in the Kleinmond LCH area are composed of two housing units built directly against one another. The attached housing units share a roof, and there is a 2 kℓ rainwater tank located in the front and at the back of each adjoined set of houses, as demonstrated in Figure 7-4 and Figure 7-5. As a result, the connected catchment area of each rainwater tank is equivalent to half of the entire roof covering both houses. Each household was assigned either the front or the back rainwater tank, as designated and agreed upon by both homeowners. The distribution of the catchment area is clarified in the top view illustration of the adjoined housing units displayed in Figure 7-6. Furthermore, the rooftops of the houses are pitched and covered with tiles producing a run-off coefficient of 0.9, selected from Table 3-1, where the most conservative value was chosen.

Figure 7-4: Front View of the Adjoined Kleinmond LCH Units

Figure 7-5: Back View of the Adjoined Kleinmond LCH Units

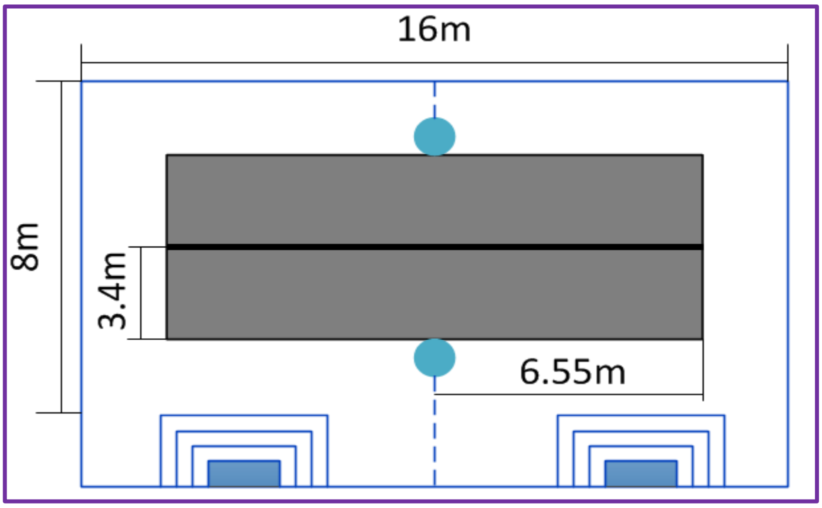

Figure 7-6: Top View Illustration of the Adjoined Kleinmond LCH Units

The monthly rainfall and number of rain days was collected from a rainfall station in Hermanus, as described in the previous chapter and displayed in Figure 7-7. There is no significant increase in the rain days during the winter months, which postulates that the rain transpired rapidly over a short period, leaving the rainwater tanks filled with sufficient water at the end of winter.

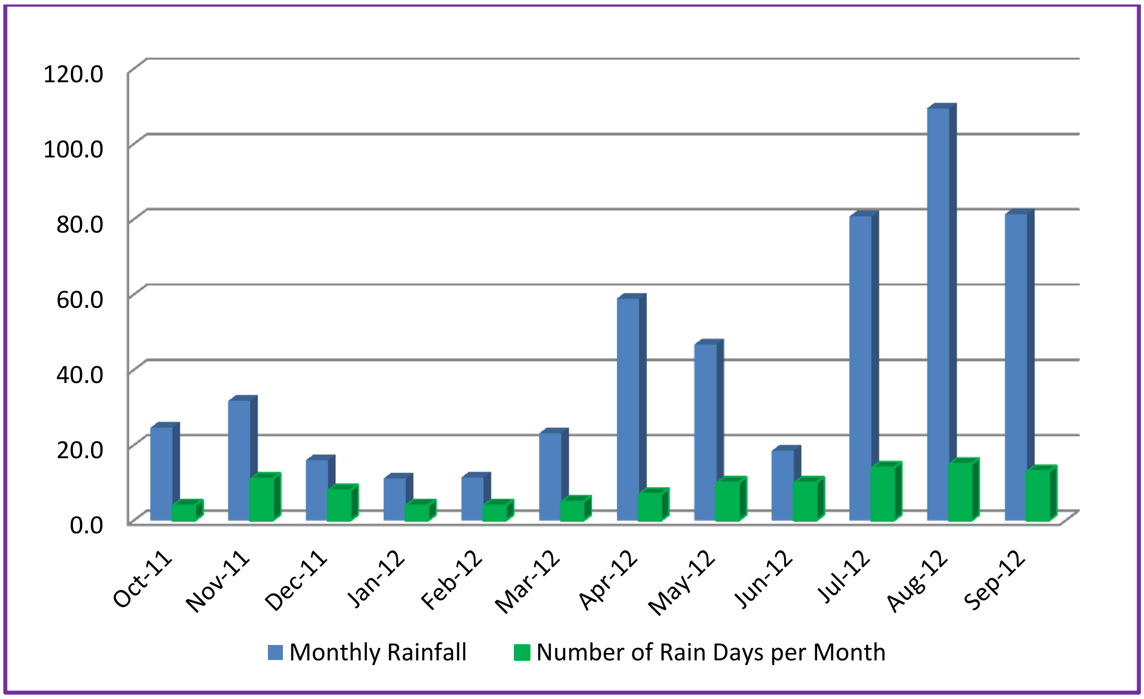

Figure 7-7: Weather Data Used in the Rainwater Availability Analysis (Adapted from SANSA, 2013)

The remainder of the minimum data requirements for RHS performance models are expressed in Table 7-2. Furthermore, it is assumed that the laundry and gardening end-uses will not take place on days when rainfall transpires. The only way to accommodate these events in the model is by incorporating their occurrences into the monthly tank-water demand computation (See Equation 17).

Table 7-2: Rainwater Harvesting System Components for Case Study Site

Rainwater Tank Data	
Initial Tank Condition (m^3)	2
Tank Capacity, C_a (m^3)	**2**
Catchment Area (m^2)	44.5
Roof run-off coefficient	0.9

In Chapter 4, the water mass balance equation for an RHS is depicted, where the inflow during a definite time interval, Q_t, and the storage volume at the end of the time interval, V_t, could be computed. However, the tank-water demand parameter, D_t, is calculated using the model established in Method 1. The average daily volume of rainwater used per end-use, as calculated by Equation 9 and consistent with the results of Method 1, is demonstrated in Table 7-3. The adapted monthly demand, for the purpose of this analysis, is accessible by Equation 17.

Table 7-3: Daily Rainwater Use Data Acquired from Method 1

DAILY RAINWATER USE					
End-use Category	Frequency of Use (events/c/day)	Event Volume (ℓ/event)	Daily End-use Volume (ℓ/c/day)	Average Household Size (PPH)	**Average Volume per End-use (ℓ/day)**
Laundry	0.143	62.00	8.866	3.81	38.125
Cleaning	1.0	6.70	6.7		28.811
Gardening	1.0	5.00	5		21.501

From Equation 11:

$$V_t = V_{t-1} + Q_t - D_t$$
$$Q_t = c_r \times R \times A_r$$

Where:

$$Monthly\ D_t(m^3) = \frac{Average\ Daily\ Volume_{Laundry\ and\ Gardening} \times No.of\ Non-Rain\ Days}{1000} + \frac{Average\ Daily\ Volume_{Cleaning} \times Total\ No.of\ Days\ per\ Month}{1000}$$

Equation 17: Monthly RHS Mass Balance for Case Study Site

The resulting monthly rainwater mass balance, based on Equation 11, is presented in Table 7-4, where the zero storage volume at the end of each month indicates that the tank-water demand is greater than the supply. It is unequivocal that the demand is much greater than the supply, throughout the majority of the year, for the defined tank size and corresponding roof area.

Table 7-4: Monthly Rainwater Mass Balance for the Kleinmond LCH Units

WEATHER INFORMATION				NON-RAIN DAYS		ANY DAY	MASS BALANCE		
Month	No. of Days per Month	Hermanus Rainfall (mm)	No. of Rain Days	Laundry	Gardening	Cleaning	**Monthly RW Demand, D_t (m^3)**	**Monthly Inflow, Q_t (m^3)**	**Storage at end of month, V_t (m^3)**
Oct-11	31	24.6	4	27	27	31	2.51	0.9876	0.482
Nov-11	30	31.8	11	19	19	30	2.00	1.2727	0.000
Dec-11	31	16.0	8	23	23	31	2.27	0.6415	0.000
Jan-12	31	11.2	4	27	27	31	2.51	0.4480	0.000
Feb-12	29	11.4	4	25	25	29	2.33	0.4582	0.000
Mar-12	31	23.1	5	26	26	31	2.45	0.9265	0.000
Apr-12	30	58.9	7	23	23	30	2.24	2.3622	0.124
May-12	31	46.7	10	21	21	31	2.15	1.8735	0.000
Jun-12	30	18.5	10	20	20	30	2.06	0.7433	0.000
Jul-12	31	80.8	14	17	17	31	1.91	3.2378	1.329
Aug-12	31	109.5	15	16	16	31	1.85	4.3884	3.868
Sep-12	30	81.3	13	17	17	30	1.88	3.2582	5.247

In the light of the previous discussion on the YAS algorithm being the preferred method for design purposes, the yield of the RHS, along with the storage volume of water, was computed using this algorithm. The method was implemented using the procedure concluded in section 4.4.2 and the product of this operating algorithm is illustrated in Table 7-5.

Table 7-5: Monthly YAS Mass Balance for the Kleinmond LCH Units

WEATHER INFORMATION				NON-RAIN DAYS		ANY DAY	YAS MASS BALANCE			
Month	No. of Days per Month	Hermanus Rainfall (mm)	No. of Rain Days	Laundry	Gardening	Cleaning	Monthly RW Demand, D_t (m^3)	Monthly Inflow, Q_t (m^3)	Yield i.e. water extracted from the tank, Y_t (m^3)	Storage at end of month, V_t (m^3)
Oct-11	31	24.6	4	27	27	31	2.51	0.9876	2.0000	0.988
Nov-11	30	31.8	11	19	19	30	2.00	1.2727	0.9876	1.273
Dec-11	31	16.0	8	23	23	31	2.27	0.6415	1.2727	0.641
Jan-12	31	11.2	4	27	27	31	2.51	0.4480	0.6415	0.448
Feb-12	29	11.4	4	25	25	29	2.33	0.4582	0.4480	0.458
Mar-12	31	23.1	5	26	26	31	2.45	0.9265	0.4582	0.927
Apr-12	30	58.9	7	23	23	30	2.24	2.3622	0.9265	2.000
May-12	31	46.7	10	21	21	31	2.15	1.8735	2.0000	1.873
Jun-12	30	18.5	10	20	20	30	2.06	0.7433	1.8735	0.743
Jul-12	31	80.8	14	17	17	31	1.91	3.2378	0.7433	2.000
Aug-12	31	109.5	15	16	16	31	1.85	4.3884	1.8491	2.000
Sep-12	30	81.3	13	17	17	30	1.88	3.2582	1.8800	2.000

There is a distinctive difference evident between the results reflected in Table 7-4 and Table 7-5, where the latter table continuously has rainwater stored at the end of each month. The main principle behind the YAS approach is that it makes provision for the monthly volume of water extracted from the tank, by selecting the minimum of either the tank-water demand or the volume of water existent inside the tank.

7.2.3 Method 3 – Effect of Storage Size on the Tank-Water Demand

The RHS mass balance in Method 2 underlines that the demand is greater than the supply, as could be expected. In view of this, an analysis was performed on the effect of different tank sizes on the tank-water demand. The analysis was completed for three different catchment areas, as previously discussed, which are accessible in Table 7-6.

Table 7-6: Three Catchment Area Variations Implemeneted

Catchment Area Variations	
50% of Roof Area (m^2)	44.5
100% of Roof Area (m^2)	89.1
Entire Plot Area (m^2)	128.0

A daily rainwater mass balance was launched by means of Equation 17, instead of a monthly procedure, with the intention of perceiving the exact day in every month when the daily tank-water demand becomes larger than the rainwater inflow.

In the event that the daily tank-water demand becomes larger than the rainwater inflow, the input tank capacity is increased for the full time series. This process was repeated for every month in the year under investigation. An example of one of the situations, where the daily tank-water demand became larger than the supply, is illustrated in Figure 7-8. From this intensified process, the hypothetical storage size for every month was recognized. This technique was repeated for three different roof area variations and the results are discussed later in the thesis.

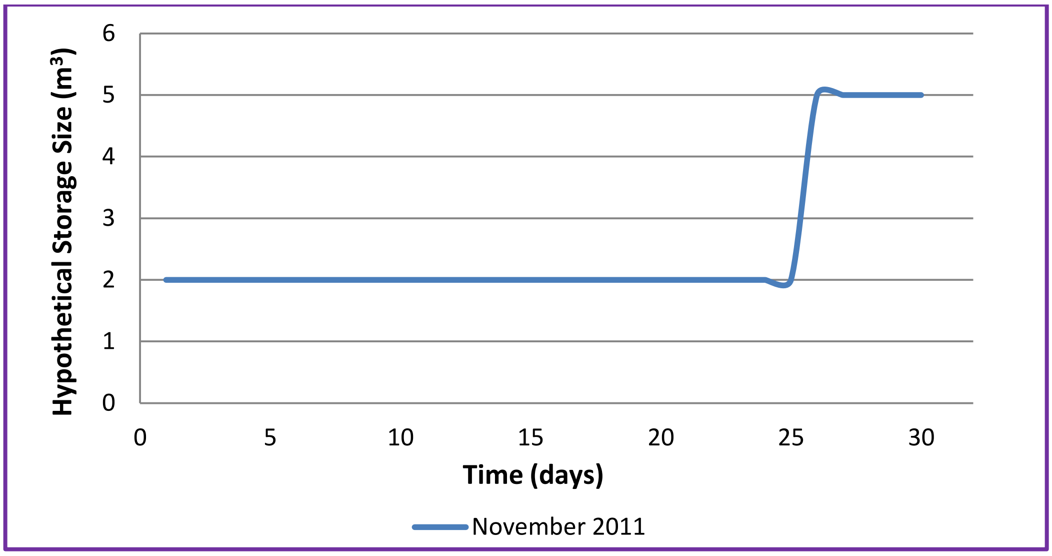

Figure 7-8: Example of Hypothetical Storage Size for One Month

The figure confirms the expected prediction that the installed rainwater tank will be able to supply the demand for a short period before a larger tank is necessitated. This scenario may be applicable to rainwater tanks in other areas, but it does not automatically insinuate that a larger tank is required. This method merely portrays a hypothetical situation in which the boundary case scenario, where the demand exceeds the supply, is investigated.

8. RESULTS

8.1 Presentation of Results

The potable water savings due to the daily application of RHSs in the Kleinmond LCH area is demonstrated in Figure 8-1, where the water savings from each end-use using the rainwater is displayed.

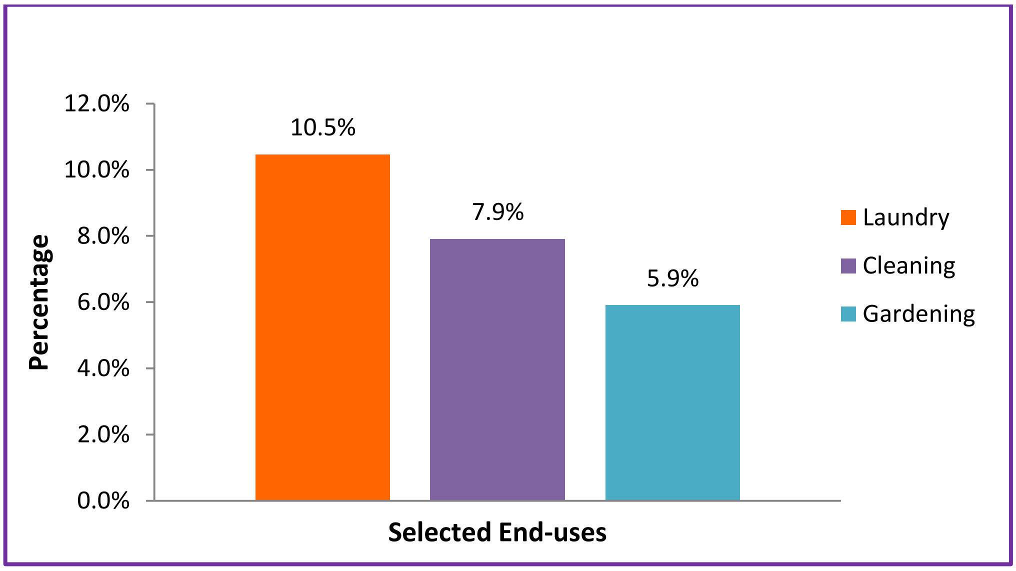

Figure 8-1: Potable Water Savings for Case Study Site

The stochastic system demand pattern for the Kleinmond LCH units, which includes all the household end-uses, is presented in Figure 8-2. Alternatively, the tank-water demand pattern, incorporating only the end-uses that use harvested rainwater, for the Kleinmond LCH units is depicted in Figure 8-3. The reduced water use pattern, by replacing the municipal WDS with a rainwater source, can be achieved from the results of the stochastic demand models, as demonstrated in Figure 8-4.

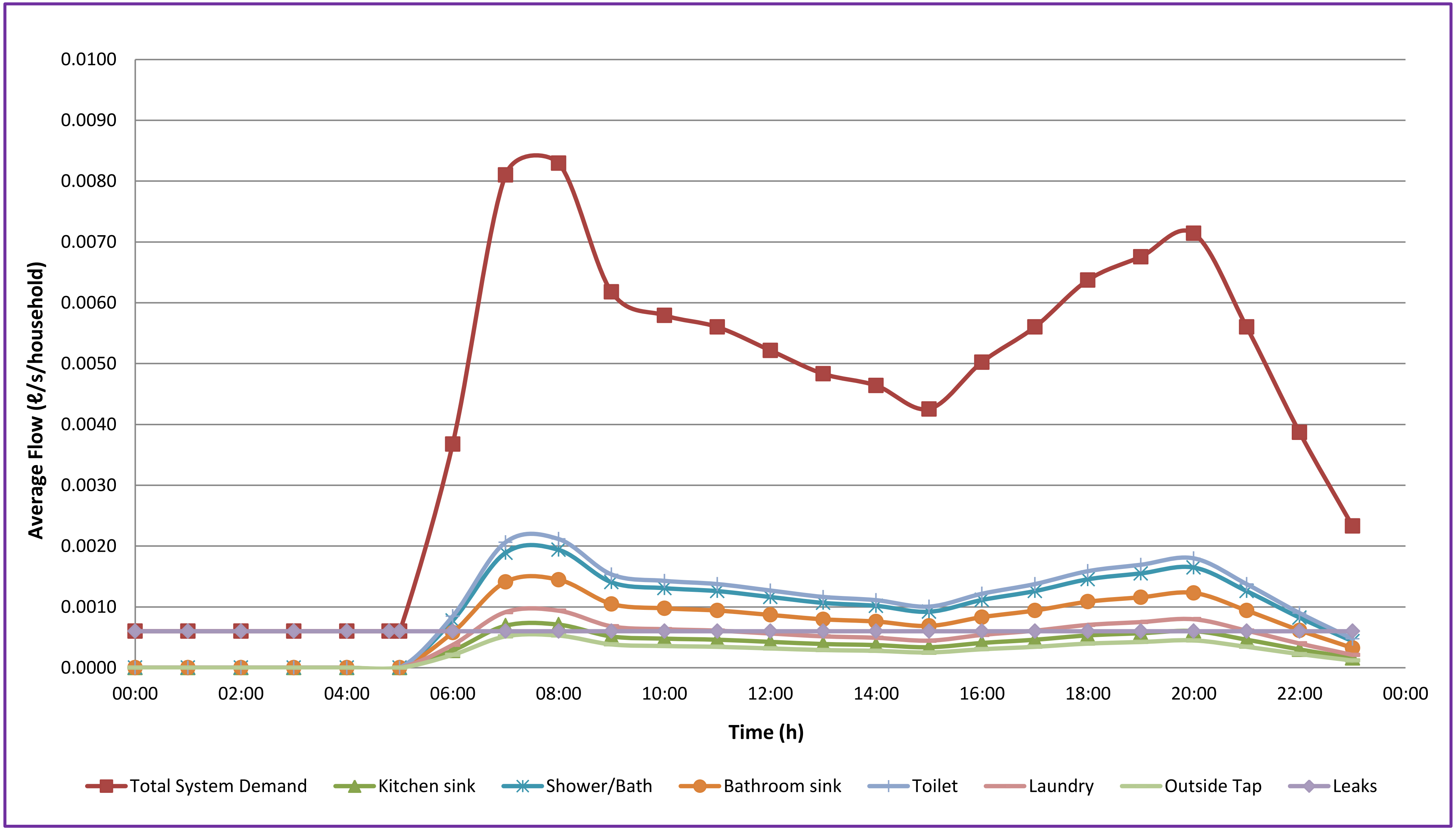

Figure 8-2: Total System Demand Profile for Kleinmond LCH

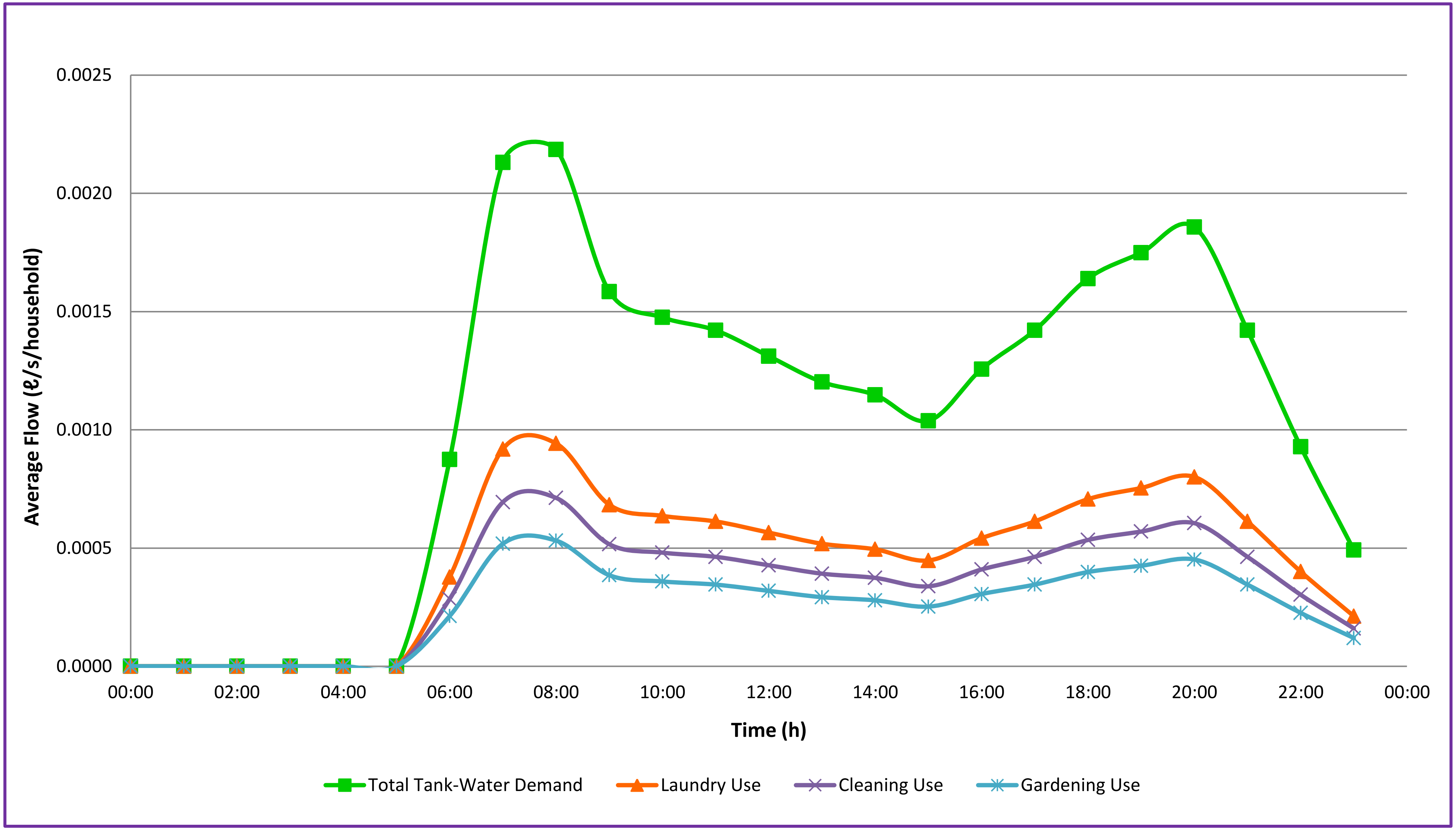

Figure 8-3: Tank-Water Demand Profile for Kleinmond LCH

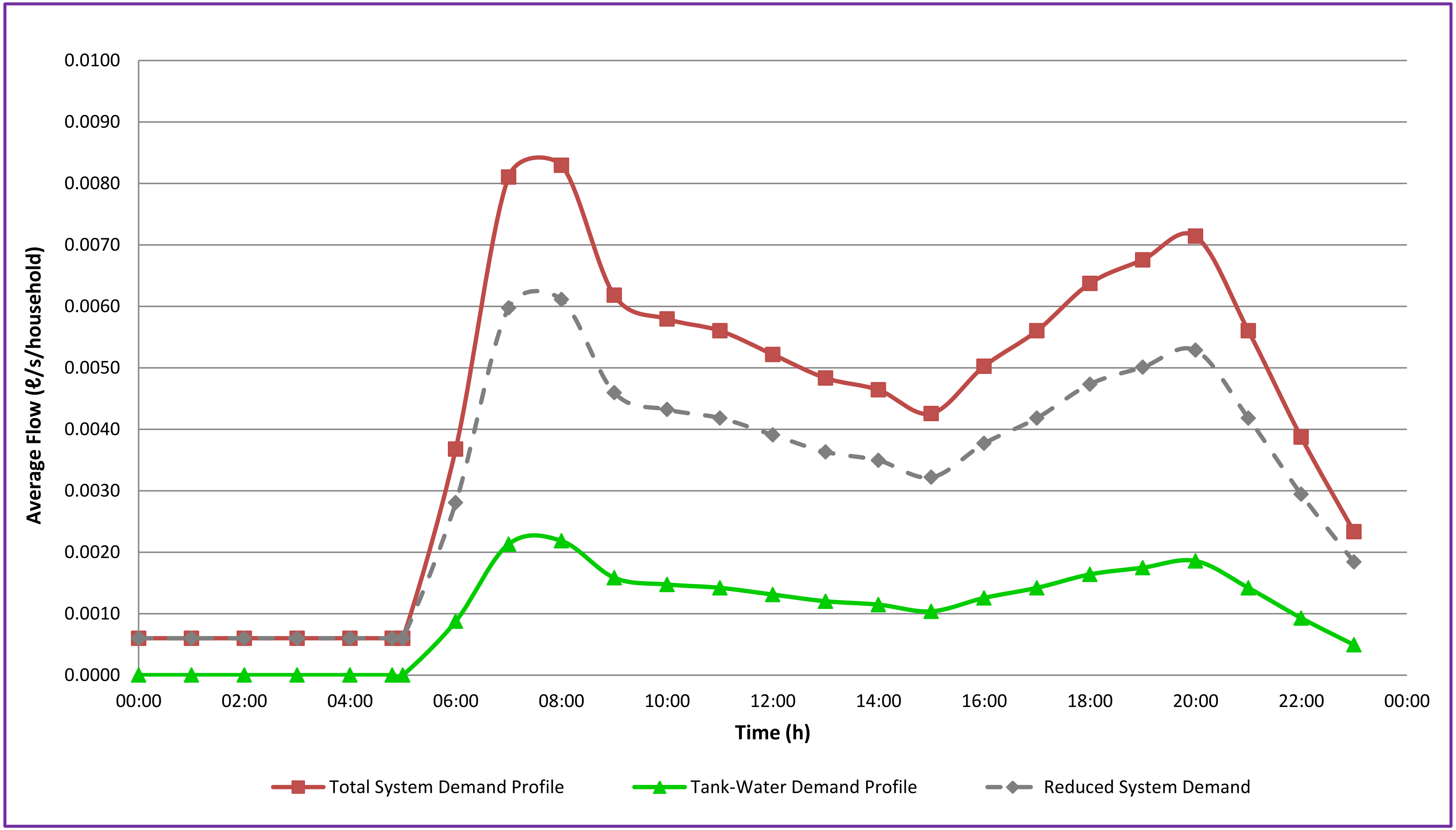

Figure 8-4: Reduced Water Use Pattern

A sensitivity analysis performed on the tank-water demand model (refer to Section 4.4.1) recognized the magnitude of the degree to which the allocated inputs affect the output of the model, by means of correlation coefficients. The rank correlations are based on the Spearman Rank correlation coefficient calculations. With this analysis, the rank correlation coefficient is calculated between the selected output variable and the samples for each of the input distributions. The higher the correlation between the input and the output, the more significant the input is in determining the output's value. An example of the coefficients used in the sensitivity analysis is demonstrated in Table 8-1.

Table 8-1: Correlation Coefficients for Sensitivity Analysis on the Tank-Water Demand Model

	Mean Value of Total Rainwater Use = 0.001024			
Rank According to effect on Output's Mean Value	**Name**	**Mean Value Lower Limit**	**Mean Value Upper Limit**	**Spearman rank coefficient (r)**
1	Household Size	0.000387	0.001827	0.99
2	Frequency of Use: Laundry	0.000941	0.001096	0.08
3	Frequency of Use: Cleaning	0.000960	0.001076	0.06
4	Volume: Laundry	0.000986	0.001085	0.06
5	Frequency of Use: Gardening	0.000977	0.001069	0.06
6	Volume: Cleaning	0.000991	0.001069	0.04
7	Volume: Gardening	0.000992	0.001058	0.02

The relationship that the frequency of use parameter has to the tank-water demand is displayed in Figure 8-5, while the addition of the event volume parameter is exhibited in Figure 8-6. The length of the bar corresponds to the magnitude of the influence; in other words, the longer the bar, the more effect this uncertain input has on the tank-water demand.

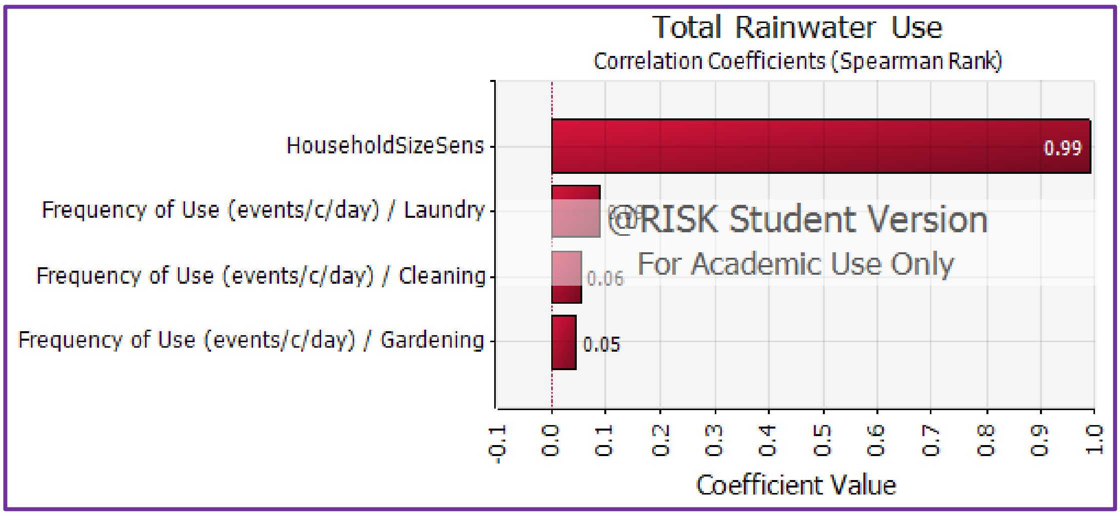

Figure 8-5: Sensitivity Analysis of the Frequency of Use Parameter

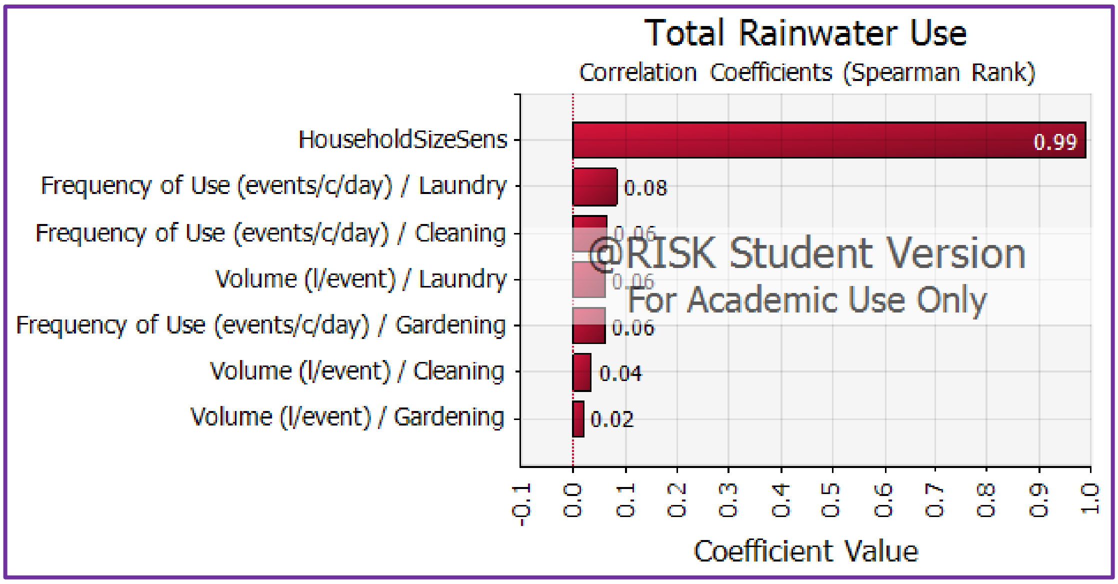

Figure 8-6: Sensitivity Analysis of All Input Parameters

The monthly rainwater availability analysis was executed on the RHSs of the Kleinmond LCH units in order to examine the difference between the supply and the demand. The formulation of the method is motivated by the uncertainty as to whether there is water present in the tank at the time of use. The outcome of the monthly rainwater availability analysis is presented in Figure 8-7, which confirms that the tank-water demand is greater than the monthly inflow of harvested rainwater.

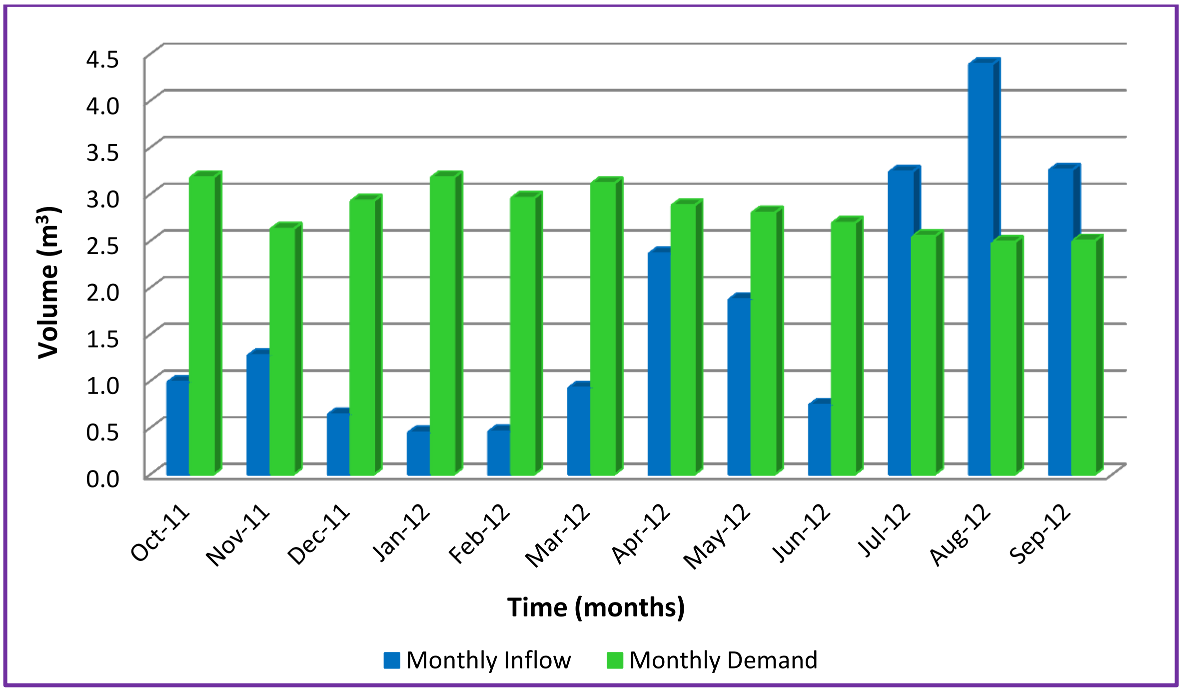

Figure 8-7: Rainwater Availability Analysis Results

An additional YAS mass balance analysis was performed on the RHSs, where the tangible volume of water that can be extracted from the tank was computed, instead of the theoretical monthly tank-water demand obtained by Equation 17. The product of this approach is displayed in Figure 8-8.

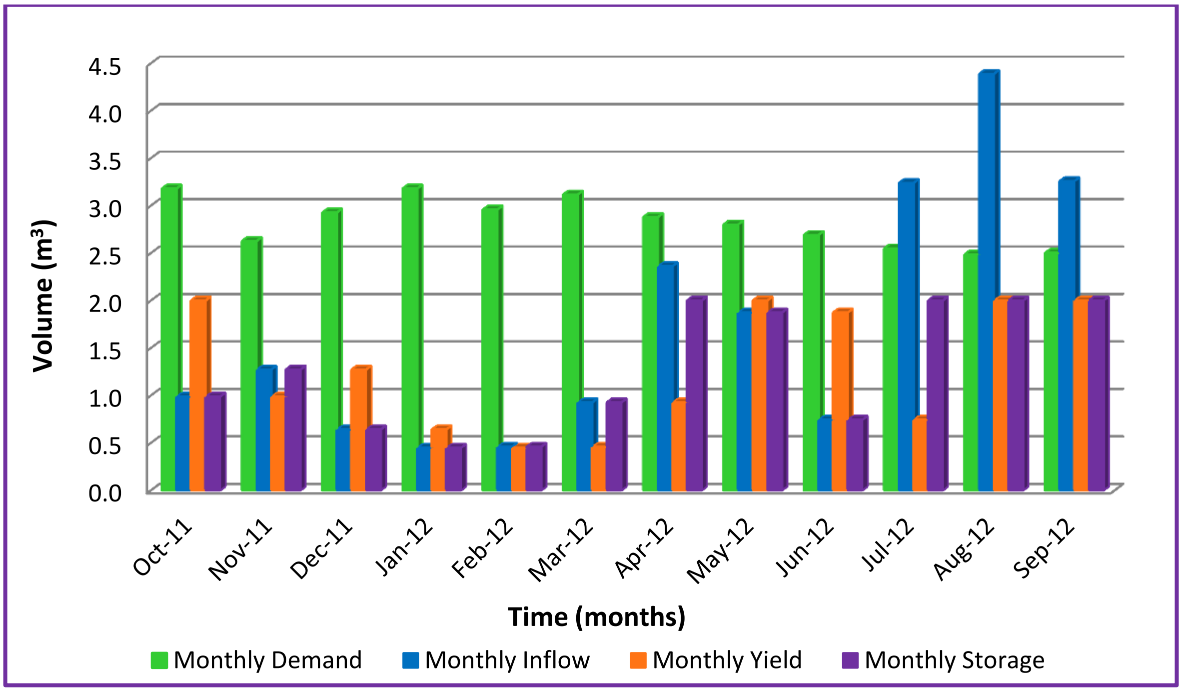

Figure 8-8: YAS Mass Balance Results

The analysis carried out with the intention of approximating a hypothetical tank size for the Kleinmond LCH units, was achieved by simulating the rainwater mass balance for the duration period of one year. The result of the model is illustrated in Figure 8-9, which expresses the ability of a large storage tank to satisfy the expected tank-water demand of a domestic household for one year.

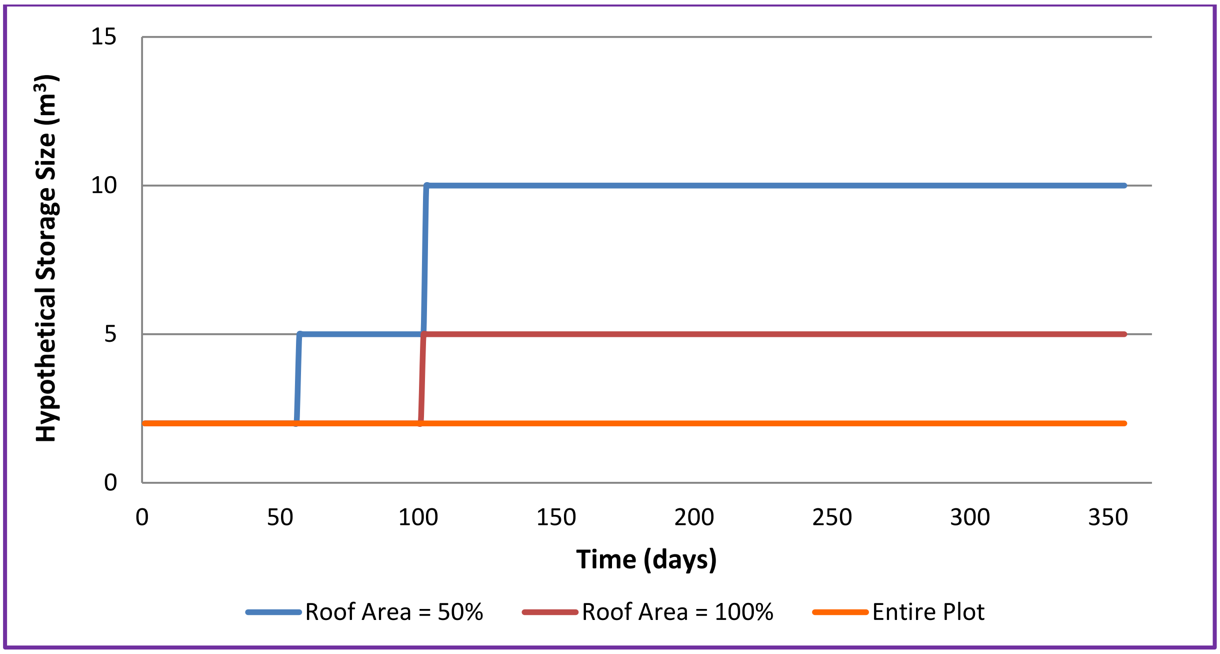

Figure 8-9: Hypothetical Storage Size for One Year

8.2 Discussion of Results

The system demand patterns of LCH units are atypical and cannot be defined by traditional models. Similarly, the use of RHSs in these areas follows an unconventional routine that is yet to be published, as no information regarding water use habits was established during the literature review. That being said, the stochastic end-use model was used to formulate the demand patterns as accurately as possible in order to benefit future research studies.

8.2.1 Stochastic Demand Profiles

The total system demand profile obtained from the Kleinmond site case study validates that the daily water consumption for a toilet is the end-use with the most significant amount of water used per day. The toilets in the case study area were, however, not connected to the RHS. From the research employed by Fewkes (1999), an estimated potable water savings of 57% of the annual system demand was achieved when using an RHS for toilet flushing purposes. In light of these observations, it would be proposed that the toilet be connected to the rainwater tank, given that this implementation will conserve the most water.

The tank-water demand pattern exhibits that the laundry end-use consumes the most harvested water, which is representative of the LCH area as the average occupancy is 3.8 PPH resulting in higher laundry volumes. The rainwater used for laundry and cleaning could be recycled for gardening purposes, but this scenario was not included in the model. The water consumed by these end-uses is considered polluted and it is not advised as good practice to re-use it for other purposes.

The results of the developed stochastic models substantiated that during the morning, 14% of the system demand was met by the rainwater source, compared with 10% during the evening. The potable water savings acquired by using the RHS for laundry, cleaning and gardening in the Kleinmond LCH area (refer to Figure 8-1) are 10%, 8% and 6%, respectively. A real-time monitoring study such as Talebpour *et al.* (2011) achieved relatively higher water savings from IPT where the laundry, toilet and irrigation end-uses accomplished water savings of 41%, 42% and 1.4%, respectively. The Kleinmond LCH units only employ external rainwater tanks where manual collection of the alternative water source is required, thus explaining why the percentages in this study are relatively lower.

From the abovementioned findings, it is clear that IPT are expected to obtain higher water savings, since the rainwater source is available directly to the end-use. Only three end-uses were selected for the purpose of this study, because the rainwater tank size in the Kleinmond LCH area is limited.

The sensitivity analysis evaluated the influence of the frequency of use and event volume parameter on the tank-water demand model. These parameters have insignificant contributions to the tank-water demand pattern in comparison to the weight of the household size parameter. There is therefore, no doubt that the PPH has the largest effect on the output values, which are used to generate the system and tank-water demand profiles. This result is consistent with the findings by Jacobs & Haarhoff (2004b).

8.2.2 Rainwater Availability Analysis

It is evident in Figure 8-7 that, for most of the year, the monthly tank-water demand is greater than the theoretical volume of harvested rainwater for the defined tank size and corresponding roof area. It is apparent that the demand can be met only during the winter months specifically, July, August and September. This situation is expected, given that the Kleinmond LCH site is situated in a winter rainfall region and the seasons of supply and demand are dissociated. The rainfall is sufficient to supply the monthly tank-water demand during the winter months, but is an ineffective water source throughout the summer.

Figure 8-8 illustrates that the YAS mass balance continually results in rainwater being stored at the end of each month. The reason for this is that the YAS algorithm calculates the physical volume of water that can be extracted from the tank, whereas the RHS mass balance, according to Equation 11, considers the theoretical performance of a specific inflow sequence. In light of these findings, the YAS approach is a more realistic representation of the functionality of an RHS in practice, since only the water stored inside the tank can actually be extracted, not the expected tank-water demand.

8.2.3 Effect of Storage Size on the Tank-Water Demand

In view of the fact that the monthly tank-water demand is much larger than the available volume of harvested rainwater, the rainwater tank size that would be able to supply the Kleinmond LCH units with its daily tank-water demand for one year was established. Contrary to the generic model created by Allen (2012), this model investigated the optimal sizing of a rainwater tank for an individual area, under a specific demand, for a one year period.

The outcome of the model displayed in Figure 8-9 suggests that the optimal rainwater tank size for a catchment area equivalent to half the roof area is 10 kℓ, since this tank size is sufficient to supply the demand for over two thirds of the year. Further observation indicates that the ideal tank size for a catchment area identical to the roof area and the entire plot capacity is 5 kℓ and 2 kℓ, respectively. The unfolding argument substantiates the demand, in the Kleinmond LCH area, is satisfied by a smaller tank size when the roof area is increased.

The Kleinmond LCH units are adjoined and thus they share a common roof, which results in the harvested rainwater being shared between the two households. For the purpose of this case study site, a sufficient tank size for half the roof area is 10 kℓ (see Figure 8-9). However, since a rainwater tank larger than 5 kℓ on a domestic property is deemed too large and the space is limited, the ideal tank size for the Kleinmond LCH units is 5 kℓ, where half the entire roof area contributes to each rainwater tank. The increased tank size would not be able to supply the area with rainwater throughout the year, but it would increase the yield, in turn, satisfying a larger volume of the expected demand.

Smaller tanks adjacent to each side of the house would theoretically be more efficient than one tank, with the same total volume, along one side of the house, as the roof of the adjoined households are pitched allowing water to be collected on either side of the house. The smaller tanks allocate both sides of the rooftop to collect the rainwater, while still being aesthetically acceptable. For example, if a total storage capacity of 10 kℓ is required, the rainwater tank arrangement should consist of 2 x 5 kℓ rainwater tanks distributed evenly alongside the house.

8.3 Comparative Analysis

The research method theoretically examines the expected tank-water demand at selected households in the Kleinmond LCH area. Although no metered consumption data was employed to establish the tank-water demand profile, the model was set in contrast to studies that include metered rainwater use. The results gained from the model are compared to previous studies estimating the system demand when incorporating a rainwater source.

8.3.1 LCH Diurnal Pattern

The study by Steyn (2013) on the Kleinmond LCH site achieved the diurnal system demand pattern without incorporating RHSs. The research comprised the real-time monitoring of water meters to compute the actual system demand of each household. The stochastic system and tank-water demand profiles were evaluated against the diurnal system demand pattern by Steyn (2013) in order to examine the impact of the RHS on the municipal WDS.

The comparison of the two studies is displayed in Figure 8-10. The diurnal pattern by Steyn (2013) depicts only the measured system demand of the Kleinmond LCH units. The stochastic tank-water demand profile was then added to the diurnal pattern to provide the overall system demand pattern.

The figure displays the total system demand profile as being slightly larger than the newly merged system demand pattern. This could be because of the maximum water volumes selected from the stochastic model in order to depict the worst case scenario if all the consumers used water at any specific time. However, except for this minor variation the stochastic demand profiles can be considered an accurate depiction of the system and tank-water demand in the Kleinmond LCH area.

From the above discussion, it can be concluded that the tank-water demand profile can be used as a reference for future research estimates of household system demand when incorporating RHSs. The effect of the tank-water demand on the system demand can be integrated into planning and design of urban water systems in the future.

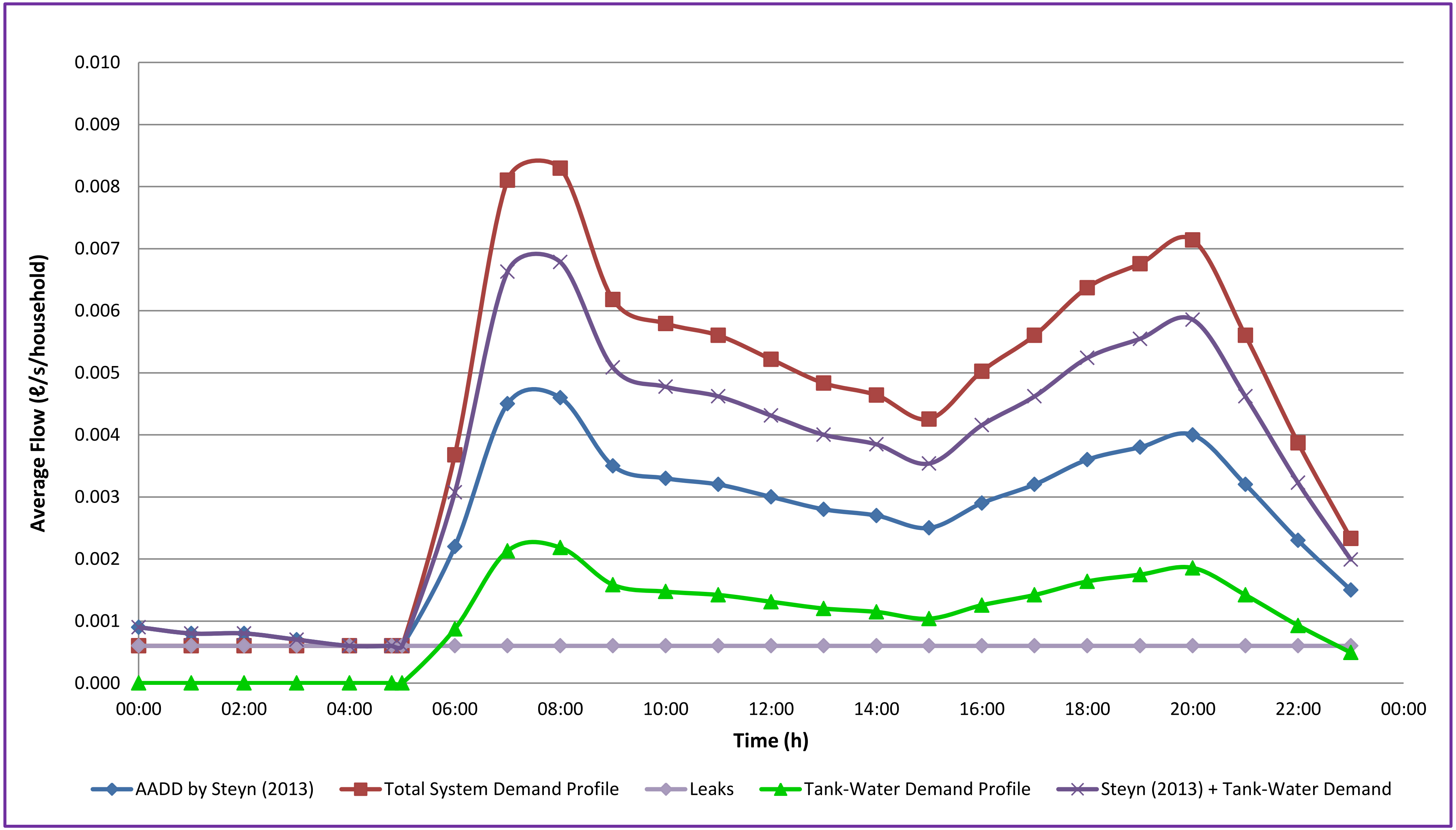

Figure 8-10: AADD from Steyn (2013) Against Stochastic Demand Profiles for Kleinmond LCH

8.3.2 Roof Model

The Roof model (Van der Zaag, 2000) uses daily rainfall data for at least 3 years to obtain the storage capacity of a rainwater tank when the daily system demand and roof area are identified. For the purpose of this study, the rainwater tank size is a known parameter and therefore the theoretical percentage of the system demand that can be supplied by the harvested rainwater is computed. Using Equation 5, the daily harvested rainwater is calculated, together with the required information supplied in Table 8-2.

Table 8-2: Roof Model Application Data to Kleinmond LCH Units

AADD per household (ℓ/day) (Steyn, 2013)	187
Catchment Area (m^2)	44.5
MAP of the Western Cape (mm)	348
Roof run-off coefficient	0.9
Harvested Rainwater, Q_t (ℓ/day)	38.22
Percentage of Water Demand Supplied by RHS	20%

The roof model estimates that 20% of the system demand could be supplied by the RHS in the Kleinmond LCH area. This potential water savings was computed using the MAP of the Western Cape, which is a requirement of the model. However, it must be borne in mind that the rainfall in the Western Cape is unevenly distributed and therefore the potable water savings amount is merely indicative. The stochastic tank-water demand model achieved 24% potable water savings when only three end-uses consumed harvested rainwater. Alternatively, the Roof model is limited by the PPH not being incorporated into the calculation process, while the household size is a fundamental input in the tank-water demand model.

The input parameters, such as the rainfall data and the integration of the household size differ for the two rainwater models. Higher water savings obtained by the stochastic tank-water demand model was accomplished by limiting the selection of fundamental components to those that affect the behavioural performance of the RHS in the specified case study site.

8.3.3 Real-Time Monitoring Approach South East Queensland, Australia

Umapathi *et al.* (2013) uses smart meters to quantify the effect of 5 kℓ IPT on potable WDSs in domestic households. The system and tank-water demand of a set of households was measured over a 12 month period in order to obtain an actual system demand pattern. The rainwater tank is connected to the toilet, washing machine, cold water taps and at least one outdoor tap. Before discussing the juxtaposition of the two studies, it is important to acknowledge that the analysis by Umapathi *et al.* (2013) employs IPT, whereas the Kleinmond LCH study evaluates external rainwater tanks.

The comparison of the real-time monitoring study by Umapathi *et al.* (2013) against the stochastic demand profiles developed in this study is demonstrated in Figure 8-11. Umapathi *et al.* (2013) investigated 20 households located in different urban areas of Australia, where the water use is expected to be higher than that of LCH units. Water use habits of residents in LCH areas are different to those of other urban residents, as water is used sparingly because of the financial implications. The system demand patterns of both studies present two peaks, with the highest water consumption being in the morning. The somewhat later morning peaks of the real-time study could be due to the type of employment or travelling schedules.

When examining the contrast in the figure, the tank-water demand patterns of both studies appear to be similar in magnitude. Umapathi *et al.* (2013) substantiates that during the morning peak, 28% of the system demand was met by the rainwater source, which is higher than the 14% system demand replacement achieved by the stochastic demand models. This could be as a result of the IPT allowing easier access to the rainwater source. This observation supports the findings by Helmreich & Horn (2009), who noted that the main advantage of a domestic RHS is to provide water nearest to the household.

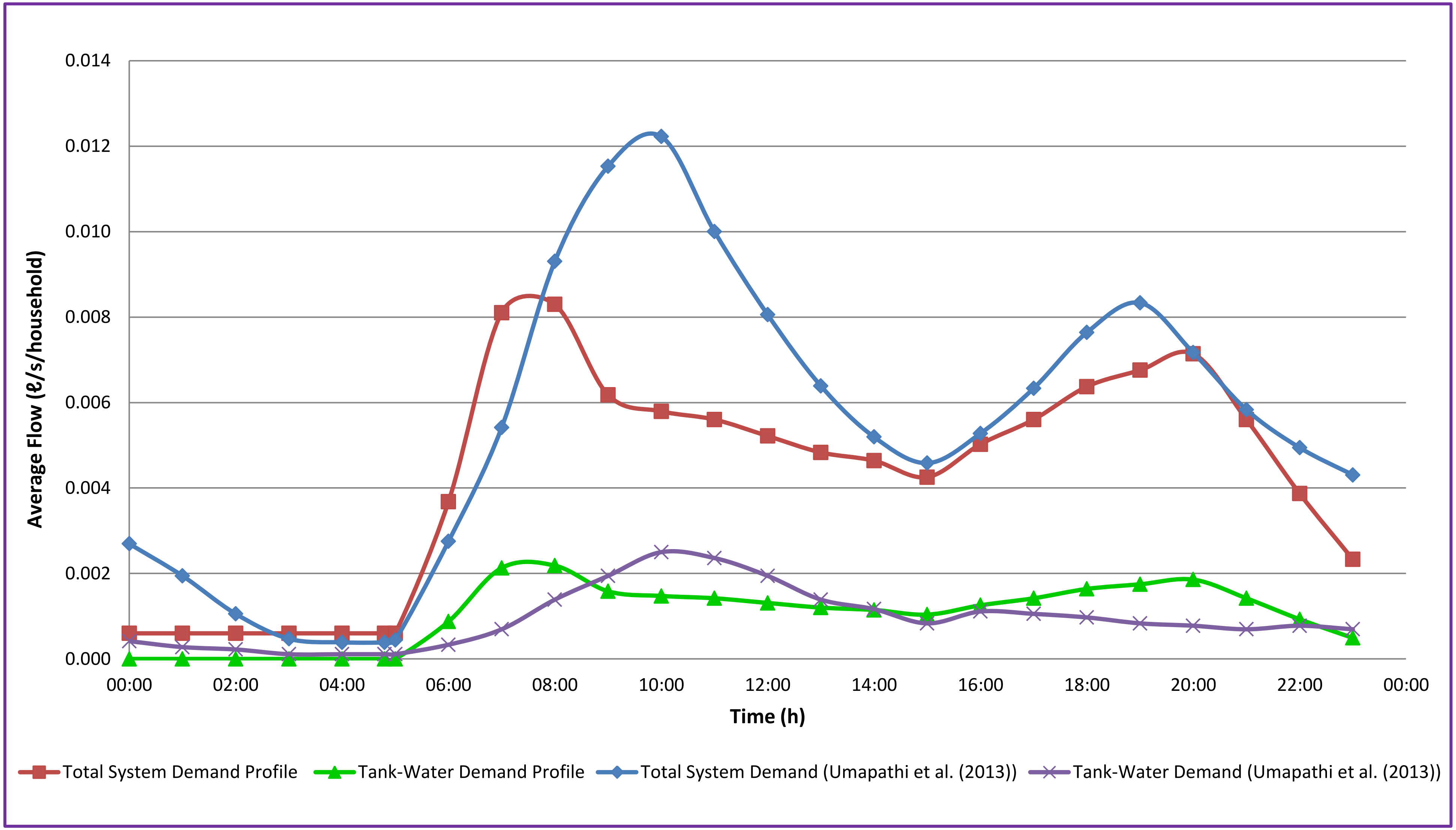

Figure 8-11: Umapathi *et al.* (2013) Against Demand Profiles for Kleinmond LCH

8.3.4 Pairwise Statistical Analysis in South East Queensland, Australia

Beal *et al.* (2012) performed a pairwise statistical analysis comparing households with IPT to those without rainwater tanks in an effort to estimate the potable water savings. The IPT are mandated to be connected to the toilets and washing machines inside domestic households. The study recognized that the extent of potable water savings, when implementing RHSs, is highly influenced by the household size.

The potable water savings from the statistical analysis was cross-checked with approximations using measured end-use data and tank-water demand predictions by means of a specified model. For the South East Queensland region, the annual potable water savings per household range between 22.5% and 25%, resembling the 24% achieved in the Kleinmond LCH area. The water savings acquired by both studies are similar in magnitude despite the difference in the rainwater accessibility.

The lack of inclusion of the household size in the analysis by Beal *et al.* (2012) resulted in a limited estimation of potable water savings. There has been a growing realisation that the incorporation of household size in a model produces increased water savings due to the convenience of the system. The stochastic tank-water demand model obtained the maximum amount of potable water savings achievable, given that only three end-uses were explored in the scope of this study.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary of Findings

The study investigated the influence of domestic RHSs on the municipal WDSs of LCH units in Western Cape, South Africa. Despite an extensive literature review, no published information regarding water use habits or system demand patterns of LCH units could be obtained, except a final year study based on the same case study area. Temporal profiles for system and tank-water demand in LCH units were developed using a computer based, stochastic end-use model.

The profile of the system demand patterns in LCH units is atypical when compared with suburban system demand patterns. Two clear peaks exist, in the morning and in the evening, with a relatively constant average flow throughout the day. The reasons for this can only be speculated upon, given that the consumer water use habits are unknown. A sensitivity analysis of all model parameters verified that the household size has the most substantial influence on the tank-water demand pattern, despite the end-use frequencies and event volumes.

Tank-water demand is relatively higher than the supply for Kleinmond LCH, which is to be expected, since it is located in a semi-arid region rendering it unlikely that an RHS will meet the total domestic system demand. The relatively small tank size cannot store enough water to supply the tank-water demand throughout the summer months. The findings of this study confirm that smaller tanks located adjacent to each side of the household would theoretically be more efficient, since this allows both sides of the rooftop to collect the rainwater while still being aesthetically acceptable.

Comparative analysis proved that more of the household system demand is met by the RHS during the morning than in the evening for any type of domestic household. The use of IPT achieves higher water savings than external rainwater tanks, because the rainwater source is available directly from the end-use. In addition, comparative analysis established that the accessibility of the rainwater source contributes to the frequent use thereof.

Finally, the stochastic demand profiles derived as part of this research agree with the metered system demand in the same area. Future research estimates can use the tank-water demand profile as a reference to estimate household system demand when a rainwater source is employed.

9.2 Conclusion

The main objective of this study was to theoretically evaluate the impact that rainwater application has on the system demand, with the intention of forming a basis for future prospects incorporating tank-water demand when deriving water demand guidelines. Previous research demonstrates diurnal system demand patterns for domestic households in the urban sector, without specific emphasis on LCH. This study focussed on LCH at a case study site in the winter rainfall region. Traditional end-use models cannot depict the unconventional system demand patterns for LCH areas and there is a lack of literature on water use practices and consumer habits in these areas.

A case study site was investigated as part of the research project, with the purpose of applying a generic methodology to generate the temporal system and tank-water demand profiles. An integral part of this research included a stochastic end-use model used to develop average flow results for the Kleinmond LCH units. The model used the actual diurnal system demand pattern from a previous study to derive the expected time of day when rainwater would be used, while the household size information was acquired from consumer surveys. Various end-use studies were used to derive individual end-use event parameters applicable to the water use in the LCH units. Probabilities based on actual water use events were used to evaluate the stochastic model in terms of reliability. The flow patterns were achieved by evaluating the maximum water volume at each time step of the simulation process.

The theoretical findings from the model were compared with those of previous studies that have acquired methods of estimating the tank-water demand pattern. The result of the comparative analysis suggests that the generated profiles for LCH units are consistent with the formerly derived diurnal system demand patterns for domestic households in urban areas. Of particular importance is the fact that the rainwater source is more likely to be used when it can be acquired inside the household with minimal effort, which results in higher potable water savings sequentially reducing the system demand.

The present applications of RHSs in South Africa are generally driven by necessity, drought or an inadequate water supply, with their employment in order to achieve a reduction in system demand and stormwater management being unusual. Although RHSs are relatively expensive and aesthetically unappealing, their use is a practical way to reduce the dependency on the municipal WDS.

With the domestic sector being the highest consumer of water in South Africa, multiple end-uses can be replaced with non-potable water.

The on-site advantage of RHSs is that it has the potential to improve the living environment in areas where access to these systems is the only available source of water. Moreover, the benefits related to RHSs are predominantly significant for households located in rural areas, where the domestic water supply is often unreliable. As published by various studies, the financial implications limit the use of RHSs where no government incentives exist and therefore prevent the extensive potential of the system being recognised.

The techniques adopted throughout this study may form a basis on which further studies can be performed by broadening it to include larger sample sizes in different domestic areas. For that reason, the information provided by this study could be considered suitable when developing strategic urban water supply systems that incorporate the application of rainwater tanks in domestic areas.

9.3 Suggestions for Future Research

This study is concluded by identifying potential possibilities for further research leading on from the work commenced in this thesis and recommendations for related work. Possible future research projects could include the following:

- The consideration of a wider range of domestic areas, which includes houses with larger roof areas, higher occupancies and inclusion of more end-uses using rainwater (including potable water applications). In addition, evaluation of RHSs in different parts of South Africa could be beneficial and allow the impact of regional climate distributions and different water utility costs to be investigated.

- The monitoring of domestic households with on-site RHSs, in a specific area, in order to compare the performance data with those households without RHSs. Various advances can be achieved by comparing households, who obtain a supplementary source of non-potable water with those who only have one primary source of water.

- The assumption that the tank-water demand would follow the same pattern as the system demand, for each household in a case study area, should be investigated. A social investigation into the water use habits of people residing in LCH units would be beneficial in tank-water demand estimation. Often an inadequate amount of attention is granted to social and economic aspects such as land occupancy and unemployment.

- The presence of leaks in LCH units is constant throughout the day, which implies that the monitored system demand will be greater than the actual system demand. An assessment of the plumbing in LCH units is required in order to achieve a reduced existence of leaks. In that way, a more accurate depiction of the system demand in LCH units can be achieved.

- The implementation of meters to monitor the actual tank-water demand would allow a measured, accurate water use pattern. It is evident from real-time monitoring studies in the literature that metered rainwater use is beneficial when evaluating the performance of such a system.

- The function of water efficient household applications such as low water use washing machines, shower roses and tap flow controllers has not been investigated for South African use by any of the literature reviewed in this study. Previous research has confirmed that these water efficient features and fixtures can contribute to the reduction in the system demand achieved by RHSs.

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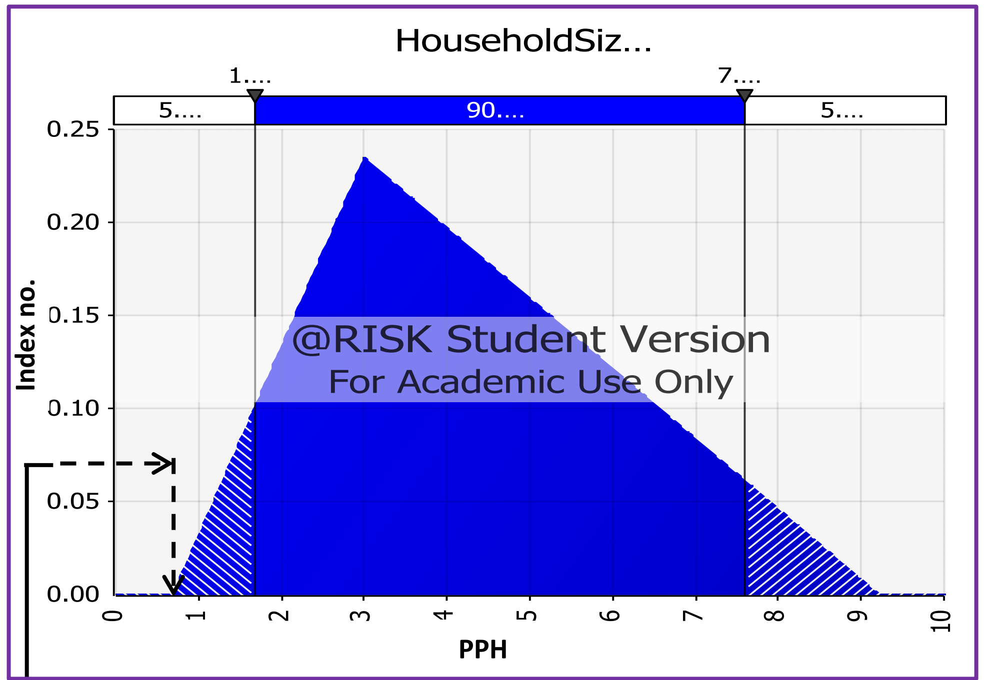
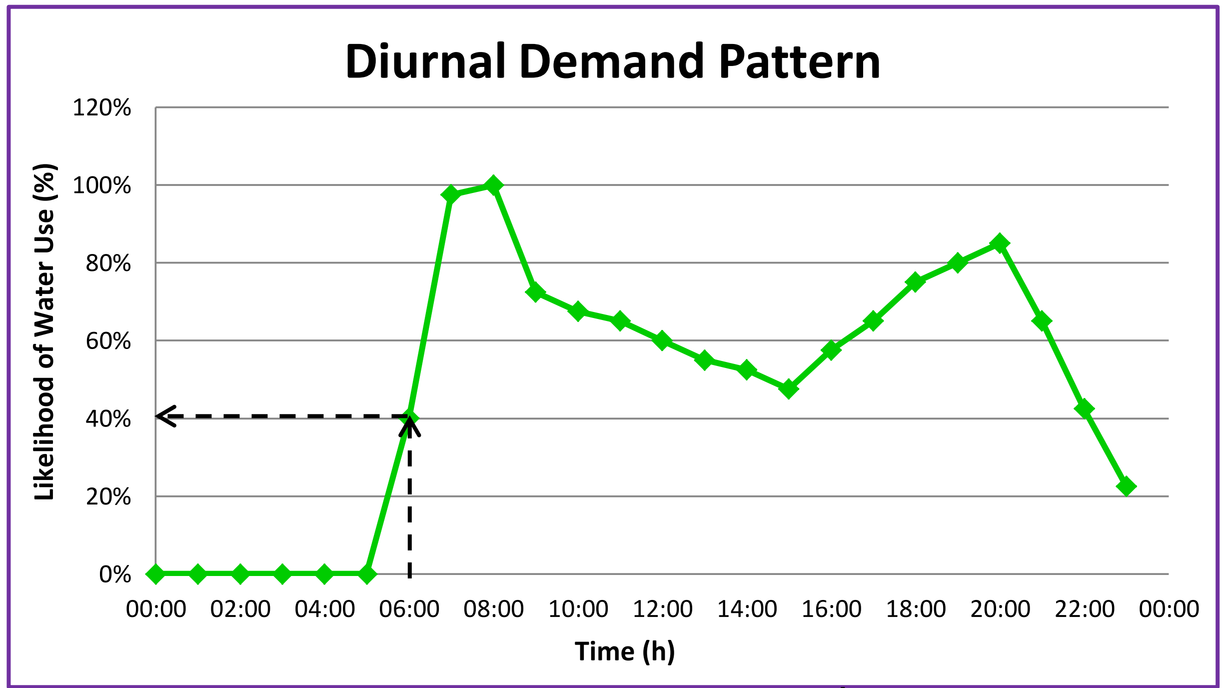
APPENDIX A: WORKED EXAMPLE OF TANK-WATER DEMAND MODEL

TANK-WATER DEMAND MODEL

Inputs





Known Inputs			
	Laundry	Cleaning	Gardening
Frequency of Use (events/c/day)	0.143	1.0	1.0
Volume (ℓ/event)	62.0	6.7	5.0

Logic Formulations

Using Equation 9:

$$\frac{0.73 \times 0.143 \times 62}{3600 \times 24} = 0.000075$$

$$0.000075 \times 0.4 = 0.000030$$

Using Equation 9:

$$\frac{0.73 \times 1.0 \times 6.7}{3600 \times 24} = 0.000056$$

$$0.000056 \times 0.4 = 0.000023$$

Using Equation 9:

$$\frac{0.73 \times 1.0 \times 5.0}{3600 \times 24} = 0.000042$$

$$0.000046 \times 0.4 = 0.000017$$

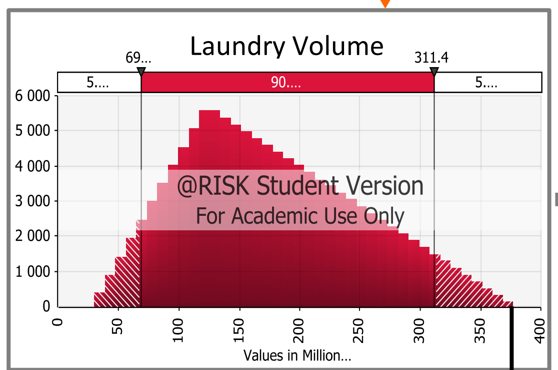
$$0.000030 + 0.000023 + 0.000017 = 0.000070$$

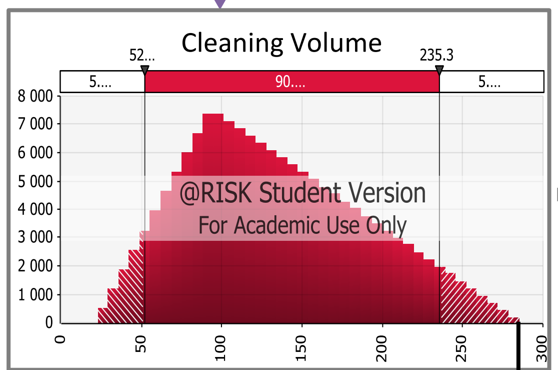
		At 06h00 with a Probable Peak Flow = 0.4						
		Laundry End-Use		Cleaning End-Use		Gardening End-Use		Total Rainwater Use at 06h00 (ℓ/s)
Index no.	PPH	Volume (ℓ/s) for all possible PPH	Volume (ℓ/s) at 06h00	Volume (ℓ/s) for all possible PPH	Volume (ℓ/s) at 06h00	Volume (ℓ/s) for all possible PPH	Volume (ℓ/s) at 06h00	
0.0156	0.73	0.000075	0.000030	0.000057	0.000023	0.000042	0.000017	0.000070
0.0364	0.94	0.000097	0.000039	0.000073	0.000029	0.000055	0.000022	0.000090
0.0582	1.15	0.000118	0.000047	0.000089	0.000036	0.000067	0.000027	0.000110
0.0795	1.36	0.000140	0.000056	0.000106	0.000042	0.000079	0.000032	0.000130
0.1008	1.58	0.000162	0.000065	0.000122	0.000049	0.000091	0.000036	0.000150
0.1221	1.79	0.000183	0.000073	0.000139	0.000055	0.000103	0.000041	0.000170
0.1434	2.00	0.000205	0.000082	0.000155	0.000062	0.000116	0.000046	0.000190
↓								
0.0771	7.07	0.000725	0.000290	0.000548	0.000219	0.000409	0.000164	0.000673
0.0691	7.28	0.000747	0.000299	0.000565	0.000226	0.000421	0.000169	0.000693
0.0606	7.49	0.000769	0.000308	0.000581	0.000232	0.000434	0.000173	0.000713
0.0535	7.70	0.000791	0.000316	0.000597	0.000239	0.000446	0.000178	0.000733
0.0450	7.91	0.000812	0.000325	0.000614	0.000246	0.000458	0.000183	0.000754
0.0369	8.13	0.000834	0.000334	0.000630	0.000252	0.000470	0.000188	0.000774
0.0289	8.34	0.000856	0.000342	0.000647	0.000259	0.000482	0.000193	0.000794
0.0218	8.55	0.000877	0.000351	0.000663	0.000265	0.000495	0.000198	0.000814
0.0123	8.76	0.000899	0.000360	0.000679	0.000272	0.000507	0.000203	0.000834
0.0057	8.97	0.000921	0.000368	0.000696	0.000278	0.000519	0.000208	0.000854
0.0000	9.18	0.000942	0.000377	0.000712	0.000285	0.000531	0.000213	0.000874

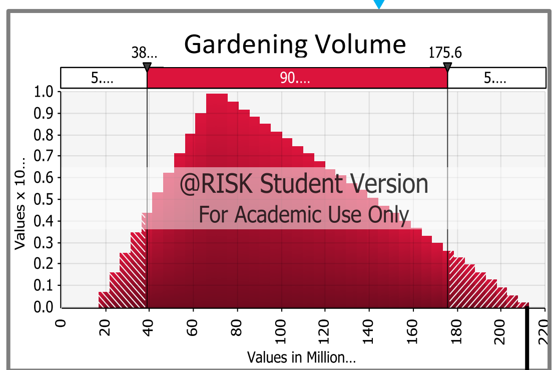
PROCESS IS REPEATED FOR EVERY TIME INTERVAL

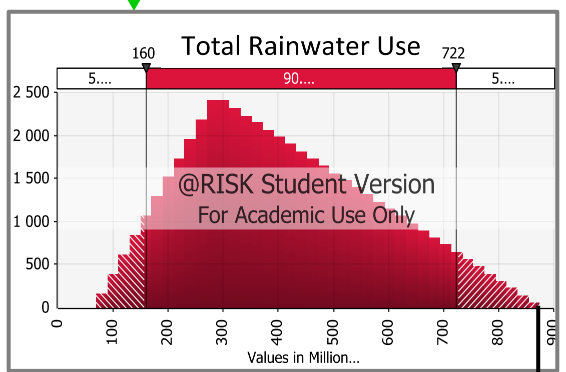
Outputs

Output from @RISK for 06h00 time interval:

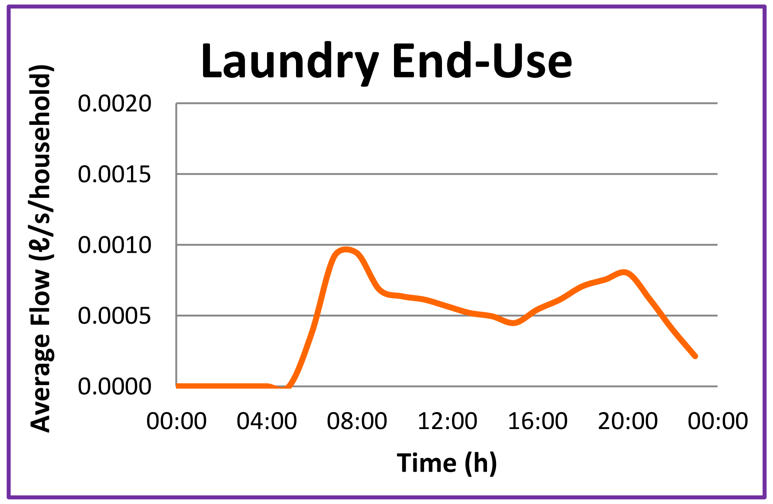


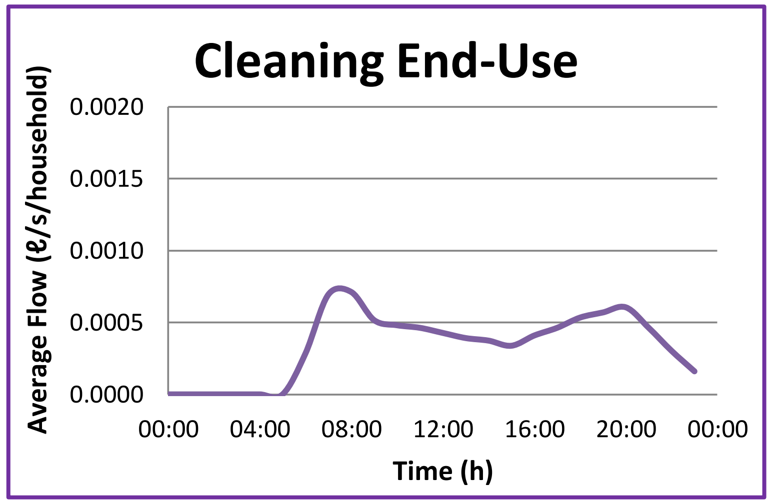


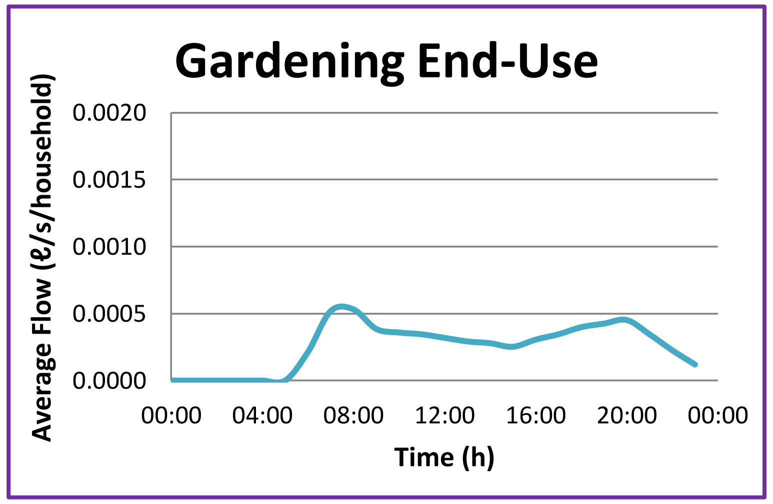


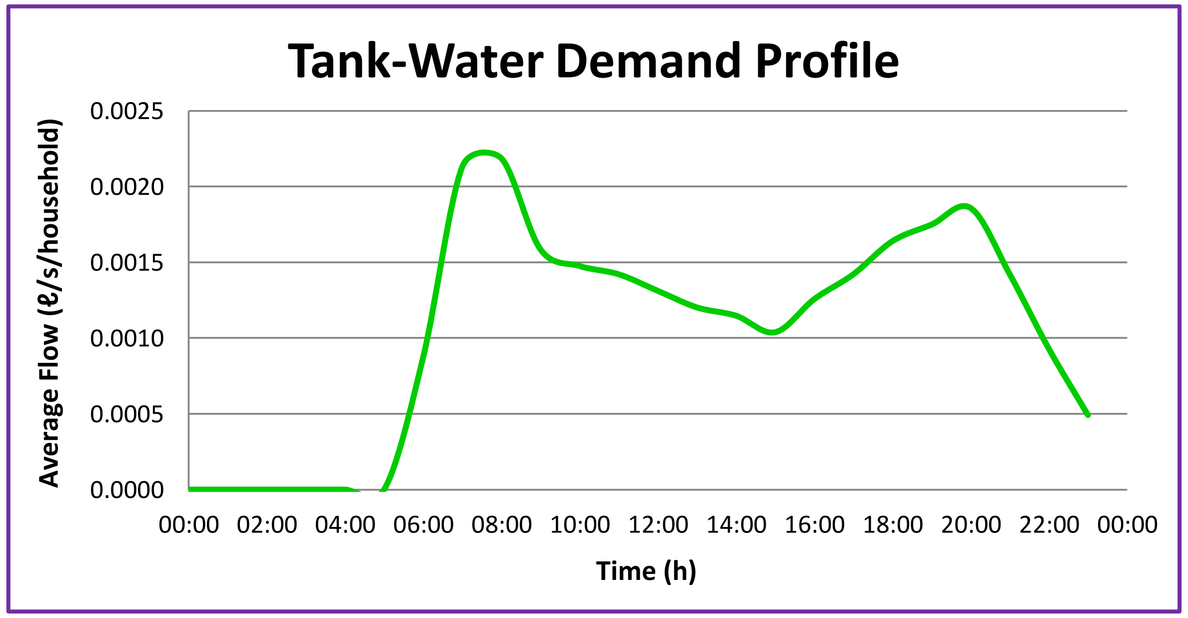


Select the maximum flow rate, for each end-use, at every time interval:


Laundry End-Use
Average Flow (ℓ/s/household)
0.0020
0.0015
0.0010
0.0005
0.0000
00:00 04:00 08:00 12:00 16:00 20:00 00:00
Time (h)


Cleaning End-Use
Average Flow (ℓ/s/household)
0.0020
0.0015
0.0010
0.0005
0.0000
00:00 04:00 08:00 12:00 16:00 20:00 00:00
Time (h)


Gardening End-Use
Average Flow (ℓ/s/household)
0.0020
0.0015
0.0010
0.0005
0.0000
00:00 04:00 08:00 12:00 16:00 20:00 00:00
Time (h)


Tank-Water Demand Profile
Average Flow (ℓ/s/household)
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
00:00 02:00 04:00 06:00 08:00 10:00 12:00 14:00 16:00 18:00 20:00 22:00 00:00
Time (h)