ESTIMATING DOMESTIC OUTDOOR WATER DEMAND FOR RESIDENTIAL ESTATES

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Declaration

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Abstract

The outdoor water consumption of residential properties is a major contributor to the seasonal fluctuation of the overall water consumption of these properties. The estimation of the relating outdoor water demand has become valuable to property developers and planners alike. This could enable designers to optimise designs of water distribution networks and assist in water resource planning and gaining legislative approvals. For the purposes of this study the outdoor water-use components were mathematically defined and combined to develop an outdoor water-demand model.

In order to evaluate the results of an outdoor water demand model on a monthly temporal scale it was necessary to develop a proxy outdoor water consumption evaluation method based on the metered monthly consumption of residential properties. The method entailed verifying that the generally non-seasonal indoor water consumption as a function of the winter water consumption. This entailed analysis of the total monthly, indoor and outdoor water consumption data adopted from a noteworthy North American water end-use project. The indoor water consumption estimated in this manner could then be subtracted from the overall monthly water consumption to obtain estimated monthly outdoor water consumption data. The estimated outdoor consumption could be compared with the simulated outdoor water demand, as described by the model.

The parameters that formed part of the mathematical outdoor water demand model were formulated from data available for residential estates, where conditions such as types of vegetation, irrigated area and size of pool could be prescribed in a constitution, usually instituted by a home owners association. The data was derived from one estate located in the Western Cape Province of South Africa. The mathematical model was simulated using the Monte Carlo method and the @Risk software. Three residential estates located in South Africa were subsequently modelled. Additionally, the model was employed to estimate outdoor water demand for houses located in Northern America for verification purposes.

The Monte Carlo simulations of the outdoor water demand model presented in this study yielded realistic results when compared with the proxy outdoor consumption figures as well as the metered actual outdoor water consumption data analysed. The peak monthly outdoor water demand estimation results were particularly close to the consumption data.

This study serves as a baseline for further research into outdoor water demand. Research into the effects of water restriction and conservation potential could follow from this work, especially in today’s environmentally conscious society.

Opsomming

Die buite waterverbruik van residensiëel eiendomme dra grootliks by tot die seisoenale fluktuasie van die algehele water verbruik van hierdie eiendomme. Die beraming van die dienooreenkomstige buite wateraanvraag kan waarde toevoeg vir eiendomsontwikkelaars and beplanners, indien dit ontwerpers kan instaat stel om water verspreindingsnetwerke te optimeer en te help met water hulpbron beplanning en wetlikke goedkeurings. Vir die doeleindes van hierdie studie is die buite waterverbruik komponente wiskundig gedefinieër en gekombineer om ‘n buite wateraanvraag model te ontwikkel.

Ten einde die resultate van ‘n buite water aanvraag model op ‘n maandelikse tydskaal te evalueer, was dit nodig om ‘n benaderingsmetode te ontwikkel, gebaseer of die gemeterde maandelikse water verbruike gebruik. Die metode behels dat die data, verkry van ‘n bekende Noord-Amerikaanse water eindverbruikprojek, van die algmeen nie-seisoenale binneshuise water verbruik vergelyk word met die maandelikse winter water verbruik. Derhalwe kon die binneshuise waterverbruik wat op hierdie manier beraam is afgetrek word van die algehel maandelikse waterverbruik om die maandelikse buitewater verbruik te beraam. Die beraamde buitewater verbruik kon sodoende vergelyk kan word met ‘n gesimuleerde buite wateraanvraag soos beskryf deur die gesimuleerde model.

Die parameters wat deel uitgemaak het van die wiskundige buite waterverbuik model was gedefinieër uit data wat beskikbaar was vir residensiële ontwikkelings, waar voorwaardes soos plantegroei, besproeiingsarea of swembad grote dikwels voorgeskryf kan word in ‘n grondwet ingestel deur ‘n huiseienaarsvereniging. Die data wat in hierdie model gebuik word is hoofsaaklik afskomstig van ‘n landgoed geleë in die Weskaap provinsie, Suid-Afrika. Die wiskundige model was gesimuleer met behulp van die Monte Carlo metode en die @Risk sagteware. Drie residensiële landgoede geleë in Suid-Afrika was daaropvolgend gemodelleer. Daarbenewens is die model gebruik die buite watergebruik van groepe huise geleë in Noord-Amerika te beraam vir verifikasie doeleindes.

Die Monte Carlo simulasies van die buite water aanvraag model van hierdie studie het realistiese resultate in vergelyking met die beraamde buite verbruike sowel as die werklike gemeterde buite water verbruiksdata opgelewer. Die piek maandelikse buite water aanvraag beramings resultate was veral vergelykbaar met die piek maandeliks waterverbruik data.

Hierdie studie dien as 'n basis vir verdere navorsing in buite waterverbruik. Navorsing gefokus op die gevolge van water beperkings en bewaring potensiaal kan as aanvullende voordele van hierdie studie ontstaan, veral in vandag se omgewingsbewuste samelewing.

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Dedications

To my beautiful wife and daughter, Sandri and Lisa. Without their love and support, the writing of this thesis would not be possible.

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List of Acronyms and Abbreviations

A	Erf size
AADD	Average annual daily demand
CSIR	Council for Scientific and Industrial Research
CF	Comparison Factor
D	Pressure in a water Network
DEADP	Department of Environmental Affairs and Department of Planning
DWA	Department of Water Affairs
DW	Department of Water
G	Geographic regions of a country
HOA	Home owners association
HI	Household income or property value as proxy for household income
LS	Standard of living
MEV	Maximum Extreme Value
P	Price of water
TPA	Transvaal Provincial Administration
SIMDEUM	Simulation of water demand and end use model
REUWS	Residential end use of water study
USA	United States of America
STD Dev	Standard deviation

List of Symbols

A_i	= The area of a property that is under irrigation.
A_p	= The surface area of a pool or water feature.
D_d	= The water level difference after performing a maintenance cycle
E_{to}	= Evapotranspiration
E_w	= Evaporation rate of water in a specific location
E_{pw}	= Events per week
F_{ep}	= Effective precipitation factor
F_{po}	= Pool ownership factor
I_e	= Irrigation efficiency
K_{bc}	= Crop coefficient
P_r	= Measured precipitation
Q_{actual}	= Actual irrigation consumption
O_m	= The occurrence of pool maintenance per calendar month.
Q_{crop}	= Theoretical crop requirement
$Q_{outdoor}$	= Outdoor water demand
Q_z	= Flow rate per irrigation zone
T	= Time per irrigation event
x	= Value on the x-axis
α	= Shape parameter
β	= Scale parameter
γ	= Location parameter
Γ	= Gamma function
σ	= Standard deviation of a total data record
μ	= Standard deviation of a sample of a data record

1 Chapter 1: Introduction

1.1 Background

Fresh water is becoming a scarce commodity, not only in South Africa, but in the entire world (Heinrich, 2007). The Department of Water Affairs of South Africa (DWA, 2008) reported that the need for proper planning and management of this scarce and vulnerable resource is essential to both economic and social facets of human life.

South Africa, in particular, has ample motivation to invest in thorough planning and management of its water resources. In comparison with the global average rainfall of 860 mm per annum (Rosewarne, 2005), South Africa, with an average annual rainfall of 497 mm is considered to be a semi-arid country (Walmsley, Walmsley & Silberbauer, 1999).

Vast areas of South Africa are generally hot and dry which results in high evaporation rates. Unless adapted for these conditions, vegetation suffers under these low rainfall and high evaporation rates (Dye, Jarmain, Le Maitre, Everson, Gush & Clulow, 2008). In order to overcome these conditions, dams and irrigation systems have been developed to provide crops with the water required to survive.

Dye et al. (2008) reported that, in South Africa, millions of hectares of original vegetation have been replaced in the past years. Indigenous grasslands and Fynbos with an annual Evapotranspiration of approximately 700-800 mm have been replaced by mainly tree species with an annual Evapotranspiration of more than 1100 mm. The results of this change in vegetation have downstream effects on the water that is yielded by specific catchments.

Population growth and rising living standards have similarly led to increased water demand. Residential estates with relatively expensive properties are reported as large consumers of water (DeOreo, Mayer, Martien, Hayden, Funk, Kramer-Duffield & Davis, 2011).

Depending on the location, landscaping and layout of an estate, household water consumption is estimated to be in the order of 30% and up to 90% of the total water consumption of an estate. It is therefore essential that the household water consumption is recognised as one of the significant aspects that should form part of the planning exercise of residential estates.

1.2 Problem Statement

Spocter (2011) reported that residential estates became popular in South Africa for the following reasons (amongst others):

- Political insecurity after the 1994 first democratic elections in South Africa;
- Desire for greater protection against crime;
- Strong economic growth in the construction sector between 1995 and 2005; and
- Municipalities viewed residential estates as a benefit to the community.

The worldwide economic downturn and the establishment of development guidelines by the South African Department of Environmental Affairs and Department of Planning (DEADP Western Cape, 2005) have hampered growth in the construction of these residential estates since 2009 (Spocter, 2011). It can, however, be expected that further residential estates will be constructed once the economy has recovered and developers have adhered to the guidelines initiated by the various state departments.

In order to adhere to the guidelines that pertain to water demand of residential estates (DEADP Western Cape, 2005), developers will have to prove that appropriate investigation and planning of the water demand of the proposed estates was conducted prior to gaining approval from the Department of Environmental Affairs. As part of such studies the household water demand will be a significant factor of the total water demand.

The CSIR (2003) is commonly used by planners and engineers to determine the Average Annual Daily Demand (AADD) based on property size. In recent years further research was done with regards to the estimation of AADD, which found the AADD calculated using the CSIR (2003) method to be conservative. Later studies suggest that mathematically structured end-use models will be compared with the empirical methods.

End-use models often separate residential water demand into indoor and outdoor water demand (Scheepers, 2012). Indoor water demand has been widely modelled by leading researchers in the field (Blokker, Vreeburg, & Van Dijk, 2010). Outdoor water consumption is often excluded because of its climatic and geographic characteristics (Scheepers, 2012). Outdoor water demand is, however, estimated to contribute approximately 40%-60% to the AADD of homes in residential estates.

It therefore becomes important to be able to estimate the indoor as well the outdoor water demand of residential properties, in support of the motivation of residential estates as part of their applications for approvals from the various state departments. This study will focus on the estimation of the outdoor water demand to supplement other studies based on the indoor water demand.

1.3 Thesis Statement

The following thesis statement is aimed at addressing the shortcomings of the engineering and planning practice identified in the problem statement:

The estimation of outdoor water consumption and the related variation in flow rate can be stochastically derived from the expected behavioural, geographical and technical aspects or parameters that describe households in a proposed residential estate.

The objectives of this study are the following to:

- conduct a thorough literature review of information that are relative to this study;
- developed an empirical estimation model to estimate outdoor residential demand for residential estates;
- stochastically derive parameters from behavioural, geographical and technical data to populate the estimation model;
- compare the results with high resolution data available from estates in the western cape; and
- compare the difference between summer and winter water consumption of various residential estates with the estimation model results.

The results derived from this study will provide insight to the estimation of outdoor water demand. This study, along with other studies compiled for the estimation of indoor water demand, will provide a more accurate approach to methods that are currently available for estimating AADD for residential estates.

1.4 Terminology

1.4.1 Water demand

In this thesis “water demand” refers to the estimated volume of water necessary to supply customers within a specified period of time. This is usually estimated by means of a prescribed guideline or mathematical model. The water demand of residential properties is used to predetermine the magnitude of required infrastructure for the development of these properties.

1.4.2 Water consumption

In contrast with “water demand”, “water consumption” is referred to in this thesis as is the actual metered volume of water supplied to a property. In this study it refers to the metered consumption of residential properties usually recorded by a municipality or private water metering companies.

1.4.3 Water end-use

A “water end-use” describes a specific type of devise, element or fixture where water is released from, such as taps, washing machines, irrigation systems, et cetera (Jacobs, 2004).

1.4.4 Residential property

The term “residential property” is used in the text to describe a single residential property, comprising of a bounded portion of land. The property often has a single dwelling with a garden, a pool, paved areas, et cetera. The following words are used in the literature to describe a property:

- lot;
- site;
- households; and
- homes.

1.4.5 Evapotranspiration

“Evapotranspiration” is a combination of two processes; evaporation and transpiration. During the process of evaporation water is lost to the atmosphere from the soil surface, and water is lost from the crop during transpiration. The factors affecting evaporation and transpiration are weather parameters, crop characteristics, management and environmental aspects. Dye, P.J., Jarmain, C., Le Maitre, D., Everson, C.S., Gush, M. & Clulow, A. (2008).

2 Chapter 2: Literature Review

2.1 Chapter overview

Residential estates are usually provided with water from a combination of the following sources:

- Potable water supplied via a piped water distribution system;
- Ground water supply (boreholes);
- Abstraction of water from a nearby river or dam;
- Treated sewage effluent; and
- Stormwater run-off.

The use of potable water supply for outdoor irrigation is of particular significance to residential properties (Veck & Bill, 2000). The water quality of the other sources prescribes that they are in most cases allocated to landscape irrigation of the non-residential areas and in some cases, fire water supply.

2.2 Residential water demand overview

The design of the water treatment facilities, water storage facilities, water supply pipelines, pump stations, water distribution networks and even components of sewerage infrastructure depends mainly on the estimation of the AADD (CSIR, 2003). The publications that described methods for estimating AADD were chronologically reported by Jacobs (2008b), as represented in Table 2.1.

The calculation of the AADD according to the CSIR (2003) is popular in South Africa, but was reported as conservative relative to other methods and data analyses (Jacobs, 2008b). Overestimation of AADD could result in the overdesign of water infrastructure for all users and in particular residential estates. In addition to the overdesign of water infrastructure many residential estates have been denied statutory approval based on the historically excessive water demand of these estates (Spocter, 2011).

Table 2.1 : Chronological overview AADD guidelines (adapted from Jacobs, 2008b)

Year	Reference	Independent Variables	Comments
1960	Lock	A, LS	First publication with water demand as function of A
1965	DW (1965)	A	First AADD guideline in South Africa with A as variable
1965	Van Duuren	A	Guideline identical to DW (1965)
1970	Port Elizabeth Mun.	A, LS	Guideline limited to Port Elizabeth
1971	Morris	N/A	Publication provides information w.r.t. end-uses
1974	Ellis, Van Duuren	H I	Results not presented as AADD
1975	Gebhardt	D	Results not presented as AADD
1975	DW (1975)	A	1965 Guideline revised and republished in June 1975
1976	TPA	A	Aimed at inland users (originally Transvaal)
1977	Turner et al.	A	Tabular AADD guideline almost identical to the TPA (1976)
1979	Garlipp	A, G, HI	First detail research of AADD with A as variable
1982	Rooseboom et al.	A	Tabular AADD guideline almost identical to the TPA (1976)
1983	CSIR	A	AADD guideline in popular document, widely promoted and used
1989	Hare	A	First verification of 1983 AADD versus metered data
1996	Stephenson, Turner	A, HI	Second verification of 1983 AADD versus metered data
1997	Van Vuuren, Van Beek	A, HI	62 Data point compared with 1983 AADD
2002	Haarhoff et al.	A, HI, P, D	Pilot project, results not presented as AADD
2004	Jacobs et al.	A, G, LS	First AADD guideline in South Africa with geographical regions
2006	Husselman, Van Zyl	A, HI	First guideline that focussed on household income
2007	Du Plessis	G	Specifically focussed on municipalities in the Western Cape, South Africa.
2008	Van Zyl et al.	A, G, HI	Guideline with large data set
2009	Jacobs, Strijdom	D	Impact of water consumption on water pressure
2009	Griffioen et al.	A, G, HI, LS	Water demand modelling on suburb level
2012	Van Zyl et al.	D	Focussed on water storage capacities
2013	Jacobs et al.	A	Effect of Land Area on AADD

Notes :
A = Erf size (Area)
D = Pressure in the water network (typically residual or static pressure)
G = Geographic regions of a country
HI = Household income or property value as proxy for household income
LS = Standard of living
P = Price of water

Various approaches are available to model and evaluate the water consumption of residential properties. The parameters included in these approaches were a combination of the following factors (Jacobs, 2008b):

- Erf size or area;
- Pressure in the water network;
- Identification of geographical regions;
- Household income;
- Standard of living; and
- Price of water.

End-use models are based on specific end-use elements as illustrated in Figure 2.1 (Scheepers, 2012).

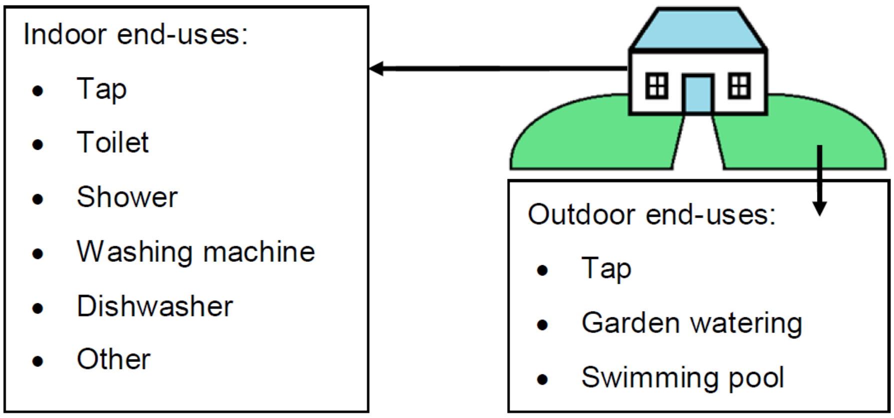

Figure 2.1 : Typical indoor and outdoor end-use elements (Scheepers, 2011)

The end-use models are derived from the contribution that each of these elements or end-uses make to the total residential water demand (Jacobs, 2008a). The focus of this study will be the estimation of the outdoor component of water demand, with specific focus on residential estate scenario.

2.3 Outdoor water demand

2.3.1 Overview

Outdoor water demand presents a combination of seasonal and behavioural aspects that are more difficult to predict than indoor end-use events (Scheepers, 2012). These hurdles are likely to be addressed more often in future, as more detailed information and high resolution data becomes readily available.

Outdoor use, including irrigation and the evaporation from pools and other water features is the main contributor to seasonal fluctuation in water consumption. Roberts (2005) recorded end-use data for two weeks in summer and two weeks in winter at 840 residential customers in the Yarra Valley, in Victoria, Australia. Roberts (2005) reported that the seasonal end uses collectively made up 32% of the total consumption during the summer logging period. Seasonal end-uses were defined as the fluctuation of water demand as the result of seasonal change in factors such as temperature, rainfall, snowfall and humidity. During the winter period, these seasonal end-uses could not be identified (Roberts, 2005).

As part of the same study by Roberts (2005) investigated billing data. The results indicated that seasonal use could account for 25.4% of the total annual residential use, where garden irrigation was estimated to account for 87.3% of the total seasonal use (Roberts, 2005). In comparison Veck and Bill (2000) reported in a contingent valuation study that outdoor use contributed 19% to the total use in the Alberton area in South Africa, of which 74% consisted of garden irrigation.

In this study, specific reference will be made to household garden irrigation, evaporation from water features and swimming pools and uses of outside taps, because these outdoor end-use events are regarded as applicable to South African conditions (Scheepers, 2012).

2.3.2 Irrigation

Specific emphasis in this study is given to garden irrigation, as it is expected to form the most significant portion of outdoor water demand. The seasonal properties of irrigation demand, and pool filling in a lesser degree, are considered to contribute to the bulk of the seasonal fluctuation of household demand patterns.

Household irrigation demand can be described as a function of the following factors (DeOreo et al., 2011):

- Irrigated area;
- Vegetation types;
- Geography (topography, weather, climate, soil conditions); and
- Human behaviour (irrigation frequency, method, price elasticity, income).

Various studies have been conducted where irrigation demands were calculated and irrigation consumption data analysed. DeOreo et al. (2011) reported that differences between irrigation demand and irrigation consumption can be defined as under-irrigation or over-irrigation. The following proposed irrigation demand theories were reviewed:

- The CSIR (2003) states that 15 kℓ/ha/day of water must be allowed for the estimation of the AADD of developed parks.
- Irrigation consumption equates to 640 ℓ/d on the Kapiti Coast district, New Zealand (Heinrich, 2007).
- Average irrigation flow reported by Roberts (2005) for the Yarra Valley was 16.3 ℓ/min and the average duration was found to be 46 min per event. The two methods identified for irrigation were the hand-held (average 37 min@14.8 ℓ/min) and sprinkler systems (average 66 min@14.8 ℓ/min).
- Midgley, Pitman & Middleton (1990) describe a method of irrigation demand calculation based on the calculation of the evapotranspiration and the effective rain and then supplementing the deficit with irrigated water per irrigation area.
- The theoretical irrigation requirement calculation as per DeOreo et al. (2011) is similar to the method presented by Midgley et al. (1990). It takes into consideration evapotranspiration, the effective rainfall and the irrigated area. The method prescribes that properties be subdivided into individual irrigation zones, each zone allocated an irrigation efficiency and a zone coefficient comprised of factors for species, density and microclimate.

Various methods of household irrigation were noted during the literature review included:

- hand-held hose irrigation;
- drip irrigation; and
- micro sprayer irrigation.

Household irrigation methods are sometimes automated and at other times manually operated. In many cases a combination of these methods is used by residents to irrigate their gardens (Roberts, 2005). Linger (2011) reported that the number of rainy days has a more significant impact on water demand than rainfall quantity, and this suggests that consumer behaviour has a greater impact than theoretical water requirements of vegetation.

It has been reported by Roberts (2005) that 57% of residents in the Yarra Valley use the hand-held hose method for 37 minutes on average, which accounts for 43% of the total irrigation volume analysed. In the same study it is reported that 29% of homes use the sprinkler method. In addition to the various methods used for irrigation of household gardens, the irrigation frequency varies from household to household. In the Yarra valley an average of 3.1 irrigation events occurs per week for the properties that irrigate their gardens (not all the properties are irrigated).

Although the choice of vegetation and the size of the irrigated area can be regarded as influenced by human behaviour, it is not affected by frequent change of behaviour. It could be expected that vegetation and the irrigation layouts of properties will vary over time because of the change of inhabitants, reduction or increase of irrigated area, and changes of vegetation types within the existing irrigation area (Val de Vie HOA, 2007).

Crop coefficients are used in irrigation-demand calculations to differentiate between various crops. Each specific crop has a characteristic crop coefficient that depicts the amount of water that the crop requires to survive relative to evapotranspiration from reference crop such as cool season grass used in the urban environment. Table 2.2 lists crop coefficients relevant to vegetation found in residential estates.

Table 2.2 : List of crop coefficients (DeOreo et al., 2011)

Plant Type	**Crop Coefficient**
Reference grass (Cool season grass for urban purposes)	1.00
Turf	0.80
Non-turf trees, shrubs	0.65
Vegetable gardens	0.80
Xeriscaping	0.30

In addition to the areas and the types of vegetation, some vegetation types' varying demand patterns depend on growth stages of the vegetation (Mayer, 2000). In general, a plant requires more water at the time that it is in its initial growth phase, than when established. Residential estates often stipulate the types of vegetation and allowable areas that may be irrigated (Val de Vie HOA, 2007). These regulations can aid in estimating relatively accurate irrigation demands, because the unknown parameters could be narrowed down.

The geographical conditions of a region are indicators of the irrigation demand of the vegetation in the region. Some vegetation is also adapted to survive better under certain conditions. A cactus plant is typically adapted to survive in arid conditions and the arum lily thrives in wetland areas, for example.

Weather and climate affects the net evapotranspiration of vegetation and therefore indirectly influence irrigation demand, and in turn outdoor use. Changing temperature, solar radiation, rainfall and wind are, in particular, the factors that contribute to the fluctuation in evapotranspiration (Dye et al., 2008).

The topography of a landscape also plays a role in the irrigation efficiency and effectiveness of the rainfall in a proposed irrigation system. Steeper slopes cause increased runoff of water, which results in a water deficit in these areas and consequently an increased irrigation demand (Kapangaziwiri & Hughes, 2008). Soil conditions range between permeable and impermeable. Sandy soil allows for well-drained conditions where clayey soils typically drain poorly. Vegetation types are adapted to their native conditions and therefore thrive in the conditions it is intended for (Midgley et al., 1990).

2.3.3 Swimming pools and water features

Swimming pools and water features are popular with home owners in residential estates, because their average income is high and the climate of South Africa is generally hot. Evaporation and leaks caused by swimming pools contribute to significant volumes of water that have to be supplemented in order to ensure that pool water levels are suitable for aesthetic and operational purposes (DWA, 2011).

As with irrigation, evaporation at swimming pools and water features is climatically dependent and therefore contributes towards the seasonal variation in outdoor use. Exposed surface area is the other factor that contributes to the water consumption required for swimming pools and water features. The water consumption that result from pools and water features can be controlled in estates by limiting its open water surface area allowed on specific properties.

Roberts (2005) reported that on average 12% of the recorded summer water was used for filling of swimming pools – for all homes that registered swimming pool consumption. This figure, however, ranged between 1% and 28% at individual homes. Swimming pools in the state of California typically require 102 mm of water per week, irrespective of pool size (DeOreo et al., 2011). A pool of 50 m^2 would for example require 5.1 kℓ/week.

Rainfall data, along with pan evaporation data collected from S-pan and A-pan measuring equipment, is used to calculate the net evaporation of a region or can be measured and calculated as site specific data (Midgley et al., 1990).

2.3.4 Outdoor tap use

Outdoor tap use for general miscellaneous purposes, tends to be erratic and measurements can be difficult to obtain from non-intrusive investigations. Survey information is typically used to determine the extent of outdoor use from taps (DeOreo et al., 2011). Outdoor taps are generally used to wash cars, rinse windows of buildings and for cleaning of impervious surfaces. Outdoor tap uses have a relatively insignificant impact on seasonal water demand cycles in comparison with garden irrigation (Roberts, 2005).

DeOreo et al. (2011) reported that taps yield between 9.5 ℓ/min and 26.5 ℓ/min. Low flow taps with a standard flow rate of 8.2 ℓ/min have since been introduced in the states of California and other parts of the USA. An average flow rate of 4.56 ℓ/min with a standard deviation of 2.58 ℓ/min has been modelled by Scheepers (2012). Roberts (2005) reported an average of 3.28 ℓ/min with a standard deviation of 2.62 ℓ/min. As a result of the relatively low consumption volumes that result from outdoor tap use, it has been deemed insignificant to be included in the model developed for this study.

2.4 Demand modelling

2.4.1 Available residential demand modelling

Jacobs (2004) reported that water demand modelling, especially in the USA, originally focussed on price elasticity. More recently, the focus has shifted from price to evaluation of water demand management issues. The reasons listed for water demand modelling were:

- The effect of water price changes on water sales revenue;
- Future water demand estimation for infrastructure design;
- Improved understanding of the use of water;
- Propose reduction of water demand measures;
- Comparison of water consumption with modelled water demand;
- Motivation for allocation of government grants; and
- Identification of future research.

Various types of modelling exist in the water demand environment. The model types listed below were described by Jacobs (2004):

- Single Coefficient Method (Bi–variate);
- Multi-Coefficient Method (Multivariate);
- Casual or Structural Models;
- Economic versus Requirement Models;
- Stochastic and Probabilistic Methods;
    - Monte Carlo;
    - Poisson pulse queuing method;
- Deterministic-Chaos Method;
- Time Series With Non-linear Climatic Effects;
- Artificial Neural Network and Memory-based Learning;
- Contingent Evaluation; and
- Free Water Allowances.

Water demand modelling is often a function of spatial and temporal aggregation levels. In water demand modelling the planners of estates are concerned with three levels of modelling (Blokker et al., 2010):

- Level 1 – The treatment of water is modelled as a demand per day. Daily and seasonal demand patterns are of importance.
- Level 2 – The transport of water is of concern. Daily demand patterns are important.
- Level 3 – The distribution of water to the specific end-users where a demand per minute (or second) becomes important and per-user demand patterns are analysed.

Blokker et al. (2010) developed a water demand end-use model to predict water demand patterns at a 1 second interval for residential estates. The model was based on statistical information such as the number of people per household; people's age; frequency of use and duration of use per event. Blokker et al. (2010) used water consumption data to develop an end-use model that is based on the principal of rectangular demand pulses. The water end-use pulses arrive at different times during the day, at different flow rates (intensities) and have different durations. These pulses are then summated for every frequency of every end use for every user in a distribution network, which results in a collective water demand pattern.

In terms of stochastic modelling, Blokker et al. (2010) proposed that the parameters for time of arrival; frequency of use; intensity and duration be derived from statistical data and fitted with probability curves.

Blokker et al. (2010) used the following probability distributions functions to describe end uses:

- Intensity - Uniform;
- Duration - Log Normal;
- Frequency - Poisson; and
- Time of arrival - A cumulative distribution function.

The proposed distribution fits were imported to the model developed by Blokker et al. (2010), after which the collective influences could be modelled. A Monte Carlo simulation method was used to randomly select stochastic data from the available distributions (Blokker et al., 2010). The selected data was then repeatedly populated in the proposed mathematical model using MATLAB software and called the SIMDEUM model, which stands for Simulation of water demand; an end-use model.

2.4.2 Monte Carlo simulations

Ripley (1987) reported that Monte Carlo is a simulation method used to stochastically solve mathematical or statistical problems. For the purposes of this study, Monte Carlo is defined as a stochastic simulation method. Monte Carlo Simulations have been developed to solve problems involving random variables with estimated probability distributions. By repeating a simulation model with randomly selected values from the assumed probability distributions, a sample of solutions is obtained (Ang & Tang, 1990). Although alternative stochastic methods have reduced computational times, they also have reduced accuracy.

Each probability distribution is sampled in order to reproduce the shape of the distribution. When the results of the model outcome are represented as a distribution, it reflects the probability that the values could occur (Vose, 2008). Monte Carlo Simulations have often been applied in the various industries to approach integral problems since World War II. Monte Carlo simulations are often limited by constraints of economy or computer capabilities. However, where no other analytical solution methods are available, or if the solutions are ineffective, Monte Carlo simulations could be used to solve problems that require realistic simulation models or for validating of approximate analytical results.

In order to conduct Monte Carlo simulations, it would be necessary to use computer software. Various software programmes are available for this purpose, including Microsoft Excel and MATLAB, that include pre-programmed functions to perform multiple repetitions of the desired model simulations.

Palisade (www.palisade.com) have developed an add-on software package, @RISK, for Microsoft Excel, which possesses the functions commonly required for performing Monte Carlo simulations.

2.4.3 Statistical characteristics

In order to develop a model for simulation of certain statistical concepts such as mean, standard deviation, range, percentile, median and mode were reviewed. Reference could be made to Montgomory & Runger (2002) for further detail with regards to these concepts.

2.4.4 Probability distribution functions

In order to describe a data set's probability distribution function mathematically, specific mathematical properties and parameters have been developed. These properties and parameters could be derived from actual data and used to mathematically estimate theoretical distribution functions that are applicable to the data. These parameters are commonly the shape, location and scale parameters.

As the name suggests, the shape parameter (α) determines the specific shape of a theoretical distribution that is used to emulate the measured data (Figure 2.2). The scale parameter (β) has an effect on the peak and the width of a distribution function (Figure 2.3). The location parameter (y) depicts the position of the distribution on the x-axis (Figure 2.4).

Various theoretical distribution functions have been developed to emulate data, in this study the distribution functions in the following subsections were applied to the variable parameters in the Monte Carlo simulations.

Table 2.3 : Probability distribution functions that apply to this study

Name	**Probability Distribution Function Equation**
Extreme Value	$f(x) = \frac{1}{\beta}\left(\frac{1}{e^{z} + \exp(-z)}\right)$ where $z \equiv \frac{(x - \alpha)}{\beta}$
Gamma	$f(x) = \frac{1}{\beta\Gamma(\alpha)}\left(\frac{x}{\beta}\right)^{\alpha-1} e^{-x/\beta}$ where Γ is the Gamma Function
Lognormal	$f(x) = \frac{1}{x\sqrt{2\pi}\sigma'} e^{-\frac{1}{2}\left[\frac{\ln x - \mu'}{\sigma'}\right]^2}$ with $\mu' \equiv \ln\left[\frac{\mu^2}{\sqrt{\sigma^2 + \mu^2}}\right]$ and $\sigma' \equiv \sqrt{\ln\left[1 + \left(\frac{\sigma}{\mu}\right)^2\right]}$
Triangular	$f(x) \frac{2(x - \min)}{(m.likely \quad \min)(\max - \min)}$ where $\min \leq x \leq m.likely$
Uniform	$f(x) = \frac{2(\max - x)}{(\max - m.likely)(\max - \min)}$ where $m.likely \leq x \leq \max$

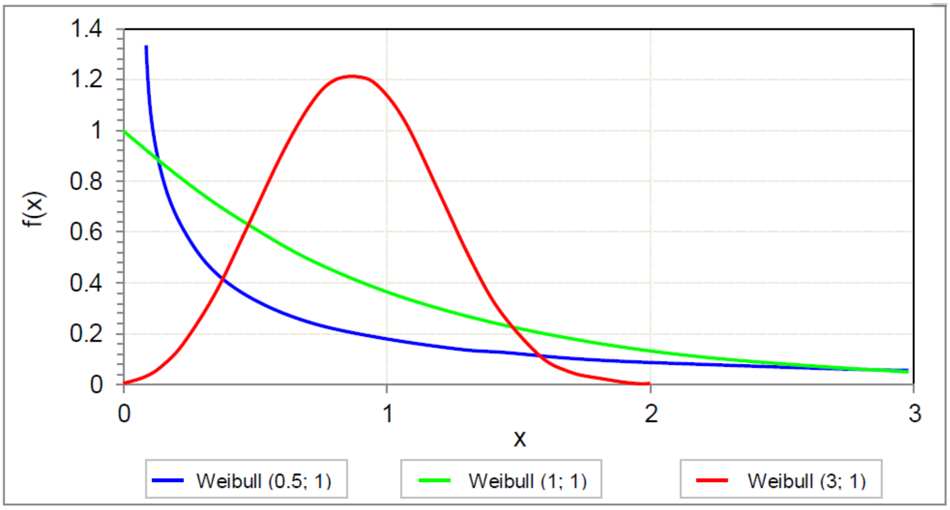

Figure 2.2 : The effect of the shape parameter on a Weibull distribution

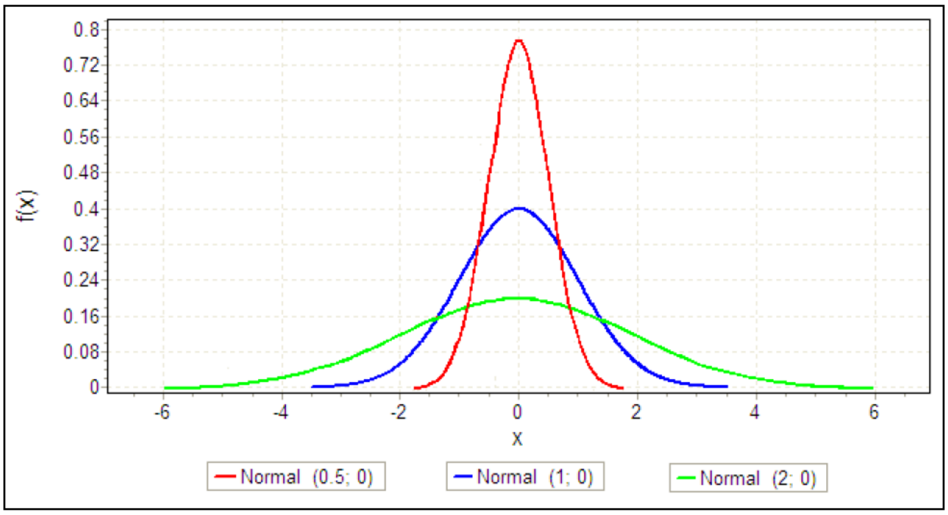

Figure 2.3 : The effect of the scale parameter on a Normal distribution

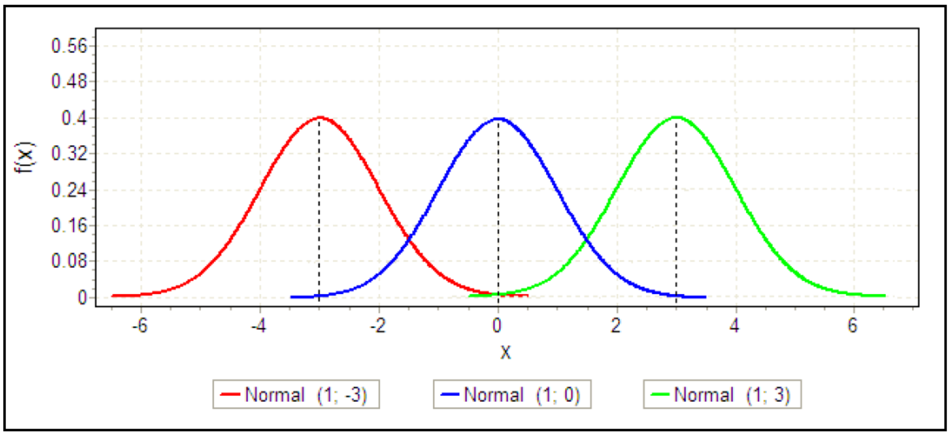

Figure 2.4 : The effect of the location parameter on a Normal distribution

2.5 Residential estates

2.5.1 Description

Residential estates are commonly referred to as gated communities, or housing estates. This type of estate is popular in many countries, including South Africa, for the reason that they offer added security and usually some type of lifestyle improvements relative to single-title homes, built on properties within general municipal suburbs (Landman, 2004). These estates are usually characterised by the similar architecture of the buildings and the group of houses is often closed off to the general public by means of a boundary wall and security-controlled entrances.

Spocter (2011) conducted a study that relates to the growth of gated residential security estates in the Western Cape, South Africa and reported a proportional growth between the increase in crime and the increase in authorised residential estates. (See Figure 2.5).

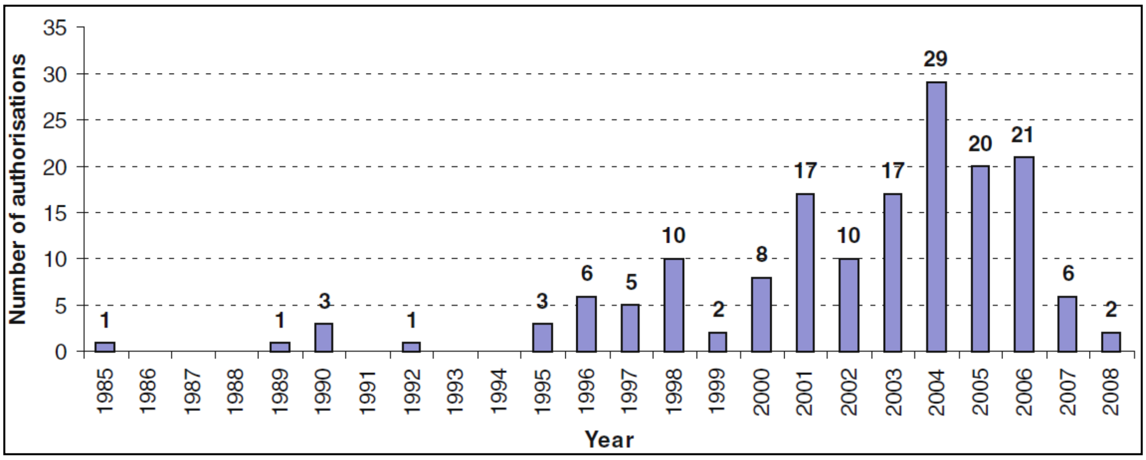

Figure 2.5 : Number of new residential estates in Western Cape (Spocter, 2011)

DEADP (2005) released a guideline document that listed eight objectives for the development of golf an polo estates. These objectives included sustainable development principals and clarity with regard to the environmental application processes that had to be followed for new estates. Spocter (2011) reports a clear decline in the number of new residential estates in South Africa. This could be due to the more stringent guidelines (DEADP, 2005) and the general economic downturn. Gated communities and residential estates, however, remain popular in South Africa.

Residential estates are often governed by trustees of homeowners associations who are responsible for the operation and the maintenance functions of the infrastructure, as well as implementing and adhering to legislation that pertains to the estate.

A constitution, along with other guidelines and rules, is typically drafted prior to the establishment of the first homes and together these act as the agreement between homeowners and the trustees. These rules and guidelines address issues pertaining to the following:

- Use and maintenance of open areas;
- Conduct in the public areas of the estate;
- Environmental management;
- Water- and electricity-demand management;
- Architectural guidelines, gardening and vegetation; and
- Security, levies, pets, et cetera.

During interviews conducted by Landman (2003), the following reasons were identified by homeowners as motivation for living in security estates:

- Safety and security;
- Sense of community and identity;
- Financial investment and market trend;
- Proximity to nature and specific lifestyle choice;
- Efficiency of services provided and independence from municipal services; and
- Status, prestige and exclusivity (elitism).

From the above reasons it could be deducted that the home owners of properties in these estates are generally of a higher income group and can afford to invest in a residential estate that offers a more expensive lifestyle.

2.5.2 Water consumption of residential estates

Residential water consumption varies from country to country and from one climatic region to the next. Linger (2011) compared the residential water consumption per capita for various states in the USA and countries in Europe (See Table 2.4). DeOreo (2011) reported that water consumption is geographically and climatically sensitive.

Table 2.4 : Comparison of residential water consumption in the USA and Europe

Region	Per capita water consumption (ℓ/capita/day)	Year of estimate
United States cities		
Albuquerque, NM	511	2001
Denver, CO	602	2001
El Paso, TX	462	2001
Las Vegas, NV	871	2001
Phoenix, AZ	545	2001
Santa Fe, NM	409	2005
Tucson, AZ	405	2001
European countries		
Denmark	132	1999
France	163	1995
Germany	129	1998
Netherlands	220	1999
Norway	223	1999
Spain	265	1998
United Kingdom	344	2000

Linger (2011) also compared the average water consumption between single- and multi-residential households in Perth, Australia. Figure 2.6, adopted from Linger (2011), illustrates the effect that socio-economic variables have on residential water consumption.

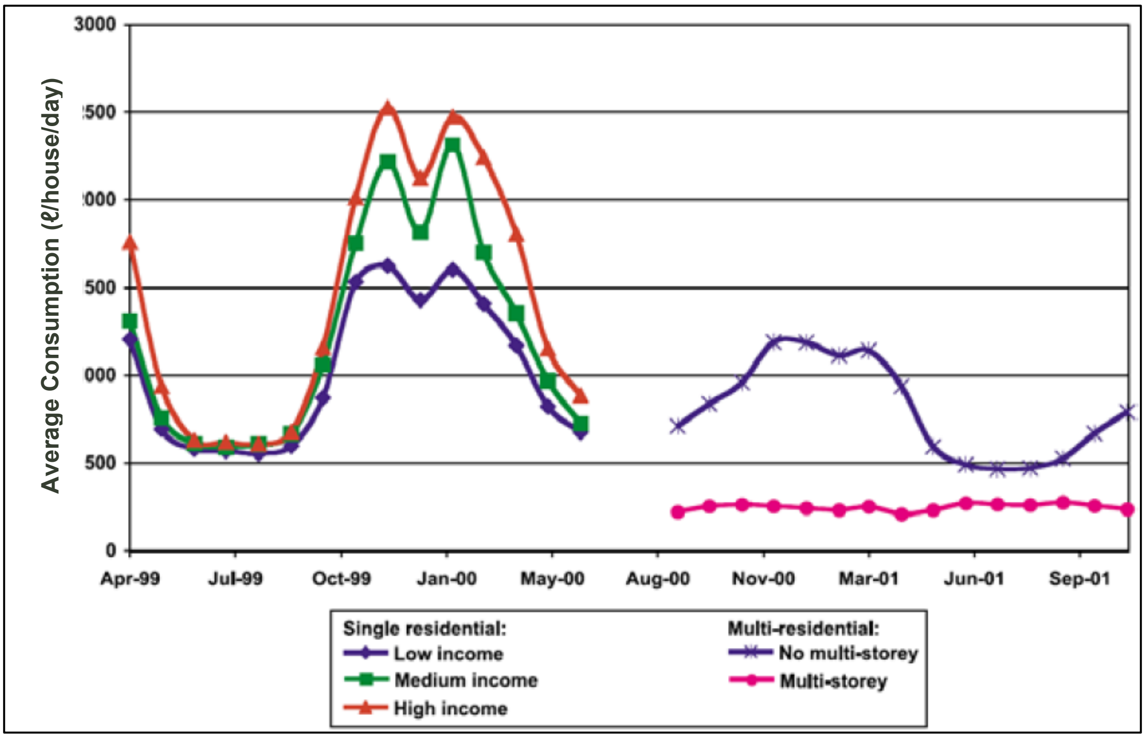

Figure 2.6 : Average monthly consumption for residential households in Perth, Australia

More often than not, properties in residential estates, as defined in this study, are owned by consumers who could afford to pay for the additional security and lifestyle that are typical of these estates, these consumers tend to also consume relatively high volumes of water (DeOreo 2011). The red line in figure 2.6 illustrates the typical annual water consumption profile of these higher income households.

2.5.3 Developmental process

The stage of development of a residential estate has significance in terms of water demand modelling, in the sense that the water consumption of the estate is dependent on the level of development that has taken place. Boucher (1993) reported the following seven steps that relate to the typical residential development process:

- Step 1 : Marketing analysis;
- Step 2 : Site selection;
- Step 3 : Site acquisition;
- Step 4 : Planning and engineering;
- Step 5 : Financing;
- Step 6 : Construction; and
- Step 7 : Marketing.

REAS (2013) describes the development process with a flow chart as illustrated in Figure 2.7.

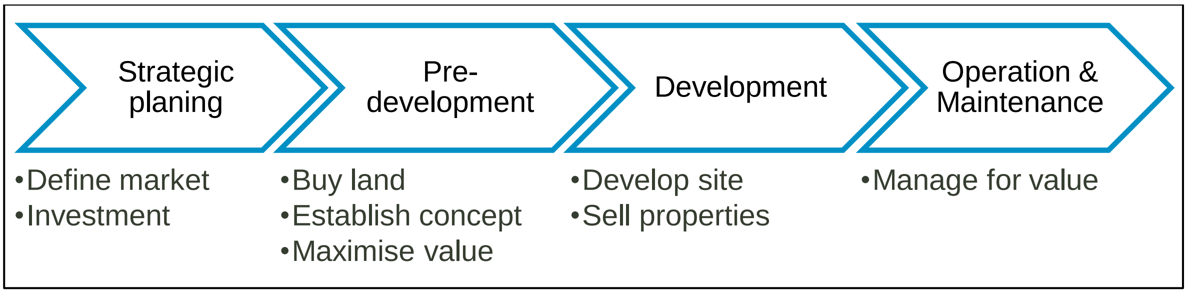

Figure 2.7 : Residential development process flow chart (adopted from REAS, 2013)

The Construction and Marketing stages usually run concurrently and therefore, by the time that the development is complete, the homeowners starts to develop the individual properties. It is therefore important that the requirement and availability of resources and existing infrastructure are investigated during the duo-diligence and feasibility stages of a project (Boucher, 1993). For the purposes of this study the total potable water demand was investigated. Further studies could involve demand during the phases of development and the sale of properties.

3 Chapter 3: Model Development

3.1 Overview

As part of this study existing water-consumption data was collected from various residential estates and was used to derive a stochastic outdoor-water demand model. The model could be used to estimate outdoor-water demand for the purposes of designing proposed residential estates. In addition to the estimation of outdoor water demand, the proposed stochastic model could be applied to evaluate the status quo of the actual outdoor water consumption of existing residential estates.

The properties that were analysed in this study have one water meter that record the total water consumption of the property on a monthly basis. The total water consumption include indoor and outdoor consumption, with no means to directly differentiate between the two. It could be advantageous to install two water meters at each property that record the indoor and outdoor water consumption separately. For the purposes of this study recording of outdoor water consumption was not executed due to the extensive on-site plumbing alterations that could result from such a retrofitting exercise. An alternative technique was researched as part of this study to theoretically assess the average monthly outdoor demand, as a portion of the total monthly water consumption at a property.

In this study results from the stochastic model were compared to the derived outdoor water demand from what is referred to as the proxy approach as illustrated in the flow diagram in Figure 3.1.

The input parameters for the stochastic model were defined by obtaining and measuring the weather, geographical and spatial data of a typical residential estate, further referred to as Estate A. The stochastic model was hereafter compiled and compared to the data of two other estates located in South Africa, and properties located in the USA. The verification was performed using parameters similar to those obtained from the initial residential estate, Estate A.

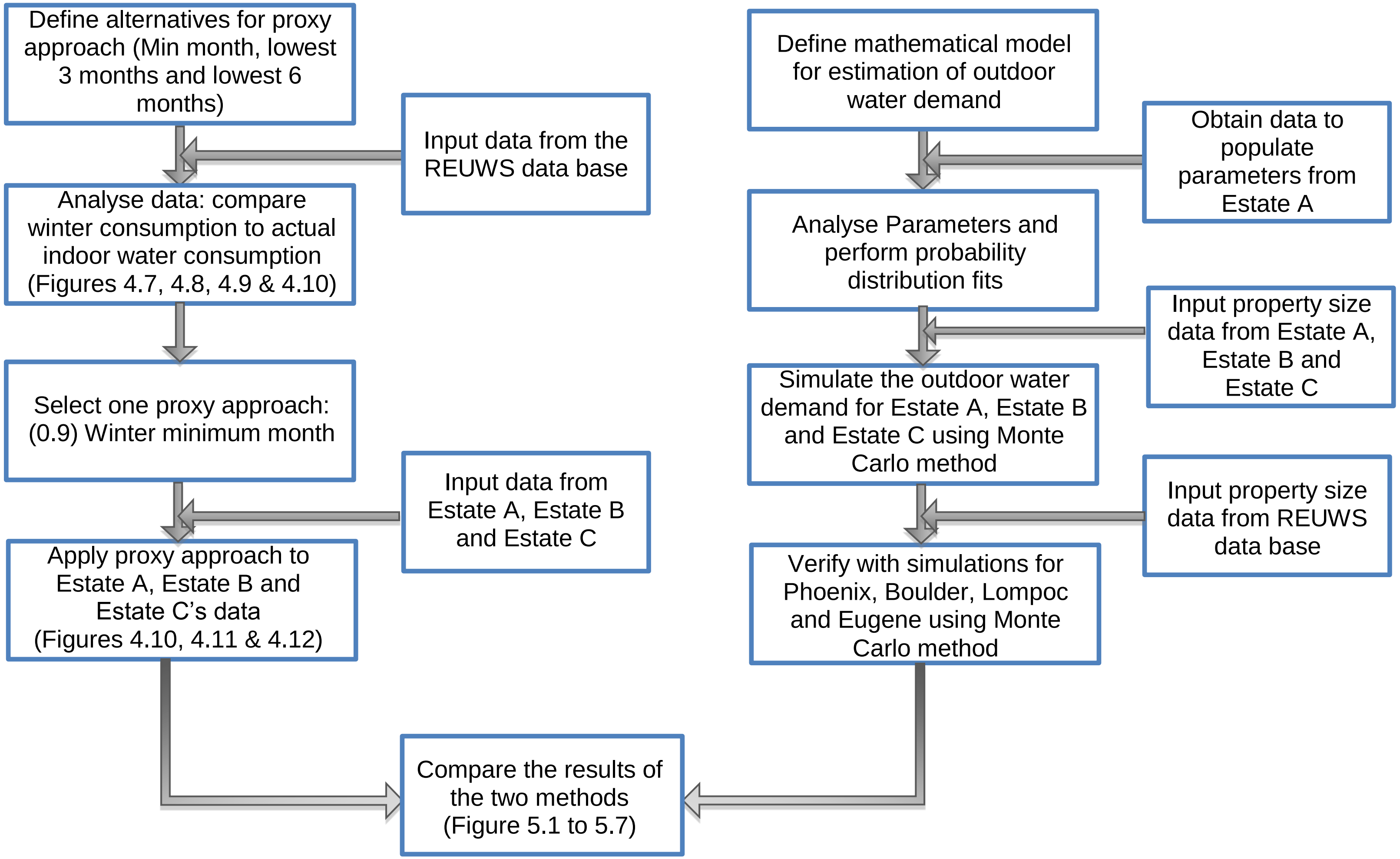

Figure 3.1 : Basic process of the methodology

3.2 Research design

3.2.1 Motivation for research design

During this research it was necessary to develop a tool for outdoor water demand estimation that could be applied to various residential estates. It was proposed that indoor water demand and outdoor water demand components be derived for the estimation of total water demand (DeOreo et al., 2011).

3.2.2 Average winter consumption versus Outdoor water demand

The seasonal fluctuation in water consumption is typically a function of the outdoor water consumption, where indoor water consumption is typically non-seasonal (DeOreo et al., 2012).

A basic technique used to determine outdoor water demand on a monthly temporal resolution was investigated and verified by DeOreo et al. (2011), using data derived from the Residential End Use of Water Study (REUWS) by Mayer et al. (1999). It was suggested by DeOreo et al. (2011) that in a single family home, the winter water consumption is an acceptable proxy for indoor use, for estimating outdoor water demand. The method assumes that either the consumption of the minimum month in year, or the average of the lowest three consecutive months is an indication of the average indoor water consumption. By subtracting the proxy indoor water consumption from the total water consumption one could arrive at an estimation of the outdoor water demand of a house.

In this study the technique was verified in relation to metered outdoor water consumption data. The data gathered by Mayer et al. (1999) included a set of outdoor water consumption data that could be correlated with the estimation technique. The estimation technique consisted of the following evaluated scenarios:

- The month with the lowest demand is equal to the average indoor use of a residential property.
- The average consumption of the three months with the lowest consumption is equal to the average indoor demand of a residential property.
- The average consumption of the six months with the lowest consumption is equal to the average indoor demand of a residential property.

3.2.3 Mathematical Model

In order to perform stochastic estimation of outdoor water demand, it was essential that a mathematical model be developed as a foundation for the simulations. DeOreo et al. (2011) stated that residential outdoor use is defined as a function of irrigation, outdoor tap use, pool or water-feature evaporation, and pool filter maintenance.

Well-kept gardens and lawns could generally be considered as popular amongst home owners in residential estates. The subsequent irrigation demand results in substantial water consumption during seasonal peak use periods. Irrigation demand, supplementary to precipitation, is dependent on the amount of water required by plants to survive during the course of seasonal weather conditions. If plants are subjected to evapotranspiration that exceeds the available water supply from precipitation, the plants could suffer from dehydration.

The theoretical irrigation requirement model as part of this research was adopted from an irrigation model developed by DeOreo et al. (2011). The equation used for the estimation of the theoretical irrigation requirement (Q_i) for this study is:

$$Q_i = A_i \frac{E_{to} \times K_{bc} - P_r \times F_{ep}}{I_e}$$

Where,

Q_i = Theoretical Irrigation requirement
A_i = The area of a property that is under irrigation
E_{to} = Evapotranspiration
K_{bc} = Crop coefficient
P_r = Measured precipitation
F_{ep} = Effective Precipitation Factor
I_e = Irrigation efficiency.

The behaviour of humans could have a significant impact on the irrigation efficiency. It could, therefore, be expected that the actual irrigation consumption would not necessarily correlate well with the theoretical irrigation requirement.

Similar to the role that evapotranspiration plays in irrigation water demand, evaporation also plays a key role in sustaining the water level of open water bodies such as pools and water features. In order to quantify the water requirement for the replenishment of pools and water features, (Q_p).

An equation was derived from Midgley et al. (1990) to calculate evaporation demand from an open water body:

$$Q_p = A_p \times (E_w - P_r)$$

Where,

Q_p = Water replenishment demand of pools and water features due to evaporation
A_p = The surface area of a pool or water feature.
E_w = Open lake evaporation rate of water in a specific location (Including pan factor)
P_r = Measured precipitation.

Pool filter maintenance contributes to the monthly outdoor water demand of a property if a pool is present on a property. The method of operating a pool filtration system varies from owner to owner and therefore involves another behavioural aspect. The estimation of pool filter water demand is portrayed in this equation:

$$Q_f = D_d \times A_p \times O_m$$

Where,

Q_f = Pool maintenance demand
D_d = The water level difference after performing a maintenance cycle
A_p = The surface area of a pool or water feature.
O_m = The occurrence of pool maintenance per calendar month.

Pool filter maintenance could result in significant outdoor water consumption where properties have large pools that are exposed to dusty conditions and in areas with low water quality.

A pool ownership factor (F_{po}) was incorporated in the equation to allow for the fraction of homes that have pools or water features.

Jacobs (2004) included the following miscellaneous outdoor water end-use flows:

- Outdoor tap use for car washing: 18.9 ℓ/capita/day at 0.02 events/capita/day;
- Outdoor tap use for car washing: 7.0 ℓ/capita/day; and
- Other miscellaneous water en-uses: 5.0 ℓ/capita/ day.

These outdoor water-consumption elements were not included in the mathematical model because of low occurrences and low demand.

The outdoor components were then combined into the following general equation:

$$Q_{outdoor} = A_i \frac{E_{to} \times K_{bc} - P_r \times F_{ep}}{I_e} + F_{po}(A_p \times (E_w - P_r) + D_d \times A_p \times O_m)$$

The average outdoor water demand ($Q_{outdoor}$) was calculated by using the above equation. For the purposes of this study the effects of human behaviour, and the estimation of deviation from an average result were desired.

3.2.4 Stochastic simulation of mathematical model

A stochastic simulation based on the mathematical model presented for the combined outdoor water demand ($Q_{outdoor}$) was conducted. The Monte Carlo method was employed for this study, because it employs elementary statistical methods to solve integrate mathematical equations, contrary to other stochastic methods. Parameter distributions were used to derive probable monthly water demand for various sites, followed by sensitivity analyses to determine the impact of the specific parameters on the model.

Monte Carlo simulations were used to stochastically estimate the most likely monthly distribution of the water demand for residential estates. Monte Carlo Simulations randomly select points on parameter distributions and perform multiple iterations for the specific mathematical model. The number of iterations improves the quality of the results received from the simulations. For the purposes of this study 1000 iterations were deemed sufficiently accurate.

In order to simulate the total outdoor water demand of a residential estate, two different approaches were evaluated:

- Approach A - An average sized property; and
- Approach B - Properties were categorised into property size categories.

Approach A was simulated with one set of parameters from which the monthly simulated outdoor water demand was multiplied by the number of properties in an estate.

With Approach B properties were grouped in area categories. The expected number of properties in each of the categories was multiplied by the relevant monthly simulated outdoor water demand. The monthly outdoor water demand of the respective categories was added to obtain the combined monthly outdoor water demand.

The two approaches were plotted for each estate. The graph in Figure 3.2 below is a typical example of the alternative approaches plotted on one graph. The blue bars indicates outdoor consumption derived from the metered total consumption. The yellow bars depicts the simulated outdoor water demand based on a single average property size (approach A). The green bars illustrates the simulated outdoor water demand of the categorized approach (approach B).

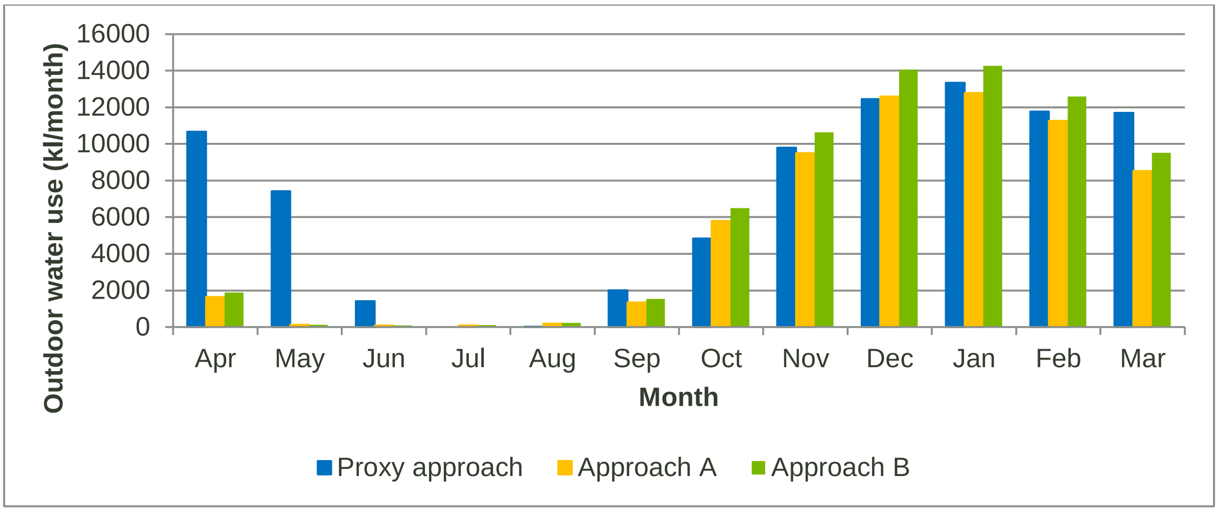

Figure 3.2 : Comparison of two Monte Carlo simulation approaches with proxy approach.

Confidence intervals were applied to the results in order to illustrate the prescribed level confidence that could be expected of a specific model.

The object of this method in Approach B was to create a stochastic model that could be replicated to estimate outdoor water demand for a group of properties of various sizes, such as residential estates. During planning stages of a residential estate, the simulated outdoor water demands along with a simulated indoor water demand could improve the total water demand estimate of such an estate and in turn reduce costs and improve project viability.

For the purposes of this study Approach B was selected, because it could provide aggregated results.

3.3 Research Instruments

3.3.1 Description of parameters

For the purposes of conducting the analyses and comparison with the stochastic simulations, data had to be sourced from existing residential properties. The data was also generated by based on known parameter distributions. The data required in order to perform the analyses included the following:

- Water consumption:
  - Total water consumption data of existing properties recorded monthly
  - Outdoor water consumption of the properties for comparison purposes
- Behavioural aspects in terms of:
  - Irrigation methods
  - Irrigation efficiency
  - Pool filter maintenance
- Geometrical information:
  - Property sizes of typical residential estates
  - The area under irrigation
  - The surface area of water features and pools
- Types of vegetation and the derived crop coefficients
- Climatological information:
  - Precipitation
  - Evaporation
  - Evapotranspiration.

The data used in this study was collected from various sources using different methods which will be covered in the sub sections hereunder.

3.3.2 Water consumption

Water consumption data from three similar residential estates located in South Africa were analysed. For the purposes of this study the estates were called Estate A, Estate B and Estate C. The estates were selected for this study based on the following characteristics:

- Estate A is a polo field estate;
  - The estate is approximately 150 ha in size;
  - There are 550 properties of which 150 are built-up;
  - The average property size is 818 m^2;
  - The estate has 24 hour security;

- Estate B is a golf course estate;
  - The estate is approximately 160 ha in size;
  - There are 500 properties of which 390 are built-up;
  - The average property size is 660 m^2;
  - The estate has 24 hour security;
- Estate C is a vineyard estate;
  - The estate is 80 ha in size;
  - There are 100 properties of which 23 is built-up;
  - The average property size is 1270 m^2; and
  - The estate has 24 hour security.

Estate C has considerably less properties that are built-up in comparison with the other estates. Estate C, was however included in this study to test the viability of the model on a reduced scale. The implications of including Estate C is further described in the results and conclusions of this thesis.

The total water consumption records of the properties were obtained from meter readings taken at the relevant estates by meter reading consultancies, by means of physical meter reading, online based automatic meter reading tools and data loggers. Table 3.1 summarises the methods used for obtaining the data.

Table 3.1 : Water consumption data source methods

Location	**Data Source Method**
Estate A	Online based automatic meter reading tool that records readings on a weekly frequency
Estate B & Estate C	Manual meter readings on a monthly basis
Housing Groups in USA	Data loggers from REUWS database recorded water consumption on a 10 second frequency at 12 study sites. The data was recorded for two weeks during summer and two weeks during winter for each house

3.3.3 Behavioural Aspects

The behavioural aspects of outdoor water consumption can be attributed to the various schools of knowledge in terms of irrigation operation, pool replenishment and filter maintenance. In order to capture the human behavioural impact of a consumer survey. The survey questions and results are summarised in Table 3.2.

Table 3.2 : Summary of survey results

Questions	Response options	Results of responses
1. What is your erf number?	Open ended response	105 Respondents completed the survey
2. What method do you use to water your garden?	Hose pipe, micro-sprayer or drip irrigation	Hose pie: 10%; micro-sprayer: 91%; drip irrigation: 15% (total is more than 100% as there are combinations)
3. Is your irrigation system automated or manual?	Automated or manual	Automated: 96%; Manual 4%
4. During the summer months, when you are at home, how many times per week do you water your garden?	Daily, once two, three, four, five, six	Daily 54%; Six times/week: 1%; Five times/week: 10%; Four times/week: 17%; Three times/week: 16%; Twice/week: 1%; on average 5.57times per week
5. During the winter, when you are at home, how many times per week do you water your garden?	Daily, once two, three, four, five, six	Daily 1%; Four times/week: 5%; Three times/week: 6%; Twice/week: 1%; on average 0.84 times/ week
6. What is the average length of your irrigation cycle (i.e. watering your whole garden)?	0-20min, 21-40min, 41-60min, 61-80min, 81-100min, 101-120min	On average between 51.5 minutes
7. At which time of day do you normally start watering your grass/garden?	Open ended response	When watering in the morning the average start time is 5:16 am (92% of respondents) and when watering in the evening the average is 5:15 pm (8% of respondents)
8. Do you have a swimming pool/water feature?	Yes or no	79% of respondents indicated that they have a pool or a water feature. (Note: only 51% was recorded from Google Earth images, it is suspected that small water features were not recognisable on the imagery, and was thus omitted because of their insignificance)

The survey dealt with the following aspects of irrigation- and pool-use that are relevant to this study:

- Method of irrigation;
- Operation time of irrigation;
- Frequency of use; and
- Number of pool or water features on a specific estate.

Seven individuals known to the author were contacted to verify the parameters obtained from the research of Jacobs (2004), into pool filtration operation. The questions that were asked included the following:

- How often do you do filter maintenance (including backwash and rinsing):
    - in summer?
    - in Winter?
- What is the method/process used to do the maintenance?
- Approximately how long in pumping minutes does it take to complete the process?
- What is the approximate size of your pool?

The objective of these interviews was to verify the volume and frequency of pool filter maintenance by typical homeowners who own pools.

3.3.4 Geometrical information

Geometrical information measured from 89 of the properties in Estates A were analysed. Measurements were taken from cadastral information and from scaled Google Earth photographs available for these properties. The surface areas of the vegetated areas, pools and property boundaries were drawn, and measured using AutoCAD. Of the 89 properties, high resolution aerial photographs of 8 of the properties were available (See Figure 3.3). The Google Earth information was correlated with coordinated aerial photographs and found to have an average accuracy of 92% and simulated accordingly with the model.

Figure 3.3 : High resolution aerial photograph geometrical analyses

3.3.5 Types of vegetation and crop coefficients

From the architectural guidelines (Val de Vie 2013) and the common crop factors of the plants used on properties in residential estates, it was found that the crop coefficients for gardens were generally similar to those of the generic grass type crop coefficient (K_{bc} = 1).

A factor of uncertainty was built into the model for this parameter to accommodate the various different vegetation types that could be found on these types of estates. In the future planning of residential estates the developers could specify crops with coefficients in a specified band within which property owners would be allowed to choose the plants for their gardens. This would considerably improve the confidence levels of the simulations that are used to estimate the outdoor water demand, in relation to the ultimate actual water damand.

3.3.6 Climatologic information

For the purposes of this report, the average precipitation and evapotranspiration figures were extracted from the SAPWAT software (Van Heerden, Crosby, Grové, Benadé, Theron, Schulze & Tewolde, 2009). The SAPWAT software contains data from weather stations located in South Africa as well as the rest of the world. As part of the SAPWAT development (Van Heerden et al., 2009), data of weather stations located outside of South Africa was adopted from the CLIMWAT database. The data exported from the SAPWAT software as part of this research a monthly temporal scale.

3.4 Methodology limitations

The outdoor water demand model developed during this study has scope for future development. The limitations of the model can form part of further research studies.

The methodology currently makes provision for residential estate conditions. The model could be extended to other residential estates and possibly to the commercial and industrial sector.

Further research could add to the accuracy of the results that are received from the model proposed in this study.

4 Chapter 4 : Data Collection and Analysis

4.1 Chapter overview

This chapter deals with the collection and analyses of the data that was used for the population of parameter distributions and the comparison with simulation results that were conducted during the course of this study. The chapter will describe the following aspects that form part of the study:

- Processing and analyses of metered water consumption data;
- Winter average monthly water consumption as proxy for indoor consumption; and
- Description and population of parameter values and distributions.

4.2 Processing and analyses of metered water consumption data

4.2.1 Data Sources

Monthly water consumption data was collected for three estates referred to in this study as Estate A, Estate B and Estate C. The estates are located in the Western Cape. The location and timeframe of the available data, the number of houses for which data was available, and the average property size of properties in the estate are also tabulated in Table 4.1.

Table 4.1 : Attributes of residential estates from which data was collected

	Location	**Timeframe of available data**	**Number of houses**	**Average property size (m^2)**
Estate A	Paarl, SA	1 year	153	818
Estate B	Stellenbosch, SA	4 years	390	666
Estate C	Franschhoek SA	3 years	23	1270

The data series was collected and grouped into complete years from April of one year to March of the following year. The reason for this grouping was that outdoor water consumption is influenced by seasonal change, and it was considered appropriate to include the latest summer peak season water consumption that was available on record. The data records were received in Microsoft Excel Format and were kept in this format for the purposes of processing and filtering using pre-programming offered by the Microsoft Excel software.

4.2.2 Data exclusion criteria

The water meter readings were obtained from two recognised consulting firms in the water meter reading industry, MVR Consulting and Applied Metering. The consultants assured a high level of accuracy of the readings and confirmed that meters were read on a monthly basis on basically the same day or within one day of the previous month. Some anomalies were, however, found during the evaluation of the data. The anomalies included the following:

- Non-residential buildings were included in the records;
- Some buildings were constructed during the timeframe analysed in this study; and
- Zero readings were detected at some homes that were completed.

All non-residential properties such as HOA offices, security buildings, maintenance yards, et cetera were excluded, as they were irrelevant to this study's analyses. These readings do contribute to the water consumption of the estate; however, they do not contribute to the residential outdoor water consumption.

The records that were received included the data for the properties that had buildings that were under construction. The properties that did not register water consumption from April to March of two consecutive years were omitted from the entire year's data. It should further be noted that the water consumption for properties where construction took place was not relevant to general outdoor water consumption as defined in this report.

Furthermore, it was detected by means of conditional filtering that there were properties that registered zero flows during multiple months in a year. This can be ascribed to the home owners being on a long term business/holiday trip, the home being used as a holiday home, the water meter is not registering correctly or the home being a rental unit that was not occupied for that period. In the case where homes were detected as having zero water consumption for two consecutive months or more, the specific year's data of these homes was excluded from the analyses.

4.2.3 Data processing

Once the data had been filtered, it was processed for further use in the comparison with the simulation models. Basic statistical methods, such as arithmetical means, and median and standard deviations of the records were used to evaluate the data.

The data records that extended over multiple years were collated by calculating the arithmetical mean of the consumption of every property for the individual months of the year.

A combined average monthly consumption dataset for each estate was attained. This record could thereby be further analysed and compared with simulation models.

The individual property sizes could then by measured by using AutoCAD software from the cadastral information on as-built drawings of each of the residential estates. These property sizes were incorporated in the water consumption records prior to the data filtration process.

Upon completion of the filtration process the sizes of the remaining properties were separately analysed. In order to improve the accuracy of the simulation models it was proposed that properties be classified into separate property size classes. The property classes were based on the major grid intervals used in the graph by CSIR (2003), in Figure 9.9 of the CSIR guidelines used to calculate Average Annual Daily Demand. Table 4.2 describes the property size boundaries for the individual classifications used in this study.

Table 4.2 : Property size classification

Property Class	Lower limit (m2)	Upper limit (m2)
$400m^2$	0	500
$600m^2$	500	700
$800m^2$	700	900
$1000m^2$	900	1100
$1200m^2$+	1100	∞

The recorded property sizes were allocated to their relevant property class using “If” functions in an Excel worksheet. Once they had been separated, the properties in each of these classes were counted.

A set of parameters relative to each class was determined, after which the classes were individually simulated using the simulation model. The resulting monthly outdoor water demand simulated for the classes was multiplied by the number of properties in each class to calculate the total outdoor water demand of each estate.

4.3 Winter consumption as proxy for indoor consumption

4.3.1 Approach overview

A set of data records that formed part of a study conducted by Mayer & DeOreo (1999) was acquired by the University of Stellenbosch. The study was titled Residential End Uses of Water (REUWS) and was published in 1999. The objectives of the REUWS study included:

- Providing residential water-related end use data for locations across the North American continent;
- Collecting disaggregated indoor and outdoor water consumption data;
- Detecting water consumption variations for individual water fixtures and appliances; and
- Developing prediction models for residential water demands.

In North America, 1188 households in twelve locations participated in the logging of water consumption on a temporal resolution of 10 seconds for two intervals of two-weeks, spaced over seasons to capture summer (peak) and winter (mostly indoor off-peak) water consumption. In addition to the water consumption data, information such as climate data and property specifics were collected.

For the purposes of this study it was necessary to develop a method to compare the simulated outdoor water demand with the actual outdoor consumption. Indoor use was regarded as non-seasonal, and could therefore be subtracted from the total monthly water consumption to obtain a monthly distribution for outdoor water consumption.

In order to test the proxy method, initially proposed by DeOreo et al. (2011), the data set was filtered for all the locations where geospatially measured irrigated area, annual indoor data and annual water consumption data was available. The locations where the required data were available are summarised in Table 4.3.

4.3.2 Deriving the proxy approach

The REUWS data was tested by comparing three alternative method for calculating the average winter water consumption:

- The consumption during the lowest month of the year;
- The average monthly consumption of the 3 lowest months in the year; and
- The average monthly consumption of the 6 lowest months in the year.

The methods were applied using MS Excel functions to the monthly water consumption data for the 390 of the properties that participated in an ad hoc portion of the REUWS, where actual indoor consumption was measured. The results from these methods were then compared to the metered average indoor consumption of each property. A comparison factor (CF) was derived as an indication of the difference between the metered indoor water consumption and the three methods used to establish the appropriate proxy approach. The comparison results are summarized in Table 4.3.

Table 4.3 : Summary of winter average versus metered indoor consumption results

Location	Analysis type	(a) Actual Average indoor (kℓ/ month)	(b) Min winter month (kℓ/ month)	(a÷b) CF	(c) Average 3 winter months (kℓ/ month)	(a÷c) CF	(d) Average 6 winter months (kℓ/ month)	(a÷d) CF
Boulder, Colorado	Average	17.3	13.4	0.78	14.4	0.83	18.4	1.06
	STD Dev	8.6	9.1	0.70	8.7	0.65	9.1	0.67
Eugene, Oregon	Average	20.5	17.0	0.83	18.6	0.90	20.7	1.01
	STD Dev	11.1	8.7	0.34	8.8	0.34	9.5	0.35
Lompoc, California	Average	18.9	21.3	1.13	24.7	1.31	29.7	1.57
	STD Dev	10.5	15.6	0.63	15.9	0.65	17.5	0.79
Phoenix, Arizona	Average	22.2	33.6	1.51	38.4	1.73	47.0	2.12
	STD Dev	10.4	166.5	1.11	23.7	1.20	28.4	1.48
Combined	Average	20.0	22.3	1.11	25.0	1.25	29.9	1.49
	STD Dev	10.9	16.5	0.79	17.9	0.86	21.2	1.05

Based on averages, the results suggest that the "Minimum winter months" approach has the closest value to the average indoor consumption with a standard deviation (STD dev) that is also the lowest of the approaches. In order to further evaluate the results, a cumulative distribution graph was created from the data that was used (see Figure 4.1).

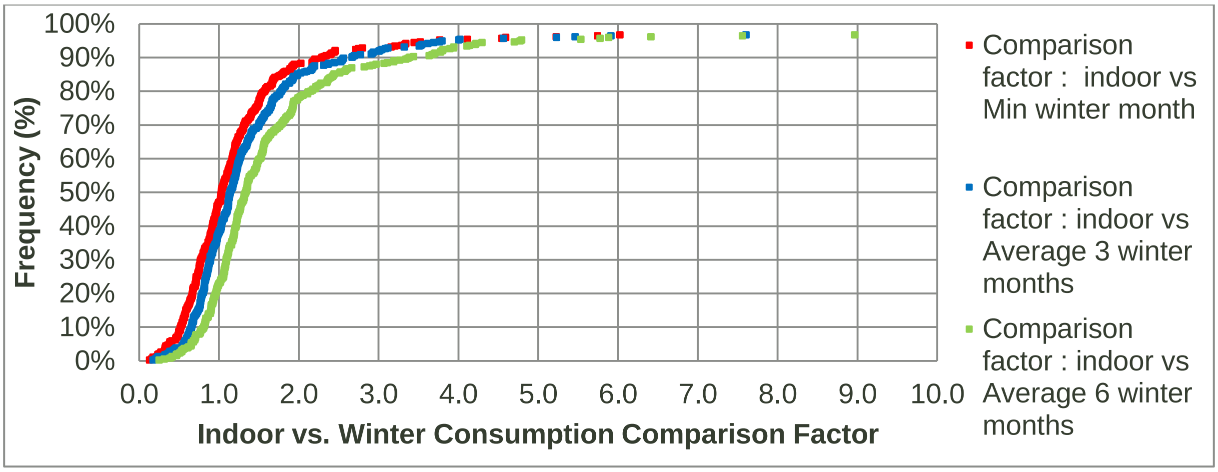

Figure 4.1 : Cumulative distribution of indoor consumption versus winter consumption

It could be derived from the cumulative distribution plot that the minimum winter month approach is more equally weighted about the CF of 1 than the others.

It can be noted the plots have extended upper regions where the CF exceeds 3, in other words the winter monthly consumption is more than 3 times as much as the indoor consumption of some of the properties. These outliers could be attributed to properties with areas that exceed 1500 m^2 and properties that are located mostly in Phoenix, Arizona, in the Sonoran Desert, which has extremely hot summers and warm winters (Balling & Cubaque, 2009) which could lead to higher outdoor water consumption during the winter months of the year.

It can further be derived that the minimum winter water consumption slightly exceeded the indoor water consumption on a monthly temporal scale. The winter water consumption could be divided the by CF of 1.11 to compensate for the difference. It was therefore proposed that the minimum winter month approach be used in conjunction with an adjustment factor (AF=0.9) which is the reciprocal of the CF (1.11) in further simulations as indicated in the following equation:

$$Outdoor\ consumption\ =\ Metered\ consumption\ -\ Minimum\ winter\ consumption\ \times\ AF$$

4.3.3 Verification of approach

In order to verify the results, the two fortnights of metered outdoor water consumption were extrapolated to a monthly consumption for the individual months during which the participating households were logged. This was used to upscale the metered data to a volume comparable to the monthly water consumption distribution.

The process followed was to divide the metered outdoor water consumption for each month by the number of days that has been logged, and then to multiply that by the number of days in that specific month. The consumption was then converted from US Gallons to kilolitres. The equation below depicts the up-scaling method used to convert the data:

$$Upscaled\ Monthly\ Outdoor\ =\ (Metered\ outdoor\ /\ logging\ days) \times Days\ per\ month \times 3785$$

Figures 4.2, 4.3, 4.4 and 4.5 illustrate the approach in relation to the upscaled metered outdoor water consumption.

The red squared points and points on the graphs indicate the upscaled metered outdoor consumption and the blue line indicates the proposed proxy outdoor water consumption. In most cases, the metered outdoor consumption is within range of the proposed proxy approach.

The proxy approach was similarly applied to the estates that had been compared to the simulated model results of this study, as illustrated in Figures 4.6, 4.7 and 4.8.

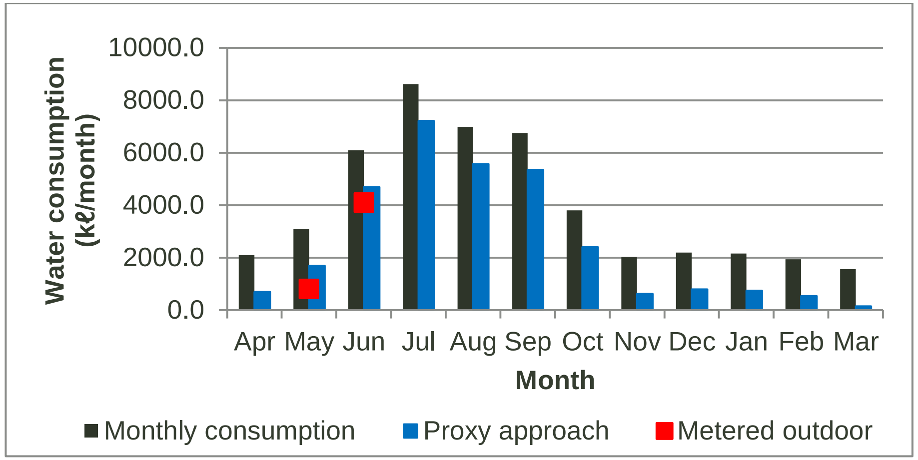

Figure 4.2 : Verification of proxy approach – Boulder

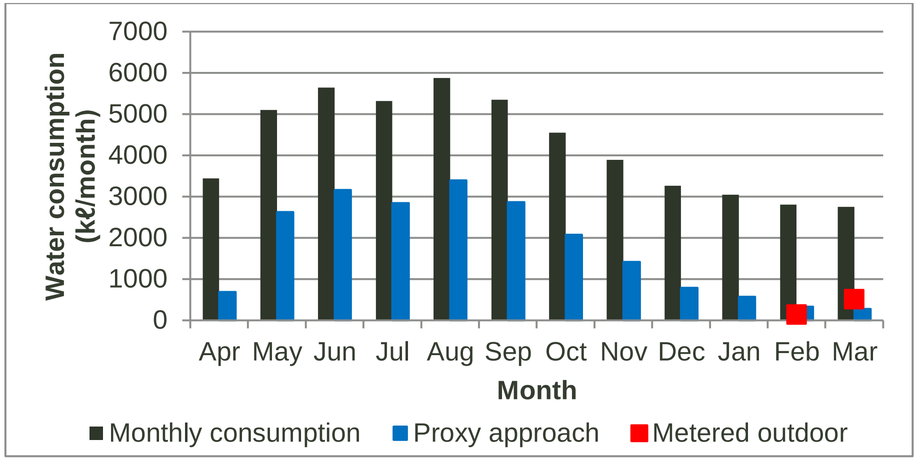

Figure 4.4 : Verification of proxy approach – Lompoc

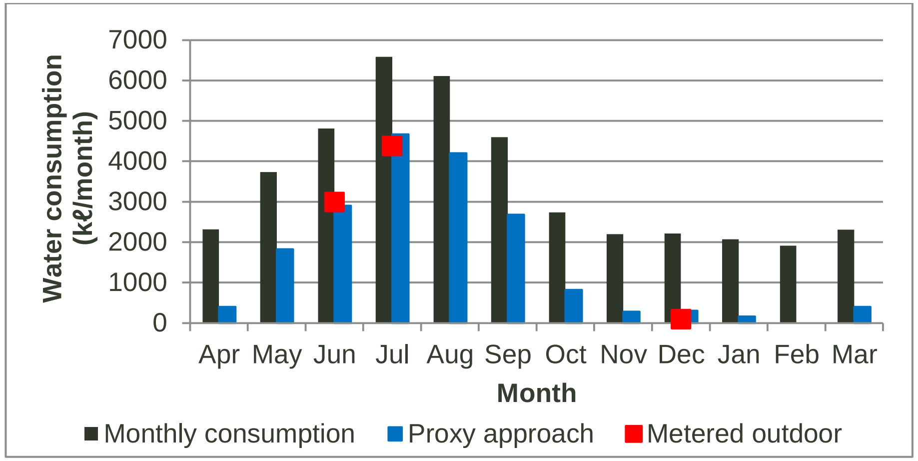

Figure 4.3 : Verification of proxy approach – Eugene

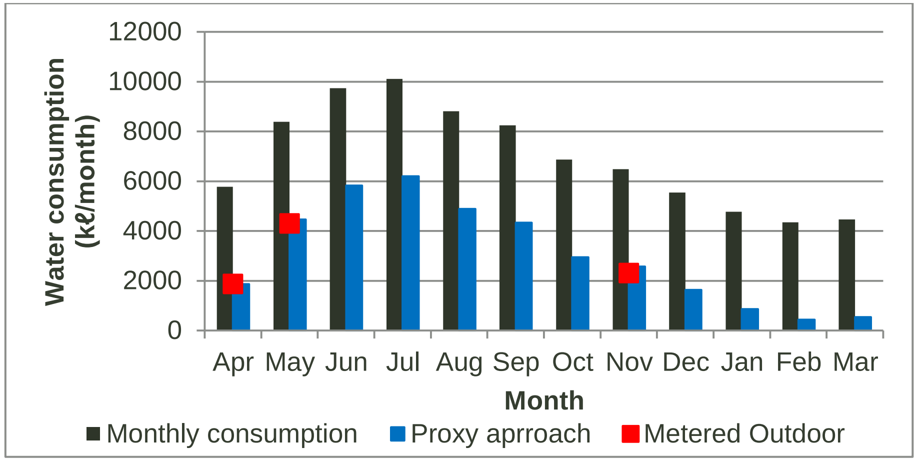

Figure 4.5 : Verification of proxy approach – Phoenix

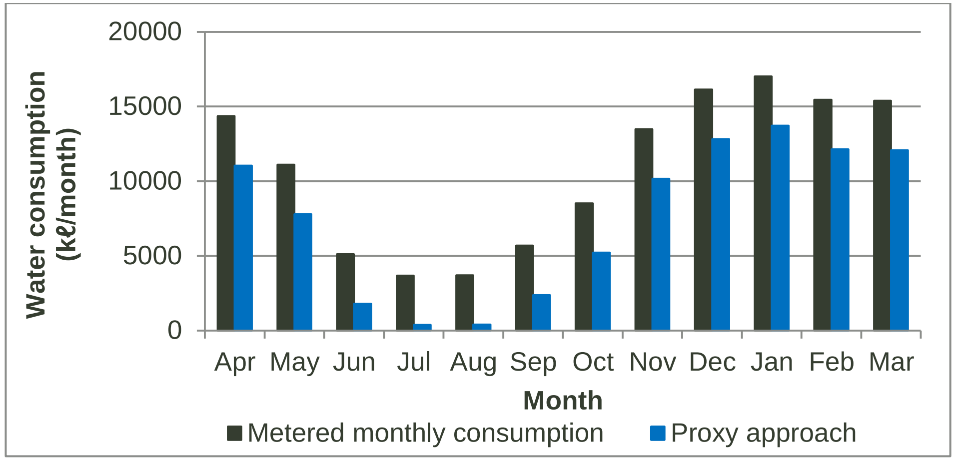

Figure 4.6 : Proxy approach – Estate A

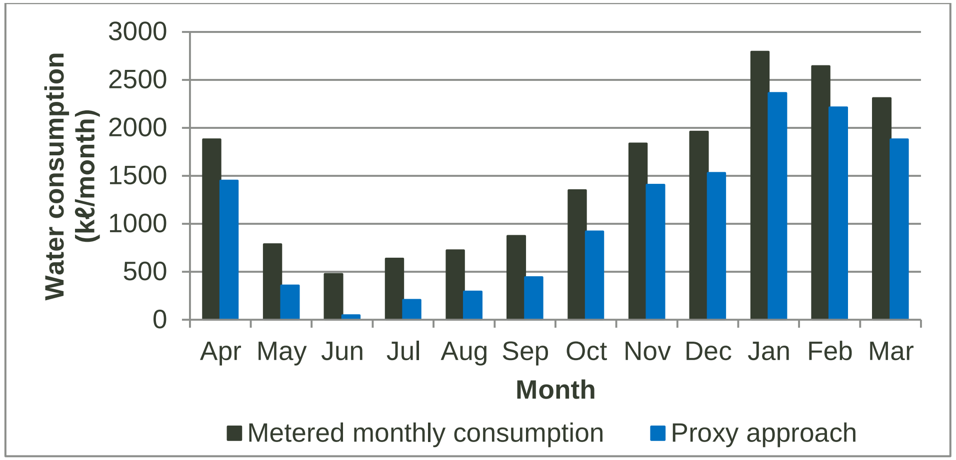

Figure 4.8 : Proxy approach – Estate C

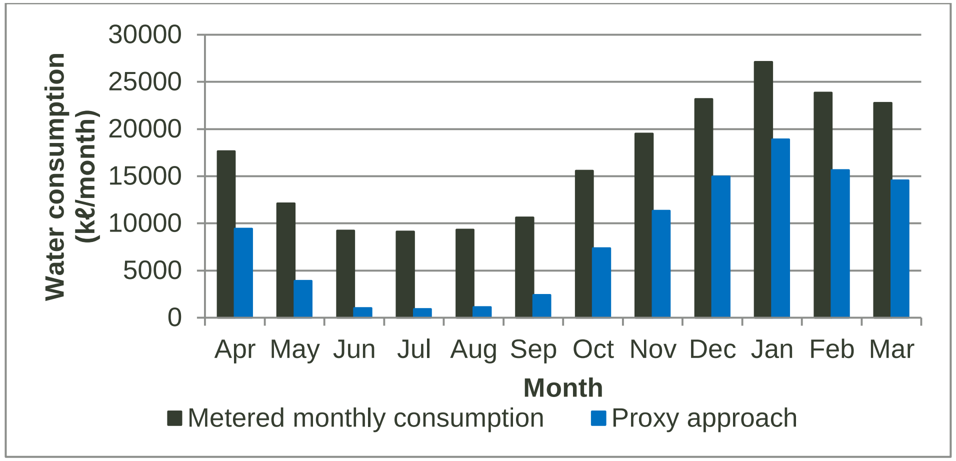

Figure 4.7 : Proxy approach – Estate B

4.4 Population of parameter values and distributions

4.4.1 Summary of model parameters

The model parameters are populated in a distribution format that enables the @Risk software to use the Monte Carlo method to sample various combinations of values for each parameter and then run multiple iterations of the mathematical model. The results of all the iterations could then be evaluated by the software to return the most likely solution for the mathematical model.

The proposed mathematical model and the parameters that were used in the construction of this model are listed below and described in the subsections that follow.

$$Q_{outdoor} = A_i \frac{E_{to} \times K_{bc} - P_r \times F_{ep}}{I_e} + F_{po}\left(A_p \times (E_w - P_r) + D_d \times A_p \times O_m\right)$$

Where,

$Q_{outdoor}$	= Outdoor water demand
A_i	= The area of a property that is under irrigation.
E_{to}	= Evapotranspiration
K_{bc}	= Crop coefficient
P_r	= Measured precipitation
F_{ep}	= Effective precipitation factor
I_e	= Irrigation efficiency
A_p	= The surface area of a pool or water feature.
E_w	= Evaporation rate of water in a specific location (Including pan factor)
P_r	= Measured precipitation
D_d	= The water level difference after performing a maintenance cycle
A_p	= The surface area of a pool or water feature.
F_{po}	= Pool ownership factor
O_m	= The occurrence of pool maintenance per calendar month.

The various physical parameters were based on the analyses of geometrical measurements taken from Estate A's cadastral layout and aerial photographs taken of the estate in 2009 and supplemented by Google Earth photographs taken in 2012.

The behavioural parameters such as irrigation efficiency, water level drawdown during backwash and monthly occurrence of backwash were determined from a contingent valuation survey and a questionnaire email.

The climatic information was obtained from the SAPWAT and CLIMWAT data basis which contains more than 50 years of climatic data.

4.4.2 Evapotranspiration and precipitation

The SAPWAT software and the CLIMWAT software were used to collect the evapotranspiration and precipitation data for the estate's and North American Cities respectively. Tables 4.4 and 4.5 summarise the collected evapotranspiration and precipitation data, whereas Tables 4.9 & 4.10 illustrate the collected data used in the development of the various model simulations. Note that precipitation includes rainfall and snowfall data.

Table 4.4 : Collected evapotranspiration data

	Monthly Evapotranspiration Distribution											
Location	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
Estate A	95.1	39.2	25.6	31.5	46.6	68.6	112.0	184.9	208.3	213.6	187.6	158.8
Estate B	82.1	54.8	45.6	45.6	54.8	76.0	109.5	136.9	146.0	152.1	146.0	112.5
Estate C	79.1	51.7	42.6	42.6	51.7	73.0	109.5	136.9	152.1	155.1	143.0	112.5
Max	85.2	57.8	45.6	45.6	60.8	82.1	112.5	143.0	161.2	164.3	152.1	121.7
Boulder, Colorado	119.8	149.0	174.9	205.3	184.0	138.4	103.4	57.8	40.2	40.2	49.9	76.3
Eugene, Oregon	77.9	109.5	137.2	157.6	142.7	102.2	53.5	32.2	19.5	21.3	36.2	55.1
Lompoc, California	142.0	199.5	245.2	259.5	228.1	175.2	111.9	56.0	29.5	31.6	55.4	90.0
Phoenix, Arizona	202.6	259.8	293.8	301.4	269.5	225.1	171.9	105.2	70.6	77.3	109.5	146.9
Max	202.6	259.8	293.8	301.4	269.5	225.1	171.9	105.2	70.6	77.3	109.5	146.9

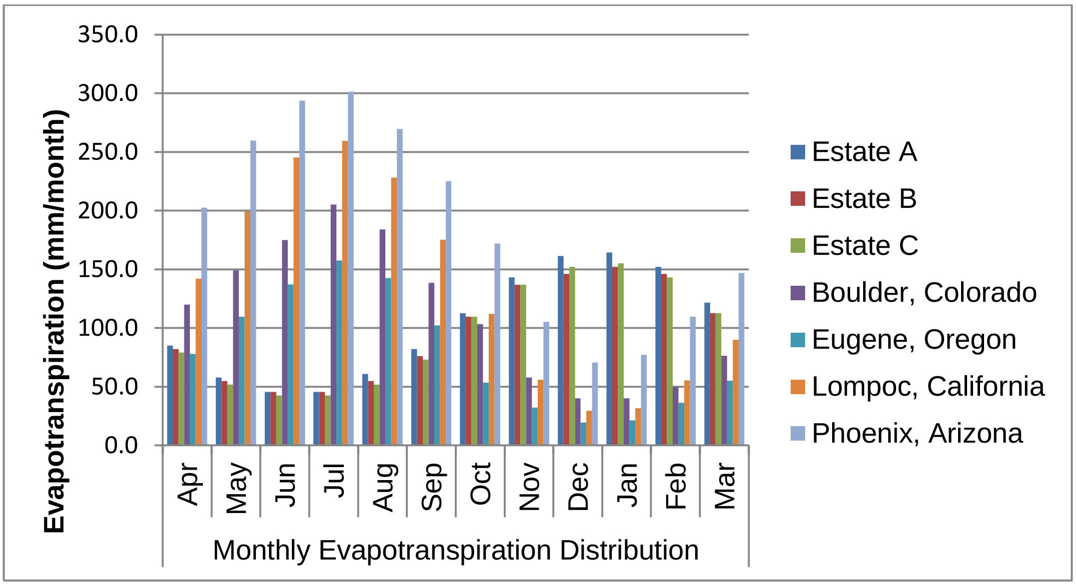

Figure 4.9 : Combined average Evapotranspiration parameter plot

Table 4.5 : Collected precipitation data

	Monthly Precipitation Distribution											
Location	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
Estate A	83.0	150.0	148.0	131.0	124.0	85.0	56.0	42.0	22.0	23.0	29.0	30.0
Estate B	71.0	110.0	128.0	107.0	100.0	71.0	44.0	45.0	17.0	20.0	22.0	26.0
Estate C	72.0	129.0	167.0	133.0	145.0	81.0	55.0	35.0	27.0	24.0	25.0	35.0
Boulder, Colorado	43.4	61.0	45.5	48.5	38.4	31.5	24.9	22.1	16.3	12.7	14.5	32.5
Eugene, Oregon	60.7	52.3	37.6	16.0	27.7	44.4	67.8	135.6	155.7	135.9	97.8	90.4
Lompoc, California	24.6	7.6	2.0	0.3	0.8	6.1	13.5	34.8	36.1	49.8	45.7	48.0
Phoenix, Arizona	5.6	3.0	3.3	21.1	24.4	21.8	16.5	16.8	25.4	17.0	17.3	22.4

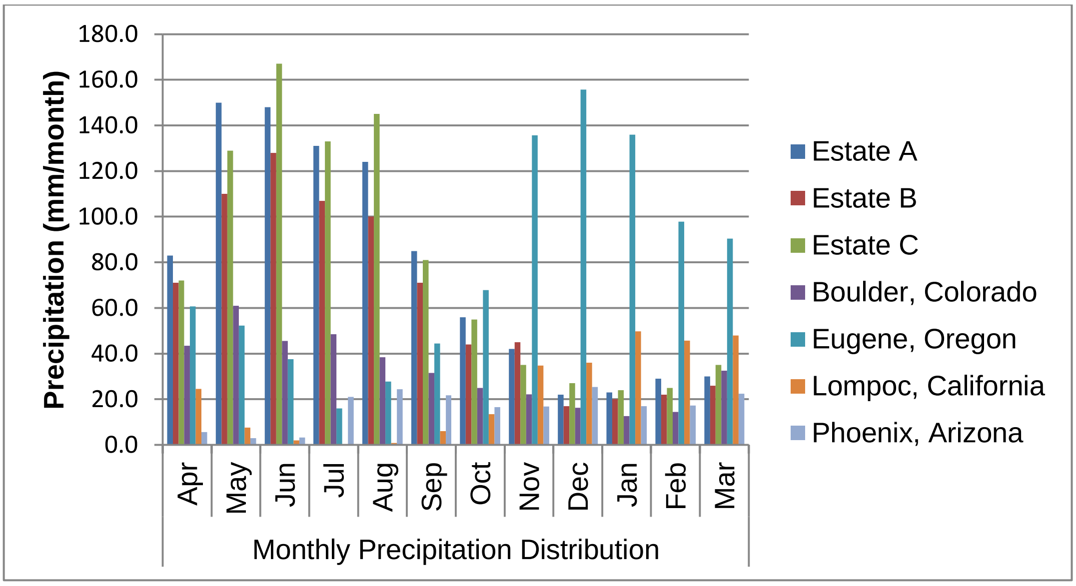

Figure 4.10 : Combined average Precipitation parameter plot

It can be noted that the estates and North American Cities are predominantly winter precipitation regions, with the exception of Phoenix, where monsoonal thunderstorms provide high humidity and localised precipitation (Balling & Cubaque, 2009). The Evapotranspiration, Precipitation and Evaporation parameters were regarded as known fixed monthly parameters. The fluctuations of these parameters were encapsulated in the Effective Rain and Irrigation Efficiency parameters.

4.4.3 Evaporation

The A-pan evaporation data for the North American locations was published by Farnsworth and Thompson (1982). The evaporation measurement stations were all within a 50 km range of the central business district of these towns/cities. In the work by Farnsworth and Thompson (1982) the pan evaporation was multiplied by a pan factor of 0.7 to obtain free lake evaporation.

The pan evaporation data of the Estates addressed in this report were sourced from Department of Water Affairs (Midgley et al., 1990), the data-set is populated from the WR90 study conducted by Midgley et al. (1990). Average A-Pan monthly values were calculated, and as with the above data, multiplied by a factor of 0.7 to obtain the free lake evaporation.

Table 4.6 summarises the converted lake evaporation data, and the bar graph in Figure 4.11 below illustrates the converted lake evaporation data.

Table 4.6 : Converted evaporation data

	Monthly evaporation distribution											
Location	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
Estate A	93.8	52.0	34.3	38.4	57.1	86.0	137.7	179.8	201.3	204.6	183.5	156.6
Estate B	91.1	50.6	33.4	37.4	55.5	83.6	133.7	174.6	195.4	198.5	177.9	152.0
Estate C	81.8	41.7	32.3	35.1	46.0	60.2	93.0	127.2	141.5	144.7	132.0	104.5
Boulder, Colorado	101.3	132.1	159.3	174.2	162.0	117.2	85.0	47.8	39.8	39.1	41.4	68.1
Eugene, Oregon	51.6	72.9	96.7	131.7	109.7	74.7	37.9	19.4	14.0	16.5	22.0	37.2
Lompoc, California	82.0	126.1	157.2	197.0	172.6	126.4	67.4	25.6	19.2	17.8	26.8	52.5
Phoenix, Arizona	177.4	236.7	263.7	258.7	225.1	187.2	138.2	85.2	62.4	64.0	77.5	124.5

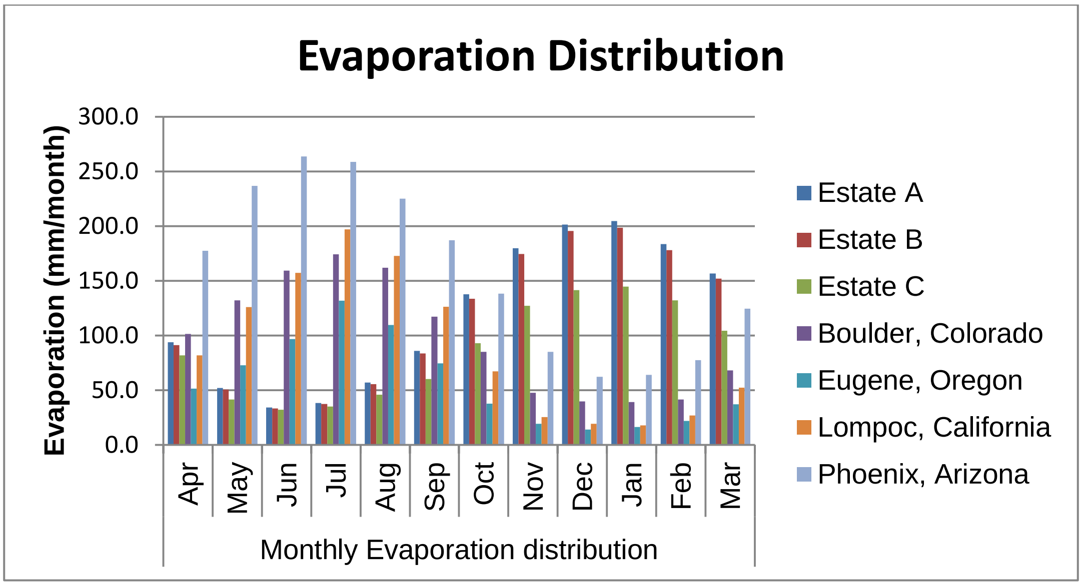

Figure 4.11 : Combined average Evaporation parameter plot

4.4.4 Effective precipitation factor

The effective precipitation factor (F_{ep}) is based on the effective rainfall factor described by Midgley et al. (1990). The main difference is that precipitation also takes snowfall into consideration. Middleton & Bailey, 2005 presented an effective rainfall factor of 0.75 which was adopted for this study. This factor usually excludes snowfall, however, for the purposes of this study the factor was applied to total precipitation.

4.4.5 Irrigation efficiency

Irrigation efficiency is a factor that is applied to the theoretical irrigation demand calculation, to compensate for the actual irrigation application rate that is applied by irrigation operators. The basic equation below describes this factor:

$$I_e = \frac{Q_{crop}}{Q_{actual}}$$

Where,

I_e = Irrigation efficiency
Q_{crop} = Theoretical crop requirement
Q_{actual} = Actual irrigation consumption.

Irrigation efficiency is usually an indication of under/over irrigation. Should the $I_e < 100\%$, it is an indication of over irrigation, whereas if $I_e > 100\%$ it is an indication of under irrigation.

Metered data of the Q_{actual} was not available for analyses in this study. It is possible to estimate Q_{actual} by considering the expected flow rate from sprinklers. The raw data collected from a contingent evaluation survey conducted by Aurecon was analysed to estimate the actual flow rate. In the survey, the following questions that pertain to actual irrigation were asked to 105 homeowners:

- Which method do you use to water your garden?
  - To which 97% of people answered that they used automated Micro-sprayer irrigation systems
- During summer, how many times per week do you irrigate your garden?
  - On average homeowners irrigate their gardens 5.6 events per week.
- During summer, what is the average length of an irrigation cycle, for example watering your whole garden?
  - The average irrigation operation time was indicated as 42 minutes and 61 minutes per event. For comparison purposes, the maximum time of irrigation for each household was used to calculate the actual summer peak irrigation consumption.

Garden irrigation is often designed by a landscape designer using the guidelines provided by an irrigation hardware manufacturer. Hunter Industries and Rainbird Irrigation are two of the most common brands in the local residential irrigation environment. Both of these manufacturers have standard specifications listed on their website. The typical irrigation performance specifications of two standard residential rotor sprayer heads from the two manufacturers are summarised in Table 4.7 below.

Table 4.7 : Typical sprayer performance specifications

	Pressure (b)	**Application radius (m)**	**Flow Rate (ℓ/min)**
Hunter	3.45	10.4	16.3
Rainbird	3.45	10.8	12.3
Average	3.45	10.6	14.6

Sprinkler systems are usually separated into irrigation zones, and these zones will normally operate individually to allow for sufficient pressure at the sprayer heads. It could be assumed that there is sufficient pressure available in the pipes to allow for the operation of 5 irrigation sprayers per zone. In order to estimate a flow rate, a system pressure had to be assumed, because flow rate is a function of pressure. Assuming a pressure of 3.45 bar with an average flow rate at 14.6 ℓ/min per sprayer, operating five sprayers at a time will result in be 71.5 ℓ/min per zone (Q_z).

The following equation could be derived to calculate the actual summer monthly irrigation demand (Q_{actual}):

$$Q_{actual} = \frac{31 Q_z T E_{pw}}{7}$$

Where,

Q_z = Flow rate per irrigation zone
T = Time per irrigation event
E_{pw} = Events per week.

The theoretical crop requirement (Q_{crop}) was calculated using the following equation:

$$Q_{crop} = A_i(E_{to} \times K_{bc} - P_r \times F_{ep})$$

Where,

A_i = The area of a property that is under irrigation.
E_{to} = Evapotranspiration
K_{bc} = Crop coefficient
P_r = Precipitation
F_{ep} = Effective precipitation factor

The irrigation efficiency was determined for each property in Estate A which had participated in the survey. The distribution fitting tool available in the @Risk software was used to fit a probability function to the Irrigation efficiency data. Figure 4.12 illustrates the proposed probability distribution function.

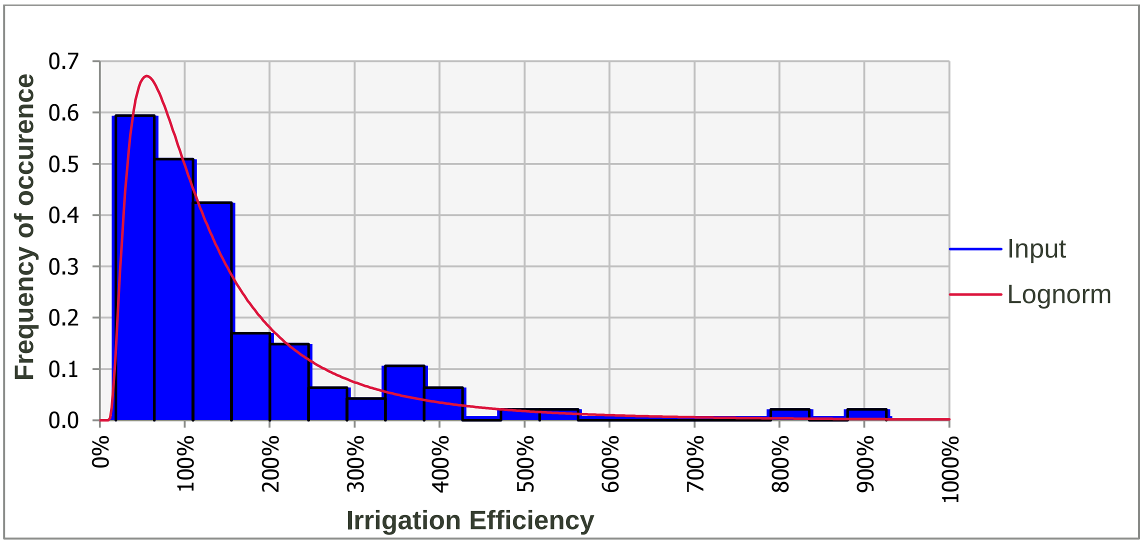

Figure 4.12 : Lognormal distribution fit to irrigation efficiency data

The statistical properties of the analysed data and the Lognormal function for the irrigation efficiency are compared in Table 4.8.

Table 4.8: Data analysis and lognormal distribution function for irrigation efficiency

Statistical characteristics	Data analyses	Lognormal distribution
Minimum	13%	9%
Maximum	1274%	∞
Mean	118%	118%
Mode	49%	42%
Median	82%	82%
Standard deviation	116%	119%

This Lognormal function could be used in the @Risk simulations of the Estates with the unknown irrigation efficiencies.

4.4.6 Irrigated area

The properties were classified in separate property size classes. Each of the properties in these classes could have different relative irrigation areas often depicted as a percentage of the total property area. Google Earth in conjunction with AutoCAD software, was used to measure all the landscaped areas of the 89 properties analysed on Estate A.

The potential irrigated areas were listed against the total property areas. The percentage of irrigated areas was calculated by dividing the irrigated area by the total surface area. Hereafter, the data was sorted according to total property size and separated into the proposed property size classes. The percentage of irrigation area versus frequency of occurrence was calculated and fitted with probability distribution functions.

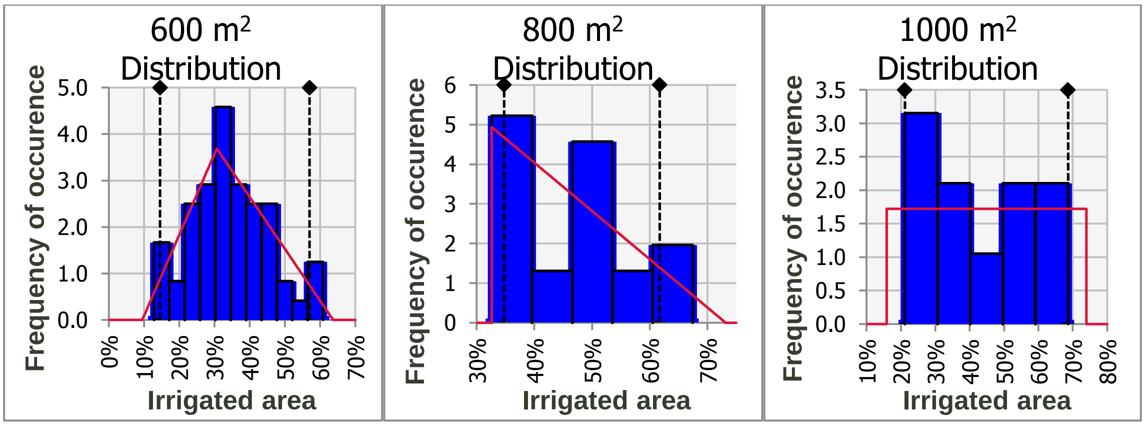

Figure 4.13 : Analysed irrigated area data and proposed probability distribution functions

The statistical characteristics of these irrigated property area distribution functions are summarised in Table 4.9.

Table 4.9 : Data analysis and probability distribution functions for irrigated area

	600m^2 comparison		**800m^2 comparison**		**1000m^2 comparison**	
Statistical characteristics	**Analysed data**	**Triangular Distribution**	**Analysed data**	**Triangular Distribution**	**Analysed data**	**Uniform Distribution**
Number of households analysed	54		23		10	
Minimum	12.8%	9.5%	32.6%	32.6%	32.6%	32.6%
Maximum	60.9%	63.7%	67.5%	73.2%	67.5%	73.2%
Mean	34.6%	34.6%	47.2%	46.1%	47.2%	46.1%
Mode	≈30.8%	30.7%	≈36.1%	32.6%	≈36.1%	32.6%
Median	33.8%	33.8%	46.8%	44.5%	46.8%	44.5%
Std Dev	11.1%	11.2%	10.4%	9.6%	10.4%	9.6%

During the analyses there were limited properties that could be completely constructed in the 400 m^2 and the 1200 m^2 available on the Google Earth Images. For the purposes of this study it is proposed that the probability distribution functions of the 600 m^2 and the 1000 m^2 classes be used to simulate the 400 m^2 and the 1200 m^2 classes respectively.

4.4.7 Crop coefficient

The aerial photograph resolution available on Google Earth makes it difficult to differentiate between types of vegetation. Upon investigation of the landscaping guidelines of Estate A, it was detected that the crop coefficients of the allowable crops on the site vary between 0.65 and 1, with 0.8 (grass) being the most likely. A triangular distribution was selected for its robustness and simplicity.

A high resolution aerial photograph from 2009 of Estate A showed 13 properties where construction was complete. On average, the grass cover of these properties was 76% and the trees, shrubs, and other plants constituted 24%. This indicates that the probability that grass will be planted 3.14 times higher than the probability that trees, shrubs and other plants will be planted. Figure 4.14 indicates the proposed distribution fit as proposed by the @Risk software.

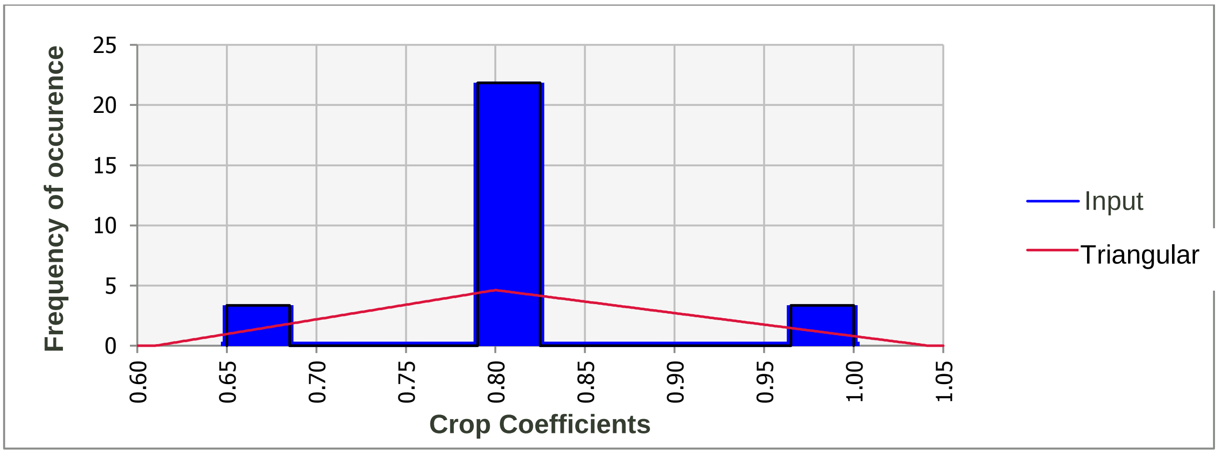

Figure 4.14 : Proposed triangular crop coefficient Triangular distribution fit

The statistical characteristics of these irrigated property area distribution functions are summarised in Table 4.10.

Table 4.10 : Data analysis and Triangular distribution function for crop coefficients

Statistical characteristics	Analysed data	Triangular Distribution
Minimum	0.65	0.61
Maximum	1.00	1.04
Mean	0.81	0.82
Mode	≈0.65	0.80
Median	0.80	0.81
Standard deviation	0.09	0.09

Limited information was available of the behavioural aspects of garden layouts. The in-depth investigation of this parameter could, in future, form part of extension of this study.

4.4.8 Pool Surface Area and Pool Ownership Factor

The imagery from Google Earth was used to determine the surface area of pools at properties if they have pools. It was determined that 51% of properties had pools and their surface areas varied between 7 m^2 and 30 m^2. The 51% was applied to the Monte Carlo simulations as a fixed pool ownership factor (F_{po}).

The measured pool surface area dataset was again analysed by the @Risk software, after which the probability distribution function was utilised in the Monte Carlo Simulation (See Figure 4.15 and Table 4.11).

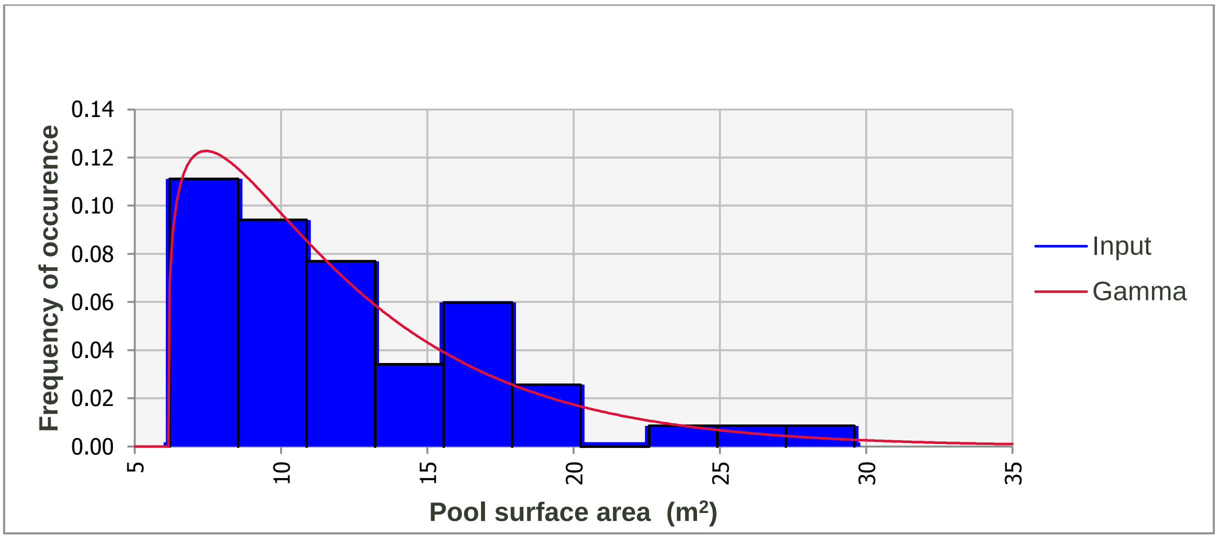

Figure 4.15 : Pool surface area Gamma distribution fit

Table 4.11 : Data analysis and Gamma distribution function for pool surface area

Statistical characteristics	**Analysed data**	**Gamma Distribution**
Minimum	6.2	6.151
Maximum	29.6	∞
Mean	12.306	12.306
Mode	≈7.500	7.442
Median	11	10.782
Standard Deviation	5.224	5.472

4.4.9 Pool maintenance occurrences and water level drawdown

A questionnaire was distributed to seven independent homeowners known to have pools. The questions that were asked and the related answers are tabulated in the Table 4.12.

Table 4.12 : Questions and answers to pool owners

	How many times per month do you backwash/ rinse your pool in summer?	**How many times per month do you backwash /rinse your pool in winter?**	**How long in minutes does your pump operate during this cycle? (min)**	**What is the surface area of your pool? (m^2)**
Pool owner 1	8	2	0.75	12.5
Pool owner 2	1	2	2.5	14
Pool owner 3	3	3	3	15.75
Pool owner 4	1	0	3	21
Pool owner 5	4	2	2.5	24.5
Pool owner 6	4	1	2.5	24.5
Pool owner 7	3	3	3	17.5

The data for the winter and summer event occurrences per month were combined to obtain a combined probability distribution function for the summer and winter events (See Figure 4.16).

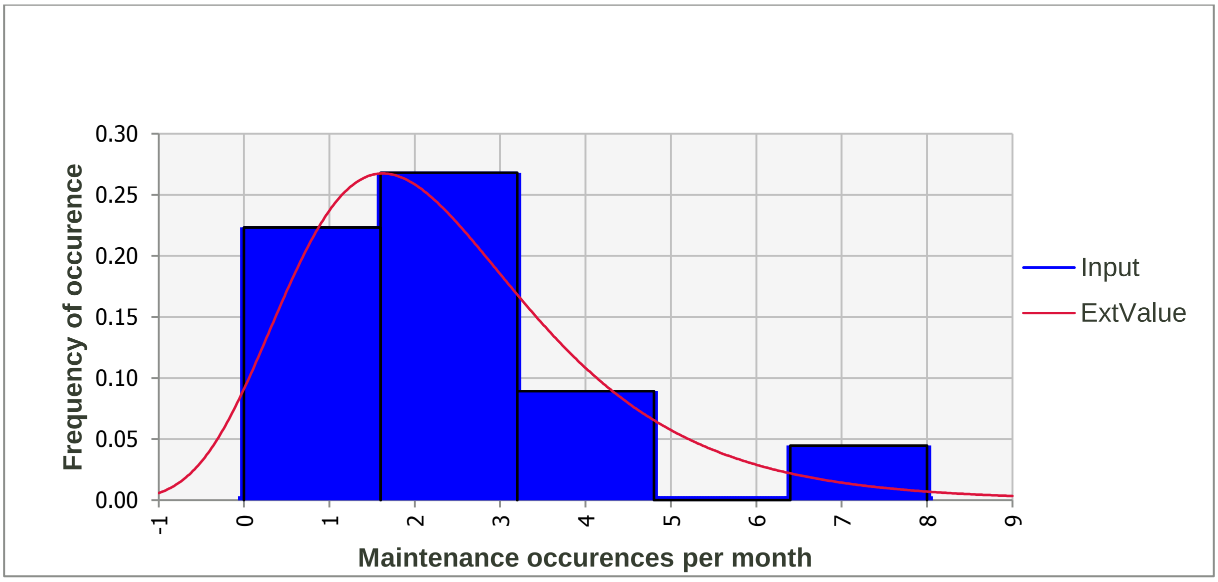

Figure 4.16 : Maintenance occurrences Maximum Extreme Value distribution fit

The @Risk-software fit proposed a maximum extreme value (MEV) distribution as representative for this data set. The statistical characteristics of the distribution are compared in Table 4.13.

Table 4.13 : Statistical properties of the data analysed and MEV distribution

Statistical characteristics	Data analysed	Maximum Extreme Value distribution
Minimum	0	$-\infty$
Maximum	8	∞
Mean	2.4643	2.419
Mode	≈1.5000	1.6248
Median	2	2.1291
Standard Deviation	2.0236	1.7647

In order to obtain the amount of pool drawdown per maintenance event it was necessary to research the standard pool pump operating flow rate. According to the specifications the standard Whirlpool model STP50 pool pump had a flow rate of 210 ℓ/min. The pool level drawdown could be calculated by multiplying the flow rate by the amount of operational time divided by the pool surface areas. Similar to the pool maintenance occurrence, the pool drawdown per pool maintenance event was also analysed and fitted with a typical uniform probability distribution function as illustrated in Figure 4.17, similarly the statistical properties are listed in Table 4.14.

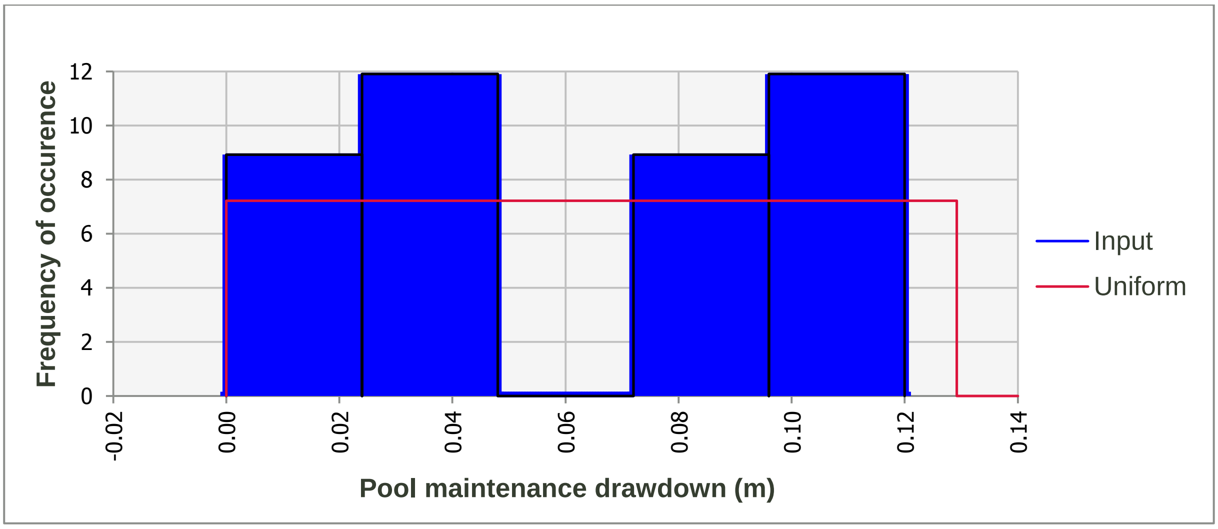

Figure 4:17 : Pool maintenance drawdown uniform distribution fit

Table 4.14 : Pool maintenance drawdown statistical characteristics

Statistical characteristics	Data Analysed	Uniform Distribution
Minimum	0	0
Maximum	0.12	0.12923
Mean	0.06216	0.06
Median	0.04286	0.06
Standard Deviation	0.04152	0.03997

5 Chapter 5 : Results and Verification of Model

5.1 Chapter overview

In this chapter the outdoor water demand results derived from the Monte Carlo simulations will be described and graphically verified against both the estimation of outdoor water consumption using the indoor proxy approach and actual outdoor consumption data. The model sensitivity results will also be presented. The results will be discussed under the following subsections:

- Comparison of results with minimum month proxy approach
- Verification of model results against actual data
- Sensitivity Analyses and Confidence interval results.

5.2 Comparison of results with minimum month proxy approach

The demand estimation model was developed during this research to simulate outdoor water demand of residential estates using climatic data that could be collected for most proposed development sites. The uncertain parameters such as irrigated area, irrigation efficiency, crop factors, pool size, pool maintenance methods and occurrences were based on data collected from Estate A.

The @Risk software was used to perform 1000 iterations of the mathematical model for each of the estates using random selections of the fitted probability distribution functions of the input parameters. The model was not calibrated for the purposes of this study. There is, however, value in comparing the simulated results with other approaches. A adjustment factor (AF) of 0.9 times the minimum monthly consumption was applied to estimate the non-seasonal indoor monthly consumption. This was used as a proxy to determine the outdoor water consumption in this study as comparison baseline for the Monte Carlo simulations performed in this study.

The following two result values derived from the simulations could be significant for the planning purposes of residential estates.

- The peak monthly demand is significant in the design of network infrastructure and could therefore be valuable to the network modeller and, in turn, the residential developer.
- The total annual outdoor water demand could be valuable in terms of sizing bulk infrastructure and applying for legislative approval.

Table 5.1 summarises the peak month and the annual total demand of the simulation in comparison with in the indoor proxy approach.

Table 5.1 : Residential Estate outdoor water demand results

Name of estate and description of result		Simulated Outdoor (kℓ)	Indoor Proxy for outdoor Approach (kℓ)	Accuracy : Simulated versus Proxy
Estate A	Annual Total	64 255	89 851	71%
	Peak Month	13 118	13 710	96%
Estate B	Annual Total	93 062	101 529	92%
	Peak Month	18 245	18 902	97%
Estate C	Annual Total	9 438	13 111	72%
	Peak Month	1 937	2 364	82%

From the results it is evident that the simulations fared better in terms of estimating the peak monthly outdoor water demand than the total annual outdoor water demand. In order to evaluate the differences the results were visually evaluated on a monthly temporal scale. Figures 5.1, 5.2 and 5.3 illustrate the results from the two methods graphically.

The simulated results of each of the three estates display a relatively similar shape and in comparison with the estimated outdoor consumption a clear anomaly exists in the autumn months (April to June). This anomaly could be ascribed to the use of automatic sprinkler systems that do not take rainfall into consideration. These systems often operate on a time scheduling basis that has to be manually adjusted for seasonal changes. This anomaly could be addressed in two ways namely:

- Awareness of seasonal changes or implementation of automatic irrigation systems that have seasonal functionality.
- Applying a monthly irrigation efficiency to compensate for the late adjustment of irrigation systems.

Estate B has the largest sample size of 4 years of data for 390 properties which proved to be the estate where the simulation results appear to be the closest to the estimated outdoor consumption based on the proxy approach. It could be expected that Estate A and Estate C would have extreme water consumption data that will not be absorbed as would be the case with a large sample size, resulting in inaccuracy of the model. The extreme water consumption data could be caused by the following:

- Construction activities;
- Localised leakage;
- Extreme over irrigation; and
- Extreme evaporation or rainfall conditions.

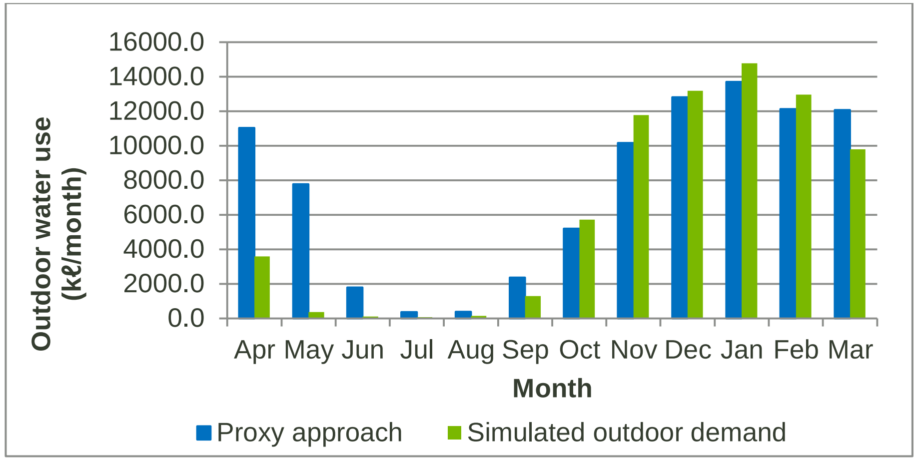

Figure 5.1 : Estate A outdoor water demand results comparison

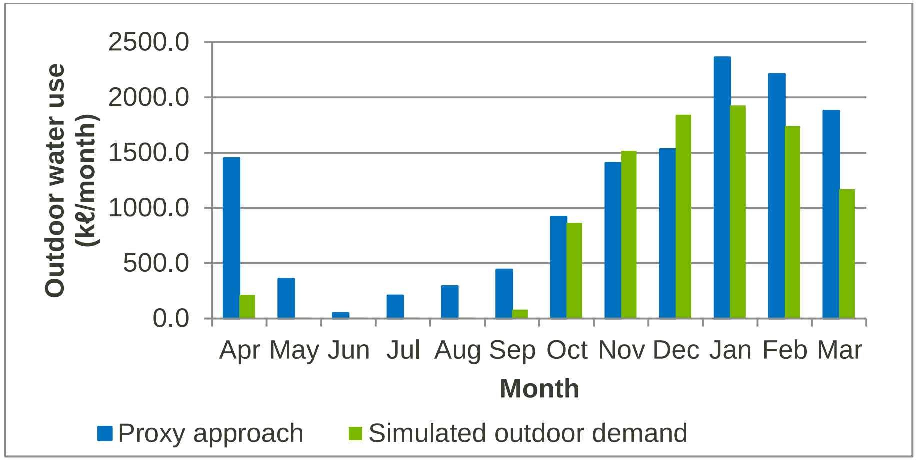

Figure 5.3 : Estate C outdoor water demand results comparison

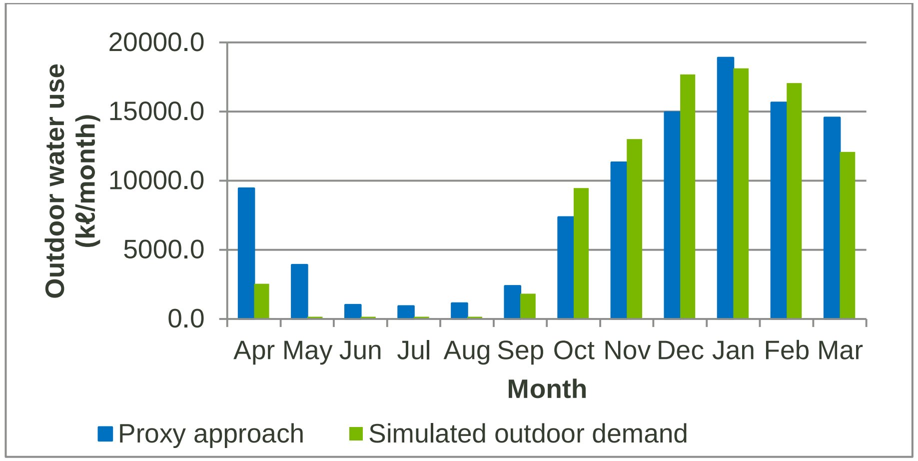

Figure 5.2 : Estate B outdoor water demand results comparison

5.3 Verification of model performance against actual data

In order to further demonstrate the accuracy of the model it could be advantageous to conduct similar simulations in the groups of houses that formed part of the REUWS data base study that had sufficient outdoor and total water consumption data for comparison purposes. The data required included property size, irrigated area, irrigation efficiency evaporation, rainfall and pool ownership. As previously discussed, the houses in Boulder, Eugene, Lompoc and Phoenix were suitable for the purposes of this study.

Similar to the results of the simulation illustrated in the Figures 5.1, 5.2, 53, the Monte Carlo Simulations were performed on the available REUWS data and compared with the indoor proxy approach method. However, the simulation of the REUWS data could also be compared to actual metered outdoor water demands. Figures 5.4, 5.5, 5.6 and 5.7 illustrate the comparison of results graphically.

From visual inspection of the results it is evident that the Eugene and Lompoc simulation results are comparable to the metered outdoor water consumption. Both Boulder and Phoenix are located in arid regions of Northern America, where water conservation strategies such as rebate programmes are implemented.

It should also be reiterated that the metered outdoor water consumption was scaled up from two week data logs to obtain estimated monthly outdoor water consumption data, as explained in the Section 4.3.3 of this report.

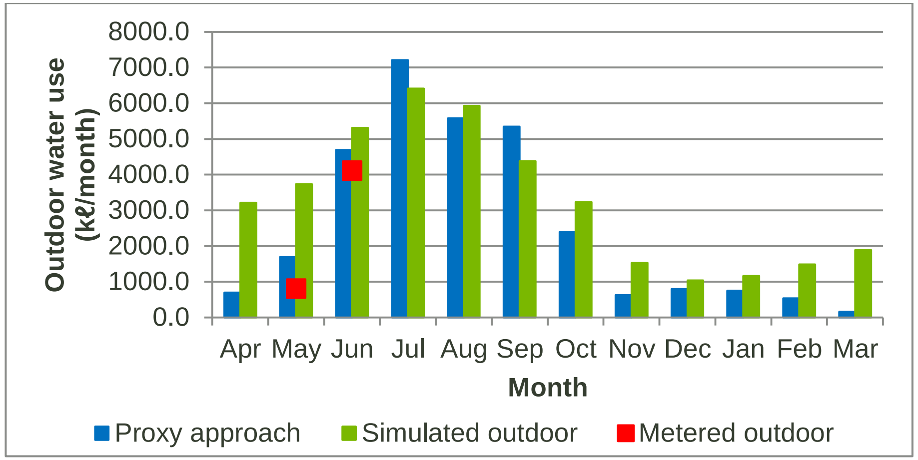

Figure 5.4 : Boulder outdoor water demand results comparison

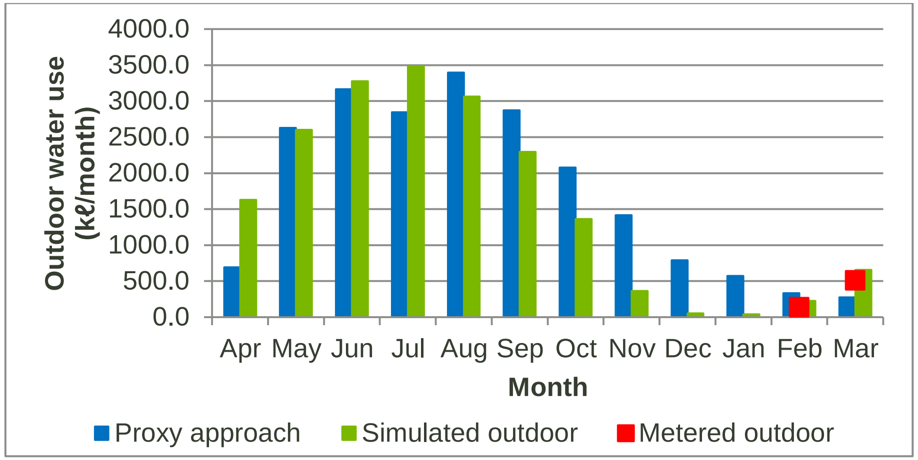

Figure 5.6 : Lompoc outdoor water demand results comparison

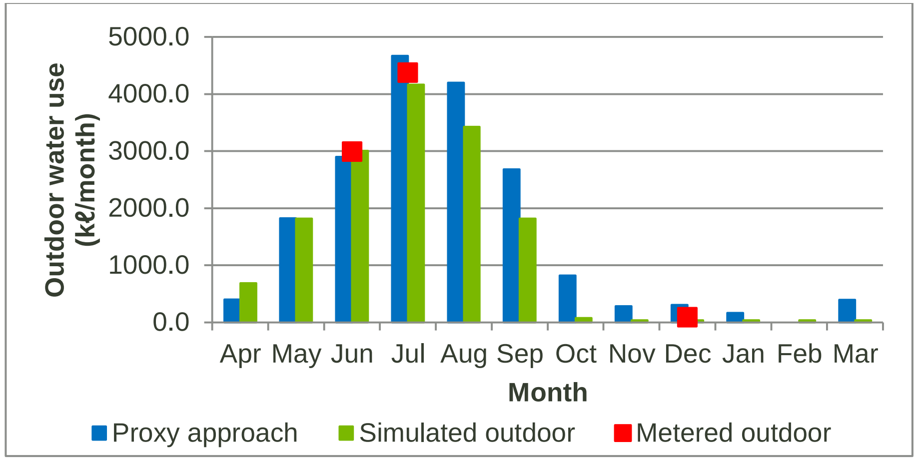

Figure 5.5 : Eugene outdoor water demand results comparison

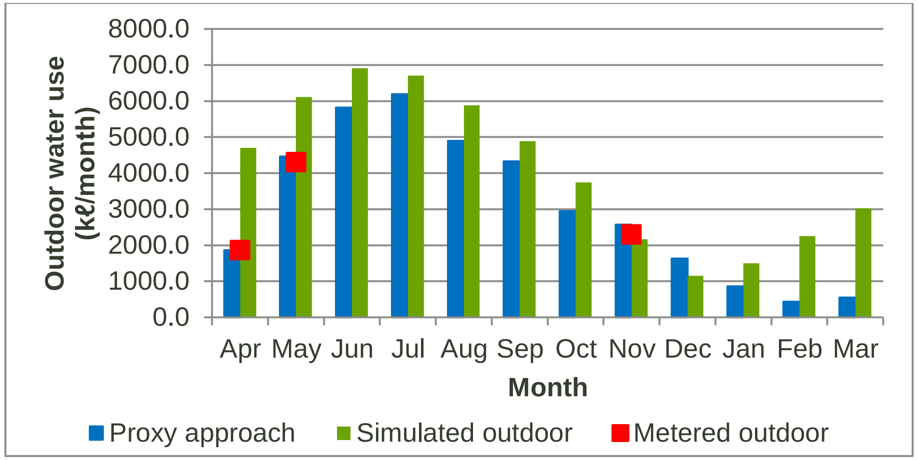

Figure 5.7 : Phoenix outdoor water demand results comparison

5.4 Sensitivity analyses and Confidence interval results

The @Risk software performed sensitivity analyses on each of the parameters that were used in the simulations. The sensitivity analysis performed on the Estate A simulations for total annual outdoor water demand and the outdoor water demand for the peak summer month (January) and low winter month (July) are illustrated in Figure 5.8, 5.9 and 5.10. The parameters are ranked and positioned on the graphs illustrated in Figure 5.8, 5.9 and 5.10, according to their effect on the final outcome of the results produced by the simulations.

From the graphs mentioned above it can be derived that the irrigation efficiency parameter plays a dominant role in the simulation of total annual and peak summer demands. During the winter demands the pool maintenance drawdown, which translates into the amount of water that is required to maintain a pool per occurrence, has the most significant impact. As a result of these analyses it can be concluded that the additional investigation aimed at the Irrigation efficiency parameter should take precedence when performing similar simulations.

Although the average precipitation, evaporation and evapotranspiration parameters were based on average data, it is expected that this data will vary on a year to year basis. The impact of this was tested for Estate A by developing probability distribution functions for each of these parameters on a monthly temporal scale, as the required data of a weather station that is in close proximity of the site was available on the Department of Water Affairs' website. These probability distribution functions were incorporated in the simulations of Estate A to illustrate the significance thereof to the sensitivity analysis results (See Figure 5.11).

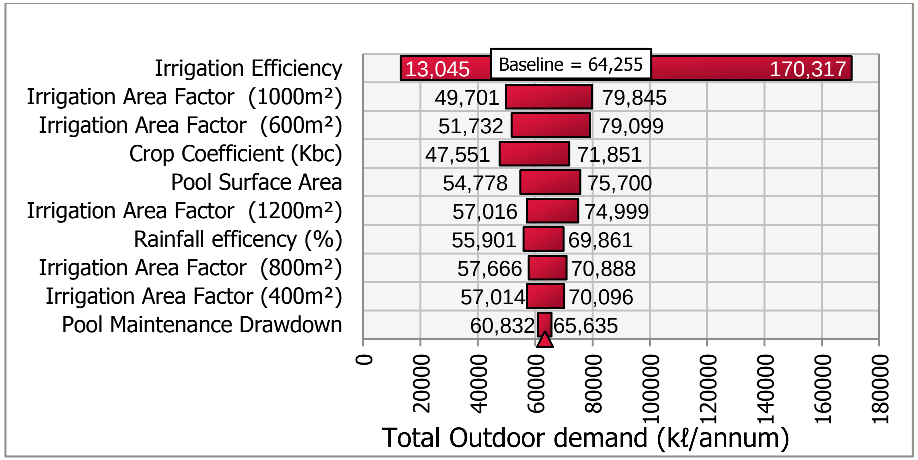

Figure 5.8 : Total annual water demand sensitivity analysis

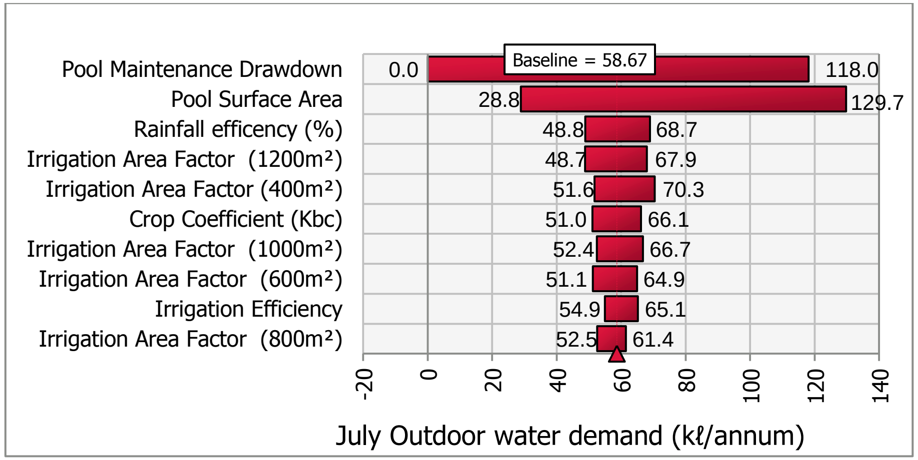

Figure 5.10 : Low winter month water demand sensitivity analysis

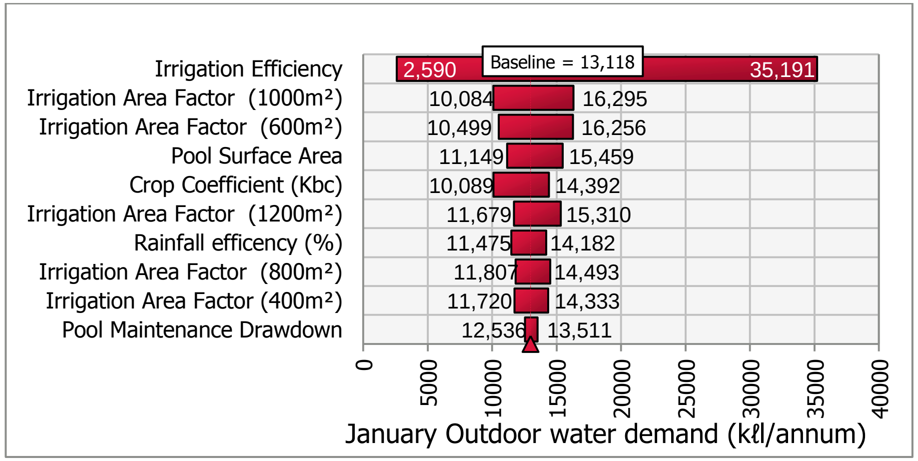

Figure 5.9: Peak summer month water demand sensitivity analysis

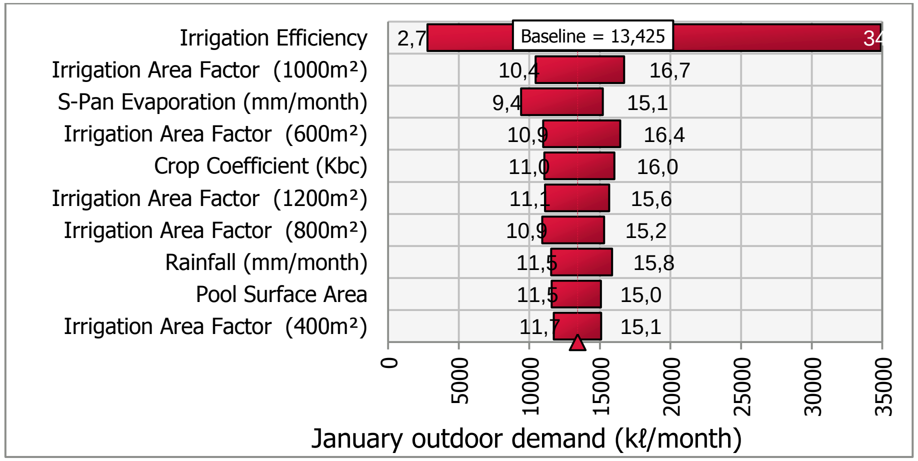

Figure 5.11: Sensitivity analysis for January, distributed weather.

The evaporation and rainfall, although ranked third and eighth respectively (Figure 5.11), did not have a major impact on the results, compared to the irrigation efficiency parameter.

The confidence intervals of the model simulations were calculated as a further demonstration of the uncertainty of the simulation results, which is illustrated graphically in Figure 5.12.

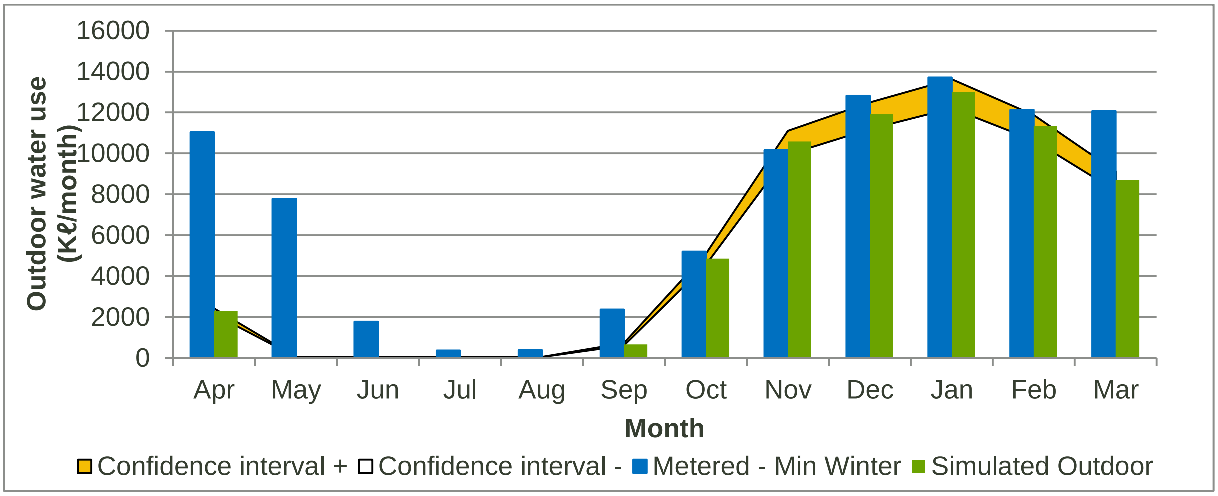

Figure 5.12 : Confidence interval plot for Estate A

The confidence band is based on a 95% confidence interval calculation method performed by the @Risk software for a simulation model of 1000 iterations. The confidence bands proved to be sufficient in the summer months; however, they are less accurate for the other months of the year. Further research into the irrigation efficiency on a monthly temporal scale could improve these results.

6 Chapter 6 : Discussion and Conclusions

6.1 Summary of Findings

The design of capacities civil infrastructure such as water distribution networks and sewage reticulation networks is often based on the calculation of an average annual daily demand and its accompanying peak factor and sewage yield factors.

Jacobs (2008b) confirmed that in South Africa the CSIR (2003) method is a popular method, which entails calculating the average annual daily demand based on a specific property size, after which it is multiplied by a peak factor that is read off a graph that depicts a relationship between probable peak factors and equivalent properties. More recent studies such as those conducted by Jacobs (2004); Husselman and Van Zyl (2006) have taken geographical regions, standard of living and household income into account when proposing AADD calculation methods.

Development of technology such as high resolution water meter logging has improved the level of accuracy with which individual end-uses could be pinpointed using tracer analysis models. From these models the end-use models originated, allowing researchers to estimate and even predict water demands on a relatively intense temporal scale (DeOreo et al., 2011; Scheepers 2012).

As part of this study a computer based stochastic model was developed specifically to address outdoor water demand of residential estates on a monthly temporal scale. An outdoor water demand mathematical model was derived from a model proposed by DeOreo et al. (2011) and consisted of the following outdoor use components:

- Irrigation;
- Pool and water feature evaporation top-up; and
- Maintenance, including rinsing and backwashing of pool filters.

Probability distribution functions were derived for the parameters required for the mathematical model. These probability distribution functions were based on literature and on data collected from one specific residential estate, called Estate A for the purposes of this study. The parameters that pertain to this mathematical model included the following:

- The area of a property that is under irrigation
- Evapotranspiration

- Crop coefficient;
- Effective precipitation factor;
- Irrigation efficiency;
- The surface area of a pool or water feature;
- Evaporation rate of water in a specific location;
- Measured precipitation;
- The water level difference before and after the performing of a maintenance cycle for pool pumps; and
- The occurrence of pool maintenance per calendar month.

Incorporating the parameters derived for Estate A, mathematical models were populated for two additional residential estates, Estate B and Estate C. These models were hereafter simulated using the @Risk software, a Monte Carlo simulation package. One thousand iterations were conducted for each residential estate. The modelled outdoor water demand results were then obtained on a monthly temporal scale.

In order to evaluate the results from the mathematical demand model an outdoor consumption approach had to be developed, as limited outdoor water consumption data exists. The REUWS database was developed by various engineering consultants for the American Water Works Association's Research foundation. The REUWS database included water end use data for 1188 houses located in 12 locations in Northern America of which the data for 398 houses had average annual indoor water consumption data as well as measured potential irrigation areas. These 398 houses were located in Boulder, Eugene, Lompoc and Phoenix.

DeOreo et al. (2011) suggested that the winter water consumption could be used as a proxy for indoor water consumption and that if indoor consumption is assumed to be non-seasonal, it could be subtracted from the total water consumption to derive a proxy approach for outdoor water consumption.

This approach was tested against the actual outdoor consumption logged for the 398 houses. It was determined by comparison that the 90% of the monthly consumption of the month with the lowest consumption could be assumed to be, on average, equal to the indoor consumption. For the purposes of this study the outdoor water consumption of the estates was assumed to be 90% of the month with the lowest water consumption subtracted from the metered monthly water consumption.

Based on the model comparisons, it was found that model performed acceptably in estimating the peak summer month demand, especially for estate B of which the sample size was the greatest.

An accuracy of 97% was reached for the peak month demand in comparison with the estimated monthly consumption determined by the proxy approach method. Less accurate results, ranging between 71% and 96%, were obtained for the total annual outdoor water demand estimations. It was, however found in all three cases that the homeowners generally over-irrigated during the autumn months of the year when evapotranspiration decreases and rainfall occurs more often.

The groups of houses that formed part of the indoor proxy portion of this model were used for further verification of the simulation model. Based on visual inspection, the simulations of two of the locations, Lompoc and Eugene, performed acceptably, whereas the simulations conducted for Phoenix and Boulder completely overestimated the outdoor water demand. The suspected reasons for this anomaly were that these houses are located in arid areas where water conservation rebates are promoted and vegetation that survives in these regions could require less watering.

From the sensitivity analyses it was evident that irrigation efficiency is the main contributor to the variation in the estimation of annual and peak summer outdoor water demand. In winter months this role is taken by the amount of water used for pool maintenance per occurrence.

As further demonstration of the uncertainty aspects of the model, the confidence intervals of the simulation results were determined and displayed for Estate A's model. The confidence intervals were based on 1000 iterations and 95% confidence. The confidence bands appeared as expected for the summer months, however, they were in accurate for the rest of the months of the year. Further research into irrigation efficiency on a monthly temporal scale could resolve this anomaly.

6.2 Conclusions

The outdoor water demand estimation model yielded results that are comparable with actual outdoor water consumption data as well as estimated outdoor water consumption data. This model could, therefore, easily be implemented to estimate outdoor water demand figures for feasibility and concept designs of residential estates where certain parameters such as proposed irrigated areas, irrigation efficiency and crop coefficient profiles could be relatively well controlled by the estates' constitutions.

The fact that the simulation results of estate with the largest sample of data were the closest to the estimated outdoor consumption, demonstrated that, within the residential estate environment, the model could perform within acceptable bounds of accuracy.

Additional attention has to be given to irrigation efficiency, as this parameter significantly dictates the outcome of the model results. With refinement of the model, it could be further implemented on a detailed design scale of water and sewerage network designs. In order to attain higher levels of accuracy, further comparison of the parameters to data collected from multiple sites could be conducted.

The comparison of the results with the groups of houses in the cities/towns that are located in North America indicted that it was possible that the model could be further implemented internationally. This, however, depends on water conservation initiatives and further investigation into local crop coefficients.

In the absence of site specific knowledge, the outdoor water demand of a residential estate could be simulated using basic climatic data and estimated residential property sizes and quantities. Combining the results from this study with the indoor water demand results from a model such as the model developed by Scheepers (2012), a developer or planner could stochastically estimate the total water demand of a residential estate on an annual or a monthly temporal scale.

The application of a model of this nature is widespread and it can be adapted for outdoor water demand prediction purposes and estimation of possible water conservation volumes should water restrictions be implemented. In areas where dual water supply systems are considered, this model could provide insight into possible water savings and could provide opportunity for the establishment of water unit prices.

6.3 Summary of Contributions

A stochastic outdoor water demand estimation model as presented in this study has not been published for the South African industry. This model could be applied to conceptual outdoor water demand figures which are elementary for the feasibility of a residential estate project. Further research and refinement of the model could improve the accuracy of the simulation results, which in turn could contribute to informed decision making during project approval stages.

The sensitivity analyses of the model parameters provided a clear demonstration that irrigation efficiency is the dominant factor in the determination of outdoor water demand suggesting that it requires further research and development.

With further research and development of the model and its parameters, this model could be expanded to determine the demand of other outdoor water consumers such as commercial, municipal industrial, and other residential properties. With these expansions, the model could become a valuable master planning tool, as well as a measure to quantification of the impact of water restriction and its conservation potential could be considered a supplementary advantage of this study, especially in today's environmentally conscious society.

6.4 Future Research

This study focussed on the development of an outdoor water demand model based on a monthly temporal scale for residential estates. It would be beneficial to further research a daily peak factor for outdoor water demand.

Although the emphasis of this study was on the outdoor water demand of residential estates, further development of the model could incorporate properties in the non-estate, commercial and industrial sectors, as well as onsite leakage and appurtenant water losses.

Further research that relates to this study could sprout from the following aspects:

- Outdoor water consumption metering and correlation with the stochastic model.
- Extended research with regard to uncertain parameters such as vegetation, irrigation efficiencies and parameters that pertain to pool replenishment and operation.
- The impact that the status quo of water supply sources has on the outdoor water demand of a residential estate.
- A home owner income parameter could be investigated for inclusion in the mathematical model.
- The effective precipitation parameter was limited to values received from literature. Experimentation techniques could result in improved estimation of the distribution of this parameter.
- Typical vegetation coefficients.
- The price of water and price elasticity of water as an influence on the outdoor water demand of an residential estate.

The mathematical model in this study made use of average precipitation, evaporation and evapotranspiration figures: however, these input parameters are known to vary extremely from year to year. Although site specific data is usually limited, a probability distribution function could be developed for each parameter on a monthly temporal scale.

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