Modelling outdoor water use of homes in gated communities

by Jacobus Lodewikus du Plessis

Dissertation presented for the degree of Doctor of Philosophy in Civil Engineering in the Faculty of Engineering at Stellenbosch University

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Abstract

Gated communities are commonly referred to as residential estates, or common interest housing developments. The homes in a particular gated community are often closed off to the general public by means of a boundary wall and security-controlled entrances. Landscaping and related outdoor water use is prescribed by governing documents of the gated communities. Outdoor water use is a major contributor to the total water use, as well as seasonal fluctuation of water use in gated communities. The accurate estimation of outdoor water use is therefore essential from a planning perspective, especially with water restrictions typically targeting outdoor water use.

Earlier research notes living inside gated communities is different from living outside gated communities. It can thus be expected that water use within homes in gated communities would be different. Benefits and constraints in terms of cost, security, lifestyle, sense of place and exclusivity of gated communities are described in literature. Specific research has been published on the estimation of residential water use based on population, spatial scales, income levels and housing typology, while some studies focussed on end-use modelling. However, none of the earlier studies have addressed water use in gated communities and homes in gated communities per se.

As part of this study monthly water use in gated communities was investigated. This study focussed on gated communities, because the unique development type has become increasingly popular and limited guidelines are available for estimating water use. Monthly water use of 2888 gated communities from three South African metropolitans was analysed in this study. The mean average water use per GC home was 0.64 kL/d, but varied between 0.49 kL/d and 0.66 kL/d in the three study samples. Some peculiarities of water use in gated communities are highlighted.

Various outdoor water use components were mathematically defined and combined in this study to model outdoor water use. The model parameters were formulated and derived to describe conditions such as types of vegetation, irrigated area and size of pool. The parameters were stochastically populated to achieve parameter distributions that were used to simulate outdoor water use using the Monte Carlo method.

Special attention was given to derive the parameter input for the garden footprint area by spatially analysing footprint areas of 1807 homes in gated communities. The results were compared with a knowledge review of architectural guidelines of existing gated communities.

It is commonly accepted that total household water use is the summation of indoor water use, outdoor water use and real losses. If the total water use is known and the indoor water use and losses can be derived, outdoor water use can be estimated. One method used in this study to disaggregate water use components was to investigate wastewater flow from a gated community in order to estimate outdoor water use. The results showed outdoor water use contributed ~56% of total annual water use for the particular gated community under investigation.

A second proxy method was derived to disaggregate indoor and outdoor components of the water use. The proxy method expresses the generally non-seasonal indoor water use as a function of lowest water use months. Based on the proxy approach analysis, indoor use was derived to be ~90% of the lowest month's water use. Indoor water use estimated in this manner was then subtracted from the total monthly water use in order to obtain monthly outdoor water use data.

The derived outdoor water use model was used to stochastically simulate outdoor water use. The simulated results were compared with actual data from three gated communities in the study group using the proxy approach of indoor use linked to the lowest month water use. The accuracy of the outdoor water use model ranged between 8% and 18%. From sensitivity analysis, it was derived that irrigation efficiency is a major influence in the accuracy of outdoor water use modelling and was also ascribed to the reason for over irrigation that occurred during transition seasons (autumn and spring). Applications of the outdoor water use model could include estimating the effect of outdoor water use restrictions, and designing the capacity of separated water distribution systems that would supply water of lower quality for outdoor water uses, specifically.

This research contributed to the understanding of water use in gated communities, particularly by presenting novel methods for estimating outdoor use in gated community homes.

Acknowledgements

I am grateful to God.

My wife, Sandri, and three beautiful daughters Lisa, Mia and Jani, deserve most of the credit for my work. They have enabled and inspired me to complete my studies through tough circumstances.

I would like to thank Prof. H. E. Jacobs for providing valuable direction and inspiration that led to the successful completion of this work.

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List of Abbreviations

AADD	Average annual daily demand
CSIR	Council for Scientific and Industrial Research
CF	Comparison factor
GC	Gated community
P	Pressure in a water network
DEADP	Department of Environmental Affairs and Department of Planning
DWA	Department of Water Affairs
HOA	Home owner’s association
HI	Household income or property value as proxy for household income
LS	Standard of living
MEV	Maximum extreme value
TPA	Transvaal provincial administration
SIMDEUM	Simulation of Water Demand and End Use Model
REUWS	Residential End Use of Water Study
USA	United States of America
STD Dev	Standard deviation

List of Symbols

A_i = The area of a property that is under irrigation.

A_p = The surface area of a pool or water feature.

D_d = The water level difference after performing a maintenance cycle

E_{to} = Evapotranspiration

E_w = Evaporation rate of water in a specific location

E_{pw} = Events per week

F_{ep} = Effective precipitation factor

F_{po} = Pool ownership factor

I_e = Irrigation efficiency

K_{bc} = Crop coefficient

P_r = Measured precipitation

Q_{actual} = Actual irrigation consumption

O_m = The occurrence of pool maintenance per calendar month.

Q_{crop} = Theoretical crop requirement

$Q_{outdoor}$ = Outdoor water demand

Q_z = Flow rate per irrigation zone

T = Time per irrigation event

x = Value on the x-axis

α = Shape parameter

β = Scale parameter

γ = Location parameter

Γ = Gamma function

σ = Standard deviation of a total data record

μ = Standard deviation of a sample of a data record

Chapter 1. Introduction

Background

Fresh water is becoming a scarce commodity, not only in South Africa, but in the entire world (Heinrich, 2007). The Department of Water Affairs of South Africa (DWA, 2008) reported that the need for proper planning and management of this scarce and vulnerable resource is essential to both economic and social facets of human life. South Africa, in particular, has ample motivation to invest in thorough planning and management of its water resources. In comparison with the global average rainfall of 860 mm per annum (Rosewarne, 2005), South Africa, with an average annual rainfall of 497 mm is considered to be a semi-arid country (Walmsley et al., 1999).

Vast areas of South Africa are generally hot and dry with high evaporation rates. Unless adapted for these conditions, vegetation suffers under these low rainfall and high evaporation rates (Dye et al., 2008). In order to overcome these challenges, dams and irrigation systems have been developed to improve the reliability of water supply to urban consumers and provide crops and residential garden flora with the water required to survive.

Dye et al. (2008) reported that, in South Africa, millions of hectares of original vegetation have been replaced in recent years. In many urban suburbs, indigenous grasslands and Fynbos with an mean annual evapotranspiration of approximately 700-800 mm have been replaced by exotic garden plants and trees, mainly tree species with an mean annual evapotranspiration of more than 1100 mm. The change in vegetation has impacted the urban water requirement per unit area.

Population growth and rising living standards have similarly led to increased water demand. Gated communities (GCs) with relatively expensive properties are reported as large consumers of water (DeOreo et al., 2011). Spocter (2011) reported that GCs have become popular in South Africa for the following reasons (amongst others):

- A sense of security experienced before first democratic elections in South Africa;
- Desire for greater protection against crime;
- Municipalities view GCs as a benefit to the community.

End-use models often separate residential water demand into indoor and outdoor water demand (Scheepers, 2012). Indoor water demand has been widely modelled by leading researchers in the field (Blokker et al., 2010). Outdoor water consumption on the other hand, is often excluded because of its climatic and geographic characteristics (Scheepers, 2012).

Outdoor water demand is, however, estimated to contribute approximately 40%-60% to the AADD of homes in GCs;

It therefore becomes important to be able to estimate the indoor as well the outdoor water demand of residential properties, and more specifically GC homes. This study will focus on the estimation of the outdoor water demand to supplement other studies based on the indoor water demand.

Problem statement

This research intends to stochastically derive outdoor water use of GC homes by means of a mathematical model, by populating parameters that describe the expected behavioural, geographical, climatological and technical aspects relating to the outdoor water use of a property.

Research objectives

The main goal of this study was to develop a model for estimating outdoor water use of residential plots in GCs, also allowing for disaggregation of the most notable end-uses. In order to achieve this goal, the following key objectives were required:

- Conduct a thorough literature review of information related to this study;
- Analyse and report on water use within gated communities;
- Develop an empirical estimation model to estimate outdoor use for houses in GCs;
- Stochastically derive parameters from behavioural, geographical and technical data to populate the estimation model;
- Disaggregate the seasonal characteristics of the water consumption data of residential properties to develop proxy use estimation approaches that could be compared to the stochastic model.

Terminology

Evapotranspiration

Evapotranspiration is a combination of two processes; evaporation and transpiration. During the process of evaporation water is lost to the atmosphere from the soil surface, and water is lost from the crop during transpiration. The factors affecting evaporation and transpiration are weather parameters, crop characteristics, management and environmental aspects (Dye et al. 2008).

Garden footprint area

The area of a “residential plot” that is covered by vegetation, typically in the form of a landscaped garden. In this dissertation, the words garden footprint area and irrigated area were used interchangeably.

Gated communities (GCs)

GCs are property developments with homes of similar architecture, usually bounded by a boundary wall or fence with secure entrances. Governing bodies manage GCs by the development and enforcement of regulations that are supplementary to the laws and bylaws prescribed by authorities. In this dissertation, the words GC and residential estates were used interchangeably.

Gated community home

The term “GC home” is used in the text to describe a single residential property inside a GC. A GC home comprise a bounded portion of land, and would typically include a single dwelling with a garden, paved areas and possibly a pool. The following words are used in the literature to describe a property: single dwelling, dwelling unit, lot, site, households and homes. A GC home is located on a demarcated plot of land. The word “plot” is used in this dissertation to describe the entire property parcel.

Water use

In this manuscript “water use” refers to the estimated or recorded volume of water necessary to supply customers within a specified period of time. This is usually estimated by means of a prescribed guideline or mathematical model. The water use of residential properties is used to predetermine the magnitude of required infrastructure for the development of these properties. In this dissertation, the words ‘water use’ and ‘demand’ were used interchangeably.

Water end-use

A "water end-use" describes a specific type of device, element or fixture where water is released from, such as taps, washing machines, irrigation systems, et cetera.

Brief chapter overview

According to the Stellenbosch University rules and policies (Section 2.1.2 of the Generic guidelines for thesis and dissertation layout, updated 20 June 2016), doctoral dissertations may consist of written chapters, written articles, articles meant for publication in academic journals or a combination of these, provided that the articles included originated after the student registered for the doctoral study. This dissertation was structured as a combination of written chapters and published articles. The format was approved as part of the initial research proposal submitted. The University requires candidates to re-format published work in a consistent manner without change to the article content, with the exception that article pages should be renumbered. The figures and tables are formatted according to the requirements of the journals in which they were published.

This dissertation comprises ten chapters, of which six are in article format. Two articles have been published in ISI-listed journals, and two articles published as international conference proceedings. A further two articles have been submitted for review and possible publication in the Water SA Journal and the Journal of Water Supply: Research and Technology – Aqua. The contribution by each author was mentioned in each article and is presented in Appendix A.

Chapter 2 presents results of a comprehensive water use analysis for GCs in South Africa. The characteristics of GCs were reviewed and residential water use was described. Water consumption data of GCs located in three regions of South Africa were analysed and compared to available residential water use guidelines. This particular contribution by Du Plessis and Jacobs (2018) was novel in the sense that water use of GCs had not been analysed and reported on before.

In the absence of measured outdoor water use, methods had to be derived by which outdoor use could be estimated. Chapter 3 contains a published journal paper that explained a novel method for disaggregating household water use under certain constraints. A crude approach to disaggregate different water use components, based on water flow analysis, was presented by Du Plessis et al. (2018).

In addition to the segregation of indoor use and outdoor use mentioned above, a model for estimating outdoor water use of GC homes was required. The newly developed outdoor water use model and the related model parameters were described (Du Plessis and Jacobs, 2014;

Du Plessis and Jacobs, 2015). The two papers are presented as Chapter 4 and Chapter 5 in this dissertation. Garden footprint area was identified as one of the most notable, yet least described, model input parameters. Chapter 6 presents an in-depth review of garden footprint area of GCs and how the garden footprint area relates to water use. Chapter 7 presents the model analysis results and verifies the results in terms of available outdoor use data. During the stochastic modelling procedure, sensitivity analyses was used to identify the model parameters that require further research.

The dissertation concludes with a comprehensive discussion (Chapter 8) and a conclusion (Chapter 9). In this manuscript, references relating to all published work were included at the end of each chapter. All other references for unpublished chapters were grouped together at the end of the dissertation.

Data sampling resolution

Water use data of GCs is generally available on multiple resolution layers. For example, total water use of an entire GC, recorded at a single or series of bulk water meters are fairly common. The bulk water meter resolution is relevant to Chapter 2 where spatial resolution was limited to GCs and not individual homes, although the number of homes per GC was obtained. Results in Chapter 2 were presented as averaged per home for each GC. It was considered essential to increase the data resolution by focussing on segregating outdoor water use from total household water use, instead of extending the geographical coverage of the data sample in terms of adding more GCs.

For this research, it would have been ideal to log leak flow, indoor and outdoor water use data. However, outdoor water use could not be measured as part of this study, neither was data available from other sources in the study area. Data from earlier published work elsewhere was therefore used to verify the outdoor water use model developed in this dissertation.

Data for this research was obtained from various sources and is discussed in detail in the respective chapters. The characteristics of all the datasets and samples used in this study are summarised in Table 1.1. Notable variation in household number, property area and climate was purposefully introduced to meet the objectives of this study.

Table 1.1: Data summary matrix

Nature of data	Total GC water use	Individual GC Home Water use	Total GC Water use	Wastewater pumping records	Aerial photography	Individual GC Home Water use	Pool behaviour Survey	Precipitation, Evaporation & Evapotranspi-ration	Data lifted from Architectural guidelines	Total GC water use	Total GC water use	Outdoor water use of 4 cities in USA
Record period	Oct 2012 to Sep 2014	Jan 2016 to Dec 2016	Jan 2013 to Dec 2015	Jan 2013 to Dec 2015	2009 and 2012	2010 and 2012	2012	Averages of data sets Varies between 1961 and 2012	2018	Oct 2012 to Sep 2014	Jan 2010 to Dec 2012	1999 and 1996
Region	Metropolitain cities in South Africa	Overstrand South Africa			Cape Winelands, South Africa	South Africa	South Africa	Western Cape South Africa and USA	Gauteng, KwaZulu Natal, Western Cape, North West, South Africa	Metropolitain cities in South Africa	Western Cape South Africa and USA	Western Cape South Africa and USA
Number of GCs in study sample	2888	1			1	3	Not Applicable	Not Applicable	21	16	5	Not Applicable
Average area of GCs (m^2)	10 442	277 619			122 700	130 000	Not Applicable	Not Applicable	462 716	49 343	128 175	Not Applicable
Number of occupied homes in study sample	95 584	347			150	563	105	Not Applicable	12410	1813	1060	398
Average plot size (m^2) of GC homes	353	800			818	727	Not Applicable	Not Applicable	783	436	502	~494 (Irrigable area)

Ethical restrictions often limit the publication of water meter data in most cases. However, the data used in this study was geographically bound to specific regions where permission was obtained. In Chapter 2, three large scale datasets of total GC information were extracted from treasury records. GC home water use data was obtained from specific GC governing bodies and other sources for more detailed analysis as discussed in the following chapters of this dissertation.

Additional sources of data included for example Scada data of wastewater pumping records Garden footprint area, aerial photographs, architectural guidelines sourced online and water use data of corresponding GCs. Precipitation, evaporation and evapotranspiration data was also obtained on a regional resolution and was sourced from SAPWAT and CLIMWAT software.

Research opportunities

During the search for available data and analysis of initial data, it was impossible to find records on outdoor water use, hence a model was necessary to estimate outdoor use of GC homes under limited data conditions. In this study, GC home outdoor water use model and relevant parameters were developed. It was further evident during the search that even if models for outdoor water use were available, outdoor water use records were not available.

The limitations in terms of available outdoor water use data introduced a need for a method to crudely segregate indoor and outdoor water use. The crude method would enable the verification of a model for GC outdoor water use. One recognised method to disaggregate indoor and outdoor water use is to derive indoor water use as a function of outdoor water use, alternatively wastewater flow of a GC as a proxy for indoor water was used to disaggregate indoor and outdoor water use. Both of these methods were investigated in this manuscript.

Chapter 2.

Analysis of water use by gated communities in South Africa

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ABSTRACT

Gated communities (hereafter GCs) are popular in many countries, including South Africa, because added security and lifestyle improvements are offered relative to homes built on freestanding properties. One of the key factors for the popularity of GC's is the availability of amenities to support the demands of the residents, such as gymnasia, walkways, golf courses, play parks and polo fields. Further benefits include the improved management of infrastructure such as telecommunication services, roads, water, sewer, electrical and stormwater assets. GCs are often governed by trustees or homeowners associations, responsible for the operation and the maintenance functions of the infrastructure, as well as implementing and adhering to legislation that pertains to the GC. As part of this study the monthly water use records of 2888 GCs in three different South African cities were analysed. Water use was evaluated for each GC as a whole, and also per household in each case. The average number of homes per GC was 33 households/GC, with the smallest GC in the study sample containing 3 houses and the largest 524 houses. One of the study sites was in the winter rainfall region, while two sites were in the summer rainfall region. The average annual water use of individual households in each GC was plotted against current guidelines and were found to be relatively low. The average annual daily demands of all properties in the winter rainfall region was 0.63 kL/d, compared to 0.66 kL/d and 0.49 kL/d for the two study sites in the summer rainfall region. The results highlighted peculiarities in the water use of GCs that have not been reported on before, in particular the relatively low water use and the differences between GC homes water use in the various rainfall regions.

Keywords: Water use, outdoor, indoor, residential estates, gated communities

BACKGROUND

Suburban areas with predominantly single family households typically comprise communal areas and private plots. Municipally controlled communal areas would include, for example, the roads, public open space (POS) and parks. Plots would be privately owned, with a house, and also possibly a garden and driveway with parking for vehicles. Some of these private homes would be enclosed by a fence for improved security. In this manuscript the term "suburban house" is used to denote such private properties, with or without enclosed fence and permitted control.

A typical layout of a gated community is shown in Figure 2.1 with residential plots, communal roads and amenities. The common areas are owned by the GC body corporate, not the local Municipal authority as would be the case for a suburban home. Plots are privately owned, but water users have to adhere to the GC rules of conduct as well as Municipal bylaws. In this text the term "GC home" was used to distinguish between homes in a GC and suburban homes. A GC is typically guarded and fenced for security purposes (Radetskiy et al., 2015).

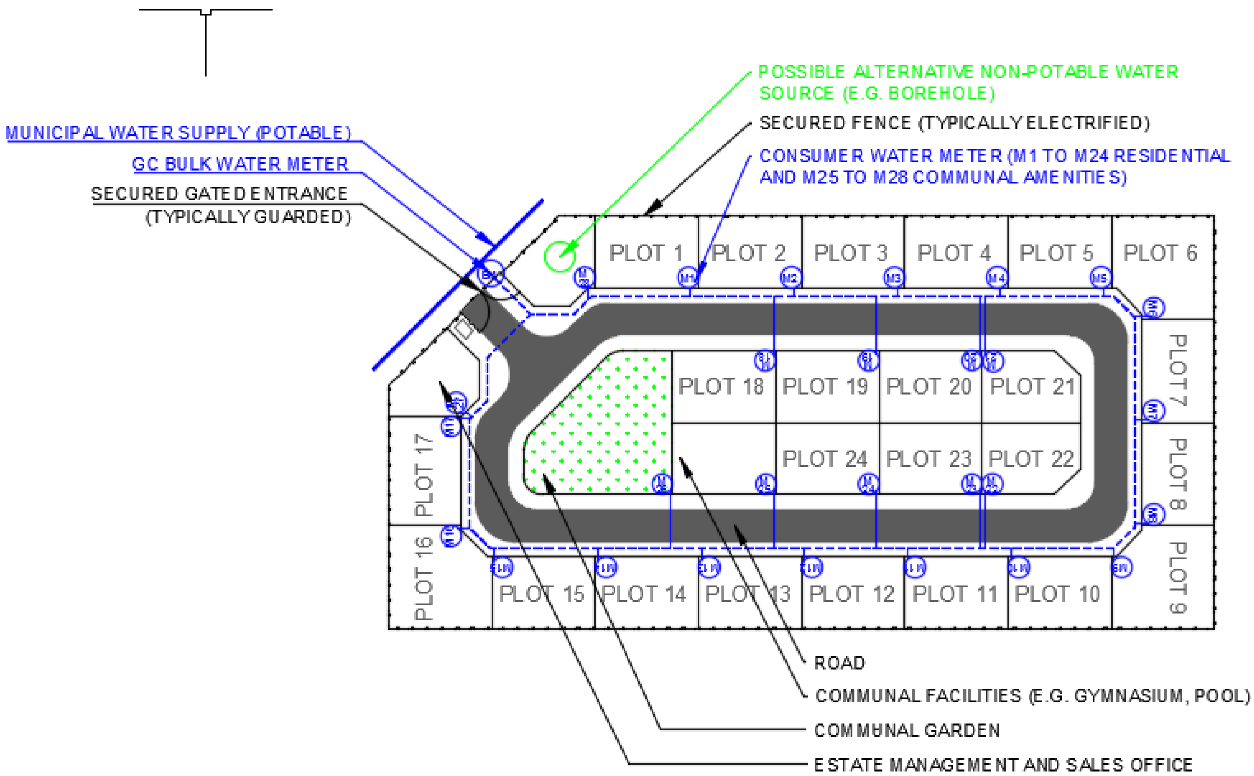

Figure 2.1: Typical layout of GC and related potable water services

GCs are commonly referred to as residential estates, common interest housing developments, or housing estates (Landman, 2003). The popularity of GCs has increased, in South Africa (Landman, 2003), but also in the Americas, Asia and Europe (Atkinson & Blandy, 2006). The growth of GCs is ascribed to aspects such as social fear and aspirations to be ex-territorial (Bauman, 2013). Glasze (2004) reported that the prevalence of GCs is an effect of globalisation causing territorial club economies, fuelled by socio-economic and socio-political transformations. GCs are also popular in South Africa because added security and lifestyle improvements are offered to GC homes (Landman, 2004). GC homes are usually characterised by the similar architecture of the buildings and the group of houses is often closed off to the general public by means of a boundary wall and security-controlled entrances. Spocter (2011) reported that GCs became popular in South Africa for the following reasons (amongst others):

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

Genis (2007), Thuillier (2005), Woo & Webster (2014) and Tedong et al. (2015) reported on the international growth in the numbers of GCs over the last two decades in various countries including South Korea, Argentina, Istanbul, Malaysia. Spocter (2011) reported a steady increase of GC authorisations in the Western Cape Province, South Africa, until 2005. The worldwide economic downturn and the establishment of development guidelines by the South African Department of Environment Affairs and Development Planning (DEADP, 2005) have hampered growth in the construction of GCs in the Western Cape Province between 2006 and 2011 (Spocter, 2011). The DEADP (2005) released a guideline that listed eight objectives for the development of golf estates and polo estates (both are a type of GC). These objectives included sustainable development principals such as responsible water use planning and effective stormwater management planning, and clarity with regard to the environmental application processes that had to be followed for new GCs. Although a decline in the number of authorised GCs was reported in South Africa since 2005, recent authorisations of GCs have included GCs with larger number of homes (in excess of 3000 homes per GC) located in the Western Cape and Gauteng Province.

GCs are governed by trustees or homeowners' associations who are responsible for the operation and the maintenance functions of the infrastructure, as well as implementing and adhering to legislation that pertains to the GC (Walks, 2014). A constitution, along with other guidelines and rules, is typically drafted prior to the establishment of the first GC homes and acts as the agreement between homeowners and the trustees. The rules typically address issues pertaining to:

- Use and maintenance of open areas;

- Conduct in the public areas of the GC;
- Environmental management;
- Water- and electricity-use management;
- Water and energy pricing strategies that have steep usage vs cost curves;
- Architectural guidelines, gardening and vegetation; and
- Security, levies and pets.

The objective of the research is to understand how the water use of homes in GCs are different to suburban homes. As the popularity of GCs increase it is important to develop a method to properly plan for efficient water infrastructure in GCs.

Residential water use in general

Guidelines commonly used by planners and engineers to determine the average annual daily water demand (AADD) of residential properties based on property size are provided by the CSIR (2003). No guidelines are available to estimate water demand of GCs specifically. In recent years further research was done with regards to the estimation of AADD of suburban homes. The AADD calculated using the CSIR (2003) method was noted to be conservative for larger homes and underestimates the water use for smaller homes (Van Zyl et al., 2008). As alternative, mathematically structured end-use models could be used to estimate water use, or estimates could be made separately for indoor- and outdoor use. End-use models allow residential water use to be split into separate water end-use components (Scheepers & Jacobs, 2014). Indoor water use has been widely modelled (Blokker et al., 2010), but outdoor use is much more variable and harder to model accurately although models for estimating outdoor use are available (Jacobs & Haarhoff, 2004; DeOreo et al., 2011; Makwiza et al., 2015). Outdoor water use, mainly garden irrigation, is estimated to contribute approximately 40%-60% to the AADD of GC homes, with a resulting seasonal water use pattern (Du Plessis & Jacobs, 2014).

Water use in GCs

Earlier research and water use guidelines do not distinguish between suburban homes and GC homes. This study focussed on the water use of GCs and also individual GC homes. GCs are usually supplied with water from one or more of the following sources:

- Potable water supplied via a piped water distribution system (normally the primary source of water);
- Groundwater supply (boreholes);
- Abstraction of water from a nearby river or dam;

- Treated sewage effluent and/or greywater reuse; and
- Stormwater run-off, often stored on site in retention ponds for irrigation purposes.

In many cases water is supplied to GCs from a potable bulk water supply pipeline at a metered connection. The bulk water supply is metered and billed, typically on a monthly basis, by a municipality. The water use costs paid by the GC are cascaded to the homeowners and the communal amenities. The individual homeowners are billed for water use on an individual meter reading basis, or a fixed rate basis. The GC bulk water meter readings were obtained from the municipal authorities, with specific ethical permissions for each of the municipalities, via records extracted from the treasury database. The data was subsequently analysed as part of this research. The water use of individual GC homes was not available from the municipal data systems and thus not available for analysis in this study.

RESEARCH METHOD

This quantitative research was based on analysis of actual monthly water use, as recorded by municipal water meters. Data was extracted for analysis from the various financial treasury systems that keep record of the billed water use data. The data was received in a GIS linked, Shape file, database format and contained records for all land use types, including business commercial, industrial, institutional and also all forms of residential properties. The water use of GCs, as recorded by means of monthly manual meter readings of the main bulk supply meter, was part of the extracted data set.

The first step was to identify records that could be classified as GCs, as per this study. Once identified, the GC water use records were analysed. Specialised software, Swift, was used to filter through the sets of water use data. Subsequent to extracting the AADD of each GC's bulk meter data, the appropriate information regarding the specific GC had to be obtained, including the number of homes in the GC, the property size of the GC and also the plot sizes of GC homes.

Data acquisition and filtering

GCs located in three of South Africa's Metropolitan Municipalities (City of Tshwane, City of Cape Town and City of Johannesburg) were obtained from treasury data. The data obtained consisted of 658 208 water use record entries in region A, 334 169 in region B and 433 796 in region C, as summarised in Table 2.1. The raw data set was subsequently filtered to include GCs exclusively.

Each data record contained the following fields, amongst others, that were essential to this study: GIS key; number of plots per record; plot size; AADD; 24 months' water use and land use. The following data filters were used to extract relevant data for GCs and further analysis:

- Only multi-plot GCs were included;
- Cluster type housing land use code was included;
- Plots size of GC homes with an area of at least 150m^2/plot were included;
- Apartments were excluded; and
- Total water use had to be more than zero for the sample period, so AADD > 0.

Once the filters were applied, only 2888 records passed through as qualifying CGs with an average age since registration of 24 years. The geographical locations of filtered data were plotted to aerial photography to check the accuracy of the filtered data. The aerial imagery was used to identify if the GCs and in terms of their enclosed nature and often repeated architecture.

The average area of plots in each GC had to be determined. Equation 2.1 describes the calculation method used for the determination of plot areas of the GCs and the individual plots in GCs:

$$A_{GC-TOT} = A_{GC-C} + \sum_{1}^{n} A_i \qquad (2.1)$$

where;

A_{GC-TOT} = Total plot area of one GC - equal to GIS polygon area
A_{GC-c} = All communal areas in the GC, including roads, parks
A_i = Plot area of one GC home i
n = Total of GC homes in the GC

Table 2.1: Summary of the filtered dataset

Description	**City of Cape Town - Region A**	**City of Tshwane - Region B**	**City of Johannesburg - Region C**	**Total/ Average**
Number of GCs in study sample	833	1402	652	2888
Average area of GCs (m^2)	7125	15800	4247	10442
Number of occupied homes in study sample	17493	72739	5352	95584
Average plot size (m^2) of GC homes	338	323	481	353
10th percentile of plot size of GC homes	163	169	260	170
90th percentile of plot size of GC homes	495	510	795	774
Record length (monthly water use)	Oct 2012 to Sep 2014	Nov 2012 to Sep 2014	Oct 2012 to Sep 2014	-

The average size of the plots in GCs are relatively small when compared to suburban homes of approximately the same market value. The average GC plot size reported in Table 2.1 falls on the left of the x-axes of typical plot-size based techniques for estimating water demand in residential areas (CSIR, 2003; Jacobs & Haarhoff, 2004; Van Zyl et al., 2008). A premium is paid for plots located in GCs (Zimmer, 2010) thus indicating an inflated value per unit plot area. Houses in GCs are relatively large compared to the plot size, with high percentage cover - and subsequently relatively small gardens.

RESULTS

The monthly water use data for the GCs listed in Table 2.1 was analysed. As part of the analysis water use was expressed in the following manner:

- The average monthly water use per GC home averaged over the entire record period, as shown in Figure 2.2; and
- The average monthly water use of the total GC area, averaged over the entire record period, as shown in Figure 2.3.

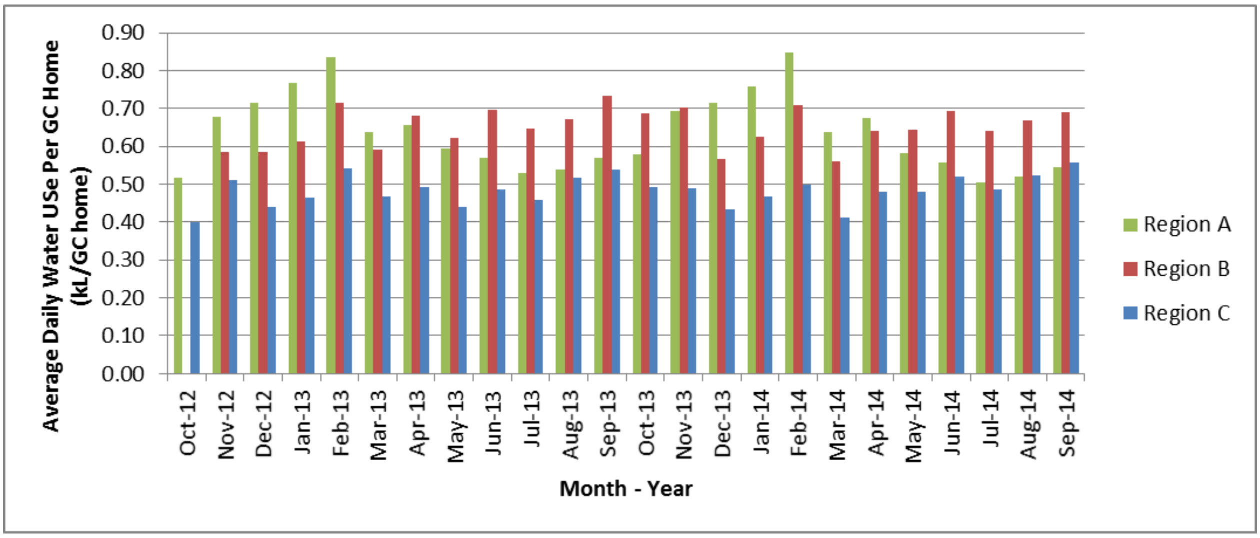

Figure 2.2: Average daily water use per GC home including common water use

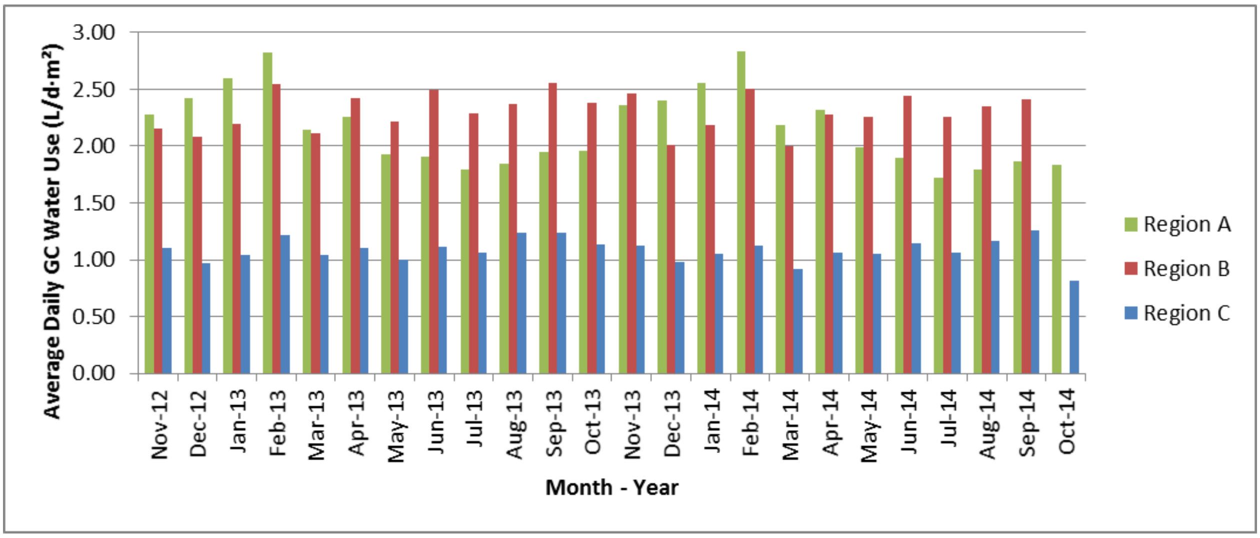

Figure 2.3: Average daily water use of GCs per unit area including common water use

From Figure 2.2 and Figure 2.3 a seasonal fluctuation in water use is evident. The dominant rainy season for region A is in the winter, while region B and region C experience summer rainfall. The water use fluctuation is more pronounced for the winter rainfall region, in line with results from theoretical end-use models (Jacobs et al., 2004). In all regions the maximum garden irrigation occurs in the summer, meaning that the winter rainfall region with hot dry summers is expected to have relatively higher water use, compared to B and C with summer rainfall.

The GC water use per unit area is illustrated in Figure 2.4. Region C had notably lower water use when compared to the other two regions. With reference to Table 2.1, the average GC home in region C had a plot size of 481 m^2, which was notably larger than plots in A (338 m^2) and B (323 m^2). The AADD of residential homes has been found to increase with plot size (CSIR, 2003; Jacobs & Haarhoff, 2004; Van Zyl et al., 2008). In contrast to the earlier studies, plot size was not linked to AADD in for GCs in the study sample. Table 2.2 summarises the AADD for GCs in all three regions.

Table 2.2: Summary of the extracted dataset

Description	Region A	Region B	Region C
AADD per GC home (kL/d)	0.63	0.66	0.49
AADD per unit area of GC (L/d·m^2)	2.15	2.32	1.09

The AADD per GC home reported in Table 2.2 are relatively low compared to other published guidelines (CSIR, 2003; Jacobs & Haarhoff, 2004; Van Zyl et al., 2008) as illustrated in

Figure 2.4. Van Zyl et al. (2008) used logarithmic regression models to estimate the AADD of residential properties. In a similar fashion, logarithmic regression models were derived for the three data sets and plotted on a graph along with three guidelines for estimating residential water use.

The published guidelines (CSIR, 2003; Jacobs & Haarhoff, 2004; Van Zyl et al., 2008) are from reputable sources and have been referenced in various other studies pertaining to water use. It can be noted that the published guidelines have evolved in approach over the years, however, the principals of stand size as benchmark for average annual water use has remained a suitable water use estimation parameter. The guidelines (CSIR, 2003) address peak daily and peak hourly demands, however for this research peak flow analysis was excluded because of the limitations of the available data.

The results are shown in Figure 2.4 and have been limited on the x-axis to 800 m^2, because 95% of the all the GC home plot sizes were smaller than 800 m^2. Possible explanations for the lower water use of GC homes could be attributed to the water pricing strategies, relatively smaller household irrigation area, average age of the GCs potentially indicating the use of water efficient appliances and geographic location.

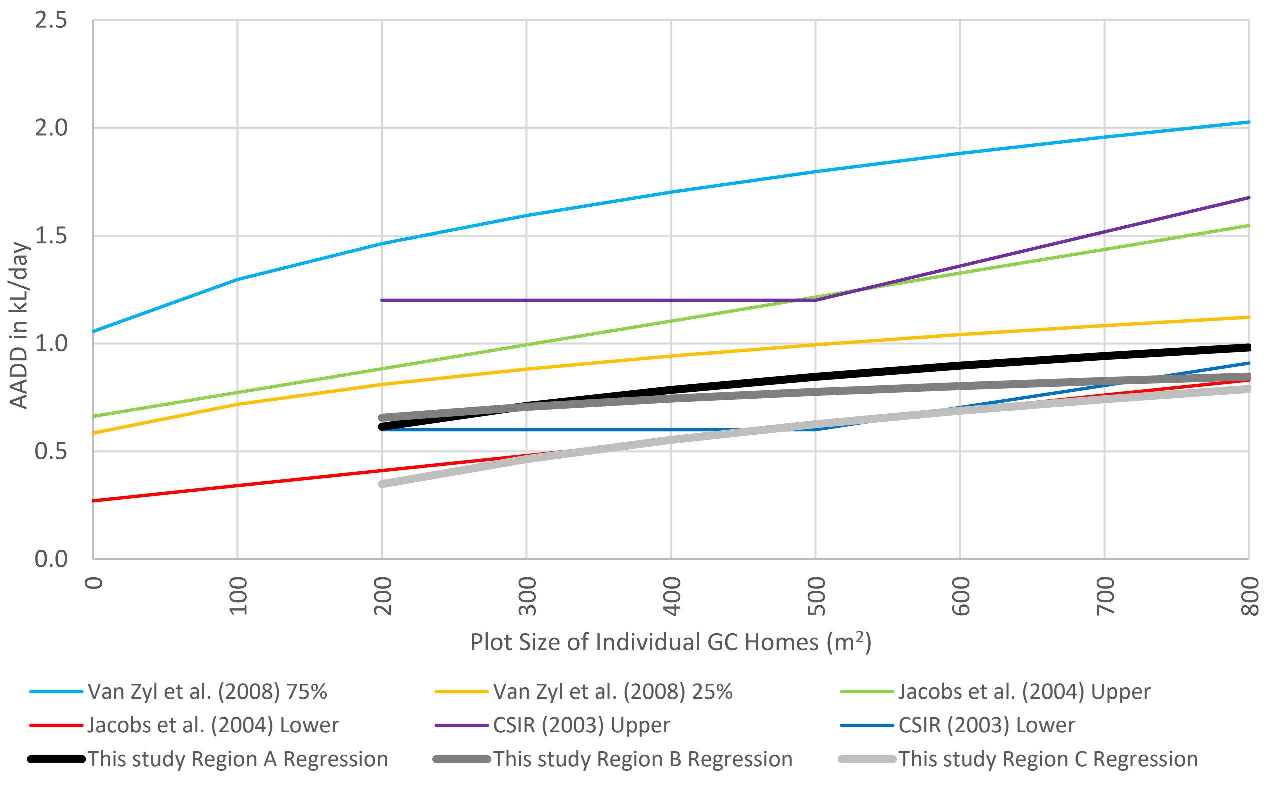

Figure 2.4: Comparison of data versus other guidelines

DISCUSSION

The water use of GC homes in all the regions was relatively low in comparison with other guidelines for residential plots. Further research, based on long term time series data is needed to better understand why the water use of GCs in the study area was in the twenty fifth percentile in relation to estimates provided in available guidelines. Communal maintenance services, including gardening are one of the desirable features of a GC (Walks, 2014). Communal garden irrigation by the GC (often with non-potable sources) may lead to reduced private GC home irrigation and/or a reduced need for an irrigated garden, leading to reduced water use in the GC homes. Bekleyen et al. (2016) stated that neighbourhood enhancements lead to increased consumer awareness of the environment. GC home owners could be considered more conservation minded, leading to water conservation and relatively lower water consumption.

Large portions of the data analysed as part of this study fell below the 500 m^2 plot size. In contrast, most of the plot size-based guidelines for estimating AADD far exceeded 500 m^2, with upper limits of 2000 m^2 (CSIR 2003), 4000 (Van Zyl et al., 2008) and even 8000 m^2 (Makwiza and Jacobs, 2015). Results for plot sizes between 200 m^2 and 500 m^2 in all guidelines was either lacking, or limited. GCs, with relatively small yet high valued properties, are a relatively new type of residential development with sufficient data for analysis only becoming available in the past decade. Most of the available guidelines were based on data preceding the growth spurt in GCs so guidelines that specifically address GCs should be investigated.

CONCLUSION

Water use of 2888 GCs in three South African cities was analysed. The results confirmed that water use in GCs is notably different from previously published residential water use estimates for AADD. The average annual GC water use from the potable municipal supply was found to be notably lower than estimates based on available guidelines for average annual demand. The differences could be attributed to the availability of alternative water sources for irrigating communal gardens, and the unique, homogeneous design of homes and garden layout in GCs, as compared to suburban homes outside GCs. Also, GC water use varied notably between the two cities in the summer rainfall season, suggesting that further research is needed to explain the disparity. The proposed research should include GCs of a greater geographical range and water use of individual GC homes. Further studies to address outdoor water use modelling of properties located in GCs would allow for better planning of GCs.

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Chapter 3.

Investigating wastewater flow from a gated community to disaggregate indoor and outdoor water use

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ABSTRACT

Disaggregating residential water use into components for indoor and outdoor use is useful in view of water services planning and demand management campaigns, where outdoor use is often the target of water restrictions. Previous research has shown that individual end-use events can be identified based on analysis of the flow pattern at the water meter, but such studies are relatively complex and expensive. A basic method to disaggregate the indoor-outdoor water use would be useful. In addressing this problem, a technique was employed in this study to disaggregate indoor–outdoor water use based on knowledge of the wastewater flow, with assumptions that link indoor use to wastewater flow. A controlled study site in a gated community, with small bore sewers, was selected to allow certain assumptions to be validated. The results provide insight into the monthly indoor and outdoor water use of homes in the study area, and show how wastewater flow could be used to assess outdoor use. Outdoor use was found to represent up to 66% of the total household water use in January, accounting for ~58% of the total annual water use in the study area 2016.

Key words: disaggregation, outdoor demand, residential water use

INTRODUCTION

Background

Household water use consists of various indoor and outdoor components. Usually the outdoor water uses are not disposed of via the sewer system (Butler 1991), while most indoor uses are connected directly to sewers. Some of the indoor water uses may potentially be reused, impacting the relationship between water use and wastewater flow. A better understanding of the relationship between indoor use, outdoor use and wastewater flow is important in view of water services planning and demand management campaigns.

Measurement of household water use is made possible by a consumer water meter, with water use billed in many countries based on the actual monthly water meter readings. In contrast, measurement of household wastewater flow is complicated and uncommon. Household wastewater flow is generally considered to be a function of water use, explaining why consumer sewer tariffs are often derived directly from water meter readings.

Indoor and outdoor water use

Indoor water use has been researched in detail (Buchberger & Wu 1995; Blokker *et al*. 2010), including analysis of individual end-uses such as shower events (Makki *et al*. 2013), bathing, toilet flushing and so forth. It is beyond the scope of this text to provide a comprehensive review of earlier studies into indoor use and end-uses of water. Total indoor water use is reasonably predictable, given that the required model input parameters are available.

Outdoor use is much more unpredictable than indoor use (Hemati *et al.* 2016), although models are available to estimate outdoor use (DeOreo *et al*. 2011; Du Plessis & Jacobs 2014). Some empirical studies have investigated outdoor use in detail. Outdoor use is mainly characterised by garden irrigation and irrigation of urban agricultural crops (Makwiza *et al*. 2017), swimming pool use (Fisher-Jeffes et al. 2014) and outdoor washing (DeOreo *et al.* 2011). Outdoor use is a function of climatic factors, thus explaining the seasonal fluctuation in potable water use at households, but also making outdoor use vulnerable to long term impact by climate change (Makwiza *et al*. 2017). Outdoor use could potentially be supplemented with alternative water sources (Jacobs *et al.* 2017), including treated effluent and greywater systems (Starkl *et al*. 2013), thus reducing the demand for potable water. Fluctuations over time and for different regions could also be introduced by different levels of water restrictions.

Household wastewater

Butler (1991) investigated wastewater flow from household appliances and found a strong correlation between water use and wastewater flow, especially in determining the resulting peak wastewater flow. Wastewater consists of sewage and the following extraneous components: stormwater ingress, groundwater infiltration and household plumbing leaks (Stephenson & Barta 2005; Erskine *et al*. 2011). Wastewater volume over a specified time interval would not equal indoor end-use volume, because not all indoor water use is disposed of via sewers. For example, some potable water is consumed or is used for watering of indoor pot plants. Butler (1991) confirmed that the non-wasted portion is relatively small. Also, wastewater consists of wasted potable water (indoor use) plus added constituents, meaning that the wastewater flow could exceed indoor use (Jabornig 2014) when the above listed extraneous components are included. For example, Drangert (1998) reported a urine excretion volume of 1,370 mL per person per day that would be added to the wastewater stream. However, the volumes of added constituents are insignificant when compared to typical indoor water use. The contribution of flushed potable water to the household wastewater stream is considered to be the most significant part, suggesting again that the indoor use would approximate wastewater flow.

PROBLEM STATEMENT

It is increasingly important in regions of water stress to distinguish between indoor and outdoor water use, because water restrictions typically target outdoor water use (Hemati et al. 2016). The total consumer water use is normally measured with only one water meter at the property boundary. Detailed end-use analysis of the flow pattern, recorded at the single water meter, would allow identification of individual end-uses to be extracted. Flow trace analysis has been widely used in previous research, but could be relatively expensive. Some of the notable studies include DeOreo *et al*. (2011) and Beal *et al*. (2011). This study addressed the problem of disaggregating indoor and outdoor water use components with limited information.

OBJECTIVE

If wastewater flow volume (outflow) could be compared to the total water use (inflow) volume, the outdoor use could be estimated by incorporating specific assumptions as set out in this paper. The research objective was to estimate outdoor water use by investigating the difference between the total water supplied into a specific district metered area (DMA) and the wastewater flow from the same area, over a specific time interval.

APPROACH

Monthly water meter readings are often recorded and are available for research purposes in South Africa (Jacobs & Fair 2012). The monthly water use is actually recorded and used for billing consumers. In this study the water use of residential properties in a gated community (GC) and the total bulk supply to the same area was obtained from water meters. Pumping records could be obtained for the wastewater pump station to which all the properties in the study area drain and were used to derive the wastewater flow from the same area.

The derived wastewater flow was used to estimate the indoor and outdoor water use components of all the homes in the study site combined – no attempt was made to investigate individual homes. Of course, the water meter only provides the total water use to a household, which would include the indoor use, outdoor use and also plumbing leaks on the property. Employing the wastewater flow as a means to disaggregate indoor and outdoor use proved useful and relatively inexpensive.

STUDY SITE

The residential area investigated was a gated community (GC), located in the Western Cape province, South Africa. The study site location is shown by the highlighted area in Figure 3.1. The GC consists of 371 individual properties, or plots, which primarily range in size from 400 to 1,200 m². During the last year of the study 338 plots were developed and occupied. The study site also included the following non-residential consumers: the management offices, a clubhouse, tennis and squash courts, a gymnasium, swimming pool and a putting course.

All homes are serviced with potable water and a small-bore wastewater collection system, also called solids-free sewers (Little 2004). Small bore sewers have relatively low extraneous flows, potentially resulting in wastewater flow from a study site with small bore sewers more accurately representing indoor use than for conventional gravity sewers. The wastewater system in the study area drains to a single wastewater pump station, for which telemetry data was available. A separate stormwater drainage system collects and drains rainwater and surface runoff in the study area. In this study small bore sewers reduced the number of unknowns because wet weather flow is limited. However, it would be possible to extend the work to regions with gravity sewers. Wet weather flow events would be identified, and infiltration rates would be estimated from available rainfall records; alternatively, the data could be recorded during dry periods.

Potable water is supplied to the study area by the water service provider via one bulk supply connection, with water use recorded by a magnetic flow water meter coupled to a GSM-based data logger. The study site was confirmed to be discrete with no cross-boundary connections. Communal landscaped areas in the study site were irrigated by a non-potable private borehole and dual supply system. Private home gardens were irrigated with potable water, supplied to each home by the service provider via the water distribution system. No on-site storage is available – all water supplied to the study site via the potable pipe network was used in the study site, and wasted water would flow away under gravity via the piped wastewater system. Each property in the study area had a water and sewer connection.

Figure 3.1: Location of the study site.

DATA ACQUISITION

Water use

The bulk water supply and wastewater pumping records of the study site were acquired. The bulk water meter readings were obtained from the municipal online platform. The data was abstracted for the period 1 January 2013 to 31 December 2015. Due to an erroneous telemetry system, data capture was interrupted from (1) 12 April 2013 to 2 September 2013, (2) 25 September 2013 to 8 October 2013, and (3) 24 March 2015 to 23 April 2015. The bulk water meter reading was recorded every 30 minutes. Values were recorded in L/s, averaged over the 30 min interval. The 30-minute readings were converted to daily and monthly averages for further analysis. For the three periods where data was unavailable, the average monthly flow rates were determined from the remaining data in an applicable month.

Since December 2015 no bulk meter flow data was available, because the magnetic water meter and data recording equipment were stolen. Problems relating to theft and vandalism are not uncommon in developing countries (Purzycki 2014). Subsequently the bulk water meter readings were unavailable for the period corresponding to wastewater pump station records. The problem was not insurmountable. Water meter readings of all the individual households in the study area were subsequently obtained for the period 1 January 2016 to 31 December 2016. The household water meter readings were collated to represent the 2016 bulk water use.

Pumping records and pump station dimensions

The wastewater flow from the study site was derived by considering pumping duration and event volume, linked to the wastewater inflow rate. Pump station event records from telemetry were available from 1 August 2015 to 31 July 2016, identifying all pump starts and stops. A total of 14,908 pump events were recorded in this period. The pump station houses two identical pumps, which under normal conditions operate in an alternating fashion. For the purpose of this study it did not matter which pump was in operation. A physical survey of the pump station sump was conducted to determine the sump volume in that section of the sump between the level switches used for switching the pump on or off.

During operation a pump would operate continuously and empty the volume between the level switches, plus the volume flowing into the sump during the particular event. The pump sump volume was physically determined to be 1.57 m^3. Determining the additional inflow volume required a few assumptions, because the wastewater inflow rate was not measured during the field experiment. The initial average wastewater inflow rate was determined by considering the pump event duration of 3 minutes and the known pump sump volume. An iterative procedure was employed to obtain a final estimate of the inflow rate, but an assumption had to be made regarding the wastewater inflow duration – inflow to the pump sump was assumed to be directly linked to water use. Water use (and thus wastewater inflow) during the period 2300–0500 h was relatively insignificant compared to the use over the remaining period of the day. The inflow volume that occurred during a pump event was thus determined to be 0.32 m^3 per event, by considering inflow over an 18 h day. The total pump event volume was thus found to be 1.89 kL/event.

ANALYSES RESULTS

Water use and seasonal pattern

The 30-minute bulk water meter readings for the period 1 January 2013 to 31 December 2015 were collated annually for 2013, 2014 and 2015, thus representing the total supply to the GC. Water meter readings of all the individual households were subsequently obtained for the period 1 January 2016 to 31 December 2016. The household water meter readings were collated to represent the 2016 bulk water use. The non-domestic component supplied to the management office and club house complex (with ~700 m² total floor area), represented about 8% of the total annual GC water use and was excluded from further analysis. Figure 3.2 illustrates the total water use by all residential consumers in relation to the average temperature and average rainfall. A clear seasonal variation is observed, with relatively hot, dry summers and cold, wet winters.

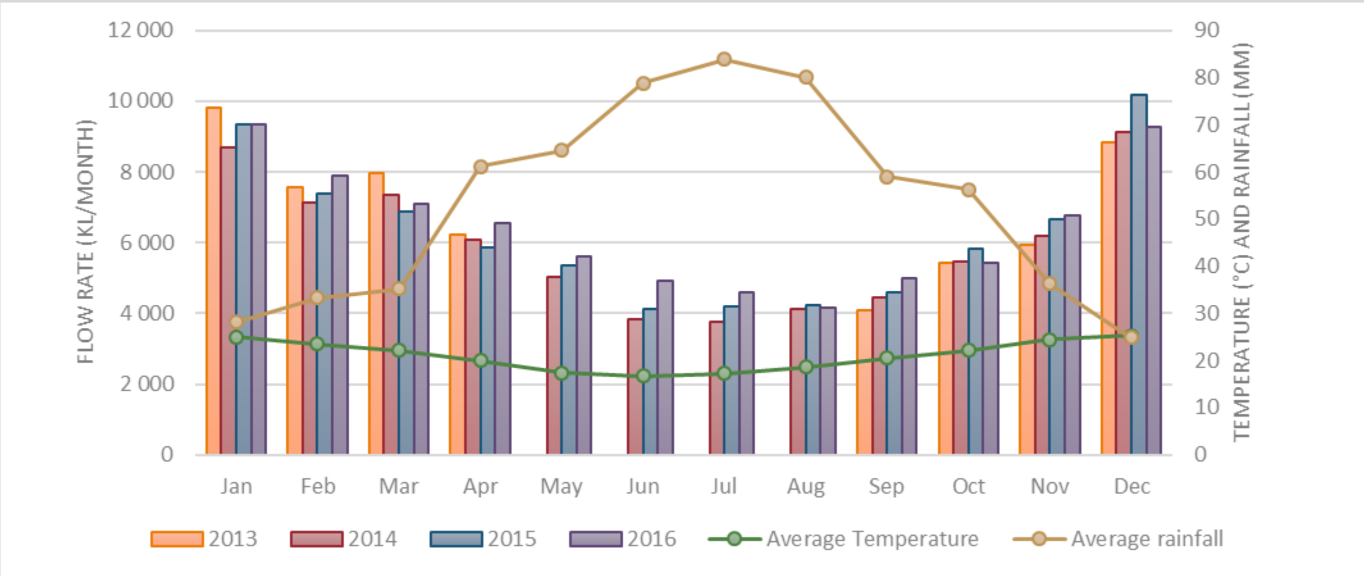

Figure 3.2 Monthly bulk water supply, average temperature and average rainfall at the GC.

Analysis of wastewater pumping records

The number of pump events were lifted from the data set and converted to monthly average volume – in order to match the flow to the monthly water use. For the purpose of this research wastewater flow volume was assumed to directly represent indoor water use. The average monthly waste water flow is illustrated in Figure 3.3.

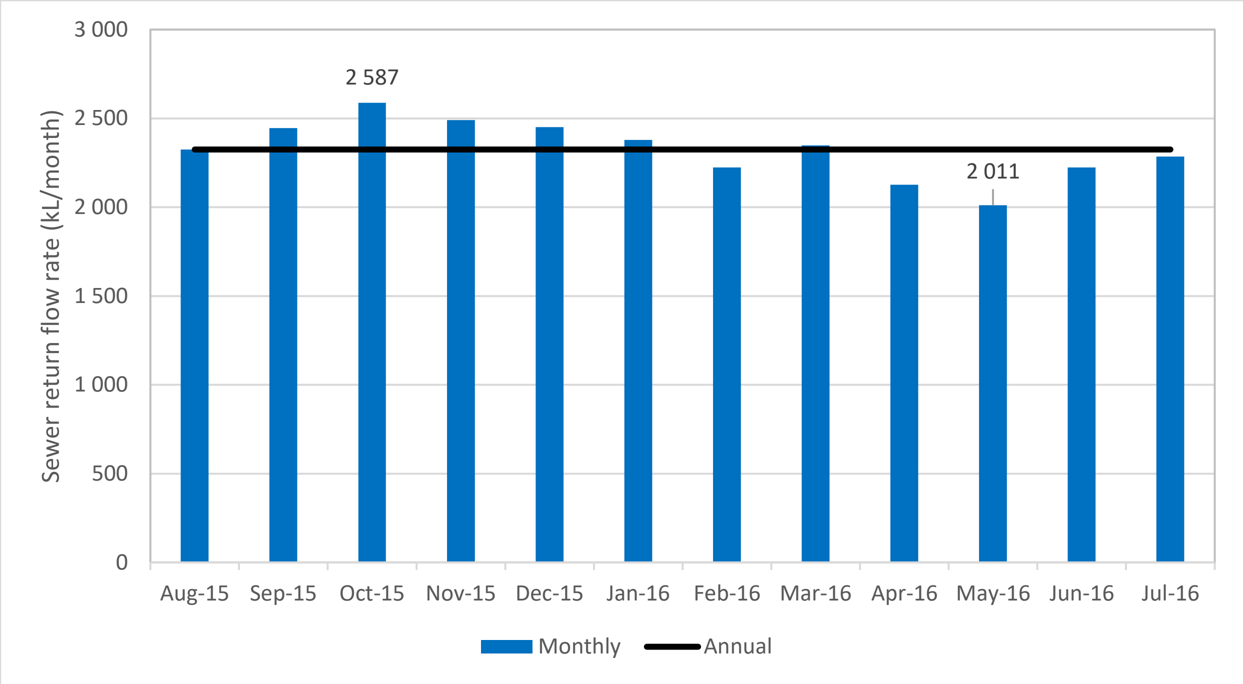

Figure 3.3: Monthly average wastewater flow (2015/2016) from the study site.

Water leakage and losses

A study by Knox (2016) assessed the water losses in the distribution systems of two GCs, one of which included the study site for this paper. Accurate water balances for the two GCs were developed and analysed by Knox (2016) by comparing household water meters with a totalling bulk water meter. It was found that the majority of the water losses in both the distribution systems were attributed to the physical leakage, with low levels of apparent loss.

Non-revenue water in the study area was determined to range between 6 and 12% during 2012 and 2013, with an average of 7% found during a detailed water balance conducted with the 2013 data. The non-revenue water was assumed to approximate real losses, because no unbilled authorised consumption was reported in the study area. Also, apparent losses are influenced by the presence of unlawful pipe connections, water meter accuracy and age, and the effectiveness of data transferral. As the study site is a relatively small and well managed, high-income area inside a GC, the apparent losses were negligible, with the 7% thus ascribed exclusively to real losses. These real losses in the distribution system were subtracted from the bulk inflow readings during the analyses.

Water use components

All data sets were superimposed so that the bulk water supply to the study site could be compared to the indoor and outdoor water use components, assuming that the wastewater flow approximates indoor use. The system input volume (average bulk water supply) and wastewater flow are presented in Figure 3.4, with the losses and non-domestic components also added.

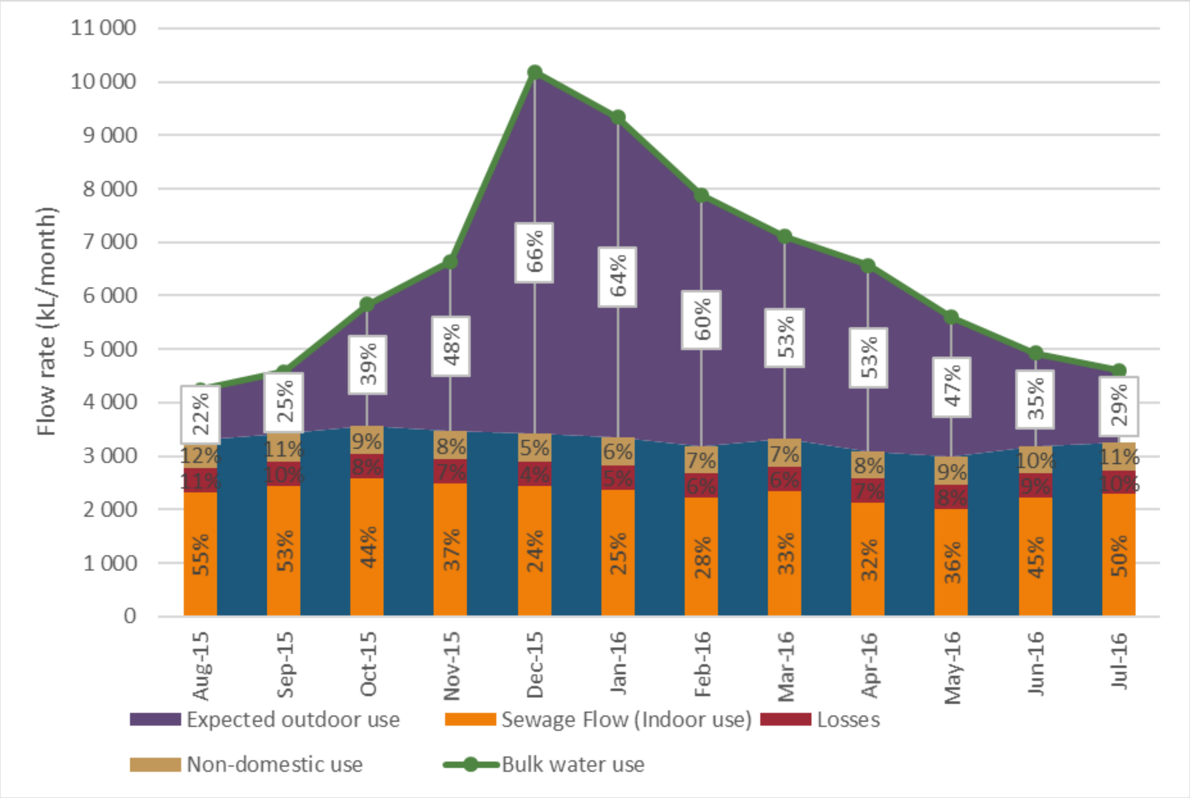

Figure 3.4: Derived water use components of the study site.

The results were recalculated exclusively for the indoor and outdoor components, thus excluding water loss and non-domestic use not returned to the sewer (Table 3.1).

Table 3.1: Recalculated result for indoor and outdoor water use exclusively

Component	Indoor use (kL/month)	Outdoor use (kL/month)	Indoor + Outdoor (kL/month)	Indoor share (%)	Outdoor share (%)
Aug-15	2,325	951	3,276	71	29
Sep-15	2,446	1,159	3,605	68	32
Oct-15	2,587	2,285	4,872	53	47
Nov-15	2,490	3,184	5,674	44	56
Dec-15	2,451	6,768	9,219	27	73
Jan-16	2,378	5,993	8,371	28	72
Feb-16	2,223	4,691	6,914	32	68
Mar-16	2,349	3,784	6,132	38	62
Apr-16	2,127	3,471	5,598	38	62
May-16	2,011	2,615	4,626	43	57
Jun-16	2,225	1,738	3,962	56	44
Jul-16	2,284	1,343	3,627	63	37
Average	2,325	3,165	5,490	42	58

DISCUSSION

The results show that outdoor water use contributed notably to the total household water use in the study area. Indoor water use remained fairly constant throughout the year, while outdoor water use varied significantly and followed a seasonal pattern. It is worth noting that no water restrictions were in place in the study area during this investigation.

In the study site it is expected that outdoor water use predominantly consists of garden irrigation, because from inspection of the aerial photography no private swimming pools were present (a communal pool facility is available to all residents). The notable variation of outdoor water use by season is ascribed to garden irrigation that is a function of seasonal parameters such as rainfall, evaporation and transpiration. Outdoor water use made up 73% of the domestic water use during the peak summer month (December) and decreased substantially in winter months, contributing only 22% to the total domestic use in August.

CONCLUSION

The wastewater return flow, aggregated with estimated water losses and non-domestic water use, was compared to total water use in order to derive proxy indoor water use estimates for the study site. Results show that the month to month indoor wastewater return flows remained fairly constant while the outdoor use component contributed notably to the total water use of the gated community – about 58% of the annual average water use was applied outdoors. The seasonality of the total water use can be attributed to the outdoor water use component, with garden irrigation probably the most notable end-use. The indoor use comprised 42% of the annual average water use, with 71% of the total water used occurring in August, the winter month with the lowest water use. Integrated analysis of the water supply and wastewater flow allowed for segregation of indoor and outdoor use, without the need to measure at household level. The approach would be valid for any relatively homogeneous fully serviced residential community with a single source and sink node.

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Chapter 4.

Model for estimating domestic outdoor water demand of properties in residential estates

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ABSTRACT

The outdoor water consumption of residential properties is a major contributor to the seasonal fluctuation of water demand. An outdoor water demand estimation model is presented where water-use components were mathematically defined and combined to develop an outdoor water demand model. The model input parameters were formulated from data available for residential security estates, where conditions such as types of vegetation, irrigated area and size of pool could be prescribed in a constitution, usually instituted by a home owners association in South Africa. Probability distribution functions of the parameters were derived from data collected from an estate located in the Western Cape Province of South Africa. This study leads the way to further research into end-use modelling of outdoor water demand. Future research into the effects of water conservation and water demand management initiatives on residential outdoor water demand would logically follow from this work.

Keywords: Demand; end-use; modelling; outdoor

OUTDOOR WATER DEMAND OVERVIEW

Outdoor water demand presents a combination of seasonal and behavioural aspects that are more difficult to predict than indoor end-use events [1]. These hurdles are likely to be addressed more often in future, as more detailed information and high-resolution data becomes readily available.

Outdoor use, including irrigation and the evaporation from pools and other water features is the main contributor to seasonal fluctuation in water consumption. The seasonal fluctuation in water consumption is typically a function of the outdoor water consumption, where indoor water consumption is typically non-seasonal [2]. Roberts [3] recorded end-use data for two weeks in summer and two weeks in winter at 840 residential customers in the Yarra Valley, in Victoria, Australia. Roberts [3] reported that the seasonal end-uses collectively made up 32% of the total consumption during the summer logging period. Seasonal end-uses were defined because the fluctuations in water demand as a result of seasonal change in factors such as temperature, rainfall, snowfall and humidity. During the winter period, these seasonal end-uses could not be identified [3].

As part of the same study by Roberts [3] billing data was investigated. The results indicated that seasonal use could account for 25.4% of the total annual residential use, where garden irrigation was estimated to account for 87.3% of the total seasonal use [3]. In comparison Veck and Bill [4] reported in a contingent valuation study that outdoor use contributed 19% to the total use in the Alberton area in South Africa, of which 74% consisted of garden irrigation. The seasonal fluctuation in water consumption is typically a function of the outdoor water consumption, where indoor water consumption is typically non-seasonal [2].

MODEL DEVELOPMENT

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

In order to perform stochastic estimation of outdoor water demand, it was essential that a mathematical model be developed as a foundation for the simulations. DeOreo et al. [2] stated that residential outdoor use is defined as a function of irrigation, outdoor tap use, pool or water-feature evaporation, and pool filter maintenance.

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

The theoretical irrigation requirement model as part of this research was adopted from an irrigation model developed by DeOreo et al. [2].

Human behaviour could have a significant impact on the irrigation efficiency. It could, therefore, be expected that the actual irrigation consumption would not necessarily correlate well with the theoretical irrigation requirement. Similar to the role that evapotranspiration plays in irrigation water demand, evaporation also plays a key role in sustaining the water level of open water bodies such as pools and water features. In order to quantify the water requirement for the replenishment of pools and water features.

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

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

A pool ownership factor (F_{po}) was incorporated in the equation to allow for the fraction of homes that have pools or water features. The outdoor components were then combined into the following general equation:

$$Q_{outdoor} = A_i \frac{E_{to} \times K_{bc} - P_r \times F_{ep}}{I_e} + F_{po}(A_p \times (E_w - P_r) + D_d \times A_p \times O_m) \quad (4.1)$$

Where,

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

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

POPULATION OF PARAMETER VALUES AND DISTRIBUTIONS

Summary of model parameters

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

The various physical parameters were based on the analyses of geometrical measurements taken from an estate located in the Western Cape of South Africa, hereinafter referred to as Estate A's cadastral layout and aerial photographs taken of the estate in 2009 and supplemented by Google Earth photographs taken in 2012.The behavioural parameters such as irrigation efficiency, water level drawdown during backwash and monthly occurrence of backwash were determined from a contingent valuation survey and a questionnaire email. The climatic information was obtained from the SAPWAT [7] data basis which contains more than 50 years of climatic data.

Evaporation Evapotranspiration and precipitation

The SAPWAT [7] software was used to collect the evapotranspiration and precipitation data for the estate's and North American Cities respectively. It was noted that the estates and North American cities are predominantly winter precipitation regions, with the exception of Phoenix, where monsoonal thunderstorms provide high humidity and localised precipitation [8]. The Evapotranspiration, Precipitation and Evaporation parameters were regarded as known fixed monthly parameters. The fluctuations of these parameters were encapsulated in the Effective Rain and Irrigation Efficiency parameters.

The A-pan evaporation data for the North American locations was published by Farnsworth and Thompson [9]. The evaporation measurement stations were all within a 50 km range of the central business district of these towns/cities. In the work by Farnsworth and Thompson [9] the pan evaporation was multiplied by a pan factor of 0.7 to obtain free lake evaporation. The pan evaporation data of the Estates addressed in this report were sourced from Midgley et al. [6]. Average A-Pan monthly values were calculated, and as with the above data, multiplied by a factor of 0.7 to obtain the free lake evaporation.

Effective precipitation factor

The effective precipitation factor (Fep) is based on the effective rainfall factor described by Midgley et al. [6]. The main difference is that precipitation also takes snowfall into consideration. Middleton & Bailey [10] presented an effective rainfall factor of 0.75 which was adopted for this study. This factor usually excludes snowfall, however, for the purposes of this study the factor was applied to total precipitation.

Irrigation efficiency

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

$$I_e = \frac{Q_{crop}}{Q_{actual}} \quad (4.2)$$

Where,

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

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

Metered data of the Q_{actual} was not available for analyses in this study. It is possible to estimate Q_{actual} by considering the expected flow rate from sprinklers. The raw data collected from a contingent evaluation survey conducted by Aurecon was analysed to estimate the actual flow rate.

The average irrigation operation time was indicated as 42 minutes and 61 minutes per event. For comparison purposes, the maximum time of irrigation for each household was used to calculate the actual summer peak irrigation consumption.

Garden irrigation is often designed by a landscape designer using the guidelines provided by an irrigation hardware manufacturer. Hunter Industries and Rainbird Irrigation are two of the most common brands in the local residential irrigation environment. Both of these manufacturers have standard specifications listed on their website.

Sprinkler systems are usually separated into irrigation zones, and these zones will normally operate individually to allow for sufficient pressure at the sprayer heads. It could be assumed that there is sufficient pressure available in the pipes to allow for the operation of 5 irrigation sprayers per zone. In order to estimate a flow rate, a system pressure had to be assumed, because flow rate is a function of pressure. Assuming a pressure of 3.45 bar with an average flow rate derived from the manufacturer's specifications at 14.6 ℓ/min per sprayer, operating five sprayers at a time will result in be 71.5 ℓ/min per zone (Q_z).The following equation could be derived to calculate the actual summer monthly irrigation demand (Q_{actual}):

$$Q_{actual} = \frac{31 Q_z T E_{pw}}{7} \tag{4.3}$$

Where,

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

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

$$Q_{crop} = A_i(E_{to} \times K_{bc} - P_r \times F_{ep}) \tag{4.4}$$

Where,

Ai = The area of a property that is under irrigation.
Eto = Evapotranspiration
Kbc = Crop coefficient
Pr = Precipitation
Fep = Effective precipitation factor

The irrigation efficiency was determined for each property in Estate A which had participated in the survey. The distribution fitting tool available in the @Risk software was used to fit a probability function to the Irrigation efficiency data. Figure 4.1 illustrates the proposed probability distribution function.

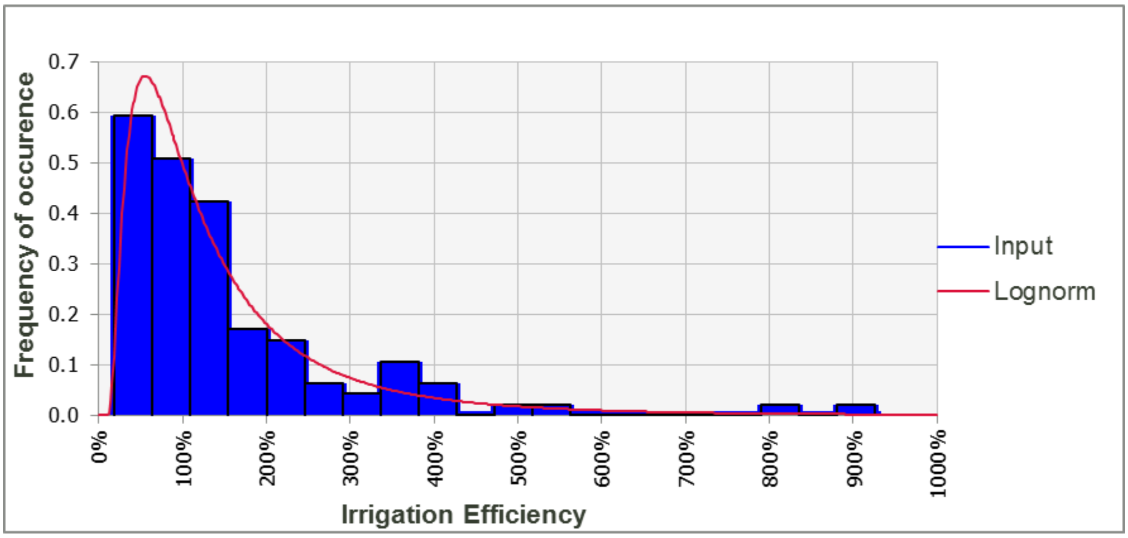

Figure 4.1: Lognormal distribution fit to irrigation efficiency data

Irrigated area

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

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

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

Crop coefficient

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

A high-resolution aerial photograph from 2009 of Estate A showed 13 properties where construction was complete. On average, the grass cover of these properties was 76% and the trees, shrubs, and other plants constituted 24%. This indicates that the probability that grass will be planted 3.14 times higher than the probability that trees, shrubs and other plants will be planted. Limited information was available of the behavioural aspects of garden layouts. The in-depth investigation of this parameter could, in future, form part of extension of this study.

Pool Surface Area and Pool Ownership Factor

The imagery from Google Earth was used to determine the surface area of pools at properties if they have pools. It was determined that 51% of properties had pools and their surface areas varied between 7 m^2 and 30 m^2. The 51% was applied to the Monte Carlo simulations as a fixed pool ownership factor (Fpo). The measured pool surface area dataset was again analysed by the @Risk software, after which the probability distribution function was utilised in the Monte Carlo Simulation (Figure 4.2).

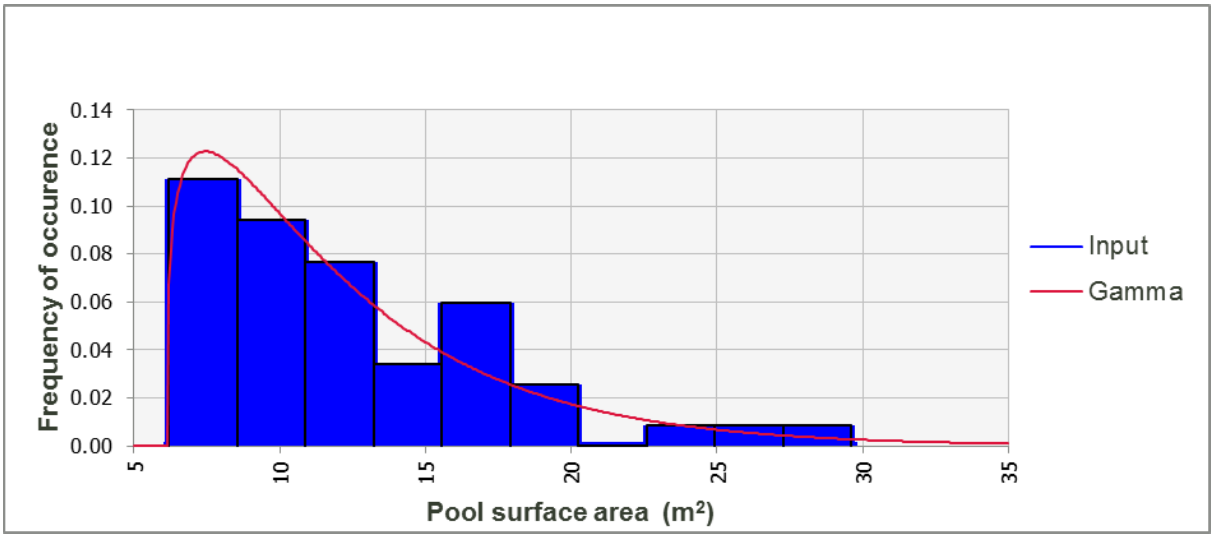

Figure 4.2: Pool surface area Gamma distribution fit

Pool maintenance occurrences and water level drawdown

A questionnaire was distributed to seven independent homeowners known to have pools. The data for the winter and summer event occurrences per month were combined to obtain a combined probability distribution function for the summer and winter events (Figure 4.3).

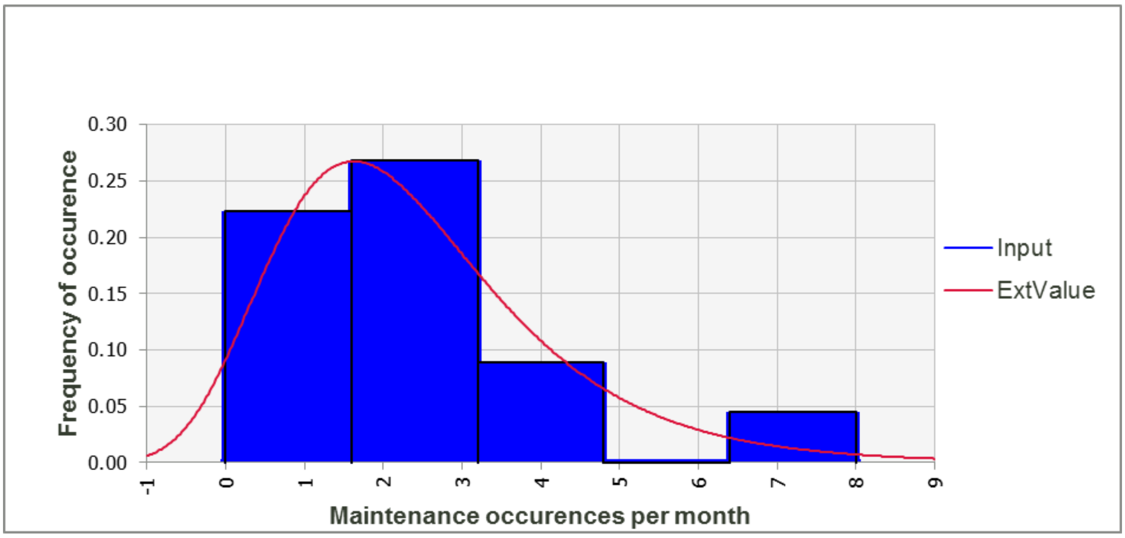

Figure 4.3: Maintenance occurrences Maximum Extreme Value distribution fit

In order to obtain the amount of pool drawdown per maintenance event it was necessary to research the standard pool pump operating flow rate. According to the specifications the standard Whirlpool model STP50 pool pump had a flow rate of 210 ℓ/min. The pool level drawdown could be calculated by multiplying the flow rate by the amount of operational time divided by the pool surface areas. The pool drawdown per pool maintenance event was also analysed and fitted with a typical uniform probability distribution function.

TYPICAL RESULTS

In order to typically illustrate the results of the model, simulations were conducted on the existing data of four groups of houses that formed part of the REUWS data base study conducted by Mayer and DeOreo [11]. These groups were selected, because there were sufficient outdoor and total water consumption data for comparison purposes. The data required included property size, irrigated area, irrigation efficiency evaporation, rainfall and pool ownership. The houses located in the North American Cities of Boulder, Eugene, Lompoc and Phoenix were suitable for the purposes of this study.

The simulation of the REUWS data could also be compared to actual metered outdoor water demands. Figures 4.4, 4.5, 4.6 and 4.7 illustrate (located at the end of the paper) the comparison of results graphically. From visual inspection of the results it is evident that the Eugene and Lompoc simulation results are comparable to the metered outdoor water consumption. Both Boulder and Phoenix are located in arid regions of Northern America, where water conservation strategies such as rebate programmes are implemented.

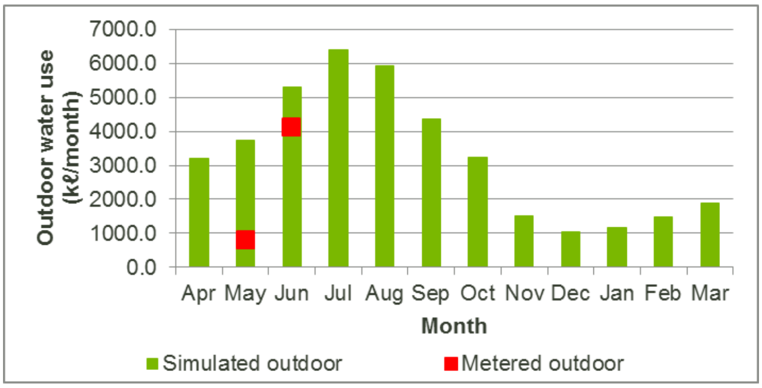

Figure 4.4: Boulder outdoor water demand results comparison

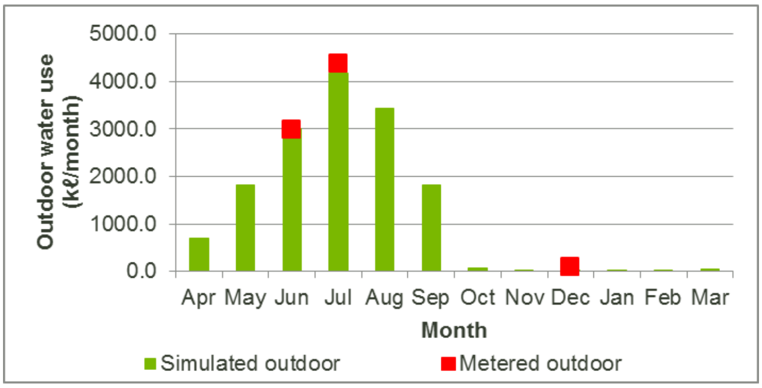

Figure 4.5: Eugene outdoor water demand results comparison

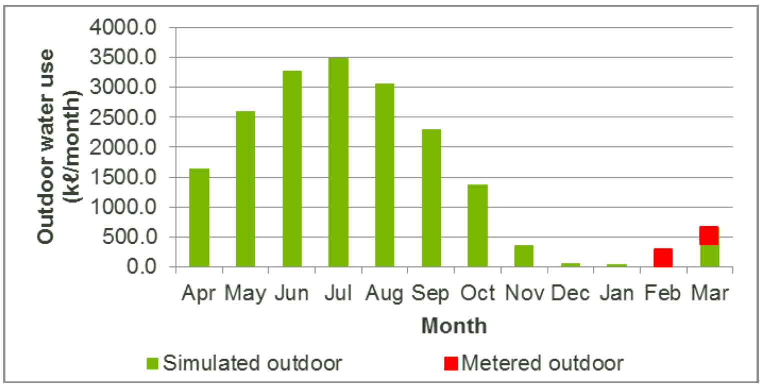

Figure 4.6: Lompoc outdoor water demand results comparison

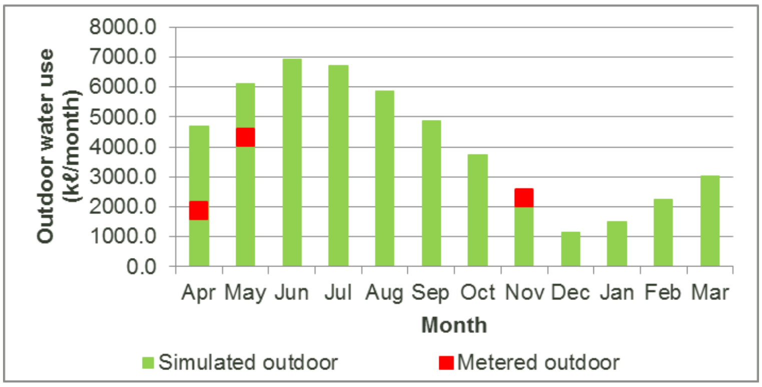

Figure 4.7: Phoenix outdoor water demand results comparison

CONCLUSIONS

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

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

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

In the absence of site-specific knowledge, the outdoor water demand of a residential estate could be simulated using basic climatic data and estimated residential property sizes and quantities. Combining the results from this study with the indoor water demand results from a model such as the model developed by Scheepers [1], a developer or planner could stochastically estimate the total water demand of a residential estate on an annual or a monthly temporal scale.

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

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Chapter 5.

Procedure to derive parameters for stochastic modelling of outdoor water use in residential estates

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ABSTRACT

The outdoor water use of residential properties is a major contributor to the seasonal fluctuation of the overall water use of these properties. The outdoor water use components were mathematically defined and combined to develop an outdoor water use model. The parameters that formed part of the mathematical outdoor water use model were formulated from data available for residential estates, where conditions such as types of vegetation, irrigated area and size of pool could be prescribed by a home owners association or local authority. The data used to populate the model parameters was derived from aerial photography and contingent valuation methods.

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Keywords: water use, end-use, model, outdoor, indoor, GIS

INTRODUCTION

Outdoor water use presents a combination of seasonal and behavioural aspects that are more difficult to predict than indoor end-use events [1]. These hurdles are likely to be addressed more often in future, as more detailed information and high-resolution data becomes readily available.

Outdoor use, including irrigation and the evaporation from pools and other water features is the main contributor to seasonal fluctuation in water use. The seasonal fluctuation in water use is typically a function of the outdoor water use, where indoor water use is typically non-seasonal [2]. Roberts [3] recorded end-use data for two weeks in summer and two weeks in winter at 840 residential customers in the Yarra Valley, in Victoria, Australia. Roberts [3] reported that the seasonal end-uses collectively made up 32% of the total use during the summer logging period. Seasonal end-uses were defined, because fluctuations in water use as a result of seasonal change in factors such as temperature, rainfall, snowfall and humidity contribute to total water use. During the winter period, these seasonal end-uses could not be identified [3].

As part of the same study by Roberts [3], billing data was investigated. The results indicated that seasonal use could account for 25.4% of the total annual residential use, where garden irrigation was estimated to account for 87.3% of the total seasonal use [3]. In comparison Veck and Bill [4] reported in a contingent valuation study that outdoor use contributed 19% to the total use in the Alberton area in South Africa, of which 74% consisted of garden irrigation. The seasonal fluctuation in water use is typically a function of the outdoor water use, where indoor water use is typically non-seasonal [2].

This study quantifies the outdoor water use parameters that relates to properties located in residential estates, where vegetation areas, vegetation types and pool size are often controlled by the estate regulations.

DESCRIPTION OF PARAMETERS

For the purposes of conducting the analyses and comparison with the stochastic simulations, data had to be sourced from existing residential properties. The data was also generated based on known parameter distributions. The data required in order to perform the analyses is summarised in Table 5.1.

Table 5.1: Estate characteristics

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

PROPOSED OUTDOOR WATER USE MODEL

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

The proposed mathematical model and the parameters that were used in the development of this model are listed below and described in the subsections that follow [5].

$$Q_{outdoor} = A_i \frac{E_{to} \times K_{bc} - P_r \times F_{ep}}{I_e} + F_{po}\big(A_p \times (E_w - P_r) + D_d \times A_p \times O_m\big) \qquad (5.1)$$

Where,

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

The various physical parameters were based on the analyses of geometrical measurements taken from Estate A's cadastral layout and aerial photographs taken of the estate in 2009 and supplemented by online lower resolution imagery photographs taken in 2012. Further analyses of these aerial photographs are being conducted to automate the process of disaggregating the surface area of the vegetation, pools, and buildings using remote sensing technology imbedded in GIS software [6].

The behavioural parameters such as irrigation efficiency, water level drawdown during backwash and monthly occurrence of backwash were determined from a contingent valuation survey and a questionnaire email. The climatic information was obtained from the SAPWAT and CLIMWAT data basis which contains more than 50 years of climatic data

DATA COLLECTION METHODOLOGY

Water use

Water use data from three similar residential estates located in South Africa were analysed. For the purposes of this study the estates were called Estate A, Estate B and Estate C. The estates were selected for this study based on the following characteristics summarised in Table 5.2:

Table 5.2: Estate characteristics

Description	Estate A	Estate B	Estate C
Type of estate	Polo field estate	Golf course estate;	Vineyard estate
Location	Paarl, Western Cape, South Africa	Stellenbosch, Western Cape, South Africa	Franschhoek, Western Cape, South Africa
Total size of estate	150 ha	160 ha	80 ha
Number of properties	550 properties of which 150 are built-up	500 properties of which 390 are built-up	There are 100 properties of which 23 is built-up
Average size of the properties	818 m^2	660 m^2	1270 m^2

The total water use records of the properties were obtained from meter readings taken at the relevant estates by meter reading consultancies, by means of physical meter reading, online based automatic meter reading tools and data loggers. Table 5.3 summarises the methods used for obtaining the data.

Table 5.3: Water use data source methods

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

Behavioural Aspects

The behavioural aspects of outdoor water use can be attributed to the various schools of knowledge in terms of irrigation operation, pool replenishment and filter maintenance. In order to capture the human behavioural impact of these behavioural aspects a consumer survey was conducted at 105 houses located in residential estates. The survey questions and results are summarised in Table 5.4. The survey dealt with the following aspects of irrigation-use and pool-use that are relevant to this study:

- Method of irrigation;
- Operation time of irrigation;
- Frequency of use; and

Number of pool or water features on a specific estate. Homeowners with pools independent of the sample summarised in Table 5.4 were contacted to verify the parameters obtained from the research of Jacobs [7], into pool filtration operation. The objective of these interviews was to verify the volume and frequency of pool filter maintenance by typical homeowners who own pools

Table 5.4: Summary of irrigation behaviour survey results

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

Geometrical information

Geometrical information measured from 89 of the properties in Estates A were analysed. Measurements were taken from cadastral information and from scaled online lower resolution imagery photographs available for these properties. The surface areas of the vegetated areas, pools and property boundaries were drawn, and measured using AutoCAD. Of the 89 properties, high resolution aerial photographs of 8 of the properties were available (See Figure 6.1). The online lower resolution imagery information was correlated with coordinated aerial photographs and found to have an average accuracy of 92% and simulated accordingly with the model. Using remote sensing technology to disaggregate the colour ranges of types of vegetation the surface areas could be measured automatically over a large number of properties [6].

Figure 5.1: High resolution aerial photograph geometrical analyses

Types of vegetation and crop coefficients

From the architectural guidelines [8] and the common crop factors of the plants used on properties in residential estates, it was found that the crop coefficients for gardens were generally similar to those of the generic grass type crop coefficient (K_{bc} = 1).

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

Climatologic information

For the purposes of this report, the average precipitation and evapotranspiration figures were extracted from the SAPWAT software [9]. The SAPWAT software contains data from weather stations located in South Africa as well as the rest of the world. As part of the SAPWAT development [9], data of weather stations located outside of South Africa was adopted from the CLIMWAT database. The data exported from the SAPWAT software as part of this research was available on a monthly temporal scale.

TYPICAL PARAMETER DESCRIPTIONS

Evapotranspiration and precipitation

The SAPWAT software was used to collect the evapotranspiration and precipitation data for the estates and North American Cities respectively. Figure 5.2 and Figure 5.3 illustrate the collected data used in the development of the various model simulations. Note that precipitation includes rainfall and snowfall data.

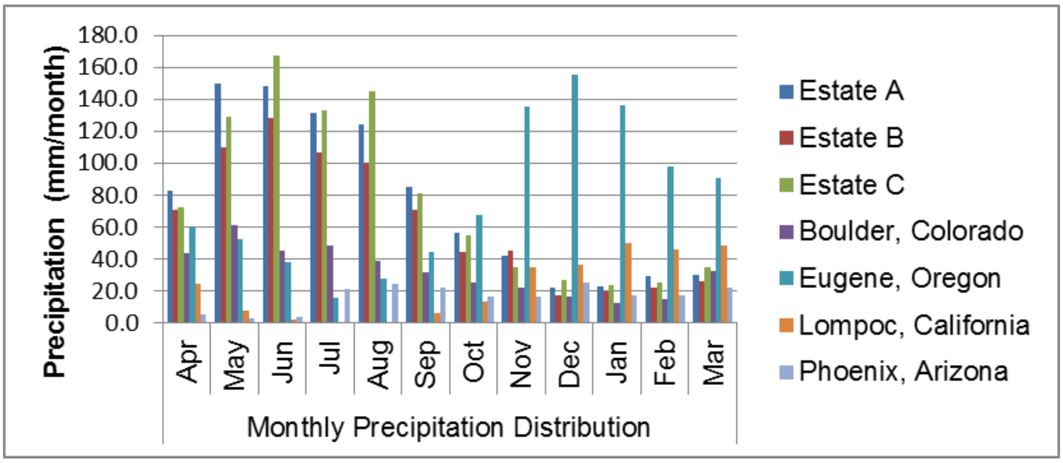

Figure 5.2: Combined average precipitation parameter plot

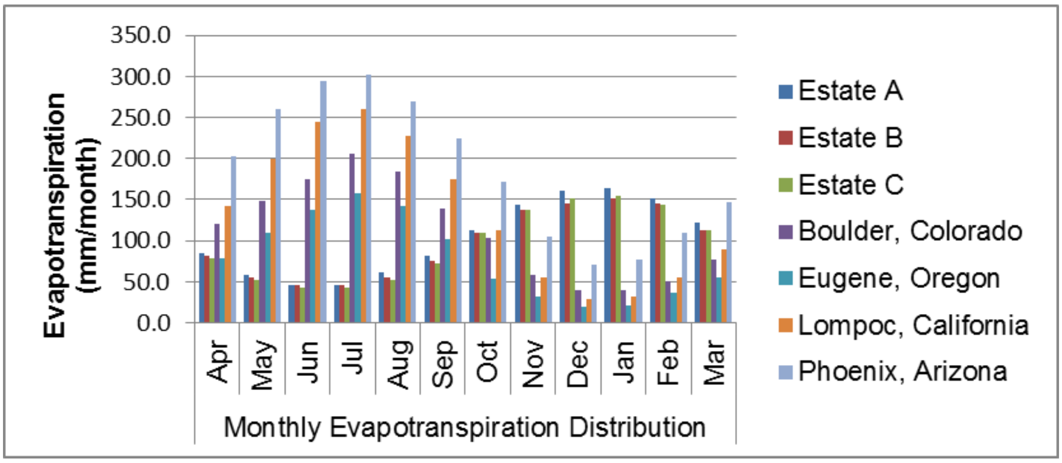

Figure 5.3: Combined average evapotranspiration parameter plot

Evaporation

The A-pan evaporation data for the North American locations was published by Farnsworth and Thompson [10]. The evaporation measurement stations were all within a 50 km range of the central business district of these towns/cities. In the work by Farnsworth and Thompson [10] the pan evaporation was multiplied by a pan factor of 0.7 to obtain free lake evaporation.

The pan evaporation data of the Estates addressed in this report were sourced from Department of Water Affairs [9], the data-set is populated from the WR90 study conducted by Midgley et al. [11]. Average A-Pan monthly values were calculated, and as with the above data, multiplied by a factor of 0.7 to obtain the free lake evaporation. The bar graph in Figure 5.4 illustrates the converted lake evaporation data.

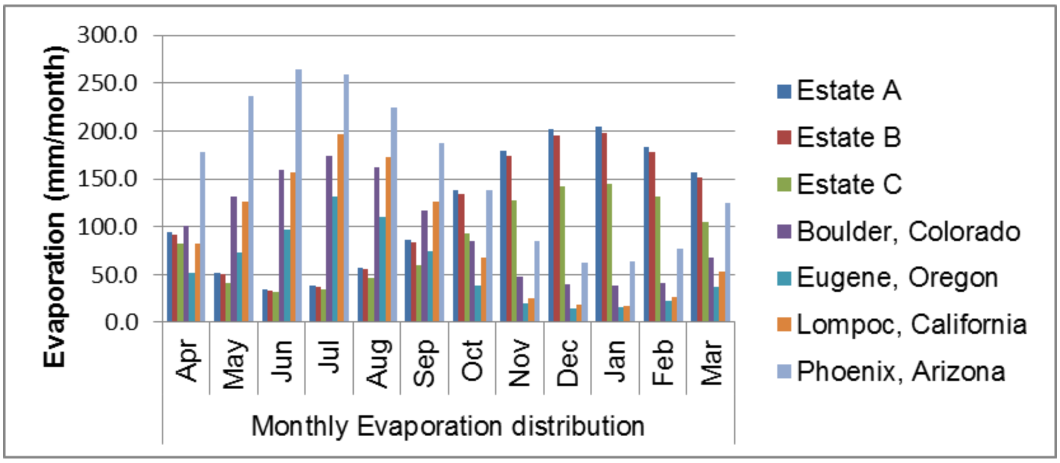

Figure 5.4: Combined average evaporation parameter plot

Effective precipitation factor

The effective precipitation factor (F_{ep}) is based on the effective rainfall factor described by Midgley et al. [11]. The main difference is that precipitation also takes snowfall into consideration. Middleton & Bailey, [12] presented an effective rainfall factor of 0.75 which was adopted for this study. This factor usually excludes snowfall, however, for the purposes of this study the factor was applied to total precipitation.

Irrigation efficiency

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

$$I_e = \frac{Q_{crop}}{Q_{actual}} \tag{5.2}$$

Where,

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

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

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

Which method do you use to water your garden?

- To which 97% of people answered that they used automated Micro-sprayer irrigation systems

During summer, how many times per week do you irrigate your garden?

- On average homeowners irrigate their gardens 5.6 events per week.

During summer, what is the average length of an irrigation cycle, for example watering your whole garden?

- The average irrigation operation time was indicated as 42 minutes and 61 minutes per event. For comparison purposes, the maximum time of irrigation for each household was used to calculate the actual summer peak irrigation use.

Garden irrigation is often designed by a landscape designer using the guidelines provided by an irrigation hardware manufacturer. Hunter Industries and Rainbird Irrigation are two of the most common brands in the local residential irrigation environment. Both of these manufacturers have standard specifications listed on their website. The typical irrigation performance specifications of two standard residential rotor sprayer heads from the two manufacturers are summarised in Table 5.5 below.

Table 5.5: Typical sprayer performance specifications

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

Sprinkler systems are usually separated into irrigation zones, and these zones will normally operate individually to allow for sufficient pressure at the sprayer heads. It could be assumed that there is sufficient pressure available in the pipes to allow for the operation of 5 irrigation sprayers per zone. In order to estimate a flow rate, a system pressure had to be assumed, because flow rate is a function of pressure. Assuming an average flow rate of 14.6 ℓ/min per sprayer, operating five sprayers at a time will result in 71.5 ℓ/min per zone (Q_z). The following equation could be derived to calculate the actual summer monthly irrigation water use (Q_{actual}):

$$Q_{actual} = \frac{31 Q_z T E_{pw}}{7} \qquad ..(5.3)$$

Where,

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

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

$$Q_{crop} = A_i(E_{to} \times K_{bc} - P_r \times F_{ep}) \quad (5.4)$$

Where,

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

The irrigation efficiency was determined for each property in Estate A which had participated in the survey.

Irrigated area

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

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

The results from the automatic disaggregation of the vegetated areas will be compared with the areas measured using AutoCAD software to determine the accuracy

Crop coefficient

Upon investigation of the landscaping guidelines of security estates, it was detected that the crop coefficients of the allowable crops on the site vary between 0.65 and 1, with 0.8 (grass) being the most likely. A triangular distribution was selected for its robustness and simplicity.

A high-resolution aerial photograph from 2009 of Estate A displayed 13 properties where construction was complete. On average, the grass cover of these properties was 76% and the trees, shrubs, and other plants constituted 24%. This indicates that the probability that grass will be planted 3.14 times higher than the probability that trees, shrubs and other plants will be planted. Limited information was available of the behavioural aspects of garden layouts. The in-depth investigation of this parameter could, in future, form part of extension of this study.

Pool Surface Area and Pool Ownership Factor

The imagery from online lower resolution imagery was used to determine the surface area of pools at properties if they have pools. It was determined that 51% of properties had pools and their surface areas varied between 7 m^2 and 30 m^2. The 51% was applied to the Monte Carlo simulations as a fixed pool ownership factor (F_{po}). As with the vegetation the results from the AutoCAD software measurements will be compared to the automatic disaggregation exercise conducted in GIS software.

Pool maintenance occurrences and water level drawdown

A questionnaire was distributed to seven independent homeowners known to have pools. The questions that were asked and the related answers are tabulated in Table 5.6.

Table 5.6: Pool maintenance questionnaire results

	How many times per month do you backwash/ rinse your pool in summer?	**How many times per month do you backwash /rinse your pool in winter?**	**How long in minutes does your pump operate during this cycle? (min)**	**What is the surface area of your pool? (m^2)**
Mean	3.43	1.86	2.46	18.54
Minimum	1.00	0.00	0.75	12.50
Maximum	8.00	3.00	3.00	24.50
Median	3.00	2.00	2.50	17.50
Standard deviation	2.19	0.99	0.74	4.52

In order to obtain the amount of pool drawdown per maintenance event it was necessary to research the standard pool pump operating flow rate. According to the specifications the standard Whirlpool model STP50 pool pump had a flow rate of 210 ℓ/min. The pool level drawdown could be calculated by multiplying the flow rate by the amount of operational time divided by the pool surface areas.

CONCLUSIONS

The proposed outdoor water use model was developed using a combination of parameters successfully implemented in various industries including agriculture, water resource management and irrigation etcetera. Taking cognisance of the laborious task of measuring surface areas by hand, the implementation of remote sensing technology offered by GIS software are essential to automate the disaggregation of vegetation, pool and building footprint areas.

The typical data used to describe the parameters that pertains to the outdoor water use model could be used to compare with the results obtained from the automatic colour disaggregation results received from future analyses of aerial photographs. These parameter values performed well in the initial stages of the development and analyses of the outdoor water use model. Parameters were populated in terms of probability distribution functions as per the outdoor water use model presented by Du Plessis and Jacobs [5]. Further developments of the input parameters will form part of future studies and will be published as part the Monte Carlo simulation results of the model in a future paper.

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Chapter 6:

Garden footprint area and water use of gated communities in South Africa

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ABSTRACT

Gated community homes in South Africa are popular amongst property buyers in urban environments such as cities and metropolitans due to the increased security and lifestyle improvements offered. Garden design and layout requirements are prescribed in architectural guidelines compiled by the Homeowners Associations of these communities. Garden footprint area in gated community homes is of importance to researchers and planners, because of the influence on water use. This study used a quantitative approach to evaluate the spatial data of garden footprint area as a percentage of total plot area for 1813 gated community homes in different regions of South Africa. The research reviewed how garden footprint area is prescribed and how it is applied in gated community homes. The impact of garden footprint area on water use was also analysed. The results were compared to relevant information lifted from specific architectural design guidelines developed for each gated community. Data from 11 gated communities was analysed and the average garden footprint area was found to be 36% of the total plot area. Gated community homes with garden area smaller than 100 m^2 were found to have limited influence on total monthly water consumption, while the water use of gated community homes with larger garden footprint area increased proportionally with garden footprint area. The seasonal fluctuation of water use is illustrative of garden irrigation and other outdoor water use. The results provided useful input for incorporation in outdoor water use modelling of gated community homes.

Keywords: Garden footprint area, water use

INTRODUCTION

Gated communities (GCs), also referred to as residential estates or security villages, have become popular in many countries, including South Africa (Landman, 2004). The typical spatial layout of GC homes transforms urban areas from open communities to an enclosed living style by restricting access. Generally, GCs consist of group housing with similar architecture, closed off to the public by means of a secured boundary. Many factors have contributed to the proliferation of GCs in South Africa, with the most prominent factors being increased security and safety, lifestyle improvements, a sense of community, proximity to nature and the need for privacy and exclusivity (Breetzke et al., 2014).

GCs are often governed by a committee or board of trustees, known as the Homeowners Association (HOA). The HOA is responsible for the operation and maintenance of the estate infrastructure. A set of rules, guidelines and restrictions are usually drafted by the HOA and must be followed by the residents. Most GC regulations include an architectural and landscaping guideline in order to protect property value and maintain a common aesthetic view. The social and structural homogeneous nature of a GC allows parameters such as building coverage, landscape area and vegetation type of each property to be easily anticipated and managed.

RATIONALE

Parameters that have an impact on outdoor water use in GCs include: (i) garden footprint area, (ii) evapotranspiration, (iii) precipitation, (iv) crop coefficient, (v) effective precipitation factor, (vi) irrigation efficiency, (vii) pool or water feature surface area, (viii) open lake evaporation, (ix) pool maintenance procedures and (x) frequency of pool maintenance (Du Plessis and Jacobs 2014). However, the watering of gardens is the most significant factor in conventional urban outdoor water use (Du Plessis et al., 2018). The rationale behind this study was to better understand plot coverage in GC homes for further incorporation of garden footprint areas as an important parameter in outdoor water use modelling, with a particular focus on GCs.

LITERATURE REVIEW

Roitman (2009) noted that GC homes exhibit similar physical features and house socially homogeneous residents. However, GCs might be diverse if different social groups aligned to class, ethnicity, interests and religion are targeted in related marketing campaigns. Often GCs are differentiated with regards to the physical elements (such as the type of housing), location, socio-economic status and age of the residents (Roitman, 2009). Properties in high-income GCs are generally characterised by large, spacious stand-alone houses with well-kept gardens and lavish green lawns (House-Peters et al., 2010). Properties in middle to lower income GCs are generally characterised by dense townhouses, complexes or apartment blocks, often with small gardens and communal open spaces.

Different types of GC homes, with different garden footprint areas, would reflect different water usage patterns. A home with a smaller garden footprint would be expected to have a lower water use than a similar home with a relatively larger garden footprint. A number of other variables also influence outdoor water use, including for example the type of vegetation (Liang et al., 2017.), climatic variables such as rainfall and evaporation (Mashhadi Ali et al., 2017), irrigation efficiency, and also the ratio of under and over irrigation (Czeslaw et al., 2016). Garden footprint area has been noted to be one of the most significant independent variables for outdoor water use (Jacobs and Haarhoff, 2007; Du Plessis and Jacobs, 2014) and is prescribed in architectural guidelines, typically developed specifically for the GC in the early development stage. Restrictions in terms of gardening, particularly the vegetation genotypes and garden footprint area, may be a requirement for development approval of a GC in terms of environmental affairs. Kaplan et al. (2014) reported that the seasonal nature of outdoor water use can be harnessed to improve water security by changing vegetation to xeric landscape and limiting pool water use. The reduction of outdoor water use results in reduced seasonal fluctuation of total water use in an urban area.

Many GCs are located in metropolitan areas where sustainable water supply has become a major challenge due to rapid urbanisation (Soederberg and Walks, 2018), resource limitations (Mazumder et al., 2018), climate change (Makwiza and Jacobs, 2018) and infrastructure deficits (Fraga et al., 2018). Quantification of outdoor water use is also essential for effective urban water planning and management from an infrastructure perspective.

RESEARCH METHOD

A knowledge review was conducted to establish how garden footprint area parameters are prescribed by the governing bodies of GCs. The aim of the knowledge review was to evaluate the similarities of the parameters that are prescribed in the architectural guidelines of the various GCs in the study sample. These parameters could enable researchers and planners to account for GCs in terms of spatial planning and water supply requirements. As part of this quantitative study, spatial data was used to evaluate garden footprint area as a percentage of total plot area. The results of a comprehensive GIS based spatial analysis were compared to data extracted from the knowledge review of architectural guidelines for GCs. The relationship between garden footprint area and water use was also investigated by analysing water use, particularly seasonal fluctuation of water use, in relation to garden footprint area.

DATA SAMPLING

As part of this study, three different databases were compiled for analysis. The databases comprised information extracted from architectural guidelines (Sample A), geo-spatial attributes lifted from aerial photographs (Sample B) and monthly water use of GCs (Sample C). Architectural guidelines and monthly water use could only be obtained for certain limited number of GCs, given project constraints. Availability of suitable aerial photographs did not limit the sample size. The names and contact details of the GCs and the related GC homes in all study samples were excluded from this text, in line with ethical requirements. A further subset of Sample B was selected based on the available monthly water use data. The subset, called Sample C was filtered from Sample B and included 11 GCs where sufficient monthly water consumption records could also be obtained.

Sample A contained information extracted from a review of 21 architectural guidelines. The GCs in Sample A were selected based on the availability of clear, specific architectural guidelines and a spread across regions in South Africa, including the following provinces: KwaZulu Natal, Western Cape, Gauteng and the North West. The architectural guidelines for each of the GCs were reviewed based on information pertaining to the regulation of vegetation, garden layout, pool use, plot coverage and general items having an impact on outdoor water use. The location and relevant number of homes per GC, for the 21 GCs in Sample A, are summarised in Table 6.1.

Table 6.1: Location and number of homes in Sample A

GC Number	Location	Number of plots
1	Overstrand, Western Cape	236
2	West Coast, Western Cape	860
3	Southern Suburbs, Western Cape	104
4	Tshwane, Gauteng	230
5	Cape Winelands, Western Cape	423
6	Stellenbosch, Western Cape	49
7	Ekurhuleni, Gauteng	660
8	Johannesburg, Gauteng	950
9	Somerset West	570
10	Midrand, Gauteng	423
11	Tshwane, Gauteng	283
12	George, Western Cape	365
13	Hartbeespoort, North West	650
14	Dolphin coast, KZN	520
15	Cape Winelands, Western Cape	3 150
16	Southern Suburbs, Western Cape	310
17	Midrand, Gauteng	185
18	Paarl, Western Cape	25
19	Paarl, Western Cape	550
20	Cape Winelands, Cape Town	33
21	Tshwane, Gauteng	850
	TOTAL	12410

Sample B included 16 GCs with recent aerial photographs at an acceptable resolution. Sample B represented 1813 different household plots in the 16 GCs. The GCs in Sample B are located in the Cape Town region, Johannesburg and Tshwane (Pretoria). Table 6.2 summarises the number of GCs and plots in each region for Sample B. The GCs in Sample B were initially selected based on available water consumption records; however, after filtering the data it became apparent that some of the GCs in Sample B contained numerous zero consumption months. Therefore, a subset of Sample B, containing the 11 GCs with sufficient water consumption records, was selected. Table 6.3 summarises the number of GCs and plots in each region for Sample C.

Table 6.2: Number of GCs and number of plots in Sample B

Region	Number of GCs in each region	Number of plots in each region
Cape Town	5	933
Tshwane	5	427
Johannesburg	6	453
Combined	16	1813

Table 6.3: Number of GCs and number of plots in Sample C

Region	Number of GCs in each region	Number of plots in each region
Cape Town	2	161
Tshwane	4	170
Johannesburg	5	404
Combined	11	735

DATA ANALYSES

GCs are known to have predetermined architectural guidelines, prepared by consultants on behalf of the HOA. The architectural guidelines contribute to the aesthetics of the homes and landscaped areas of a GC. The intent is that an architectural character is developed as part of the GC's identity (Stubblefield, 1996). As part of this research, the architectural guidelines developed specifically for the 21 GCs in Sample A were obtained and reviewed. The architectural guidelines of some GCs are published online. The guidelines reviewed in this study were sourced from the relevant GC websites and subsequently examined. The review focused on attributes such as property area, building footprint area, garden footprint area, type of vegetation and pool specifications.

Sample B contained a different set of GCs, as described earlier. Aerial photographs of all GCs in sample B were analysed visually to disaggregate the building footprint, garden footprint and pool footprint of the GC homes in the sample. The aerial photographs of 1813 households in the 16 GCs in Sample B were analysed using Autodesk Civil 3D software. The Civil 3D program polygon tool was employed to measure irregular shaped objects and calculate the footprint area of property boundaries and various plot sub-areas. Each GC home was analysed individually. The surface areas of the plot, roof, vegetation, hard surface and pool were visually identified from the electronic aerial photograph image, with each type of land cover subsequently traced by adding polygons. The area of each polygon was determined and linked to the cover type per plot (an example is shown in Figure 6.1). The plot area was taken as the total area within an external wall or boundary, including the driveway, verge and garage area. The garden area included the lawn and any vegetation or tree cover within the property boundary (excluding bare soil, which was added separately).

Figure 6.1: Typical example of garden footprint spatial disaggregation

Results of architectural guideline review (Sample A)

The architectural guidelines in Sample A ranged in plot size and number of plots to enable a representative view of the housing typology. With reference to Table 4, the GCs in Sample A had 611 homes on average, while the average plot size was 783 m^2. The typical values specified in the guidelines were a maximum building coverage of 50% and an average minimum building floor area of between 150 m^2 and 250 m^2. Results of the analysis are summarised in Table 6.4.

Table 6.4: Geophysical characteristics of GCs.

Number of plots per GC	Range (Number of plots)	Number of plots < 300	300 ≤ Number of plots < 600	600 ≤ Number of plots < 900	Number of plots ≥ 900
	Number of GCs in range	8	7	4	2
Average plot area per GC	Range (m²)	Plot area<500	500≤Plot area<700	700≤Plot area<900	Plot area≥900
	Number of GCs in range	2	7	6	6
Prescribed maximum building coverage per GC	Range (%)	Building coverage=30 %	Building coverage=40%	Building coverage=50%	Building coverage=60 %
	Number of GCs in range	1	1	15	4
Prescribed minimum building floor area per GC	Range (m²)	Not prescribed	Floor area<150	150≤Floor area<250	Floor area≥250
	Number of GCs in range	5	3	10	3

Nine of the 21 guidelines in Sample A prescribed the lawn grass genotype. The prescribed varieties included buffalo grass, kweek grass, common russet, giant spear grass, paspalum grass and Bermuda grass. Three GC guidelines stated specifically that kikuyu grass is not allowed. Of the guidelines investigated, 16 stated that no invasive plants would be permitted, 13 of which prescribed either water wise and/or indigenous plant genotypes. In three cases, the minimum number of plants or trees per plot were recommended. In addition to plot coverage restrictions, the guidelines in Table 6.5 were also of interest.

Table 6.5: Additional architectural guidelines relating to outdoor spaces

Descriptor	**Guidelines**	**No of GCs applicable**
Balconies	Balconies may not exceed 30 m^2	1
Pools	Maximum pool size of 60 kL	1
Landscaping, vegetation	All edges must have 1 m to 2 m wide planted and landscaped strip on the inside of all boundaries. At least one tree every 5 m to 7.5 m length of boundary.	5
	Verges and sidewalks should be fully landscaped. Minimum of three different plant species.	
	Landscaping on the sidewalks must be undertaken. The portion between building lines and street boundaries must be landscaped.	
	Verges should be planted and covered with chip stone.	
	It is encouraged to minimise lawn areas and maximise landscaped areas.	
Open space	Minimum of 80 m^2 – 100 m^2 for private open space (patio, deck, paving, lawn etc.)	1
Water re-use, irrigation	Greywater recycling and rainwater collection tanks are encouraged. Drip irrigation encouraged.	5
	Irrigation is only allowed from alternative water sources and not potable water.	
	Irrigation system must be connected to the house potable water, or no alternative water source is allowed.	
	Rain water harvesting and grey water use is encouraged.	
Water features	Use of water features is encouraged.	1
Artificial grass, storm water, ground water	Artificial grass may be used if a retention pond for storm water has been designed. No boreholes allowed.	1
Hard surface area	Paving shall not cover more than 25% of the plot area. Minimum of 25% of the plot must be soft landscaping.	1

Spatial analysis results (Sample B)

The prescribed spatial arrangements were compared to actual spatial arrangements of GC homes as part of this study. The aerial photographs of the 16 GCs in Sample B were analysed spatially to determine how the individual plots are developed in relation to vegetation, pool, and hard surface coverage. The GC were then classified into different regions, namely Cape Town and surrounds, Tshwane and Johannesburg. A summary of the average plot area, garden area, percentage garden area of all the plots combined and of the plots according to region, is presented in Table 6.6.

Table 6.6: Average plot area and relative garden area per region

Region	**Number of plots**	**Average plot area (m²)**	**Average garden area (m²)**	**Percentage garden area of total plot area**
Cape Town	933	553	233	41.0%
Tshwane	427	334	87	22.9%
Johannesburg	453	289	118	38.8%
Combined	1813	436	170	36.2%

The plots located in the Cape Town region had larger than average plot areas (553 m^2) and higher than average garden footprint percentage (41%), while the homes in Johannesburg had relatively smaller average plot areas (289 m^2), although the garden footprint area percentage was relatively high (38.8%). Figure 6.2 indicates the frequency distribution of garden footprint area percentage, per region.

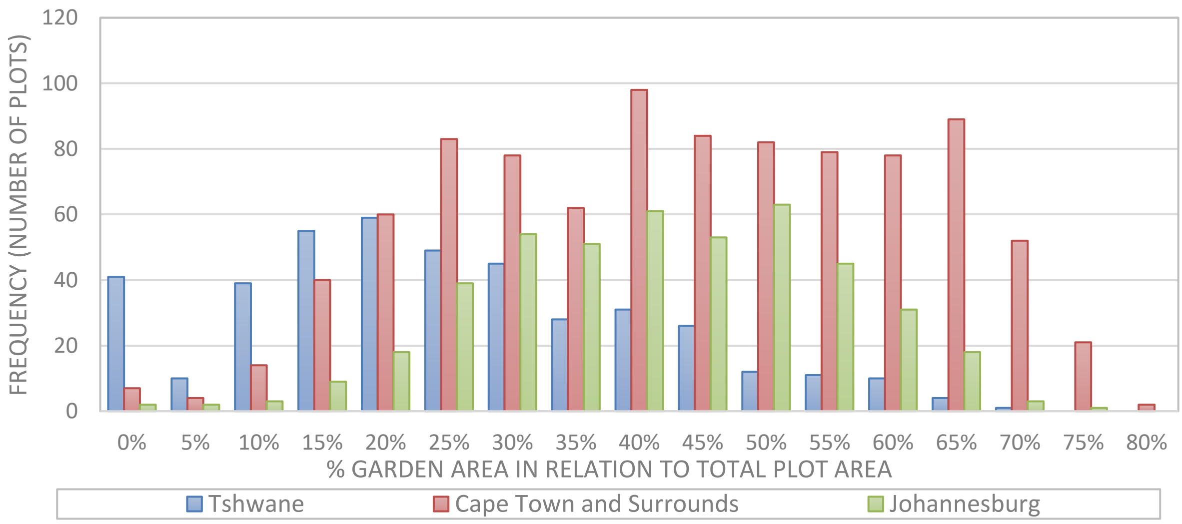

Figure 6.2: Frequency distribution of garden area percentage per region.

Water use analysis results (Sample C)

Monthly water use data was obtained for 11 of the 16 GCs in Sample B. The sub-set of sample B that also included water consumption data, was termed Sample C. The average annual daily demand (AADD) was determined for each of the 11 GCs in Sample C, based on monthly water consumption for the period October 2012 to September 2014. The average AADD per home in each GC was derived by dividing the total AADD for each GC by the number of homes in the GC. The average AADD per home was subsequently plotted relative to the garden footprint area. The values were collated into garden footprint area categories with a 50 m^2 bin size. The average garden footprint area (x-axis) and the average AADD per GC home (y-axis) were determined for each category, indicated by the larger circles in Figure 6.3.

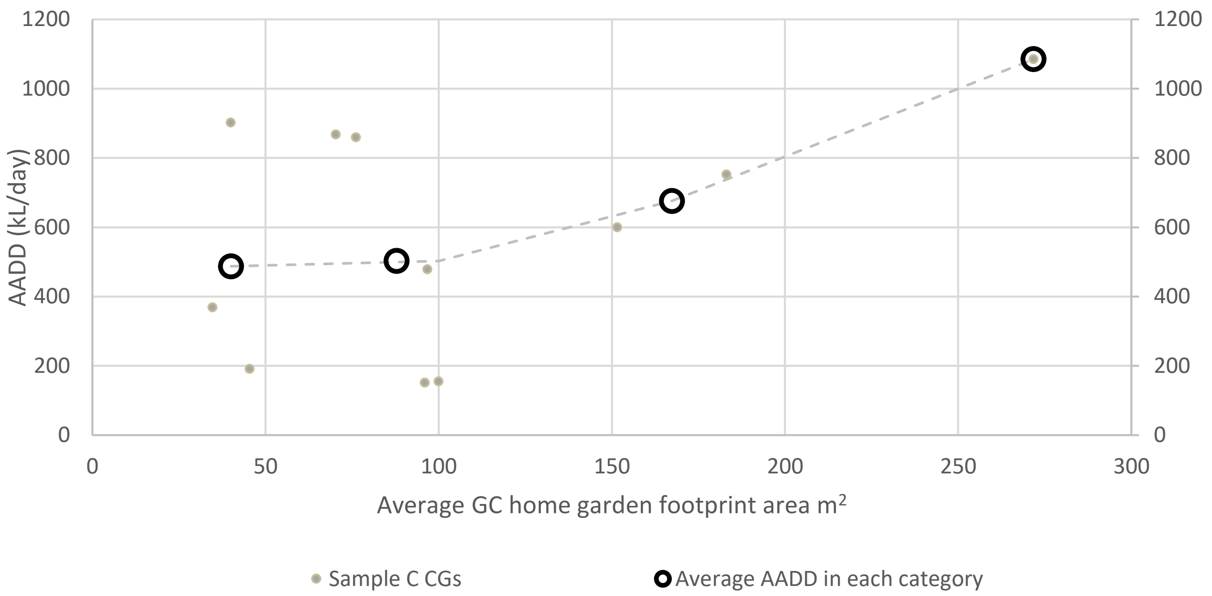

Figure 6.3: Average household water use in relation to average garden footprint area

An approximately linear relationship is suggested between averaged GC household AADD and corresponding garden footprint area. As expected, the water use of homes in GCs increases with increased garden footprint area, but only above a certain minimum threshold value. It is expected that the GCs with an average garden footprint area of less than 100 m^2 mostly have indoor water use, while outdoor water use influences total water use in homes with larger garden footprint areas. Although the average values appear to show a linear relationship between garden footprint area and water use, the AADD-values in the garden footprint classes smaller than 100 m^2 vary notably from one GC to the next. The data sample used in this study was not large enough to justify extrapolation of the findings to GC homes in general, nor could a valid linear relationship be found from this sample.

The seasonal fluctuation of domestic water use is usually indicative of outdoor water use, especially gardening (Du Plessis et al, 2018). An indication of the seasonal water use was obtained by assuming, in line with earlier work (Ghavidelfar et al., 2018; Du Plessis et al., 2018), that the minimum winter consumption is indicative of indoor water use. The water requirement of plants and in particular grass, is often expressed as millimetres irrigated per week (McCready and Dukes, 2011; Venter and Grove, 2016). The seasonal fluctuation in water use of the 11 GCs in this sample was transformed by dividing monthly GC water use, express as a litre per week scale, by the corresponding garden footprint area (m^2) in order to express the water use in units of mm/week. The seasonal fluctuation was subsequently evaluated by subtracting the minimum monthly consumption in each case from the corresponding peak monthly consumption, as an approximation of outdoor use. The analysed data for the GCs in each of the applicable cites were subsequently ranked as plotted, as illustrated Figure 6.4. The average seasonal fluctuation in water use in relation to the garden area for all of the GCs is 14.85 mm/week, but varies between 3 mm/week and 30.9 mm/week.

The weekly irrigation reported in this study is in the same order of magnitude as values published by others: 15.8 mm/week in California, USA (Chen et al., 2015); 21 mm/week in Florida, USA, (Davis and Dukes, 2015); 47 mm/week in Florida, USA, (Maheshwari, 2016); 35 mm/week Cape Town, South Africa (Nel et al., 2017). In some other regions with relatively low evaporation and relatively high rainfall, the irrigation may be negligible (Saeed Ghavidelfar, Asaad Y. Shamseldin and Bruce W. Melville, 2018).

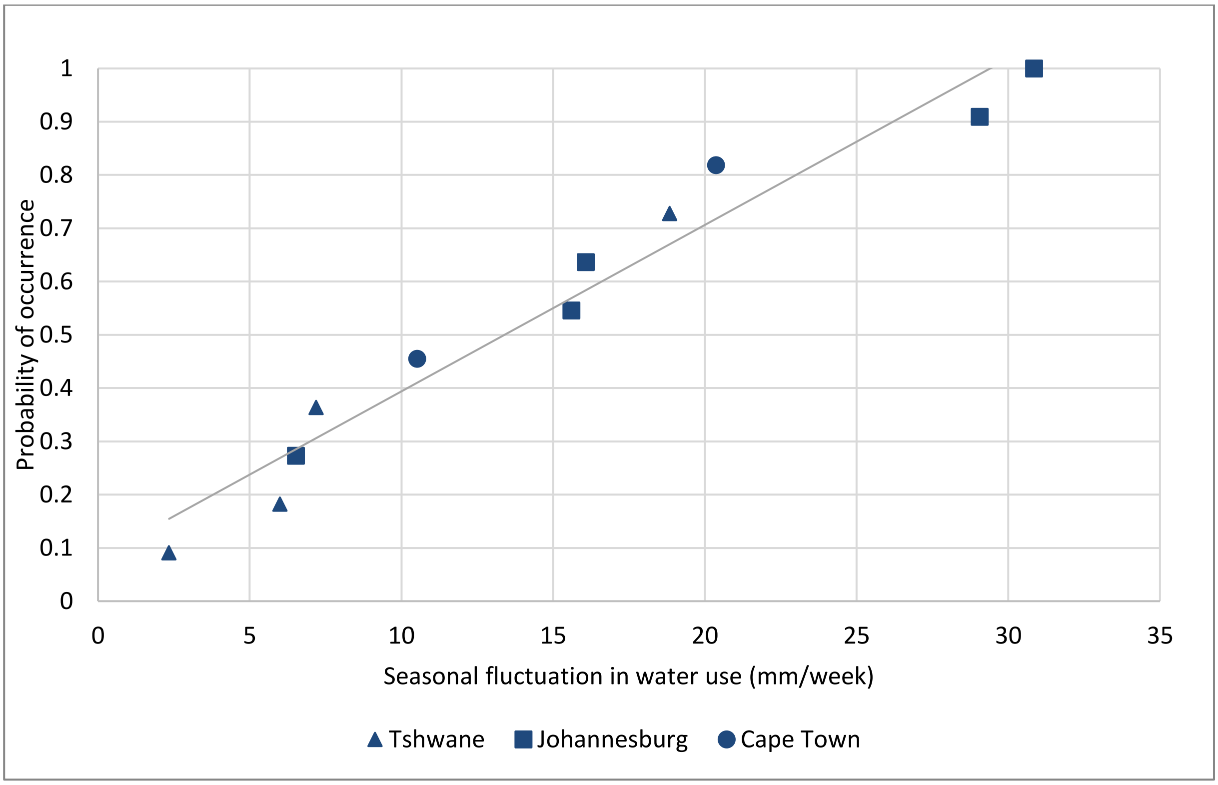

Figure 6.4: Probability of occurrence - seasonal fluctuation in water use

DISCUSSION

As expected, the disaggregation of garden footprint area for GC homes in three identified geographic regions compared well with peak monthly water consumption presented in earlier work for the same regions (Du Plessis and Jacobs, 2018). Homes in Tshwane had the lowest garden footprint area percentage, while homes in Cape Town (and surrounds) generally had relatively higher garden footprint areas. What was unexpected was that Johannesburg had larger garden footprint area percentages than Tshwane, although the Johannesburg homes had the lowest average plot size. The Tshwane homes' garden footprint percentage ranged between 0 and 70%, with an average of 22.9%, while the Johannesburg homes' garden footprint percentage ranged between 0% and 75%, with an average of 38.8%. The Cape Town and surrounds homes' garden footprint percentage ranged between 0% and 80%, with an average of 41.0%.

The water use of GC homes correlates with the garden footprint area as AADD increases when the garden footprint area increases. As part of a further study, the findings in this study was implemented to model outdoor water of GC homes.

CONCLUSION

A maximum building footprint area of between 30% and 60% is prescribed by regulations in the different GCs reviewed in this study, but the majority prescribed a maximum building footprint area of 50%. Although no specific reference is made to maximum garden footprint area, the vegetation genotype is specified in some cases, often to encourage indigenous plants, or to prevent plant genotypes that require extensive watering.

The garden footprint area of GC homes is notably influenced by total plot area and varies notably by geographic region. The average garden footprint area in relation to the total plot area was found to be 36.3% for all samples, with a standard deviation of 17.5%. In cases where the garden footprint areas of GC homes were larger than 100 m^2, a proportional relationship was noted between the AADD of GC homes and the average garden footprint area. Based on the assumptions for seasonal analysis of Sample C, an average of 14.85mm/week irrigation was determined, although the irrigation demand of the 11 sample GCs was uniformly spread between 3mm/week and 30mm/week.

Findings from this study was incorporated in the parameter calibration of outdoor water use models. Results from this study provide a useful foundation for future research into modelling water use of GC homes.

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Chapter 7:

Verification and calibration of outdoor water use model to gated communities

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ABSTRACT

A model for estimating outdoor water use within gated communities required verification and calibration. Other research addressed by the authors has reported on outdoor water use modelling, deriving of parameters and implementing winter water use or waste water flow as a proxy to segregate indoor and outdoor water use. Existing literature, however, is limited in the verification and calibration of outdoor water use models for gated communities. In this article a model was used to stochastically simulate outdoor water use of gated communities by means of Monte Carlo simulations. Simulated results were compared to segregated outdoor water use of five gated communities on a monthly temporal scale. Sensitivity analyses were used to identify parameters that have the most significant impact on the results of the model simulations. The irrigation efficiency parameter and a calibration factor were used to calibrate the model for a specific gated community.

Keywords: Water use, outdoor, indoor, residential estates, gated communities

INTRODUCTION

Gated communities (GCs) have increased in popularity in South Africa (Landman, 2003), but also in the Americas, Asia and Europe (Atkinson & Blandy, 2006). Social fear and aspirations to be ex-territorial has contributed to the growth in GC numbers (Bauman, 2013). The effect of globalisation cause club economies, fuelled by socio-economic and socio-political transformations which are motivators for the proliferation of GCs (Marquardt, 2013). The growth in GC developments thus calls for research in the water use of GCs.

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

End-use models allow residential water use to be split into separate water end-use components (Scheepers & Jacobs, 2014). Indoor water use has been widely modelled (Blokker et al., 2010), but outdoor use is much more variable and harder to model accurately although models for estimating outdoor use are available (Jacobs & Haarhoff, 2004; DeOreo et al., 2011; Makwiza et al., 2015). Outdoor water use, mainly garden irrigation, is estimated to contribute approximately 40%-60% to the AADD of GC homes, with a resulting seasonal water use pattern (Du Plessis & Jacobs, 2014).

Jacobs (2004) reported that water use modelling, especially in the USA, originally focussed on price elasticity. More recently, the focus has shifted from price to evaluation of water use management issues. Various types of modelling exist in the water use environment. Water use modelling is often a function of spatial and temporal aggregation levels. In water use modelling the planners of GCs are concerned with three levels of modelling (Blokker et al., 2010):

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

RATIONALE

Outdoor water use for GC homes was estimated by employing the model first presented by Du Plessis and Jacobs (2014). The estimates were compared to actual readings reported elsewhere (Mayer et al. 1999) and also to outdoor water use obtained by alternative means as part of this study (Du Plessis et al. 2018).

APPROACH

As part of this study existing water use data was collected from various GCs and was compared to stochastically modelled outdoor water use by means of the model and relevant parameters presented by Du Plessis and Jacobs (2014; 2015). Due to the complex nature of outdoor water use and the metering thereof, data was not available for the study sites pertaining to this research, a proxy approach was required to represent outdoor water use. DeOreo et al. (2011) and Fisher-Jeffes et al. (2015) reported that winter water use could be used as a proxy for indoor water consumption when indoor consumption is assumed to be non-seasonal. Earlier publications reported that winter water consumption could be subtracted from the total water consumption to derive a proxy approach for outdoor water use (Ghavidelfar et al., 2018). Balling et al. (2008) reported that not all winter water use is equal to the indoor water use, because certain outdoor water uses will be required in winter times. For the purposes of a further study the indoor water use of GCs was assumed to be 90% of the month with the lowest water use. The indoor water use was then subtracted from the metered monthly water consumption to derive outdoor water use. Four approaches were used to compare model results with outdoor water use data.

The first approach was to stochastically simulate outdoor water by use means of Monte Carlo simulations and compare the results to the derived outdoor water use from what is referred to as the minimum month proxy method. The input parameters for the stochastically simulated model were defined by obtaining and defining parameters from climatic, geographical and spatial data as presented by Du Plessis and Jacobs 2015. A sensitivity analysis of one GC was conducted in addition to the simulations in order to identify parameters that could cause significant variations in the simulation results.

Secondly, Monte Carlo simulations were conducted on households located in four cities that formed part of the Residential End Uses of Water (REUWS) study conducted by Mayer et al. (1999), because the participating households in the four cities had available outdoor water use data. The minimum month proxy method and simulated outdoor water use was compared with the available outdoor water use.

As a third approach, the mean values of the irrigation efficiency, effective precipitation, crop coefficient, pool maintenance depth and occurrence input parameters were used to crudely model outdoor water use of a GC with a long water use record. The model results were compared to the minimum proxy approach, in a record period without water restrictions and a record period with water restrictions, because water restrictions often target outdoor water use (Hemati et al. 2016).

Lastly a means was investigated to calibrate the outdoor water use model for specific scenarios. Outdoor water use for a specific case study site in the Western Cape, South Africa was modelled and compared with the outdoor water use results as presented by Du Plessis et al. (2018). A calibration of the model parameters was undertaken to achieve a matching outdoor water use profile.

DATA SAMPLING

Various datasets with different resolutions were required to execute the four approaches. Water use data was obtained from earlier publications employing North American homes, and was also collected for entire GCs and individual GC homes in South Africa. The type of data included survey responses, aerial photography, climatic variables, metered water flow rates and monthly consumption, as well as wastewater pump records used to estimate sewage flows.

Monthly water consumption data was obtained for five GCs referred to in this study as GC-A, GC-B, GC-C, GC-D and GC-E. Further outdoor water use data was available for households in the United States of America (USA) cities. The location and timeframe of the available data, the number of houses for which data was available, and the average property size of properties in the GC are tabulated in Table 7.1.

Table 7.1: Attributes of GCs from which data was collected

	Location	**Duration of available data**	**Number of houses**	**Average property size (m^2)**
GC-A	Paarl, South Africa	1 year	153	818
GC-B	Stellenbosch, South Africa	4 years	390	666
GC-C	Franschhoek South Africa	3 years	23	1270
GC-D	Cape Town, South Africa	15 years	150	553
GC-E	Overstrand, South Africa	1 year	350	800
Boulder	USA	2 weeks	100	605 (Garden footprint area)
Lompoc	USA	2 weeks	100	436 (Garden footprint area)
Eugene	USA	2 weeks	98	638 (Garden footprint area)
Phoenix	USA	2 weeks	100	843 (Garden footprint area)

The data series was collected and grouped into complete years from April of one year to March of the following year, except for GC-E where only data for August 2015 to July 2016 was analysed to coincide with the data used in a study by Du Plessis et al. (2018). The reason for obtaining data from April to March was that outdoor water consumption is influenced by seasonal change, and it was considered appropriate to include the latest summer peak season water use that was available on record.

Water meter readings were obtained from two recognised consulting firms in the water meter reading industry. The consultants assured a high level of accuracy of the readings and confirmed that meters were read on a monthly basis on about the same day or within one variance. Some anomalies were, however, found during the evaluation of the data. The anomalies included the following: (i) Non-residential buildings were included in the records; (ii)

Some buildings were constructed during the timeframe analysed in this study; and (iii) Zero readings were detected at some homes that were completed.

All non-residential properties such as HOA offices, security buildings, maintenance yards, commercial and administrative related buildings were excluded, as they were irrelevant to this study's analyses. Non-residential use does contribute to the water use of GCs; however, they do not contribute to domestic outdoor water use.

Conditional filtering was applied to eliminate properties that registered zero flows during multiple months in a year. The zero flows can be ascribed to (i) home owners being on a long-term business/holiday trip, (ii) the home being used as a holiday home, (iii) the water meter is not registering correctly or the home being a rental unit that was not occupied for that period. In the case where homes were detected as having zero water consumption for two consecutive months or more, the specific year's data of these homes was excluded from the analyses.

The data records of GC-A, GC-B and GC-C that extended over multiple years were collated by calculating the arithmetical mean of the consumption of each property for the individual months of the year. A combined average monthly consumption dataset for each GC was attained. This record was thereby further analysed and compared with simulation models.

The individual property sizes was measured by using AutoCAD software from the cadastral information on as-built drawings of each of the GCs (Du Plessis and Jacobs 2019). These property sizes were incorporated in the water consumption records prior to the data filtration process. The derived model parameters (Du Plessis and Jacobs, 2015) was used to simulate outdoor water use of GCs as per the model by Du Plessis and Jacobs (2014).

The REUWS database was developed by various engineering consultants for the American Water Works Association's Research foundation (Mayer et al. 1999). The REUWS database included water end-use data for 1188 houses located in 12 locations in Northern America of which the data for 398 houses had average annual indoor water consumption data as well as measured potential irrigation areas. These 398 houses were located in Boulder, Eugene, Lompoc and Phoenix.

GC-D was used to verify the model over an extended record period and test the effect of water restrictions on outdoor water use. GC-E's disaggregated outdoor water use component presented by Du Plessis et al. (2018) was used to calibrate the model for the specific case.

MODELLING AND RESULTS

Minimum month proxy approach

In this section, modelled monthly outdoor water use was compared to findings based on a proxy approach for outdoor water use. DeOreo et al. (2011) suggested that the winter water consumption could be used as a proxy for indoor water use. In other words, monthly outdoor water use could be derived based on this proxy approach, given total monthly household water use. Outdoor water use could also be estimated by means of an outdoor end-use model (Du Plessis and Jacobs, 2014), allowing for comparison of the monthly water use. The outdoor end-use model was used to simulate outdoor water use of GCs using climatic data that was collected for study sites GC-A, GC-B and GC-C. The parameters such as irrigated area, irrigation efficiency, crop coefficients, pool size, pool maintenance methods and occurrences were based on results presented by du Plessis and Jacobs (2015).

The @Risk software was used to perform 1000 iterations of the outdoor water use model for GC-A, GC-B and GC-C using random selections of the fitted probability distribution functions of the input parameters. A factor 0.9 times the minimum monthly consumption was used to estimate the non-seasonal indoor monthly consumption and subtract the indoor use from total water use to derive outdoor water use. Results from the proxy approach were compared to modelled results based on Monte Carlo simulations for each of the three study sites, as shown in Figure 7.1, Figure 7.2 and Figure 7.3.

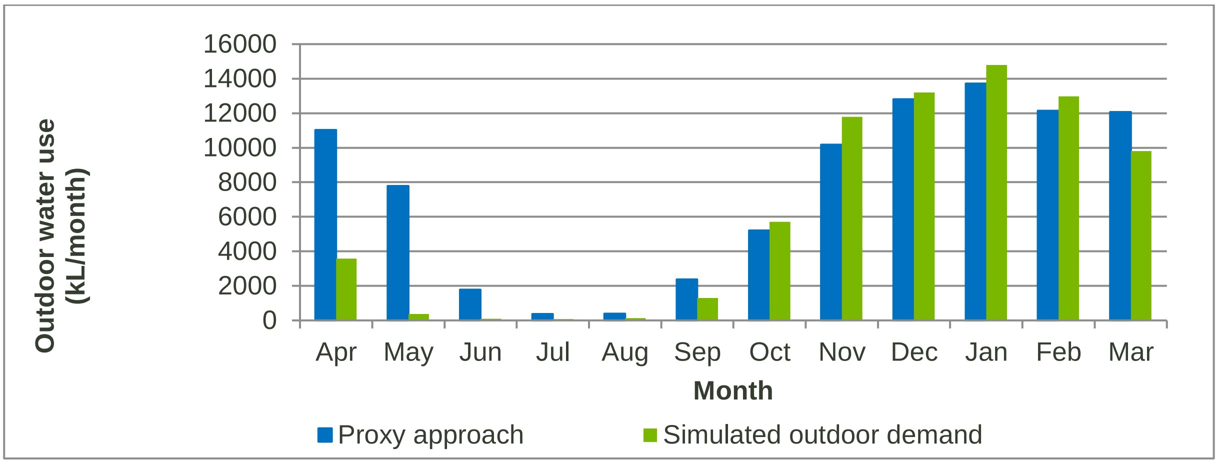

Figure 7.1: GC-A outdoor water use results comparison

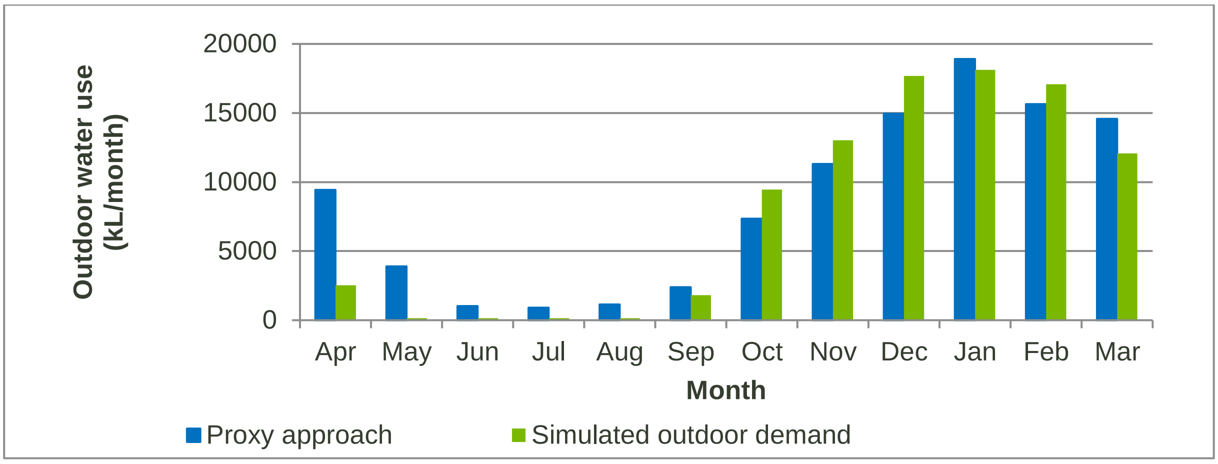

Figure 7.2: GC-B outdoor water use results comparison

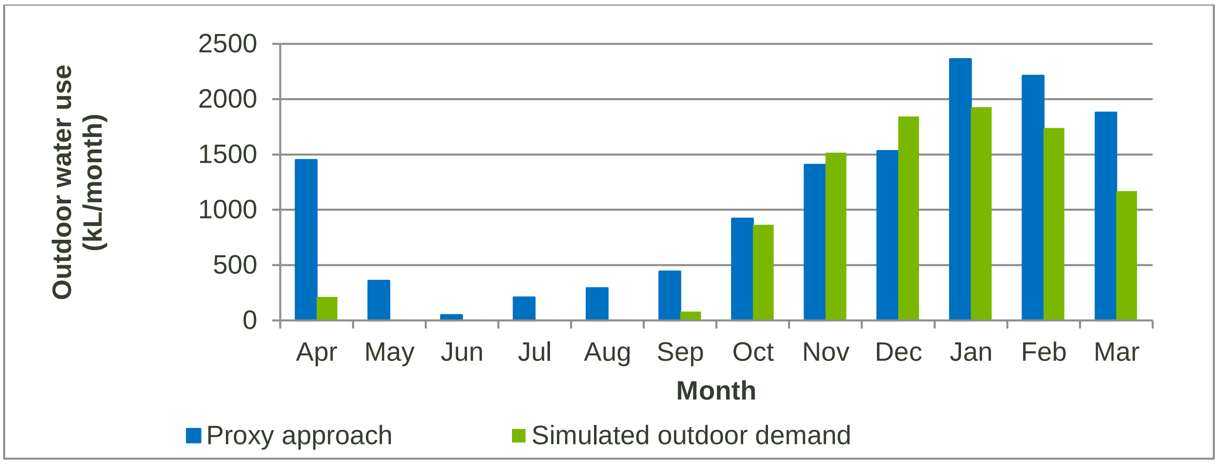

Figure 7.3: GC-C outdoor water use results comparison

The peak monthly use is significant in the design of network infrastructure and could therefore be valuable to the network modeller. The total annual outdoor water use could be valuable in terms of sizing bulk infrastructure and applying for legislative approval. Table 7.2 summarises the peak month and the annual total use of the simulation in comparison with the indoor proxy approach.

Table 7.2: GC outdoor water use results

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

From the results, it is evident that the simulations fared better in terms of estimating the peak monthly outdoor water use than the total annual outdoor water use. In order to evaluate the differences, the results were visually evaluated on a monthly temporal scale.

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

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

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

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

Verification of model performance in relation to USA households

Outdoor water use as presented in Mayer et al. (1999) was compared to the proxy approach and modelled results in Figure 7.4, Figure 7.5, Figure 7.6 and Figure 7.7. The red squared points on the graphs indicate the outdoor consumption by Mayer et al. (1999) and the blue bars indicate the proposed proxy outdoor water use. The green bars represent the modelled outdoor water use. The suspected reasons for the anomaly in the simulated and proxy results for the houses in Boulder and Pheonix were that these houses are located in arid areas where water conservation rebates are promoted and vegetation that survives in these regions require less watering.

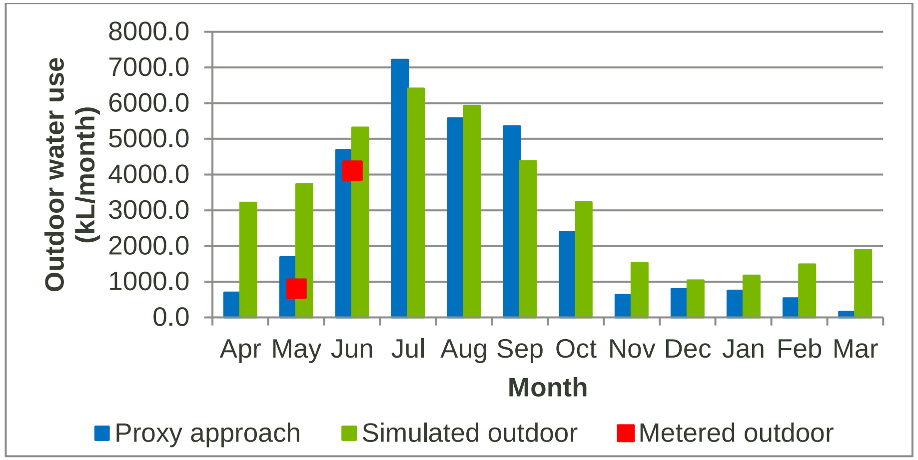

Figure 7.4: Verification of proxy approach – Boulder

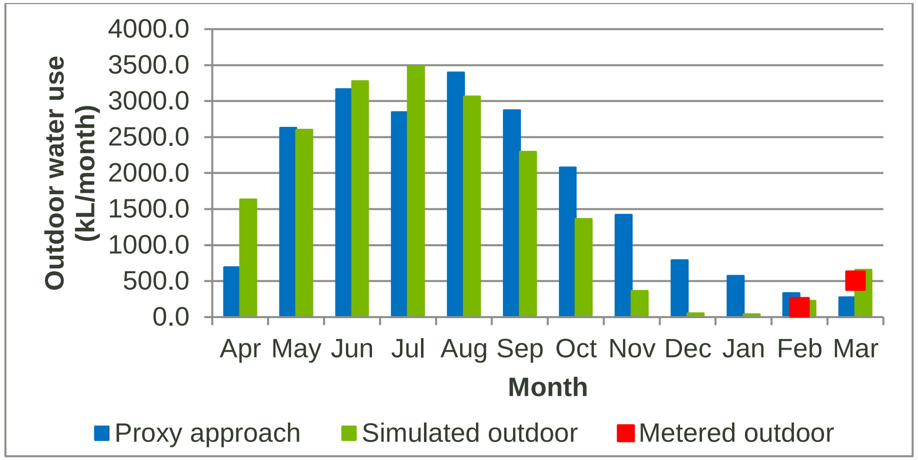

Figure 7.6: Verification of proxy approach – Lompoc

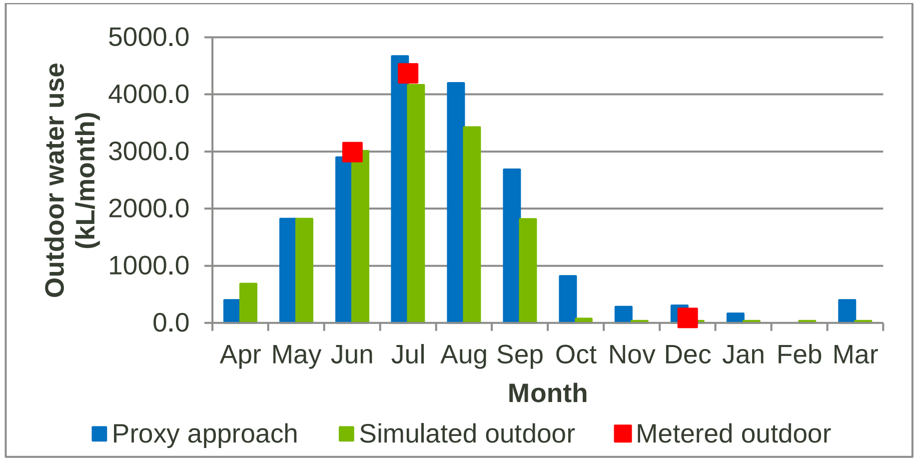

Figure 7.5: Verification of proxy approach – Eugene

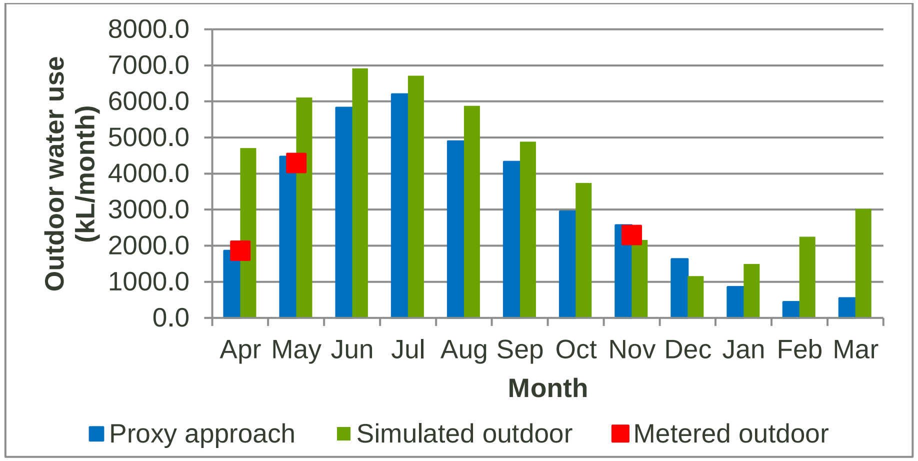

Figure 7.7: Verification of proxy approach – Phoenix

Sensitivity analyses and Confidence interval results

The @Risk software was used to perform sensitivity analyses on each of the model parameters. The sensitivity analysis was performed on the GC-A simulations for total annual outdoor water use and the outdoor water use for the peak summer month (January) and low winter month (July). The parameters were ranked and positioned on the graphs illustrated in Figure 7.8, Figure 7.9, Figure 7.10 and Figure 7.11, according to their effect on the final outcome of the results produced by the simulations.

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

Although the average precipitation, evaporation and evapotranspiration parameters were based on average data, it is expected that this data will vary on a year to year basis. The impact of the variation was tested for GC-A by developing probability distribution functions for each of these parameters on a monthly temporal scale. Although ranked third and eighth respectively, evaporation and rainfall did not have as significant impact as the irrigation efficiency parameter in the sensitivity analysis.

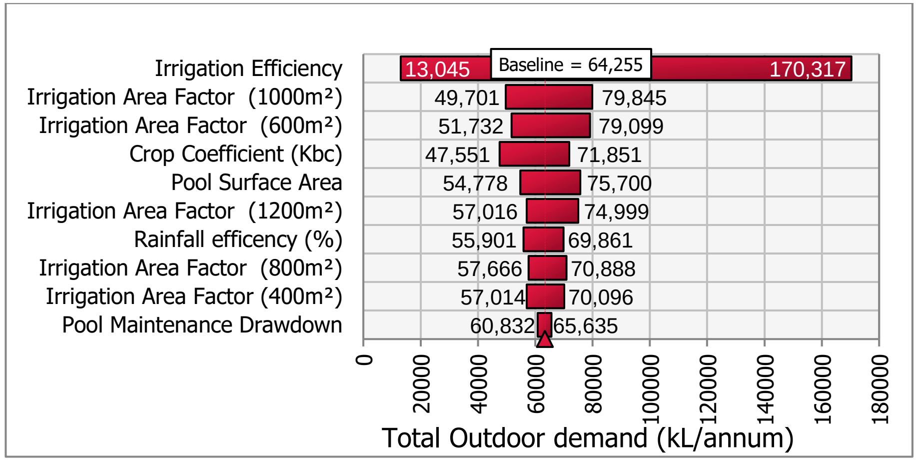

Figure 7.8: Total annual water use sensitivity analysis

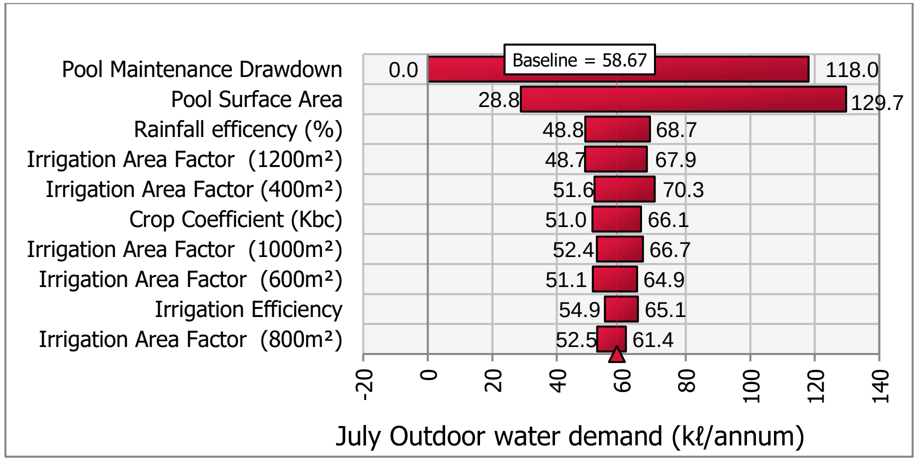

Figure 7.10: Low winter month water use sensitivity analysis

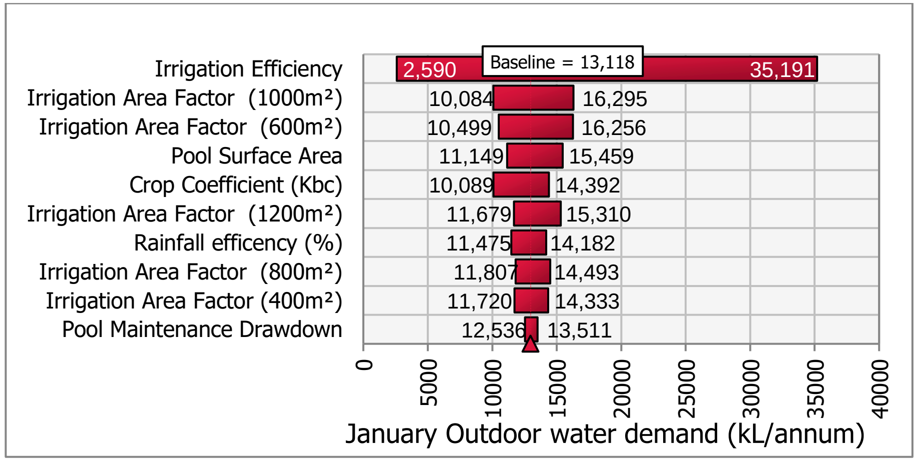

Figure 7.9: Peak summer month water use sensitivity analysis

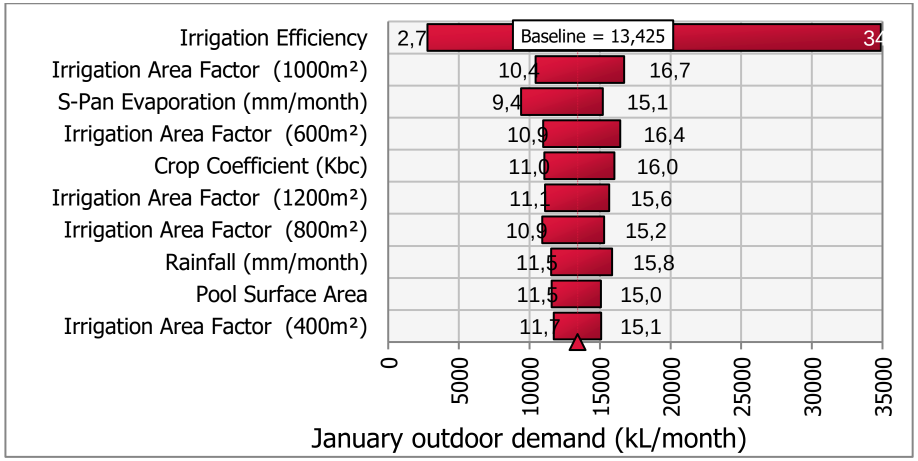

Figure 7.11: Sensitivity analysis for January, distributed weather

Model simulation on extended time series

A continuous 174-month (Sep 2003 to Feb 2018) water use record was obtained for a case study site in Cape Town, South Africa. The particular gated community was labelled GC-D. Water use of the particular GC was modelled using actual monthly evaporation and rainfall data from a nearby rainfall station maintained by the South African department of Water Affairs and Sanitation. Vegetation types and outdoor water use was estimated from data collected during a site visit. Garden footprint area and pool area was derived from aerial photography as shown in Figure 7.12.

Figure 7.12: Garden footprint area of GC-D

The input parameters used for the simulations were derived and applied to the outdoor water use model as presented by Du Plessis and Jacobs (2014; 2015). Figure 8.13 shows the outdoor water use estimation methods for GC-D. The record included 12 years of water use with no water restrictions and three years (2004/2005, 2016/2017 and 2017/2018) where water restrictions were enforced by the City of Cape Town. Water restrictions were imposed in October 2004 (Jacobs et al., 2007), clearly leading to reduced outdoor water use as visible in Figure 7.13. Recent water restrictions had a similar effect on the outdoor water use, although the impact of a potential Day Zero scenario and related emergency restrictions was more severe.

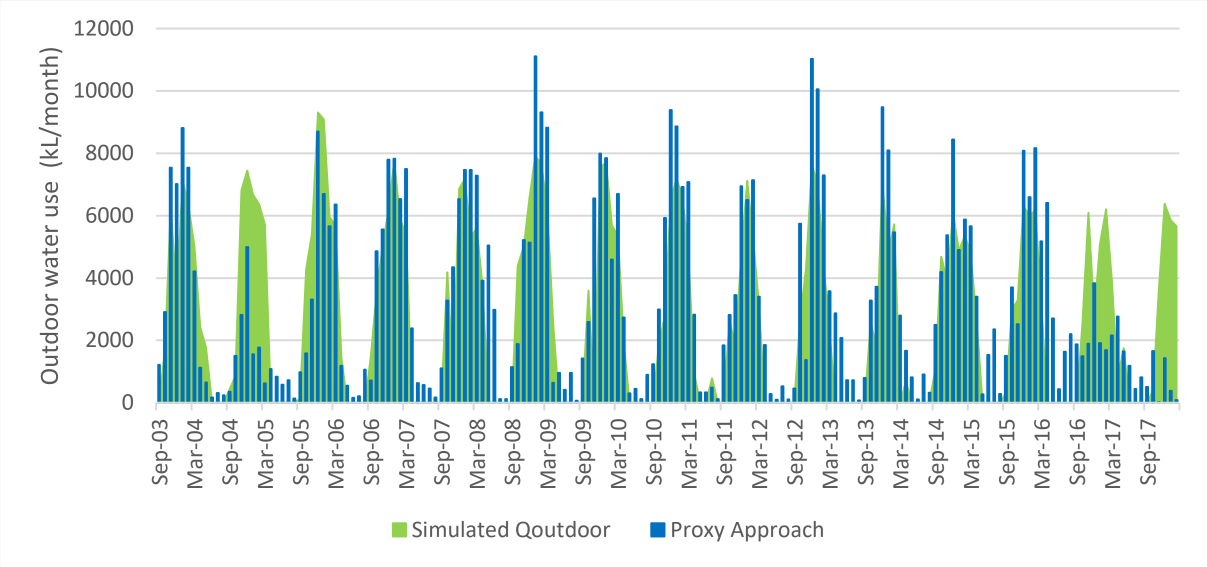

Figure 7.13: Extend time series of outdoor water use for GC-D

The correlation between results for the simulated and proxy monthly outdoor water use was investigated. The coefficient of determination was also calculated. Figure 7.14 shows the correlation plot between the 144 monthly results (periods of water restrictions relating to outdoor water use were excluded). The coefficient of determination was found to be $R^2 = 0.80$. Winter rainfall significantly exceeds evapotranspiration in the study area, resulting in numerous near-zero values in winter months. These low consumption months were not filtered out, and negatively impact the R^2 value. It would be useful to calibrate the model in an attempt to improve the correlation.

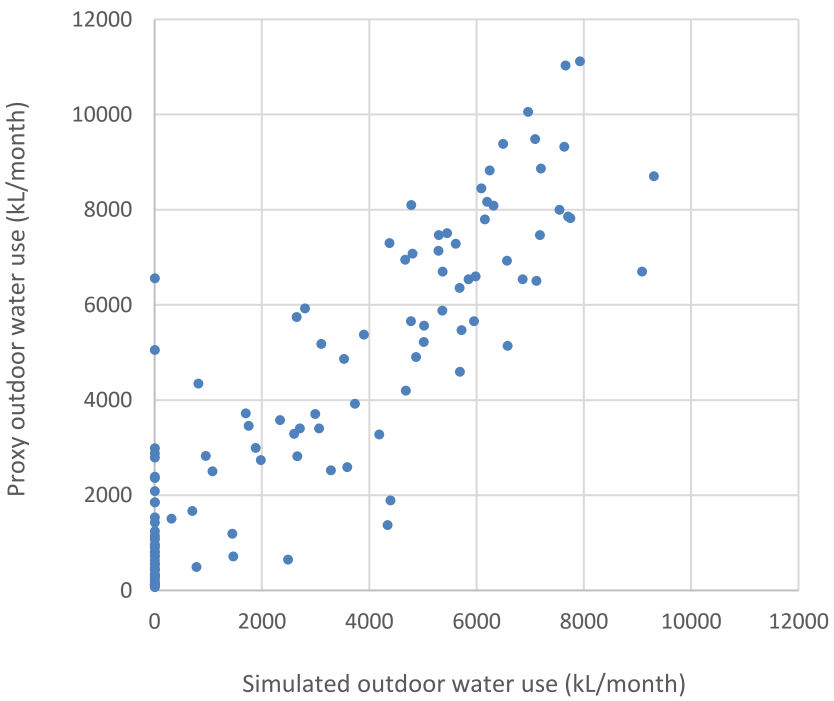

Figure 7.14: GC-D model correlation

Model calibration

In order to calibrate the model, a simulation of outdoor water use was conducted for GC-E, because the outdoor water use of GC-E presented by Du Plessis et al. (2018) was compared to the simulated outdoor water use. It was reported for this site that the occupation rate was 72% due to some of the homes being holiday homes, therefore this ratio was applied to the garden footprint area of the total GC. From site inspections it was reported that the vegetation of the homes is generally indigenous as promoted by the GC's architectural guidelines. A crop coefficient of 0.6 was thus applied. The irrigation of the homes was found to be of high efficiency and thus an irrigation efficiency factor of 0.95 was allowed for. The simulation results are presented in Figure 7.15.

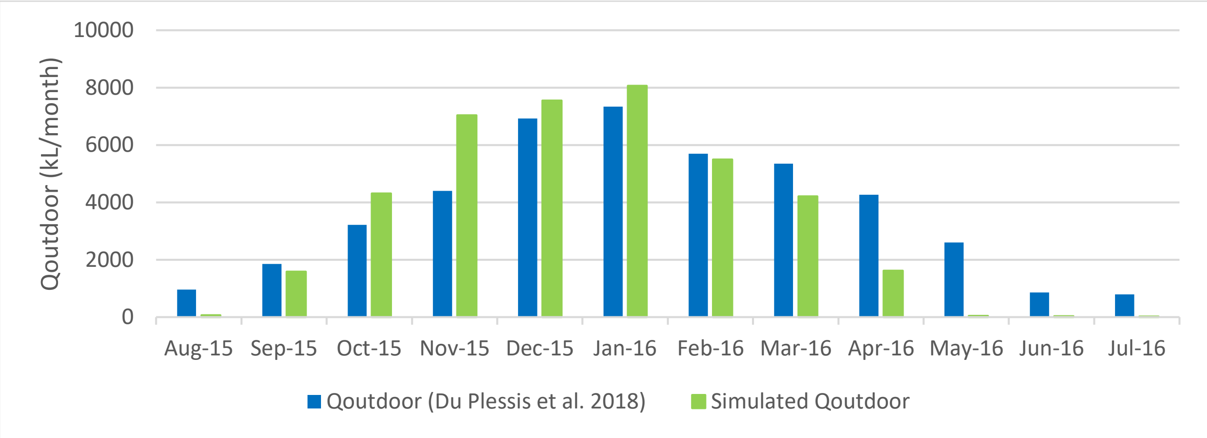

Figure 7.15: GC-E outdoor water use profile

As with GC-E, a correlation between the Outdoor water use (Du Plessis et al., 2018) and the simulated outdoor water use exists (Figure 7.16), however, the R^2 of the correlated data is only 0.80.

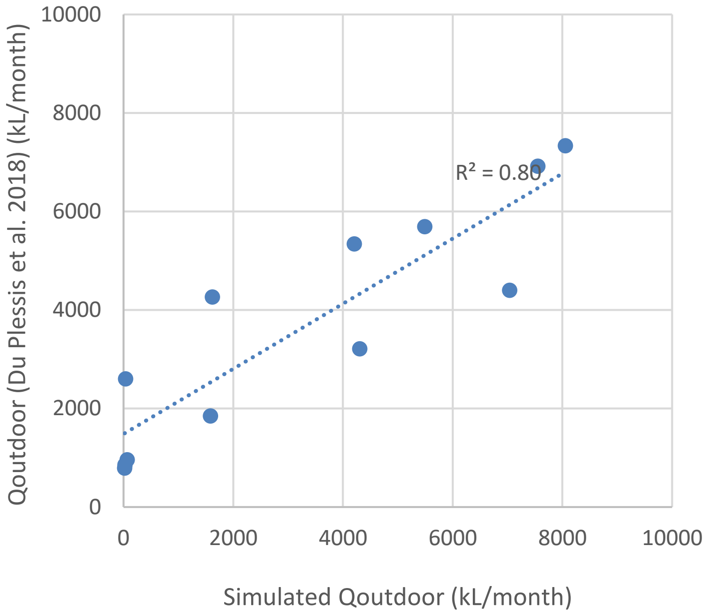

Figure 7.16: GC-E model correlation

In an aim to improve the correlation, a calibration of the irrigation efficiency and an additional calibration factor was investigated. The calibration factor accounts for other minor outdoor water uses not modelled, metering errors and potential model errors. For the purposes of this study a calibration factor of 2.25 kL/home/month was added to the simulated model results, and the irrigation efficiency was varied in 0.05 increments to achieve a correlation of R^2 = 0.98, demonstrated in Figure 7.17. Improved accuracy of the model could be achieved by means of iterative algorithms, but would require further research into the irrigation efficiency parameter and the proposed calibration factor.

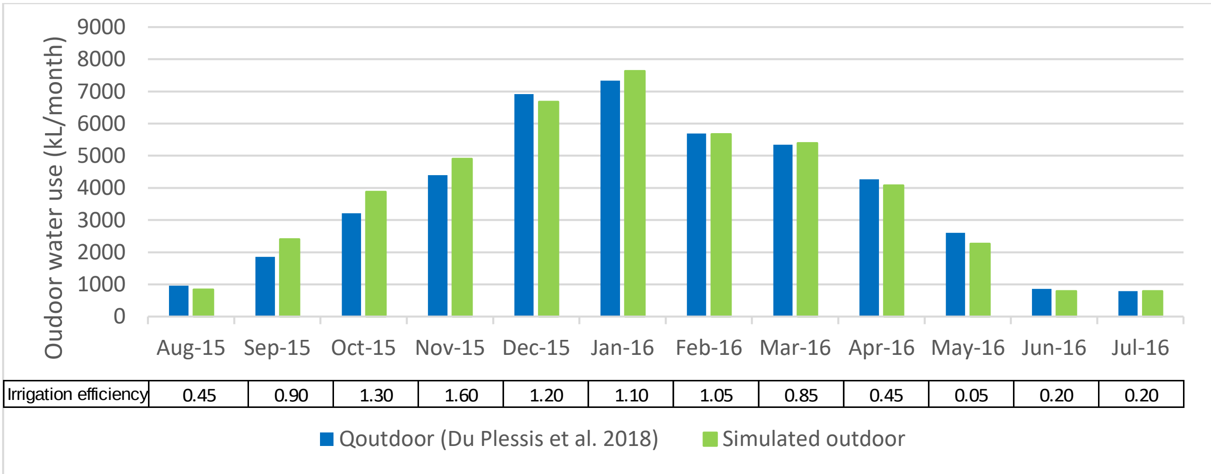

Figure 7.17: GC-E calibrated outdoor water use profile

Considering the irrigation efficiency in the spring and fall (transition) months, it is noted that a response lag to seasonal change, which have an over irrigation effect. This could be ascribed to homeowner uptake response lag as experience in behavioural change initiatives in other industries (Guo et al., 2016) .

CONCLUSION

Development of technology such as high-resolution water meter logging has improved the level of accuracy with which individual end-uses could be pinpointed using tracer analysis models. From these models the end-use models originated, allowing researchers to estimate and even predict water use on a relatively intense temporal scale (DeOreo et al., 2011; Scheepers 2012). As part of previous studies an outdoor water model was developed specifically to address outdoor water use of GCs on a monthly temporal scale (Du Plessis and Jacobs, 2014, 2015). The model consisted of the following outdoor use components namely (i) Irrigation; (ii) Pool and water feature evaporation top-up and (i) Maintenance, including rinsing and backwashing of pool filters.

Incorporating the parameters derived by Du Plessis and Jacobs (2014, 2015), models for five GCs and homes in four USA cities were simulated using the @Risk software, a Monte Carlo simulation package. One thousand iterations were conducted for three of the GCs and the homes in the USA cities. The modelled outdoor water use results were then obtained on a monthly temporal scale.

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

From the sensitivity analyses it was found that irrigation efficiency is the main contributor to the variation in the estimation of annual and peak summer outdoor water use. In winter months this role is taken by the amount of water used for pool maintenance per occurrence. The simulation results of GC-A with the largest sample of data was the closest to the estimated outdoor consumption, demonstrating that, within the GC environment, the model could perform within acceptable bounds of accuracy, even when crude mean values are used in the simulations.

The model was further verified over a longer record period for GC-D to compare the minimum month proxy approach with the simulated results for an extended period. It was found that the model performed well even when crude mean values are used to define the model parameters. The effects of water restrictions were also evident in the results.

The outdoor water use data available for GC-E was used to calibrate the model by iteratively changing the irrigation efficiency parameter. Additional attention should given to irrigation efficiency and a proposed calibration factor, because these parameters significantly dictate the outcome of the model results. With refinement of the model, it can be further implemented on a detailed design scale of water, greywater and alternative water systems.

The comparison of the results with the groups of houses in the cities/towns that are located in North America demonstrated that, with further research, the model could potentially be further implemented internationally and outside the GC environment. The research proved that in the absence of site-specific knowledge, the outdoor water use of a GC could be simulated using basic climatic data and estimated residential property sizes and quantities. Combining the results from this study with the indoor water use results from a model such as the model developed by Scheepers (2012), developers, designers and planners can stochastically estimate the total water use of a GC on an annual or a monthly temporal scale.

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Chapter 9: General discussion

Unique Character of gated communities

GCs typically comprise occupied homes, vacant plots, communal roads, parks and amenities. The common areas are owned and maintained by a GC home owners' associations (HOAs), not the local Municipal authority as would be the case for a suburban home. Although homes in GCs are privately owned, owners have to adhere to the GC rules of conduct as well as Municipal bylaws. A GC is typically guarded and fenced for security purposes (Radetskiy et al., 2015).

In contrast to GC homes, suburban residential areas predominantly comprise roads, communal areas and private plots. Communal areas including public open space and parks are controlled and maintained by a municipality (utility). Plots are privately owned and consist of a house, and also possibly a garden and driveway with parking for vehicles. Some of these private homes would be individually enclosed by a fence for improved security.

GC homes are unique in the shared ownership of facilities, communal areas, infrastructure and resources. The often strict HOA guidelines that prescribe architecture, landscaping, water use, safety and security, allow for uniformity in GCs. The distinctiveness of uniformity and complete ownership of GCs benefit research objectives, because certain parameters are more predictable than with the case of homes in normal suburban areas.

GC water use and data limitations

Earlier publications (DeOreo et al., 2011) are limited in the reporting on GC water use and thus further research was required. The water use of GC homes in the study area was relatively low in comparison with other guidelines for residential plots (Du Plessis and Jacobs 2018 - Chapter 2). The garden footprint area of plots in GCs was found to be relatively small in comparison to plots in suburban neighbourhoods. Garden footprint area is discussed in further detail under the particular section of the Discussions chapter. Communal garden irrigation by the GC, often with non-potable sources, may lead to reduced private GC home irrigation and/or a reduced need for an irrigated garden, leading to reduced water use in the GC homes. Bekleyen et al. (2016) stated that neighbourhood enhancements lead to increased consumer awareness of the environment. GC home owners could be considered more conservation minded, leading to water conservation and relatively lower water consumption.

Elements prescribed by HOAs that target outdoor water use such as vegetation, pool water use, irrigation philosophy, rainwater use and greywater reuse, contribute to the unique nature of GCs. These elements offer the opportunity of specific research into outdoor water use of GCs. However, the availability of outdoor water use data is limited, because of the intrusiveness and cost of outdoor end-use metering, which led to the development of proxy approaches to derive outdoor water use. One method use widely is to use winter water use as a proxy for indoor water use. Outdoor water use could subsequently be estimated, if the total use is known.

Another approach involved using the wastewater flows derived from pump records to disaggregate indoor and outdoor water use (Du Plessis et al., 2018 – Chapter 4). The wastewater return flow, aggregated with estimated water losses and non-domestic water use, was compared to total water use in order to derive proxy indoor water use estimates for the study site. Results showed that the month to month indoor wastewater return flows remained fairly constant while the outdoor use component contributed notably to the total water use of the gated community. The seasonality of the total water use can be attributed to the outdoor water use component, with garden irrigation probably the most notable end-use. Integrated analysis of the water supply and wastewater flow allowed for segregation of indoor and outdoor use, without the need to measure at household level. The approach was found to be valid for the specific case, however could be considered for implementation on relatively homogeneous fully serviced residential communities where the boundary conditions relating to water inflow and sewage outflow is accurately measured. The proxy approaches were developed in the aim to have a set of data for further research comparisons.

Model for outdoor water use in GCs

The outdoor use model by Du Plessis and Jacobs (2014) was developed from principles presented in other publications (Midgely et al. 1994; Mayer et al.; 1999; Jacobs, 2004; DeOreo et al., 2011). The mode differs from previous models as it addresses pool ownership and pool maintenance in further detail. Irrigation efficiency was also incorporated into the model in the format presented in international publications (Canone et al., 2015). It was found suitable to develop the GC outdoor water use model and relevant parameters to allow for stochastic simulations. The research specifically also focussed on garden footprint area and pool water use.

Garden footprint area

Garden footprint area was identified as a driver for outdoor water use. A method was required to derive garden footprint area from aerial photography. Computer aided design software was used to derive garden footprint area of GC homes (Du Plessis and Jacobs, 2019 – Chapter 6).

Garden footprint area was compared to water use GC homes in three identified geographic regions. Homes in Tshwane had the lowest garden footprint area, while homes in Cape Town and surrounds generally had relatively higher garden footprint areas. What was unexpected was that Johannesburg had larger garden footprint area percentages than Tshwane, although the Johannesburg homes had the lowest average plot size. The findings could be attributed to the property price, income levels and the lower price of water for properties using less than 35 kL/month in Johannesburg. Further research into these parameters could be conducted as part of future research. In general, the water use of GC homes correlates with the garden footprint area as AADD increases when the garden footprint area increases. The results from the garden footprint area analysis supports the low GC water use of the City of Tshwane (Region C in Du Plessis and Jacobs, 2018), because it was shown that GCs in the City of Tshwane generally have smaller garden footprint areas.

Pool use

In Chapter 4 and 5 (Du Plessis and Jacobs, 2014; 2015) imagery from Google Earth was used to determine the surface area of pools at properties. It was determined that pools surface areas varied between 7 m^2 and 30 m^2. It was required to determine pool maintenance behaviour. Results from a questionnaire were used to depict the pool drawdown depth and frequency of pool backwashing procedures by home owners. The data extracted from geospatial analysis of aerial photography and the survey was applied to pool ownership factor and the pool surface area and pool maintenance parameters of the Monte Carlo simulations. The measured pool surface area dataset was again analysed using @Risk software, after which the probability distribution function was utilised in the Monte Carlo Simulation. The pool maintenance behaviour varies from home owner to home owner and requires further research.

Model verification and calibration

In Chapter 8 (Du Plessis and Jacobs, in press 2019) computer based stochastic simulations of the outdoor water use model for GCs were conducted on a monthly temporal scale. Probability distribution functions were derived for the parameters required for the mathematical model. These probability distribution functions were based on literature and on data collected from GCs. Incorporating the parameters, model simulation scenarios were populated for five GCs. These models were hereafter simulated using the @Risk software. Modelled outdoor water demand results were then obtained on a monthly temporal scale. The model was further compared to the REUWS database which included outdoor water use data for 398 houses located in Boulder, Eugene, Lompoc and Phoenix in the USA.

Based on model comparisons, it was found that the model performed adequately in estimating the peak summer month demand, especially for GC-B and GC-C of which the sample size was the largest. The simulations of two of the locations, Lompoc and Eugene, performed acceptably, whereas the simulations conducted for Phoenix and Boulder overestimated the outdoor water demand. The suspected reasons for this anomaly were that these houses are located in arid areas where water conservation rebates are promoted and vegetation that survives in these regions likely require less watering.

Comparison of the model results versus the winter proxy data for GC-D showed the effect of water restrictions on outdoor water use. With further research, application of the outdoor water use model to determine potential water savings through water restriction actions would be valuable. The model was calibrated for GC-E by using a simple incremental iterative fitting technique to achieve a correlation that could be applied in practice. A more complex method of calibration could be developed as part of future research to attain an increased of level of correlation.

Sensitivity analyses were conducted and it was found that irrigation efficiency was the main contributor to the variation in the estimation of outdoor water use. In winter months, this role is taken by the amount of water used for pool maintenance per occurrence. The irrigation efficiency parameter could be further developed as part of future research to narrow down the variation in the effect on the water use model. The results suggest that GCs' irrigation efficiency would vary monthly as certain GC homeowners would have different irrigation philosophies, which could have a temporal impact on the water use in GCs. The simulation results indicate that GC homes have a notable lagged response to seasonal change in climate, which cause under and over irrigation in transition months. The specific behaviour could potentially be addressed by awareness campaigns introduced by GC HOA's.

Model application

The application of a model of this nature is widespread and it can be adapted for outdoor water use prediction purposes and estimation of possible water conservation volumes, should water restrictions be implemented. In areas where dual water supply systems are considered, this model could provide insight into possible water savings and could provide opportunity for the establishment of water unit prices. The model could also be used to estimate outdoor water use for the purposes of designing proposed GCs. In addition to the estimation of outdoor water use, the outdoor water use model could be applied to evaluate the status quo of the actual outdoor water consumption of existing GCs.

In the absence of site-specific knowledge, the outdoor water demand of a GC could be simulated using basic climatic data and estimated residential property sizes and quantities. Combining the results from this study with the indoor water demand results from a model such as the model developed by Scheepers and Jacobs (2014), a developer or planner could stochastically estimate the total water demand of a GC on an annual or a monthly temporal scale.

Since the development of the outdoor water use model for GCs, the model has been applied to a baseline adjustment project pertaining to shared water savings contracts for the South African National Department of Public Works (Jacobs et al., in press 2019). The outdoor end-use model could find further application in future to residential water saving and water conservation projects.

Chapter 10: Conclusion

Summary of findings

The results for an analysis of 2888 GCs confirmed that water use in GCs is notably different, generally lower, from previously published residential water use estimates for AADD. The difference could be attributed to the availability of alternative water sources for irrigating communal gardens, and the unique, homogeneous design of homes and garden layout in GCs, as opposed to suburban standalone homes. An investigation of GC regulations and design standards has motivated research in outdoor water use of GCs. However, data limitations brought about a need for innovative alternatives to estimate outdoor water use of GC homes.

Wastewater return flow derived from pump records, aggregated with estimated water losses and non-domestic water use was used to segregate indoor and outdoor water use. Results showed that the month to month indoor water use remained fairly constant while the outdoor use component contributed notably to the seasonal fluctuation of total water use of the gated community. About 58% of the annual average household water use was applied outdoors, while a 73% outdoor water use was recorded in the peak summer month's water use.

An outdoor water use model for GCs was developed to further account for data limitations. Parameters were derived for stochastic simulations of the outdoor water use model using Monte Carlo methods. The outdoor water use model simulations yielded results that are comparable with outdoor water use data as well as proxy outdoor water use data. This model could, therefore, easily be implemented to estimate outdoor water use for feasibility and designs of GCs where certain parameters such as proposed irrigated areas, irrigation efficiency and crop coefficient profiles could be defined by GC developers. In order to validate the results, the simulated outdoor water use was expressed as a ratio in relation to the winter month proxy water use. In other words, where the ratio is less than 100% the model simulations underestimated outdoor water use. An average ratio of 92% was reached for the peak month outdoor water use estimation relative to proxy outdoor water use data, while an average ratio 82% was obtained for the total annual outdoor water use estimations in relation to proxy outdoor water use data. Homeowners generally over-irrigated during the transition months of the year when evapotranspiration decreases and rainfall increases, which contribute to the under estimation of outdoor water use on an annual scale.

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

The model was calibrated by applying a calibration factor and iteratively varying the irrigation efficiency on an incremental basis to improve the coefficient of determination from R^2=0.80 to R^2=0.98. A calibration factor and varying the irrigation efficiency thus improved the model relevance and is proposed for future application where more information is available regarding the outdoor water use behaviour of inhabitants of GC homes.

Novel contributions

The research contribution is unique in the estimation of domestic outdoor water use of GCs in the sense that:

- Outdoor water use parameters such as garden footprint area, vegetation, irrigation scheduling, pool size and consumer behaviour was derived using novel methods;
- A novel outdoor water use model for GCs was developed, simulated and verified against indoor water use as a function of the lowest water use month;
- The research demonstrated a correlation between water use and garden footprint area of GC homes; and
- Wastewater flow from a GC as a proxy to disaggregate indoor and outdoor water use for GCs

Future Research

GC water use varied notably between three cities in the study sample, suggesting that further research is needed to explain the disparity. Two of the cities were located in a summer rainfall region and one was located in a winter rainfall region, which explains the difference in water use of one of the cases. A study (presented in Chapter 6) was conducted to confirm whether the garden footprint area of GCs in the three regions were notably different. The results suggested that GCs in Pretoria had notably smaller average garden footprint areas, partially explaining the reason for the disparity between water use in Johannesburg and Pretoria. Further research could include GCs of a greater international geographical range and measured outdoor water use of individual GC homes.

The outdoor water use model presented in this research contains parameters for irrigation efficiency and effective precipitation which accounts for moisture content, soil types and topography. However, other irrigation models pertinently define moisture content, soil types topography as separate parameters, which could be incorporated in the outdoor water use model for GCs.

The pool water use parameters included in the simulation of the outdoor use model accounts for environmental and behavioural aspects of GC homes, which incorporates the methodologies of maintenance, and pool size and ownership parameters. However, the effectivity of pool maintenance, pool cover methods could be researched to improve the outdoor water use model.

The proses of deriving garden footprint area for aerial photography could be automated using remote sensing. In combination with drone technology, near infrared cameras, the normalized difference vegetation indexing and enhanced vegetation indexing the data accuracy and volume for garden footprint areas can be improved. As an added benefit the health of vegetation could be derived and fed into the irrigation efficiency parameter.

Irrigation efficiency is a complex parameter that is made up of technical and behavioural aspects, which could be further investigated by means of quantitative and qualitative research. Site investigations, consumer surveys and vegetation health sensing in relation to actual irrigation water use would be valuable in future modelling of outdoor water use. A calibration method using neural networks or machine learning techniques can improve the calibration of the model.

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Appendix A: Declarations of candidate and co-authors

Declaration by the candidate (Chapter 2)

The nature and scope of my contribution to Chapter 2 of this dissertation, the published paper "Analysis of water use by gated communities in South Africa", were as follows:

Nature of contribution	Extent of contribution
- Literature review - Data collection from Swift database - Obtaining ethical approvals - Data analysis - Writing of the published article	95%

The following co-authors contributed to Chapter 2 of this dissertation:

Name	e-mail address	Nature of contribution	Extent of contribution
H. E. Jacobs	hejacobs@sun.ac.za	Contributed to writing of the paper	5%

Signature of candidate: ……………………………………………………

Date: 29 October 2018

Declaration by co-authors:

The undersigned hereby confirm that

1. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 2 of this dissertation.
2. No other author contributed to Chapter 2 of this dissertation besides those specified above, and
3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 2 of this dissertation.

Signature	Institutional affiliation	Date
	Stellenbosch University	29 October 2018

Declaration by the candidate (Chapter 3)

The nature and scope of my contribution to Chapter 3 of this dissertation, the published paper "Investigating wastewater flow to disaggregate indoor and outdoor water use", were as follows:

Nature of contribution	Extent of contribution
- Literature review - Obtained data - Performed data analysis - Conceptualised the study and wrote paper	75%

The following co-authors contributed to Chapter 3 of this dissertation, "Investigating wastewater flow to disaggregate indoor and outdoor water use ":

Name	e-mail address	Nature of contribution	Extent of contribution
H. E. Jacobs	hejacobs@sun.ac.za	Contributed to editing of the paper	5%
C Loubser	carloloubser@sun.ac.za	Contributed to writing portions of the paper	10%
A. J. Knox	16993187@sun.ac.za	Assisted with leakage data analysis	5%
B. Herbst (Née Faasen)	Belinda.herbst@aecom.com	Assisted with pump record data analysis	5%

Signature of candidate: ....

Date: ....29 October 2018..........

Declaration by co-authors:

The undersigned hereby confirm that

4. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 3 of this dissertation "
5. No other author contributed to Chapter 3 of this dissertation, and
6. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 3 of this dissertation,

Initials and Surname	Signature	Institutional affiliation	Date
H. E. Jacobs		Stellenbosch University	27 Oct. 2018
C. Loubser		Stellenbosch University	26-10-2018
A. J. Knox		Stellenbosch University	23-10-2018
B. Herbst		Stellenbosch University	27.10.2018

Declaration by the candidate (Chapter 4)

The nature and scope of my contribution to Chapter 4 of this dissertation, the published paper "Model for estimating domestic outdoor water demand of properties in residential estates", were as follows:

Nature of contribution	Extent of contribution
- Literature review - Model development - Data collection from REUWS database - Obtaining ethical approvals - Data analysis - Writing of the published article	95%

The following co-authors contributed to Chapter 4 of this dissertation:

Name	e-mail address	Nature of contribution	Extent of contribution
H. E. Jacobs	hejacobs@sun.ac.za	Contributed to writing of the paper	5%

Signature of candidate: ....

Date: 29 October 2018

Declaration by co-authors:

The undersigned hereby confirm that

4. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 4 of this dissertation.
5. No other author contributed to Chapter 4 of this dissertation besides those specified above, and
6. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 4 of this dissertation.

Signature	Institutional affiliation	Date
	Stellenbosch University	29 October 2018

Declaration by the candidate (Chapter 5)

The nature and scope of my contribution to Chapter 5 of this dissertation, the published paper "Procedure to derive parameters for stochastic modelling of outdoor water use in residential estates", were as follows:

Nature of contribution	Extent of contribution
- Literature review - Model development - Data collection - Data analysis - Writing of the published article	95%

The following co-authors contributed to Chapter 5 of this dissertation:

Name	e-mail address	Nature of contribution	Extent of contribution
H. E. Jacobs	hejacobs@sun.ac.za	Contributed to writing of the paper	5%

Signature of candidate: ……………………………………………………

Date: 29 October 2018 ……………………………………………………

Declaration by co-authors:

The undersigned hereby confirm that

7. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 5 of this dissertation.
8. No other author contributed to Chapter 5 of this dissertation besides those specified above, and
9. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 5 of this dissertation.

Signature	Institutional affiliation	Date
	Stellenbosch University	29 October 2018

Declaration by the candidate (Chapter 6)

The nature and scope of my contribution to Chapter 6 of this dissertation, the paper submitted and accepted for peer review "Garden footprint area and water use of gated communities in South Africa ", were as follows:

Nature of contribution	Extent of contribution
- Literature review - Obtained data - Performed data analysis - Conceptualised the study and wrote paper	85%

The following co-authors contributed to Chapter 6 of this dissertation, "Garden footprint area and water use of gated communities in South Africa":

Name	e-mail address	Nature of contribution	Extent of contribution
H. E. Jacobs	hejacobs@sun.ac.za	Contributed to writing of the paper	5%
A. J. Knox	16993187@sun.ac.za	Assisted with data analysis and knowledge review	10%

Signature of candidate: ....

Date: ...25 October 2018..

Declaration by co-authors:

The undersigned hereby confirm that

13. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 6 of this dissertation "
14. No other author contributed to Chapter 6 of this dissertation, and
15. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 6 of this dissertation,

Initials and Surname	Signature	Institutional affiliation	Date
H.E. Jacobs		Stellenbosch University	29 October 2018
A. J. Knox		Stellenbosch University	19.02.2019

Declaration by the candidate (Chapter 7)

The nature and scope of my contribution to Chapter 7 of this dissertation, the published paper "Verification and calibration of outdoor water use model to gated communities", were as follows:

Nature of contribution	Extent of contribution
- Model simulation, verification and calibration - Data collection - Data analysis - Writing of the published article	95%

The following co-authors contributed to Chapter 8 of this dissertation:

Name	e-mail address	Nature of contribution	Extent of contribution
H. E. Jacobs	hejacobs@sun.ac.za	Contributed to writing of the paper	5%

Signature of candidate: ……………………………………………………

Date: 29 October 2018

Declaration by co-authors:

The undersigned hereby confirm that

10. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 7 of this dissertation.
11. No other author contributed to Chapter 7 of this dissertation besides those specified above, and
12. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 7 of this dissertation.

Signature	Institutional affiliation	Date
	Stellenbosch University	29 October 2018