MODELLING WATER DEMAND FOR RESIDENTIAL HOUSEHOLDS BY SEGREGATING INDOOR AND OUTDOOR USES

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DECLARATION

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ABSTRACT

The ability of municipalities to deliver a sustainable supply of water to South African customers has become a major problem. Water scarcity is a profound challenge facing most countries worldwide that will continue to escalate without intervention. The need for proper infrastructure planning, effective demand management policies, climate change adaption strategies and the development of alternative water sources, is of critical importance. A key input to achieving these tasks, is the ability to provide accurate estimates of the current and future water demands.

The residential water demand is a major component of the urban water use profile with a large water saving potential. Water restriction campaigns often target non-essential, outdoor uses which often account for a large portion of household consumption, especially during the summer months. Guidelines commonly used in South Africa are relatively insensitive to important parameters that influence residential demand and they do not account for seasonal variation. More advanced methods have been developed, such as end-use models, to forecast detailed end-use demand patterns, but are often complex and require extensive input datasets.

As part of this study, a model was constructed to estimate the water demand for residential households on a monthly basis, at a reasonable level of accuracy. An attempt was made to incorporate the important influential factors, including relatively few inputs and requiring data that can be sourced fairly easily. The concept of the demand model was to estimate the indoor and outdoor components of household consumption separately. An extensive review of available literature and research papers was done in order to identify and select the most critical factors to include in the model. Household size was found to have the greatest influence on indoor consumption. The surface area of the garden and swimming pool, crop type and climatic variables were identified as important factors affecting outdoor demand. The model could offer insight into the seasonal patterns of household demand and provide a basis for future work on the conservation potential of household water use.

An evaluation procedure was conducted by applying the proposed demand model to existing households and comparing the modelled results to the actual consumption. A total of 1 055 households were selected from gated communities in the Western Cape and Gauteng for analysis. Where site data was not available to populate the input parameters, information sourced from previous studies and relevant literature references was used. The monthly meter readings were obtained for each study site and compared to the demands estimated by the model. The model provided reasonably accurate results for 6 out of the 10 study sites, with an accuracy of above 80% for predicting the AADD. This method could be valuable for planning future housing developments and sizing water infrastructure.

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Background

Fresh water has become an increasingly scarce resource in most regions around the world. Countries experiencing rapid urbanization, economic development and population growth are placing tremendous pressure on this limited resource. South Africa is the 30th driest country in the world, with unpredictable and below average rainfall patterns, high evaporation rates and extreme weather conditions (DWAF, 2004; Department of Water Affairs, 2013). In conjunction with the increasing demand and aridity, the impacts of climate change are creating further stress on South Africa's available and valuable water supply.

Fresh water plays an important role in the location, function, growth and development of a community (Arbués et al., 2003). Water scarcity can negatively affect the health of the population and the socio-economic aspects of a country (Town *et al.*, 2019). The semi-arid nature and highly variable climate in South Africa, as well as the increased urbanization and population growth in cities, highlights the importance of protecting and sustaining water resources.

Water shortage has been acknowledged as a major, worldwide problem. As a result, increased attention has been drawn to alternative solutions, including: dual reticulation systems, desalination plants, water reuse and water efficient appliances (Gurung *et al.*, 2015). Water demand management strategies have also been implemented in most water stressed countries by preventing the misuse and overuse of water and encouraging conservational efforts.

The domestic sector represents the largest component of urban water use in South Africa (Jacobs *et al.*, 2007; Walker, 2009; Sadalla *et al.*, 2012). Population and economic growth in South Africa has led to an increase in domestic water demand. It is therefore imperative for local authorities to implement effective water demand management initiatives at a household level (World Water Assessment Programme, 2012). A key input to planning sustainable demand management initiatives is accurate demand forecasts of the current and future water requirements. This task requires a detailed understanding of household consumption behaviour (Inman and Jeffrey, 2006). An in-depth knowledge of water use at a household scale could also improve the effectiveness of water restrictions during water shortages or drought periods (Brooks, 2006).

The CSIR (2005) and Department of Human Settlement (2019) guidelines are commonly used by engineers in South Africa for estimating water demand. The demand estimates for households in developed areas, provided in the CSIR (2005) and Department of Human Settlement (2019) guidelines, are based on land use, connection type, unit density and plot size.

1.2. Problem statement

One of the main challenges facing water scarce regions, is ensuring a sustainable supply of potable water to a ever growing population (Fisher-Jeffes et al., 2015). The most recent drought period in South Africa (2015-2018) resulted in severe water shortages in many areas. The current state of water resources in South Africa highlights the importance of efficient planning and implementation of water resource management strategies (Jansen and Schulz, 2006). Proper water service planning requires a detailed understanding of water use behaviour and appropriate forecasting techniques.

The South African guidelines commonly used to estimate domestic water demand rely on plot size, density and population as independent variables (CSIR, 2005; Department of Human Settlement, 2019). Two researchers have found the CSIR design guidelines to be conservative (Jacobs *et al.*, 2004; van Zyl *et al.*, 2007). Therefore, an improved method for forecasting household water use is needed.

Residential consumers use water for various indoor and outdoor needs. The indoor and outdoor components are influenced by different variables and exhibit different seasonal patterns. Outdoor use is often the target of water restriction strategies during periods of water shortages and conservation efforts. Research on modelling indoor and outdoor water use separately is limited. The main reason is that most households have a single water meter that measures the total household consumption. Flow trace analysis is widely used by researchers to identify flow patterns and derive the individual contribution of each end-use element (Jacobs and Haarhoff, 2004; DeOreo *et al.*, 2011). However, flow trace analysis is often expensive, complex and data intensive. Additionally, some of the available end-use models exclude outdoor consumption and do not consider the effect of household size (Jacobs and Haarhoff, 2004).

1.3. Motivation

Domestic water is one of the most important commodities and it represents a large portion of the total urban water demand. In this water scarce country, it is essential that the most efficient and effective solutions be found to ensure a constant and sustainable supply of potable water. Household consumption can be spilt into indoor and outdoor uses. In semi-arid regions, garden irrigation can account for a up to 70% of the summer water demand (Hayden *et al.*, 2015). Outdoor water uses are non-essential and thus form a crucial focus for conservation measures. Considering indoor and outdoor use separately in a combined residential water use model would improve demand estimation and could ultimately lead to enhanced service provision. The results of this study could assist design engineers when constructing new housing developments, as well as offer insight to water utilities and managers when planning water demand management strategies and drought contingency plans.

1.4. Research objectives

The main purpose of this study was to develop a segregated model for estimating water demand in residential households. The model was designed to split the total water usage into indoor- and outdoor components, accounting for the different factors that influence indoor- and outdoor uses. This analysis was conducted to provide further insight into the nature of indoor and outdoor consumption patterns and the influential factors effecting demand at a household level. The objectives of this research study were to:

- Conduct an extensive review of previous publications (both international and domestic) on residential water demand, influential factors and estimation methods
- Develop a model to estimate residential demand; separately accounting for indoor and outdoor use
- Select a sample of existing sites to represent a suitable range of residential households
- Collect the relevant data sets to populate the model parameters for the study sites
- Compare the demand model results with actual water consumption records
- Evaluate the demand model and draw conclusions.

1.5. Scope and limitations

This research focused on residential households situated in developed areas. Residential demand comprises of indoor and outdoor water use together with on-site leakage. Leakage has been reported as site specific and therefore was not modelled in this study (Roberts, 2005). Outdoor consumption generally includes garden irrigation, swimming pool use and outdoor tap use. Due to reports of relatively low volumes from outdoor tap use for purposes other than gardening or the swimming pool, it was deemed insignificant and excluded from the study (Roberts, 2005). Other limitations of this study were: number and variability of study sites (1 055 homes in two regions) and households in gated community developments.

2. LITERATURE REVIEW

2.1. Overview

This chapter presents a review of the significant literature on residential water use, factors influencing consumption and estimation methods. The researched literature was sourced from various scientific journals, thesis reports, guidelines and books found in the Stellenbosch University library and on various electronic databases.

2.2. Definitions

It is necessary to provide a clear definition for certain concepts used in this study, as some terms may be ambiguous or have several meanings. To provide clarity, a brief definition has been provided for the following technical terms and are used in this context throughout this report.

(i) *Annual average daily demand (AADD)*: is defined as the total volume of water used by a customer or customer group for one year, divided by the number of days in a year (Arunkumar and Mariappan, 2015)

(ii) *Effective precipitation:* is the portion of precipitation that penetrates the soil and is stored for use by landscape plants, not lost to deep percolation or run-off (Connellan, 2002)

(iii) *End-use*: is the smallest identifiable use of water on a stand, such as a shower event (Jacobs and Haarhoff, 2004)

(iv) *Evapotranspiration:* is a measure of water lost through transpiration from the plant and evaporation from the ground surface (Allen et al., 1998)

(v) *Gated community:* is a residential area with designated perimeters and restricted access designed to privatize public areas (Blakely and Snyder, 1997)

(vi) *Plot:* (also known as stand or erf) is a residential house and the surrounding area within the property boundary (Jacobs and Haarhoff, 2004)

(vii) *Water conservation:* "the minimisation of loss or waste, the care and protection of water resources and the efficient and effective use of water" (Department of Water Affairs, 2004)

(viii) *Water consumption:* refers to the actual volume of water utilized by a consumer or group of consumers, usually measured by a water meter placed on or near the property boundary (CSIR, 2005)

(ix) *Water demand:* the quantity of water required to supply customers in a water distribution system within a defined period, excluding leakage from the main reticulation system and water required for system flushing and fire-fighting (Arunkumar and Mariappan, 2015)

(X) *Water demand management:* "the adaptation and implementation of a strategy by a water institution or user to influence the water demand and usage of water in order to meet any of the following objectives: economic efficiency, social development, social equity, environmental protection, sustainability of water supply and services, and political acceptability" (Department of Human Settlement, 2019).

2.3. Residential water demand

Water is used for various activities or needs on a residential property, including cooking, cleaning, human consumption, personal hygiene and garden irrigation (Memon and Butler, 2006). These household needs are some of the most important uses for water. Household consumption can be split into indoor and outdoor end-uses. The end-uses typically found on a residential property are the indoor tap, toilet, shower, washing machine, dishwasher, outdoor tap, garden watering, swimming pool and other.

2.3.1. Indoor consumption

Indoor consumption is the amount of water used by all water consuming appliances inside the household. Typical indoor water using appliances found in a home are: toilet, bath, shower, dishwasher, washing machine and indoor taps. The Department of Human Settlement (2019) guidelines provide a typical breakdown of each indoor end-use activity, these values have been illustrated as a percentage of the total indoor consumption in Figure 1.

				
Dishwasher 2%	Toilet 25%	Shower/Bath 30%	Tap 18%	Washing machine 25%

Figure 1 Percentage indoor end use contribution (Department of Human Settlement, 2019)

Previous studies have stated that indoor water consumption patterns remain fairly constant, with very little to no evidence of seasonal fluctuation (Mayer *et al.*, 1999; Roberts, 2005; Beal et al., 2010). Coghlan and Higgs (2003) and Rathnayka et al. (2015) did however observe a small increase in shower use, indoor taps and air conditioning systems during the summer months. The change in water use patterns for indoor activities between the summer and winter months is generally considered insignificant (Roberts, 2005; Heinrich, 2007). Evidence taken from Coghlan and Higgs (2003) supporting this statement has been illustrated in Figure 2.

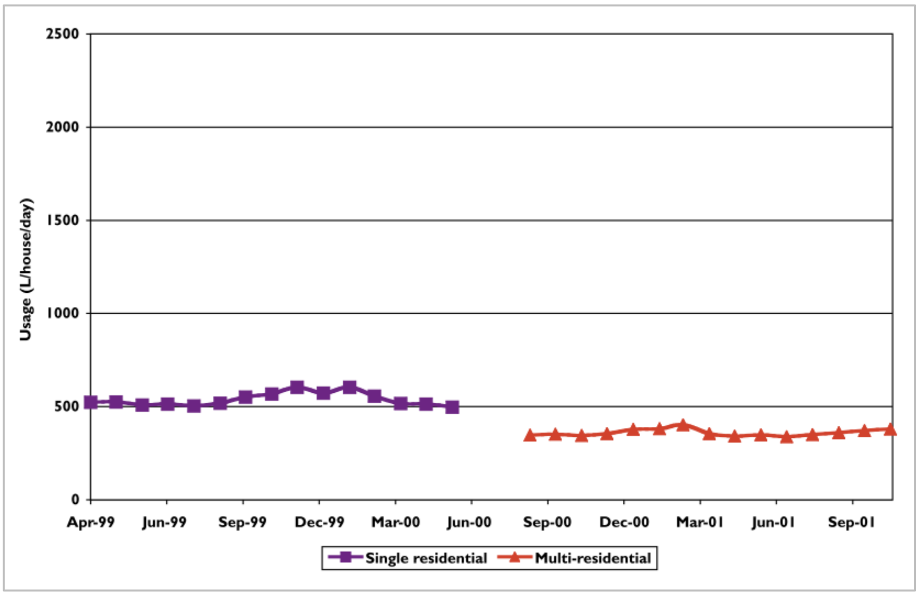

Figure 2 Indoor consumption patterns for single and multi-residential households (Coghlan and Higgs, 2003)

Indoor water consumption is generally related to demographic, socio-economic and behavioural habits of the residents as well as the type and efficiency of indoor appliances (Makki *et al.*, 2015). The main factors influencing indoor use include: household size and income level (Bennett et al., 2012; Makki *et al.*, 2015).

2.3.2. Outdoor consumption

Outdoor water consumption generally includes garden irrigation, water for refilling swimming pools and outdoor water features and outdoor taps. Studies have reported various factors that influence outdoor consumption, including: garden area (Harlan *et al.*, 2007), vegetation type (Wentz and Gober, 2007), irrigation method (Roberts, 2005), size of swimming pool (Domene and Saurı, 2006), climatic variables (Gato et al., 2007), human behaviour (Balling and Gober, 2007) and income level (Van Zyl et al., 2008; Lowry et al., 2011). The Department of Human Settlement (2019) guidelines provide an estimate of outdoor water use as a percent of the AADD, based on land use categories, see Table 1.

Table 1 Percentage outdoor water use (Department of Human Settlement, 2019)

Land use category		Percentage of AADD (%)
Low income housing		0 - 15
Single residential stands	< 500m^2	0 - 20
	500m^2 - 1 000 m^2	0 - 30
	1 000 m^2 - 1 600 m^2	0 - 40
	1 500 m^2 - 2 000 m^2	0 - 50
	> 2 000m^2	0 - 60
Cluster housing		0 - 10

Outdoor water demand is largely driven by climatic variables, which cause the seasonal fluctuation in household consumption patterns (Roberts, 2005). A recent study, analysing the consumption patterns of 338 high income properties in Cape Town, estimated that 73% of the total water use was used outdoors during the peak summer month (Du Plessis et al., 2017). During the winter months, the outdoor use decreased significantly, contributing only 29% to the total demand.

Estimating outdoor water demand is a difficult task. The challenges are a result of these end-use activities being influenced by factors that are difficult to quantify, such as: human behaviour, climate, alternative water sources and landscape design. Outdoor water use is non-essential and is often the primary target of water conservation campaigns and water restrictions during periods of water shortages (Jacobs, 2008).

2.3.3. Leakage

On-site leakage is defined as water lost on a residential property, downstream of the customers water meter (Couvelis and van Zyl, 2015). The quality and age of infrastructure and water using appliances as well as the pressure of the reticulation system can influence leakage in terms of likelihood, frequency and volume (Saghi and Aval, 2015). The attitudes and characteristics of the residents can also affect the level of leakage by ability to afford maintenance, type and age of water using appliances and the ability to detect and repair leaks within the household.

Some South African studies have investigated onsite leakage in suburban households (Lugoma et al., 2012; Couvelis and van Zyl, 2015; Ncube and Taigbenu, 2016). The leakage statistics from previous South African studies for middle to high-income properties are summarized in Table 2.

Table 2 Typical leakage from South African households

Reference	Location	Number of properties	Properties with leaks (%)	Mean leakage rate of all properties (L/hr)
Couvelis and van Zyl (2015)	Cape Town	402	17	3.6
Couvelis and van Zyl (2015)	Bloemfontein	166	28	11.1
Lugoma et al. (2012)	Johannesburg	128	67	15.7
Ncube and Taigbenu (2016)	Johannesburg	141	48	14.7

Onsite leakage has been investigated by many researchers, however, this component is very difficult to estimate since it is site specific (DeOreo et al., 1996). In most forecasting models, leakage is either excluded or added as an additional component. On-site leakage was not included in the model developed as part of this study.

2.4. Nature of residential demand

Residential consumption varies from country to country and region to region (Grafton *et al.*, 2011). The variation is attributed to many different factors including: climate, economic wellbeing, legislative incentives, technological advancement, sanitation habits, cultural influences, type of supply and availability of fresh water (Memon and Butler, 2006). Figure 3 shows the variation in household per capita consumption between different countries (Memon and Butler, 2006).

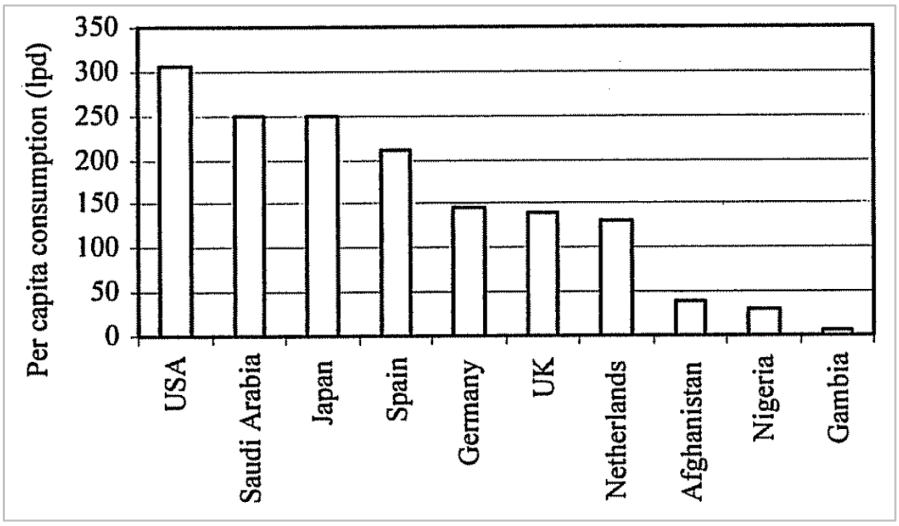

Figure 3 Household per capita consumption for various countries (Memon and Butler, 2006)

Consumption patterns at a household scale are partly influenced by unpredictable human behaviour. This behaviour depends on demographic (age, gender and household size) and socio-economic aspects (income and education level). Other important factors reported by House-Peters and Chang (2011), include housing characteristics (age, type, size of dwelling, garden area and type of vegetation) and climate (temperature, precipitation and evaporation). The importance and effect of each factor depends on the type of consumption examined (end-use, indoor, outdoor or total), the consumer group (residential, commercial or industrial) and the spatial and temporal scales of analysis (Wentz and Gober, 2007). This research analysed the indoor and outdoor components of water consumption in residential households.

Within a home, water use varies significantly on hourly, daily, monthly and seasonal time scales (Buchberger and Wells, 1996). The use and combination of different water using activities in a household produces a water demand pattern. Generally, residential consumers have similar periodic activities, such as school or work that in turn effect the schedule of water use patterns.

This study focused on consumption patterns at monthly and seasonal time scales. The monthly and seasonal variation is caused mainly by climatic influences. A notable increase in consumption is usually experienced during the warmer, summer months due to increased irrigation, swimming pool requirement and water for personal hygiene. Conversely, during the cooler winter months, a decrease in residential demand is often observed. An increase in demand is also experienced during the holiday months from a temporary increase in the number of residents consuming water in a household throughout the day, such as school children, working residents and additional family and friends.

2.5. Factors affecting residential consumption

The consumption behaviours and patterns of each individual consumer are derived from different psychological, cultural and educational backgrounds (Sant'Ana, 2011). These patterns and behaviours can also be changed or influenced by different incentives depending on factors such as age, education, income and conservation policies.

From various literature references, the most important factors affecting household water use were identified and grouped into three main categories. A brief description of each variable and its relationship has been provided.

- Socio-demographic variables: household size; age distribution; income level
- Physical housing characteristics: housing typology; property area; garden area; vegetation type; swimming pool
- Climatic variables: precipitation; evaporation; evapotranspiration.

These factors were deemed relevant for analysing monthly household demand patterns. Analysing water use at different spatial and temporal scales to this study could depend on a completely different set of influential factors.

2.5.1. Socio-demographic variables

In this thesis the term household size is used to describe the number of individuals permanently living in a household. Studies have found household size to be one of the most important factors affecting indoor consumption (Loh and Coghlan, 2003; Domene and Saurı, 2006). The consumption of a household increases as the household size increases since more people are consuming water (Wilson, 1989; Foster and Beattie, 1979; Cavanagh et al., 2002). However, there is a general agreement that the per capita consumption decreases with an increase in household size (Wentz and Gober, 2007; Momen and Butler, 2006).

Edwards and Martin (1995) reported that the per capita consumption for a single person household was 40% greater than the per capita consumption for a two-person household, see Figure 4.

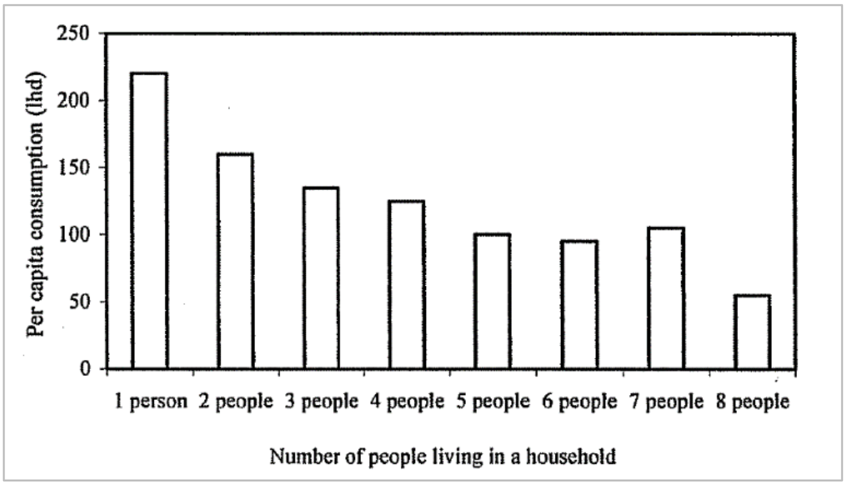

Figure 4 The relationship between per capita consumption and household size (Edwards and Martin, 1995)

The decrease in per capita consumption with an increase in household size has been attributed to consumers sharing certain water end-use activities in the household such as: cooking, cleaning, washing machine and dish washer (Arbués et al., 2003).

The age distribution of the residents influences the household demand as different age groups tend to demonstrate different water use behaviours (Ouyang *et al.*, 2014). Children tend to consume less water than adults for washing and hygiene purposes (Schleich and Hillenbrand, 2009; Rathnayaka *et al.*, 2017). There are conflicting views on the influence of retired residents. Some studies find that elderly members tend to use less water (Arbués et al., 2010; Beal et al., 2011), while other studies report that retired residents consume more water than working aged adults as they spend more time at home (Memon and Butler, 2006; Willis *et al.*, 2009; Huang, 2010).

Household income has been reported in many studies to influence residential water consumption (Arbués et al., 2003; Domene and Saurı, 2006). A positive correlation between household income and residential demand has been observed (Syme et al., 2004; Guhathakurta and Gober, 2007; Schleich and Hillenbrand, 2009; Kenney et al., 2008).

High-income households have the means to afford and maintain a high standard of living, which has shown to require a high volume water (Harlan *et al.*, 2007; House-Peters and Chang, 2011). Affluent households tend to have larger homes with more water using appliances and devices, larger gardens, greener landscapes, larger swimming pools and fashionable water features, which are highly water intensive (Memon and Butler, 2006; Runfola *et al.*, 2013). In addition, the concern regarding water bills becomes less for wealthier households as the proportion of general expenditure for water decreases (Arbués et al., 2003). A domestic water use study, conducted in Perth, found a relationship between water use and income level, see Figure 6 (Loh and Coghlan, 2003).

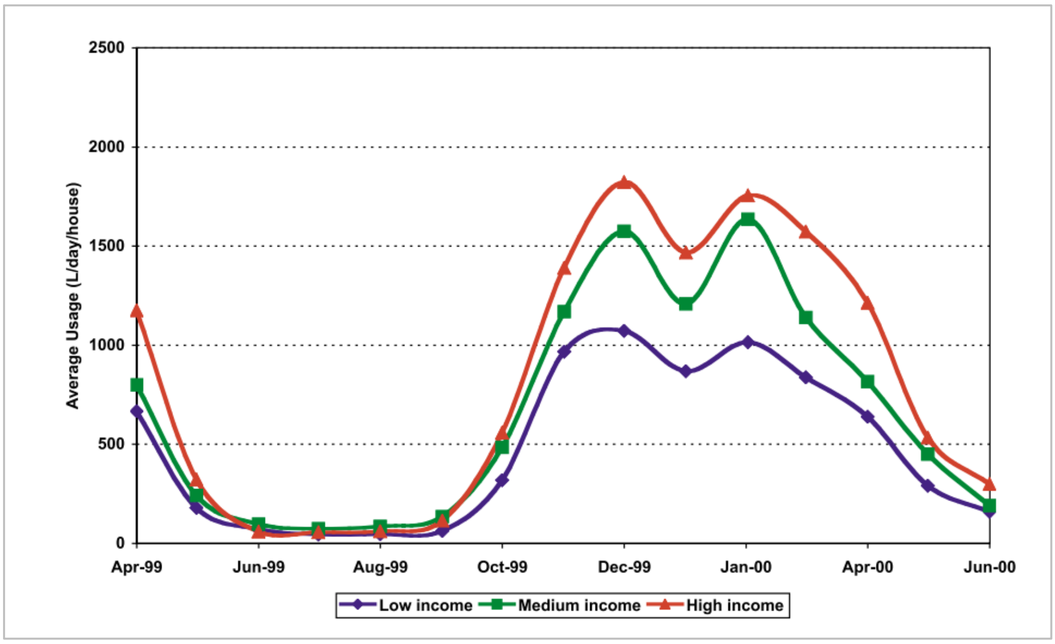

Figure 5 Average household water use for different income levels (Loh and Coghlan, 2003)

Figure 5 shows a notably higher water use from high income, single family households, especially during the summer months. The increase during the summer months could indicate that wealthier households require additional water for outdoor uses. On the contrary, wealthier households are more likely to be well educated and therefore more environmentally sensitive resulting in the use of water efficient appliances and practising water-saving behaviour, potentially resulting in lower water demands (Ouyang *et al.*, 2014).

2.5.2. Physical housing characteristics

Housing typology is defined by the household's location relative to adjacent buildings (Department of Spatial Planning and Urban Design, 2016). Three categories of housing typology are commonly used: detached households, semi-detached households and terrace households (also known as row housing). A definition of the housing typologies, taken from Fox et al. (2009), has been provided in Table 3 and a visual representation of each category can be seen in Figure 6 (EThekwini Municipality, 2013).

Table 3 Definition of housing typologies (Fox et al., 2009)

Housing typology	Definition
Detached	Property is not joined to any other adjacent property building or joined only by external boundary walls
Semi-detached	Property is joined to another property building on one side only
Terrace	Property is joined to other property buildings on both sides

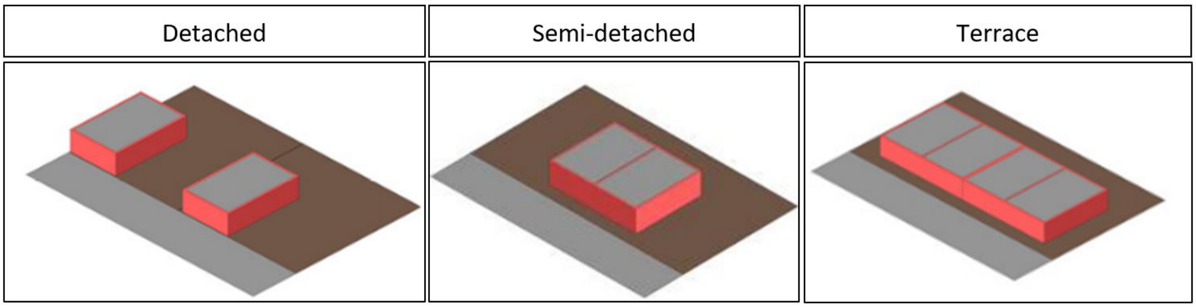

Figure 6 Different housing typologies

Researchers have observed that the housing typology can be related to certain demographic and physical characteristics of a household. The type of housing has shown to influence property area (Domene and Saurı, 2006), garden area (Balling and Gober, 2007; Smith et al., 2009; Fernández-Cañero et al., 2011), vegetation type (Whitford et al., 2001; Gaston *et al.*, 2005), pool ownership (Hof and Schmitt, 2011), household size (Troy et al., 2005; Heinonen and Junnila, 2014) and income level (Balling et al., 2008; Balling and Cubaque, 2009). Detached properties are typically large in size with a spacious garden area, more occupants, more likely to own a swimming pool and tend to have a higher income (Domene and Saurı, 2006; Fox et al., 2009; Chang et al., 2010). Semi-detached and terrace properties tend to be smaller in size as they are joined to adjacent buildings, limiting the space available for a garden and swimming pool.

Property area has been acknowledged as an important parameter influencing residential consumption (Cavanagh et al., 2002; Guhathakurta and Gober, 2007; Harlan *et al.*, 2007; van Zyl *et al.*, 2007; Gurung *et al.*, 2015). The CSIR (2005) guidelines use property area as the main parameter for estimating water demand. Large households tend to consume more water than smaller properties. Households with bigger areas have more room for a large property (Wentz and Gober, 2007), tend to have more residents (Russac et al., 1991), own more water-using appliances (Mayer *et al.*, 1999), have the space available for larger garden areas (House-Peters et al., 2010; DeOreo *et al.*, 2011; Hof and Wolf, 2014; Chen *et al.*, 2015) and are more likely to own a swimming pool (Hof and Wolf, 2014; Fisher-Jeffes et al., 2015). The relationship between property area and outdoor demand has been documented by Cole and Stewart (2013), who analysed a sample of households from the Hervey Bay area, see Figure 7.

Dwelling type	Dwelling size	Outdoor demand per household per day (L/hh/d)
Single-residential	Average	116.5
	Largest (3155 m^2)	194.2
	Medium-large (1392 m^2)	143.7
	Medium-small (832 m^2)	83.6
	Smallest (521 m^2)	45.9
Multi-residential	<300 m^2	26.9

Figure 7 Relationship between property size and outdoor consumption (Cole and Stewart, 2013)

The garden area refers to the proportion of landscape vegetation within a property boundary. The size of the garden is a significant factor affecting the outdoor consumption (Howe and Linaweaver, 1967; Domene and Saurı, 2006). As the garden area increases, the portion irrigated also increases (Du Plessis et al., 2018). A study done by Landon et al., (2016) observed that households with small lawns, although using less water for irrigation overall, are more likely to over irrigate compared to households with larger lawns.

Type of vegetation refers to the type and growth stage of household plants. Under the same weather conditions, plant species have different water requirements due to variations in plant characteristics and anatomy (Pittenger, 2014). Turf grasses generally require more water to survive compared to other vegetation types such as shrubs and trees. Older plants with well-developed roots generally require less water than younger plants in the initial growth stage (Mayer *et al.*, 1999). The type and growth stage of household plants have shown to influence outdoor water use significantly (Domene and Saurı, 2006; Cubino et al., 2014).

Swimming pools have been observed to affect outdoor consumption patterns (Wentz and Gober, 2007; Vidal., 2011). Households owning a swimming pool can consume significantly more than those without, especially during the summer months (Fisher-Jeffes et al., 2015). Swimming pools require water to replace the amount lost from general use and evaporation and for filtering and maintenance backwashing purposes. Climatic conditions such as evaporation and precipitation are major factors influencing swimming pool demand, causing seasonal fluctuations. The presence of a swimming pool, surface area, filtering method and frequency and pool cover ownership also affect swimming pool consumption and depend largely on the behavioural habits and choices of residents. The swimming pool demand can therefore vary significantly from household to household (Balling and Gober, 2007).

2.5.3. Climatic variables

Precipitation influences the volume required for irrigation and swimming pool purposes. Swimming pools and other outdoor water features will require less or no water during periods of high precipitation, therefore decreasing the outdoor demand (Guhathakurta and Gober, 2007; Kenney et al., 2008; Harlan et al., 2009). During dry periods of no precipitation, the garden plants will require sufficient water for survival causing an increase in the outdoor demand. Some studies have stated that precipitation is the most important climatic variable (Gutzler and Nims, 2005; Rhoades and Walski, 1991).

Evaporation rates mainly affect the volume of water lost from swimming pools and outdoor water features. High evaporation rates increase the water lost, which increase the outdoor consumption. Evapotranspiration influences the amount of water lost from soil and vegetation surfaces. High evapotranspiration rates will deplete the water available for garden plants a lot quicker. Outdoor demands will increase to supplement the additional water required by the plants for survival (Billings and Agthe, 1981; Wilson, 1989; Farag *et al.*, 2011).

2.6. Forecasting residential demand

Water used for residential consumption is an important commodity in the urban context (Ojeda de la Cruz *et al.*, 2017). Estimating the current and future residential demand is of great importance to ensure availability and proper distribution. Future estimates also support demand management plans, help predict potential water shortages and assist in the development and maintenance of water and sewer infrastructure.

Residential consumption is a complex interaction between human and urban natural systems that are cross-scale (spatial and temporal) and multi-scale (household, regional and national) in nature (Makki *et al.*, 2015). Forecasts can be developed for long-term trend assessment or short-term operational purposes (Memon and Butler, 2006). An appropriate forecasting method should be chosen according to: purpose or application of forecast, accuracy of forecast required, time horizon of forecast, data availability and size and complexity of serviced area (Billings and Jones, 2008). The most commonly used methods for forecasting water demand have been summarized in Table 4 (Billings and Jones, 2008).

Table 4 Description of common forecasting methods (Billings and Jones, 2008)

Method	Description
Unit water demand	Based on a unit demand rate multiplied by the number of users
Time series extrapolation	Future projections based on historical demand trends
Multivariate statistical models	Estimates demand as a function of explanatory variables
End-use models	Estimates the volume from each individual water using activity

Table 4 summaries the main methods used by water utilities, a larger variety of models and software programs have been developed, ranging from basic, informal estimation methods to more sophisticated structural models with multiple variables that require large, complex data sets.

2.7. Water demand guidelines

Water demand estimates should be preferably based on actual consumption records (Howe and Linaweaver, 1967). However, actual consumption records are not always available or reliable and therefore an estimation technique based on other parameters must be used (CSIR, 2005). Water demand estimation generally requires an average daily per capita use value that is multiplied by the total population of a specific area (Van Zyl et al., 2008)

The most commonly used guideline to estimate water demand in South Africa is a document titled "Guidelines for human settlement planning and design" or more commonly known as the "Red Book". The "Red Book" was first published in 1994 and revised in 2000, 2005 and 2019, remaining relatively unchanged. The Department of Human Settlement (2019) guidelines provide estimation techniques for domestic and non-domestic water demand projections. The following three methods can be used to estimate the AADD, based on the information available:

- Area-based demand
- Unit demand
- Per capita demand.

The area-based demand method is used when stand layout information for a development is limited. The AADD is estimated by multiplying an area-based demand rate (kL/ha/d) by the total area. The recommended area-based demand rates for domestic developments in the CSIR guidelines are shown in Table 5.

The unit demand method is used when more detailed stand information is available for a development. The AADD is estimated by multiplying a unit demand rate (kL/unit/d) by the number of units, depending on land use, stand size and density. The recommended unit demand rates for domestic developments in the Department of Human Settlement (2019) guidelines are provided in Table 5.

Table 5 Recommended unit AADD for area-based and unit demand calculations (Department of Human Settlement, 2019)

Land use		Density (units/ha)	Plot size (m²)	Demand rate	
				Area (kL/ha/d)	Unit (kL/unit/d)
Residential plot	High density, small size	20 - 12	400 - 670	11	0.60 - 0.80
	Medium density, medium size	12 - 8	670 – 1 000	9	0.80 - 1.00
	Low density, large size	8 - 5	1 000 – 1 600	8	1.00 - 1.30
	Very low density, extra-large size	5 - 3	1 600 – 2 670	7	1.30 - 2.00
Group housing	High density	60 - 40	130 - 200	21	0.40 - 0.45
	Medium density	40 - 30	200 - 270	17	0.45 - 0.50
	Low density	30 - 20	370 - 400	14	0.50 - 0.60
Retirement village		20 - 12	400 - 670	11	0.60 - 0.80

The per capita demand method is used when information is available regarding the type of water supply infrastructure (standpipe, yard or house connection). The AADD is estimated by multiplying a per capita demand rate (L/c/d) by the population size, depending on land use. The recommended per capita demand rates and typical household size values for house connections in the CSIR guidelines, are provided in Table 6.

Table 6 Recommended AADD for per capita method (Department of Human Settlement, 2019)

Land use		Persons per unit	Unit per capita demand rate	
			Typical (L/c/d)	Range (L/c/d)
House connection	Residential	5	230	120 - 400
	Group housing	5 - 3	120	120 - 130
	Flats	1 - 4	150	110 - 250

2.8. Water demand studies in South Africa

Many studies in the field of residential water demand estimation have been conducted in South Africa. A brief overview of the general findings and limitations of the most influential publications has been summarized in Table 7.

Table 7 Overview of South African water demand studies

Reference	Influential factor	Comment
Garlipp (1979)	Household size, temperature, plot size, income and access to borehole water	Investigated domestic demand in various South African cities. Conducted during the apartheid era, difficult to compare to the present political and socio-economic characteristics
Stephenson and Turner (1996)	Plot size, type of housing, level of service, income and population density	Analysed household consumption from all income groups in Gauteng. An average plot area was used for each zone, causing possible misrepresentation of plot area
Van Vuuren and Van Beek (1997)	Income, water restrictions and climate	Investigated water demand of domestic and non-domestic users in Gauteng. Limited by data accuracy of metering readings and land-use characteristics
Veck and Bill (2000)	Price of water	Assessing the impact of the price of water using a contingent valuation method. Based on 150 surveys from Gauteng households, using customers perceived consumption
Van Zyl (2003)	Price of water, income, plot size and water pressure	Used end-use modelling to investigate influential factors of Gauteng households. Limited by investigating the impact of one influential factor at a time
Jacobs (2004)	Plot size, climate and socio-economic level	Single variable models produced for suburban and township stands in three different geographic locations
Husselmann (2004)	Plot size and plot value	Reported an increase in water demand with increasing plot value and plot size. Study limited to Gauteng households
Van Zyl et al. (2007)	Plot size, plot value and geographic location	Investigated influential factors using multiple regression analysis of domestic and non-domestic users across four Municipalities

A general finding from the water demand publications summarized in Table 7, was that the most significant parameter influencing residential consumption was plot size. Other important factors include: income, type of development, water price, climate and household size. Common limitations of South African water demand studies include: sample size, effect of geographic location and combined effect of multiple influential factors.

2.9. Chapter overview

A detailed examination of published literature, research papers and relevant studies was completed to gain further insight into household water use patterns, potential influential factors and various demand estimation methods. The CSIR (2005) and Department of Human Settlement (2019) guidelines, currently used, exclude the effects of important influential factors to estimate household demand. An important issue discussed in previous literature was that the indoor and outdoor components of residential water consumption differ significantly with regards to seasonal pattern and influential factors.

For a household, indoor consumption patterns are typically non-seasonal, remaining relatively constant throughout the year. It was observed that indoor use was affected by demographic and socio-economic aspects of the residents, which determine the volume, frequency and duration of indoor water using appliances. The most important factor influencing indoor consumption, was found to be household size. It was well documented that outdoor consumption is the main cause of seasonal fluctuation in residential water use patterns. The most common factors influencing outdoor demand were garden size, type of vegetation, size of swimming pool, behavioural habits and weather parameters.

A number of studies have observed a relationship between housing type and household size. It was also evident that housing typology can influence physical property characteristics (Grove *et al.*, 2006; Troy *et al.*, 2007; Boone *et al.*, 2010). Characteristics such as household size, property and garden size and the presence of a swimming pool can often be inferred from the housing type (Russac et al., 1991).

3. MODEL STRUCTURE

3.1. Indoor water demand

Indoor consumption patterns can vary from household to household depending on demographic, socio-economic and behavioural influences. Indoor demand is known to be non-seasonal with low levels of fluctuation between the winter and summer months. Indoor water use is required for many different end-use activities. The consumption of each indoor end-use can be modelled using volume and frequency parameters. Household size was considered the most important factor effecting indoor consumption. Washing machines and dishwashers are the two main end-uses that are affected by an increase in household size. One of the research objectives was to develop an equation that estimates household water use that is easy to use and provides reasonably accurate results. Modelling the frequency and volume of each indoor end-use activity and the impact of household size would lead to a very complicated equation structure and require large datasets. Instead of including each indoor end-use separately, it was decided to model one parameter representing the total indoor demand.

Whenever people share a mutual resource, such as water, there is a tendency for the per capita consumption to be lowered. It is well known that the indoor per capita consumption rate decreases as the household size increases (Beal et al., 2011; DeOreo *et al.*, 2011; Arbon *et al.*, 2014). Some water demand models assume that household consumption increases linearly with household size (Jacobs and Haarhoff, 2004; Cahill, 2011). By assuming linearity, projections will over-estimate the demand for large household sizes and under-estimate the demand for small household sizes (DeOreo, 2011).

Many literature studies have highlighted the importance of the relationship between household size and indoor consumption, and therefore used to describe the indoor demand. Due to data constraints, the relationship between indoor consumption and household size was derived from findings in previous literature studies. After an extensive review of literature publications, studies that showed a relationship between household size and indoor consumption were obtained and analysed. The following publications were utilized:

1. Residential End Uses of Water (Mayer et al., 1999)
2. Analysis of Water Use in New Single-family Homes (DeOreo, 2011)
3. California Single Family Water Use Efficiency Study (DeOreo et al., 2011)
4. Residential End Uses of Water Study 2013 Update (DeOreo and Mayer, 2014)
5. 2004 Residential End Use Measurement Study (Roberts, 2005)
6. Forecasting Urban Residential Water Demand (Gato, 2006)
7. Domestic Water Use in Perth, Australia (Metropolitan Water Authority, 1985)
8. South East Queensland Residential End Use Study (Beal and Stewart, 2011).

Most of the publications contained a large sample size, that represented different age groups and income levels (see Table 8). However, almost all the homes were detached, single-family households. The required data results were extracted from each publication and plotted on a single graph, see

Figure 8. The publications are summarized in Table 8 and are indicated in Figure 8 using the labels provided in the Acronym column of Table 8.

Table 8 Description of publications

Research study	Acronym	Number of homes
Residential End Uses of Water	REUWS (1)	1 188
Analysis of Water Use in New Single-family Homes	REUWS NH	302
California Single Family Water Use Efficiency Study	CSFWUES	780
Residential End Uses of Water Study 2013 Update	REUWS (2)	761
2004 Residential End Use Measurement Study	Roberts	96
Forecasting Urban Residential Water Demand	Gato	193
Domestic Water Use in Perth, Australia	DWUP	2 891
South East Queensland Residential End Use Study	SEQREUS	252

Figure 8 illustrates a common trend between household size and total indoor consumption. A non-linear relationship was observed in all the publications, with a clear decrease in the total indoor consumption as the household size increases. In Figure 8, the relationship observed in the REUWS (1) publication was not as prominent compared to the other publications. A very significant decrease in the total indoor consumption was reported from households analysed in the SEQREUS.

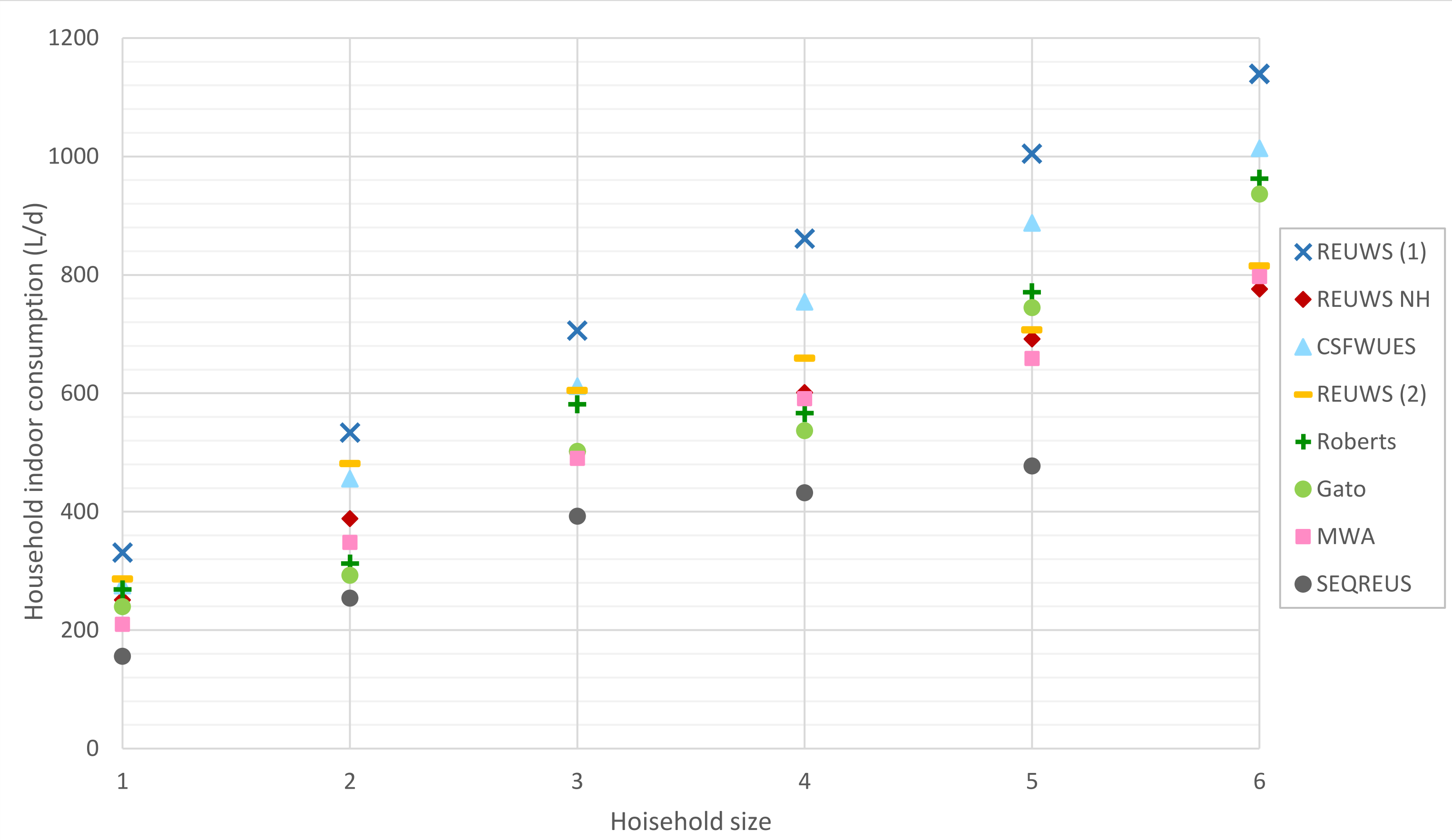

Figure 8 Relationship between indoor consumption and household size

The results illustrated in Figure 8 indicate that household size has a significant impact on indoor consumption. A relationship was formulated to estimate the impact, using results taken from the selected publications (see Equation 5).

3.2. Outdoor water demand

Outdoor water uses typically include garden irrigation, swimming pool use, car washing and cleaning impervious surfaces. Irrigation and swimming pool demand generally contribute to the bulk of outdoor consumption in households, especially during the hot, summer months (Balling et al., 2008; Hof and Wolf, 2014). Jacobs et al. (2007) showed that large irrigation and swimming pool demands are common for high income properties. The presence of a swimming pool is popular amongst residents in middle to high income areas of South Africa, due to the semi-arid climate (Fisher-Jeffes et al., 2015). Due to their significance, irrigation and swimming pool use were chosen to model outdoor consumption patterns of residential households.

3.2.1. Garden irrigation

Household garden irrigation is a function of climatic conditions, landscape variables and behavioural characteristics (DeOreo *et al.*, 2011; Lowry Jr et al., 2011). The landscape variables refer to the area of vegetation subject to irrigation, the type of vegetation and the soil characteristics. The behavioural characteristics refer to the method of irrigation and irrigation frequency decided by the resident (Mitchell et al., 2001; Monteith, 2003). The climatic conditions refer to the precipitation and evapotranspiration rate.

Garden irrigation is often closely related to moisture deficit, which is evapotranspiration minus effective rainfall (Linaweaver et al., 1967). The outdoor model component developed in this study (see Equation 6) followed the same approach as that presented by Linaweaver et al. (1967). A single parameter was included in the outdoor model component to represent the irrigation efficiency, thus incorporating the behavioural characteristics of homeowners and effectiveness of irrigation systems.

3.2.2. Swimming pool

Swimming pool demand is a function of climatic conditions, geometric variables and behavioural characteristics (Siebrits, 2012; Fisher-Jeffes et al., 2015). The climatic conditions refer to rainfall and open water evaporation rates. The geometric variables refer to the size of the swimming pool and the behavioural characteristics refer to the presence, pool cover ownership and method and frequency of maintenance. The main contribution to the swimming pool demand is water used for refilling purposes. The amount required to refill a swimming pool was estimated as the net volume of water lost, which was calculated as the open water evaporation minus precipitation.

The water used for maintenance backwashing is non-seasonal as it is not affected by climatic conditions but depends on the pool size and the behaviour of the resident. The behavioural patterns are difficult to predict and often complicated to model and were not included in the outdoor model.

3.3. Demand model

An equation was derived based on the non-linear relationship between indoor consumption and household size. The outdoor use was estimated by modelling garden irrigation and swimming pool use. Factors that describe the residents, housing characteristics and weather conditions are crucial when forecasting the demand patterns of the household. It was hypothesized that the total water demand can be estimated by adding the indoor and outdoor components separately, as shown in Equation 1 and 2:

$$Q_{INDOOR} = f(household\ size) \tag{1}$$

$$Q_{OUTDOOR} = f(garden\ area, crop\ type, swimming\ pool\ area\ and\ climate) \tag{2}$$

Equation 1 uses a similar approach to the Neighbourhood Planning and Design Guideline, however, incorporates the non-linear effect of household size on indoor water consumption.

4. MODEL DEVELOPMENT

The development of the demand model followed three steps:

- Identify the most important influential factors and analyse significant changes reported in household consumption patterns (Chapter 3)
- Plan a model structure that estimates the indoor and outdoor components of a residential household (Chapter 3)
- Derive a mathematical equation with suitable input parameters (Chapter 4).

The model development is presented in this chapter using existing models, available software programs and knowledge reviewed earlier in the thesis. The two main model components, namely indoor and outdoor consumption, are discussed separately.

4.1. Indoor consumption

For this study, a key objective was to develop a simple mathematical model that does not require large, complex datasets. For this reason, the indoor end-use activities were not modelled individually. Household size was considered the most important factor affecting indoor consumption, and thus formed the basis of the indoor model. The equation estimating indoor demand was formulated using a relationship between household size and an indoor per capita consumption rate.

As observed in Chapter 3, the results from the selected publications all illustrate a non-linear relationship between household size and indoor use. The first step was to fit a curve to each data set, using the least squares fitting method (Archontoulis and Miguez, 2015). The least squares method is commonly used to develop a function that best represents a dataset by minimizing the sum of the squared residuals (SSR). The SSR is the error between the measured and predicted data points (Render, 2012) and is calculated using Equation 3.

$$\text{SSR} = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \tag{3}$$

where:

y_i = the measured data value for point *i*
$\hat{y}_i$ = predicted data value from the fitted curve for point *i*
n = number of data points.

The same functional form was selected to fit the data sets. The solver function in Microsoft Excel was utilized to determine the best fit equation through an iterative process. The measured data points were inserted into a spreadsheet and the modelled equation was set up to calculate the predicted data points, by estimating the initial parameter values. The SSR was calculated using the measured and modelled points. The Solver tool was then utilized to determine the minimum SSR of the modelled equation by changing the initial value of the parameters. This process calculated the optimal parameter values of the modelled function that give the minimum possible SSR.

The household size relationship has been represented using various functional forms, including: linear, logarithmic, power and polynomial. The power function, used by DeOreo et al. (2012), was chosen as the most suitable form for this model. The basic form of the power function is illustrated in Equation 4.

$$y = a \times x^b \tag{4}$$

where:

y = dependant variable (total indoor consumption)

a = scaling coefficient (indoor per capita consumption rate)

x = independent variable (household size)

b = the power of *x*.

The main variable required to represent the relationship was the power of *x*, which determines the shape of the curve. The scaling coefficient representing the indoor per capita consumption rate was not required. The indoor per capita consumption rate has shown to vary considerably depending factors such as geographical location, income, resident age, appliance efficiency and conservation efforts. For this reason, indoor model allows the user to populate the parameter using actual measured data or with a value that best represents the type of household to be modelled.

Each dataset was fitted to a power function to determine the power factor that best represents the relationship of that dataset. The power factors ranged from 0.514 to 0.926, with an average of 0.714. The average power factor was used to represent the influence of household size on indoor consumption for the indoor demand model. Figure 9 shows the derived curve, using a dummy value for the scaling coefficient.

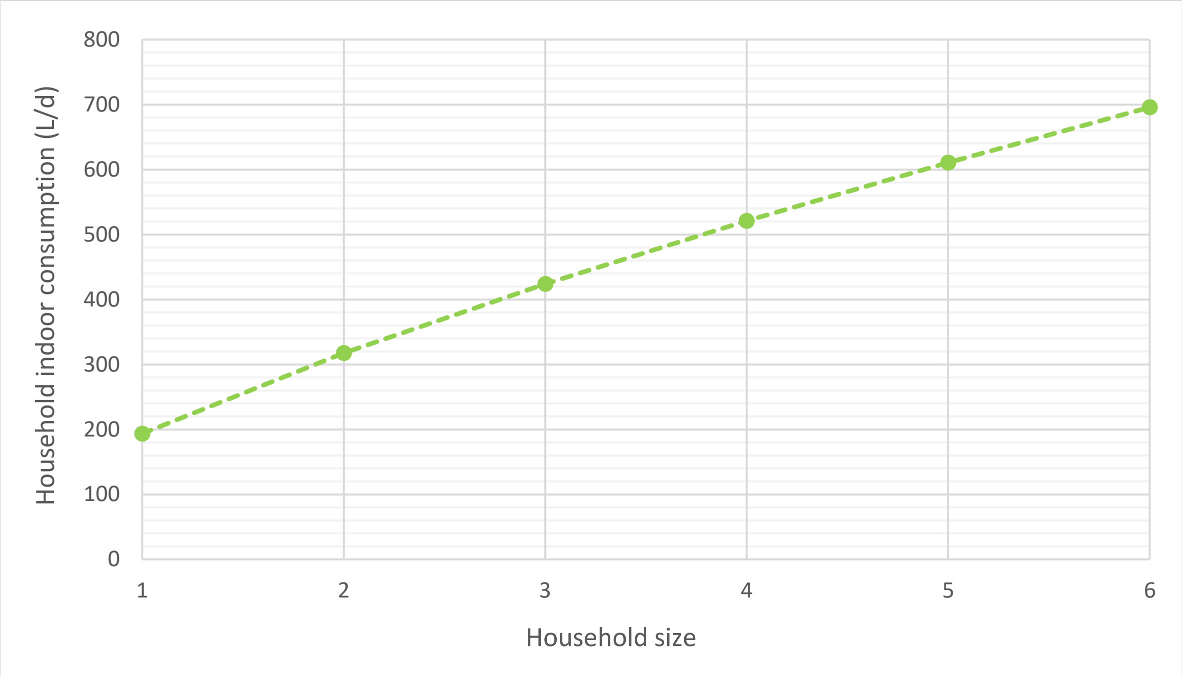

Figure 9 A curve derived showing the relationship between household size and total indoor consumption

The indoor consumption was modelled using two parameters: an indoor per capita consumption rate for a single person household and household size. The model calculates the daily indoor consumption for a household, see Equation 5.

$$Q_{INDOOR} = q_i(H)^{0.7143} \tag{5}$$

where:

Q_{INDOOR} = total indoor consumption for a household (L/d)

q_i = indoor per capita consumption rate for single person household (L/d)

H = household size.

4.2. Outdoor consumption

The irrigation demand for residential gardens was defined as the volume of water required by plants for survival (Pittenger, 2014). The irrigation model was developed based on an approach used by Lowry et al. (2011), taking into account the crop water requirement, effective precipitation and irrigation efficiency. The crop water requirements were calculated based on the Penman-Monteith method, which uses a daily reference evapotranspiration and crop coefficient (Allen *et al.*, 1998). The irrigation demand was calculated on a monthly basis, using Equation 6.

$$Q_{IRRIGATION} = \frac{A_C[(k_c \times ET_o) - P_e]}{I_e} \tag{6}$$

where:

$Q_{IRRIGATION}$ = irrigation requirement (L/month)

A_c = garden area (m^2)

k_c = crop coefficient

ET_0 = reference evapotranspiration (mm/month)

P_e = effective precipitation (mm/month)

I_e = irrigation efficiency.

The swimming pool demand was estimated as the amount required for refilling purposes (Harlan *et al.*, 2007). The amount used for refilling purposes was calculated as the evaporation loss, using an equation taken from Midgley et al. (1990). The water required for backwashing maintenance purposes can count for a large portion of the swimming pool demand. For this study, it was not taken into account due to data limitations. As a result, the model could potential underestimate the demand for the study sites. A factor could be included in the model that accounts for backwashing activities, which could improve the accuracy especially for households with large swimming pools. The swimming pool demand was calculated on a monthly basis, using Equation 7.

$$Q_{POOL} = A_p \times \left[\left(f_e \times E_p\right) - P_t\right] \tag{7}$$

where:

Q_{POOL} = swimming pool use (L/month)

A_p = area of swimming pool (m^2)

f_e = free lake evaporation factor

E_p = pan evaporation (mm/month)

P_t = precipitation (mm/month).

The outdoor demand was modelled by combining the irrigation equation (for each applicable crop type or plant group present in the household that is to be modelled) and the swimming pool use equation (if a swimming pool is present). The model calculates the monthly outdoor consumption for a household, see Equation 8.

$$Q_{OUTDOOR} = \frac{A_C[(k_c \times ET_O) - P_e]}{I_e} + A_p \times \left[\left(f_e \times E_p\right) - P_t\right] \tag{8}$$

where:

$Q_{OUTDOOR}$ = total outdoor consumption for a household (L/month).

4.3. Input parameters

To estimate household water use, the demand model requires certain information and various datasets describing the household. The input parameters that need to be populated are classified into five main categories:

- Household characteristics:
    - Indoor per capita consumption rate for a single person household *(q_i)*
    - Household size *(H)*
- Geometric measurements:
    - Garden area *(A_c)*
    - Swimming pool surface area *(A_p)*
- Climatological information:
    - Reference evapotranspiration *(ET_0)*
    - Pan evaporation *(E_p)*
    - Free lake evaporation factor *(f_e)*
    - Precipitation *(P_t)*
    - Effective precipitation *(P_e)*
- Vegetation information:
    - Crop coefficient *(k_c)*
- Behavioural characteristics:
    - Irrigation efficiency *(I_e).*

5. DATA COLLECTION

5.1. Input data requirement

The performance of the demand model was evaluated by modelling a sample of existing residential households. The input parameters were populated with the best available datasets that represented the sample households. Water meter readings were collected and used to compare the modelled results to the actual water consumption. The objective of the evaluation process was to include a large sample of households, with a wide variety of housing types, property characteristics, occupant characteristics, income levels and climatic conditions. A more diverse dataset will ensure a more accurate assessment of the demand model and a better evaluation of how significant the influential factors are, that were initially hypothesised.

5.2. Site selection

For this study, the sample of households selected to evaluate the demand model were situated in gated community developments. Gated communities are a type of development consisting of multiple residential households in an area with designated perimeters and restricted security access. There are many types of gated community developments in South Africa, from high-income residential estates with leisure activities and amenities to smaller housing complexes. Some gated communities implement a set of rules and regulations pertaining to landscaping, architecture, conduct and maintenance, that each resident must adhere to. Gated communities are often governed by a private management body, known as the home owner's association. The role of the home owner's association is to manage and maintain the estate and its facilities and is supported by a monthly fee payed by the residents. The households in gated communities tend to be of a similar housing typology, exhibit similar architectural and landscaping characteristics and the residents tend to fall in the same income group.

The study sample included 1 055 homes from 10 different gated communities, located in two different regions of South Africa (Western Cape and Gauteng). The study sites represented a range of housing characteristics, income levels and climatic conditions. Obtaining a more diverse sample was limited due to availability, accuracy and accessibility problems of various data sets and information. For this report, the selected sample of gated communities were referred to as Site A to J. The naming convention was used to satisfy ethical requirements and protect the identity of consumers taking part in the research study. A summary of the study sites has been provided in Table 9.

Table 9 Description of study sites

Site	Location	Total area (ha)	Number of properties	Average property size (m²)	Density (units/ha)
A	Radiokop	1.45	30	410	21
B	Glenvista	16.58	234	337	14
C	Witpoortjie	0.63	29	162	46
D	Lone Hill	1.51	54	206	36
E	Mill Hill	2.80	60	245	21
F	Bracken Heights	3.20	92	259	29
G	Brackenfell South	1.82	69	137	38
H	Hermanus	42.69	285	759	7
I	Westlake	11.44	150	553	13
J	Olympus	3.94	55	613	14

5.3. Site location

5.3.1. Gauteng

Gauteng is situated in the summer rainfall region of South Africa. Most of the area's rainfall occurs between October and February, the hot summer months. During the winter months, cold and dry conditions are experienced. A map has been provided of the six study sites that are located in Gauteng, see Figure 10.

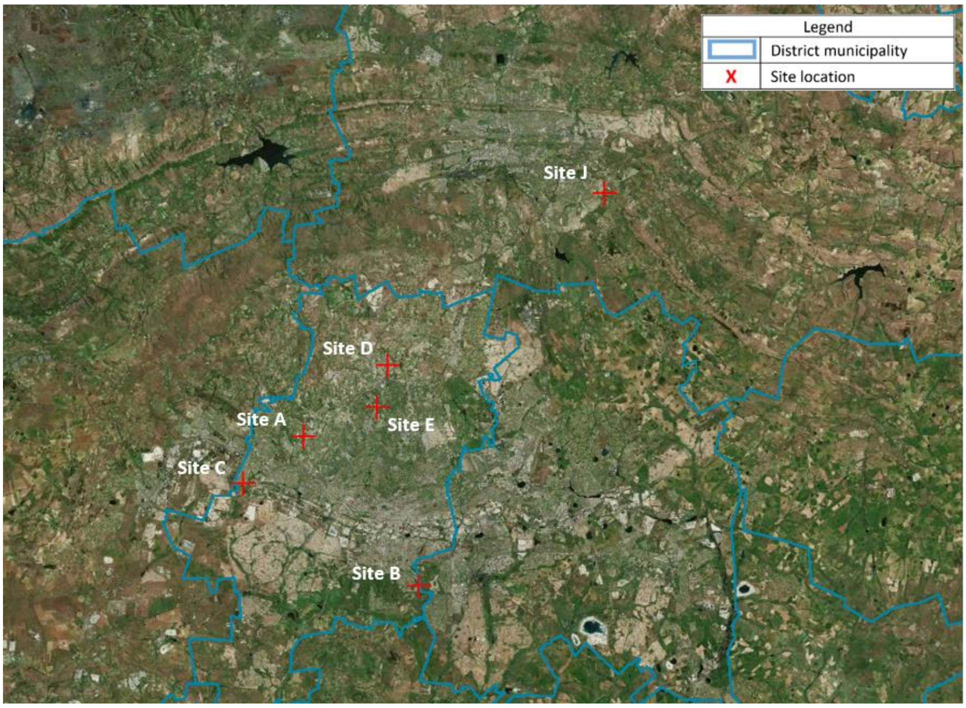

Figure 10 Location of study sites in Gauteng

5.3.2. Western Cape

The Western Cape climate differs from the rest of the country as it is characterised by a Mediterranean climate experiencing wet winters and dry summers. With very little to no summer rainfall, significant peaks in outdoor water demand are often observed during these months. The remaining four sites are located in the Western Cape, see Figure 11.

Figure 11 Location of study sites in Western Cape

5.4. Water consumption data

The water consumption data for most of the study sites were extracted from a software program called Swift (Jacobs et al., 2013). Swift allows the user to analyse and extract useful information on municipal databases (such as water meter readings) and has been implemented by most municipalities in South Africa (van Zyl *et al.*, 2007; Jacobs et al., 2013). The database provides the following useful information: monthly meter readings, date the reading was taken and the land use category (industrial, business commercial and residential). For residential properties, the type of housing is also specified (group housing or stand-alone households). The water consumption is recorded on a monthly basis for each stand-alone house, however, for group housing or gated communities the monthly consumption is recorded as a single bulk value.

Water consumption data was also available from two different research studies that were conducted previously in the area (Water Research Commission, 2012; Knox, 2013). The water meter readings were first extracted from the different data sources and exported to Excel. The water consumption datasets were sorted and assessed to ensure that no errors existed in the dataset (such as negative readings) and identify any records that should be excluded (for example a vacant home).

The sets of meter readings were made available to the research team with prior ethical clearance, making the data less complicated to access. A summary of the collected data for each study site has been provided in Table 10.

Table 10 Description of water meter data

Site	Source	Reading period	Length	Number of errors (months)
A	Swift	Dec 2012 – Sept 2014	1 year, 10 months	0
B	Swift	Dec 2012 – Sept 2014	1 year, 10 months	0
C	Swift	Nov 2012 – Sept 2014	1 year, 11 months	0
D	Swift	Nov 2012 – Sept 2014	1 year, 11 months	0
E	Swift	Dec 2012 – Sept 2014	1 year, 10 months	1
F	Swift	Oct 2012 – Sept 2014	2 years	0
G	Swift	Oct 2012 – Sept 2014	2 years	0
H	Water Resources Commission	Jan 2012 – Dec 2014	3 years	0
I	Department of Public Works	Jan 2009 – Dec 2014	5 years	0
J	Swift	Nov 2012 – Sept 2014	1 year, 11 months	2

The water consumption records were only collected up to 2014 because of the drought period experienced from 2015. A future investigation could be done to potentially incorporate the effect of a drought into the model.

5.5. Household size

The household size parameter is an important factor and can vary significantly from one property to the next. The household size can also vary within a household, on an hourly and daily basis. However, at a monthly scale the size within a household was assumed to remain constant. A few studies have noted that the number of people in a household is affected by the housing typology and income level (Domene and Saurı, 2006; Fox, McIntosh and Jeffrey, 2009). Similar findings were evident in South African studies. Typical values have been sourced for households in the South African context for various housing characteristics, see Table 11.

Table 11 Typical South African household sizes

Reference	Housing type	Description	Average household size
Meyer (2000)	Detached	Low density	3.1
	Detached	Medium density	3.8
	Townhouse	Low density	2.1
	Townhouse	Medium density	3.3
Hall and Watson (2000)	Detached		3.4
	Townhouse		2.7
Veck and Bill (2000)		High income	3.0 - 4.1
		Medium income	3.3 - 4.7

The values in Table 11 show that detached households tend to be occupied by more people compared to townhouses. It was also evident from Table 11 that more dense areas with lower incomes also tend to have more occupants which, at a larger scale, is typical for homes in South African townships. If the household size is unknown, values can be sourced from available literature studies or government census documents for a type of household or an area. Russac et al. (1991) reported that three or more occupants were recorded for detached properties in 65% of the households analysed. Terrace housing types generally have the least occupants with detached households having the most.

For this research, the household size information was not available for the study sample. To populate the parameter, values had to be sourced from available literature references. The household size was considered an important input which made it necessary to populate the parameter with data that best represents the study sites. Probability distribution profiles were constructed for a typical household and used to populate the household size parameter (see Figures 12, 13 and 14). Datasets were sourced from literature references and research papers to generate household size frequency distributions for the three household types.

Results from five research studies were obtained and used to model the household size parameter for detached properties. These studies were conducted in different countries (including one from South Africa) and only included medium to high income households. A household size frequency distribution was derived from averaging the frequencies of the five literature studies, which represented a detached household, see Figure 12.

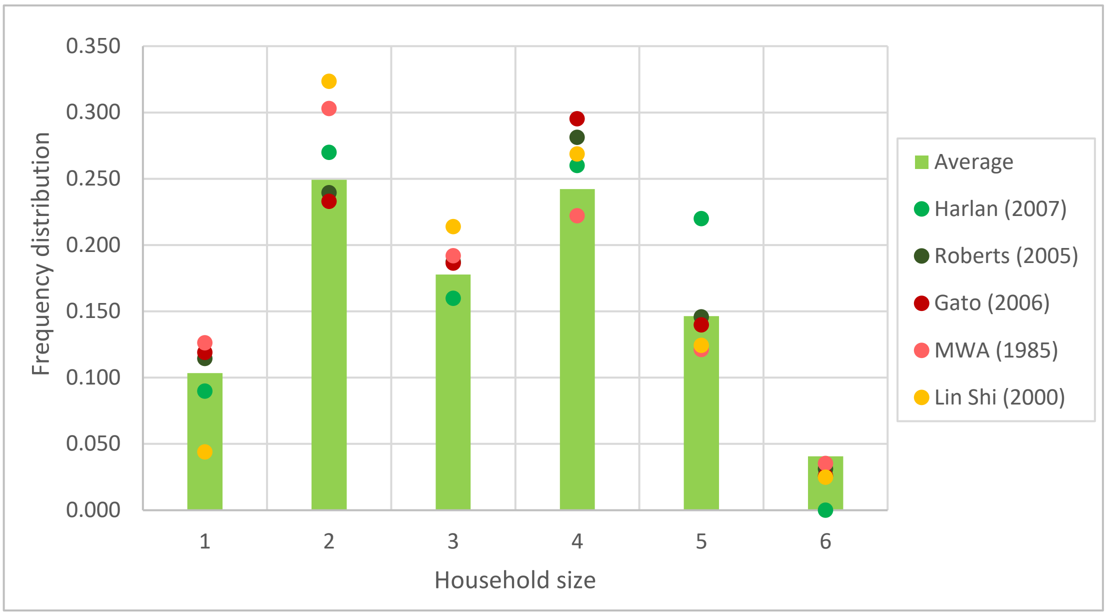

Figure 12 Household size frequency distribution for detached households

From Figure 12, there are two distinct peaks evident in the frequency distribution plots, indicating that detached homes have either 2 or 4 residents most often. The average household size for the representative detached household was 3.16, which matches the typical values found in South African literature, see Table 11.

Three studies were selected to model the household size for a typical semi-detached property. The studies were conducted in the UK and Sydney and only included medium to high income households. The household size frequency distribution representing semi-detached households is shown in Figure 13.

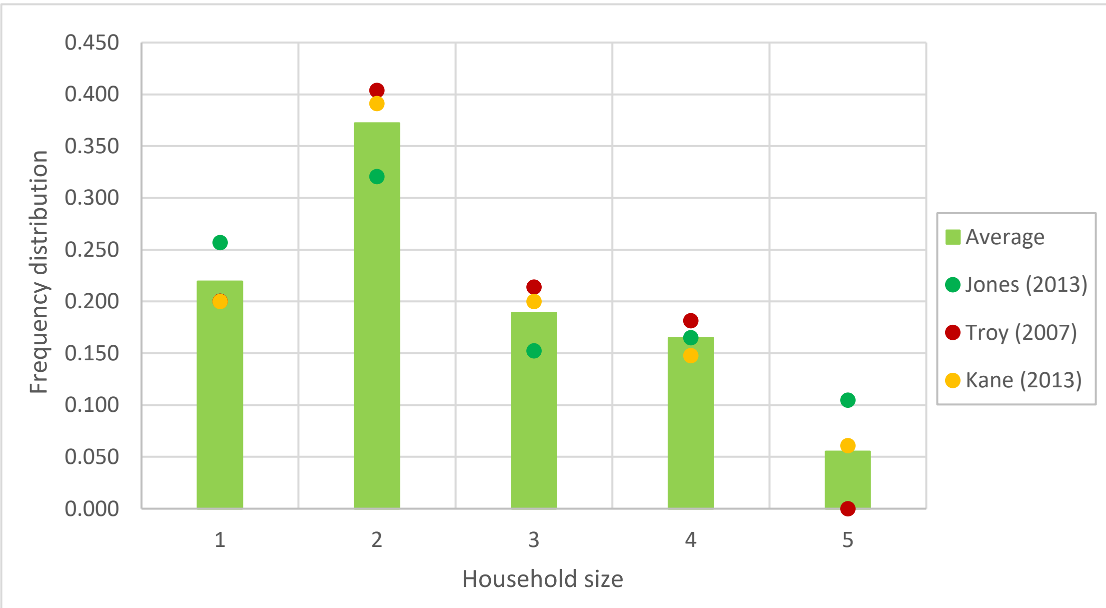

Figure 13 Household size frequency distribution for semi-detached households

From Figure 13, a single peak is evident in all the frequency distributions, indicating that semi-detached homes are more likely to be occupied by 2 residents. The semi-detached homes analysed in the three studies only went up to five residents. The average household size for the representative semi-detached household was 2.46.

Three studies and a set of survey results were selected to model the household size for a typical terrace property. These studies were conducted in the UK, Sydney and South Africa and included mostly medium income households with a few representing high income households. The household size frequency distribution representing terrace households is shown in Figure 14.

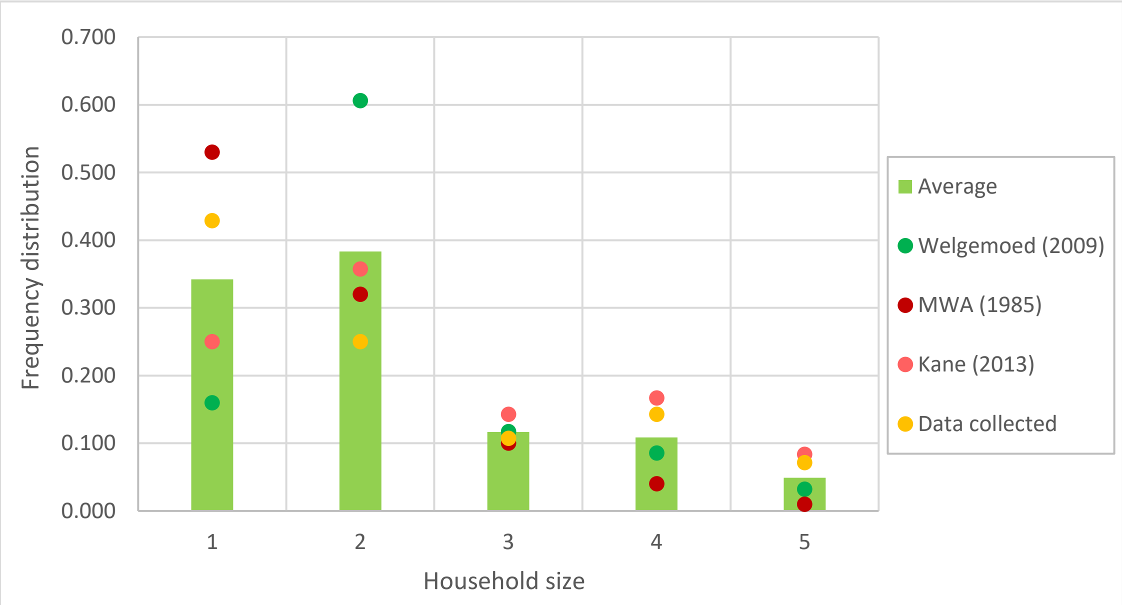

Figure 14 Household size frequency distribution for terrace households

From Figure 14, a general peak is evident in the frequency distributions, indicating that terrace homes are more likely to be occupied by 1 or 2 residents. The terrace homes analysed in the studies only went up to five residents. The average household size for the representative terrace household was 2.14.

To populate the household size parameter, each site was classified into the respective typology group, using the definitions provided in Chapter 2, Table 3. Google Earth Pro was utilized to view, evaluate and categorize each household. The household size was then estimated using the random number generator function in Microsoft Excel, together with the probability distribution profiles. An example of the estimation procedure has been shown in Figure 15, with the formula given in Equation 9.

$$Household\ size = INDEX(A2{:}A7, COUNTIF(C2{:}C7, "<=" \& RAND()) + 1) \tag{9}$$

	A	B	C
1	Household size	Frequency probability	Cumulative frequency
2	1	0.099	0.099
3	2	0.274	0.373
4	3	0.188	0.561
5	4	0.266	0.827
6	5	0.150	0.977
7	6	0.023	1.000

Figure 15 Example of estimation procedure

5.6. Indoor per capita consumption rate for a single person household

The indoor per capita consumption rate for a single person household can vary significantly depending on factors such as housing typology, climate, income, age, type and efficiency of indoor appliances, and behaviour. However, the indoor water use of a single person household is not usually a parameter that is measured. This parameter is assumed to remain constant throughout the analysis period and should be populated using typical values that best represent the household that is to be modelled. Indoor consumption rates for a single person household are reported in various literature sources for a range of demographic, socio-economic and housing characteristics. The international studies reporting water use for single person households that were sourced for the study sites in this analysis are shown in Table 12.

Table 12 Indoor end-uses for single person households

Reference	Indoor end-use consumption for a single person household (L/d)							
	Bath	Tap	Dishwasher	Shower	Washing	Toilet	Leak	Total
Arbon (2014)	3.0	32.0	1.7	33.0	36.0	38.0	10.5	154.2
Mitchell et al. (2001)			25.0	76.0	32.0	67.0	4.1	204.1
Roberts (2004)	3.2	41.0	6.1	49.1	50.1	30.4	15.9	195.9
Beal (2014)	0.6	25.5	7.0	32.0	26.9	31.6	32.5	156.1
MWA (1985)			35	86	18	71		210.0
Gato (2006)		42.1	9.4	85.8	77.2	49.0		263.4
Mead (2008)	34.7	15.1	3.8	61.2	56.4	14.2		185.4
Willis et al. (2011)	2.8	38.0	2.3	61.8	45.1	28.8		178.8
Average	8.9	32.3	11.3	60.6	42.7	41.3	15.8	193.5

There is considerable variation in the indoor per capita consumption rates that were taken from selected studies, see Table 12. The datasets summarized in Table 12 represent households located in different countries, households with medium to very high incomes and include detached, semi-detached and terrace typologies. The dataset was considered to be a reasonable representation of the study sample selected for this analysis. Due to limitations in data availability, the average value from Table 12 was used to populate the indoor per capita consumption rate for a single person household parameter for all study sites.

5.7. Geometric measurements

The garden area and swimming pool surface area are significant factors that influence outdoor consumption (Loh and Coghlan, 2003; Fisher-Jeffes et al., 2015). Obtaining individual garden and swimming pool area measurements can be very time consuming and is not always possible as accurate measurements require access to high resolution imagery and possibly a software program. For most residential areas, the property area or area range is often known or easily accessible. The property area for future housing developments can also be easily anticipated by planners and developers. Various researchers have found a linear relationship between property and garden area (DeOreo et al., 2011). If a strong relationship exists, the property area could be used to populate the garden area parameter.

In this study, the garden and swimming pool surface areas were measured for each site and used to populate the model. The property area was also captured, and a statistical analysis was conducted on the property, garden and swimming pool measurements. The surface areas were identified and distinguished using Google Earth Pro and measurements were recorded using AutoCAD Civil 3D software and Bing Maps. Although, Google Earth Pro has 3D imagery capability at a higher resolution than Bing Maps, the measuring tools were not as precise or efficient as Civil 3D. Civil 3D also allows the user to outline irregular shaped objects, such as gardens and swimming pools, with a better accuracy. The analysis was conducted over a period of about 2 years for most sites, and thus the geometric parameters were assumed to remain constant. An example of the measurement procedure is shown in Figure 16.

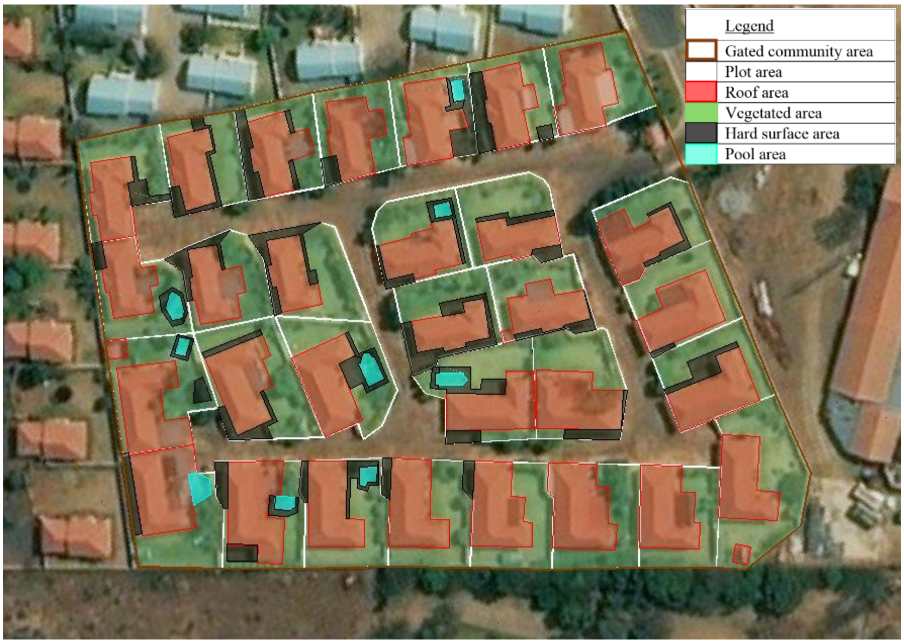

Figure 16 Geometric measurement procedure

For this study, the garden area was defined as the total surface area within a property boundary that is covered with turf grass, shrubs, trees and any other vegetation. It was assumed that the total garden area was irrigated. The swimming pool surface area included all open water features used by the residents, such as water fountains or Jacuzzis. The property area was defined as the total area of the residential stand, including the garden area, roof area, swimming pool area and all impervious surfaces. The property boundaries were not always visible from the available imagery and the exact location of the property boundary was not always clear. Incorrect judgement of the true extent of property boundaries would result in a bigger (or smaller) area recorded for the garden and cause inaccurate outdoor demand estimates.

5.8. Reference evapotranspiration

The reference evapotranspiration data was sourced from a software program called SAPWAT. SAPWAT is an internationally accepted program that estimates crop irrigation requirements using an extensive database (Crosby, 1996). SAPWAT4 integrates datasets from the CLIMWAT program which comprises of 3 262 weather stations in 144 countries (Van Heerden and Walker, 2016). SAPWAT4 also includes approximately 350 additional weather stations with 50 years of daily climatic data for each quaternary drainage region in South Africa (Heerden et al., 2009).

The reference evapotranspiration is the amount of water that is required by a standardized crop to survive. The reference evapotranspiration rate is largely affected by climatic variables which causes seasonal variation. The reference evapotranspiration parameter must be populated monthly. Obtaining monthly reference evapotranspiration data can often be difficult, as software programs with extensive databases are not always available. However, the reference evapotranspiration rate can be calculated using daily weather parameters that are generally measured by most local weather stations.

The quaternary weather station records available in SAPWAT4 contained 50 years of historical daily weather data. SAPWAT4 automatically calculates the daily reference evapotranspiration rate for each station, using the FAO 56 Penman-Monteith method (Allen *et al.*, 1998). For the study sites, the reference evapotranspiration parameter was populated using the measurements from the various quaternary weather stations. The datasets were extracted for each applicable quaternary weather stations and have been summarized in Table 13.

Table 13 Summary of SAPWAT quaternary weather stations

Site	Quaternary catchment	Longitude (°)	Latitude (°)	Record period	Average ET_0 (mm/d)
A	A21E	27.8664	-26.0183	1950 - 1999	3.8
B	C22D	28.0286	-26.3536	1950 - 1999	3.6
C	C22A	27.8723	-26.2568	1950 - 1999	3.6
D	A21C	28.0410	-26.0561	1950 - 1999	3.6
E	A21C	28.0410	-26.0561	1950 - 1999	3.6
F	G22E	18.7011	-33.9422	1950 - 1999	3.1
G	G22E	18.7011	-33.9422	1950 - 1999	3.1
H	G40H	19.2350	-34.3855	1950 - 1999	2.8
I	G22D	18.5159	-34.0386	1950 - 1999	2.9
J	A23A	28.3901	-25.7767	1950 - 1999	3.8

The reference evapotranspiration parameter was regarded as a fixed monthly value, which represents the average reference evapotranspiration rate calculated over the length of the historical record period.

5.9. Pan evaporation

The pan evaporation parameter influences the amount of water required to refill swimming pools, outdoor Jacuzzis and any other water features. For this analysis, these features were considered free surface water bodies. Evaporation rates from a free surface water body can be estimated using S-pan or A-pan evaporation data with an applicable conversion factor. Both evaporation measurements are available from local weather station records, however, the quaternary weather stations incorporated in the SAPWAT4 database do not contain evaporation readings. The evaporation measurements should ideally be taken from the same source as the precipitation and reference evapotranspiration measurements, however, the effect of the evaporation parameter on the overall demand is minimal and only effects the small portion of homes with swimming pools. The reference evapotranspiration and precipitation parameters are more important and thus should be populated with the best available datasets.

The DWA control numerous gauging stations throughout South Africa and provide open access to the public. The DWA website contains a database of various map layers, including the geographical location of the gauging stations, which was imported into Google Earth Pro. The evaporation records for the stations nearest to each study site were extracted from the DWA database. A final gauging station was chosen to represent a site based on the record length, distance from the study site, number of missing values and surrounding topographic characteristics. Of the selected stations, S-pan evaporation readings were available for all stations, but only a few recorded A-pan evaporation data. S-pan readings can easily be converted to A-pan readings; however, S-pan evaporation readings were used to ensure uniformity. A description of the DWA gauging stations selected for each site has been provided in Table 14.

Table 14 Summary of DWA gauging stations

Site	Station number	Station Name	Distance (km)	Record period	Length (years)	Missing data (%)	MAE (mm)
A	C2E007	Zuurbekom	21.05	1959 - 2019	60	2	1506.6
B	C2E007	Zuurbekom	26.38	1959 - 2019	60	2	1506.6
C	C2E007	Zuurbekom	15.08	1959 - 2019	60	2	1506.6
D	A2E001	De Rust	35.50	1926 - 2013	88	1	1727.4
E	A2E002	Rietvlei	33.00	1935 - 2019	84	3	1574.5
F	G2E006	Elsenburg	14.55	1957 - 1997	40	1	1481.6
G	G2E006	Elsenburg	11.79	1957 - 1997	40	1	1481.6
H	H6E001	Theewaterskloof	37.20	1974 - 2019	45	4	1610.9
I	G2E014	Cape Town	6.69	1969 - 2003	34	1	1480.4
J	A2E003	Hatfield Pretoria	9.30	1935 - 1986	49	1	1533.3

The only weather stations near Site H were located almost 40kms away and were separated by the Hottentots Holland mountain range. The evaporation rates measured at these stations could be notably different to the actual evaporation rates experienced at Site H. The MAP measured at H6E001 station was similar to the MAP measured at the quaternary rainfall station for site H, and thus considered an acceptable source. The S-pan evaporation parameter was regarded as a fixed monthly value, which represents the average evaporation rate calculated over the length of the historical record period.

5.10. Free lake evaporation factor

To convert S-pan evaporation to free surface evaporation, a free lake evaporation factor is used in the swimming pool demand model. For this study, the free lake evaporation factor was extracted from the surface water resources of South Africa study (Midgley et al., 1994), see Table 15.

Table 15 Monthly free lake evaporation factor (Midgley et al., 1994)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Free lake evaporation factor	0.84	0.88	0.88	0.88	0.87	0.85	0.83	0.81	0.81	0.81	0.82	0.83

5.11. Precipitation

The precipitation rate influences the amount of water required for irrigating gardens and for refilling swimming pools. Precipitation data is often easy to access from local weather station records. The average monthly precipitation rates were extracted from the quaternary weather station records available from the SAPWAT4 database, Table 16.

Table 16 Description of SAPWAT quaternary weather stations

Site	Quaternary catchment	Elevation (masl)	MAP (mm)	Average temperature (°C)	Rainfall region
A	A21E	1482	679	17.4	Summer
B	C22D	1534	657	16.3	Summer
C	C22A	1602	658	15.6	Summer
D	A21C	1488	662	17.0	Summer
E	A21C	1488	662	17.0	Summer
F	G22E	76	585	16.4	Winter
G	G22E	76	585	16.4	Winter
H	G40H	101	591	16.0	Winter
I	G22D	8	826	16.4	Winter
J	A23A	1355	680	17.2	Summer

The precipitation rate was only used to populate the swimming pool demand model. This was regarded as a fixed monthly value, which represents the average precipitation rate calculated over the length of the historical record period.

5.12. Effective precipitation

The effective precipitation can be estimated as the amount of precipitation that reaches and is stored in the soil profile and is available as usable water for a crop. This parameter influences the frequency and volume of irrigation that is required to satisfy a crop's agronomical needs. Numerous methods have been developed for estimating effective precipitation, including empirical methods based on monthly rainfall increments, direct measurements, historical estimates based on soil type and root zone depth, soil water balance approaches and the use of a single factor relating to monthly rainfall. A suitable method must be chosen depending on the availability of data, required accuracy and purpose of the data. For this study, the USDA-SCS method was used, which incorporates the soil water balance approach. This method was developed based on 50 years of data from 22 weather stations in the United States and is designed for monthly time step calculations (Ali and Mubarak, 2017). The basic concept is to use the moisture balance in the soil to determine the effectiveness of a plant's water use by incorporating precipitation, irrigation and crop evapotranspiration (Ali and Mubarak, 2017). The soil balance approach is shown in Figure 17.

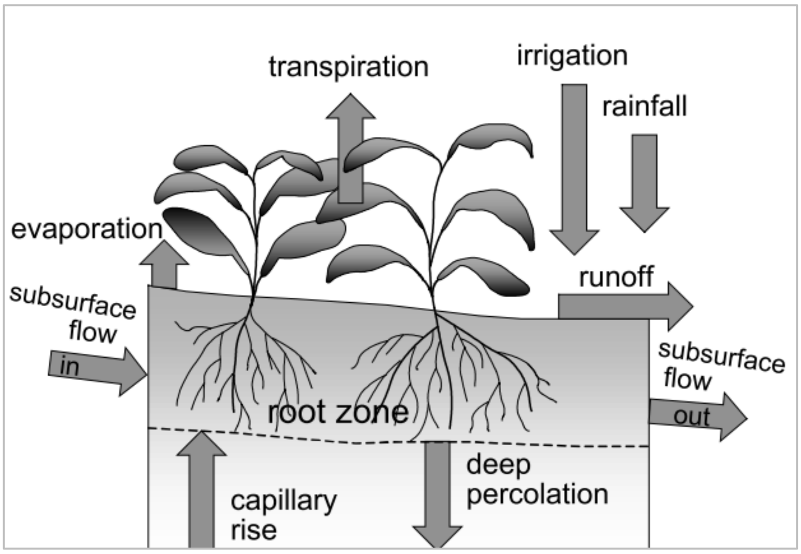

Figure 17 Soil water balance (Allen et al., 2006)

The effective precipitation calculation is shown in Equation 10.

$$P_e = SF(1.25 \times P_t^{0.824} - 2.93)(10^{0.000955 \times ET_c}) \tag{10}$$

where:

P_e = monthly effective precipitation (mm)
SF = soil water storage factor (see Equation 11)
P_t = monthly precipitation (mm)
ET_c = monthly crop evapotranspiration (mm).

For Equation 11, the monthly effective precipitation cannot exceed either the monthly precipitation or the monthly crop evapotranspiration. If the effective precipitation results in a value larger than either one, the effective precipitation must equal the lesser of the two. The soil water storage factor was calculated using Equation 11.

$$SF = 0.531747 + 0.295164\left(\frac{RAW}{25.4}\right) - 0.057697\left(\frac{RAW}{25.4}\right)^2 - 0.003804\left(\frac{RAW}{25.4}\right)^3 \quad (11)$$

where:

RAW = readily available water in the soil (mm).

The Readily Available Water (RAW) is the portion of the Total Available Water (TAW) that can be used by a plant without the plant suffering water stress (Stevens and Buys, 2012). When the soil water content drops below a certain threshold value, the plant begins to experience stress and soil water becomes more difficult to extract. The RAW can be calculated using a depletion fraction multiplied by the TAW. A value of 0.5 is commonly used for the depletion fraction for most crops, and is based on an average daily evapotranspiration rate of 5 mm/d. The depletion factor differs depending on the plant and is largely influenced by the daily evapotranspiration. The depletion factor was adjusted to account for the fluctuating evapotranspiration values observed at the study sites. An equation reported in the FAO Irrigation and Drainage Paper (Allen et al., 2006) was used with the values recommended for adjusting the depletion fraction, see Equation 12.

$$\rho = \rho_{table} + 0.04(5 - ET_C) \quad (12)$$

where:

ρ = adjusted depletion fraction
ρ_{table}= depletion fraction
ET_c = average daily evapotranspiration rate (mm/d).

The TAW is the total available soil water in the root zone, which can be determined using an Equation taken from the FAO Irrigation and Drainage Paper, see Equation 13 (Allen et al., 2006).

$$TAW = 1000\,(\theta_{FC} - \theta_{WP})\,Z_r \quad (13)$$

where:

TAW = total available soil water in the root zone (mm)
θ_{FC}= water content in soil at field capacity (m^3/m^3)
θ_{WP}= water content in soil at wilting point (m^3/m^3)
Z_r = rooting depth (mm).

The values for the water content in the soil at field capacity and at wilting point are specific to a type of soil and can be obtained from various different literature sources. The rooting depth determines how much water can be abstracted from the soil profile, any water passing below the plants roots, is essentially lost to ground water. The RAW was calculated using an Equation taken from the FAO Irrigation and Drainage Paper, see Equation 12 (Allen et al., 2006).

$$RAW = \rho\ (TAW) \tag{14}$$

The method used that was used to calculate the effective precipitation for this analysis, requires detailed information describing certain crop and soil characteristics. Often, complicated methods are not practical when applied to large samples or when the required information is not available. The effective rainfall should be calculated using the method that best suits the study context. The information and data sources used to calculate the effective precipitation have been summarized in Table 17.

Table 17 Summary of crop and soil data

Information	Symbol	Data source
Soil type		WR90 soil Map
Daily crop evapotranspiration	ET_c	SAPWAT database
Rooting depth	Z_r	SAPWAT database
Soil water content at field capacity	θ_{FC}	SAPWAT database
Soil water content at wilting point	θ_{WP}	SAPWAT database
Available water holding capacity of soil	AC	SAPWAT database
Total available soil water	TAW	Calculated (Equation 13)
Depletion fraction	ρ_{table}	FAO Irrigation and Drainage Paper
Adjusted depletion fraction	ρ	Calculated (Equation 12)

The monthly effective precipitation rate was calculated using crop parameters for turf grass plants only, since information for non-turf plants was not available. Including non-turf plants would increase the effective rainfall, but this increase was considered insignificant as they cover a small portion of the garden area. The effective precipitation parameter was regarded as a fixed monthly value, which represents the average precipitation rate calculated over the length of the historical record period.

5.13. Crop coefficient

The type and area of vegetation has a significant affect on the water required for irrigation (Wentz and Gober, 2007; Balling et al., 2008). Residential gardens often contain a diverse range of lawn and plants species, resulting in different evapotranspiration rates and overall water demand (Bush *et al.*, 2008). The choice and layout of residential gardens is generally influenced by human behaviour, however, properties in gated communities can be restricted by landscaping guidelines in terms of area coverage and plant species (Wentz *et al.*, 2016).

Crop coefficients are assigned to different types of vegetation based on specific plant characteristics and anatomy (Kjelgren *et al.*, 2016). The crop coefficient determines how much water a specific type of crop needs to survive relative to the reference evapotranspiration. The crop coefficient depends mainly on climatic conditions, causing seasonal variation. Pittenger (2014) suggested average crop coefficients for various plant types, see Table 18.

Table 18 Average crop coefficients (Pittenger, 2014)

Plant type	Crop coefficient
Cool-season turf grass	0.8
Warm-season turf grass	0.6
Woody plants (trees, shrubs and groundcovers) – humid areas	0.7
Woody plants (trees, shrubs and groundcovers) – arid areas	0.5
Flowering plants	0.8
Desert plants/Xeriscaping	0.3

Identifying and measuring all the different plant species and covered area was not possible with the limited cadastral imagery available. Garden areas can be divided into sections that contain groups of plants with similar water use characteristics. For this study, the garden area was divided into two groups: turf grass (lawn) and non-turf plants (trees, shrubs, plants and other vegetation). A study conducted on households in a residential estate reported that turf grass covered 76% of the garden area (du Plessis, 2014). For most residential landscapes, turf grasses generally make up most of the garden vegetation (Kjelgren, Rupp and Kilgren, 2000; Smith *et al.*, 2005). Whitford et al. (2012) found that lawn cover represented 75% of the domestic garden area. For this study, the study sites were assumed to exhibit the same garden cover patterns as the households reported by du Plessis (2014).

5.13.1. Turf grass

The water requirement for turf grass can vary, depending on the species. Common types of turf species used in South African gardens are kikuyu grass (Penisetum clandestinum) and buffalo grass (Stenotaphrum secundatum) (Jacobs and Haarhoff, 2004; Prescott and Potter, 2004). Both species are warm-season grasses, however, kikuyu grass has a larger water requirement than buffalo grass. In Potchefstroom, an analysis of 100 households revealed that Kikuyu grass was the most favoured species among homeowners (Lubbe et al., 2011). In some gated communities, kikuyu grass is not permitted or strongly discouraged in residential gardens (du Plessis et al., 2018). The more conservative approach was taken for this study and the turf grass was modelled as kikuyu. The SAPWAT4 program was used to calculate the monthly crop coefficients for kikuyu grass using the quaternary weather station and soil type information.

5.13.2. Non-turf plants

In this study, the non-turf plant group represented a range of different landscaping plants found in domestic gardens (trees, shrubs, flowering plants and groundcovers). The crop coefficients for the non-turf plants types were sourced from available literature, because the crop database in the SAPWAT4 program did not include data for trees, shrubs, flowering plants or groundcovers applicable to residential gardens. Pettinger (2014) suggested an average crop coefficient of 0.5 for woody plants (trees, shrubs and groundcovers) in arid areas and an average crop coefficient of 0.8 for flowering plants. By assuming equal coverage of both plant types in the non-turf plant group portion of a garden, an average of 0.65 was estimated for non-turf plants.

The monthly distribution of non-turf plants was presumed to follow a similar pattern to that of “tropical bushveld”, a natural veld type found in South Africa presented by Midgley et al. (1994). Jacobs and Haarhoff (2004) used these monthly crop factors to represent garden bed plants in the REUM. It was considered appropriate to apply this distribution pattern to the non-turf plants crop coefficient. The monthly crop factors for “tropical bushveld” were sourced from the WR90 study and are provided in Table 19.

Table 19 Monthly crop factor for "tropical bushveld" (Midgley et al., 1994)

Vegetation type	Crop factor											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tropical bushveld	0.59	0.59	0.58	0.50	0.44	0.32	0.27	0.35	0.45	0.51	0.56	0.59

The crop coefficient parameters were populated as fixed monthly values.

5.14. Irrigation efficiency

The irrigation efficiency is the ratio between the total water applied to an area and the amount that reaches the crop root zone and is utilized for plant consumption. Generally, irrigation methods vary considerably, depending on the residents, who do not always water their gardens according to the plants agronomical needs and often have a tendency to over or under irrigate their gardens. Not all water supplied by an irrigation system reaches and penetrates the plants root zone, nor is equivalent to the plants ideal water requirement. Factors such as run-off, evaporation, deep percolation, human behaviour (type of system and frequency) and irrigation system over spray and spacing, all contribute to the excess water that is not utilized by the plants. Due to the uncertainty of human behaviour, an assumption was made that all residents watered their gardens according to their plant’s agronomical needs. Future research to model a relationship between the modelled and applied irrigation would be highly beneficial.

The irrigation efficiency factor was included to account for distribution uniformity and system efficiency. The distribution uniformity and system efficiency for irrigation systems that are commonly used in domestic gardens were sourced from various literature studies and summarized in Table 20.

Table 20 System efficiency and distribution uniformity values

Reference	System efficiency (%)			Distribution uniformity (%)
	Sprinkler	Micro-sprayer	Drip system	
SAPWAT4	78 - 90	85	95	100
USDA (1997)	60 - 90	85	90	
Connellan (2002)	70 - 80		80 - 95	> 75
DWAF (2000)	75	90	95	85

Table 20 illustrates how the system type can influence the irrigation demand. An irrigation efficiency was estimated by multiplying the system efficiency by the distribution uniformity. The irrigation efficiency was determined for each system, by averaging the referenced values, see Table 21.

Table 21 Estimated irrigation efficiencies

Irrigation system	Estimated irrigation efficiency (%)
Sprinkler	67
Micro-sprayer	75
Drip system	80

Du Plessis (2014) surveyed 105 homes from a high-income residential estate in Cape Town and found that 91% used Micro-sprayer irrigation systems. A Micro-sprayer irrigation system was assumed for the households in this study.

6. DATA ANALYSIS

6.1. Geometric measurements

The property, garden and swimming pool areas were measured for each individual property. A statistical analysis was performed on the geometric measurements of the households to evaluate and assess possible relationships. The communal garden and swimming pool areas were included in the demand model calculation but excluded from the statistical analysis.

The total sample comprised of 1 055 properties ranging from 1 623 m² to 84 m² in size, with an average of 462 m². The results from a simple statistical analysis has been summarized in Table 22. A frequency histogram illustrating the variation in property size for the total sample, see Figure 18.

Table 22 Statistical analysis of property area

Site	Number of properties	Property area (m²)			
		Mean	Standard deviation	Minimum	Maximum
A	30	410	60	340	589
B	234	337	92	161	613
C	29	162	32	114	249
D	54	196	33	150	312
E	57	245	53	117	355
F	92	259	83	142	491
G	69	137	29	84	277
H	285	759	308	354	1623
I	150	553	160	309	1224
J	55	613	80	446	850

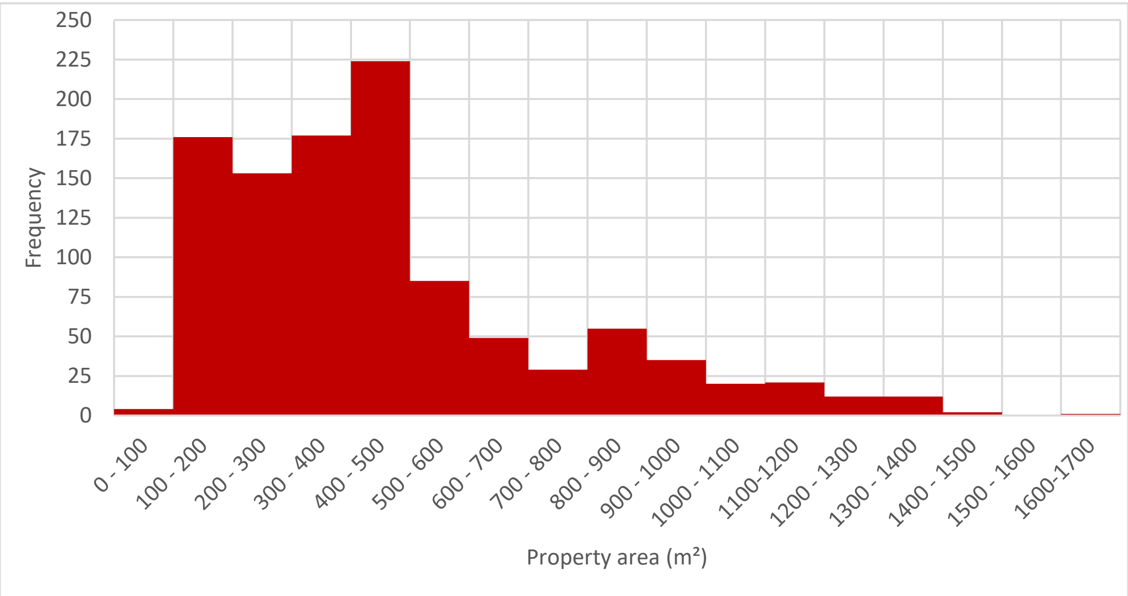

Figure 18 Frequency distribution of property area

The garden area of the households ranged from 1 015 m² to 0 m², with an average of 221 m². Results from the statistical analysis are summarized in Table 23 and a frequency histogram illustrating the variation in garden size is provided in Figure 19.

Table 23 Statistical analysis of garden area

Site	Garden area (m²)			
	Mean	Standard deviation	Minimum	Maximum
A	183	53	90	391
B	152	62	41	372
C	70	29	21	152
D	52	31	0	140
E	76	34	0	176
F	97	65	0	306
G	35	19	15	128
H	359	225	30	1 015
I	366	148	157	993
J	272	81	86	469

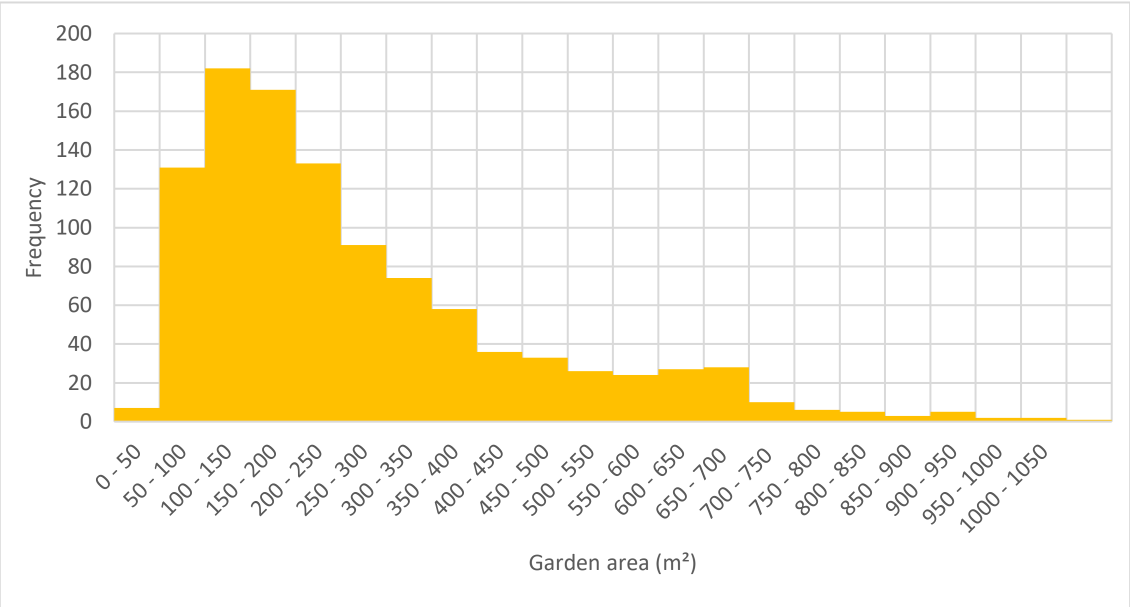

Figure 19 Frequency distribution of garden area

The garden area is not always known or too time consuming to measure for a large sample. Information regarding the property area is often known and can be related to the garden area. The property and garden areas of the 1 055 households were plotted in Figure 20 to analyse a possible relationship.

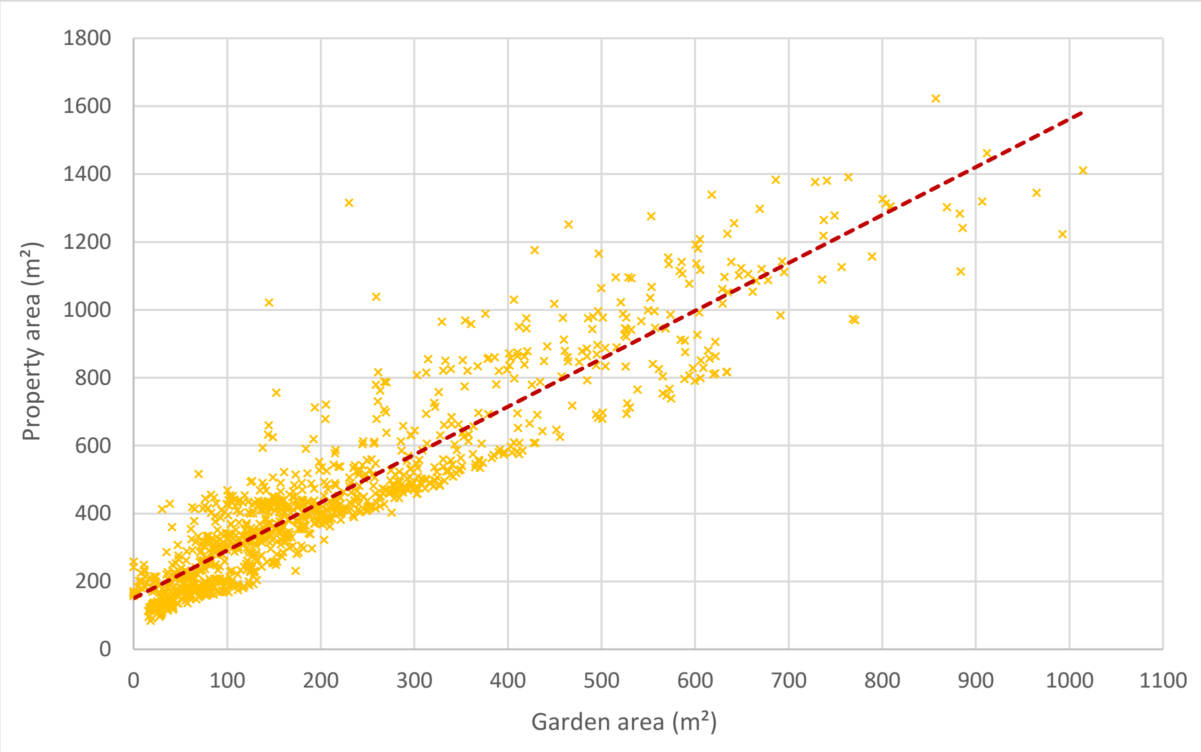

Figure 20 Relationship between property area and garden area

Figure 20 illustrates a very strong linear relationship ($R^2 = 0.8597$) between the property and garden area of the study sample, see Equation 15. For this analysis, the garden area was used, however; if only the property area is known, the equation in Figure 20 could possibly be used to estimate the garden area.

$$y = 1.4x + 150.1 \tag{15}$$

where:

y = the property area (m²)

x = garden area (m²)

Of the 1 055 households analysed, only 51 owned a swimming pool. A reason for the low number could be due to the households residing in gated community developments and could possibly be restricted by rules and guidelines set out by the HOA. Another reason could be attributed to Site B being a retirement village and retired residents are less likely to own pool. Gated communities generally have communal areas including swimming pool facilities, this could discourage residents from owning a pool. Of the 10 sites analysed, only 2 communities appeared to have communal swimming pools. However, the analysis was conducted using Google Earth imagery, and indoor swimming pools could not be detected. Results from the statistical analysis conducted on households that owned swimming pools has been summarized in Table 24.

Table 24 Statistical analysis of swimming pool area

Site	Number of properties	Number of pools	Percentage with pool (%)	Swimming pool area (m^2)			
				Mean	Standard deviation	Minimum	Maximum
A	30	9	30	16	5	11	25
D	54	4	7	11	5	7	20
H	285	18	6	19	8	5	34
I	150	3	2	14	4	11	20
J	55	17	31	16	8	6	34

6.2. SAPWAT climatic data

The quaternary stations derived in the SAPWAT program contain daily records of weather parameters for a period of 50 years. The reference evapotranspiration and precipitation rates were extracted from the database for the applicable quaternary catchment and analysed. The daily temperature values were also extracted for comparison purposes.

Site A fell within quaternary drainage region A21E, which is characterised by summer rainfall. The mean annual precipitation for the catchment area was 684 mm, the monthly mean reference evapotranspiration was 114 mm and the average temperature was 17.4°C. The monthly distribution of the climatic parameters has been provided in Table 25 and Figure 21.

Table 25 SAPWAT climatic parameters for site A

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET_0 (mm)	155	129	124	96	81	66	71	93	120	136	144	155
P_t (mm)	108	120	93	40	19	8	3	8	20	59	100	106
T (°C)	22	22	21	17	14	11	11	13	17	20	21	22

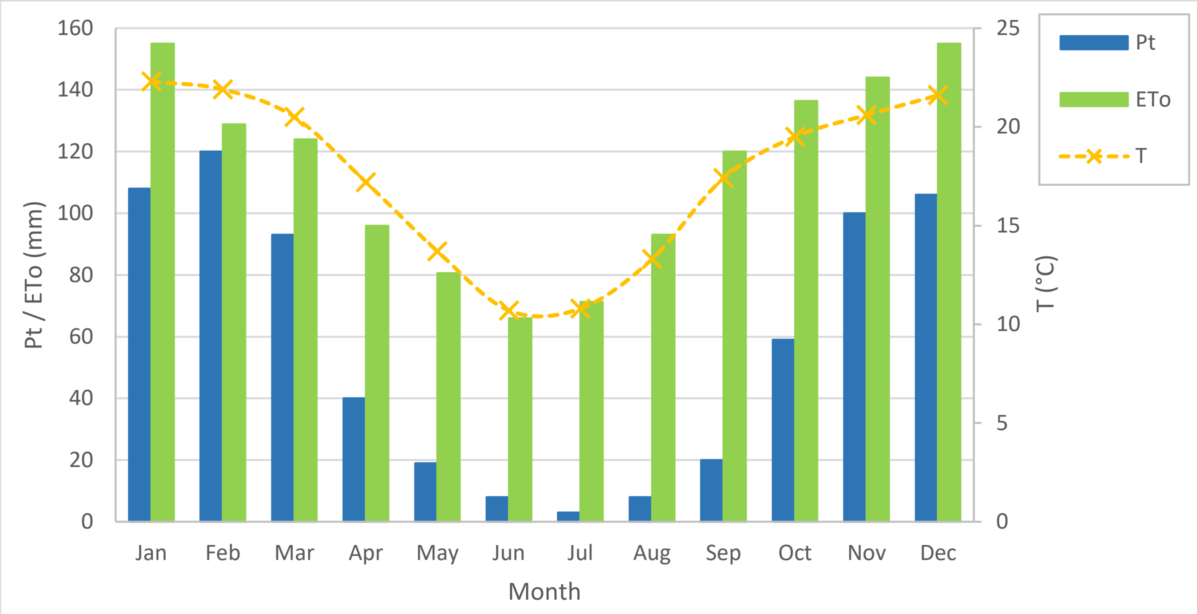

Figure 21 SAPWAT climatic parameters for site A

Site B fell within quaternary drainage region C22D, which is characterised by summer rainfall. The mean annual precipitation for the catchment area was 662 mm, the monthly mean reference evapotranspiration was 108 mm and the average temperature was 16.4°C. The monthly distribution of the climatic parameters has been provided in Table 26 and Figure 22.

Table 26 SAPWAT climatic parameters for site B

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET_0 (mm)	146	123	118	87	74	60	68	90	117	130	138	149
P_t (mm)	106	107	83	39	22	5	5	8	28	58	97	104
T (°C)	21	21	19	16	13	10	10	13	17	18	19	20

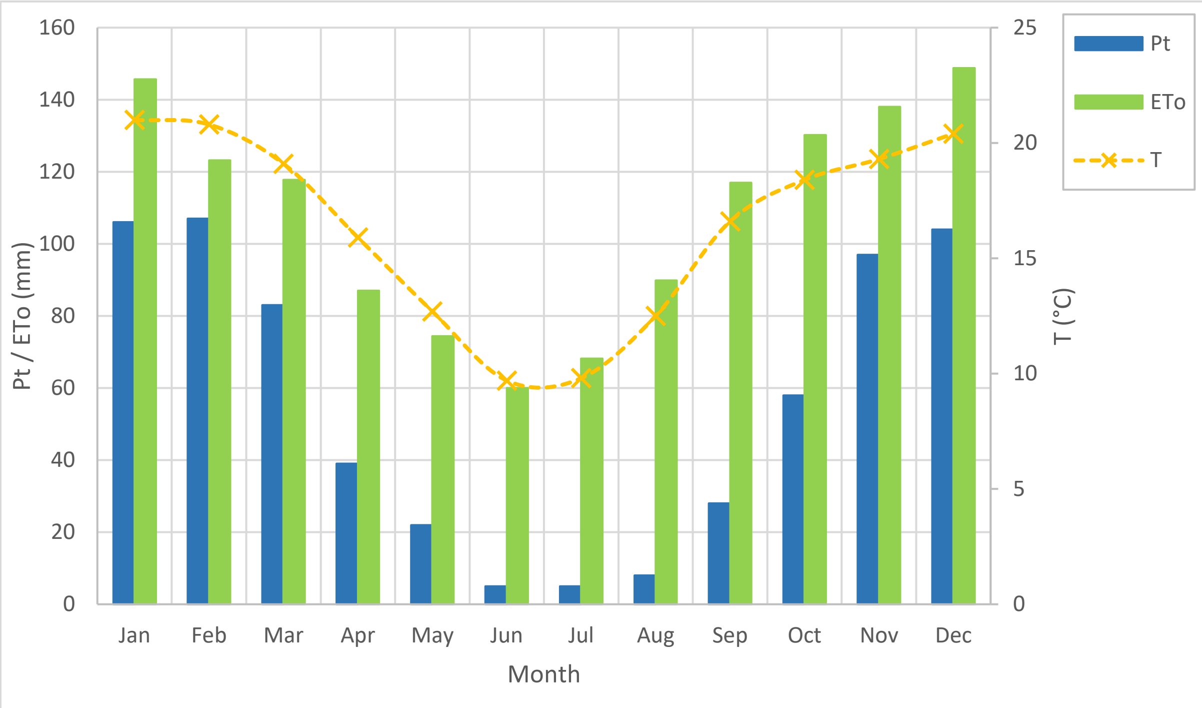

Figure 22 SAPWAT climatic parameters for site B

Site C fell within quaternary drainage region C22A, which is characterised by summer rainfall. The mean annual precipitation for the catchment area was 662 mm, the monthly mean reference evapotranspiration was 110 mm and the average temperature was 15.6°C. The monthly distribution of the climatic parameters has been provided in Table 27 and Figure 23.

Table 27 SAPWAT climatic parameters for site C

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET_0 (mm)	146	123	121	93	78	63	71	93	117	130	135	146
P_t (mm)	114	111	90	40	16	7	7	7	20	58	91	101
T (°C)	20	20	18	15	12	9	9	12	16	18	19	20

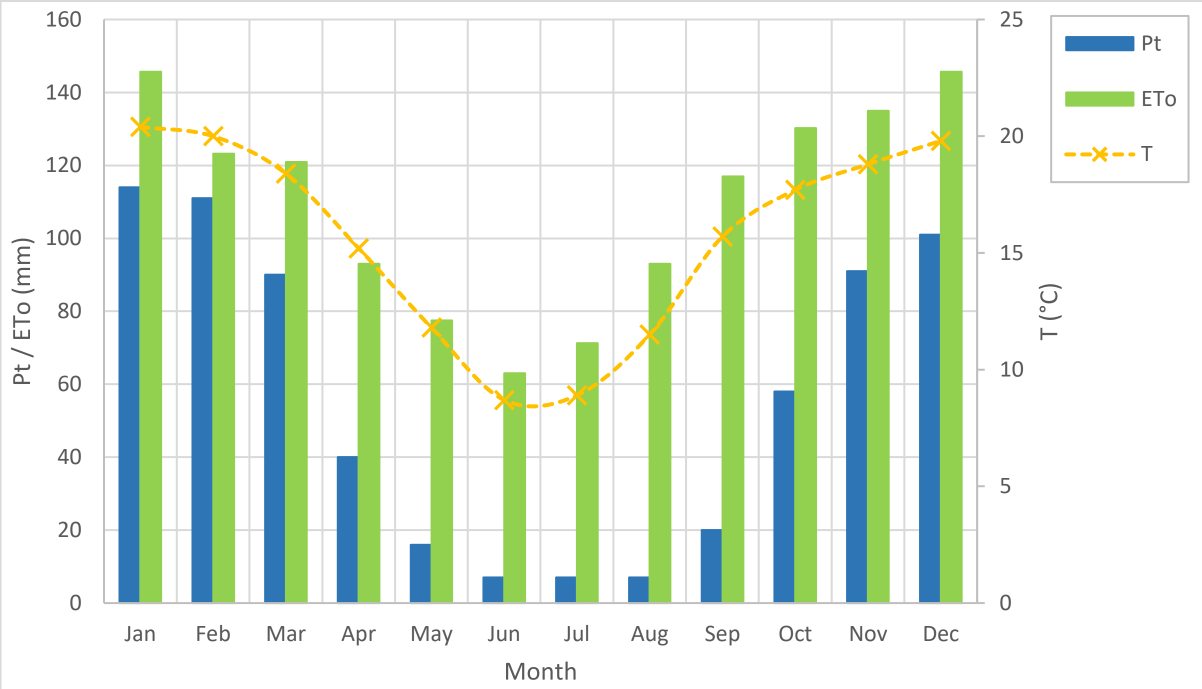

Figure 23 SAPWAT climatic parameters for site C

Site D and E fell within quaternary drainage region A21C, which is characterised by summer rainfall. The mean annual precipitation for the catchment area was 663 mm, the monthly mean reference evapotranspiration was 110 mm and the average temperature was 17.0°C. The monthly distribution of the climatic parameters has been provided in Table 28 and Figure 24.

Table 28 SAPWAT climatic parameters for site D and E

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Et_0 (mm)	143	120	121	96	81	66	71	90	117	133	138	146
P_t (mm)	115	99	99	38	21	9	4	5	18	55	102	98
T (°C)	21	21	20	17	14	11	11	13	17	19	20	20

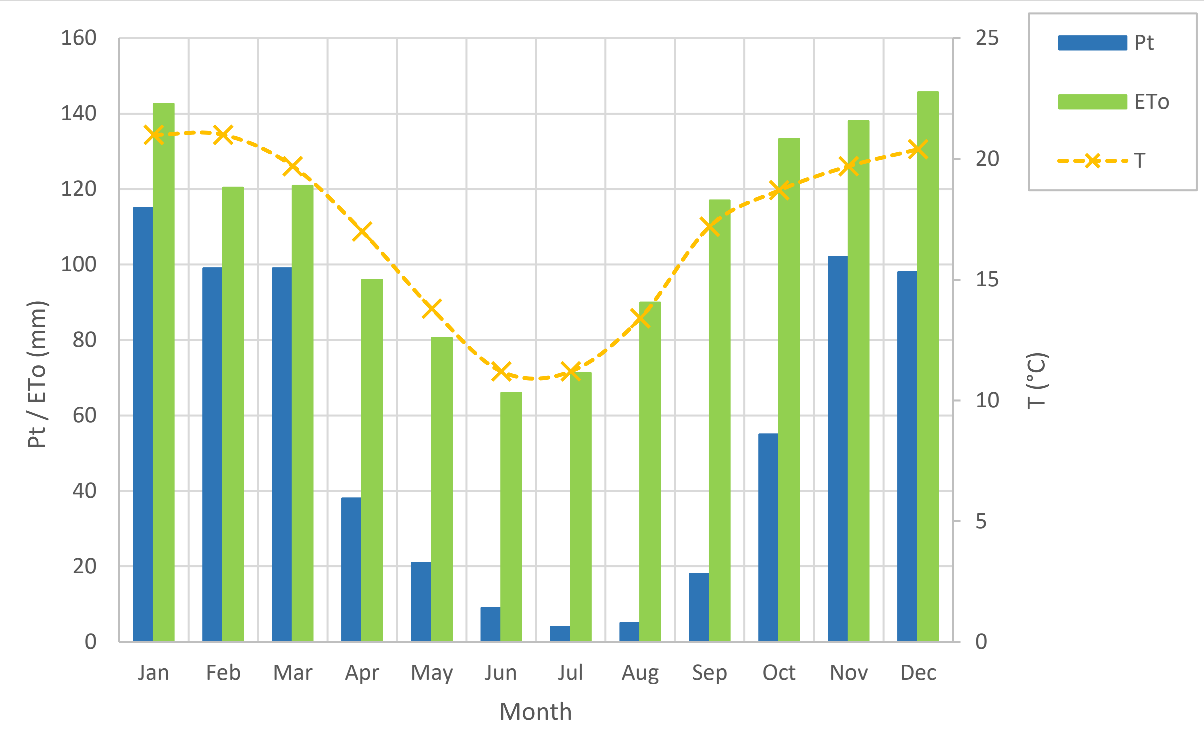

Figure 24 SAPWAT climatic parameters for site D and E

Site F and G fell within quaternary drainage region G22E, which is characterised by winter rainfall. The mean annual precipitation for the catchment area was 583 mm, the monthly mean reference evapotranspiration was 94 mm and the average temperature was 16.4°C. The monthly distribution of the climatic parameters has been provided in Table 29 and Figure 25.

Table 29 SAPWAT climatic parameters for site F and G

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Et_0 (mm)	152	132	115	78	53	39	43	56	75	109	132	149
P_t (mm)	12	22	18	53	91	98	88	77	47	33	29	15
T (°C)	21	21	20	17	15	13	12	12	13	16	18	19

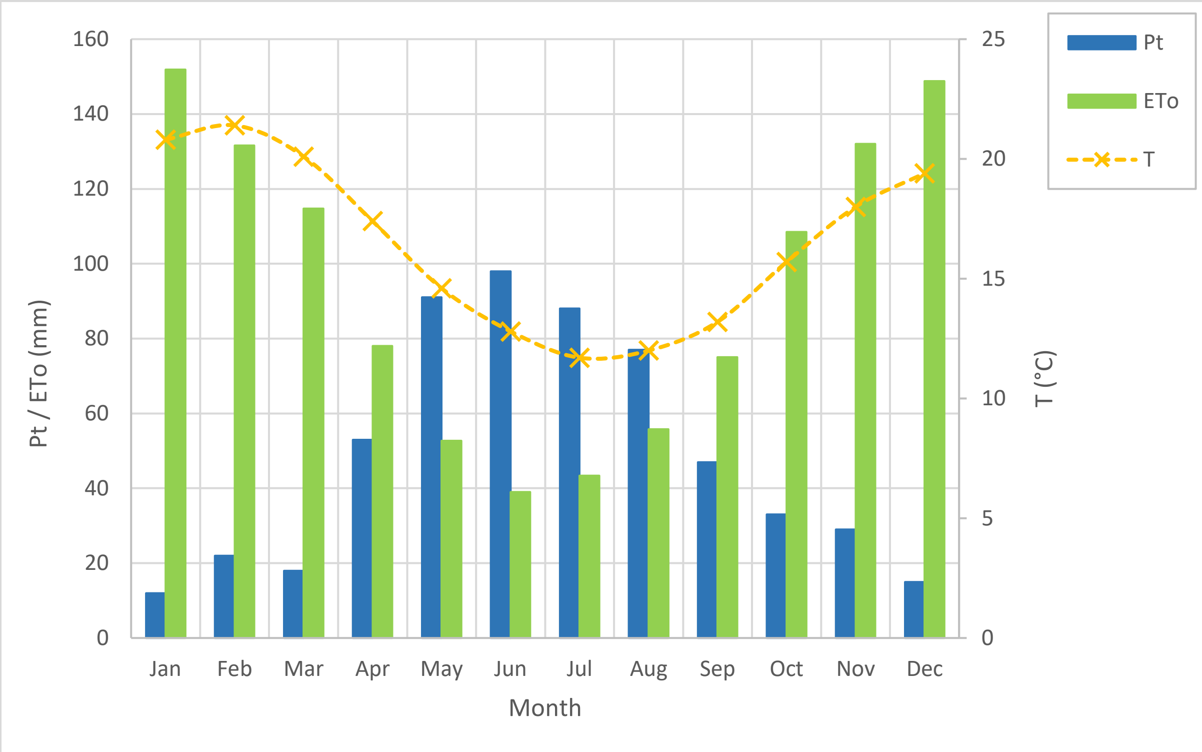

Figure 25 SAPWAT climatic parameters for site F and G

Site H fell within quaternary drainage region G40H, which is characterised by winter rainfall. The mean annual precipitation for the catchment area was 592 mm, the monthly mean reference evapotranspiration was 84 mm and the average temperature was 16.0°C. The monthly distribution of the climatic parameters has been provided in Table 30 and Figure 26.

Table 30 SAPWAT climatic parameters for site H

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Et_0 (mm)	140	112	96	69	47	36	37	50	66	96	120	140
P_t (mm)	23	31	33	53	66	82	69	71	60	44	36	24
T (°C)	20	20	19	17	15	13	12	12	13	16	17	19

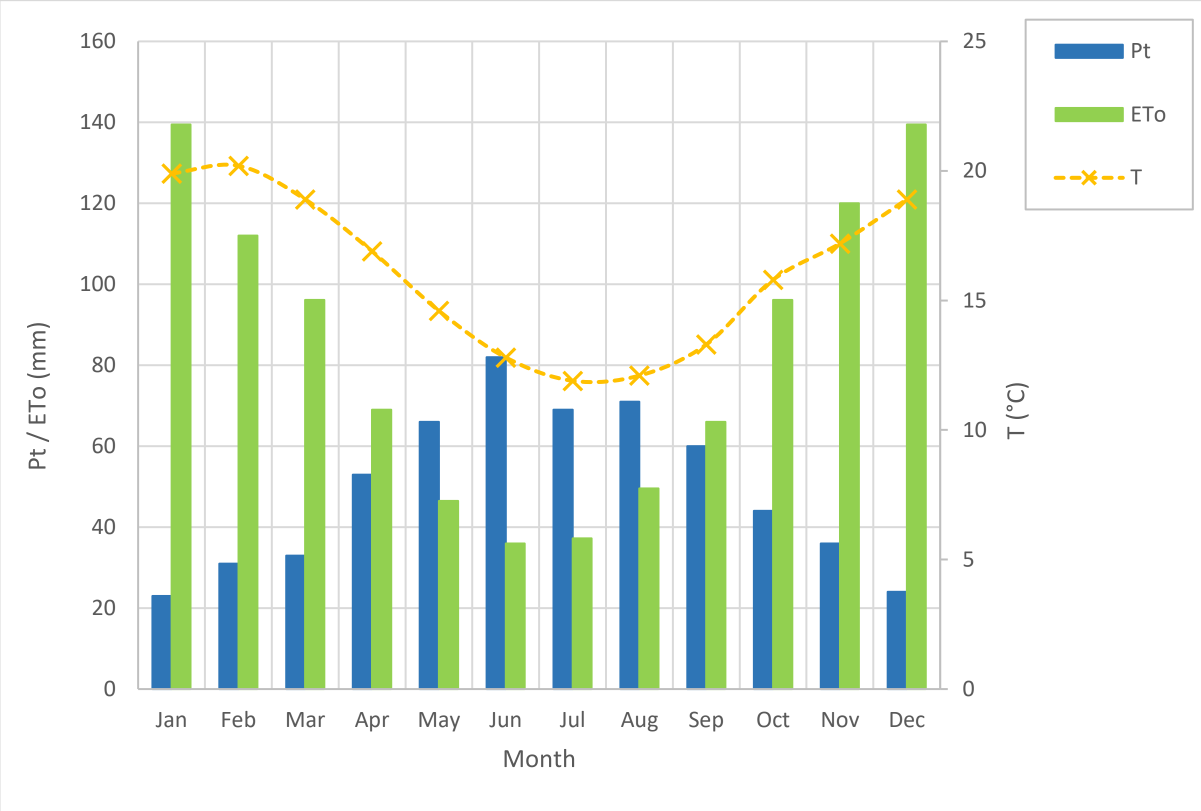

Figure 26 SAPWAT climatic parameters for site H

Site I fell within quaternary drainage region G22E, which is characterised by winter rainfall. The mean annual precipitation for the catchment area was 826 mm, the monthly mean reference evapotranspiration was 94 mm and the average temperature was 16.5°C. The monthly distribution of the climatic parameters has been provided in Table 31 and Figure 27.

Table 31 SAPWAT climatic parameters for site I

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Et_0 (mm)	140	115	105	75	53	42	43	56	75	102	120	143
P_t (mm)	12	24	24	67	111	164	124	129	73	48	29	21
T (°C)	21	21	20	17	15	13	12	13	14	16	18	20

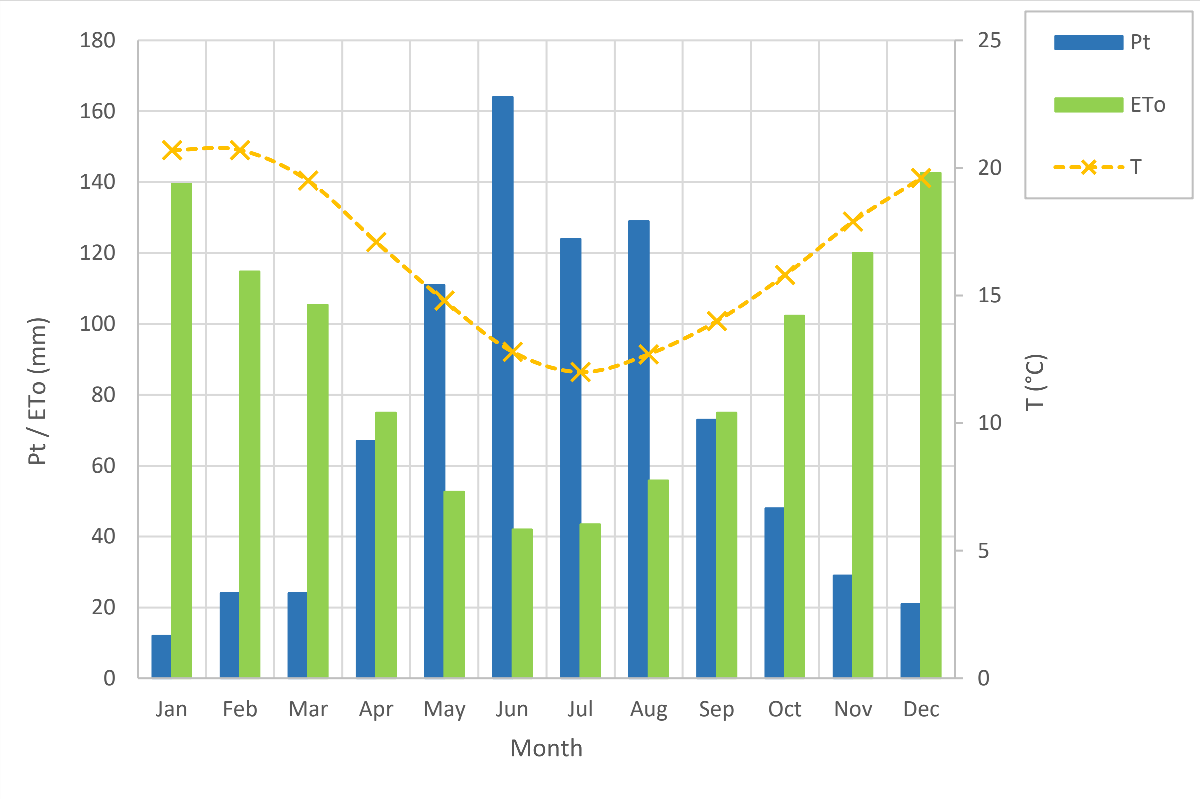

Figure 27 SAPWAT climatic parameters for site I

Site J fell within quaternary drainage region A23A, which is characterised by summer rainfall. The mean annual precipitation for the catchment area was 683 mm, the monthly mean reference evapotranspiration was 116 mm and the average temperature was 17.2°C. The monthly distribution of the climatic parameters has been provided in Table 32 and Figure 28.

Table 32 SAPWAT climatic parameters for site J

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Et_0 (mm)	155	129	127	99	84	69	74	96	123	140	144	152
P_t (mm)	138	107	86	38	14	9	3	5	17	60	100	106
T (°C)	22	22	20	17	14	11	11	13	17	19	20	21

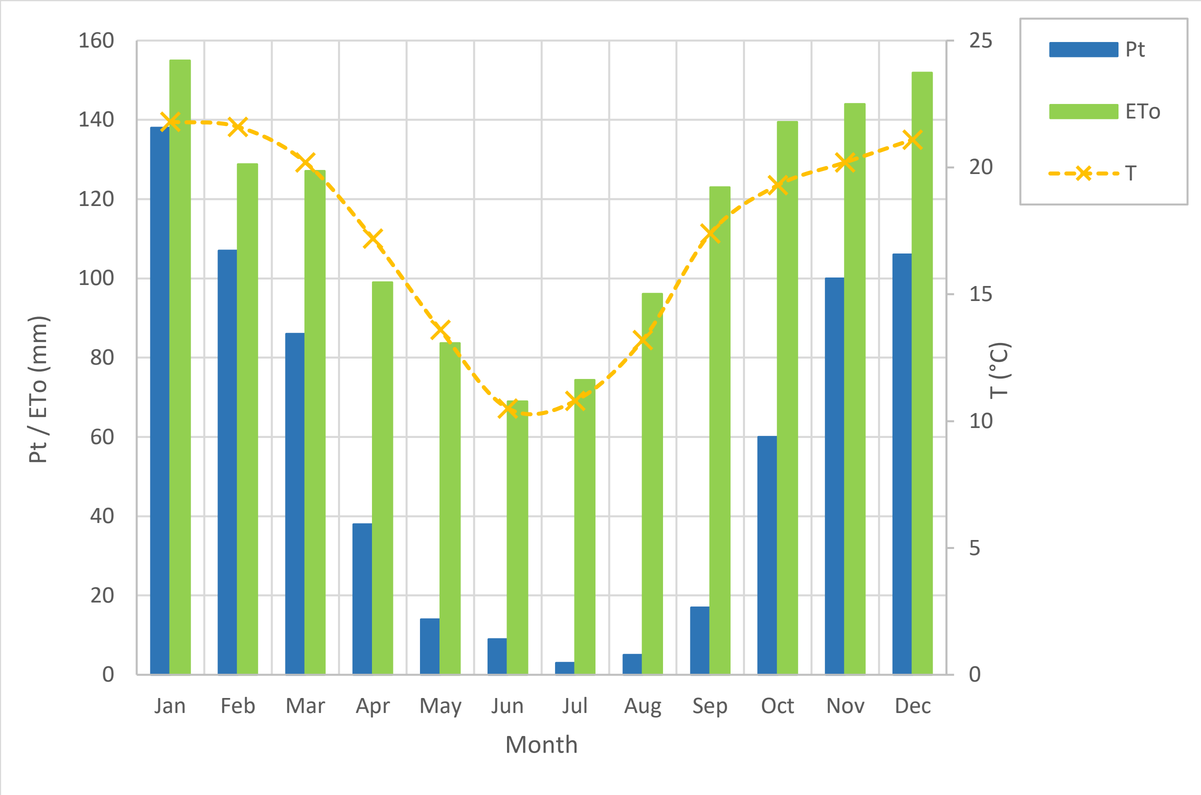

Figure 28 SAPWAT climatic parameters for site J

6.3. Crop coefficient

The monthly crop coefficients for kikuyu grass were obtained using the SAPWAT4 program. The crop type, weather station and soil type were plugged into the program and the resulting monthly crop coefficient distribution was extracted. The average crop coefficient for the turf grass parameter is summarized for each site in Table 33.

Table 33 Crop coefficient for turf grass

Site	Crop coefficient (turf grass)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A	0.948	0.948	0.877	0.770	0.664	0.624	0.629	0.697	0.807	0.915	0.957	0.948
B	0.944	0.942	0.805	0.599	0.397	0.310	0.310	0.311	0.443	0.656	0.870	0.942
C	0.941	0.940	0.808	0.601	0.398	0.310	0.310	0.311	0.442	0.655	0.867	0.940
D	0.942	0.944	0.812	0.603	0.397	0.310	0.310	0.311	0.443	0.657	0.867	0.941
E	0.942	0.944	0.812	0.603	0.397	0.310	0.310	0.311	0.443	0.657	0.867	0.941
F	0.951	0.949	0.804	0.573	0.392	0.310	0.310	0.311	0.437	0.656	0.868	0.949
G	0.951	0.949	0.804	0.573	0.392	0.310	0.310	0.311	0.437	0.656	0.868	0.949
H	0.930	0.927	0.786	0.559	0.391	0.310	0.310	0.311	0.430	0.641	0.851	0.933
I	0.933	0.935	0.794	0.569	0.392	0.310	0.310	0.311	0.433	0.644	0.857	0.936
J	0.948	0.946	0.812	0.604	0.398	0.310	0.310	0.311	0.444	0.659	0.871	0.947

The monthly crop coefficient for non-turf plants calculated in Chapter 5, was distributed using the tropical bushveld values from the WR90 study. The average crop coefficient for the non-turf plants parameter is provided in Table 34 and illustrated in Figure 29.

Table 34 Crop coefficient for non-turf plants

Site	Crop coefficient (non-turf plants)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
All	0.800	0.800	0.787	0.678	0.597	0.434	0.366	0.475	0.610	0.692	0.760	0.800

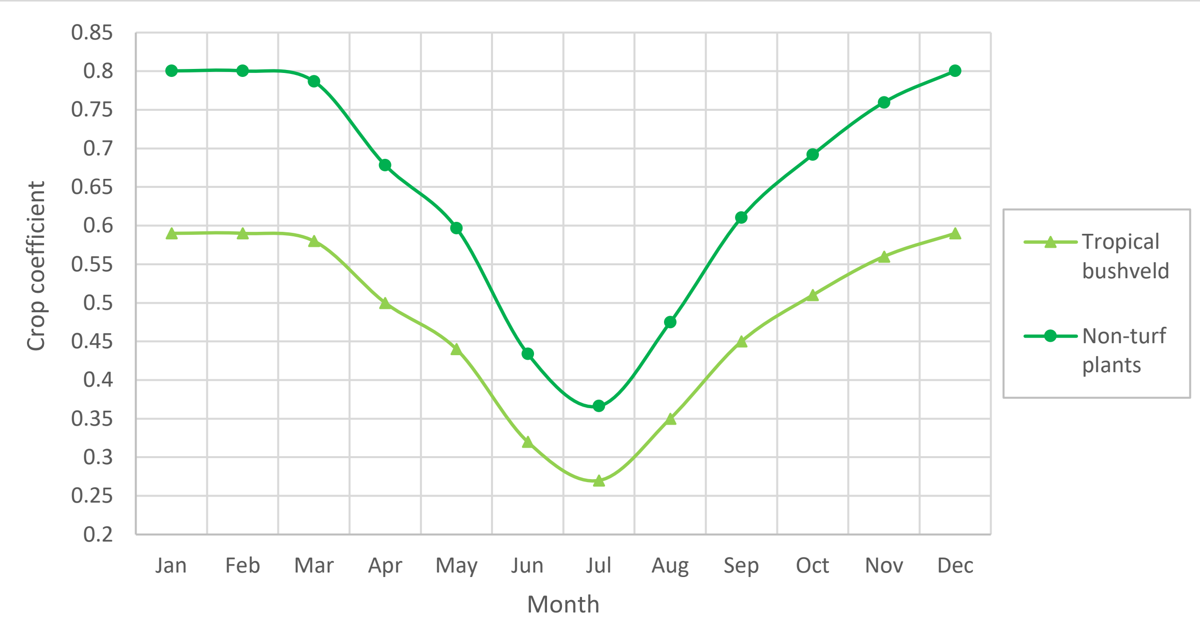

Figure 29 Distribution of non-turf plants and "tropical bushveld"

6.4. Crop evapotranspiration

The reference evapotranspiration rate can be multiplied by a crop coefficient to determine the crop evapotranspiration rate. The monthly evapotranspiration distribution for turf grass is provided in Table 35 and the distribution for non-turf plants is provided in Table 36.

Table 35 Monthly distribution of crop evapotranspiration for turf grass

Site	Evapotranspiration for turf grass (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A	147	122	109	74	54	41	45	65	97	125	138	147
B	138	116	95	52	30	19	21	28	52	85	120	140
C	137	116	98	56	31	20	22	29	52	85	117	137
D	134	114	98	58	32	20	22	28	52	88	120	137
E	134	114	98	58	32	20	22	28	52	88	120	137
F	144	125	92	45	21	12	13	17	33	71	115	141
G	144	125	92	45	21	12	13	17	33	71	115	141
H	130	104	76	39	18	11	12	15	28	62	102	130
I	130	107	84	43	21	13	13	17	32	66	103	133
J	147	122	103	60	33	21	23	30	55	92	125	144

Table 36 Monthly distribution of crop evapotranspiration for non-turf plants

Site	Evapotranspiration for non-turf plants (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A	124	103	98	65	48	29	26	44	73	94	109	124
B	117	99	93	59	44	26	25	43	71	90	105	119
C	117	99	95	63	46	27	26	44	71	90	103	117
D	114	96	95	65	48	29	26	43	71	92	105	117
E	114	96	95	65	48	29	26	43	71	92	105	117
F	122	105	90	53	31	17	16	26	46	75	100	119
G	122	105	90	53	31	17	16	26	46	75	100	119
H	112	90	76	47	28	16	14	24	40	66	91	112
I	112	92	83	51	31	18	16	26	46	71	91	114
J	124	103	100	67	50	30	27	46	75	97	109	122

6.5. Effective precipitation

The effective precipitation was calculated using the USDA-SCS method. The soil properties and crop characteristics required for the USDA-SCS calculation were determined using the WR90 soil map, crop database on SAPWAT and the FAO irrigation and drainage manual. The datasets are present and analysed for each study site.

At site A, the soil was classified as sandy loam with an available water holding capacity of 0.12 m^3/m^3. The mean annual effective precipitation was calculated as 579 mm, accounting for 85% of the mean annual precipitation. The average daily evapotranspiration rate was determined to be 3.19 mm/d. The monthly distribution of the effective precipitation, percentage effective precipitation of total precipitation and daily evapotranspiration have been provided in Table 37.

Table 37 Monthly distribution of effective precipitation and daily evapotranspiration for site A

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P_e (mm)	92	97	78	36	17	6	0	6	19	53	85	90
P_e (%)	85	81	84	89	90	75	8	77	93	90	85	85
Et_c (mm/d)	4.7	4.4	3.5	2.5	1.7	1.4	1.4	2.1	3.2	4.0	4.6	4.7

The monthly distribution of the effective precipitation, total precipitation and daily evapotranspiration have been provided in Figure 30.

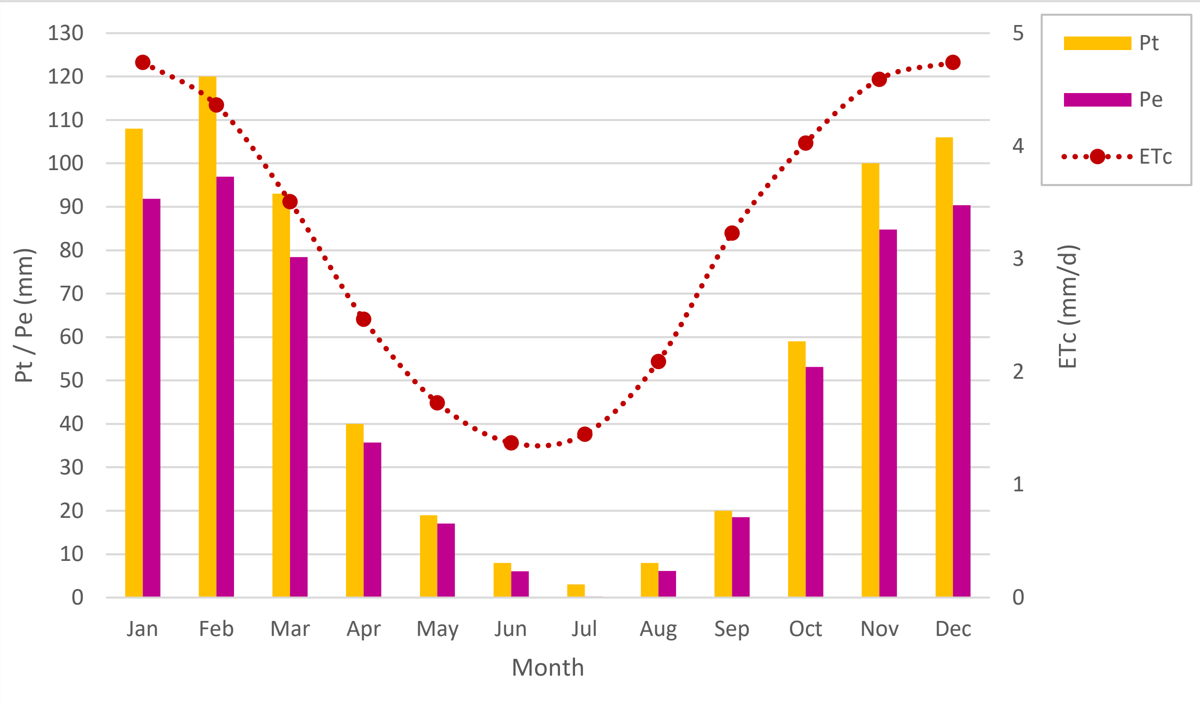

Figure 30 Monthly distribution of effective precipitation and daily evapotranspiration for site A

At site B, the soil was classified as sandy loam with an available water holding capacity of 0.12 m^3/m^3. The mean annual effective precipitation was calculated as 558 mm, accounting for 84% of the mean annual precipitation. The average daily evapotranspiration rate was determined to be 2.46 mm/d. The monthly distribution of the effective precipitation, percentage effective precipitation of total precipitation and daily evapotranspiration have been provided in Table 38.

Table 38 Monthly distribution of effective precipitation and daily evapotranspiration for site B

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P_e (mm)	90	87	70	34	19	3	3	6	25	51	82	88
P_e (%)	85	82	85	88	88	53	53	75	90	88	84	85
Et_c (mm/d)	4.4	4.1	3.1	1.7	1.0	0.6	0.7	0.9	1.7	2.8	4.0	4.5

The monthly distribution of the effective precipitation, total precipitation and daily evapotranspiration have been provided in Figure 31.

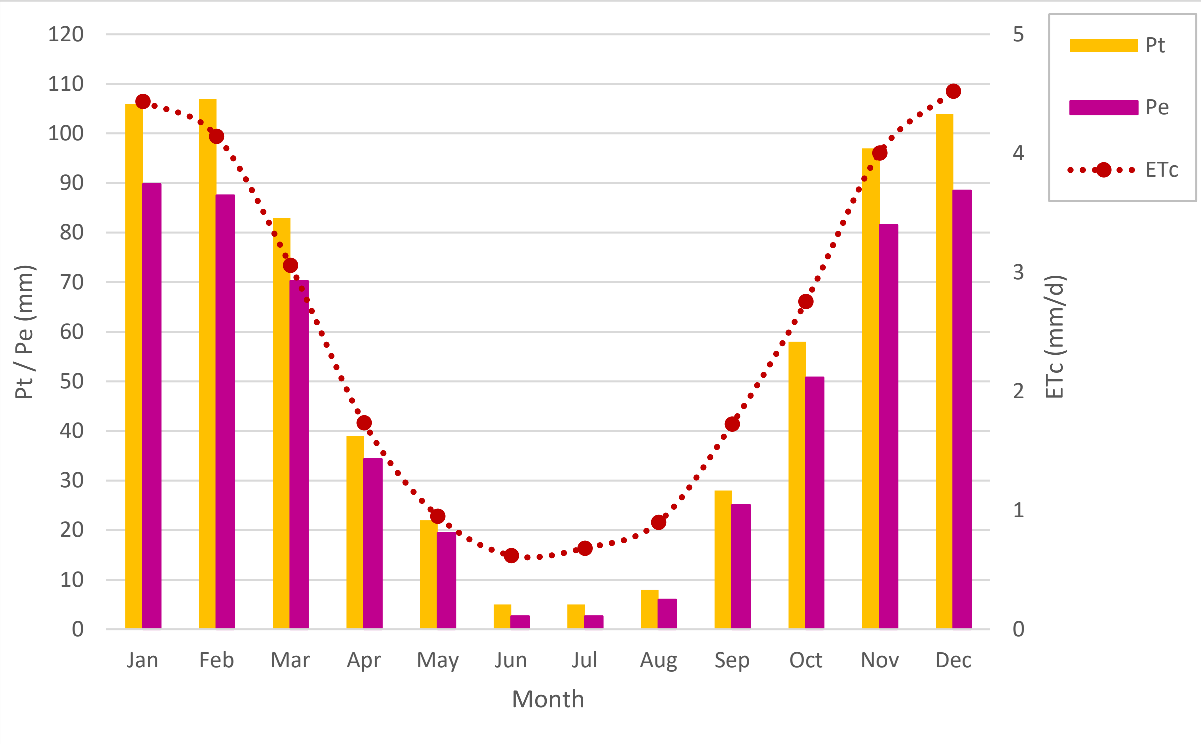

Figure 31 Monthly distribution of effective precipitation and daily evapotranspiration for site B

At site C, the soil was classified as sandy loam with an available water holding capacity of 0.12 m^3/m^3. The mean annual effective precipitation was calculated as 557 mm, accounting for 84% of the mean annual precipitation. The average daily evapotranspiration rate was determined to be 2.47 mm/d. The monthly distribution of the effective precipitation, percentage effective precipitation of total precipitation and daily evapotranspiration have been provided in Table 39.

Table 39 Monthly distribution of effective precipitation and daily evapotranspiration for site C

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P_e (mm)	96	90	76	35	14	5	5	5	18	51	77	86
P_e (%)	84	81	84	88	87	69	70	70	90	88	85	85
Et_c (mm/d)	4.4	4.1	3.2	1.9	1.0	0.7	0.7	0.9	1.7	2.7	3.9	4.4

The monthly distribution of the effective precipitation, total precipitation and daily evapotranspiration have been provided in Figure 32.

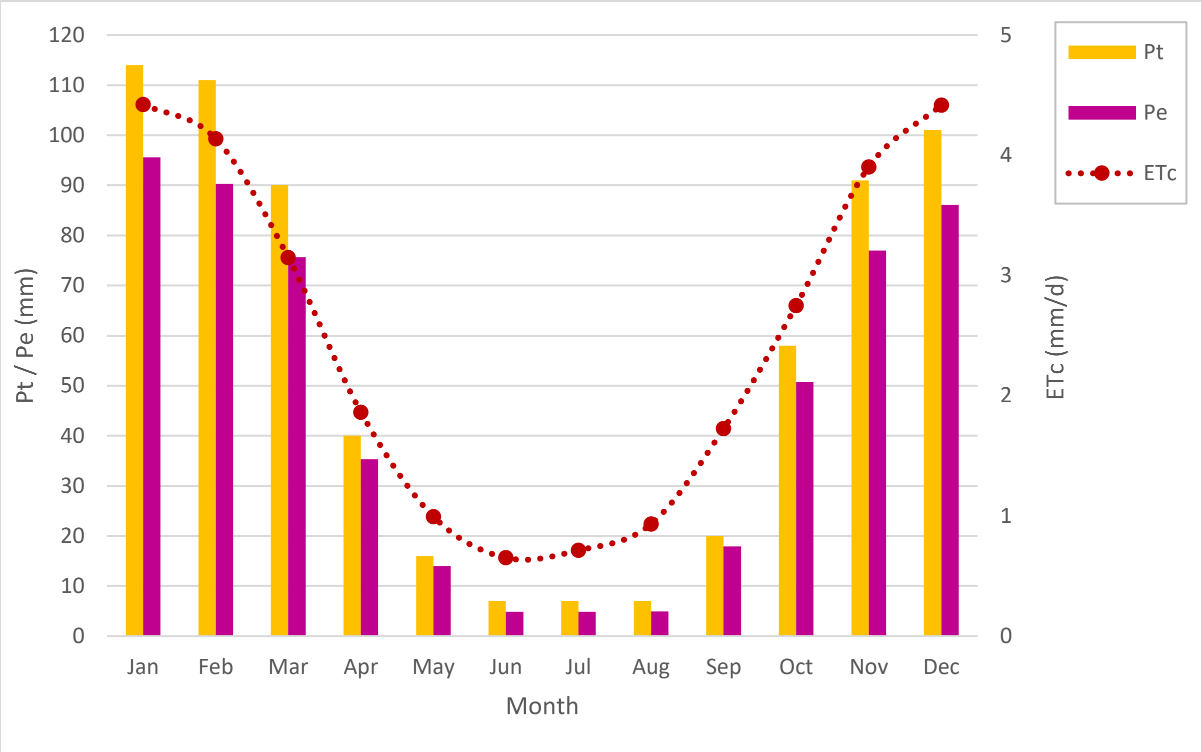

Figure 32 Monthly distribution of effective precipitation and daily evapotranspiration for site C

At site D and E, the soil was classified as sandy loam with an available water holding capacity of 0.12 m^3/m^3. The mean annual effective precipitation was calculated as 557 mm, accounting for 84% of the mean annual precipitation. The average daily evapotranspiration rate was determined to be 2.48 mm/d. The monthly distribution of the effective precipitation, percentage effective precipitation of total precipitation and daily evapotranspiration have been provided in Table 40.

Table 40 Monthly distribution of effective precipitation and daily evapotranspiration for site D and site E

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P_e (mm)	96	82	82	34	19	7	1	3	16	48	85	84
P_e (%)	84	82	83	89	89	77	37	53	89	88	84	86
Et_c (mm/d)	4.3	4.1	3.2	1.9	1.0	0.7	0.7	0.9	1.7	2.8	4.0	4.4

The monthly distribution of the effective precipitation, total precipitation and daily evapotranspiration have been provided in Figure 33.

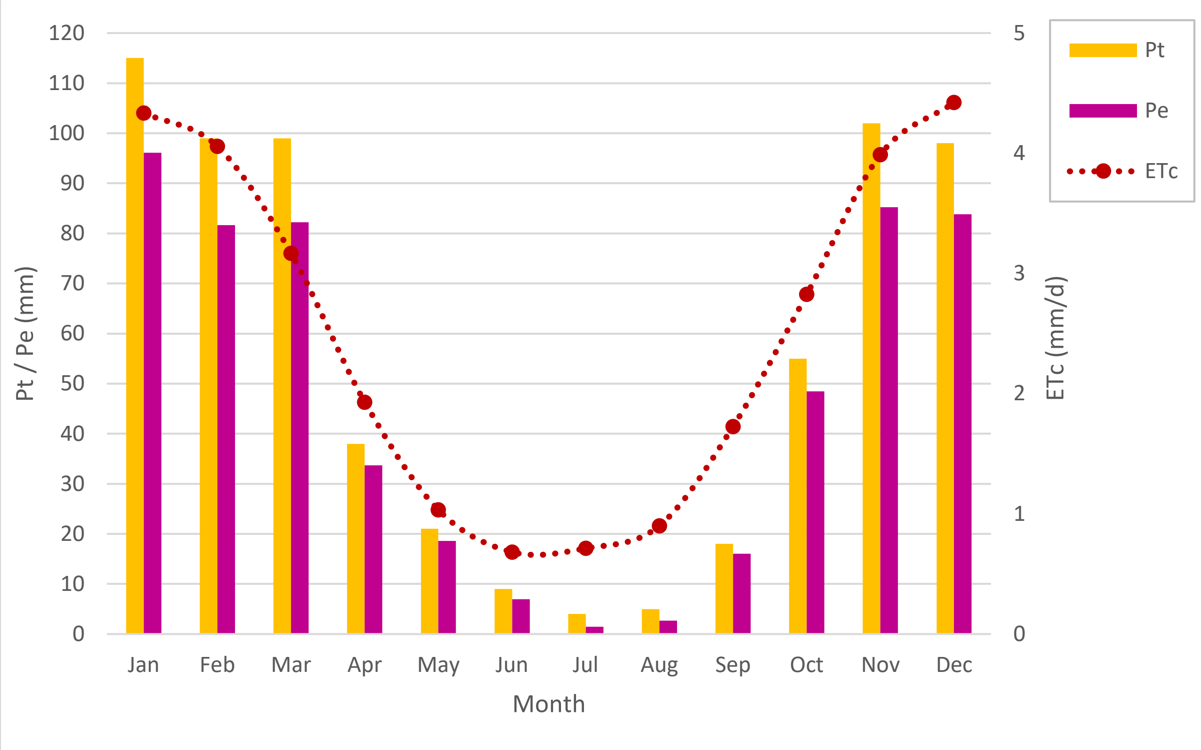

Figure 33 Monthly distribution of effective precipitation and daily evapotranspiration for site D and site E

At site F, the soil was classified as sandy with an available water holding capacity of 0.07 m^3/m^3. The mean annual effective precipitation was calculated as 216 mm, accounting for 37% of the mean annual precipitation. The average daily evapotranspiration rate was determined to be 2.29 mm/d. The monthly distribution of the effective precipitation, percentage effective precipitation of total precipitation and daily evapotranspiration have been provided in Table 41.

Table 41 Monthly distribution of effective precipitation and daily evapotranspiration for site F

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P_e (mm)	8	16	12	33	21	12	13	17	29	22	20	11
P_e (%)	70	71	69	62	23	12	15	23	62	67	71	72
Et_c (mm/d)	4.7	4.5	3.0	1.5	0.7	0.4	0.4	0.6	1.1	2.3	3.8	4.6

The monthly distribution of the effective precipitation, total precipitation and daily evapotranspiration have been provided in Figure 34.

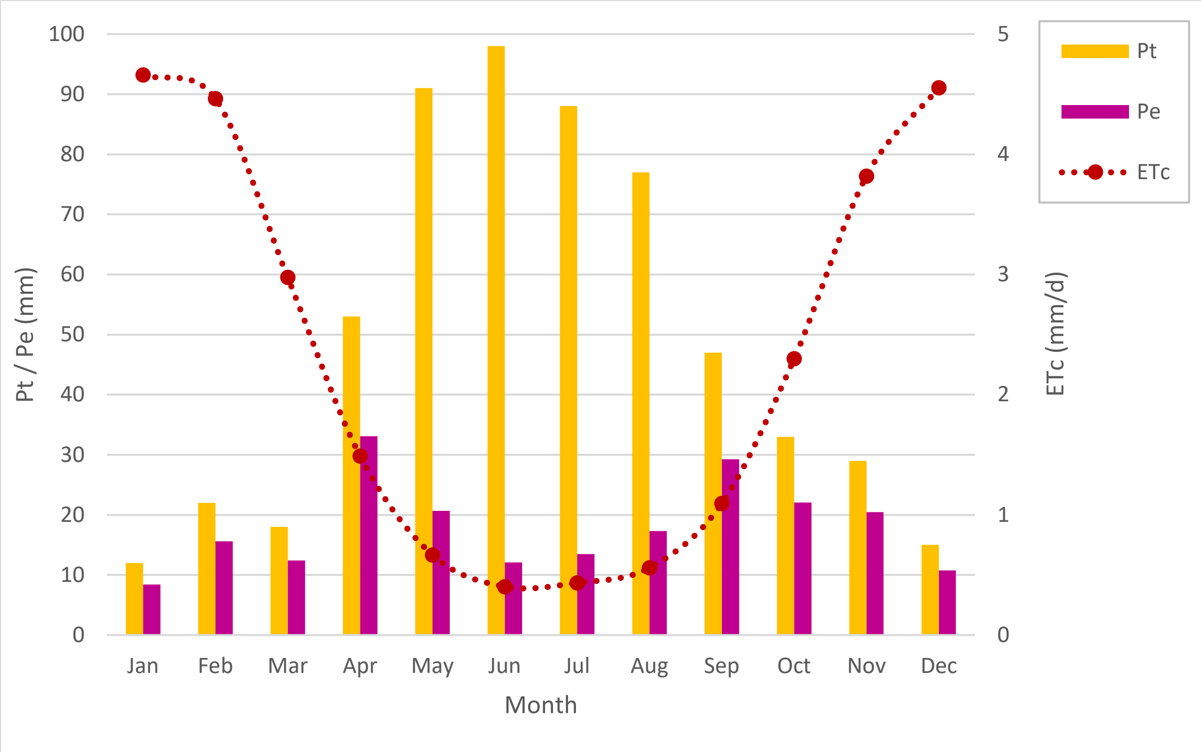

Figure 34 Monthly distribution of effective precipitation and daily evapotranspiration for site F

At site G, the soil was classified as clayey loam with an available water holding capacity of 0.165 m^3/m^3. The mean annual effective precipitation was calculated as 270 mm, accounting for 46% of the mean annual precipitation. The average daily evapotranspiration rate was determined to be 2.28 mm/d. The monthly distribution of the effective precipitation, percentage effective precipitation of total precipitation and daily evapotranspiration have been provided in Table 42.

Table 42 Monthly distribution of effective precipitation and daily evapotranspiration for site G

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P_e (mm)	12	22	18	45	21	12	13	17	33	33	29	15
P_e (%)	100	100	100	84	23	12	15	23	70	100	100	100
Et_c (mm/d)	4.7	4.5	3.0	1.5	0.7	0.4	0.4	0.6	1.1	2.3	3.8	4.6

The monthly distribution of the effective precipitation, total precipitation and daily evapotranspiration have been provided in Figure 35.

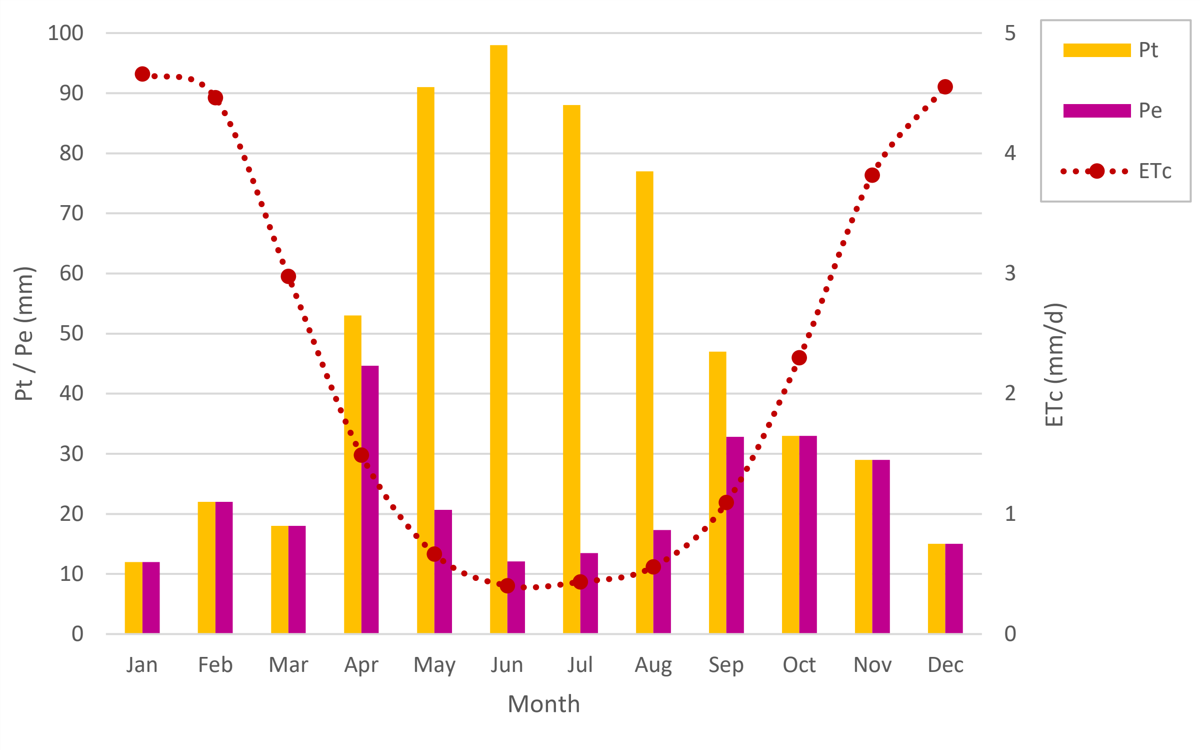

Figure 35 Monthly distribution of effective precipitation and daily evapotranspiration for site G

At site H, the soil was classified as sandy with an available water holding capacity of 0.07 m^3/m^3. The mean annual effective precipitation was calculated as 248 mm, accounting for 42% of the mean annual precipitation. The average daily evapotranspiration rate was determined to be 2.00 mm/d. The monthly distribution of the effective precipitation, percentage effective precipitation of total precipitation and daily evapotranspiration have been provided in Table 43.

Table 43 Monthly distribution of effective precipitation and daily evapotranspiration for site H

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P_e (mm)	17	21	22	33	18	11	12	15	28	29	25	17
P_e (%)	72	69	67	62	28	14	17	22	47	65	69	72
Et_c (mm/d)	4.2	3.7	2.4	1.3	0.6	0.4	0.4	0.5	0.9	2.0	3.4	4.2

The monthly distribution of the effective precipitation, total precipitation and daily evapotranspiration have been provided in Figure 36.

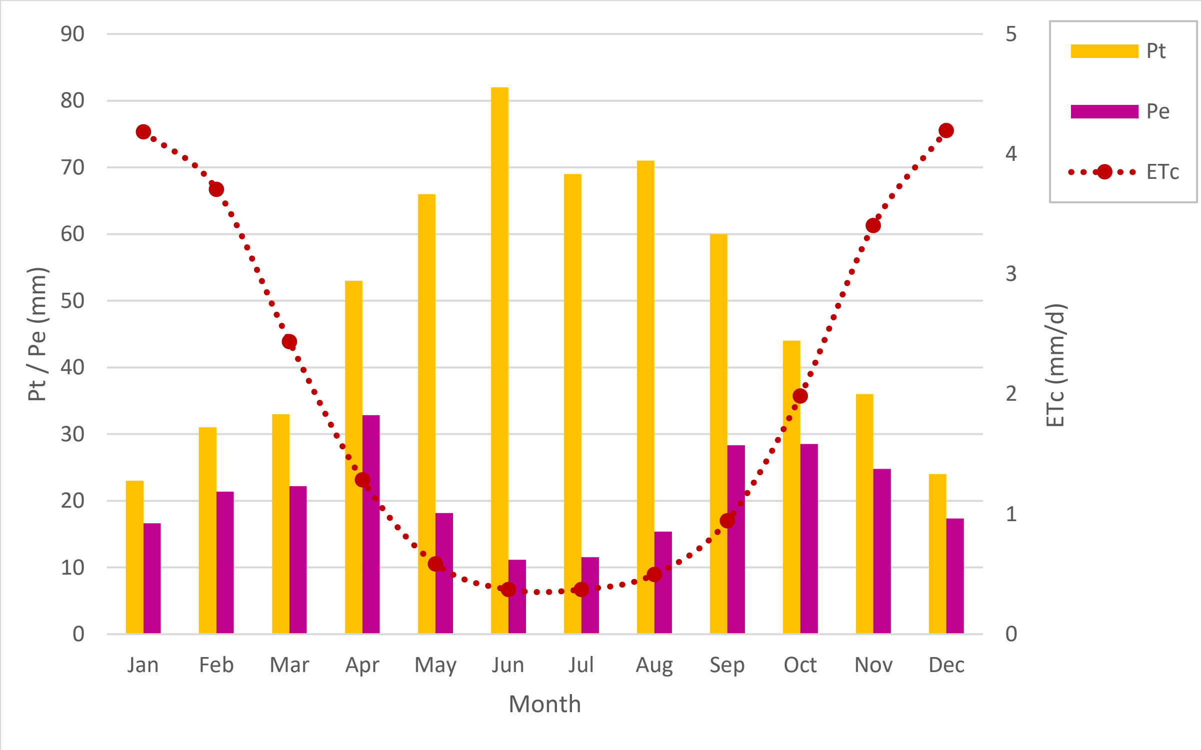

Figure 36 Monthly distribution of effective precipitation and daily evapotranspiration for site H

At site I, the soil was classified as sandy with an available water holding capacity of 0.07 m^3/m^3. The mean annual effective precipitation was calculated as 246 mm, accounting for 30% of the mean annual precipitation. The average daily evapotranspiration rate was determined to be 2.10 mm/d. The monthly distribution of the effective precipitation, percentage effective precipitation of total precipitation and daily evapotranspiration have been provided in Table 44.

Table 44 Monthly distribution of effective precipitation and daily evapotranspiration for site I

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P_e (mm)	8	17	16	41	21	13	13	17	32	31	20	15
P_e (%)	69	70	69	61	19	8	11	13	44	65	70	73
Et_c (mm/d)	4.2	3.8	2.7	1.4	0.7	0.4	0.4	0.6	1.1	2.1	3.4	4.3

The monthly distribution of the effective precipitation, total precipitation and daily evapotranspiration have been provided in Figure 37.

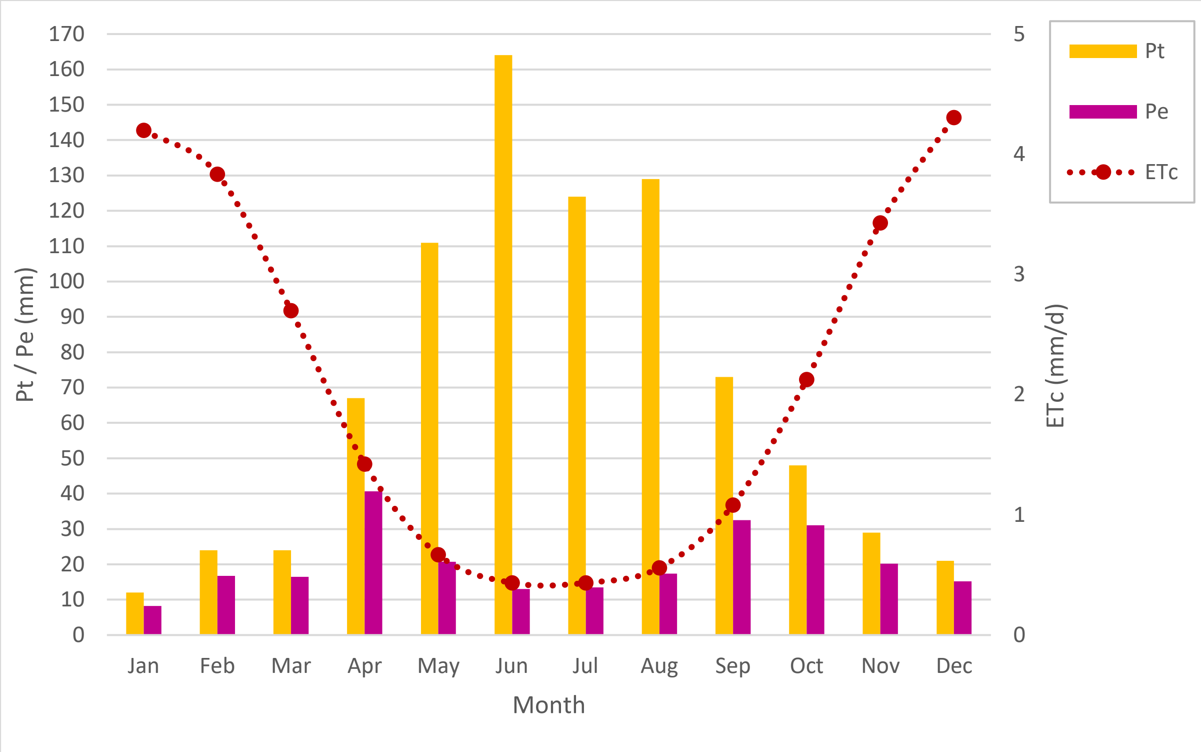

Figure 37 Monthly distribution of effective precipitation and daily evapotranspiration for site I

At site J, the soil was classified as sandy loam with an available water holding capacity of 0.12 m^3/m^3. The mean annual effective precipitation was calculated as 572 mm, accounting for 84% of the mean annual precipitation. The average daily evapotranspiration rate was determined to be 2.63 mm/d. The monthly distribution of the effective precipitation, percentage effective precipitation of total precipitation and daily evapotranspiration have been provided in Table 45.

Table 45 Monthly distribution of effective precipitation and daily evapotranspiration for site J

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P_e (mm)	113	88	73	34	12	7	0	3	15	53	84	90
P_e (%)	82	82	85	89	86	78	8	53	89	88	84	85
Et_c (mm/d)	4.7	4.4	3.3	2.0	1.1	0.7	0.7	1.0	1.8	3.0	4.2	4.6

The monthly distribution of the effective precipitation, total precipitation and daily evapotranspiration have been provided in Figure 38.

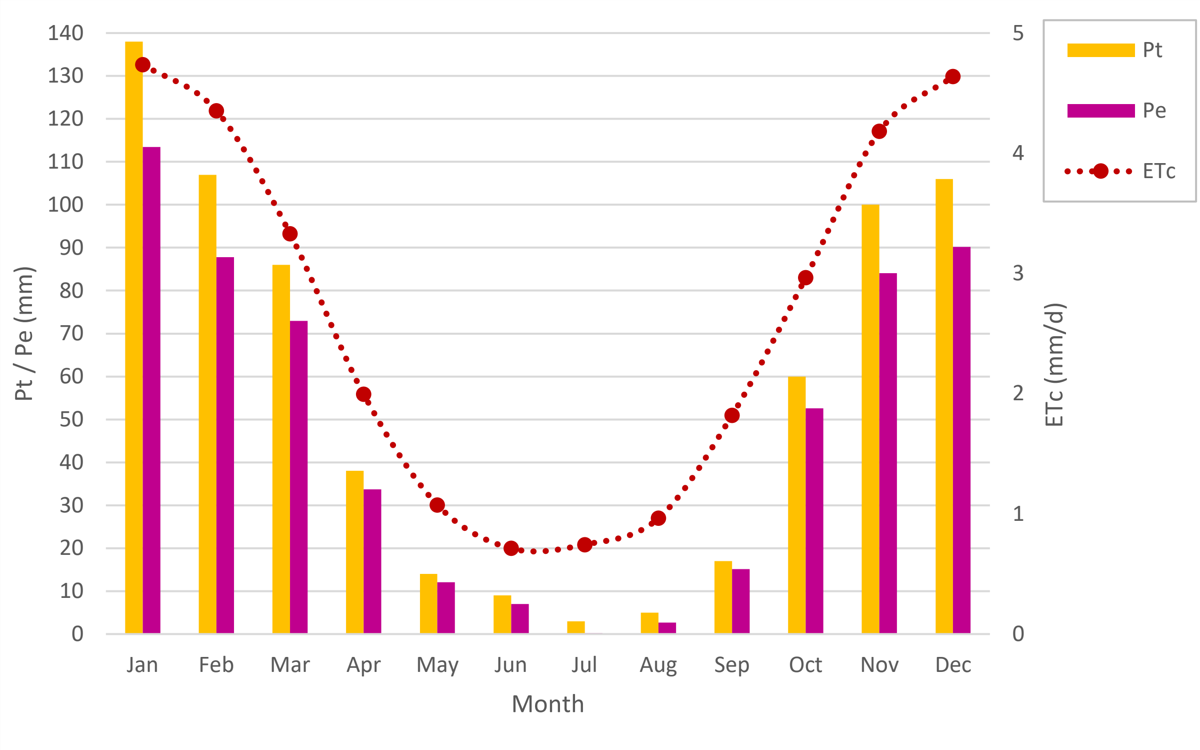

Figure 38 Monthly distribution of effective precipitation and daily evapotranspiration for site J

6.6. Free surface evaporation

S-pan evaporation data was sourced from gauging stations operated by the DWA and multiplied by a free lake evaporation factor, taken from the WR90 study. The average monthly evaporation from a free surface water body for each site has been provided in Table 46.

Table 46 Monthly distribution of free surface evaporation

Site	Evaporation (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A	140	121	113	89	74	58	63	86	117	131	133	142
B	140	121	113	89	74	58	63	86	117	131	133	142
C	140	121	113	89	74	58	63	86	117	131	133	142
D	147	129	122	93	76	59	64	85	116	140	141	150
E	147	129	122	93	76	59	64	85	116	140	141	150
F	194	171	144	85	50	35	35	43	61	101	148	183
G	194	171	144	85	50	35	35	43	61	101	148	183
H	198	166	138	94	65	49	47	59	82	119	153	186
I	187	157	129	78	48	35	36	53	74	120	151	179
J	146	144	151	145	125	111	82	66	58	65	88	122

7. RESULTS

7.1. Comparison of model results to actual use

A sample of existing households were selected to test the performance of the proposed demand model. The datasets required to populate the input parameters were collected and the water demand was modelled for each site. The actual metered monthly consumption was used to evaluate the effectiveness of the model. The error was calculated as the difference between the modelled water use and the metered water use.

The AADD for the metered consumption was 0.752 kL/household/d and the AADD for the modelled consumption was 0.796 kL/household/d for site A. The average monthly metered and modelled consumption has been illustrated in Table 47 and Figure 39.

Table 47 Metered and modelled consumption for site A

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Modelled use (kL)	772	516	609	662	669	633	706	809	937	886	734	783	8 717
Metered use (kL)	683	706	614	634	689	757	693	688	716	770	641	647	8 236
Error (kL)	89	190	5	28	20	123	14	121	222	116	93	137	481
Accuracy (%)	88	73	99	96	97	84	98	85	76	87	87	83	95

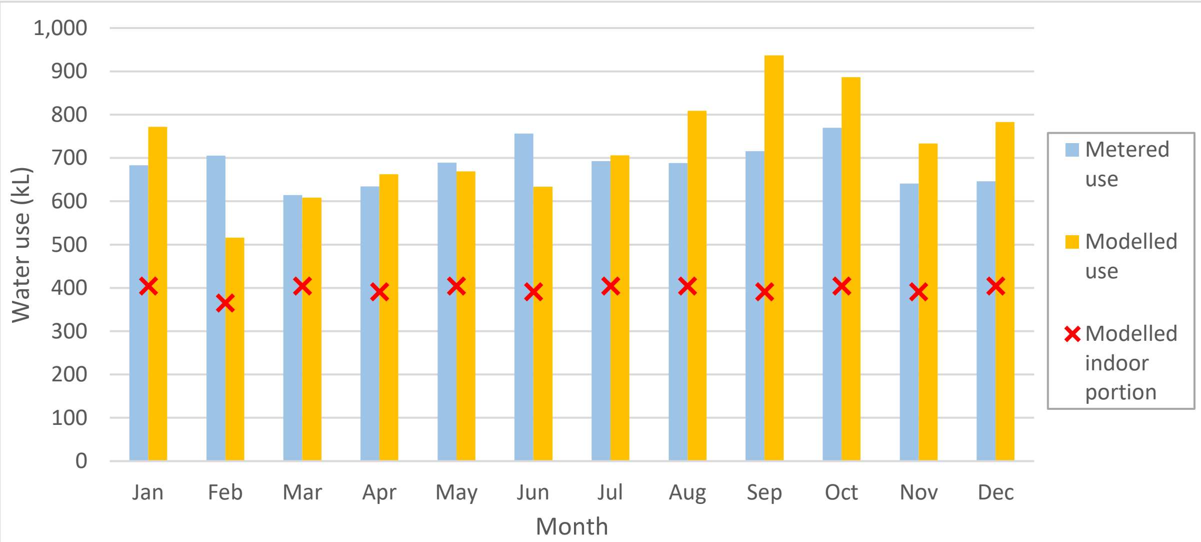

Figure 39 Metered and modelled consumption for site A

Figure 39 showed that the measured water consumption at site A fluctuated only slightly during the summer months. This was expected because of the summer rainfall. The month with the highest measured water use was October and the lowest during March. The model overestimated the total water consumption at site A, but had an overall accuracy of 95%. A reason for this overestimation could be due to the assumed input parameters.

The AADD for the metered consumption was 0.600 kL/household/d and the AADD for the modelled consumption was 0.574 kL/household/d for site B. The average monthly metered and modelled consumption has been illustrated in Table 48 and Figure 40.

Table 48 Metered and modelled consumption for site B

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Modelled use (kL)	5110	3668	3868	3485	3174	3375	3559	3963	4286	4647	4513	5373	49020
Metered use (kL)	4304	4715	3589	4004	3753	3910	3718	4601	5729	4630	5023	3248	51221
Error (kL)	807	1047	279	519	579	535	159	637	1443	17	510	2126	2201
Accuracy (%)	84	78	93	87	85	86	96	86	75	100	90	60	96

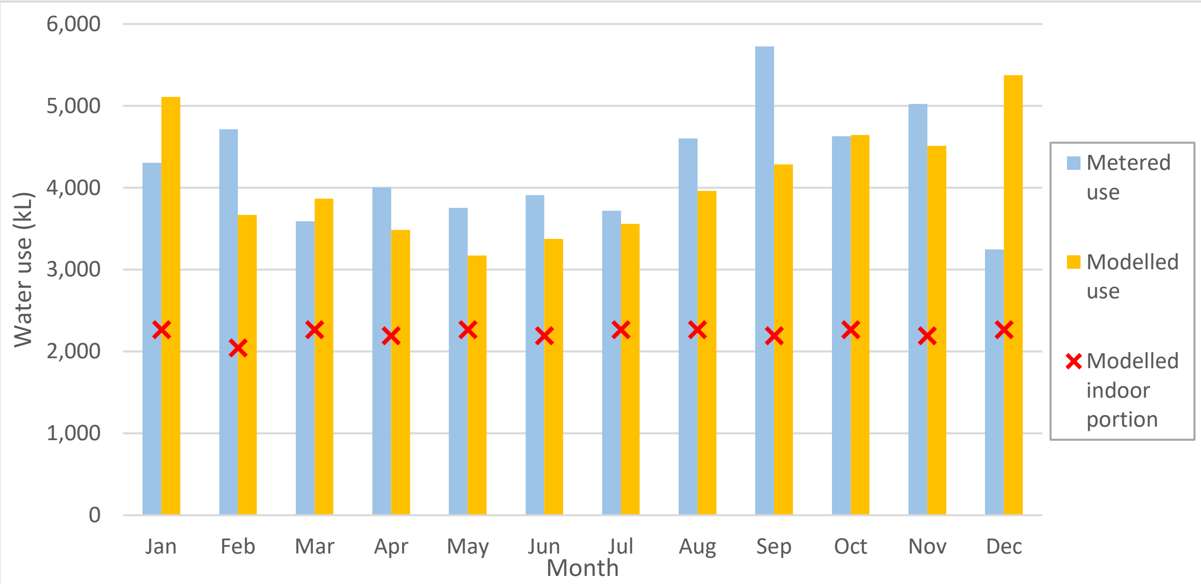

Figure 40 Metered and modelled consumption for site B

Figure 40 showed that the measured water consumption at site B fluctuated during the summer months. The metered consumption during September was unusually high and unusually low in December. A possible reason could be attributed to site B being a retirement village, and visitors could be expected from family member during the school holidays, causing high volumes in September. Low volumes in December could be from residents going away on holiday. The month with the highest measured water use was September and the lowest during December. The model underestimated the total water consumption at site B, but had an overall accuracy of 96%. Retired residents tend to stay home more often and are more involved with gardening, which could account for the increased water use. An adjustment factor could be incorporated to account for retirement homes.

The AADD for the metered consumption was 0.868 kL/household/d and the AADD for the modelled consumption was 0.461 kL/household/d for site C. The average monthly metered and modelled consumption has been illustrated in Table 49 and Figure 41.

Table 49 Metered and modelled consumption for site C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Modelled use (kL)	435	361	394	386	392	370	385	411	430	432	424	461	4880
Metered use (kL)	696	689	653	734	709	824	844	836	743	926	765	771	9188
Error (kL)	261	327	259	348	317	454	459	425	313	494	340	310	4308
Accuracy (%)	63	52	60	53	55	45	46	49	58	47	55	60	53

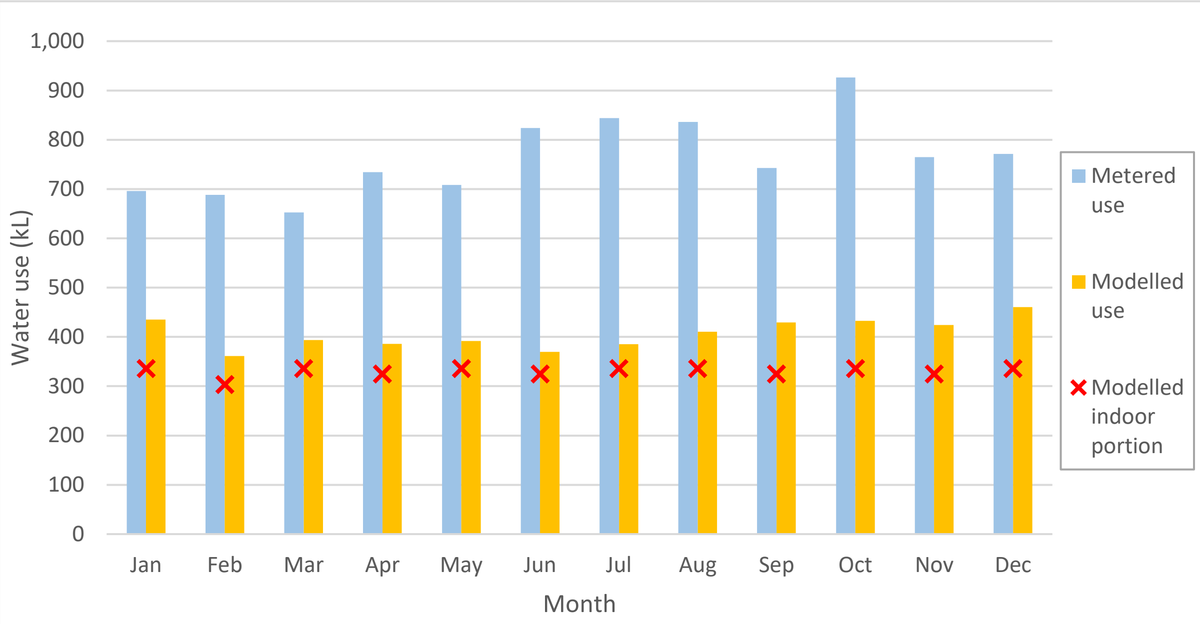

Figure 41 Metered and modelled consumption for site C

Figure 41 showed that the measured water consumption at site C increased during the winter months, this increase was evident from June 2013 to Jan 2014. This was not expected as site C was a small gated community with no communal garden areas or swimming pools and the households where closely spaced with small garden areas. A reason for this high volume could be from a leak in the system. The month with the highest measured water use was October and the lowest during March. The model underestimated the total water consumption at site C, with an accuracy of 53%.

The AADD for the metered consumption was 0.651 kL/household/d and the AADD for the modelled consumption was 0.631 kL/household/d for site D. The average monthly metered and modelled consumption has been illustrated in Table 50 and Figure 42.

Table 50 Metered and modelled consumption for site D

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Modelled use (kL)	1114	971	844	986	877	830	942	1050	1204	1220	1057	1337	12433
Metered use (kL)	1288	1087	1117	993	1078	1029	1076	1095	1032	901	1040	1089	12823
Error (kL)	174	116	273	7	201	199	134	44	172	319	18	248	390
Accuracy (%)	86	89	76	99	81	81	88	96	86	74	98	81	97

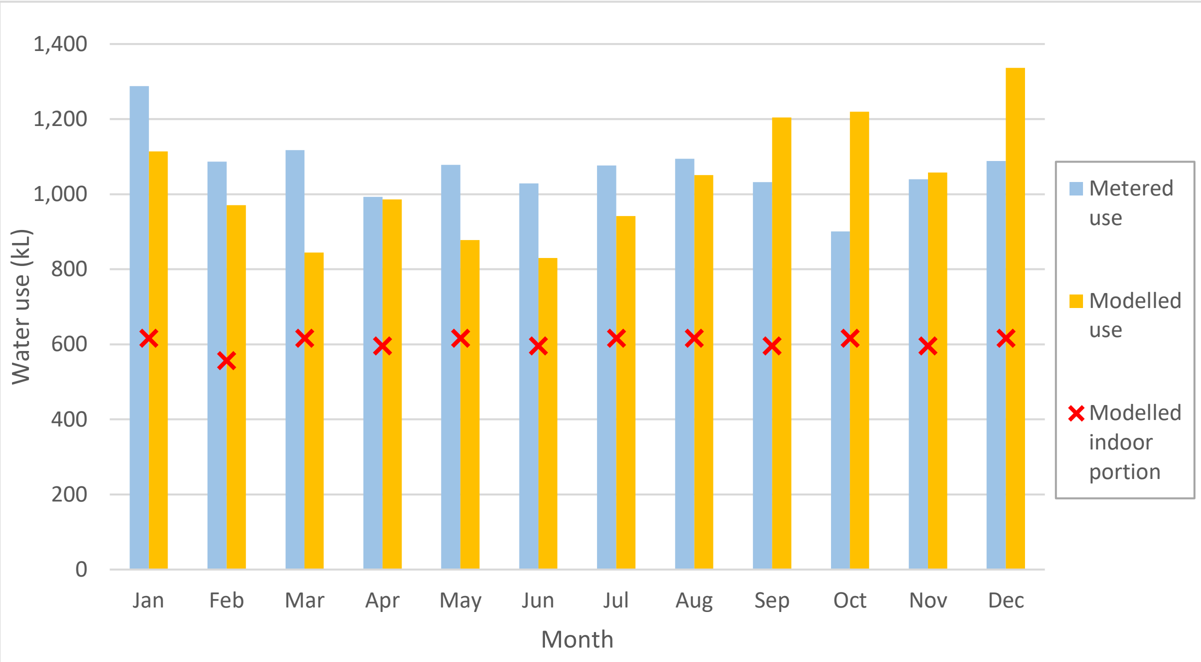

Figure 42 Metered and modelled consumption for site D

In Figure 42, there was no clear seasonal pattern in the measured water consumption at site D. The month with the highest measured water use was January and the lowest during October. The model underestimated the total water consumption at site D, but had an overall accuracy of 97%.

The AADD for the metered consumption was 0.904 kL/household/d and the AADD for the modelled consumption was 0.581 kL/household/d for site E. The average monthly metered and modelled consumption has been illustrated in Table 51 and Figure 43.

Table 51 Metered and modelled consumption at site E

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Modelled use (kL)	1087	945	810	957	844	797	910	1022	1182	1196	1031	1316	12096
Metered use (kL)	1590	1590	1436	1581	1506	1575	1746	1610	1483	1548	1614	1538	18813
Error (kL)	503	644	626	623	662	778	836	588	301	352	583	222	6716
Accuracy (%)	68	59	56	61	56	51	52	63	80	77	64	86	64

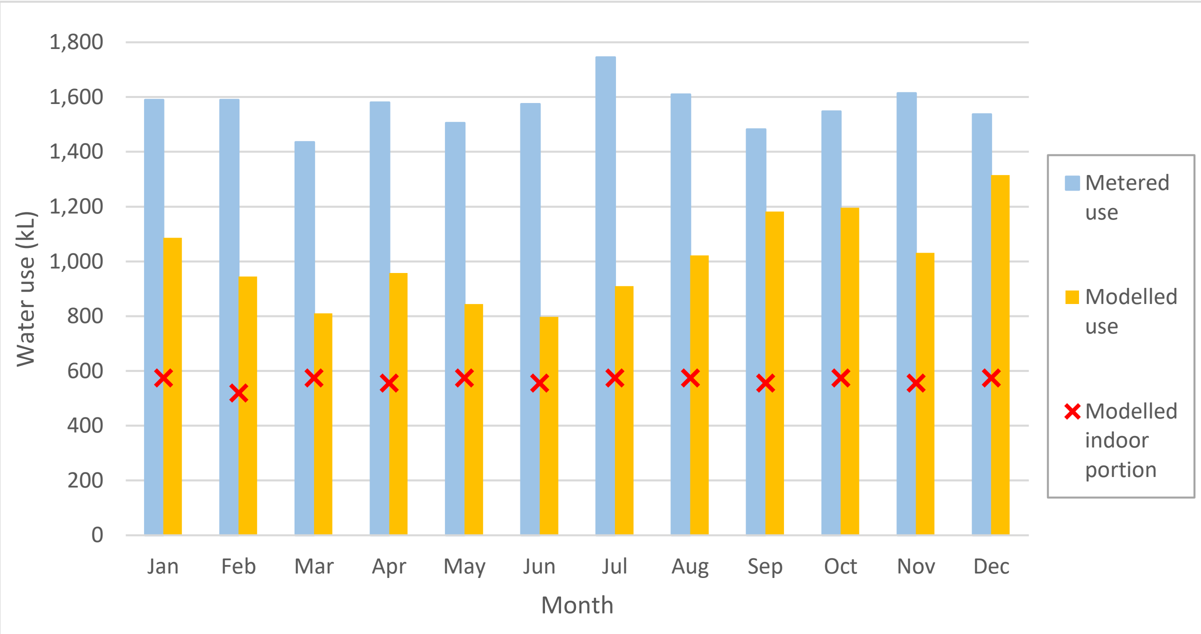

Figure 43 Metered and modelled consumption at site E

In Figure 43, there was no clear seasonal pattern in the measured water consumption at site E. The month with the highest measured water use was July and the lowest during March. The model underestimated the total water consumption at site E, but had an overall accuracy of 64%.

The AADD for the metered consumption was 0.479 kL/household/d and the AADD for the modelled consumption was 0.544 kL/household/d for site F. The average monthly metered and modelled consumption has been illustrated in Table 52 and Figure 45.

Table 52 Metered and modelled consumption for site F

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Modelled use (kL)	2526	2122	1913	1092	989	941	965	984	1008	1560	2016	2459	18576
Metered use (kL)	1591	1549	1328	1320	1247	1242	1183	1248	1215	1302	1369	1485	16077
Error (kL)	935	574	585	228	258	300	218	264	207	258	647	974	2500
Accuracy (%)	63	73	69	83	79	76	82	79	83	83	68	60	87

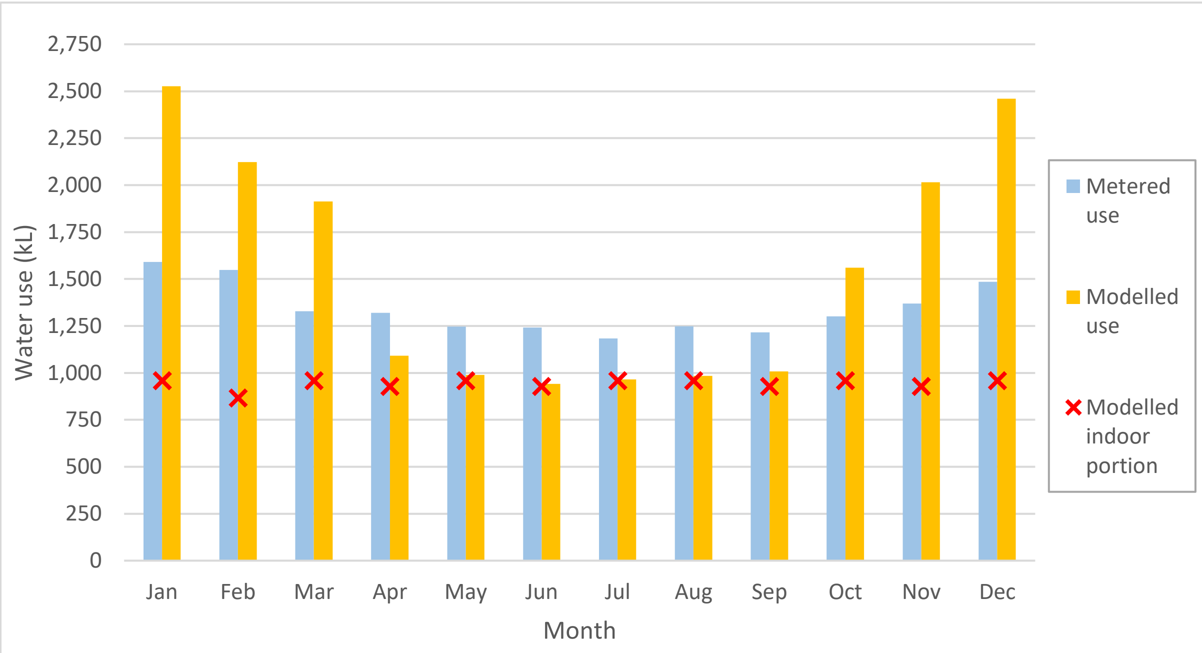

Figure 44 Metered and modelled consumption for site F

Figure 45 showed that the measured water consumption at site F fluctuated slightly during the summer months. Site F experiences winter rainfall, thus a larger fluctuation was expected during summer. The month with the highest measured water use was January and the lowest during July. The model underestimated the total water consumption at site F, but had an overall accuracy of 88%.

The AADD for the metered consumption was 0.370 kL/household/d and the AADD for the modelled consumption was 0.435 kL/household/d for site G. The average monthly metered and modelled consumption has been illustrated in Table 53 and Figure 45.

Table 53 Metered and modelled consumption for site G

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Modelled use (kL)	1187	1019	1017	762	789	760	783	788	766	908	1018	1167	10964
Metered use (kL)	905	892	788	769	735	719	693	707	718	712	789	867	9292
Error (kL)	282	127	229	7	54	41	91	81	48	196	230	300	1673
Accuracy (%)	76	88	78	99	93	95	88	90	94	78	77	74	85

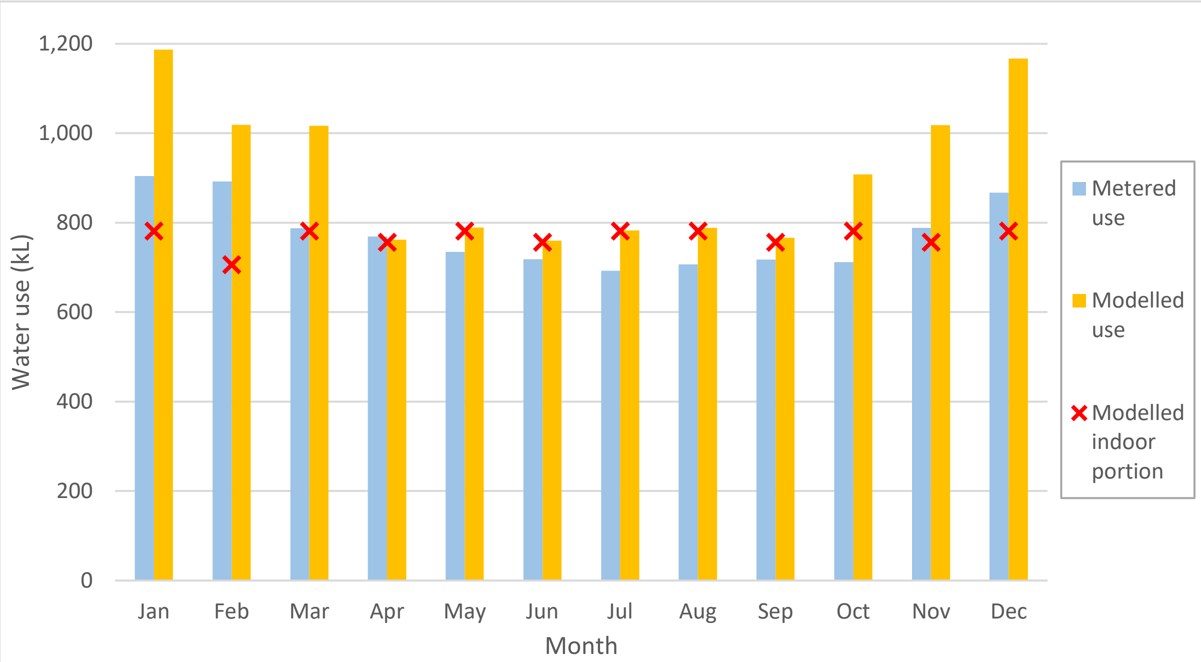

Figure 45 Metered and modelled consumption for site G

Figure 45 showed that the measured water consumption at site G fluctuated during the summer months. The month with the highest measured water use was January and the lowest during July. The model underestimated the total water consumption at site G, but had an overall accuracy of 85%.

The AADD for the metered consumption was 0.543 kL/household/d and the AADD for the modelled consumption was 1.008 kL/household/d for site H. The average monthly metered and modelled consumption has been illustrated in Table 54 and Figure 46.

Table 54 Metered and modelled consumption for site H

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Modelled use (kL)	18279	14030	10705	4417	3479	3485	3376	3647	3674	8078	13583	18141	104894
Metered use (kL)	6933	5854	5461	4568	3958	3351	3342	3346	3444	4107	4940	7144	56449
Error (kL)	11346	8176	5244	151	479	135	34	301	230	3971	8644	10996	48445
Accuracy (%)	38	42	51	97	88	96	99	92	94	51	36	39	54

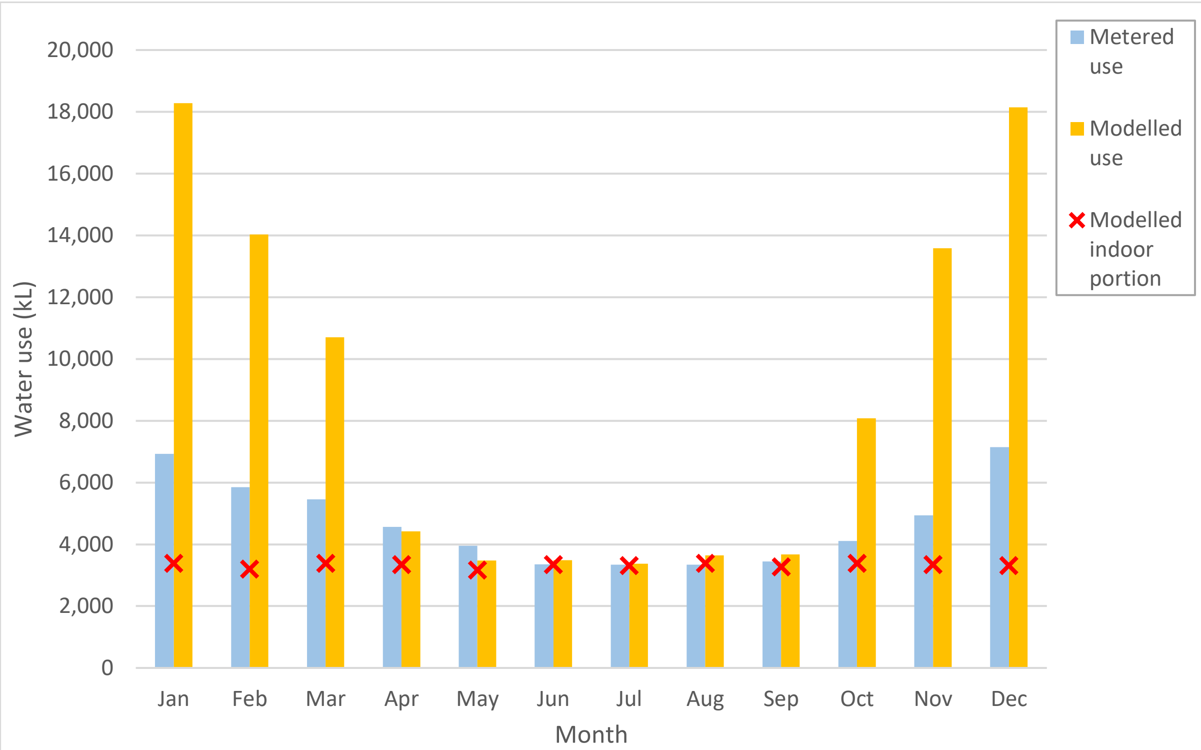

Figure 46 Metered and modelled consumption for site H

Figure 46 showed that the measured water consumption at site H fluctuated during the summer months. The month with the highest measured water use was December and the lowest during July. The model overestimated the total water consumption during the summer months at site H, with an overall accuracy of 54%. The inaccuracy of the model during the summer months could be a result of the garden areas, which were very large. A significant portion of the measured garden areas were possibly not irrigated.

The AADD for the metered consumption was 1.653 kL/household/d and the AADD for the modelled consumption was 0.979 kL/household/d for site I. The average monthly metered and modelled consumption has been illustrated in Table 55 and Figure 47.

Table 55 Metered and modelled consumption for site I

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Modelled use (kL)	9937	7686	6245	1622	1477	1423	1362	1492	1554	3974	7181	9637	53591
Metered use (kL)	12336	11437	10521	7325	5397	4477	4466	4563	4771	6545	8057	10610	90504
Error (kL)	2399	3750	4276	5703	3920	3054	3104	3071	3217	2571	875	973	36913
Accuracy (%)	81	67	59	22	27	32	30	33	33	61	89	91	59

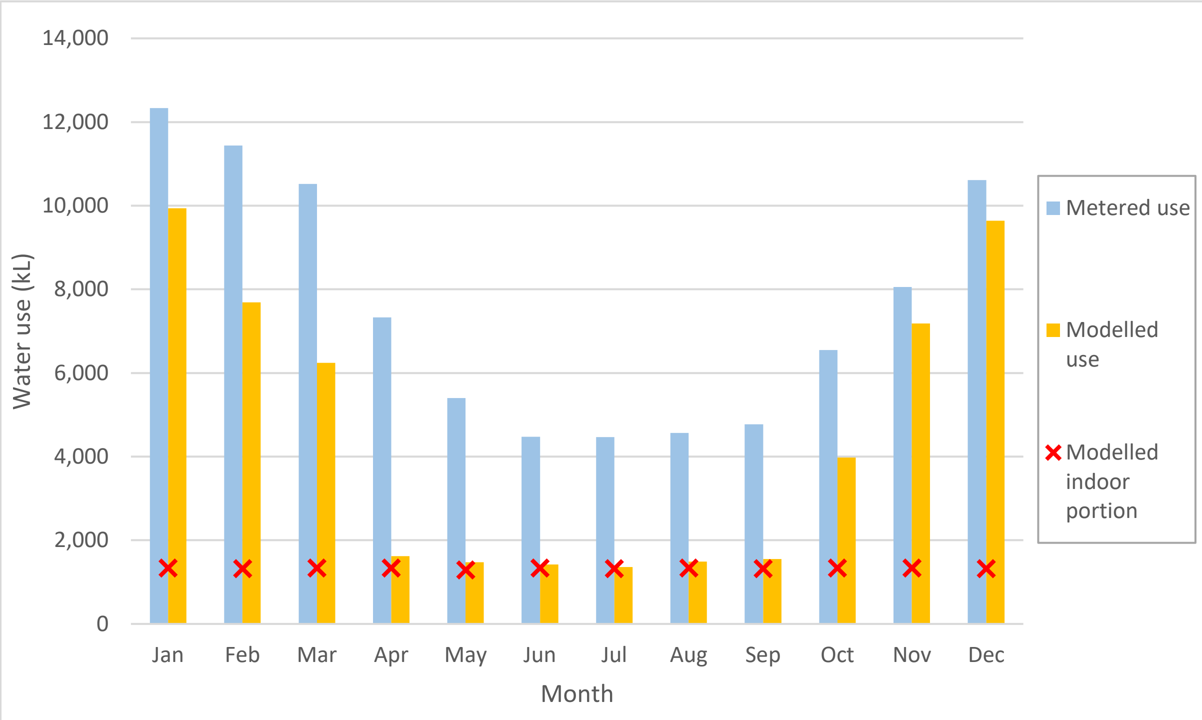

Figure 47 Metered and modelled consumption for site I

Figure 47 showed a large increase in the measured water consumption at site I during the summer months. This was expected because of the large garden areas and winter rainfall. The month with the highest measured water use was January and the lowest during July. The model underestimated the total water consumption at site I, with an overall accuracy of 59%.

The AADD for the metered consumption was 0.993 kL/household/d and the AADD for the modelled consumption was 0.819 kL/household/d for site J. The average monthly metered and modelled consumption has been illustrated in Table 56 and Figure 48.

Table 56 Metered and modelled consumption for site J

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Modelled use (kL)	1324	1295	1612	1628	1558	1189	1263	1400	1393	1144	1059	1575	16441
Metered use (kL)	1861	1640	1586	1635	1332	1377	1573	1885	1737	1640	1861	1801	19925
Error (kL)	537	345	26	6	226	187	309	484	344	496	802	226	3484
Accuracy (%)	71	79	98	100	85	86	80	74	80	70	57	87	83

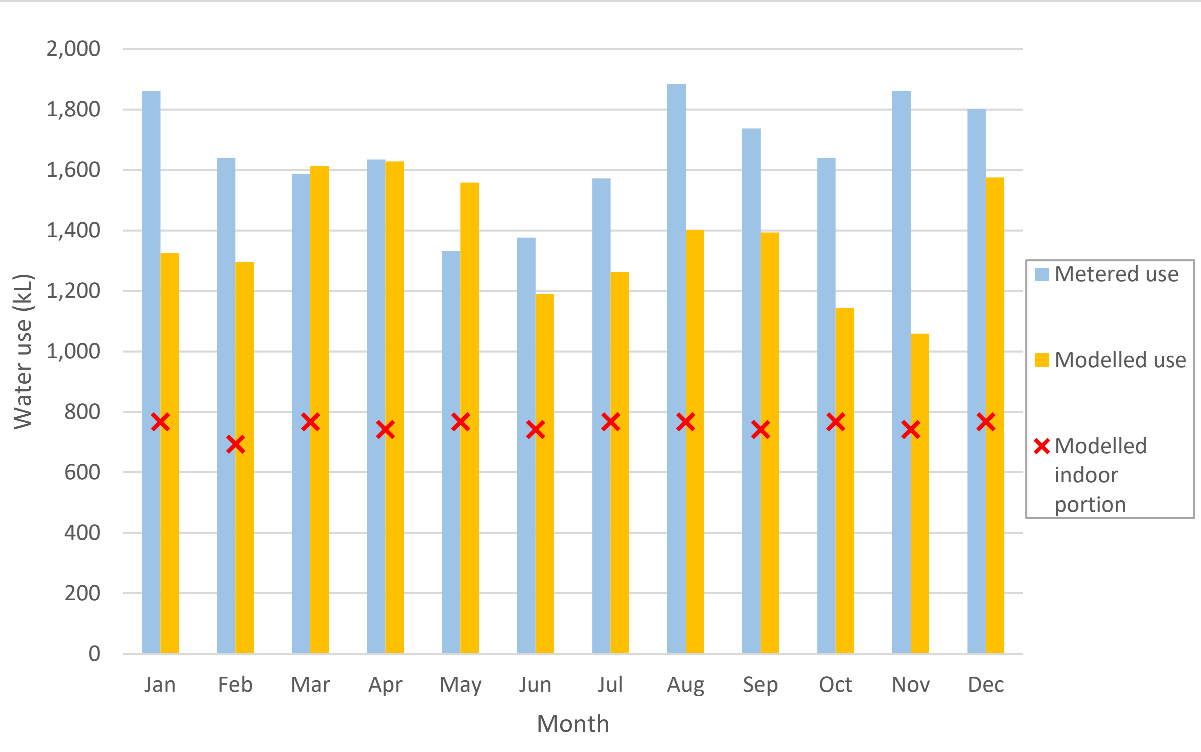

Figure 48 Metered and modelled consumption for site J

In Figure 48, there was no clear seasonal pattern in the measured water consumption at site J, although higher volumes were observed from November to January. The month with the highest measured water use was August and the lowest during May. The model underestimated the total water consumption at site J, but had an overall accuracy of 83%.

7.2. Evaluation of South African guidelines

The CSIR (2005) and Department of Human Settlement (2019) guidelines that are currently used to estimate water demand exclude important factors that influence household consumption. The three methods available from the Department of Human Settlement (2019) guidelines were used to estimate the water demand for the study sample. Each method is summarized in Table 57 and compared to the metered and modelled results.

Table 57 Results from Department of Human Settlement (2019) guidelines

Site	South African guidelines (kL/d/site)			Meter readings (kL/d/site)	Model results (kL/d/site)
	Area based method	Unit demand method	Per capita method		
A	20.30	18.00	12.35	22.56	23.88
B	182.38	140.40	74.36	140.33	134.30
C	13.23	12.33	9.75	25.17	13.37
D	31.71	24.30	16.38	35.13	34.06
E	39.20	30.00	15.99	51.54	33.14
F	54.40	43.70	26.00	44.05	50.08
G	38.22	29.33	22.36	25.46	30.04
H	597.66	183.00	12.87	154.65	287.38
I	160.16	90.00	49.14	247.96	146.82
J	55.16	33.00	23.92	54.59	45.05

The three methods presented in Table 57 produced different results for each site, with the area based method being the most accurate, compared to the meter readings. Table 57 indicates that the model produced relatively accurate estimates for Site A, B, D, F, G and J.

8. CONCLUSIONS

8.1. Summary of findings

This study presented a simple mathematic model that can be used to estimate residential water use. The concept of the model was to incorporate significant factors that influence consumption patterns and to account for the seasonal fluctuation. The effectiveness of the model was evaluated by modelling existing residential households. The metered consumption was compared to the modelled consumption. A summary of the demand model results for the study sample has been summarized in Table 58.

Table 58 Summary of metered and modelled consumption for all study sites

Site	Number of properties	AADD		
		Modelled (L/unit/d)	Metered (L/unit/d)	Accuracy (%)
A	30	796	752	95
B	234	574	600	96
C	29	461	868	53
D	54	631	651	97
E	60	581	904	64
F	92	544	479	88
G	69	435	369	85
H	285	1 008	543	54
I	150	979	1 653	59
J	55	819	993	83

Table 58 shows that the model provided reasonably accurate results for 6 out of the 10 study sites, with an accuracy of above 80% for predicting the AADD. What is of concern is that in six of the cases the model underestimates the water use, three of these by a significant amount. However, household water use is driven by individual habits and no model will be able to forecast this accurately. Given this, the development of a model that provides an average consumption related to specific regions, climatic factors and level of land use or development class will provide a useful tool in forecasting water use in reticulation systems.

8.2. Discussion

Accurate water demand forecasts are a vital element in water resource planning, infrastructure design and demand management strategies. The CSIR (2005) and Department of Human Settlement (2019) guidelines often used in South Africa exclude important factors that affect demand. End-use models are often too complicated and data intensive to use on a large scale. A robust, accurate forecasting model that incorporates influential factors and seasonal variation could be beneficial to municipalities and water planners.

The main concept was to split indoor and outdoor uses. The indoor and outdoor components are influenced by different factors and exhibit different consumption patterns on a daily, weekly, monthly and seasonal scale and thus should be modelled separately. Another important issue is that indoor uses are considered a necessity for survival, whereas outdoor activities are for leisure and recreational purposes. Quantifying the outdoor portion of household demand could improve the planning and efficiency of conservation strategies and assist during times of drought. The recent drought and increasing threat of water scarcity stress the importance of being able to quantify indoor and outdoor uses.

The model consisted of the following input parameters:

- Indoor per capita consumption rate for a single person household
- Household size
- Garden area
- Swimming pool area
- Reference evapotranspiration
- Pan evaporation
- Free lake evaporation factor
- Precipitation
- Effective precipitation
- Crop coefficient
- Irrigation efficiency.

Climatic data is generally available from most local weather stations or point specific estimations can be extracted from various software programs such as SAPWAT or CLIMWAT. The accuracy of the outdoor equation is influenced by the accuracy of the climatic data. The crop coefficient can be sourced from available literature or from software programs such as SAPWAT or CROPWAT.

8.3. Future research

The model developed as part of this research was based on a number of simplifying assumptions. The principal of segregating indoor and outdoor demand proved useful, and further study could build on this model framework. Future research could be conducted to address the following key issues that remain unanswered:

- Type of water supply source (Municipal, groundwater, greywater and rainwater)
- Indoor end-uses
- Outdoor tap
- Account for swimming pool maintenance
- Indoor and outdoor leakage
- Regional variations in garden plant types and level of indigenous plant use
- The impact of water restrictions and water demand management measures.

9. REFERENCES

Ali, M. and Mubarak, S. (2017) Effective Rainfall Calculation Methods for Field Crops: An Overview, Analysis and New Formulation, *Asian Research Journal of Agriculture*, 7(1), pp. 1–12.

Allen, R. *et al.* (1998) *Crop evapotranspiration- Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56*.

Arbon, N. *et al.* (2014) Understanding and Predicting Household Water Use for Adelaide, (14), p. 163.

Arbués, F. et al. (2003) Estimation of residential water demand: a state-of-the-art review, *Journal of Socio-Economics*, 32(1), pp. 81–102.

Arbués, F., Villanúa, I. and Barberán, R. (2010) Household size and residential water demand: An empirical approach, *Australian Journal of Agricultural and Resource Economics*, 54(1), pp. 61–80.

Archontoulis, S. and Miguez, F. (2015) Nonlinear Regression Models and Applications in Agricultural Research'

Arunkumar, M. and Nethaji Mariappan, V. (2015) Water Demand Analysis of Municipal Water Supply Using Epanet Software Software, p. 19.

Balling, R. and Cubaque, H. (2009) Estimating Future Residential Water Consumption in Phoenix, Arizona Based on Simulated Changes in Climate, *Physical Geography*, 30(4), pp. 308–323.

Balling, R. and Gober, P. (2007) Climate variability and residential water use in the city of Phoenix, Arizona, *Journal of Applied Meteorology and Climatology*, 46(7), pp. 1130–1137.

Balling, R., Gober, P. and Jones, N. (2008) Sensitivity of residential water consumption to variations in climate: An intraurban analysis of Phoenix, Arizona, *Water Resources Research*, 44(10), pp. 1–11.

Beal, C., Stewart, R. and Huang, T. (2010) South East Queensland Residential End Use Study : Baseline Results - Winter 2010 Urban Water Security Research Alliance Technical Report No . 31.

Beal, C., Makki, A. and Stewart, R. (2011) Identifying the Drivers of Water Consumption: a Summary of Results from the South East Queensland Residential End Use Study, *Science Forum and Stakeholder Engagment: Building Linkages, Collaboration and Science Quality*, pp. 126–132.

Bennett, C., Stewart, R. and Beal, C. (2012) ANN-Based Residential Water End-use Demand Forecasting Model ANN-Based Residential Water End-use Demand Forecasting Model, 40(4), pp. 1014–1023.

Billings, B. and Agthe, D. (1981) Price elasticities for water: A case of increasing block rates, *Land Economics*, 57(2), pp. 276–278.

Billings, B. and Jones, C. V. (2008) Forecasting Urban Water Demand, p. 367. Available at: http://books.google.com/books?id=Lf4OHCdV78kC.

Blakely, E. and Snyder, M. (1997) Divided We Fall: Gated and Walled Communities in the United States, *Architecture of Fear*.

Boone, C. *et al.* (2010) Landscape, vegetation characteristics, and group identity in an urban and suburban watershed: Why the 60s matter, *Urban Ecosystems*, 13(3), pp. 255–271.

Brooks, D. (2006) An operational definition of water demand management, *International Journal of Water Resources Development*, 22(4), pp. 521–528.

Buchberger, S. and Wells, G. (1996) Intensity, duration, and frequency of residential water demands, *Journal of Water Resources Planning and Management*, 122(1), pp. 11–19.

Bush, S. *et al.* (2008) Wood anatomy constrains stomatal responses to atmospheric vapor pressure deficit in irrigated, urban trees, *Oecologia*.

Cahill, R. (2011) *Household Water Use and Conservation Models Using Monte Carlo Techniques for 20 the East Bay Municipal Utility District*. University of California.

Cavanagh, S., Hanemann, W. and Stavins, R. (2002) Muffled Price Signals: Household Water Demand under Increasing-Block Prices, *SSRN Electronic Journal*.

Chang, H., Hossein Parandvash, G. and Shandas Nohad Toulan, V. (2010) Spatial Variations of Single-Family Residential Water Consumption, *Urban Geography*, 31(7), pp. 953–972.

Chen, Y. *et al.* (2015) Measuring Spatio-temporal Trends in Residential Landscape Irrigation Extent and Rate in Los Angeles, California Using SPOT-5 Satellite Imagery, *Water Resources Management*, 29(15), pp. 5749–5763.

Connellan, G. (2002) Efficient Irrigation : A Reference Manual for Turf and Landscape as part of an Irrigation Best Management Training, *Water*.

Couvelis, F. and van Zyl, J. (2015) Apparent losses due to domestic water meter under-registration in South Africa, *Water SA*, 41(5), pp. 698–704.

Crosby, C. (1996) *SAPWAT 1.0 - A computer program for estimating irrigation requirements in Southern Africa*. Pretoria.

CSIR (2005) *Guidelines for Human Settlement Planning and Design*. Pretoria: CSIR Building and Construction Technology.

Cubino, J., Subirós, J. and Lozano, C. (2014) Maintenance, modifications, and water use in private gardens of Alt Empordà, Spain, *HortTechnology*, 24(3), pp. 374–383.

Danielson, L. (1979) An analysis of residential demand for water using micro time-series data, *Water Resources Research*, 15(4), pp. 763–767.

DeOreo, W. (2011) Analysis of water use in new single family homes, p. 156.

DeOreo, W. *et al.* (2011) *California Single Family Water Use Efficiency Study*.

DeOreo, W., Heaney, J. and Mayer, P. (1996) Flow trace analysis to access water use, *Journal - American Water Works Association*.

Department of Human Settlement (2019) *The Neighbourhood Planning and Design Guide: Section J Water Supply*. South Africa.

Department of Spatial Planning and Urban Design (2016) *Discussion document: towards guidelines for the planning, design and implementation of human settlements projects in Cape Town*.

Department of Water Affairs (2004) *Water Conservation and Water Demand Management Strategy for the Water Services Sector*.

Department of Water Affairs (2013) *National Water Resource Strategy*.

Domene, E. and Saurı, D. (2006) Urbanisation and Water Consumption : Influencing Factors in the Metropolitan Region of Barcelona Urbanisation, pp. 1605–1623.

DWAF (2004) Overview of the South African Water Sector, *National water resource strategy*, 1, pp. 1–

35.

EThekwini Municipality (2013) *Housing Typologies Study*.

Farag, F. *et al.* (2011) Quantifying urban landscape water conservation potential using high resolution remote sensing and GIS, *Photogrammetric Engineering & Remote Sensing*, 77(1), pp. 1113–1122.

Fernández-Cañero, R., Ordovás, J. and Machuca, M. (2011) Domestic gardens as water-wise landscapes: A case study in southwestern Europe, *HortTechnology*, 21(5), pp. 616–623.

Fisher-Jeffes, L., Gertse, G. and Armitage, N. (2015) Mitigating the impact of swimming pools on domestic water demand, *Water SA*, 41(2), pp. 238–246.

Foster, H. and Beattie, B. (1979) Urban Residential Demand for Water in the United States, *Land Economics*, 55(1), p. 43.

Fox, C., McIntosh, B. and Jeffrey, P. (2009) Classifying households for water demand forecasting using physical property characteristics, *Land Use Policy*, 26(3), pp. 558–568.

Gaston, K. *et al.* (2005) Urban domestic gardens (IV): The extent of the resource and its associated features, *Biodiversity and Conservation*, 14(14), pp. 3327–3349.

Gato, S., Jayasuriya, N. and Roberts, P. (2007) Forecasting Residential Water Demand : Case Study, 133, pp. 309–319.

Grafton, R. *et al.* (2011) Determinants of residential water consumption: Evidence and analysis from a 10-country household survey, *Water Resources Research*, 47(8), pp. 1–14.

Grove, J. *et al.* (2006) Characterization its Implications of Households for the Vegetation and of Ecosystems, *Ecosystems*, 9(4), pp. 578–597.

Guhathakurta, S. and Gober, P. (2007) The impact of the Phoenix urban heat Island on residential water use, *Journal of the American Planning Association*, 73(3), pp. 317–329.

Gurung, T. *et al.* (2015) Smart meter enabled water end-use demand data: Platform for the enhanced infrastructure planning of contemporary urban water supply networks, *Journal of Cleaner Production*. Elsevier Ltd, 87(1), pp. 642–654.

Gutzler, D. and Nims, J. (2005) Interannual Variability of Water Demand and Summer Climate in Albuquerque, New Mexico, *Journal of Applied Meteorology*, 44(12), pp. 1777–1787.

Harlan, S. *et al.* (2007) Household water consumption in an arid city: Affluence, affordance, and attitudes, *Society and Natural Resources*, 22(8), pp. 691–709.

Hayden, L. *et al.* (2015) Residential landscape aesthetics and water conservation best management practices: Homeowner perceptions and preferences, *Landscape and Urban Planning*, pp. 1–9.

Heerden, P. *et al.* (2009) *Integrating and Updating of Sapwat and Planwat To Create a Powerful and User-Friendly Irrigation Planning Tool, WRC REPORT NO. TT 391/08, Water Research Commission, Pretoria*.

Van Heerden, P. and Walker, S. (2016) Upgrading of SAPWAT3 as a management tool to estimate the irrigation water use of crops revised edition SAPWAT4, Report to the Water Research Commission.

Heinonen, J. and Junnila, S. (2014) Residential energy consumption patterns and the overall housing energy requirements of urban and rural households in Finland, *Energy and Buildings*, 76, pp. 295–303.

Heinrich, M. (2007) Water End-Use and Efficiency Project (Weep) – a Case Study, *Transforming Our*

Built Environment, 136, p. 8.

Hof, A. and Schmitt, T. (2011) Urban and tourist land use patterns and water consumption: Evidence from Mallorca, Balearic Islands, *Land Use Policy*, 28(4), pp. 792–804.

Hof, A. and Wolf, N. (2014) Estimating potential outdoor water consumption in private urban landscapes by coupling high-resolution image analysis, irrigation water needs and evaporation estimation in Spain, *Landscape and Urban Planning*, 123, pp. 61–72.

House-Peters, L. and Chang, H. (2011) Urban water demand modeling: Review of concepts, methods, and organizing principles, *Water Resources Research*, 47(5).

House-Peters, L., Pratt, B. and Chang, H. (2010) Effects of urban spatial structure, sociodemographics, and climate on residential water consumption in Hillsboro, Oregon, *Journal of the American Water Resources Association*, 46(3), pp. 461–472.

Howe, C. and Linaweaver, F. (1967) The impact of price on residential water demand and its relation to system design and price structure, *Water Resources Research*, 3(1), pp. 13–32.

Inman, D. and Jeffrey, P. (2006) A review of residential water conservation tool performance and influences on implementation effectiveness, *Urban Water Journal*, pp. 127–143.

Jacobs, H. *et al.* (2004) Estimating residential water demand in Southern Africa, *Journal of the South African Institution of Civil Engineering*, 46(4), pp. 2–13.

Jacobs, H. *et al.* (2007) Analysis of water savings: A case study during the 2004/05 water restrictions in Cape Town, *Journal of the South African Institution of Civil Engineering*, 49(3), pp. 16–26.

Jacobs, H. (2008) Residential water information management, 10(3).

Jacobs, H. and Haarhoff, J. (2004) Application of a Residential End-Use Model for Estimating cold water and hot water demand, waste water flow and salinity, *Water SA*, 30(3), pp. 305–316.

Jacobs, H. and Haarhoff, J. (2004) Structure and data requirements of an end-use model for residential water demand and return flow, *Water SA*, 30(3), pp. 293–304.

Jacobs, H., Scheepers, H. and Sinske, S. (2013) Effect of land area on average annual suburban water demand, *Water SA*, 39(5), pp. 687–693.

Jansen, A. and Schulz, C. (2006) Water demand and the urban poor: A study of the factors influencing water consumption among households in Cape Town, South Africa, *South African Journal of Economics*, 74(3), pp. 593–609.

Du Plessis, J. et al. (2017) ‘Estimating outdoor water use by analysing sewer return flow in gated communities.

Kenney, D. *et al.* (2008) Residential water demand management: Lessons from Aurora, Colorado, *Journal of the American Water Resources Association*, 44(1), pp. 192–207.

Kjelgren, R. *et al.* (2016) Simplified landscape irrigation demand estimation: Slide rules, *Applied Engineering in Agriculture*, 32(4), pp. 363–378.

Kjelgren, R., Rupp, L. and Kilgren, D. (2000) Water conservation in urban landscapes, *HortScience*, 35(6), pp. 1037–1040.

Knox, A. (2013) *Water Balance for Residential Security Estates*.

Landon, A., Kyle, G. and Kaiser, R. (2016) Predicting compliance with an information-based residential outdoor water conservation program, *Journal of Hydrology*, 536, pp. 26–36.

Linaweaver, F., Geyer, J. and Wolff, J. (1967) Summary Report on the Residential Water Use Research Project, *Journal - American Water Works Association*, 59(3), pp. 267–282.

Loh, M. and Coghlan, P. (2003) Domestic Water Use Study. In Perth, Western Australia 1998-2001', *Hydro 2000: Interactive Hydrology*, p. 36.

Lowry, J., Ramsey, R. and Kjelgren, R. (2011) Predicting urban forest growth and its impact on residential landscape water demand in a semiarid urban environment, *Urban Forestry and Urban Greening*, 10(3), pp. 193–204.

Lubbe, C., Siebert, S. and Cilliers, S. (2011) Floristic analysis of domestic gardens in the Tlokwe City Municipality, South Africa, *Bothalia*, 41(2), pp. 351–361.

Lugoma, M., van Zyl, J. and Ilemobade, A. (2012) The extent of on-site leakage in selected suburbs of Johannesburg, *Water SA*.

Makki, A. *et al.* (2015) Novel bottom-up urban water demand forecasting model: Revealing the determinants, drivers and predictors of residential indoor end-use consumption, *Resources, Conservation and Recycling*, 95, pp. 15–37.

Mayer, P. *et al.* (1999) *Residential End Uses of Water*.

Memon, F. and Butler, D. (2006) Water consumption trends and demand forecasting techniques, *Water Demand Management*, pp. 1–26.

Mitchell, V., Mein, R. and McMahon, T. (2001) Modelling the urban water cycle, *Environmental Modelling & Software*, 16(7), pp. 615–629.

Monteith, P. (2003) *Crop water relationships and climate*.

Ncube, M. and Taigbenu, A. (2016) Consumption Characterisation and On-Site Leakage in Johannesburg, South Africa, in *Proceeding of the IWA Water Loss Conference 2016*.

Ojeda de la Cruz, A. *et al.* (2017) Determinants of domestic water consumption in Hermosillo, Sonora, Mexico, *Journal of Cleaner Production*, 142, pp. 1901–1910.

Ouyang, Y. *et al.* (2014) A multi-scale analysis of single-family residential water use in the phoenix metropolitan area, *Journal of the American Water Resources Association*, 50(2), pp. 448–467.

Pittenger, D. (2014) Methodology for Estimating Landscape Irrigation Demand Review and Recommendations.

Du Plessis, J. (2014) Estimating domestic outdoor water demand for residential estates, p. 87.

Du Plessis, J., Knox, A. and Jacobs, H. (2018) Garden Footprint Area and Water Use of Gated Communities in South Africa.

Rathnayaka, K. *et al.* (2017) Prediction of urban residential end-use water demands by integrating known and unknown water demand drivers at multiple scales I: Model development, *Resources, Conservation and Recycling*, 117, pp. 85–92.

Render, B. (2012) *Quantitative Analysis For Management Eleventh Edition*.

Rhoades, S. and Walski, T. (1991) Using regression analysis to project pumpage, *Journal of American Water Works Association*, 83(12), pp. 45–50.

Roberts, P. (2005) 2004 Residential End Use Measurement Study, *Yarra Valley Water*, pp. 1–77.

Runfola, D. *et al.* (2013) A growing concern? Examining the influence of lawn size on residential water use in suburban Boston, MA, USA, *Landscape and Urban Planning*, 119, pp. 113–123.

Sadalla, E. *et al.* (2012) Priorities in Residential Water Use: A Trade-Off Analysis, *Environment and Behavior*, 46(3), pp. 303–328.

Saghi, H. and Aval, A. (2015) Effective Factors in Causing Leakage in Water Supply Systems and Urban Water Distribution Networks, *American Journal of Civil Engineering*, 3(2), p. 60.

Sant'Ana, D. (2011) A socio-technical study of water consumption and water conservation in Brazilian dwellings, p. 411.

Schleich, J. and Hillenbrand, T. (2009) Determinants of residential water demand in Germany, *Ecological Economics*, 68(6), pp. 1756–1769.

Siebrits, R. (2012) Swimming pools and intra-city climates: Influences on residential water consumption in Cape Town, *Water SA*, 38(1), pp. 133–144.

Smith, C., Clayden, A. and Dunnett, N. (2009) An exploration of the effect of housing unit density on aspects of residential landscape sustainability in England, *Journal of Urban Design*, 14(2), pp. 163–187.

Smith, R. M. *et al.* (2005) Urban domestic gardens (V): Relationships between landcover composition, housing and landscape, *Landscape Ecology*, 20(2), pp. 235–253.

Stevens, J. and Buys, F. (2012) *Training material for extension advisors in irrigation water management*.

Syme, G. *et al.* (2004) Predicting and understanding home garden water use, *Landscape and Urban Planning*, 68(1), pp. 121–128.

Troy, A. *et al.* (2007) Predicting opportunities for greening and patterns of vegetation on private urban lands, *Environmental Management*, 40(3), pp. 394–412.

Troy, P., Holloway, D. and Randolph, B. (2005) Water use and the built environment: patterns of water consumption in Sydney, *Sydney*, pp. 1–86.

Walker, A. (2009) The Independent Review of Charging for Household Water and Sewerage Services, *UK Government Reports*, pp. 1–204.

Water Research Commission (2012) Full-scale Trail to Investigate the Correlation Between Modelled and Measured Residential Water Demand and Wastewater Flow Based onEnd-use Modelling.

Wentz, E. *et al.* (2016) Impact of Homeowner Association (HOA) landscaping guidelines on residential water use, *Water Resources Research*, 52(5), pp. 3373–3386.

Wentz, E. and Gober, P. (2007) Determinants of small-area water consumption for the City of Phoenix, Arizona, *Water Resources Management*, 21(11), pp. 1849–1863.

Whitford, V., Ennos, A. and Handley, J. (2001) "City form and natural process" - Indicators for the ecological performance of urban areas and their application to Merseyside, UK, *Landscape and Urban Planning*, 57(2), pp. 91–103.

Willis, R *et al.* (2009) Gold Coast Domestic Water End Use Study, *Water*.

Wilson, L. (1989) Addition of a climate variable to the Howe and Linaweaver Western Sprinkling Equation, *Water Resources Research*, 25(6), pp. 1067–1069.

World Water Assessment Programme (2012) *World Water Development Report Volume 4: Managing Water under Uncertainty and Risk*, *Water demand: What drives consumption?*

Van Zyl, H., Ilemobade, A. and Van Zyl, J. (2008) An improved area-based guideline for domestic water demand estimation in South Africa, *Water SA*, 34(3), pp. 381–391.

van Zyl, H. *et al.* (2007) *Water Consumption Levels in Selected African Cities*, *Water Research Commission*.