Estimating household groundwater abstraction by means of a probability model

by

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DECLARATION

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ABSTRACT

Abstracted groundwater can be used as a valuable resource supplementary to the potable municipal supply in urban areas. Previous research has demonstrated groundwater to be ideal for irrigation purposes because of its relatively good quality, access to large volumes, and availability. However, the actual volume of groundwater abstracted at residential stands, has not yet been explored. The monitoring of household groundwater abstraction is important to estimate whether the actual groundwater supply can meet irrigation demand. The variations in temperature of the outflow pipes at household garden boreholes were investigated in this study, to determine the pumping duration at residential stands. This cost effective and non-invasive method proved to be a potential solution to the lack of knowledge surrounding residential pumping habits. Monte Carlo simulations were executed to determine whether actual groundwater supply could meet irrigation demand at single residential stands, based on published demand guidelines and a demand model to assess expected irrigation use. The results are similar to predictions made by previous studies, and demonstrate that household garden boreholes are likely to meet the demand for residential garden irrigation.

OPSOMMING

Grondwater is ‘n waardevolle hulpbron wat as ‘n aanvulling gebruik kan word tot die munisipale watertoevoer in residensiële gebiede. Vorige studies het aangedui dat boorgatwater ideaal is vir die besproeiing van tuine as gevolg van die relatiewe goeie waterkwaliteit, groot stoorkapasiteit, asook die beskikbaarheid daarvan. Nietemin, die volume boorgatwater wat onttrek word op residensiële erwe is huidiglik onbekend. Inligting oor die werklike hoeveelheid groundwater wat onttrek word is belangrik om te bepaal of residensiële boorgate genoeg water kan voorsien vir besproeiingsdoeleindes. Die tydsduur wat huiseienaars pomp is bepaal deur die veranderinge in temperatuur te meet van die uitlaatpype van pompe. Die koste effektiewe metode kan 'n potensiële oplossing wees om meer inligting oor residensiële boorgat pomp gewoontes te bekom. Monte Carlo simulasies is uitgevoer om te bepaal of die volume grondwater wat gepomp word, voldoende is om in besproeiingsbehoefte te voorsien. Die volume water wat benodig word vir besproeiingsdoeleindes is gebaseer op gepubliseerde riglyne. Die studie het getoon dat die gebruik van boorgate waarskynlik aan residensiële besproeiingbehoeftes kan voorsien.

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LIST OF SYMBOLS

Δt	absolute difference in temperature
A	stand size
a	minimum
A^2	AD statistic
b	maximum
D	KS statistic
Day_i	a single day I, from 00h00 – 24h00
F	cumulative distribution function
f	pumping frequency
g	gravitational acceleration
H	pumping head
I	household income
I_w	percentage of total household water demand used for irrigation purposes
k	number of bins
M	max $(1 \leq i \leq N)$.
n	sample set size
N	number of observed data points
NS	a segment with a negative gradient
NS_n	all segments with a negative gradient
p	water pressure
P	power of the pump
PS	a segment with a positive gradient
PS_n	all segments with a positive gradient
Q	flow rate of groundwater abstraction point
Q_{ave}	average annual water demand
Q_{high}	upper envelope of average annual water demand
Q_{low}	lower envelope of average annual water demand
Q_y	potential groundwater yield
R^2	R-squared
Subscript $_1$	before a change
Subscript $_2$	after a change
Subscript $_b$	bin number
Subscript $_i$	first number in the sample set

Subscript $_n$	sample size
T	water price
t_0	start time of a mission
T_{max}	baseline maximum temperature in Day_i
T_{min}	baseline minimum temperature in Day_i
t_n	end time of a mission
t_p	pumping duration
V_D	garden irrigation water demand for a single household
V_{PD}	demand model accounting for daily peak flow
V_s	actual groundwater yield
x^2	chi-squared statistic
Y	ordered data
α	significance level
B	a measure of elasticity
β	regression coefficients
γ	rank correlation
ε	expected number of data points
η	pump efficiency
μ	mean
ρ	density of the liquid
σ	standard deviation

ABBREVIATIONS AND ACRONYMS

AADD	Average annual daily demand
ASUP	Appliance Stock and User Pattern
AD	Anderson-Darling
CDF	Cumulative distribution function
CSIR	Council for Scientific and Industrial Research
DI	DRASTIC Index
DWS	Department of Water and Sanitation
GAP	Groundwater abstraction point
GOF	Goodness of fit
IPC	International Plumbing Code
KS	Kolmogorov-Smirnov
NGWD	National Groundwater Database
NWA	The National Water Act
NWRS	National Water Resources Strategy
PDF	Probability density function
PF	Peak flow factor
RWH	Rainwater harvesting
UPC	Uniform Plumbing Code
UWC	University of the Western Cape
WRC	Water Research Commission
WSA	Water Service Act

1 INTRODUCTION

1.1 Background

South Africa is considered a semi-arid country (Walmsley *et al.* 1999) with an average annual rainfall of 497 mm, well below the world average of 860 mm per year (Rosewarne 2005). South Africa is a water scarce country that is experiencing an increase in water demand due to the rapid rate of population growth (Vörosmarty *et al*. 2005). The Cape Town Metropolitan is mostly supplied by surface water sources (Saayman and Adams 2002), and droughts generally occur during the hot and dry summer months due to relatively low average rainfall during the cooler, wet winter months. Water demand is typically highest during the summer season due to the higher temperatures and need for residents to water their gardens (Parker and Wilby 2012). Numerous demand guidelines exist in South Africa to estimate the water demand at residential stands by using stand size, household income, water price, available pressure, and type of development as the dependant variables. Stand size is positively correlated to water demand, probably attributed to the presence and size of gardens.

The use of alternative water sources can lessen some of the negative impacts of population growth on the country's water resources. The most common alternative water resources for households include rainwater harvesting (RWH) from rooftops, greywater reuse, and groundwater abstraction. The quality of these resources typically limits application to non-potable uses, such as garden irrigation.

The Cape Town Metropolitan area is largely underlain by shallow aquifers with substantial groundwater exploitation potential (Maclear 1995). The high water table is ideal for groundwater abstraction. Groundwater is generally used for irrigation purposes, due to its good quality, access to large volumes, and availability at almost any location where it is needed (Garlipp 1979; MacDonald and Calow 2009). Groundwater comprises the largest volume of fresh water in Africa, and is also the most widely distributed resource (MacDonald *et al*. 2012). A major benefit of groundwater as alternative resource is the large storage capabilities of aquifers, as the storage capabilities provide a vital buffer against variable climates and potential droughts (MacDonald *et al.* 2009).

Many privately owned groundwater abstraction points (GAPs) exists across South Africa and are in regular use. Limited research is available regarding homeowners' borehole pumping trends and information on residential use of groundwater is insufficient. Pietersen *et al.* (2011) mention the monitoring of groundwater abstraction at local levels in South Africa to be unsatisfactory. During the water restrictions between 2004 and 2005, the City of Cape Town first asked homeowners to register alternative water sources; the process remained ongoing at the time of this study. The registration process also included questionnaires, requesting information regarding the estimated pumping schedule.

1.2 Terminology

Different definitions for certain terms relating to the topic of this research project were used in the literature. It was considered appropriate to add this section to avoid ambiguous or vague statements. The following key terms were used in this thesis:

1.2.1 Average annual daily demand

The average annual daily demand (AADD) refers to the volume of water a household use per day, averaged over one calendar year. The AADD is expressed in units of kL/day, and is constant for any given year.

1.2.2 Data logger

A data logger is defined by the Oxford Press (2016) as a device that records a succession of measurements in digital form. In this thesis, thermal data recording devices were used and were referred to as "data loggers", as discussed in Chapter 3.

1.2.3 Groundwater abstraction point

Adopting terminology used by Wright and Jacobs (2016), the point at which groundwater is abstracted on residential stands is termed the groundwater abstraction point (GAP). Examples of a GAP include a garden borehole and garden well-point.

1.2.4 Groundwater potential yield

The groundwater potential yield, also known as the yield potential, is defined by the Department of Water and Sanitation (DWS) as the potential capacity of an aquifer that can assure a sustainably supply volume of water, similar to the supply volume from surface water (DWS 2010). The potential yield does not take into consideration the size, setting, or density of GAPs in the vicinity.

1.2.5 Groundwater actual yield

The groundwater actual yield, also referred to as the pumping yield, is the current supply volume of GAPs. The actual yield is dependent on the setting, size, and density of the GAPs. This report also uses the notation "actual supply volume" to reference groundwater actual yield.

1.2.6 Groundwater pumping yield capacity

The groundwater pumping yield capacity, or just pumping yield capacity, is the installed pump discharge capacity of the GAPs based on the pumps characteristics and aquifer water level.

1.2.7 Stand

Adopting notation from earlier research publications (Garlipp 1979; Van Zyl *et al*. 2008), a stand was defined as an occupied single residential property, or plot. The word "erf" has also been used in some older studies (CSIR 2003). In terms of water use, a stand includes a house and garden.

1.2.8 Total water demand

Total water demand is referred to in this report as the quantity of water per time unit required to fulfil residential water needs. This includes water consumption for indoor and outdoor end-uses such as drinking, cooking, washing, swimming pools, and garden irrigation.

1.3 Problem statement

Understanding household groundwater abstraction is important for water resource and water demand managers, as well as water infrastructure planners. Previous studies have investigated groundwater abstracted for residential garden irrigation, however, the estimations of the total volume of water abstracted are based on surveys, and no direct measurements have been taken to verify the surveyed values. Household groundwater abstraction is one of various important parameters needed to evaluate the supply-demand balance for household water use. The research problem centred around better understanding parameters needed for stochastically modelling of residential outdoor water use, with a focus on groundwater use.

1.4 Motivation

Information on boreholes and well points in South Africa can be found in the National Groundwater Database (NGWD); however, not all GAPs have been registered (DWS 2016). Of the registered GAPs, no information on the GAP actual yield or the pumping duration is available. The method of measuring the variation in temperature of the outlet pipe to determine groundwater pumping duration has been used successfully in India (Massuel *et al*. 2009), but has not yet been used at residential stands in South Africa. The method studied by Massuel *et al*. (2009) could thus pave the way for groundwater managers and authorities to monitor household groundwater abstractions to ensure the sustainability of aquifers. The advantage of this method of determining pumping durations at residential stands is the equipment. The thermologgers are cost effective and the small size of the data loggers contributes to the non-invasive nature of the method.

When the pumping rate of a garden borehole can be determined, the volume of water being abstracted on a daily basis can be estimated. Quantification of the garden borehole supply can be compared to the total household consumption and garden irrigation requirements, to ultimately determine whether abstracted groundwater can meet garden irrigation needs. Because the future garden irrigation habits of residents cannot be accurately predicted, the use of statistical models is ideal for theoretical estimations.

1.5 Research objectives

The objectives of this study include:

- Assembling household groundwater abstraction data
- Estimate household groundwater abstraction rates and habits for a sample group
- Estimate water demand and supply for residential irrigation purposes by means of predictive statistical models
- Comparing groundwater supply to garden irrigation needs in urban areas.

1.6 Scope and limitations

Water demand can be categorised into indoor and outdoor use, and outdoor use can be separated into swimming pool, irrigation, and taps. This study focusses on garden irrigation; the other end-uses are beyond the scope of this study. No consideration was given to water leaks, however, with the relatively small sample group, site inspections showed no clear presence of water leaks. The small sample size may be attributed mainly to the lack of willingness of residents to participate in such a study, as was reported with earlier studies (Tennick 2000).

Water demand for irrigation purposes varies seasonally. Water use for irrigation purposes can also be affected by factors such as the type of irrigation system, stand sizes and demographics (Day and Howe 2003). This study assumed the water demand for irrigation to be a percentage of the total water demand, and the type of irrigation system and demographics were not taken into account. The total water demand estimations can be influenced by numerous factors including social economic class, household size, and water price. Estimations for water demand were based on published guidelines using stand size as the sole dependant variable. This was assumed to be acceptable for statistical analysis purposes.

Due to time restraints, only a short-term study of groundwater actual yield was tested and no distinctions were made for seasonal variability in household groundwater abstraction. The tests were conducted in April and May as this time of the year was assumed to best represent the annual average water demand for irrigation.

1.7 Chapter overview

This thesis is divided into eight chapters, with the first being the introduction. Chapter 2 provides a comprehensive literature review, including water demand trends and estimation methodologies, alternative resources to the municipal water supply, focusing on abstracted groundwater, and an overview of statistical theories and software. The process of data collection is described in Chapter 3, and Chapter 4 explains the methodologies followed to process and analyse the data. The set-up of the statistical models and a description of their variables is presented in Chapter 5 and Chapter 6, for the supply and demand models respectively. Chapter 7 discusses the results of the statistical models and analysed data. A conclusion of the findings is presented in Chapter 8.

2 LITERATURE REVIEW

2.1 Water demand

2.1.1 End-uses

Water demand is often separated into two categories, according to the type of consumer, either residential water consumer or non-residential consumer. Residential water consumer can furthermore be categorised into different land use categories, including single residential stands and multiple family units, such as apartments. Jacobs *et al.* (2004) mention the requirements for stands to be classified as single-residential units, and these are listed below.

- The house must be occupied
- Each individual stand must only have one water meter that registers the water use of that property alone
- Water use must be less than 20 kL/day
- The stand size must be larger than 50 m^2 and smaller than 2 050 m^2
- The land use category of the property must be registered as single residential.

Several researchers have reported on various different methods to determine the end-uses of water demand on single residential stands. One of these methods involved direct measurements (Edwards and Martin 1995). A flow meter was used to measure the flow at each individual appliance and end-use for 100 households in the United Kingdom. Another method to predict end-use demand is called flow trace analysis. The method includes measuring the flow of water from municipal water meters, and then using software to determine the end-use by means of identifying a unique flow pattern for every end-use. This method has been used by a significant number of researchers (De Oreo *et al.* 1996; Mayer *et al.* 1999; Mayer *et al.* 2003; Loh and Coghlan 2003; Roberts 2005; Willis *et al.* 2009; Heinrich 2007; De Oreo *et al.* 2011). Another method of determining the water demand of end-uses is through consumer surveys. Appliance Stock and User Pattern (ASUP) surveys collected the data through household visits in 2003 and 2007. In 2011, a hybrid approach was followed for the ASUP surveys, which included a web-based survey for 1 241 households, as well as visits to 247 households in Yarra Valley, Australia, to take measurements of flow rates (Roberts 2012).

Residential water end-uses can be categorised into indoor and outdoor use. Previous studies suggest outdoor use to be seasonal whilst indoor use is not (Howe and Linaweaver 1967; Aquacraft 2011; Fisher-Jeffes *et al.* 2015). Typical indoor and outdoor end-uses are summarised in Table 2-1.

Table 2-1 Typical indoor and outdoor end-uses for single residential stands

Indoor	Outdoor
Bath	Irrigation
Dishwasher	Swimming pool
Shower	Tap
Tap	Car washing
Toilet	Miscellaneous
Washing machine	
Miscellaneous	

A significant portion of household water demand is attributed to outdoor use (Fox *et al.* 2009; Domene and Sauri 2007; Syme *et al.* 2004; Hall *et al.* 1988). Water demand for garden irrigation is often determined based on a percentage of the total water use for a property, expressed as the AADD. The main irrigation methods mentioned by Roberts (2005) include the hand held hose, manual sprinkler, and the automatic sprinkler. Table 2-2 lists a range of reported values representing the percentage of total water demand used for irrigation purposes.

Table 2-2 Garden irrigation demand as a percentage of total household demand

Literature reference	Location	% Irrigation of total water demand (over study period)
Heinrich (2007)	Auckland, New Zealand	8.3
Willis *et al.* (2011)	Golden Coast, Australia	10.8
Willis *et al.* (2011)	Golden Coast, Australia	12.0
Veck and Bill (2000)	Alberton, South Africa	14.0
Willis *et al.* (2011)	Golden Coast, Australia	14.0
Roberts (2005); Roberts (2004)	Yarra Valley, Australia	17.5
Willis *et al.* (2011)	Golden Coast, Australia	18.0
Heinrich (2007)	Auckland, New Zealand	21.0
Roberts (2005)	Yarra Valley, Australia	22.9
Jacobs *et al.* (2006)	Cape Town, South Africa	23.0
Roberts (2005)	Melbourne, Australia	25.0
Roberts (2005)	Yarra Valley, Australia	28.0
Parsons (2000)	South Africa	30.0
Jacobs *et al.* (2006)	Cape Town, South Africa	37.0
Loh and Coghlan (2003)	Perth, Australia	54.0
Mayer and DeOreo (1999)	USA	58.7

2.1.2 Factors influencing domestic water demand

A desktop review identified a wide range of factors that could potentially influence residential water demand. Table 2-3 lists the independent variables causative factors impacting water demand. The literature review included results obtained from surveys, water metering, and end-use modelling.

Table 2-3 Factors influencing residential water demand

Water demand factors	Literature reference
Appliance water use	Whitford (1972); Hall *et al.* (1988)
Changes in technology	Agthe and Billings (2002); Day and Howe (2003)
Climate	Foster and Beattie (1979); Metzner (1989); Weber (1989); Tamada *et al.* (1993); Martinez-Espineira (2002); Zhou *et al.* (2002); Goodchild (2003); de Lourdes Fernandes Neto *et al.* (2005)
Conservation attitudes	Syme *et al.* (2004)
Day of the week	Edwards and Martin (1995); Letpalangsunti *et al.* (1999)
Demography	Day and Howe (2003); Jacobs *et al.* (2004)
Distance from city	Durga Rao (2005)
Economy	Bradley (2004)
Employment	Huei (1990); Bradley (2004); Koo *et al.* (2005)
Garden presence and size	Billings and Jones (1996); Day and Howe (2003); Syme *et al.* (2004); Fox *et al.* (2009)
Household income	Foster and Beattie (1979); Billings and Jones (1996); Clarke *et al.* (1997); Liu *et al.* (2003); van Zyl *et al.* (2003); Syme *et al.* (2004); Husselmann and van Zyl (2006)
Household size (people per household)	Metzner (1989); Russac *et al.* (1991); Martinez-Espineira (2002); Liu *et al.* (2003); Bradley (2004)
Housing patterns	Whitford (1972)
Land use	Day and Howe (2003); Durga Rao (2005)
Lifestyle	Syme *et al.* (2004)
Number of rooms	Huei (1990); Agthe and Billings (2002)
Number of persons	Foster and Beattie (1979); Huei (1990)
Occupancy	Martinez-Espineira (2002); Kowalski and Marshalsay (2005)
Property type	Russac *et al.* (1991); Clarke *et al.* (1997); Bradley (2004); Troy and Holloway (2004); Kowalski and Marshalsay (2005); Fox *et al.* (2009)
Population	Koo *et al.* (2005); Durga Rao (2005)

Socio-economic	Day and Howe (2003); Kowalski and Marshalsay (2005)
Soils	Durga Rao (2005)
Stand size	Clarke *et al.* (1997); CSIR (2003); van Zyl *et al.* (2003); Jacobs *et al.* (2004); Husselmann and van Zyl (2006); Fox *et al.* (2009)
Swimming pools	Agthe and Billings (2002); Fisher-Jeffes *et al.* (2015)
Tenure	Clarke *et al.* (1997)
Vacancy rates	Agthe and Billings (2002)
Value per bedroom	Agthe and Billings (2002)
Water pressure	van Zyl *et al.* (2003)
Water price	Whitford (1972); Döckel (1973); Foster and Beattie (1979); Howe (1982); Weber (1989); Dandy *et al.* (1997); Veck and Bill (2000); Agthe and Billings (2002); Liu *et al.* (2003); van Zyl *et al.* (2003); De Lourdes Fernandes Neto *et al.* (2005)
Water use behaviour	Herrington (1996); Day and Howe (2003)
Water using appliance ownership	Power *et al.* (1981); Hall *et al.* (1988); Russac *et al.* (1991); Herrington (1996)

Van Zyl *et al.* (2007) identified climate, stand size, household income, water price, available pressure, and type of development as the factors that most significantly affect water demand in South Africa. Some characteristics of water demand influenced by these factors are listed below:

- Water demand is significantly higher in the dry months than water demand during wet months (Power *et al.* 1981; Jacobs *et al.* 2007; Fox *et al.* 2009)
- Outdoor use is proportional to seasonal use, and thus garden irrigation increases over the dry months (Parker and Wilby 2012; Roberts 2005)
- Larger stand sizes typically have larger irrigated gardens, leading to an increase in water demand (CSIR 2003; van Zyl *et al.* 2003; Jacobs *et al.* 2004; Fox *et al.* 2009)
- Stands in high income residential areas consume more water than stands in middle and low income areas (van Vuuren and van Beek 1997; van Zyl *et al.* 2003)
- Increasing water prices could lead to a decrease in water use, which is more significant in less affluent suburbs (Döckel 1973; Veck and Bill 2000; van Zyl *et al.* 2003)
- Water pressure effects leakage and normal consumption, and higher water pressure results in higher flow rates, which increases leakage and household consumption (van Zyl *et al.* 2003).

2.1.3 Municipal water demand estimation methodologies

Estimations of AADD should preferably be based on the actual recorded water consumption of the specific suburb or township (Howe and Linaweaver 1967; van Zyl *et al.* 2007). However, if no temporal variation is considered, approximating the AADD is more reliable when estimations are made from historical billing, instead of from current data (Roberts 2005). Additionally, water consumption data is not always readily available, and consequently, AADD estimation guidelines are predominantly based on variables that can be accurately determined in a cost effective way, such as stand size (CSIR 2003; Jacobs *et al.* 2004).

Methods have been developed using stand area dating back to 1979 (Garlipp 1979), and similar stand size based guidelines are still widely used (Austin 1995; CSIR 2003). The available guidelines for estimating AADD were compared in this study, as shown in Figure 2-1. The upper and lower limits of the Council for Scientific and Industrial Research (CSIR) envelope curves allow for the influences of other factors on water demand; however, stand size is the only influential variable incorporated in the estimation.

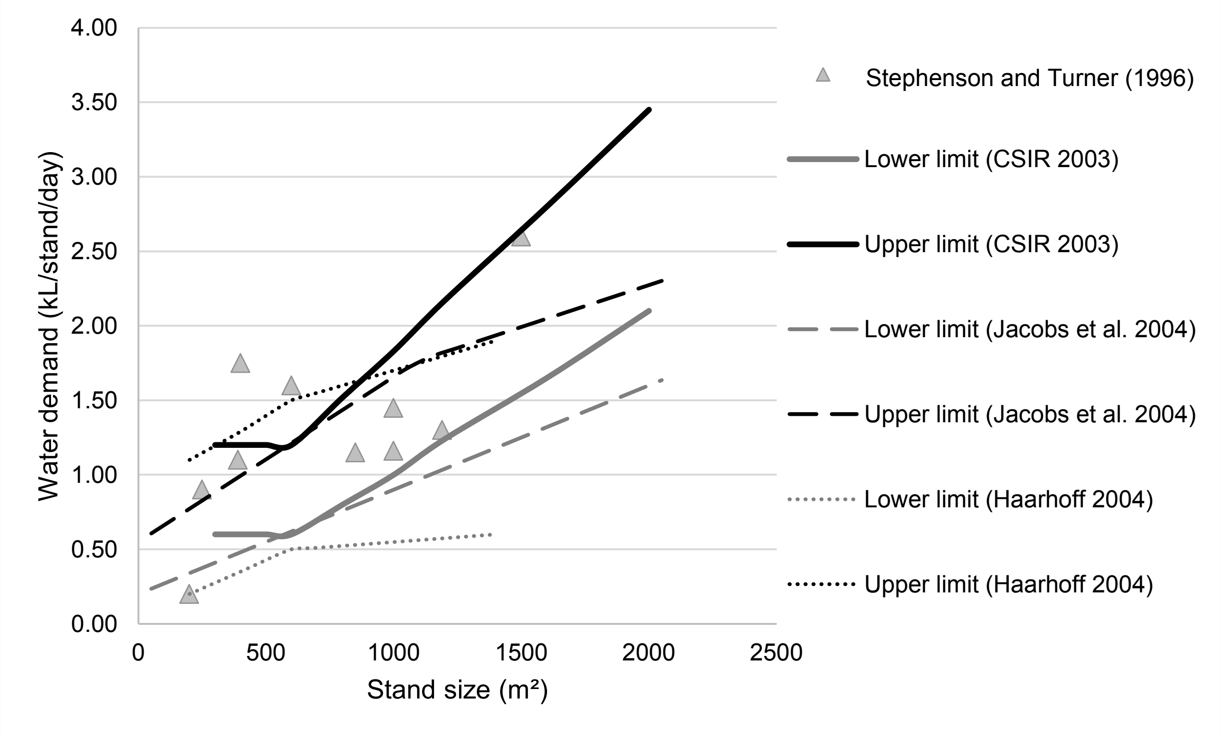


Figure 2-1 **Comparison of different AADD estimation guidelines**

Other South African based AADD estimation methodologies, developed since the CSIR's original guidelines were published in 1983, are summarised chronologically in the rest of this section.

The research conducted by Stephenson and Turner (1996) investigated 9 731 domestic stands in high, medium, and low income areas in Gauteng. Although the study did not focus on stand sizes, the relationship between stand area and AADD was investigated. The results are compared to the CSIR guidelines and are presented in Figure 2-1. Stephenson and Turner (1996) provided valuable insight into factors influencing water demand, such as income and dwelling type, and also confirmed the positive relationship between stand size and AADD

Van Zyl *et al.* (2003) developed a water demand estimation model that investigated water price, household income, stand size, and water pressure elasticity for residential homes in the Gauteng Province. The study included only suburbs and townships in its sample group of 31 170 stands. The mathematical model is presented in Equation 2-1.

$$AADD = AADD_{average}\left(\frac{T_2}{T_1}\right)^{\beta_T}\left(\frac{I_2}{I_1}\right)^{\beta_I}\left(\frac{A_2}{A_1}\right)^{\beta_A}\left(\frac{P_2}{P_1}\right)^{\beta_P} \qquad (2\text{-}1)$$

where

AADD = average annual daily demand

T = water price

I = household income

A = stand size

p = water pressure

β = a measure of elasticity

Subscript $_1$ = before a change

Subscript $_2$ = after a change.

Although the study did not develop a comprehensive model for water demand estimations, the results are still good indicators of factors effecting water demand. An increase in either the household income or stand size increased the water demand, and a decrease in either water pressure or water price increased the water demand.

Jacobs *et al.* (2004) investigated the relationship between water demand and stand size. The study developed three separate single-coefficient models for single residential stands based on their geographic location, namely, coastal winter rainfall regions, coastal annual rainfall regions, and inland summer rainfall regions. The latter also distinguished between development types such as townships and suburbs. The curves for the coastal winter rainfall regions are plotted in Figure 2-1, and equations of the curves are shown in Equations 2-2 to 2-4.

$$\mathrm{Q_{ave}} = \begin{bmatrix} 0.0011059 * \mathrm{A} + 0.287 & (50\mathrm{m}^2 \leq \mathrm{A} < 840\mathrm{m}^2) \\ 0.00056253 * \mathrm{A} + 0.745 & (840\mathrm{m}^2 \leq \mathrm{A} < 2\,050\mathrm{m}^2) \end{bmatrix} \quad (2\text{-}2)$$

$$\mathrm{Q_{high}} = \begin{bmatrix} 0.0011059 * \mathrm{A} + 0.551 & (50\mathrm{m}^2 \leq \mathrm{A} < 1\,100\mathrm{m}^2) \\ 0.00056253 * \mathrm{A} + 1.148 & (1\,100\mathrm{m}^2 \leq \mathrm{A} < 2\,050\mathrm{m}^2) \end{bmatrix} \quad (2\text{-}3)$$

$$\mathrm{Q_{low}} = [0.0007000 * \mathrm{A} + 0.200 \quad (50\mathrm{m}^2 \leq \mathrm{A} < 2\,050\mathrm{m}^2)] \quad (2\text{-}4)$$

where

A = single residential stand size (m^3)

Q_{ave} = average annual water demand (kL/stand/day)

Q_{high} = upper envelope of average annual water demand (kL/stand/day)

Q_{low} = lower envelope of average annual water demand (kL/stand/day).

Although Jacobs *et al.* (2004) developed single-coefficient models with stand size as the only independent variable; geographic regions, climate, and dwelling types were also accounted for.

Husselmann and van Zyl (2006) evaluated the relationships between income and stand size on AADD. The study accepted the international practice of using stand value as a proxy for income (Dandy *et al.* 1997), and categorised stand sizes with respect to stand value. The resulting proposed new guideline curves are plotted in Figure 2-1.

2.2 Supplementary resources to potable municipal supply

2.2.1 Available alternative sources

Groundwater, which forms the focus of this research, is one of various alternative water sources available to residential consumers. Greywater reuse and rainwater harvesting justify a brief review since these sources could be used as well for garden irrigation.

2.2.2 Greywater

Greywater is wastewater collected from baths, showers, kitchen sinks, and washing machines, but excludes toilet water or any water that has come into contact with faeces. Some researchers even exclude kitchen wastewater from the definition (Al-Jayyousi 2003). Water is collected from the various sources, transferred to a storage tank which is generally underground, treated if necessary, and then distributed to appropriate end-uses.

Jakson and Ord (2000) discussed the quality of greywater, and concluded that the greywater should meet the bathing standards of the United Kingdom. Greywater is thus acceptable to use for non-potable applications such as toilet flushing and garden irrigation. The use of greywater has become common for golf course irrigation (Qian and Mecham 2005). With many detergents and soaps being biodegradable, treatment of the water is not always necessary, making greywater an economically viable resource. However, greywater was not included in this study due to the contentious issues with untreated greywater (Barnes 2006).

2.2.3 Rainwater

Rainwater harvesting is used to describe the process of collecting, storing, and using rainwater runoff to supply water for domestic, commercial, and agricultural use (Gould 1999). Roof catchment is the most common form of RWH, as the runoff quality is relatively good compared to that of runoff water collected from surface catchments (Gobel *et al.* 2007). It is important to note that the quality of roof runoff is dependent on various factors, including the type of roof, the local climate, atmospheric pollution, and other environmental conditions. Atmospheric pollution is a noteworthy restraint for the use of RWH around the world, as it could potentially make the rainwater undrinkable. Rainwater can still be used for non-potable uses, such as toilet flushing or irrigation.

One of the main advantages of an RWH system is that the source of the water is close to the end-use, thus there is no need for costly distribution systems. Harvesting of rainwater also has the potential to reduce urban flooding and relieve pressure on stormwater drainage. Unfortunately, RWH has high investment costs and additional plumbing might be necessary. The system is also dependent on weather conditions and will not provide a good buffer against drought in a variable climate, such as the Western Cape, with winter rainfall linked to a high outdoor demand in summer.

2.2.4 Groundwater

Groundwater is considered the largest and most widely distributed water resource in Africa (MacDonald *et al.* 2012). The storage capability of aquifers provides a vital buffer against the variability of climates, including drought, which makes groundwater a more reliable source than rainfall (Calow *et al.* 1997; Calow *et al.* 2010). Generally, the quality of groundwater is adequate for non-potable uses such as irrigation, without needing treatment. According to Giordano (2009) and MacDonald and Calow (2009), exploiting groundwater sources will become vital to assure reliable water supplies in Africa. Jacobs (2010) suggests that the actual yield of a GAP is significantly higher than that of greywater or RWH, and could theoretically meet 100% of the irrigation demand of urban homes in South Africa.

Groundwater from aquifers is an important alternative resource, not only because of the large storage capabilities and acceptable water quality, but also as a result of general availability. Since groundwater is often available relatively close to the demand node, costly bulk supply schemes are not needed.

Groundwater can be abstracted through different means, including a well-point, a borehole, or a shallow well. Geological formations and the depth of the water table are the two main driving factors in determining the type of GAP to employ for residential use. Well-points consist of a shallow shaft, not exceeding 8-10 m and boreholes generally have a depth of about 30 m to 100 m (City of Cape Town 2016). Installing a GAP is generally expensive, due to installation and pumping equipment, but the cost varies depending on the GAP-type and the geology of the location. Well-points are more cost effective than boreholes and take less time to install.

A simple schematic of a typical groundwater supply system is shown in Figure 2-2.

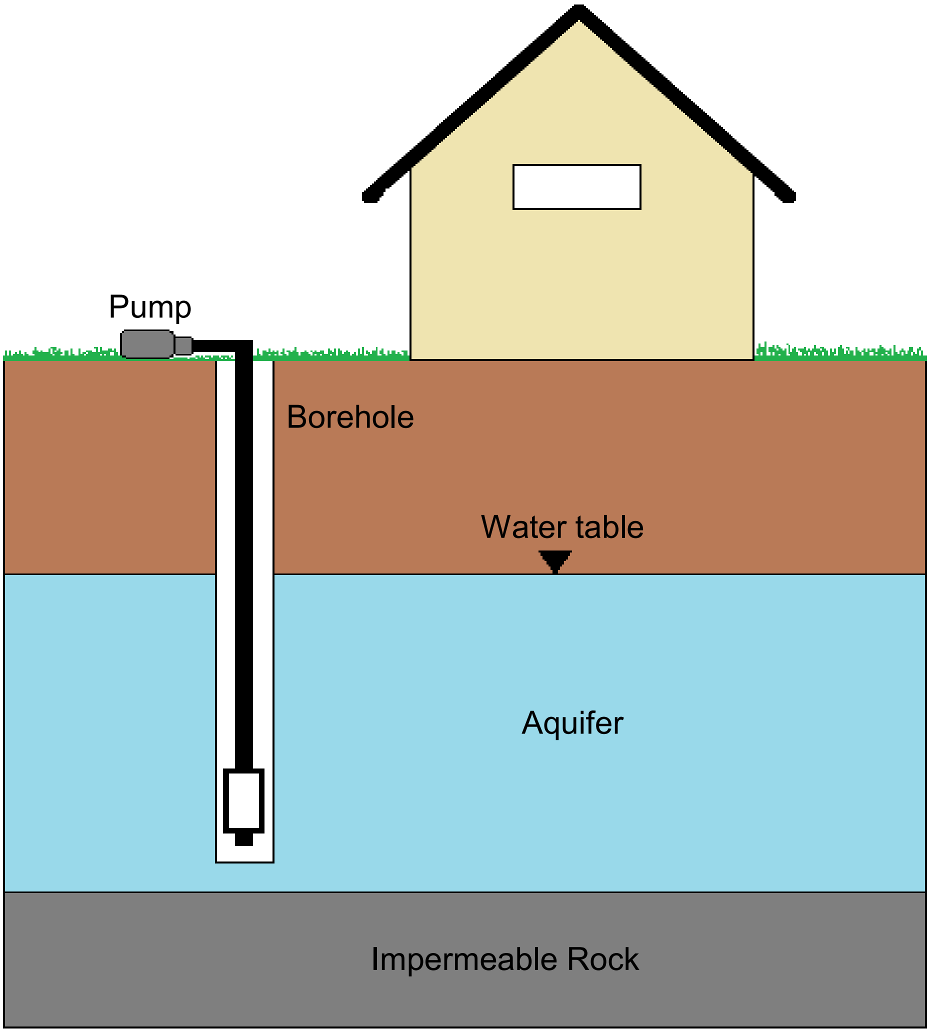


Figure 2-2 A typical groundwater supply system

Groundwater quality is generally not a concern for non-potable uses, as it is naturally protected from pathogenic contamination. The quality of groundwater, as regards to the salinity levels, is suitable for irrigation purposes (City of Cape Town 2016). In some environments, however, increased levels of either, iron, fluoride, or arsenic concentrations can cause certain issues (Smedley 1996; Edmunds and Smedley 2005). Increased levels of iron, though not affecting the soil quality, could stain walls (City of Cape Town 2016).

2.2.5 South African legislation and regulations

Sustainable management of resources is dependent on effective regulatory tools. The National Water Act 36 of 1998 (Republic of South Africa 1998) and The Water Services Act 108 of 1997 (Republic of South Africa 1997) are the legal tools for water resource management in South Africa. The National Water Act (NWA) provides the guiding principles and interpretation is left to the Water Service Act (WSA). The WSA handles water supply networks and sanitation services and the NWA stipulates the development of the National Water Resources Strategy (NWRS). The NWRS is a legal document that strategises long term water resource planning, allocations, and policies (DWS 2010). All establishments performing duties or exuding authority under the NWA have to comply with the NWRS.

A review by Mwenge Kahinda *et al.* (2005) concluded that South Africa’s legislation is not clear on the use of water captured from RWH systems. The current regulations are also different for the use of runoff water from a rooftop for commercial use and RWH for domestic use. The use of rainwater acquired and stored through rooftop catchment is allowed, but the owner of the RWH system is required to get approval from their water service provider according to Section 6 of Chapter 1 of the WSA. NWA Chapter 4, Part 1, Section 22, Schedule 1 brings further confusion, as it distinguishes the right to use stored rainwater for reasonable domestic activity, but explicitly excludes commercial use. However, Section 22 (1) does permit the use of water acquired through roof catchment for these purposes (Mwenge Kahinda and Taigbenu 2011).

South Africa is not the only country with confusing legislation on RWH; until August 2010, the United States did not directly address RWH in their national Uniform Plumbing Code (UPC) or International Plumbing Code (IPC). RWH for non-potable use is not federally regulated in the USA, and state regulations vary tremendously between locations. However, cities trying to encourage water conservation have started to issue policies to define RWH and make clear distinctions between rainwater harvested, greywater, and recycled water (County of Los Angeles 2010).

Groundwater legislation has seen drastic changes over the past two decades. Previous laws gave groundwater ownership to the proprietor of the overlaying property. In 1912 priority was given to the agricultural use of groundwater by The Irrigation and Conservation of Water Act (Republic of South Africa 1912) and in 1956 the Water Act 54 of 1956 (Republic of South Africa 1956) ingrained the idea that groundwater is a private source that does not need to be shared equally. Current legislation by the NWA defines groundwater as part of the water cycle, and groundwater is thus recognised as public water, contrary to the 1956 Water Act (DWS 2010). In other words, the National Water Act of 1956 abolished the National Water Act of 1912 and the National Water Act of 1956 was in turn repealed by the National Water Act 36 of 1998 (Uys 2008).

In South Africa, licensing of groundwater is not required for permissible or small quantities of water use, as stated by Schedule 1 Water Use of the NWA. Therefore, registration of GAPs by urban homeowners is not currently required. Additionally, at the time of the study, groundwater is available to everyone in Cape Town, and no restrictions apply when the water is used for irrigation purposes (City of Cape Town 2016). The only requirement the City has is that the home owner should identify which type of GAP is used for non-potable water use, by means of signage visible from the street.

2.3 Case studies – Urban groundwater use

2.3.1 Gauteng Province, South Africa

A WRC research study conducted in the Pretoria region assessed more than 2 000 properties with GAPs (Simpson 1990). Simpson (1990) evaluated the locations of the GAPs, the abstraction rates, the groundwater levels, and the household's municipal water use. The research applied a stratified cluster sampling technique and reported that roughly 37% of the properties surveyed had GAPs and that properties with GAPs use about 1.78 kL of groundwater a day. The abstracted groundwater volume was plotted against the municipal water use and the resulting graph suggested that stands with GAPs use less municipal water than stands without (Simpson 1990).

2.3.2 Hermanus pilot census, Western Cape, South Africa

Hermanus is located in the coastal winter rainfall region of South Africa. A pilot hydro-census was conducted for Hermanus in 2000 and was discussed later by Tennick (2008). The study investigated the groundwater levels and the number of GAPs in the area, in order to determine the quality and amount of water being abstracted. Door-to-door surveys were conducted and Tennick (2000) found that many residents were reluctant to share information, mainly due to the fear of having to start paying for the water use. The study suggested the typical flow rates for GAPs in Hermanus to be 1 kL/h for a pumping head of 2.2 m.

2.3.3 City of Cape Town water restrictions

During the water restrictions enforced in Cape Town in 2004 and 2005, property owners were asked to register their boreholes and or well points and to fill in questionnaires regarding the use of the boreholes. Jacobs (2010) found that 4 500 home owners completed the registration process, and Wright and Jacobs (2016) analysed the records of the registration process and concluded that residents with access to groundwater only use roughly 65% from municipal supply of the estimated average annual daily demand when compared to published water demand guidelines.

2.3.4 Comparing Cape Town and Perth

Cape Town and Perth share many similarities when it comes to their geographical settings and climate. Both cities are located on similar latitudes and share a Mediterranean climate, characterised by winter rains and dry summers. A comparative study was conducted by Saayman and Adams (2002) evaluating urban groundwater use. The study compared the two cities' annual precipitation, hydrogeology, groundwater supply and quality, construction methods and estimated costs of construction. Although the two cities share a similar climatic regime and latitude, and both have shallow aquifers, their water strategies are quite different. Perth uses 50% groundwater for its domestic and industrial use (Saayman and Adams 2002), whereas groundwater contributes only roughly 15% of the total water consumed in Cape Town (DWAF 2002). Saayman and Adams (2002) concluded that the political and social stance needs to be adjusted in Cape Town if the city wants to become more sustainable with regard to its water sources.

2.3.5 South African groundwater governance

Pietersen *et al.* (2011) evaluated the groundwater governance in South Africa at the national and local level. The study explored South Africa's groundwater policies, knowledge availability of groundwater sources and the capacity of those sources, as well as the financial support available to manage and strengthen the groundwater governance status. The case study by Pietersen *et al.* (2011) was based on previous work by the DWS, including the South African Groundwater Strategy (DWS 2010). Pietersen *et al.* (2011) found that on the local level, apart from basic technical provisions such as hydrogeological maps, the governance policies across the thematic of the study were insufficient. Pietersen *et al.* (2011) concluded that the monitoring of groundwater abstraction was insufficient and that numerical groundwater models at the local level were absent.

2.4 Groundwater potential

2.4.1 Groundwater use

Groundwater is often exploited for urban and industrial uses, because of the cost effectiveness and acceptable water quality (DWS 2010; Troskie and Johnstone 2016). Clarke *et al.* (1995) claimed that, worldwide, roughly 50% of all urban water use is supplied by groundwater. Approximately two-thirds of China's cities make use of groundwater for urban water supply, and 80% of groundwater abstraction in China Agenda 21 of 1994 is devoted to irrigation needs (People's Republic of China 1994). In the United States, groundwater withdrawals are used for public supply, domestic use, irrigation, livestock, aquaculture, industrial, mining, and thermoelectric power. In 2005 irrigation accounted for 68% of the total groundwater withdrawals, and the second highest use of groundwater was public supply, with 19% (USGS 2005). Groundwater also supplies 42% of the total water demand for irrigation, 60% of the total water demand for livestock, and 63% of the total water demand of mining in the USA (USGS 2005).

Similarly to the USA, groundwater use in South Africa can be categorised into seven sectors, namely, rural, municipal, irrigation, livestock, mining, industry, and aquaculture (DWS 2010). A breakdown of the sectoral uses of groundwater was provided by Hughes (2004), which states that 64% of South Africa's abstracted groundwater is used for agricultural irrigation. The majority of privately own GAPs in urban areas are also used for irrigation purposes (Garlipp 1979).

2.4.2 Aquifer vulnerability

The water balance is a well-known concept, which describes the flow of water in and out of a system. In other words, the amount of water entering a system needs to be equal to the amount of water exiting the system. Without recharge, there would be no discharge.

It is important to understand the vulnerability of an aquifer in order to decide whether groundwater abstraction should be encouraged. Various methods are available to evaluate the vulnerability of groundwater. The DRASTIC method developed by Piscopo (2001) is widely acknowledged as the most appropriate. DRASTIC is an acronym of the seven parameters used in the method, namely: Depth to water table, Recharge, Aquifer media, Soil media, Topography, Impact on the vadose zone (the region between the land surface and the top of the saturated zone where water is found), and Conductivity. The DRASTIC approach involves weighing the different parameters and adding them up to calculate the DRASTIC Index (DI). The weighing scale is normally numbered from 1 to 5, with 1 having the least significance and an almost negligible impact on the aquifer, and 5 being significant in terms of aquifer vulnerability. The DI is often altered by including a weight for local influences considered important. For instance, Meinardi *et al.* (1994) considered human activity to be a higher risk than contamination, Leal and Castillo (2003) included the effect of anthropogenic sources on contamination of groundwater, including agriculture, mining and industrial waste, as well as septic tanks. Stigter *et al.* (2006) evaluated the impact of agricultural pollution on groundwater contamination.

Musekiwa and Majola (2013) evaluated groundwater vulnerability in South Africa using the DRASTIC approach. The seven parameters, in the order of the acronym, were assigned weighting parameters of 5, 3, 4, 2, 1, 5, 3, and 1, respectively. Vulnerability maps of South Africa were compiled for each parameter (Musekiwa and Majola 2013). The spatial resolution of the results unfortunately does not allow for an assessment of vulnerability at the scale of individual suburban areas.

2.4.3 Estimated groundwater actual yield

It is important to distinguish between potential yield, actual yield and pumping yield capacity. The potential yield refers to the potential capacity of the aquifer and pumping yield capacity refers to the pumping capacity of the GAP. The potential yield does not take into consideration the size, setting, or density of GAPs in the vicinity, whereas the actual yield is dependent on the setting, size, and density of the GAPs. The actual yield refers to the volume of groundwater currently supplied by GAPs, and is dependent on the groundwater supply flow rate.

The estimated flow rates at boreholes over the continent range from 0.36 kL/h to 1.10 kL/h for community hand pumps (MacDonald *et al.* 2012). Tennick (2000) reported that the actual flow rates in Hermanus, South Africa, range between 1 kL/h and 2 kL/h. According to Matji and Associates (2008) and Jacobs (2010), the typical flow rate in Cape Town is expected to exceed 1 kL/h, and the actual yield is estimated to be 4 kL/day, when a 4 hour pumping day is assumed.

2.4.4 Groundwater threats

Theis (1940) states that the abstraction of groundwater by means of a well-point, natural spring, or a borehole, needs to be balanced by either increasing the recharge of the aquifer, decreasing the original natural discharge, or by reducing the storage in the aquifer. Where the water table is shallow and the recharge is sufficient, pumping of groundwater can lower the water level, and increase the recharge potential and available storage capacity (Zhou 2009). However, when the abstraction rate is greater than the recharge rate, the water table will continue to decrease and the aquifer storage will ultimately be depleted. Groundwater abstraction can thus be beneficial to an aquifer, if care is taken that this alternative source is not overexploited. Overexploitation of an aquifer has many potential consequences, such as aquifer depletion, induced downward leakage that could adversely affect the water quality, salt water intrusion problems, and land subsidence (Foster 2001; Zhou 2009).

Urbanisation has been shown to have an effect on groundwater recharge and quality of the water, and could potentially pose a threat to groundwater sources. Water quality is influenced by urbanisation, as a result of exposure to new contamination sources and changes in solute transportation paths (Collin and Melloul 2003, Wang *et al.* 2005, Dietz and Clausen 2008). Subsequently, the availability of water-supplies for local use will be impacted by the change in water quality. Despite the dangers of over-exploitation, groundwater is increasingly being exploited as a source of water supply. Groundwater could be a viable and easily accessible resource in urban residential areas and is ideal for garden irrigation purposes because of its relatively good quality.

2.5 Methods for estimating household groundwater abstraction

2.5.1 Surveys

Data from residential end-use surveys have been used to estimate water-use and household groundwater abstraction. Surveys could be in the form of electronic questionnaires send out to residential homeowners, or could include interviews that are conducted through site visits. Tennick (2000) prepared a questionnaire and conducted door-to-door surveys in the Hermanus area, South Africa, asking residents to supply information regarding privately owned GAPs. Tennick (2000) found that many residents were reluctant to share information, probably fearing possible future payments.

Roberts (2004) conducted Appliance Stock and Usage Patterns (ASUP) surveys in the Yarra Valley region, which included visits to 840 households. Information was gathered regarding the frequency and duration of indoor and outdoor end-uses, to better understand residential water use. The data gathered was based predominantly on residents' estimates. The 2007 ASUP surveys included house visits, similar to 2003's surveys, whereas the surveys conducted in 2011 were strictly web-based, and received responses from 1 241 households (Roberts 2012). Comparing the ASUP surveys to end-use measurements showed that respondents had a good idea of how often they irrigated their lawns; however, the comparison also showed that residents underestimated their actual irrigation duration by 33% to 40% (Roberts 2005). Although surveys may provide an indication of water use, other more accurate methods are preferred.

2.5.2 Direct measurements

The most efficient direct method to measure household groundwater abstraction is to install flowmeters at each GAP. The cost of installing flowmeters is relatively high, but more importantly, homeowners may not always accept the installation of meters at GAPs (Massuel *et al.* 2009). Groundwater withdrawals of large users have been metered in Victoria, Australia, since the 1960s (Turral *et al.* 2005), however, at the time of the study, metering groundwater abstraction at residential stands has not yet been reported.

2.5.3 Pump power

An alternative method to determine household groundwater abstraction would be to monitor the power supply of the electric pump. This is a viable method when a detailed pumping schedule based on power supply is available. However, the expense was estimated to be approximately double that of the temperature data loggers, discussed next.

2.5.4 ThermoLoggers

Relatively small temperature data loggers were traditionally used to monitor the temperature of shipped fresh food. The use has recently expanded to include numerous applications, including measuring skin temperatures (Lichtenbelt *et al.* 2006), measuring surface air temperatures (Sudiarta 2014), and hydrological research (Massuel *et al.* 2007; Chapmin *et al*. 2014).

A temperature data logger consists of a computer chip with a permanent digital address, which is included in a stainless steel case (Hubbart et al. 2005). Each data logger contains a battery and a silicon chip which can log temperature and humidity data, read and write to memory, and can synchronise with a computer to log real time data. A data logger has the ability to capture specified data and transfer the summarised data onto a computer, using specific software. The temperature data logger is durable (tested to last at least 10 years), waterproof, and can withstand relatively large temperature differences (Hubbart et al. 2005). Different models of temperature data loggers available include the Thermochron iButton, Maxim iButton, Prolabmas EBI, and the KIMO KITSTOCK, to name a few.

The popularity of the method of using temperature data loggers to monitor temperature variations is becoming more evident in hydrogeology studies and applications. Dewandel *et al.* (2007) developed a method whereby temperature data loggers were used to analyse groundwater withdrawals. The results were used to assist in decision making regarding groundwater management in Gajwel, India. The method involves monitoring the temperature of the groundwater abstraction outlet pipe, and using the variations in temperature to determine the pumping state (on and off). The relatively inexpensive method of using temperature data loggers was tested by Massuel *et al.* (2009) during field trails in South India, and the method proved to be a well-suited alternative to flowmeters. The experiments conducted by Massuel *et al.* (2009) tested the accuracy of the thermologgers by comparing the measurements of the thermologgers to the actual pump switch times. The uncertainty was found to be about 1.5%, which was considered satisfactory.

Some limitations of thermal data loggers include a lack of storage space and thus limited temporal resolution and total duration of tests before data has to be physically downloaded. The number of data points that can be stored is proportional to the data recording rate. Wolaver and Sharp (2007) identified water leakage as a limitation in current models, however, Johnson *et al.* (2005) also evaluated the performance of a variety of models and did not encounter the same problem. The thermal data loggers could be used to determine the pumping duration, but data of the pump flow rates have to be determined by alternative methods.

iButton temperature data loggers are widely used in research, but have not yet been employed to estimate household groundwater abstraction rates in South Africa. Due to the relatively low cost and small size, temperature data loggers were considered ideal for application in this research project. The temperature recorders had an added advantage above alternative methods in the sense that the water supply temperature could also be approximated by assuming the groundwater temperature to be equal to the pipe wall temperature after prolonged pumping. Water temperature supply to households is important for various reasons and has for example been the focus of recent research into electricity demand (Parker 2003), temperature of domestic water (Bagge and Hohansson 2011), and heating of domestic hot water (Richard 2016). The temperature data loggers were subsequently selected for this research project, with possible application of the thermal results in a parallel study on household water temperature.

2.6 Statistical analysis

2.6.1 Goodness of fit test

Goodness of fit (GOF) of a statistical model refers to the similarities between a random dataset and a theoretical distribution. GOF tests assess the statistical compatibility between the dataset and selected distribution. Examples of statistical GOF tests include the Anderson-Darling (AD) test, the chi-squared test, and the Kolmogorov-Smirnov (KS) test.

Anderson and Darling (1954) introduced the AD test by modifying the Kolmogorov statistic. The AD statistic tests compare the cumulative distribution curve of the estimated data to the fitted distribution, and determine the area between the two curves. A smaller area indicates a better fit. The test is more sensitive at the tails of the distribution, rather than at the median. The AD statistic (A^2) is defined as:

$$A^2 = -N - \sum_{i=1}^{N} \frac{(2i-1)}{N} \left[\ln F(Y_i) + \ln\left(1 - F(Y_{N+1-i})\right)\right] \tag{2-5}$$

where

F = cumulative distribution function

N = sample size

Y_i = ordered data

Pearson (1900) introduced the GOF chi-squared test which could be applied to continuous distributions. The data points are divided into discrete bins, in terms of equal width or equal probability, and the test compares the degree to which the bins match the fitted distribution. A minimum of 5 data points is required for the chi-squared statistic test to be applicable. The chi-squared statistic (x^2) is given as:

$$x^2 = \sum_{b=1}^{k} \frac{(N_b - \varepsilon_b)^2}{\varepsilon_b} \tag{2-6}$$

where

ε = expected number of data points

k = number of bins

N = sample size

Subscript $_b$ = bin number.

The KS statistic test compares the cumulative distribution curve of the estimated data to the fitted distribution, and determines the greatest vertical difference between them (Chakravarti *et al.* 1967). A smaller maximum distance indicates a better fit. The test is less sensitive at the tails and more sensitive near the centre of the distribution. KS statistic (D) is defined as:

$$D = M\left(F(Y_i) - \frac{i-1}{N}, \frac{i}{N} - F(Y_i)\right) \tag{2-7}$$

where

F = cumulative distribution function

M = max ($1 \leq i \leq N$)

N = sample size

Y_i = ordered data.

2.6.2 Statistical distributions

The AD test, chi-squared test, and KS test compare the fit of theoretical statistical distributions to the collected data. Table 2-4, adapted from Walck (2007), lists the distributions with their corresponding mathematical descriptions as used in the @Risk Software (Palisade 2016). Only distributions used for statistical analysis during this research project are listed.

Table 2-4 Mathematical descriptions of statistical distributions (Adapted from Walck 2007)

Distribution	Parameter 1	Parameter 2	Parameter 3	CDF
Triangular	a (minimum)	μ (mean)	b (maximum)	0 $x \leq a$ $\frac{(x-a)^2}{(b-a)(\mu-a)}$ $a < x \leq \mu$ $1-\frac{(x-a)^2}{(b-a)(\mu-a)}$ $\mu < x < b$ 1 $x > b$
Loglogistic	γ (rank correlation)	β (regression coefficients)	-	$\frac{1}{1+\left(\frac{x}{\alpha}\right)^{-\beta}}$
Lognormal	μ (mean)	σ (standard deviation)	-	$\frac{1}{2}+\frac{1}{2}\mathrm{erf}[\frac{\ln x-\mu}{\sqrt{2}\sigma}]$
Gamma	α (significance level)	β (regression coefficients)	-	$\frac{1}{\Gamma(\alpha)}\gamma(\alpha,\beta x)$
Uniform	α (significance level)	β (regression coefficients)	-	0 $x < a$ $\frac{(x-a)}{(b-a)}$ $x \in [a,b)$ 1 $x \geq b$

2.6.3 Monte Carlo analysis and software

Monte Carlo analysis is a probabilistic method dating back to the 1940s as part of an atomic bomb program which modelled the diffusion of neutrons (Hammersley and Handscomb 1964). The first example of Monte Carlo simulations to solve hydrological problems estimated the yield of the Nile Floodwaters (Hurst *et al.* 1965). The Monte Carlo method uses a large number of uncertainty variables to solve mathematical problems that cannot otherwise be solved (ARR 2013). Monte Carlo analysis is thus a stochastic method for numerical integration (Pokaradi and Molnar 2011; Mascagni 2015). The key steps of the Monte Carlo method include defining and generating input variables, constructing a probability model and solving the model by running numerous simulations to develop an output distribution. Figure 2-3 was adapted from Polkoradi and Molnar (2011) and visually describes this concept.

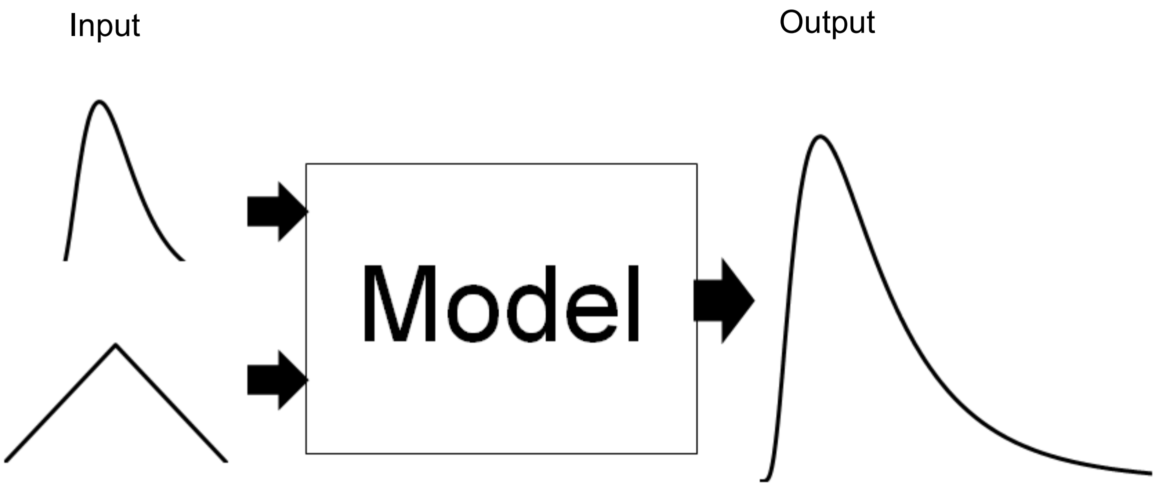


Figure 2-3 **Monte Carlo simulation (Adapted from Polkoradi and Molnar 2011)**

For this study, Monte Carlo analysis was used to transform uncertainties in input variables into stochastic model outputs. Qualitative research is generally used to define the input variables. The distribution of values is gathered from investigative methodologies, which could include literature and field research. The next step involves defining a mathematical model, which is used to generate a quantitative output for the system based on the aforementioned input data. The mathematical model is used to solve the problem through stochastic simulations, randomly selecting the uncertain input variables and artificially building a probabilistic distribution to create an expected range of model uncertainty.

The Monte Carlo method is used by numerous software applications for risk analysis. Some software tools combine Microsoft Excel's built in spreadsheet functions with Monte Carlo simulations to perform risk analysis, while others use a stand-alone graphical user interface. A few software products available in South Africa for this purpose are listed:

Crystal Ball

Crystal Ball is a spreadsheet-based application software program used for Monte Carlo analysis. The software, developed by Oracle, uses Microsoft Excel's built in spreadsheet functions. The input variables are quantified by adding probabilistic distribution functions to the data, and Table 2-5 lists continuous and discrete probability distributions available in Crystal Ball. The software imitates the uncertainty input variables using Monte Carlo simulations to perform risk analysis. The best distribution fit for the input variables and generated outputs are determined in Crystal Ball by means of a GOF test, such as the AD, chi-squared or KS tests.

GoldSim

GoldSim was developed by GoldSim Technology Group and uses a graphical system interface (GoldSim 2016). The software is a stand-alone package which goes beyond the use of spreadsheets. GoldSim allows the user to visually create and manipulate data and equations to provide statistical variables as inputs into the system. The Monte Carlo model is built by drawing an influence diagram of the system and allocating probabilistic distributions to the input variables. The probability distributions available within GoldSim are summarised in Table 2-5. Once all the input values have been defined, random outputs are generated using Monte Carlo simulations.

@Risk

@Risk, similar to Crystal Ball, is also a spreadsheet-based Monte Carlo analysis software program, developed by Palisade Corporation (2016). Input data are specified in Microsoft Excel and computed by adding different probabilistic distribution functions to the specified input cells. Table 2-5 lists the probability distributions offered by the @Risk software. @Risk also performs GOF tests by making use of the AD test, chi-squared test, and KS test.

Table 2-5 Probability distributions available from selected software

Probability distributions	Software applications		
	GoldSim	Crystal Ball	@Risk
Beta	x	x	x
Beta (Generalised)			x
Beta (Subjective)			x
BetaPERT		x	x
Binomial	x	x	x
Boolean	x		
Chi-Squared			x
Cumulative	x		x
Discrete	x		x
Discrete Uniform		x	x
Erlang			x
Error Function			x
Exponential	x	x	
Extreme Maximum Value	x	x	x
Extreme Minimum Value	x	x	x
Gamma	x	x	x
Geometric		x	x
Histogram			x
Hypergeometric		x	x
Integer Uniform			x
Inverse Gaussian			x
Logistic		x	x
Log Logistic			x
Lognormal	x	x	x
Negative Binomial	x	x	x
Normal	x	x	x
Pareto	x	x	x
Pearson Type III	x		
Pearson Type V			x
Pearson Type VI			x
Poisson	x	x	x
Rayleigh			x
Simple Result	x		
Student’s t	x	x	x
Triangular	x	x	x
Uniform	x	x	x
Weibull	x	x	x
Yes-No (Bernoulli)		x	

3 DATA COLLECTION

3.1 Introduction

At the time of the study no direct measurements have been taken to quantify household groundwater abstraction for garden irrigation. The estimations of total volume of groundwater used for garden irrigation has been reported on by previous studies, however, the estimations are based on surveys, and no direct measurements have been taken to verify the surveyed values. The study site and non-invasive method used to measure household groundwater abstraction at privately own boreholes are discussed in this chapter.

3.2 Study site

Wright and Jacobs (2016) developed a spatial distribution map of verified residential properties with GAPs in the Cape Town Metropolitan area, which was used to select a study site. The study site was chosen based on the researcher's personal contacts in an area where a clustering of GAPs on residential properties were present. The GAP distribution map, obtained from Wright and Jacobs (2016), and the selected study location of the research project are shown in Figure 3-1.

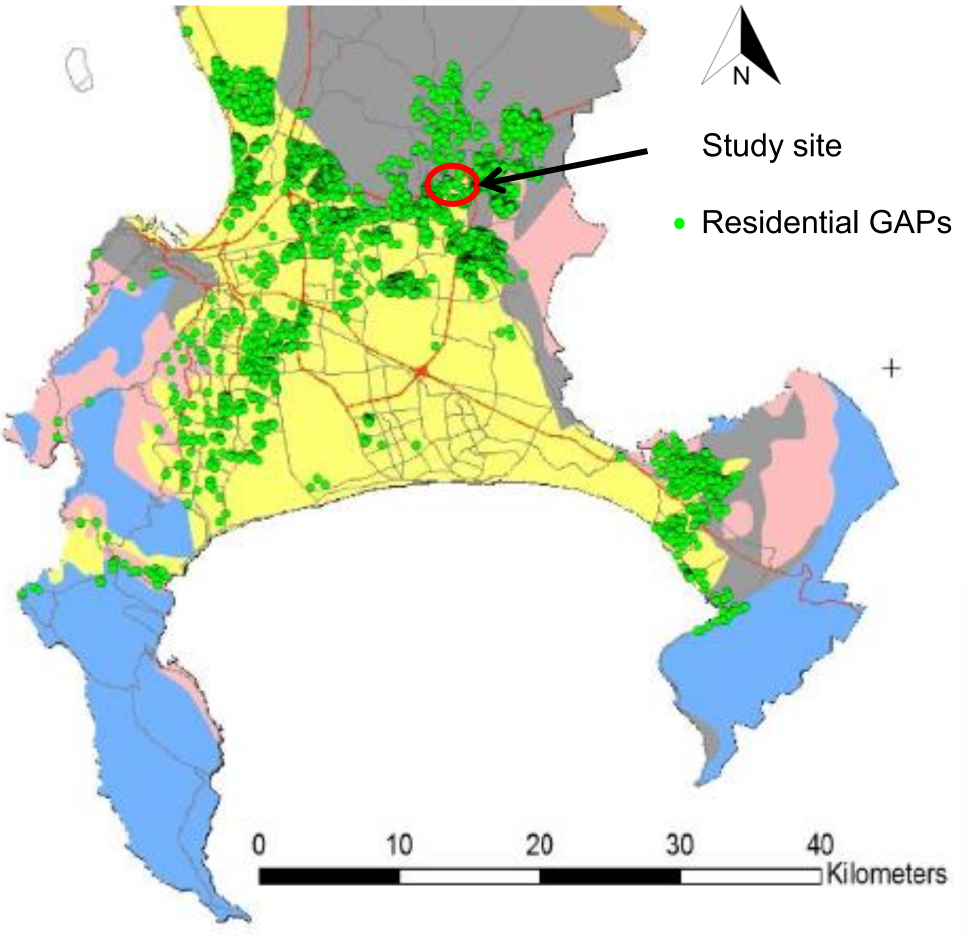


Figure 3-1 Spatial distribution of GAPs and study site location (Adapted from Wright and Jacobs 2016)

The specific study site has a Mediterranean climate with winter rainfall, and overlay a shallow aquifer. The type of development of the study site is classified as suburban, and it is considered a medium density and medium income residential site. Suburban areas have a higher percentage residential stands with gardens than city centres, leading to relatively high water demand (Domene and Sauri 2007).

The specific sample was selected for analysis based on residents' willingness to participate in the study. The sample includes 10 stands, which were divided into two smaller groups of five houses each. All the houses in the sample size were considered single residential stands, with property sizes ranging from 600 m^2 to 1 400 m^2. Prominent gardens and lawns were present in all homes. Two stands from the study site each had a swimming pool, however, the homeowners assured that the abstracted groundwater was explicitly used for garden irrigation. Figure 3-2 shows an aerial view of the study site and the boundaries of the two sample groups. The addresses and suburb names were omitted for residential anonymity, in line with ethical requirements.

Figure 3-2 **Aerial view of sample groups at study site**

Relatively small sample sizes are not unusual for studies where end-uses in urban areas are investigated. Former end-use studies with small sample sizes are listed in Table 3-1. Furthermore, @Risk, the software used for the statistical analysis, requires a minimum sample size of 5 values to generate a distribution fitting. The sample size of 10 homes for this study was thus considered adequate to ensure appropriate input values for the Monte Carlo analysis. Additionally, the manageable sample size enabled the author to inspect individual properties for leaks and to conduct follow up inspections.

Table 3-1 End use studies with small sample sizes

Literature reference	Sample Size
Butler (1991)	28
DeOreo et al. (1996)	16
DeOreo et al. (2001)	37
Jacobs (2007)	10

3.3 Pumping flow rate

Non-intrusive pipe clamp-on ultrasonic flow meters were considered to measure flow rates. However, when the pipe diameter is smaller than 900 mm, the clamp-on units have lower accuracy. Residential GAPs' pipes are generally much small than 900 mm, therefore, ultrasonic flow meters were not used. Consequently, a different method, approved by the residents, had to be executed to determine the flow rate at the specific stands. The actual flow rates at the GAPs were determined using volumetric measurement.

The water was pumped at a constant rate through a hand held hose connected to the GAP pump. Eight out of the ten stands only used a hosepipe for garden irrigation. The other two stands made use of an automatic irrigation system in addition to the hand held hose. On the final day of testing, ten measurements were taken at every GAP, and the mean flow rate at every stand was used for statistical analysis. The results of the tests are discussed in Section 5.3.2.

3.4 Household groundwater abstraction

3.4.1 Temperature data logger

Fairbridge Technologies, based in South Africa, is a distributor of temperature and humidity monitoring products, such as iButtons. An iButton comprises a single silicon chip which combines a digital thermometer, clock and calendar, and a protected memory. For this study, the DS1922 Thermochron Hi Resolution iButtons were selected to monitor temperature variations of groundwater abstraction outlet pipes. The DS 1922 was selected based on its size, ruggedness, accuracy, cost, and availability. The ruggedness and size of the data loggers made for convenient placement at all GAPs without inconveniencing the homeowners. The total cost was within the financial constraints of this study. Figure 3-3 shows the dimensions and shape of the selected temperature data logger.

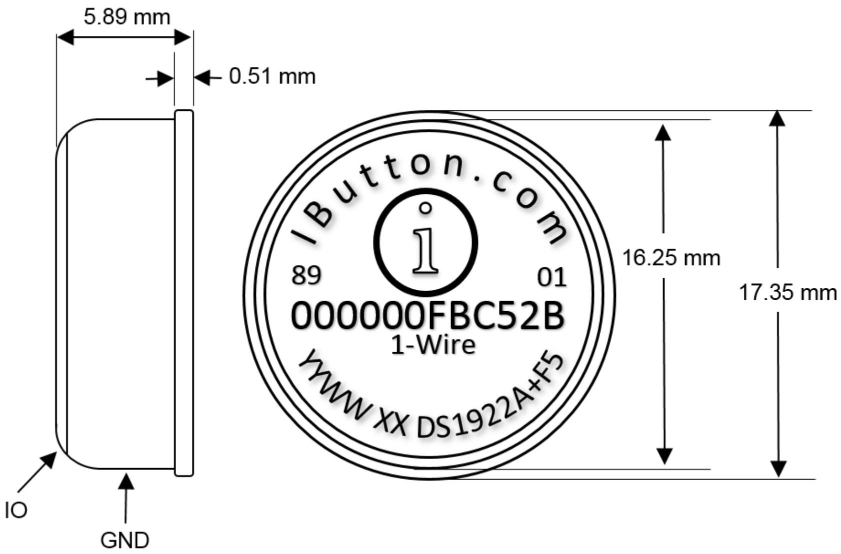


Figure 3-3 DS1922 Thermochron Hi Resolution iButton

ColdChain ThermoDynamics software was used to extract and save the recorded data. Before the devices could be activated to start taking measurements, each iButton had to be pre-configured with a customised set of parameters, including start time and sample rate. The study sample of 10 houses, that was used to populate the parameters relating to borehole water use, was divided into 2 groups. Within a group, each iButton was synchronised to start at exactly the same time on exactly the same date. The starting times for Group 1 and Group 2 were 8 April at 6 pm and 26 April at 6 am respectively, as shown in Table 3-2. The test dates for the study were chosen based on predictions by weather services, to make sure that no precipitation was likely to occur during the test period (thus encouraging garden irrigation and borehole water use). A unique code was allocated to identify the location of each stand and data logger in order to ensure the anonymity of the residents. One data logger code was given to the two data loggers placed at the same GAP. The first number of the unique data logger code indicates the group number (Group 1 or Group 2), and the second number of the data logger code represents the stand number within that specific group (ranging from 1 to 5). The unique data logger code is presented in Table 3-2. All the data loggers in both groups were programmed to have a sampling rate of 2 minutes, thus taking consecutive temperature measurements every 2 minutes. The memory allowed for a total duration of 11 days and 9 hours, equating a sample count of 8 192 records for each iButton.

Table 3-2 Sample group summary

Group #	Date	Data logger code
1	9 April 2016 to 19 April 2016	1_1
		1_2
		1_3
		1_4
		1_5
2	26 April 2016 to 6 May 2016	2_1
		2_2
		2_3
		2_4
		2_5

3.4.2 Set up and testing

After pre-configuring the iButtons, the device was activated to start recording data according to the parameters specified. The period between the recording start time and end time is referred to in the software suite as running a mission. After the data loggers were activated and before the specified start time, the iButtons were placed on the outlet pipe of the GAPs, using adhesive electrical tape. To prevent faulty equipment from causing outliers in the dataset, it is recommended to position more than one iButton at each GAP, in order that their results can be compared. Ideally three iButtons should be used, placed at different locations along the outlet pipe, for instance, two at the bottom of the pipe (position 1 and 2) and one on top of the pipe (position 3), as shown in Figure 3-4.

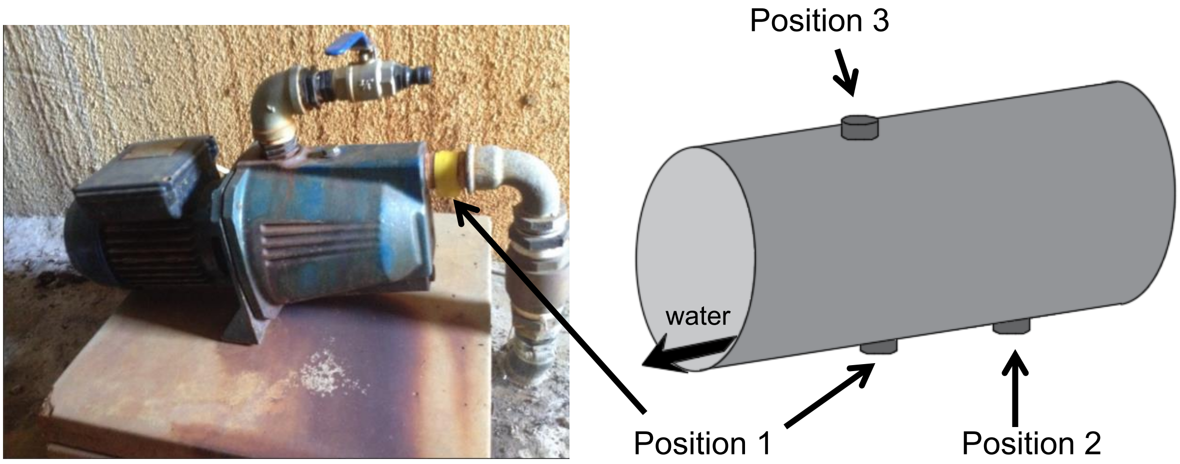


Figure 3-4 Location of data loggers on the outlet pipes

However, with limited data loggers available for testing, using three iButtons was not realistic, and two iButtons were used for this study. Massuel *et al.* (2009) recommends placing the data loggers at the bottom of the outlet pipes (position 1 and position 2). The reasoning behind this is that when the pipe flows partially full, gravity will cause the water to flow at the bottom of the pipe, causing the highest temperature difference at position 1 and position 2. At some GAPs there was no access to the outlet pipe. In those instances, one data logger was placed on the elbow of the outlet, and one on the inlet pipe.

All the stands had their GAPs in their backyards, but the pump and pipe systems were positioned in different environments. Some were placed in an environment that completely protected the data logger from any climatic conditions; others had no protection and were fully exposed to direct sunlight. Table 3-3 provides a brief description of the environment the data loggers were placed in and a comprehensive description of each environment type with site photographs is available in Appendix A.

Table 3-3 Data loggers environment placement

Data logger code	Type of environment	Environment description
1_1	Environment A	Partially protected from sunlight.
1_2	Environment B	Fully protected from sunlight; in permanent shade
1_3	Environment C	Fully exposed; no protection from sunlight
1_4	Environment A	Partially protected from sunlight
1_5	Environment B	Fully protected from sunlight; in permanent shade
2_1	Environment A	Partially protected from sunlight
2_2	Environment A	Partially protected from sunlight
2_3	Environment A	Partially protected from sunlight
2_4	Environment A	Partially protected from sunlight
2_5	Environment C	Fully exposed; no protection from sunlight

In this study, the environment in which the data loggers were placed was noted to affect the temperature changes measured by the iButtons. The data loggers exposed to direct sunlight recorded larger temperature variations than those in the shade. Due to the significant differences in temperature variations between the environments, a unique solution to estimate pump status and water abstraction rate from a GAP, based on recorded temperature, had to be derived for each property.

3.4.3 Data retrieval

Subsequent to the collection of the iButton thermal data recorders from each site, the data was extracted. Using ColdChain ThermoDynamics software, the data was accessed and downloaded to a computer via USB functionality. The temperature readings were exported to Microsoft Excel for further analysis. A report including an executive summary of one data logger, the mission setup, temperature graph, and the first page of the readings are included in Appendix B. The reports of all the data loggers are available in electronic format on the CD included in the back cover. In keeping with ethical requirements, some information in the reports was blacked out.

4 ESTIMATING PUMPING EVENTS FROM THERMAL DATA

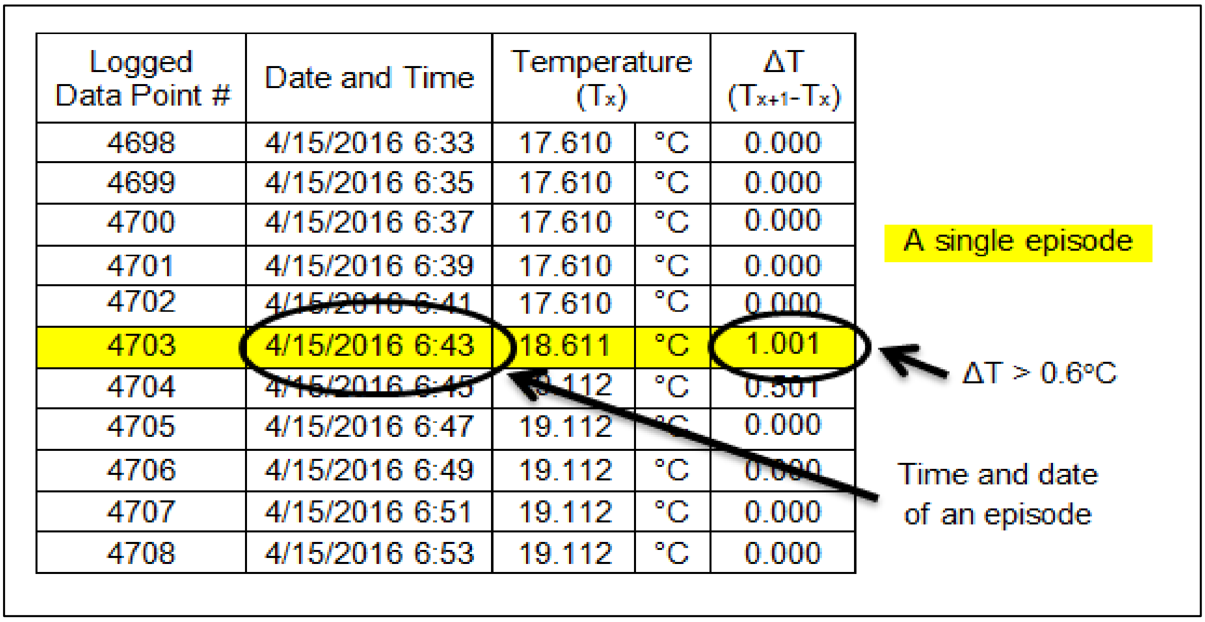
4.1 Introduction

Recorded thermal data for each borehole were analysed in order to derive pump status (on or off) and to ultimately estimate the flow rate in each case. The groundwater flow rate and volume abstracted was needed to populate the end-use supply model, as explained in the following chapter. The procedure that was employed to derive pumping events and to estimate flow rate based on thermal recordings is presented in this chapter.

When water is flowing through the pipe near the borehole pump, the pump was deemed operational – termed a pumping event. Each pumping event represents a single garden irrigation occurrence and it is characterised by the process of a pump being turned on, water flowing through the pipe and the pump being turned off again. The pipe wall temperature measured by the data loggers was used to determine the pumping events, similar to the methodology followed by Massuel *et al.* (2009). When the distinction between pumping events was unclear, Massuel *et al.* (2009) used an Excel Macro to manually interpret values from a temperature variation graph. Microsoft Excel was used in this study to develop temperature variation graphs to interpret the derived values. Two methods were used, namely (i) temperature gradient analysis and (ii) temperature variation analysis.

4.2 Method 1 – Temperature gradient analysis

The first method is based on the assumption that when the temperature gradient of the pipe wall changes notably, a pump was turned either on or off. The temperature change is induced by groundwater of a cooler temperature suddenly starting to flow (or no longer flowing) in the pipe. A notable change in the temperature gradient was termed an episode. The first step of Method 1 was to compute the temperature difference between consecutive data points. Thus, for every 2 minutes, Δt, the absolute difference in temperature was calculated. The threshold value used to identify episodes was determined to be $0.6\ ^{o}C/\Delta t$. Thus, if the difference between consecutive data points was greater than $0.6\ ^{o}C/\Delta t$, an episode was identified. Figure 4-1 shows an example of identifying an episode. Each event is bordered by at least two episodes – one at the start and one at the end of an event.



Logged Data Point #	Date and Time	Temperature (T_x)		ΔT ($T_{x+1}-T_x$)
4698	4/15/2016 6:33	17.610	°C	0.000
4699	4/15/2016 6:35	17.610	°C	0.000
4700	4/15/2016 6:37	17.610	°C	0.000
4701	4/15/2016 6:39	17.610	°C	0.000
4702	4/15/2016 6:41	17.610	°C	0.000
4703	4/15/2016 6:43	18.611	°C	1.001
4704	4/15/2016 6:45	19.112	°C	0.501
4705	4/15/2016 6:47	19.112	°C	0.000
4706	4/15/2016 6:49	19.112	°C	0.000
4707	4/15/2016 6:51	19.112	°C	0.000
4708	4/15/2016 6:53	19.112	°C	0.000

Figure 4-1 **Identifying an episode**

All episodes were graphed and the y-values were converted to a common value, namely one. Figure 4-2 shows the graphical representation of a normalised curve for data logger 1-2. The limitation to Method 1 is that not all episodes could immediately be linked to events. Each episode, per definition, has a duration of 2 minutes. However, the pipe wall temperature could take more than 2 minutes on hot days to cool down after the start of a pumping event. The pipe wall temperature ultimately approaches the cooler groundwater temperature in the pipe. Thus, when water starts to flow through the pipe, several episodes could occur before the pipe temperature reaches that of the groundwater temperature. Similarly, once the water stops flowing, several episodes could occur before the pipe wall temperature increases again and returns to the ambient temperature. The time it takes for the pipe wall temperature and ambient temperature to balance, is dependent on solar exposure, temperature gradient, and pipe material (Massuel et al. 2009). A group of successive episodes could represent a pumping event. The small sample size allowed for inspection of every event. Excel was used to derive the procedure, and the events were verified by means of inspection. Figure 4-2 shows an example that demonstrates the grouping of episodes to determine an event.

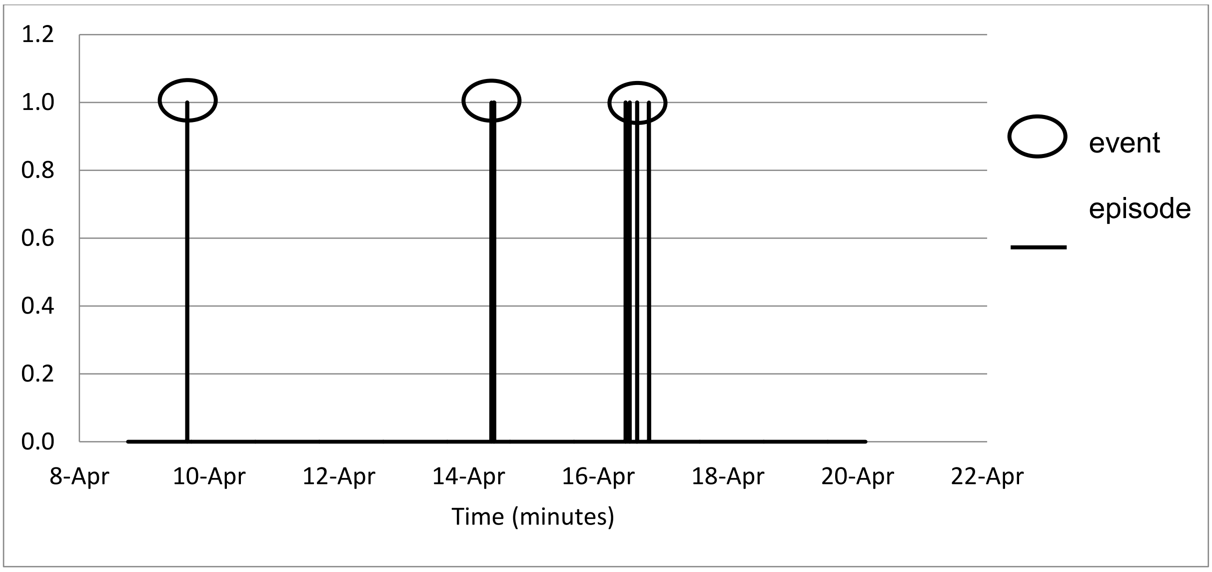


Figure 4-2 Method 1: Identifying an event

The number of episodes per event was influenced by the time of day, the groundwater temperature, and the environment the data logger was placed in. The complete Excel spreadsheet showing all episodes and all events for all 10 GAPs is available in electronic format on the CD in the back cover.

Method 1 allowed for identification of 59 pumping events at the 10 GAPs. Conversations with the homeowners confirmed the results obtained from this method; however, Method 1 was not sufficient to determine the duration of all events. As a result, Method 1 was used in conjunction with Method 2 to accurately estimate the pumping frequency and durations.

4.3 Method 2 – Temperature variation analysis

4.3.1 Approach

The variation between the pipe wall temperature and the ambient temperature was inspected with Method 2. An assumption was made that when no water is flowing through the pipe, the pipe wall temperature would equal the ambient temperature. Thus, to determine an event, the recorded temperatures of the pipe and that of the air could be subtracted to help identify the pumping events (Massuel *et al.* 2009). The ideal process would have included placing an additional thermal data logger next to the pipe, not connected to any part of the pipe or pump, to measure the air temperature. However, due to limited data loggers, an additional data logger could not be placed at every GAP to measure the ambient temperature. The available loggers were rather placed at GAP to measure the pipe wall temperatures, to have a larger sample size. Although Massuel et al. (2009) used measured ambient temperature; all that is needed is some baseline temperature which can be used to identify interruptions in the expected graph pattern. In other words, in the absence of ambient temperature any expected temperature curve could be used for this purpose.

4.3.2 Cape Town International weather station temperature data

The hourly air temperature at the Cape Town International weather station was obtained from Weather Underground (2016). Figure 4-3 shows the ambient temperatures of Logger 1_2 superimposed on the measured pipe wall temperatures.

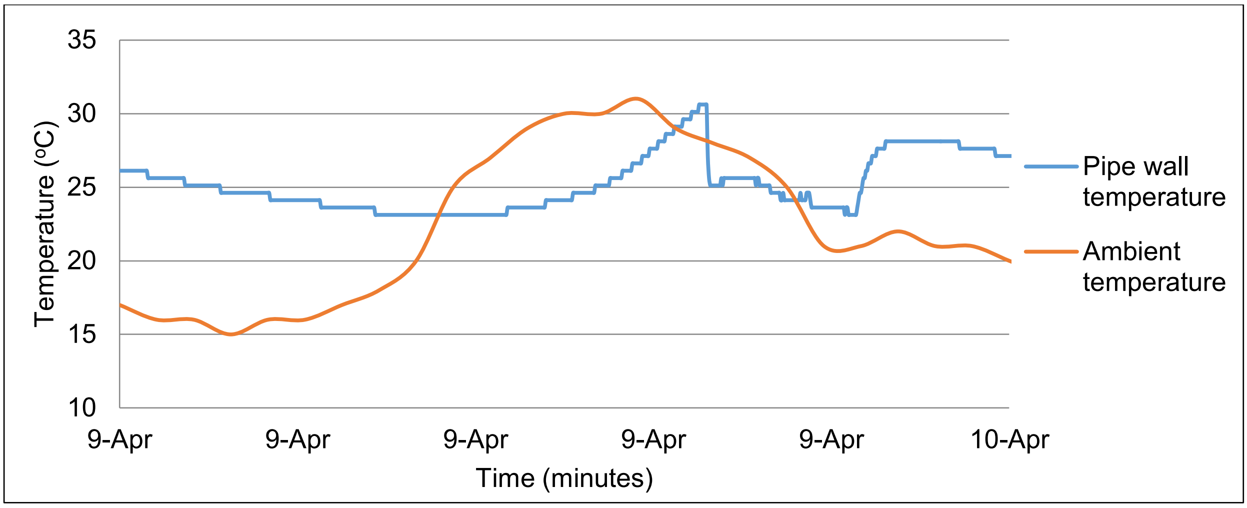


Figure 4-3 **Pipe wall temperature vs ambient temperature**

Figure 4-3 shows that when no water is flowing through the pipe, the pipe wall temperature is not equal the ambient temperature. The significant difference between the temperatures could be because the ambient temperature data was taken from a nearby weather station and not at the specific GAP location. Using temperature measurements taken from weather station also do not take the different environments the loggers were place in into account. The use of weather stations to determine the ambient temperatures in this study could thus not be used, and an alternative method to develop a baseline temperature needed to be developed.

4.3.3 Derived baseline temperature

In the absence of ambient temperature, a baseline curve was derived for Method 2, after which the derived curve was compared to the measure pipe wall temperatures. Method 2 was a timely process, which can be explained in five steps.

The first step was to divide time-series data into segments by identifying maximum and minimum temperatures for every day. A segment is defined as consecutive data points extending between the minimum and maximum temperatures of a single day. A schematic of the procedure is presented in Figure 4-4, which will be referenced throughout the remainder of this chapter.

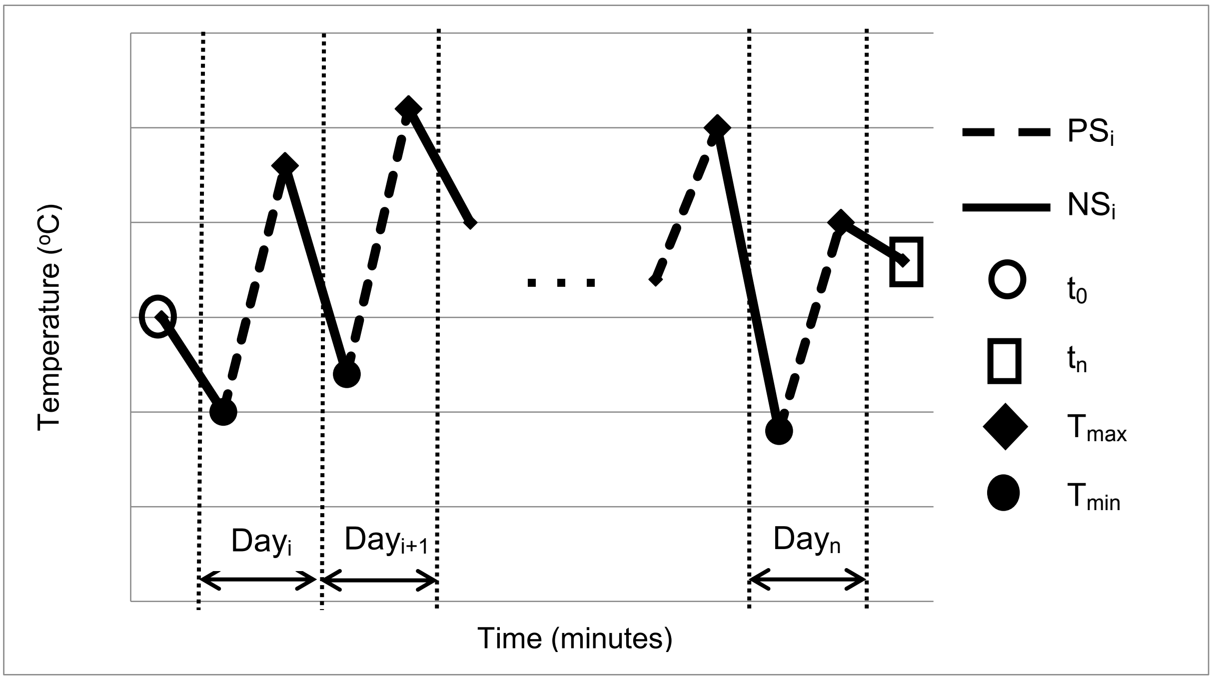


Figure 4-4 Schematic model of a time-series

In this method, the following definitions are applicable:

PS	= a segment with a positive gradient
NS	= a segment with a negative gradient
Subscript $_i$	= first number in the sample set
Subscript $_N$	= total sample size
t_0	= start time of a mission
t_n	= end time of a mission
Day$_i$	= a single day i, from 00:00 – 24:00
T_{max}	= baseline maximum temperature in Day$_i$
T_{min}	= baseline minimum temperature in Day$_i$

The second step was to determine the most accurate regression type, to determine the shape of the baseline curve being derived. This was done by first creating a superimposed scatter graph for all segments with a positive gradient (PS_N), and normalising the graph. Linear, quadratic, and cubic trendlines were generated and the regression type with the highest R^2 value was used to shape the baseline temperature curve. This step was also repeated for all segments with a negative gradient (NS_N). Figure 4-5 shows an example of a superimposed scatter graph with the respective R^2 values.

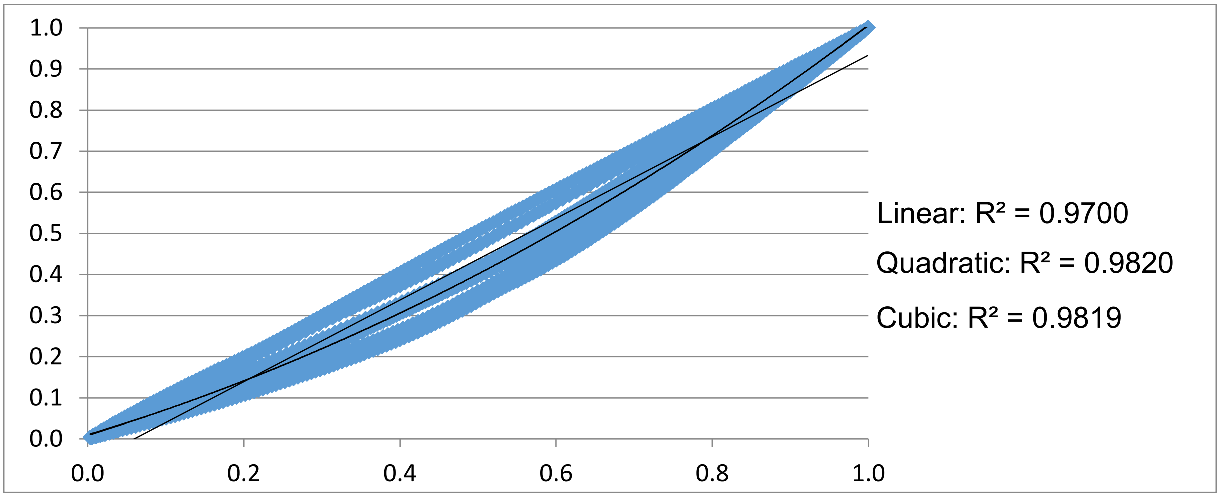


Figure 4-5 Comparing accuracy of regression types

As shown in Figure 4-5, the quadratic regression has the best R^2 value of 0.9820. The quadratic equation proved to have the best R^2 value for both negative and positive segments of all the datasets. Thus, baseline temperatures were derived in step 3 using a quadratic function: $f(x) = a*x^2 + b*x + c$.

In the third step, the pipe wall temperatures of each individual segment (S_i) were plotted on a scatter graph, and a quadratic type trendline was generated. If the R^2 value was higher than 0.9, the equation of the trendline produced was used to develop the baseline curve for that individual segment, S_i. If the R^2 value was less than 0.9, step 3 was repeated, however, this time omitting the pipe wall temperatures representing pumping episodes, which was determined in Method 1. Figure 4-6 shows the scatter graph of the first segment (S_1) of Logger 1_2 and the trendline generated. The equation of the trendline used to derive the baseline curve, as well as the R^2 value, is also shown on the graph.

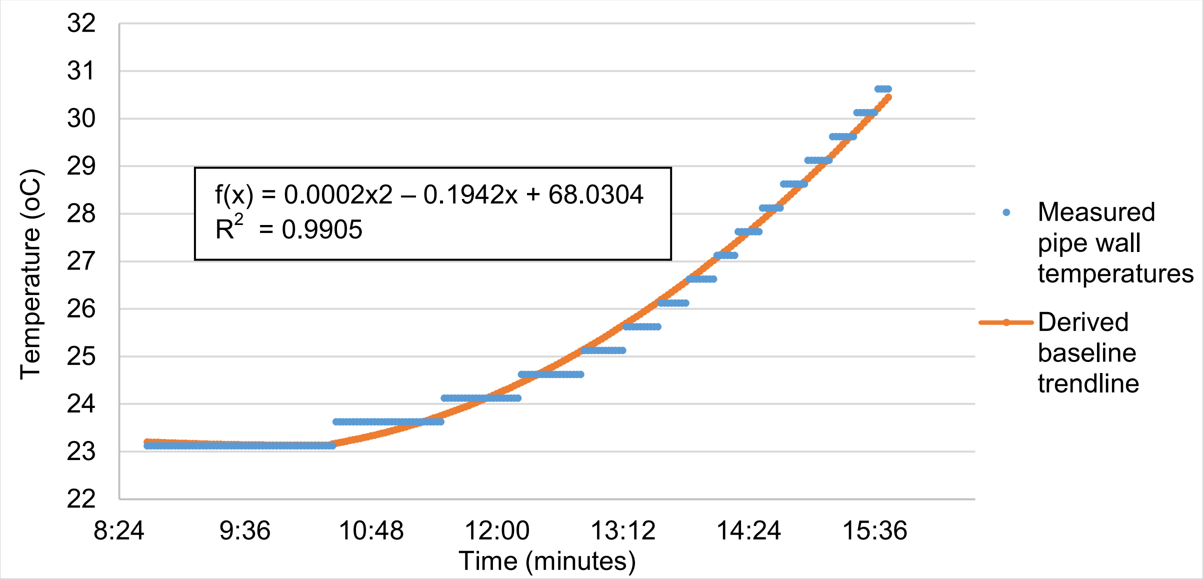


Figure 4-6 Derived baseline trendline S_1 of Logger 1_2

Figure 4-7 shows the final graph developed once the baseline curve for all segments (S_n) of Logger 1_2 were determined. The blue graph represents the recorded pipe wall temperatures and the orange graph represents the theoretical baseline temperatures. When an event occurs the derived baseline (ambient) temperatures would typically be significantly greater or less than the measured pipe wall temperatures, due to the difference in temperature between the groundwater and the pipe wall (prior to pumping). Whether the derived baseline temperatures are greater or less than the recorded pipe wall temperatures is dependent on the time of day, as well as the groundwater temperature. Consider the case when a pumping event was to occur at 5:00 with the ambient temperature being 5°C and the groundwater temperature 15°C, a baseline temperature greater than the recorded pipe wall temperature will be noted. On the other hand, in the late afternoon when the ambient temperature is, say 25°C, which will result in cooling of the pipe wall when pumping occurs due to the groundwater temperature of 5°C.

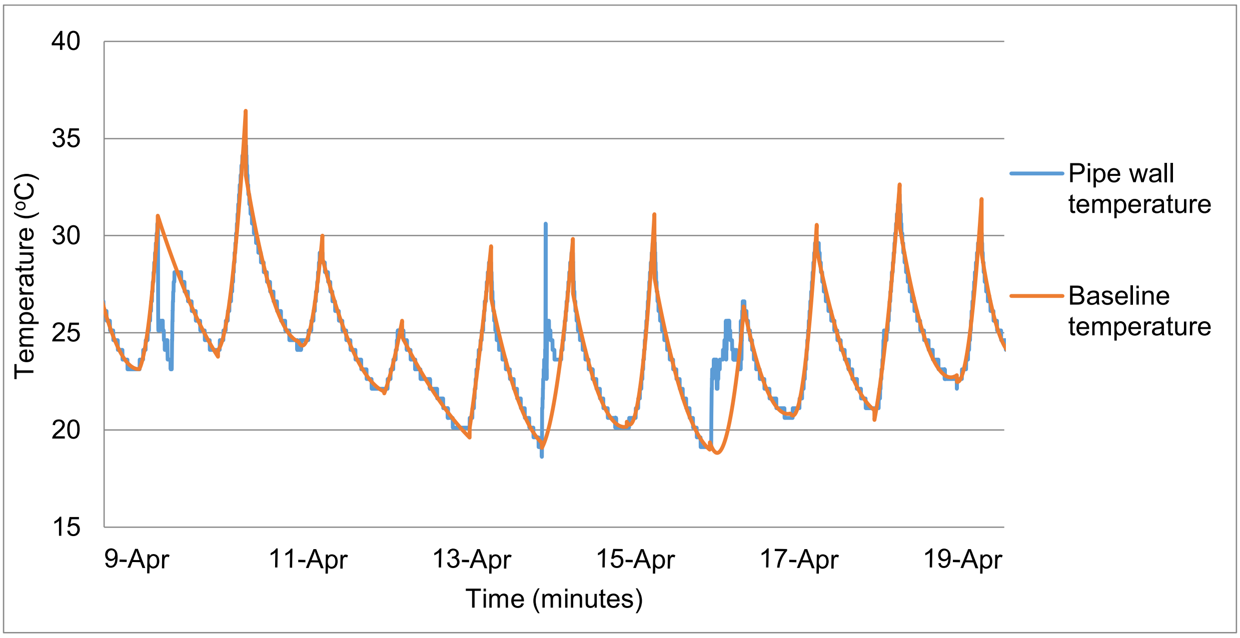


Figure 4-7 Recorded pipe wall temperatures and theoretical baseline temperatures

4.3.4 Determining pumping events

Step 4 was to subtract the derived baseline temperatures from the measured pipe temperatures. Hypothetically, if no water is flowing, the difference between the derived baseline temperature and the pipe temperature should be zero. In reality, however, a small difference in temperature will always be present. The differences between the pipe wall and baseline temperatures of Logger 1-2 are plotted in Figure 4-8.

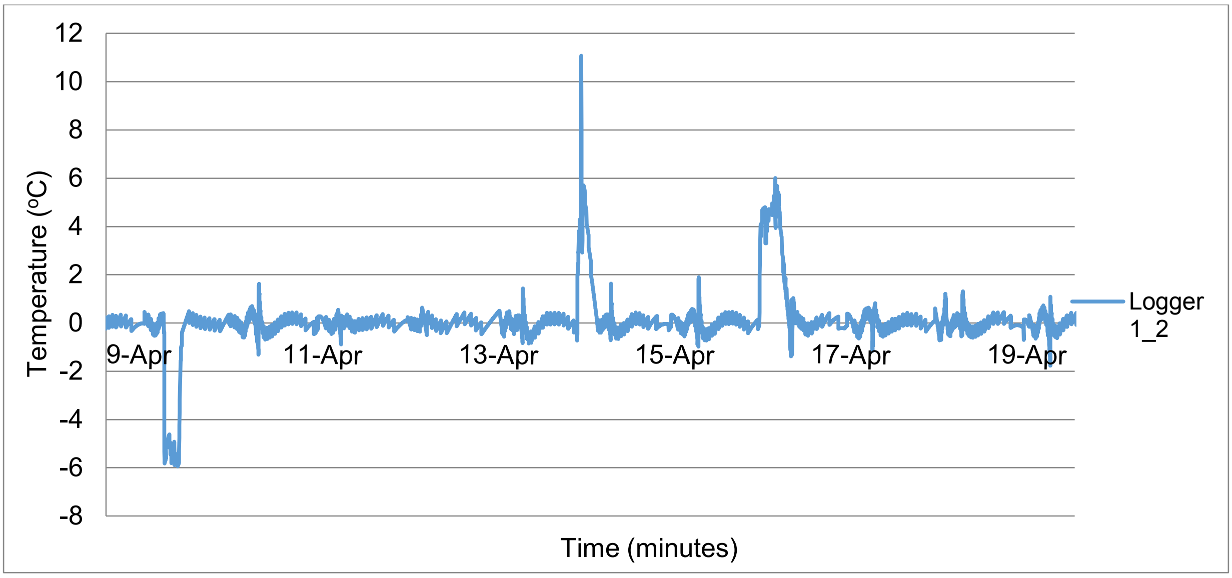


Figure 4-8 **Differences between pipe and baseline temperatures**

A threshold temperature was determined to filter data and identify pumping events. Massuel *et al.* (2009) recommended a threshold of 2.6°C. However, the threshold for this study was adjusted on a case-by-case basis to suit the type of environment the data logger was placed in, and varied between 1°C and 3°C. The threshold temperatures were determined using a trial and error method. Results were verified against actual pumping events by comparing the times of identified events to the times and durations documented by three homeowners. Figure 4-9 shows an example of the resulting filtered curve.

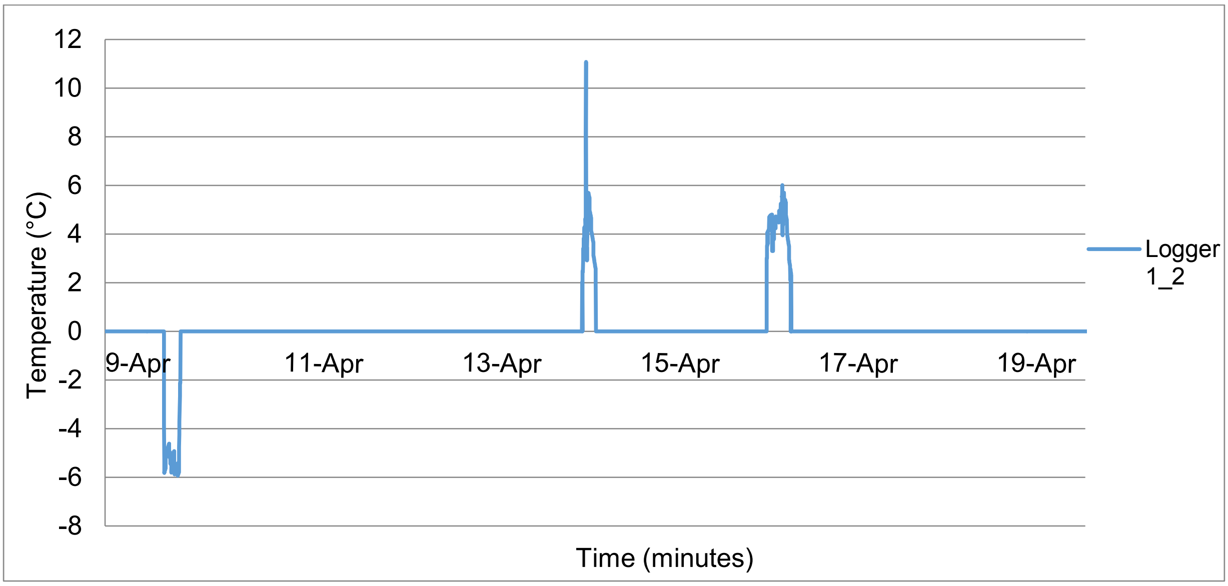


Figure 4-9 **Filtered differences between pipe and baseline temperatures**

Method 2 is summarised in a flowchart presented in Figure 4-10. The results from Method 1 and Method 2 were combined in order to identify the number of events and event durations as discussed in Chapter 7.

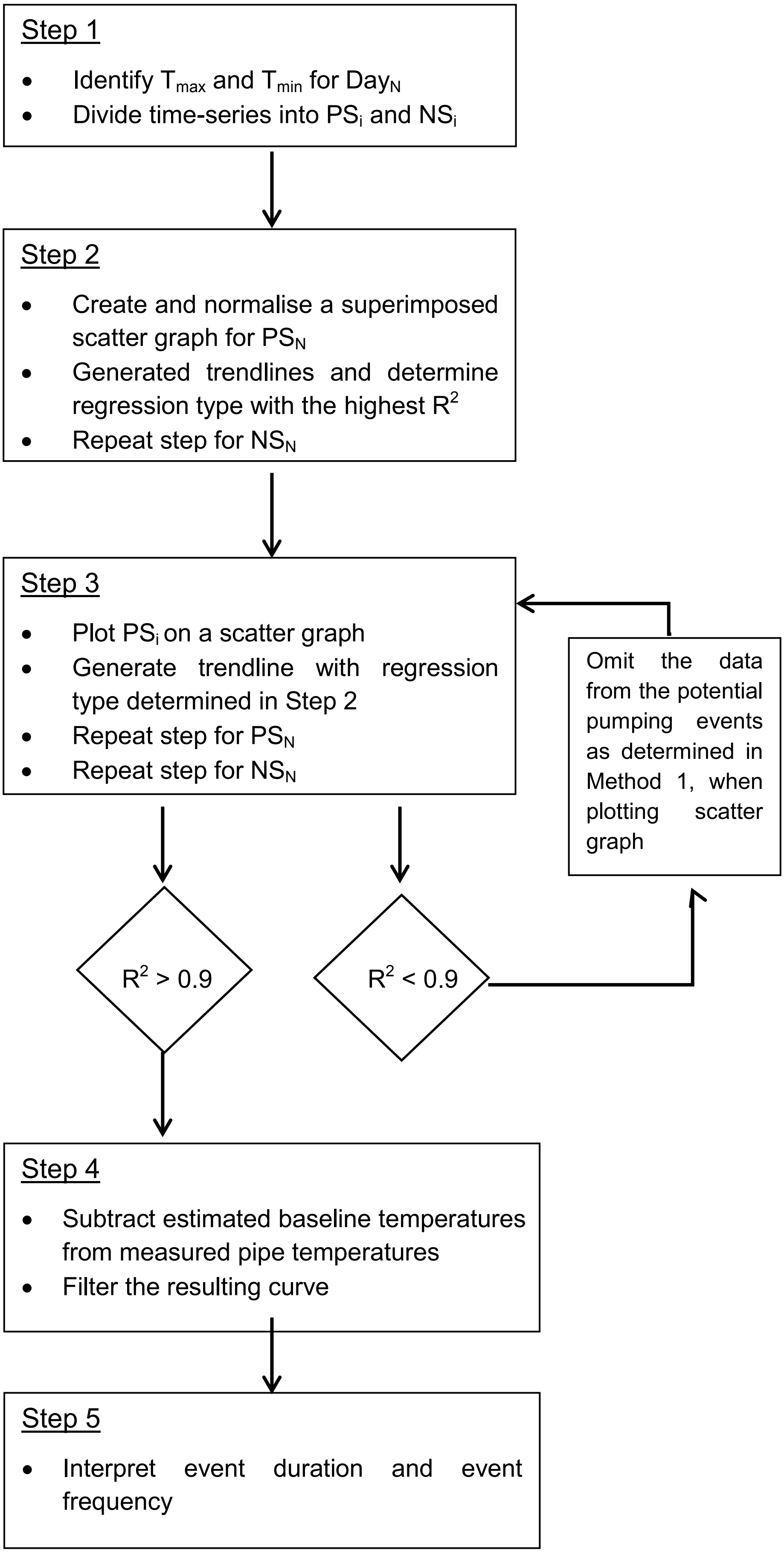


Figure 4-10 Flow chart to determine pumping events: Method 2

5 PROBABILISTIC SUPPLY MODEL

5.1 Overview

In this study the only supply resource evaluated was abstracted groundwater. Both the estimated pumping yield capacity and actual groundwater yield were stochastically determined in order to evaluate the extent to which the supply can meet irrigation demand for single residential stands. The groundwater actual supply volume was determined by combining the measured pumping durations at residential stands with the pumping flow rate, measured volumetrically on-site. The groundwater actual yield was estimated by constructing two models in Microsoft Excel and assessing different independent variables using Monte Carlo simulation. The independent variables for the pumping yield capacity and actual yield include pumping duration (t_p), flow rate (q), pump power (P), pump efficiency (η), and pumping head (H). A trial and error method determined the computer capacity for running the simulations.

5.2 Software selection

Microsoft Excel, Matlab, and Fortran are all software applications that can be used to develop statistical models, analyse data, and perform complex calculations. Excel is the most commonly used application because of its availability and simple, user friendly interface. The Excel spreadsheet function is used by Monte Carlo simulation software to construct distribution models. Another advantage of Excel compared to the other software applications is that extensive knowledge of the programming language is not necessary. Microsoft Excel was thus used in this study for statistical analysis.

An Excel add-on suite called @Risk was the chosen software for the Monte Carlo simulation, because it is affordable and is often used for research in the Department of Civil Engineering at Stellenbosch University. @Risk also includes options for discrete and continuous distributions, and performs GOF tests by making use of the K-S test, the A-D test, and the chi-squared test to compare the theoretical distributions with the given data. The maximum number of iterations in the Monte Carlo simulation was restricted by the computational capacity and available simulation time of the personal computer used, and was determined to be 1 000 000 iterations. According to Palaside (2016), using 1 000 to 5 000 iterations for a simulation is sufficient for most models. The 1 000 000 iterations used for this study surpasses Palaside's guidelines (2016) and is thus considered more than sufficient to represent accurate estimated results for this study.

5.3 Supply model construction

5.3.1 Potential household groundwater abstraction yield model

Two supply models were set up in Excel, using the @Risk add-in, to run a Monte Carlo analysis. The first supply model (Equation 5-1) determines the groundwater pumping yield capacity. This model shows the capacity of the GAPs, and should not be confused with the actual pumping yield. The typical pump-power equation was used, allowing for unit conversion to kL/h and kW.

$$Q_y = \frac{P\ x\ \eta\ \mathrm{x}\ 3.6}{\rho\ x\ g\ x\ H} \qquad (5\text{-}1)$$

where

Q_y = potential groundwater yield (kL/h)

P = power of the pump (kW)

η = pump efficiency (%)

ρ = density of the liquid (kg/m³)

g = gravitational acceleration (m²/s)

H = pumping head (m).

The second supply model estimates the actual supply volume from the GAPs. The model was constructed by multiplying the average volumetric flow rate of each GAP by the derived pumping durations, discussed in Chapter 4. This model is used to determine the daily volume of groundwater abstracted, which is compared to the daily garden irrigation demand. The model is shown in Equation 5-2.

$$\mathrm{V}_s = \mathrm{t}_p\ \mathrm{x}\ \mathrm{q}\ \mathrm{x}\ \mathrm{f} \qquad (5\text{-}2)$$

where

V_s = actual groundwater yield (kL/stand/day)

t_p = pumping duration (hours/event)

q = flow rate at GAP (kL/h)

f = pumping frequency (events/stand/day).

The pumping yield capacity of the GAP and the actual yield were specified as outputs, whereas the rest of the variables were considered inputs for the @Risk simulation. All the model variables and the relevant probabilistic distributions are discussed in the following sections.

5.3.2 Pumping flow rate

The actual flow rates of the GAPs were determined by conducting volumetric tests, as discussed in Section 3.3. The raw data and calculated results from the volumetric tests are included in Appendix C. A summary of the measured average flow rates are presented in Table 5-1 and were used as input variables for the supply model.

Table 5-1 Average recorded flow rates

Data logger code	Average measured flow rate (kL/h)
1_1	1.20
1_2	1.12
1_3	1.06
1_4	1.17
1_5	1.18
2_1	1.13
2_2	1.13
2_3	1.19
2_4	1.15
2_5	1.08

The measured values are within the estimated range of 0.98 kL/h to 2 kL/h for residential stands, as determined by previous publications (Tennick 2000; Roberts 2005; Matji and Associates 2008; Adelana *et al.* 2010; Jacobs 2010). The flow rates measured were therefore considered acceptable to use for further analysis.

The flow rates measured only represent a small sample group; therefore @Risk was used to develop a statistical distribution of the flow rates to be used as input variable in the supply model. The cumulative distribution function (CDF) of all the measured flow rates is plotted in Figure 5-1 and the best fit statistical distribution for the simulated flow rates (uniform distribution) are superimposed onto the graph. The simulated flow rates represent 1 000 000 iterations executed by @Risk.

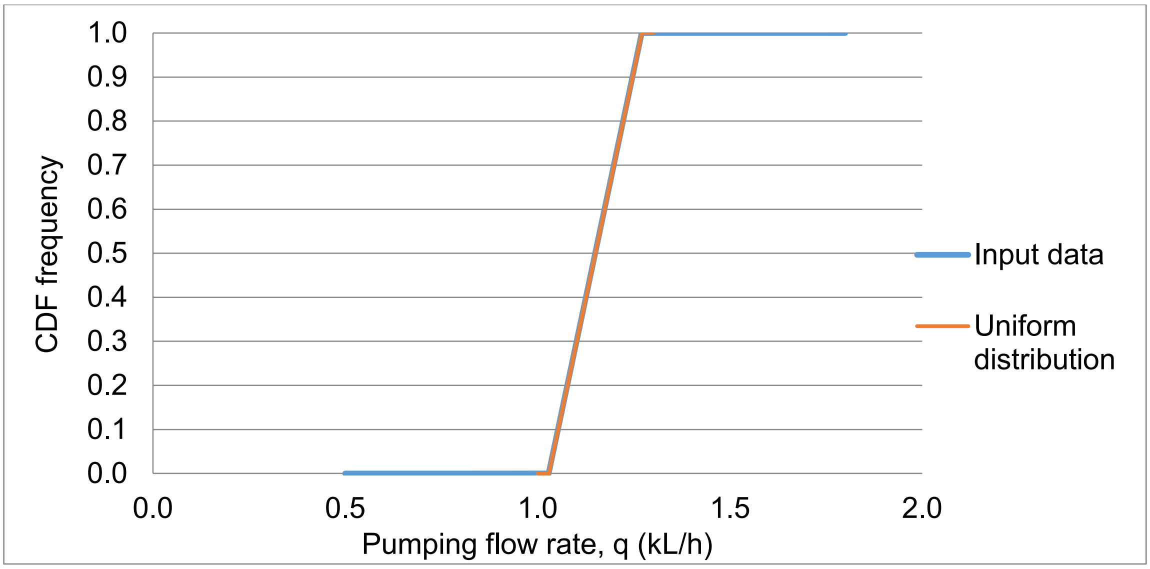


Figure 5-1 Cumulative distribution function (CDF): pump flow rate

Table 5-2 summarises the statistical parameters of the simulated flow rates. A comprehensive @Risk report, including both the input flow rate data and simulated flow rate values, are enclosed on the CD.

Table 5-2 Statistical parameters for the pumping flow rate

Variable	Distribution	Minimum (a)	Maximum (b)
Pumping flow rate (kL/h)	Uniform	1.029	1.271

5.3.3 Pumping duration and frequency

Since there is a discontinuity in irrigation patterns over an extended period of time, the frequency of pumping events was evaluated on a daily basis rather than on an individual event basis. The results from the analysed time-series are discussed in Chapter 7. However, a summary of the results is presented in Table 5-3 and were used as input variables for the supply model.

Table 5-3 Pumping duration per event

Date (2016)	Data logger code	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11
		Pumping duration (hours)										
9 April to 19 April	1_1	1.00	1.10	1.50	-	1.50	1.50	-	-	1.00	-	-
	1_2	-	4.30	-	-	-	-	3.60	-	6.50	-	-
	1_3	1.70	4.80	1.10	-	-	6.50	-	-	-	-	2.80
	1_4	3.60	2.30	2.80	1.80	2.00	3.80	4.80	2.80	3.30	2.00	4.40
	1_5	-	-	-	-	-	-	4.50	-	-	-	-
27 April to 7 May	2_1	-	1.30	-	-	-	0.40	-	2.50	-	-	-
	2_2	1.60	2.00	1.50	1.00	2.00	2.30	1.80	1.80	2.00	2.00	2.00
	2_3	1.90	2.10	2.30	3.00	2.80	3.00	2.50	2.50	2.80	2.50	2.80
	2_4	-	-	-	-	0.80	-	0.90	-	1.80	2.10	-
	2_5	-	1.60	-	-	-	-	4.00	-	7.00	-	7.00

Some pumping trends can be assumed from Table 5-3. Logger 1_4, Logger 2_2 and Logger 2_3 have fixed start times and pumping durations throughout the entire time series due to automated control systems and programmed irrigation events. Other pumping events that could be considered outliers were reported by Logger 2_5 on day 9 and day 11. The duration of these events is significantly longer than all other events in the dataset. Considering the timeframe of these events (around midnight), an argument can be made that the homeowner could have forgotten that the pump was running. The two outliers were not removed from the dataset, because of the likelihood that relatively long events could occur.

The CDF of all events is plotted in Figure 5-2. @Risk was used to perform GOF tests to determine the compatibility of the probability distributions with the measured data. The lognormal distribution was selected as the best fit based on the overall ranking determined by the GOP tests.

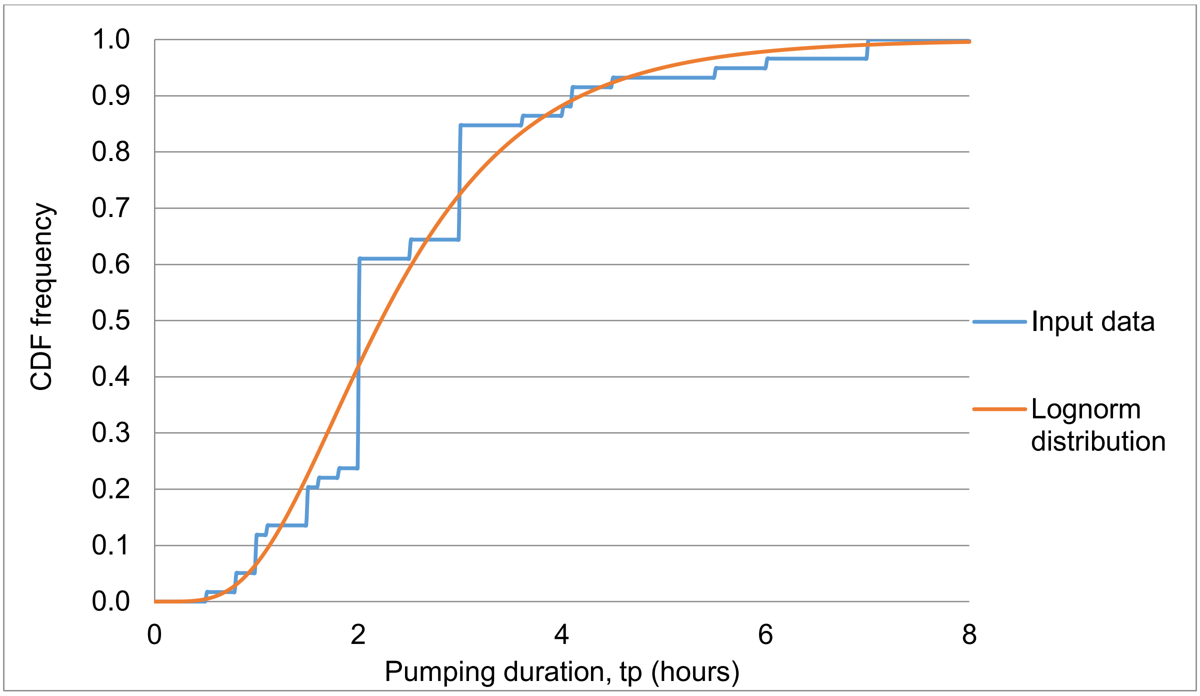


Figure 5-2 **Cumulative distribution function (CDF): pumping duration**

The summary of all GOP tests, the relevant parameters and best fit rankings for the different distributions are included on the CD. A comprehensive @Risk output report can also be found on the CD.

In addition to the average pumping duration per event, the number of events per day was calculated from the dataset in Table 5-3. A summary of the calculated event frequencies is listed in Table 5-4.

Table 5-4 Events per day of each sample

Data logger code	Events per day (f)
1_1	0.545
1_2	0.273
1_3	0.455
1_4	1.000
1_5	0.091
2_1	0.273
2_2	0.545
2_3	1.000
2_4	0.364
2_5	0.364

A best fit probability distribution was selected for the event frequency dataset by combining the rankings given to the distributions by the GOF tests. The lognormal distribution function is also graphed in Figure 5-3. The statistical summary and the relevant test fit results, as well as the complete @Risk report are included on the CD.

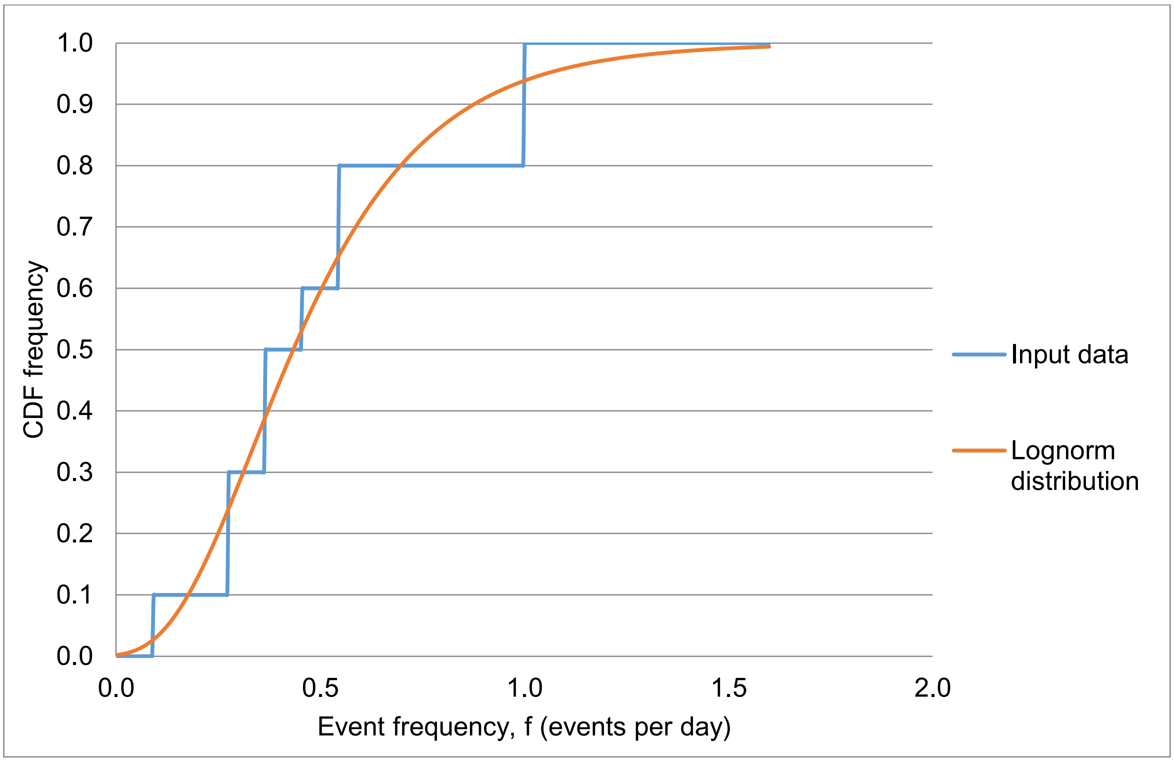


Figure 5-3 Cumulative distribution function (CDF): event frequency

The proposed statistical parameter values for the input variables t_p and f are summarised in Table 5-5. For both these variables a minimum boundary was set equal to 0, as negative pumping duration and events cannot occur.

Table 5-5 Statistical parameters for frequency factor and pumping duration

Variable	Distribution	Mean (μ)	Standard deviation (σ)	Shift factor
t_p (hours)	Lognormal	2.739	1.320	-0.245
f (per day)	Lognormal	0.672	0.298	-0.181

5.3.4 Pump hydraulics

The pumping power for all 10 datasets was recorded and is summarised in Table 5-6.

Table 5-6 Pump power of each sample

Data logger code	Pump power (kW)
1_1	1.50
1_2	1.13
1_3	1.10
1_4	1.20
1_5	0.74
2_1	1.50
2_2	1.13
2_3	1.50
2_4	1.13
2_5	1.13

The efficiency of each pump was determined using a range of average percentages as given by the pump manufacturers, including MAXAM, Pedrollo and DAB. Since no measurements were taken to determine the efficiency of the pumps and the values were solely based on information from the literature, a triangular distribution was chosen for statistical analysis of pumping efficiency. The minimum, average, and maximum pumping efficiency values used for the statistical parameters are 69%, 77.5% and 85% respectively.

Only pumps designed for the application of extraction at private GAPs were considered. Consequently, only a small number of pumps were selected for this input variable. If all available pumps were included, the curve would look different. The triangular distribution was therefore considered acceptable because the input data for this variable is quite crude. Figure 5-4 shows the theoretical simulated and the statistical triangular distribution for the pump power and Table 5-7 summarises the values of the statistical parameters for the pump hydraulics.

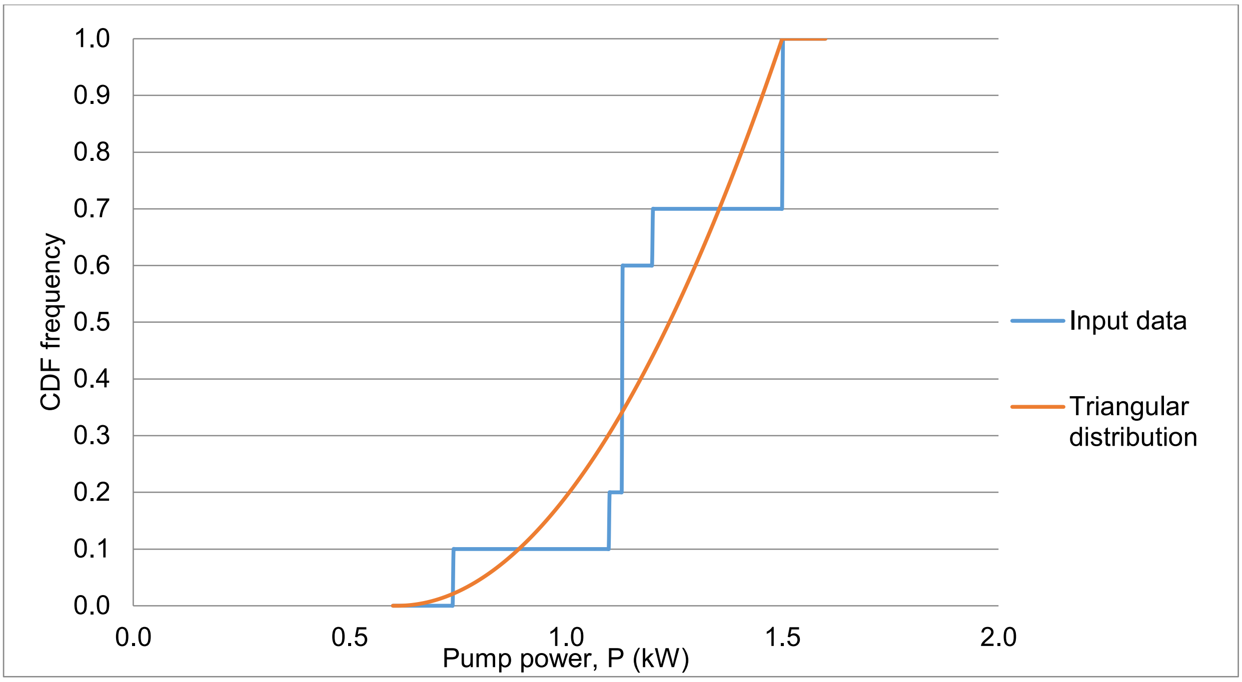


Figure 5-4 **Cumulative distribution function (CDF): pumping power**

Table 5-7 **Pump hydraulics statistical parameters**

Variable	Distribution	Minimum (a)	Mean (μ)	Maximum (b)
P (kW)	Triangular	0.610	1.500	1.500
η (%)	Triangular	69.000	77.500	85.000

The statistical summary and abbreviated test fit results for pumping power can be found on the CD attached. The pump efficiency and the comprehensive @Risk report are also included on the CD.

5.3.5 Pumping head

The borehole pump head is directly related to groundwater table depth, which is known to vary over time and by season based on the aquifer recharge rate and abstraction. The groundwater table depth was determined from earlier reports in literature (Adelena *et al.* 2010; Musekiwa and Majola 2013).

Since the actual pumping head values are unknown for the specific stands, a triangular distribution was considered to best represent the probability distribution of the data. The theoretical distribution curve for pump head was determined based on the highest ranked GOF test, as determined by the @Risk software. The triangular distribution had the highest combined ranking. The CDF distribution of the input data and best fit distribution curve are represented in Figure 5-5.

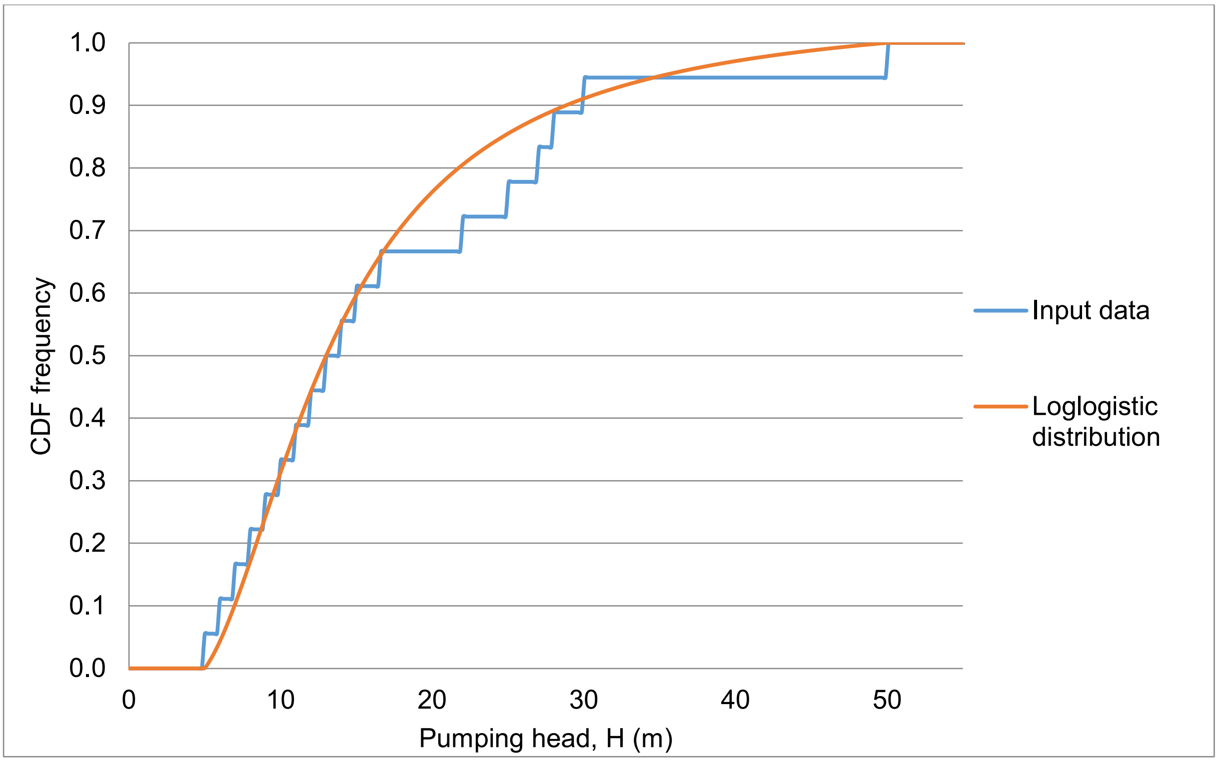


Figure 5-5 **Cumulative distribution function (CDF): pumping head**

The statistical parameters of the pumping head variable are summarised in Table 5-8. A comprehensive summary of all the simulated data values is included on the CD.

Table 5-8 **Statistical parameters for pumping head**

Variable	Distribution	Rank correlation (γ)	Regression coefficients (β)	Significance level (α)
H (m)	Loglogistic	3.986	9.380	1.817

6 PROBABILISTIC DEMAND MODEL

6.1 Overview

The water demand model was used to compare stochastically generated water demand to the supply model, in order to determine whether the expected groundwater actual yield can meet the irrigation demand. Irrigation factor (I_w), stand size (A) and average annual daily demand (AADD) were used as input variables in the model. The statistical parameters were selected based on results reported in literature from previous studies, as well as pilot studies and field tests.

6.2 Variability in outdoor demand

Outdoor use for garden irrigation varies significantly from one property to the next. Factors influencing outdoor demand for garden irrigation include precipitation, evapotranspiration, groundcover, presence of swimming pool, garden size, and vegetation type (Day and Howe 2003; Fox *et al.* 2009; Fisher-Jeffes *et al.* 2015). The estimated outdoor garden irrigation use in the study site is based on a percentage of total water demand at the residential stands. Various publications reported irrigation as a percentage of total household water use (Mayer and DeOreo 1999; Loh and Coghlan 2003; Roberts 2005; Heinrich 2007). Outdoor demand also experiences a peak flow, which refers to the period when maximum flow occurs. The peak flow factor (PF) is the ratio between the maximum flow rate and the average flow rate observed over an extended period of time. Peak demand will generally occur during the dry summer months in Cape Town. An assumption was made that the irrigation demand pattern for 2016 is an acceptable representation of historic and future household groundwater abstraction patterns for similar sites. The assumption was based on historical climatic data over the past ten years (2006-2015) with that of 2016. The results of the temperature and rainfall comparisons are enclosed in Appendix D.

6.2.1 Garden irrigation water demand model

A simplistic demand model was used, which multiplies the AADD by an irrigation factor, and is represented in Equation 6-1.

$$V_D = Q_{ave} x \frac{I_w}{100} \qquad (6\text{-}1)$$

where

V_D = garden irrigation water demand for a single household (m^3)

Q_{ave} = average annual water demand (kl/day/household)

I_w = % of total household water demand used for irrigation purposes (%).

Numerous more complex end-use models are available for estimating outdoor irrigation (Jacobs and Haarhoff 2004; du Plessis and Jacobs 2015).

Outdoor end-use models are dependent on factors such as garden size, climatic variables and vegetation type, but do not allow for AADD as independent variable. The model used in this research was useful because the AADD was included as independent variable. Unfortunately, the actual AADD, which could be derived from the monthly water meter readings, could not be obtained during this project due to newly approved ethical restrictions on consumer meter data. Estimated values based on local guidelines were used instead. Accounting for daily peak flow, Equation 6-1 was multiplied 2.3, the suggested PF according to Vorster *et al.* (1995). The demand model accounting for daily peak flow (V_{PD}), is shown in Equation 6-2.

$$V_{PD} = PFxV_D \tag{6-2}$$

where PF is taken as 2.3. All the input variables and their selected distributions are listed below.

6.2.2 Irrigation factor

The irrigation factor was defined as the percentage of household water demand used for irrigation purpose. The statistical parameters for the irrigation factor were obtained from a variety of sources in the literature that used different methods, including surveys (SWC 2000; Roberts 2004; Roberts 2012), metering (Roberts 2005) and Trace Wizard analyses (Roberts 2005). The values listed in Table 2-2 were used to investigate this variable. The distribution fit boundaries were set to have an unknown maximum. A triangular distribution was considered for the statistical analysis, as shown in Figure 6-1, and the GOF tests confirmed that the triangular distribution was the best representation of the dataset.

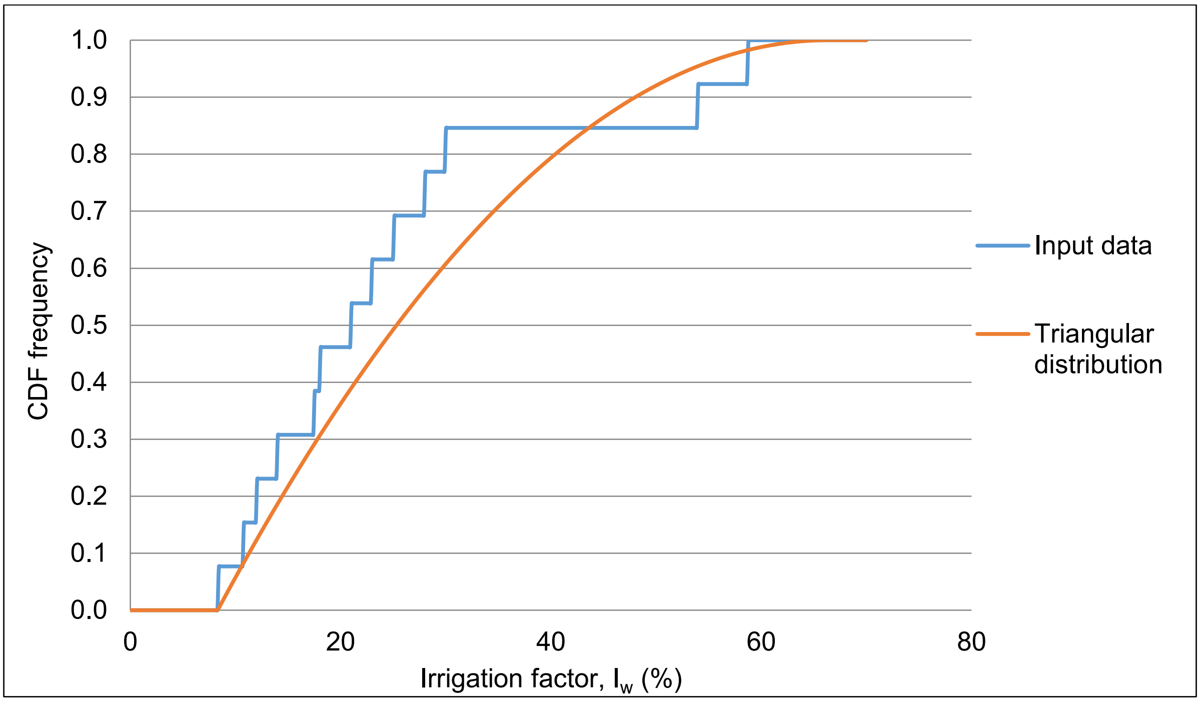


Figure 6-1 Cumulative distribution function (CDF): irrigation percentage

The simulated data points and distribution graphs are included on the CD, and the statistical parameters of the theoretical distribution are summarised in Table 6-1.

Table 6-1 Statistical parameters of irrigation as end-use percentage

Variable	Distribution	Minimum (a)	Likely minimum (a_1)	Maximum (b)
I_w (%)	Triangular	8.300	8.300	66.375

6.2.3 Stand sizes

The stand sizes of all the plots in the study sample were captured, using Google Earth, and are listed in Table 6-2. The reported area is the entire stand size, thus including impervious surfaces (roof, paving), irrigated area, and other non-irrigated areas.

Table 6-2 Stand sizes of sample group

Data logger code	Stand size (m^2)
1_1	828
1_2	824
1_3	972
1_4	884
1_5	921
2_1	816
2_2	643
2_3	968
2_4	1161
2_5	1355

The stand areas fall within the norm and do not represent any outliers. The stand sizes are within the range of 50 m^2 to 2050 m^2, as per the AADD guidelines published by Jacobs *et al.* (2004). Table 6-3 summarises the statistical parameters for the stand size input variable, and Figure 6-2 graphically shows the estimated data range and distribution of a single simulation.

Table 6-3 Statistical parameters for stand sizes

Variable	Distribution	Rank correlation (γ)	Regression coefficients (β)	Significance level (α)
A (m^2)	Loglogistic	50.000	860.410	8.815

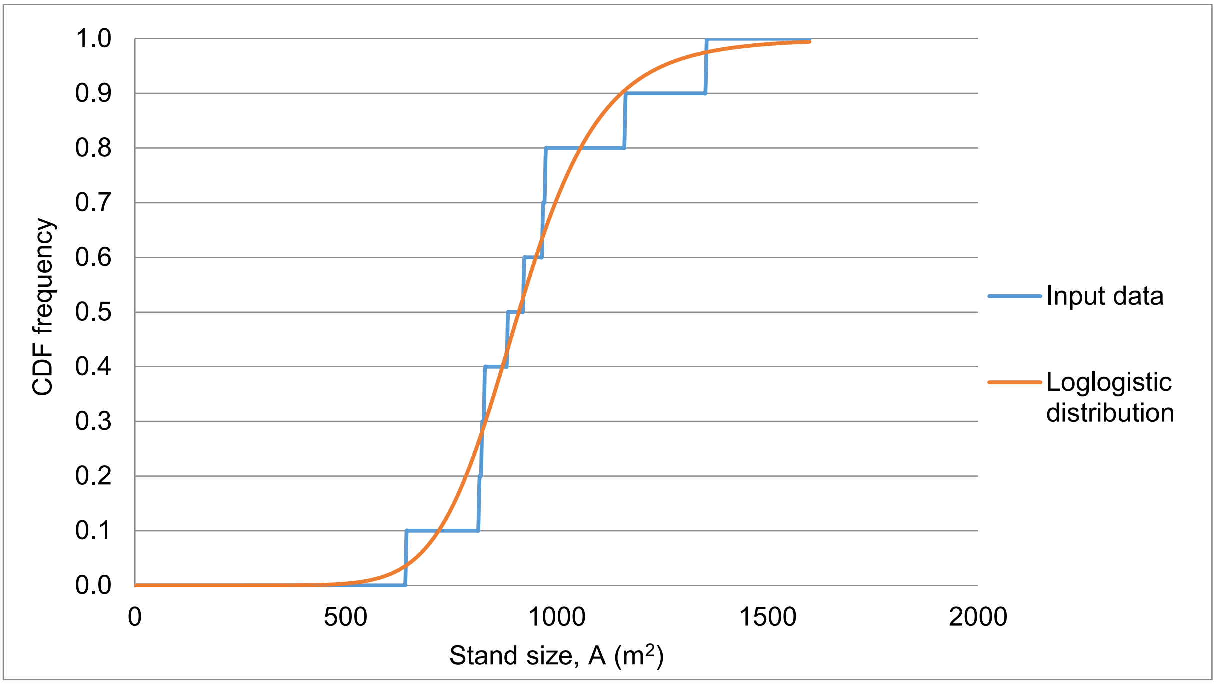


Figure 6-2 Cumulative distribution function (CDF): stand sizes

The loglogistic distribution was ranked first by all three GOF tests and was thus chosen to represent the distribution of the data. The statistical summary and abbreviated test fit results for stand size are included in on the CD, as well as the comprehensive @Risk report.

6.2.4 Average annual daily demand

Van Zyl *et al.* (2007) identified stand size, water price, income, climate and type of development (suburb vs. township) as the most significant parameters that affect residential water demand in South Africa. Based on available data, stand size was chosen to estimate water demand for this study. Different South African estimation guidelines using stand size as the determining variable were considered. Similar to the other estimation methodologies, Jacobs *et al.* (2004) developed a single-coefficient model with stand size as the only variable. Unlike the other estimation methodologies, Jacobs *et al.* (2004) also incorporated other factors influencing water demand, namely, geographic regions, climate, and dwelling types. Therefore, the demand model presented by Jacobs *et al.* (2004) was chosen for prediction of the AADD.

As previously mentioned, the study site used for evaluating the groundwater pumping rate is located in a coastal winter rainfall region, and subsequently, the envelope curves for that geographic region were used when estimating AADD. Jacobs *et al.* (2004) states that the upper boundary envelope is more critical than the lower boundary, and therefore the equation for the upper boundary envelope (Equation 2-2) was used for residential water demand estimations. The AADD was defined in @Risk as an output, with stand size as its only input. A CFD plot of the simulated results is shown in Figure 6-3.

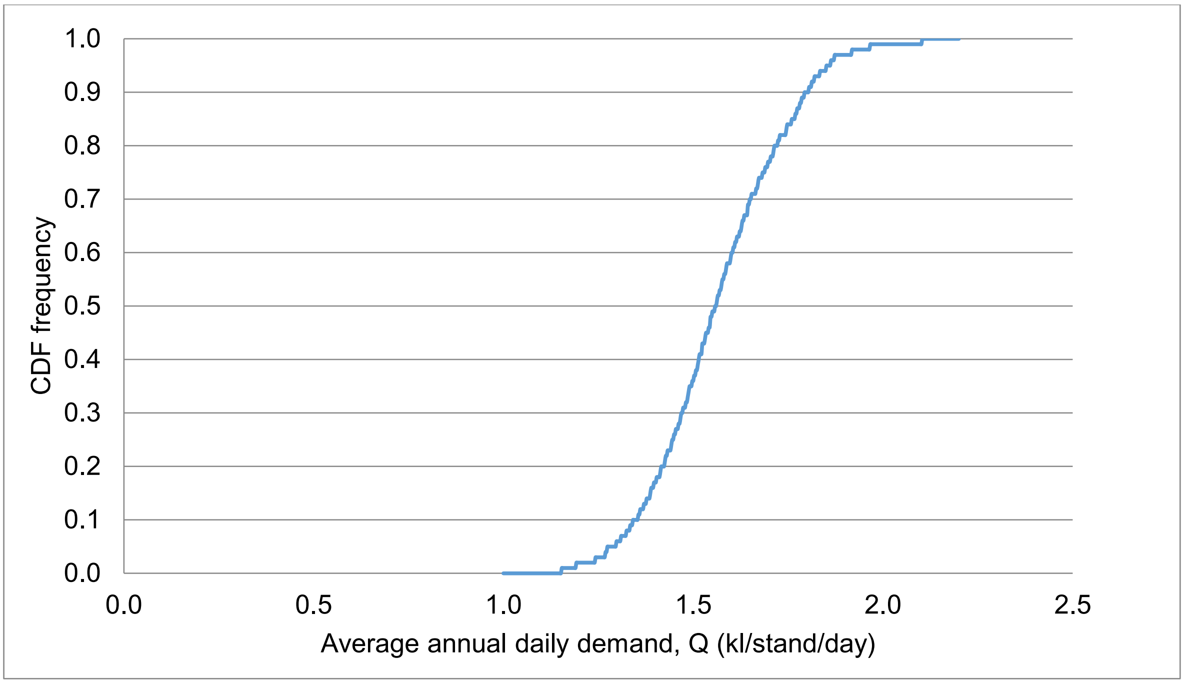


Figure 6-3 Cumulative distribution function (CDF): AADD

7 RESULTS

7.1 Identification of pumping events - Thermologgers

With reference to Section 4.3 the comprehensive results for Steps 4, 5, and 6 are presented in this section. The time of day and duration of pumping events were determined by evaluating the measured pipe wall temperatures and the derived baseline temperatures as discussed earlier.

Figures E-1(a) through Figure E-10(a) in Appendix E show the superimposed graphs of the pipe wall temperatures and baseline temperatures of the different data loggers. Figures E-1(b) to Figure E-10(b) in Appendix E show the differences between the pipe wall temperature and baseline temperature. The resultant filtered curves are shown in Figure E-1(c) through Figure E-10(c) in Appendix E. As previously stated, the threshold temperature that was used to identify the pumping events varied from one home to the next, depending on the environment in which the data loggers had been placed.

The average duration of all 59 pumping events ultimately identified was 2.46 hours per event. Considering a pumping frequency of 0.408, the average GAP supply time is roughly 1 hour. Using an assumed flow rate of 1.27 kL/h, the average volume of water pumped in a day is roughly 1.27 kL. Table 7-1 shows the potential total daily irrigated volumes for assumed flow rates, namely 1 kL/h, 1.25 kL/h, 1.5 kL/h, 1.75 kL/h, and 2.00 kL/h. The values are in line with the reported irrigation volumes (Tennick 2000; Meyer 2001; Matji and Associates 2008, Jacobs 2010), as could be expected.

Table 7-1 Total monthly irrigated volumes for identified flow rates

Flow rate (kL/h)	Volume of water pumped per day (kL/day)
1.00	1.01
1.25	1.26
1.50	1.51
1.75	1.77
2.00	2.02

The event durations used to calculate the volume of water pumped were derived from Figure E-1(c) through Figure E-10(c). The pumping stop and start times as well as the threshold temperatures for both Group 1 and Group 2 are given in Table 7-2 and Table 7-3, respectively.

Table 7-2 Start and stop times of pumping events: Group 1

Data logger code	Threshold temperature	Start time	Stop time	Duration (hours)
1_1	2°C	9-Apr 16:08	9-Apr 17:14	1.0
		10-Apr 15:12	10-Apr 16:28	1.1
		11-Apr 06:32	11-Apr 07:54	1.5
		13-Apr 16:02	13-Apr 17:34	1.5
		14-Apr 09:16	14-Apr 10:48	1.5
		17-Apr 16:06	17-Apr 17:12	1.0
1_2	2°C	9-Apr 15:52	9-Apr 20:16	4.3
		14-Apr 08:30	14-Apr 12:10	3.6
		16-Apr 10:12	16-Apr 16:48	6.5
1_3	3°C	9-Apr 06:50	9-Apr 08:32	1.7
		10-Apr 10:40	10-Apr 15:24	4.8
		11-Apr 12:18	11-Apr 13:24	1.1
		14-Apr 18:48	15-Apr 01:22	6.5
		19-Apr 05:06	19-Apr 07:54	2.8
1_4	1.5°C	9-Apr 05:16	9-Apr 07:04	1.8
		9-Apr 07:30	9-Apr 09:18	1.8
		10-Apr 05:24	10-Apr 07:02	1.6
		10-Apr 07:42	10-Apr 08:24	0.7
		11-Apr 05:18	11-Apr 07:04	1.8
		11-Apr 07:48	11-Apr 08:50	1.0
		12-Apr 05:12	12-Apr 07:04	1.8
		13-Apr 05:06	13-Apr 07:06	2.0
		14-Apr 05:06	14-Apr 08:54	3.8
		15-Apr 05:08	15-Apr 09:48	4.8
		16-Apr 05:06	16-Apr 07:08	2.0
		16-Apr 07:24	16-Apr 08:10	0.8
		17-Apr 05:16	17-Apr 07:08	0.9
		17-Apr 07:18	17-Apr 09:40	2.4
		18-Apr 05:08	18-Apr 07:04	2.0
		19-Apr 05:12	19-Apr 07:12	2.0
		19-Apr 07:34	19-Apr 08:40	1.0
		19-Apr 09:14	19-Apr 10:38	1.4
1_5	1°C	15-Apr 06:34	15-Apr 11:00	4.5

Table 7-3 Start and stop times of pumping events: Group 2

Data logger code	Threshold temperature	Start time	Stop time	Duration (hours)
2_1	2°C	27-Apr 11:52	27-Apr 13:12	1.3
		1-May 16:06	1-May 16:28	0.4
		3-May 11:38	3-May 14:06	2.5
2_2	2°C	26-Apr 14:15	26-Apr 15:51	1.6
		27-Apr 07:28	27-Apr 09:32	2.0
		28-Apr 07:32	28-Apr 09:06	1.5
		29-Apr 08:30	29-Apr 09:32	1.0
		30-Apr 07:28	30-Apr 09:24	2.0
		1-May 07:28	1-May 09:44	2.3
		2-May 07:30	2-May 09:18	1.8
		3-May 07:30	3-May 09:16	1.8
		4-May 07:28	4-May 09:32	2.0
		5-May 07:28	5-May 09:34	2.0
		6-May 07:30	6-May 09:24	2.0
2_3	2°C	27-Apr 04:22	27-Apr 06:14	1.9
		28-Apr 04:22	28-Apr 06:30	2.1
		29-Apr 04:22	29-Apr 06:38	2.3
		30-Apr 04:20	30-Apr 07:16	3.0
		1-May 04:20	1-May 07:02	2.8
		2-May 04:22	2-May 07:26	3.0
		3-May 04:22	3-May 06:56	2.5
		4-May 04:20	4-May 06:54	2.5
		5-May 04:20	5-May 07:00	2.8
		6-May 04:20	6-May 06:56	2.5
		7-May 04:22	7-May 07:02	2.8
2_4	2°C	30-Apr 11:24	30-Apr 12:10	0.8
		2-May 09:50	2-May 10:42	0.9
		4-May 08:30	4-May 10:10	1.8
		5-May 23:34	6-May 01:42	2.1
2_5	3°C	27-Apr 09:06	27-Apr 10:44	1.6
		2-May 23:44	3-May 03:50	4.0
		3-May 21:24	4-May 04:22	7.0
		5-May 21:36	6-May 04:12	7.0

The groundwater temperature at every event was identified and a CDF curve of the values were plotted in Figure 7-1. Appendix E shows the tabulated groundwater temperatures at every event. The groundwater temperatures were not used in the statistical simulation models; however, this collection of data could be used for future research on household water temperature. The average groundwater temperature was 21.45°C, with a standard deviation of 2.14°C.

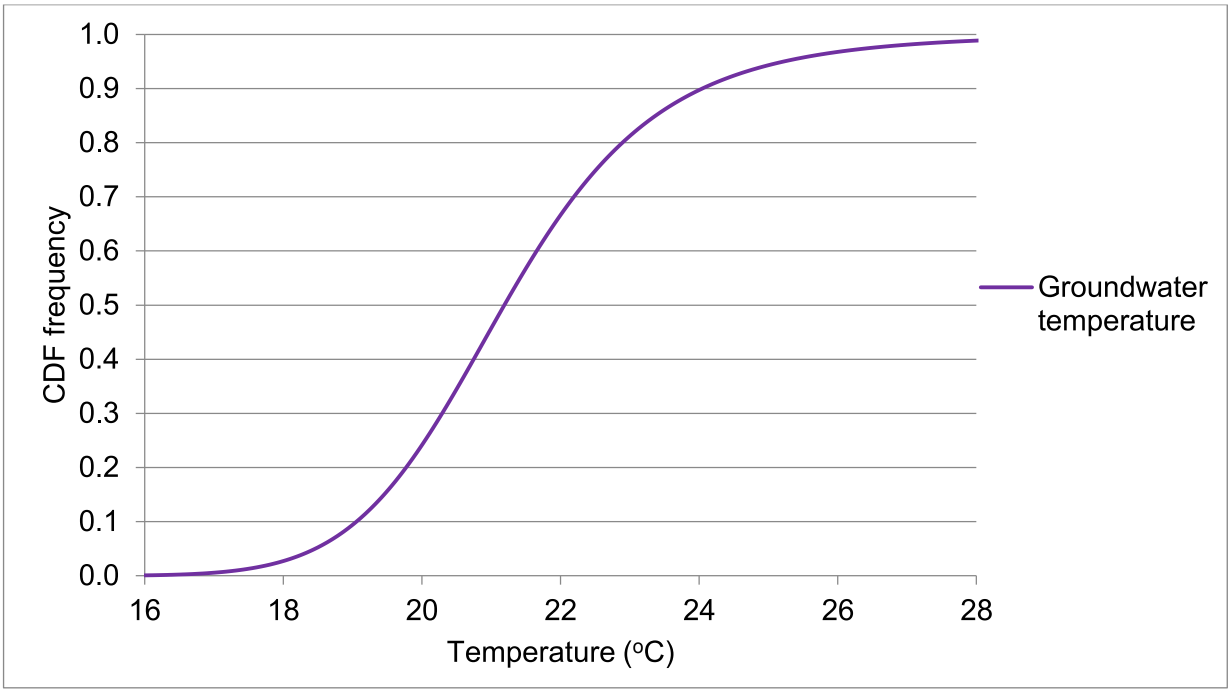


Figure 7-1 **Recorded groundwater temperatures for all events**

7.2 Supply model

7.2.1 Input parameters – supply model

The purpose of the supply model developed for Monte Carlo simulations was to generate different solutions that take into account numerous different scenarios, to best estimate the pumping habits of residential homeowners. The simulated input variables include 1 000 000 iterations executed by @Risk. The software performed Monte Carlo simulations by selecting a combination of sample-values from the defined input variables, and storing the calculated value. This process was repeated 1 000 000 times until all of the iterations had been completed.

Table 7-4 compares the defined supply input parameters to the simulated input parameters. The defined input parameters, accumulated from small sample sizes, were used to develop the simulated input parameters, which consists of 1 000 000 data points. The simulated input values were used to populate the supply model. A comprehensive @Risk report of all the input variables is included on the CD.

Table 7-4 Supply model input variables

Input variables	Defined input parameters			Simulated input parameters		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
q (kL/h)	1.04	1.14	1.26	1.03	1.15	1.27
η (%)	69.00	77.50	85.00	69.11	77.17	84.96
P (kW)	0.74	1.21	1.50	0.74	1.25	1.50
H (m)	5.00	17.14	50.00	5.00	15.72	49.97
t_p (hr)	0.50	2.50	7.00	0.19	2.46	7.75
f (events/day)	0.09	0.54	1.00	0.00	0.44	1.00

7.2.2 Results – supply model

Using the simulated input variables, two different supply output models were constructed, simulated and evaluated. The first model (Equation 5-1) determined the pumping yield capacity of the GAPs at single residential stands and the second model (Equation 5-2) estimated the actual pumping yield at the GAPs.

The pumping yield capacity is the current installed supply capacity based on the pumps at the residential stands. If larger pumps are installed more water could be pumped. The actual aquifer sustainable yield could be less than the installed pump discharge capacity if the pumps are used for most of the day. This report cannot comment on the aquifer, and therefore, the first model could not be used to compare with the demand model. As a result, the second model (Equation 5-2) was constructed to determine the actual yield of the GAPs, and is solely referred to as the supply model for the rest of the report. The supply model was used to compare with residential irrigation demand to ultimately determine whether the estimated supply from GAPs could meet the theoretical irrigation demands. The probability density function (PDF) of the supply model results is plotted in Figure 7-2.

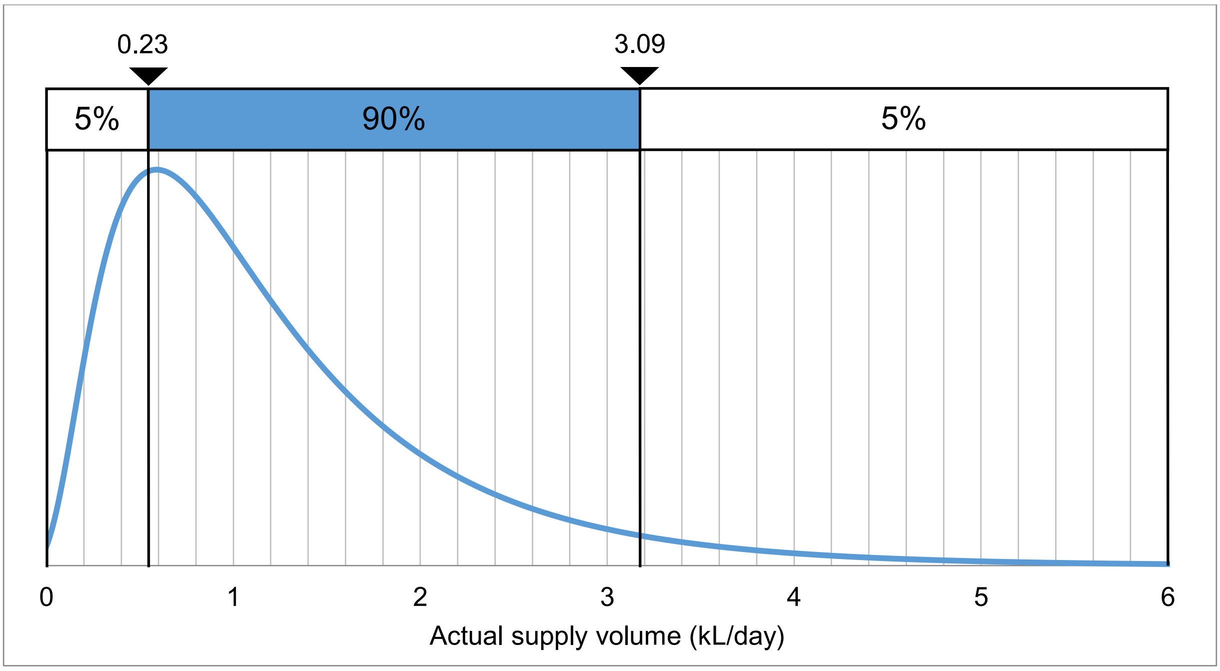


Figure 7-2 **Probability density function (PDF): supply model output**

The stochastic results of the GAP actual supply volume, shown in Figure 7-2, suggest that 90% of the actual groundwater supply is between 0.23 kL/day and 3.09 kL/day. The stochastically estimated mean volume of water supplied by the GAPs on a daily basis was 1.25 kL. The mean actual supply volume is less than that of previous studies (Tennick 2000, Matji and Associates 2008, Jacobs 2010), as expected, since the values estimated in literature assumed the water is pumped daily, whereas the supply model took the event frequency into consideration.

7.2.3 Sensitivity analysis – supply model

A sensitivity analysis was carried out to identify the parameters with the most notable impact on the supply model results, and a tornado chart was used to identify the most important uncertainty variables. A tornado chart is a type of bar chart that is typically used for decision-making, and Howard (1988) first published the term. Tornado charts are often used in engineering to conduct sensitivity analyses, and were employed by Porter *et al.* (2002) and Lee and Mosalam (2006). The data for the tornado chart was generated using @Risk software, and the derived diagram is shown in Figure 7-3.

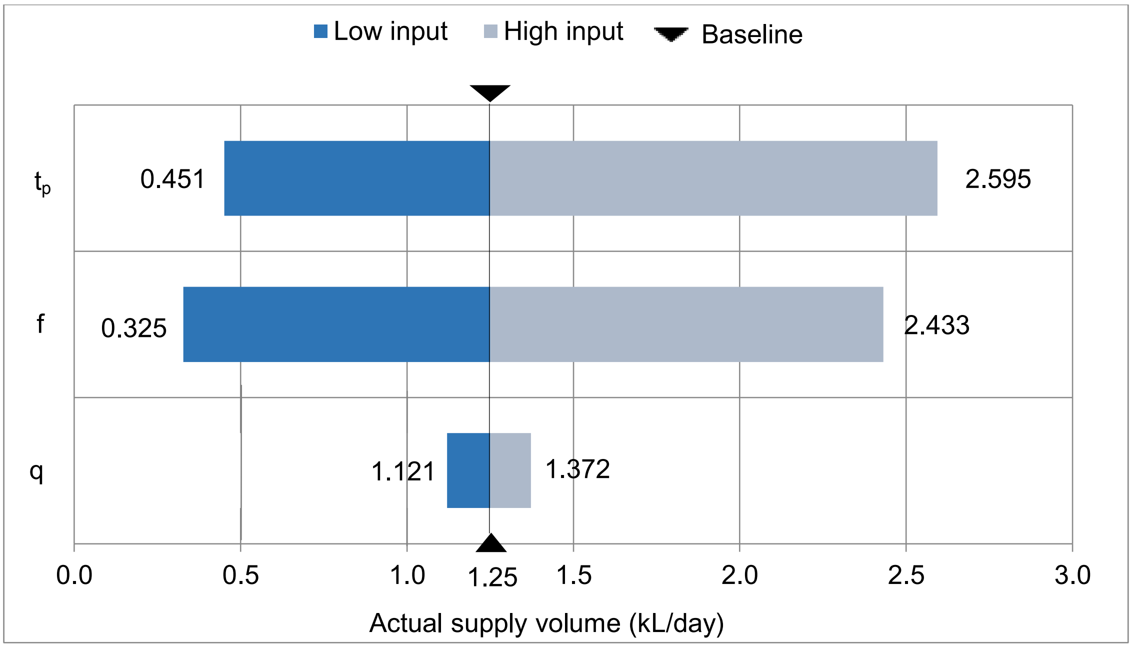


Figure 7-3 Tornado chart: supply model sensitivity analysis

The results from the tornado chart show how the actual supply volume is affected by all the input parameters. The best estimate value for each input parameter is used to calculate the mean actual supply volume, and is specified on Figure 7-3 as the baseline value. The vertical line at 1.25 kL/day gives the mean actual supply volume when all the input parameters are taken at their 50th percentile values. The high and low inputs are the 10th percentile and 90th percentile values of the input parameters. The resulting actual supply volume calculated from the high and low inputs are represented by the ends of the horizontal bars.

The parameters in the tornado chart are shown in decreasing order of their effect on the actual supply volume. Meaning, the parameter with the biggest effect on actual supply volume is the pumping duration. This emphasise the importance of measuring the pumping durations at GAPs.

The event frequency also greatly influences the actual supply volume. This is one of the reasons why the actual yield estimated is less than the values estimated by earlier publications (Tennick 2000; Matji and Associates 2008; Jacobs 2010). The literature estimates are based on the assumption that water is pumped daily, whereas the supply model considers the event frequency. Figure 7-4 shows the PDF of the supply model results if daily pumping is assumed.

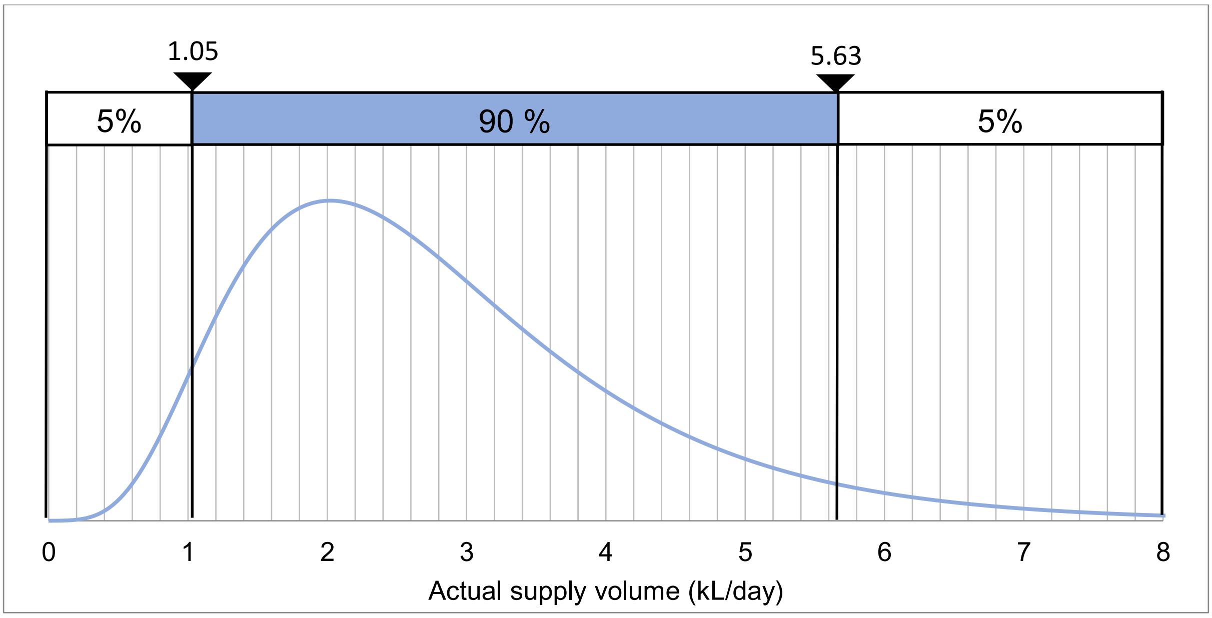


Figure 7-4 Probability density function (PDF): supply model output assuming daily pumping

When the supply model omits the pump frequency variable, the actual supply volumes increase significantly. If daily pumping is assumed, the mean actual supply volume increases to 2.83 kL/day, and the 90% range of values expands between the volumes of 1.05 kL/day and 5.63 kL/day, as shown in Figure 7-4. These values correlate with previous publications (Tennick 2000; Matji and Associates 2008; Jacobs 2010).

Although the output supply model from Figure 7-2 is a more realistic representation of household groundwater abstraction during the study period, the model based on the assumption of daily pumping was used in this study. Assuming daily pumping resulted in higher estimations of groundwater abstraction volumes, which will account for the peak season. Therefore, the model omitting event frequency was used to determine whether the estimated actual supply from GAPs could meet the theoretical irrigation demands.

7.3 Demand model

7.3.1 Input parameters – demand model

The demand model was used to estimate the volume of irrigated water. The simulated demand input parameters, as well as the defined demand input parameters used to develop the simulated values, are summarised in Table 7-5. A comprehensive @Risk report, listing all 1 000 000 simulated data points, is included on the CD. No visible leaks were present and were thus omitted from the end-use demand investigations.

Table 7-5 Demand model input variables

Input variables	Defined input parameters			Simulated input parameters		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
I_w (%)	8.30	24.63	58.70	8.30	23.66	66.38
A (m^2)	643.00	937.20	1 355.00	306.54	928.09	2 049.86

The maximum and minimum simulated stand size values vary significantly from the defined input parameters. This is because the defined input parameters include stand sizes of only 10 residential stands, where the simulated input parameters account for 1 000 000 possible residential stands.

7.3.2 Results – demand model

The simulated input values were used to populate the demand model (Equation 6-2), and the PDF of the demand model results is plotted in Figure 7-5.

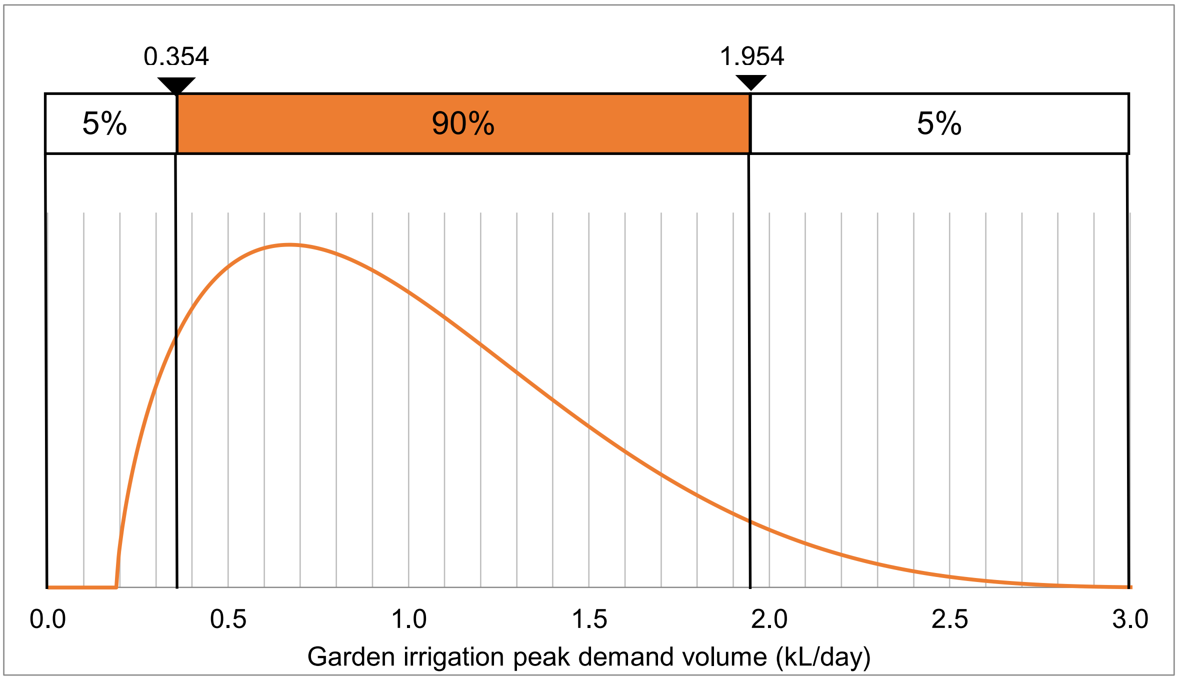


Figure 7-5 Probability density function (PDF): demand model output

The mean peak demand for garden irrigation is 0.9963 kL/day, and the PDF curve in Figure 7-5 estimates that 90% of the simulated data lies between 0.347 kL/day and 1.954 kL/day. The simulated theoretical maximum garden irrigation demand is 3.061 kL/day.

7.3.3 Sensitivity analysis – demand model

A sensitivity analysis was carried out by means of a tornado chart to identify the most important uncertainty demand variables. The @Risk software was used to determine the effect the parameters had on garden irrigation demand, and the derived tornado chart diagram is shown in Figure 7-6. The parameters in the tornado chart are shown in decreasing order of their effect on garden irrigation peak demand.

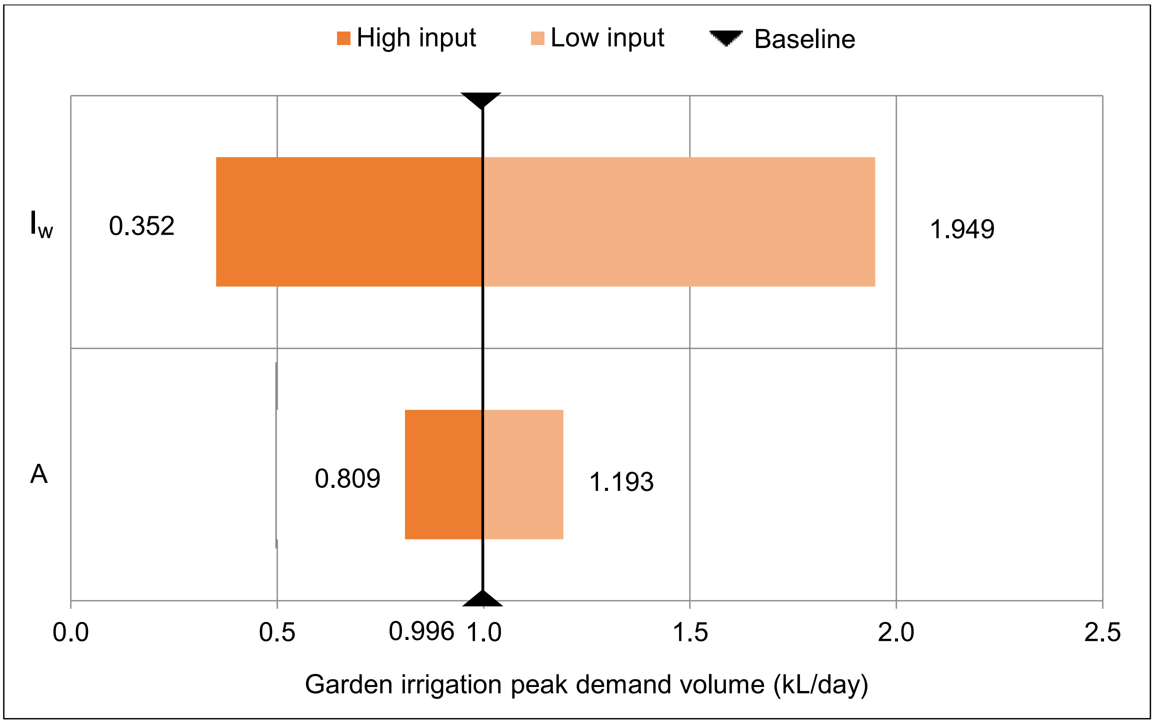


Figure 7-6 **Tornado chart: demand model sensitivity analysis**

The results shown in Figure 7-6 suggests that the irrigation percentage variable has a larger effect on the demand output than that of the stand sizes variable. In-order to compare this demand model with the supply model, accurate predictions of irrigation habits are thus important. When all the input parameters are taken at their 50th percentile values, the garden irrigation peak demand is 0.996 kL/day.

7.4 Demand versus supply

Results of the supply and demand models were compared in order to evaluate the extent to which water supplied by GAPs could meet the peak water demand for irrigation purposes. The simulated results listed in the previous section showed that the theoretical maximum demand for irrigation use is 3.061 kL/day, the mean is 0.996 kL/day, and 90% of the data lies between 0.347 kL/day and 1.954 kL/day. To determine what percentage of the supply model results can meet the garden irrigation demands specified, Figure 7-4 was modified. The modified graph is plotted in Figure 7-7.

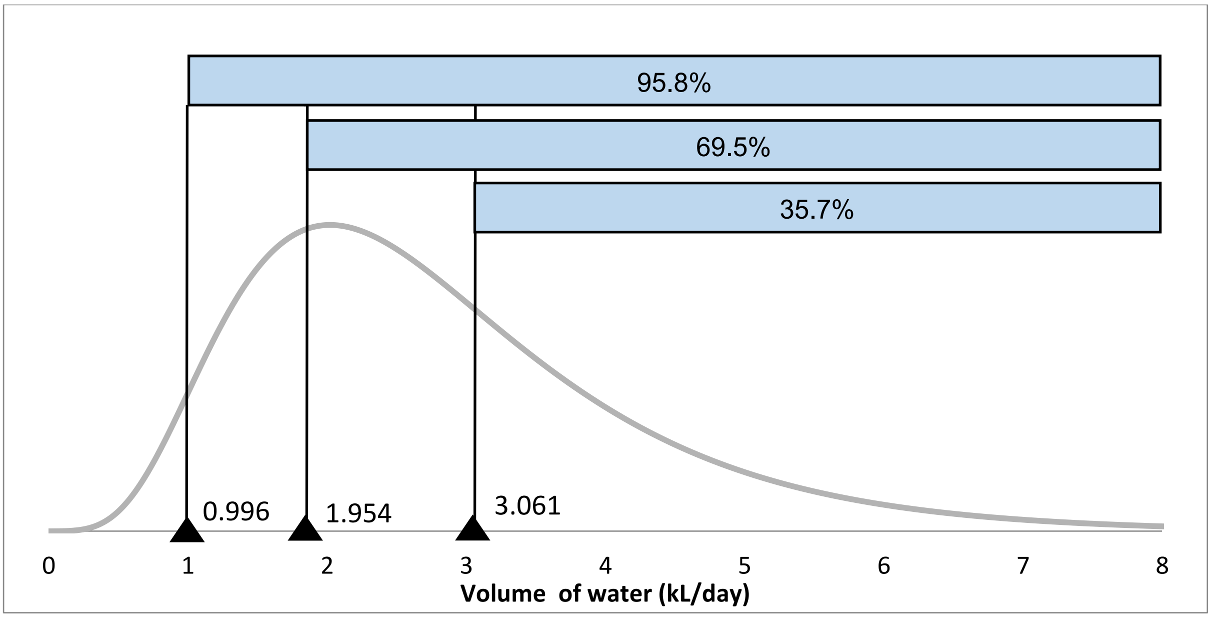


Figure 7-7 **Probability density function (PDF): supply model results modified**

Figure 7-7 suggests the following:

- 35.7% of the maximum garden irrigation peak demand (3.061 kL/day) could be met by household groundwater abstraction
- the average garden irrigation peak demand (0.996 kL/day) will be met 95.8% of the time by residential GAPs
- groundwater supply can meet the 90th percentile of garden irrigation peak demand (1.954 kL/day) with a certainty of 69.5%.

Another way to interpret the results is by normalising both the demand and supply probability density functions and superimposing the curves, as seen in Figure 7-8.

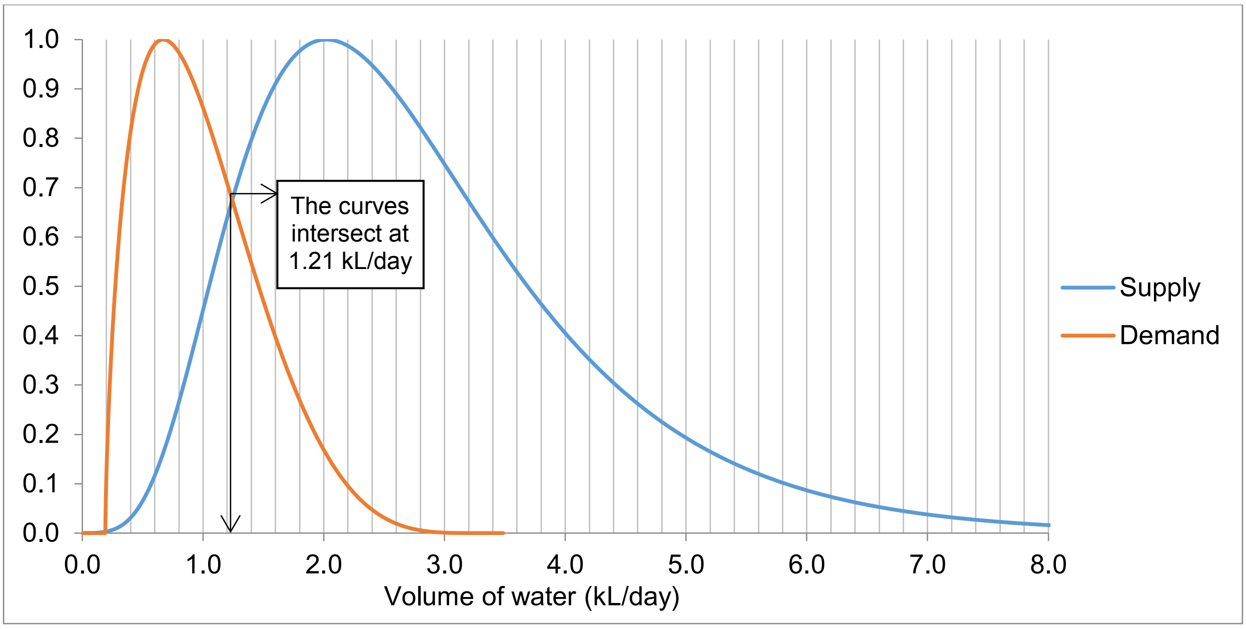


Figure 7-8 **Normalised probability density function (PDF): supply vs demand**

The peaks of the curves correspond to the volume of water that has the highest probability of being in demand or supply. The values are 2.842 kL/day and 0.996 kL/day for the supply and demand curve respectively. The supply is ample to meet irrigation demands. The intersection of the two curves indicates the portion of the demand met by GAPs. Figure 7-8 shows the intersection point to be 1.211 kL/day as indicated by the black arrows. Thus, when the peak demand is higher than 1.211 kL/day, there is a possibility that the GAPs will not be able to supply groundwater sufficiently. The percentage of simulated data points exceeding 1.211 kL/day in the demand model is 34%. Thus, the stochastic analysis shows that theoretically 66% of total irrigation peak demand at residential stands could be met on average.

8 CONCLUSION

8.1 Summary of findings

The literature review suggests that groundwater is a good alternative resource to the municipal potable supply and can be used for garden irrigation. Previous studies also suggest that groundwater actual yield can meet residential irrigation demand. This research study used the Monte Carlo method to simulate supply and demand curves, to theoretically determine whether irrigation demand can be sufficiently supplied by privately owned boreholes and well-points.

Various AADD estimation methodologies were investigated to determine a residential stand's water demand. Guideline curves developed by Jacobs *et al.* (2004) were chosen for this study – the single-variable model used stand size as the dependant variable, and partially considered other factors influencing water demand such as climate, geographic location, and dwelling type. The percentage of the estimated AADD needed for garden irrigation purposes was obtained from literature, and was used to develop the demand model. The percentages ranged from 8.3% to 58.7% for the specific study site in the Cape Town area.

The supply model was based on household groundwater abstraction rates and pumping duration. One of the challenges faced during the study was to estimate borehole pump event frequency and duration of pumping events – variables needed to estimate household groundwater abstraction rates. Thermologgers were used to determine the pumping durations and frequencies. The method proved to be non-invasive, causing little to no disruptions to the residents. Residents were also willing to partake in the study since only the pipe wall temperature was measured and no water meters were installed.

Jacobs (2010) suggested the "best guess" for groundwater flow rates from privately owned boreholes and well-points to be between 1 kL/h and 2 kL/h, in line with other literature sources. The results from this study found the average flow rate at GAPs to be 1.25 kL/h for the specific study site, which falls within the range suggested by the literature. The pumping duration was determined by measuring the variations in the temperature of outlet pipes using thermologgers, and interpreting the data to estimate abstraction duration. The results from this study estimated the average pumping duration to be 2.46 hours, which is slightly higher than the estimated duration for borehole irrigation events of 2 hours (Tennick 2000).

The stochastically derived results show that the groundwater actual supply volume can meet daily peak irrigation demand with a certainty of 66%. When the outdoor irrigation peak demand is higher than 1.211 kL/day, there is a possibility that the GAPs will not be able to supply a sufficient amount of groundwater, based on the existing pump durations for the 10 stands. The percentage of simulated data points exceeding 1.211 kL/day in the demand model is 34%.

8.2 Conclusion

The method of monitoring household groundwater abstraction at privately owned GAPs was investigated by measuring temperature variations in outlet pipes. It was found that thermologgers could potentially be used to determine pumping durations at single-residential stands in South Africa. The method proved to be simple, cost effective, and caused little to no disturbance to the homeowners. The environment the data loggers were placed in affected the temperature measurements, and should be taken into consideration when interpreting the recorded data.

Developing predictive statistical models to estimate actual groundwater supply and irrigation demand is an acceptable method that could be used by water managers. With the assumption that residents pump water every day, it was found that the 10 homes studied would be able to abstract sufficient amounts of groundwater to meet irrigation needs.

8.3 Future research and suggestions

This study assumed the pumping frequency and durations measured for two periods of 11 days each to be a good representation of typical long-term values. No distinctions were made for seasonal variability. Future research should extend the period of testing to include multiple years of data, and seasonal variability.

The estimations used for AADD were based on a single-variable model that represents multiple South African households. If local data is available, future research should use historical billing to predict AADD of stands at the specific study site, and include those values in the probability distribution models. It will also be valuable to compare water demand volumes prior to GAP installations with water demand volumes after the installation of GAPs.

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APPENDIX A
Type of environment

Environment A: Refers to an environment where the pump and outlet pipes are partially protected from direct sunlight and precipitation by means of a four walled enclosure with a removable roof. The shape and size of this type of enclosure is similar to that of a typical medium sized dog's doghouse. Most of the samples were placed in this type of environment and Figure 3-4 shows a picture of a typical Environment A structure.

Figure A-1 Pump-pipe system: Environment A

Environment B: The pump and outlet pipes placed in this type of environment are fully included and are not exposed to any sunlight or climatic conditions. This type of environment experiences fewer temperature changes than Environment A. A picture of a pump system placed in this environment is shown in Figure 3-5.

Figure A-2 Pump-pipe system: Environment B

Environment C: Refers to an environment where the pump and outlet pipes have no protection from any weather conditions. These loggers received direct sunlight and therefore experience significant temperature changes compared to the other two environments. An example of a logger placed in an open environment is presented in Figure 3-6.

Figure A-3 Pump-pipe system: Environment C

APPENDIX B

ThermoDynamics executive summary

[redacted]

Testing by Bettina

Executive Summary

360000002D4C1641

Company Details

Company	Stellenbosch University
Report Number	# 3
Requested By	Bettina
Report Date	2016/04/20 13:34:59
Contact Number	[redacted]
Email Address	[redacted]

Logger Details

Logger Type	Temperature: High precision general purpose.
Mission Start Time	2016/04/08 17:59:01
Serial Number	360000002D4C1641

Descriptions

Field	Data
Descriptions	[redacted]

Mission Set Up Details

Mission Running	Yes	Started on Alarm	No
Mission Sample Count	8192	Start Delay	No
Mission Sample Rate	2 minutes	Rollover Enabled	No
Rolled Over	No	Roll-Over/End In	2016/04/20 03:03:01
Low Temperature Alarm	-41.278 °C	Low Humidity Alarm	0.000 %RH
High Temperature Alarm	86.276 °C	High Humidity Alarm	0.000 %RH
Temperature Resolution	0.5000 °C	Humidity Resolution	Humidity Not Enabled

[redacted]

Testing by Bettina

Executive Summary

360000002D4C1641

Mission Set Up Details

Mission Running	Yes	Started on Alarm	No
Mission Sample Count	8192	Start Delay	No
Mission Sample Rate	2 minutes	Rollover Enabled	No
Rolled Over	No	Roll-Over/End In	2016/04/20 03:03:01
Low Temperature Alarm	-41.278 °C	Low Humidity Alarm	0.000 %RH
High Temperature Alarm	86.276 °C	High Humidity Alarm	0.000 %RH
Temperature Resolution	0.5000 °C	Humidity Resolution	Humidity Not Enabled

Quick View Mission Result

Mission Alarm	No		
High Temperature Alarm	No	High Humidity Alarm	N/A
Low Temperature Alarm	No	Low Humidity Alarm	N/A
Highest Temperature	35.606 °C	Highest Humidity	N/A
Lowest Temperature	10.596 °C	Lowest Humidity	N/A
Average Temperature	20.041 °C	Average Humidity	N/A
Mean Kinetic Temperature	19.965 °C		

Summary Exception Information

Alarm Type	Time	Alarm Duration
No data		

Routing Information

Description	Date
Serial No.	Location
[redacted]	2016/04/20 13:33:29
8900000033227081	1

360000002D4C1641

[redacted]

Testing by Bettina

Executive Summary

Mission Set Up Details

Mission Running	Yes	Started on Alarm	No
Mission Sample Count	8192	Start Delay	No
Mission Sample Rate	2 minutes	Rollover Enabled	No
Rolled Over	No	Roll-Over/End In	2016/04/20 03:03:01
Low Temperature Alarm	-41.278 °C	Low Humidity Alarm	0.000 %RH
High Temperature Alarm	86.276 °C	High Humidity Alarm	0.000 %RH
Temperature Resolution	0.5000 °C	Humidity Resolution	Humidity Not Enabled

Quick View Mission Result

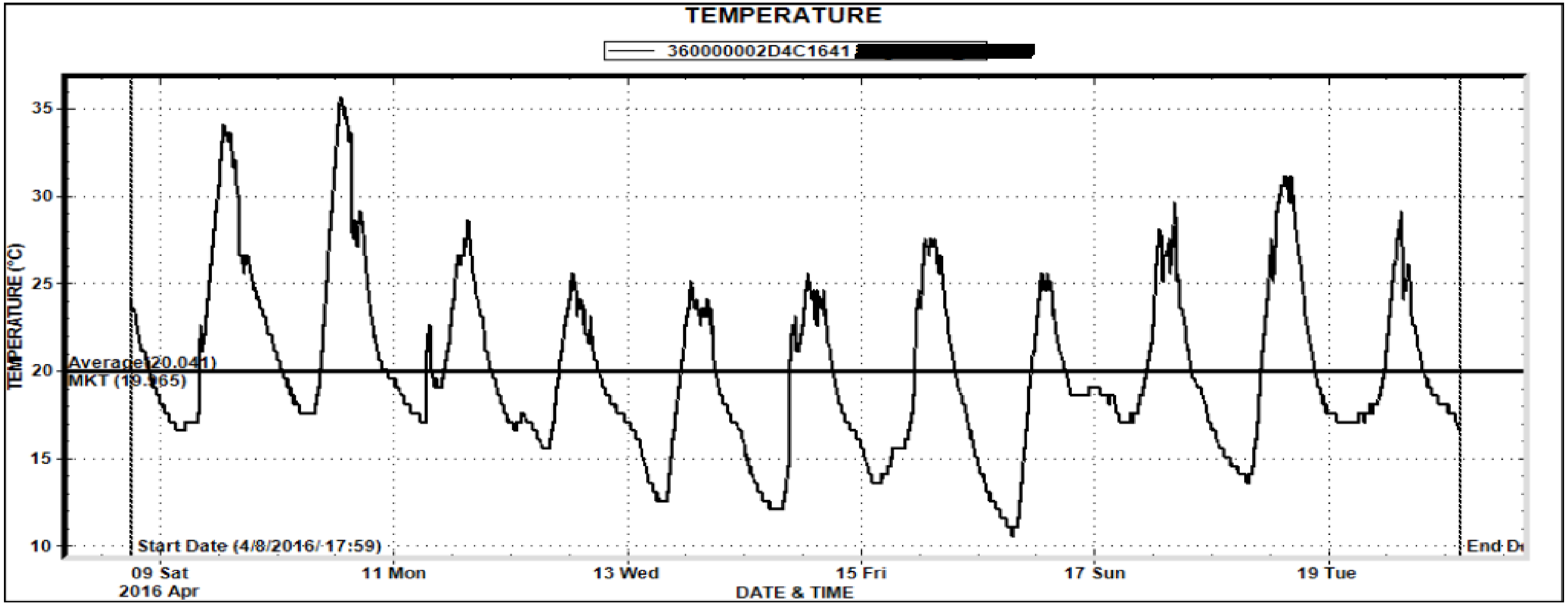
Mission Alarm	No		
High Temperature Alarm	No	High Humidity Alarm	N/A
Low Temperature Alarm	No	Low Humidity Alarm	N/A
Highest Temperature	35.606 °C	Highest Humidity	N/A
Lowest Temperature	10.596 °C	Lowest Humidity	N/A
Average Temperature	20.041 °C	Average Humidity	N/A
Mean Kinetic Temperature	19.965 °C		

coldchain
Thermo Dynamics

360000002D4C1641

[redacted]
Testing by Bettina

TEMPERATURE GRAPH



coldchain
Thermo Dynamics

[redacted]
Testing by Bettina

Readings

360000002D4C1641

Readings

Number	Date and Time	Temperature
1	2016/04/08 17:59:01	24.115 °C
2	2016/04/08 18:01:01	24.115 °C
3	2016/04/08 18:03:01	24.115 °C
4	2016/04/08 18:05:01	23.615 °C
5	2016/04/08 18:07:01	23.615 °C
6	2016/04/08 18:09:01	23.615 °C
7	2016/04/08 18:11:01	23.615 °C
8	2016/04/08 18:13:01	23.615 °C
9	2016/04/08 18:15:01	23.615 °C
10	2016/04/08 18:17:01	23.615 °C
11	2016/04/08 18:19:01	23.615 °C
12	2016/04/08 18:21:01	23.615 °C
13	2016/04/08 18:23:01	23.615 °C
14	2016/04/08 18:25:01	23.615 °C
15	2016/04/08 18:27:01	23.615 °C
16	2016/04/08 18:29:01	23.615 °C
17	2016/04/08 18:31:01	23.615 °C
18	2016/04/08 18:33:01	23.615 °C
19	2016/04/08 18:35:01	23.615 °C
20	2016/04/08 18:37:01	23.615 °C
21	2016/04/08 18:39:01	23.615 °C
22	2016/04/08 18:41:01	23.615 °C
23	2016/04/08 18:43:01	23.615 °C
24	2016/04/08 18:45:01	23.615 °C
25	2016/04/08 18:47:01	23.115 °C
26	2016/04/08 18:49:01	23.115 °C
27	2016/04/08 18:51:01	23.115 °C
28	2016/04/08 18:53:01	23.115 °C
29	2016/04/08 18:55:01	23.115 °C
30	2016/04/08 18:57:01	23.115 °C
31	2016/04/08 18:59:01	22.615 °C
32	2016/04/08 19:01:01	22.615 °C
33	2016/04/08 19:03:01	22.615 °C

APPENDIX C
Pumping flow rate

Logger 1_1	Time	Mass of bucket (empty)	Date
	45 s	1 kg	19-Apr-16

Measurement #	Mass of bucket (with water) (kg)	Water mass (kg)	Calculated flow rate (kL/h)
1	16.00	15.00	1.20
2	16.20	15.20	1.22
3	16.00	15.00	1.20
4	16.50	15.50	1.24
5	15.80	14.80	1.18
6	16.00	15.00	1.20
7	16.30	15.30	1.22
8	15.50	14.50	1.16
9	16.10	15.10	1.21
10	15.90	14.90	1.19
		Average	1.20

Logger 1_2	Time	Mass of bucket (empty)	Date
	45 s	1 kg	19-Apr-16

Measurement #	Mass of bucket (with water) (kg)	Water mass (kg)	Calculated flow rate (kL/h)
1	15.20	14.20	1.14
2	14.90	13.90	1.11
3	15.30	14.30	1.14
4	15.00	14.00	1.12
5	14.00	13.00	1.04
6	15.10	14.10	1.13
7	15.60	14.60	1.17
8	15.50	14.50	1.16
9	15.10	14.10	1.13
10	14.90	13.90	1.11
		Average	1.12

Logger 1_3	Time	Mass of bucket (empty)	Date
	45 s	1 kg	19-Apr-16

Measurement #	Mass of bucket (with water) (kg)	Water mass (kg)	Calculated flow rate (kL/h)
1	14.40	13.40	1.07
2	14.50	13.50	1.08
3	13.90	12.90	1.03
4	14.80	13.80	1.10
5	13.80	12.80	1.02
6	14.60	13.60	1.09
7	14.00	13.00	1.04
8	14.20	13.20	1.06
9	14.30	13.30	1.06
10	14.50	13.50	1.08
		Average	1.06

Logger 1_4	Time	Mass of bucket (empty)	Date
	45 s	1 kg	19-Apr-16

Measurement #	Mass of bucket (with water) (kg)	Water mass (kg)	Calculated flow rate (kL/h)
1	15.90	14.90	1.19
2	16.00	15.00	1.20
3	15.90	14.90	1.19
4	15.90	14.90	1.19
5	16.10	15.10	1.21
6	15.50	14.50	1.16
7	15.40	14.40	1.15
8	15.10	14.10	1.13
9	15.60	14.60	1.17
10	15.40	14.40	1.15
		Average	1.17

Logger 1_5	Time	Mass of bucket (empty)	Date
	45 s	1 kg	19-Apr-16

Measurement #	Mass of bucket (with water) (kg)	Water mass (kg)	Calculated flow rate (kL/h)
1	15.50	14.50	1.16
2	16.10	15.10	1.21
3	16.30	15.30	1.22
4	15.90	14.90	1.19
5	15.80	14.80	1.18
6	15.90	14.90	1.19
7	15.40	14.40	1.15
8	15.60	14.60	1.17
9	15.60	14.60	1.17
10	15.90	14.90	1.19
		Average	1.18

Logger 2_1	Time	Mass of bucket (empty)	Date
	45 s	1 kg	7-May-16

Measurement #	Mass of bucket (with water) (kg)	Water mass (kg)	Calculated flow rate (kL/h)
1	14.90	13.90	1.11
2	14.90	13.90	1.11
3	15.30	14.30	1.14
4	15.00	14.00	1.12
5	15.50	14.50	1.16
6	15.20	14.20	1.14
7	15.70	14.70	1.18
8	15.00	14.00	1.12
9	15.10	14.10	1.13
10	15.20	14.20	1.14
		Average	1.13

Logger 2_2	Time	Mass of bucket (empty)	Date
	45 s	1 kg	7-May-16

Measurement #	Mass of bucket (with water) (kg)	Water mass (kg)	Calculated flow rate (kL/h)
1	15.00	14.00	1.12
2	15.50	14.50	1.16
3	14.90	13.90	1.11
4	14.60	13.60	1.09
5	15.00	14.00	1.12
6	15.00	14.00	1.12
7	14.90	13.90	1.11
8	15.00	14.00	1.12
9	15.20	14.20	1.14
10	15.90	14.90	1.19
		Average	1.13

Logger 2_3	Time	Mass of bucket (empty)	Date
	45 s	1 kg	7-May-16

Measurement #	Mass of bucket (with water) (kg)	Water mass (kg)	Calculated flow rate (kL/h)
1	16.00	15.00	1.20
2	16.30	15.30	1.22
3	15.90	14.90	1.19
4	16.50	15.50	1.24
5	16.40	15.40	1.23
6	15.80	14.80	1.18
7	16.30	15.30	1.22
8	15.50	14.50	1.16
9	15.00	14.00	1.12
10	15.50	14.50	1.16
		Average	1.19

Logger 2_4	Time	Mass of bucket (empty)	Date
	45 s	1 kg	7-May-16

Measurement #	Mass of bucket (with water) (kg)	Water mass (kg)	Calculated flow rate (kL/h)
1	14.90	13.90	1.11
2	15.50	14.50	1.16
3	14.90	13.90	1.11
4	15.20	14.20	1.14
5	15.90	14.90	1.19
6	15.40	14.40	1.15
7	15.00	14.00	1.12
8	15.30	14.30	1.14
9	15.90	14.90	1.19
10	15.30	14.30	1.14
		Average	1.15

Logger 2_5	Time	Mass of bucket (empty)	Date
	45 s	1 kg	7-May-16

Measurement #	Mass of bucket (with water) (kg)	Water mass (kg)	Calculated flow rate (kL/h)
1	14.50	13.50	1.08
2	14.70	13.70	1.10
3	14.00	13.00	1.04
4	14.50	13.50	1.08
5	13.90	12.90	1.03
6	14.60	13.60	1.09
7	14.90	13.90	1.11
8	14.20	13.20	1.06
9	14.80	13.80	1.10
10	14.70	13.70	1.10
		Average	1.08

APPENDIX D
Climatic data

Temperature and rainfall is known to affect garden irrigation. Higher temperatures and less rainfall increase water demand for garden irrigation use. The daily maximum, minimum, and average temperatures of the past 10 years (2006-2015) were obtained from Weather Underground (2016). These temperatures were plotted, as shown in Figure D-1, along with the daily maximum, minimum, and average temperatures of 2016. Figure D-1 also shows the mean temperature variations over the past 10 years.

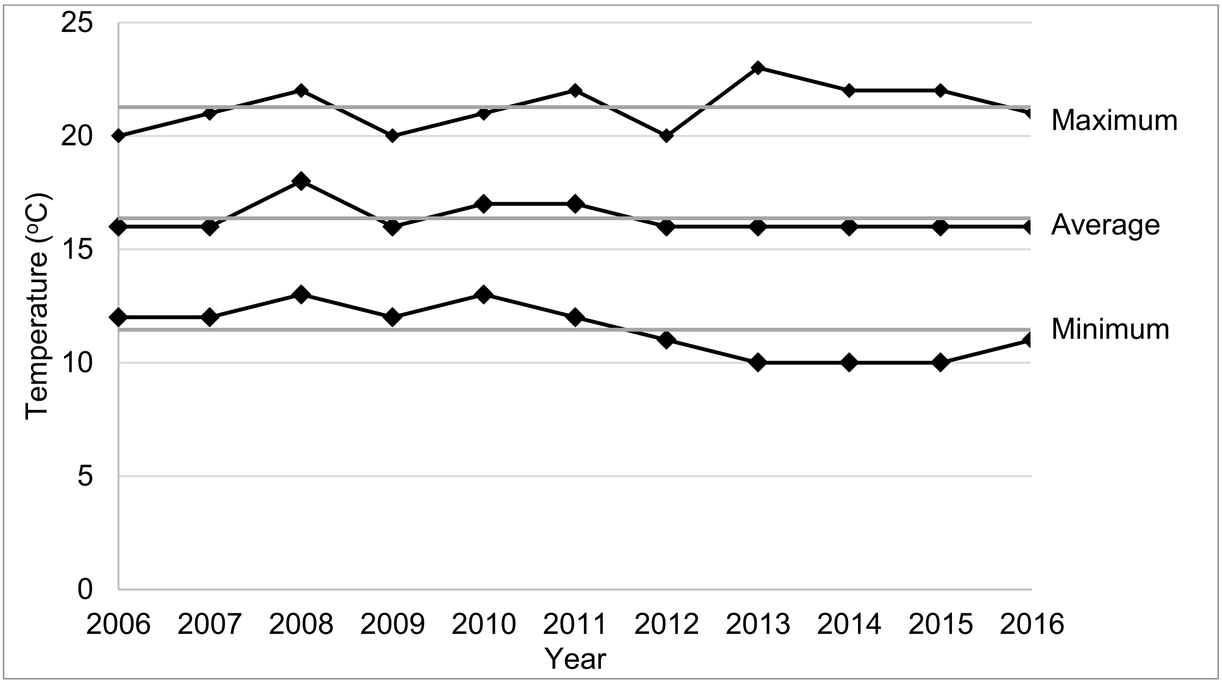


Figure D-1 **Mean of daily maximum, minimum and average temperatures (2006-2016)**

Figure D-1 clearly shows the temperatures over the extent of this study to be very similar to the historic 10-year mean temperatures. The mean daily maximum, minimum, and average temperatures over the testing duration in 2016 were 26 ^{o}C, 13 ^{o}C, and 20 ^{o}C respectively. The historical daily means were 24 ^{o}C, 14 ^{o}C, and 19 ^{o}C respectively. The study was thus conducted under normal temperature conditions.

The daily total precipitation of the past 4 years (2012-2015) was obtained from Weather Underground (2016). Figure D-2 compares the historic rainfall over the tested period (9 to 19 April and 26 April to 8 May 2016) to that of 2016, illustrating 2016 to be a low rainfall year. Accordingly, an assumption was made that the theoretical irrigation demand pattern determined in this study is an acceptable representation of historic and future residential groundwater abstraction patterns for similar sites.

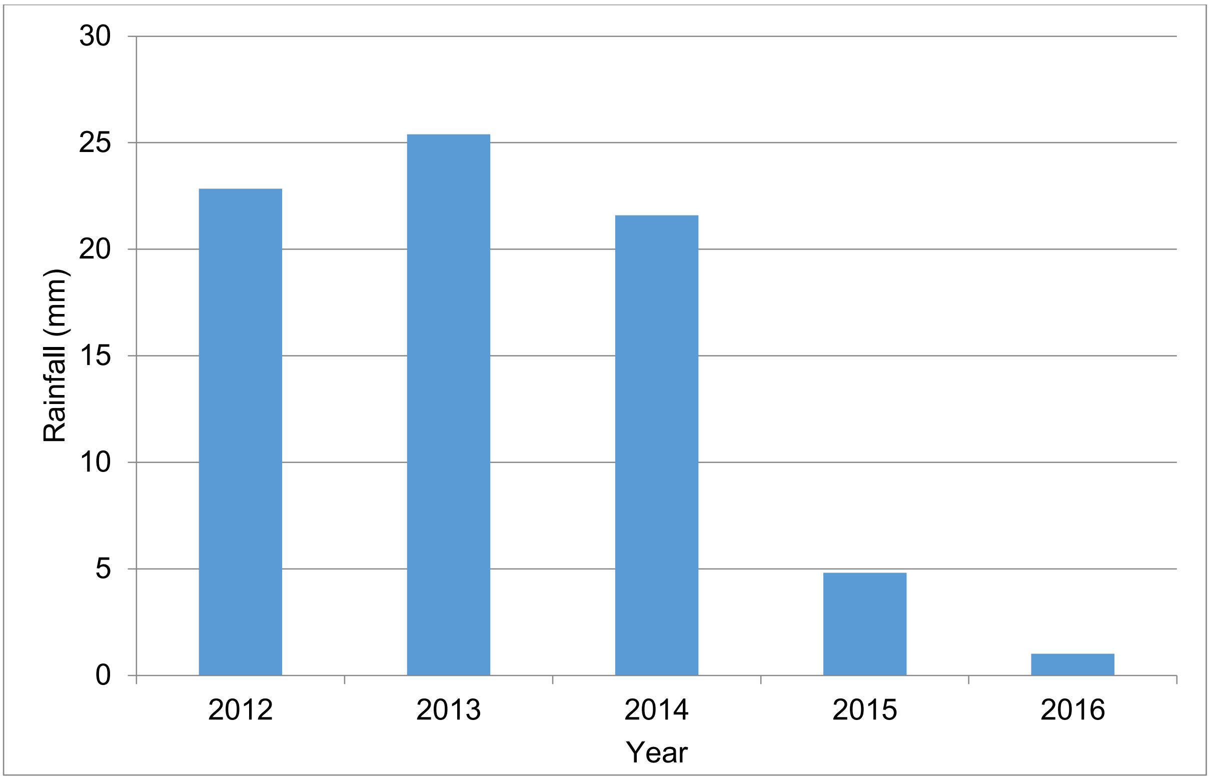


Figure D-2   Total rainfall over study period (2012-2016)

APPENDIX E

Identifying pumping events

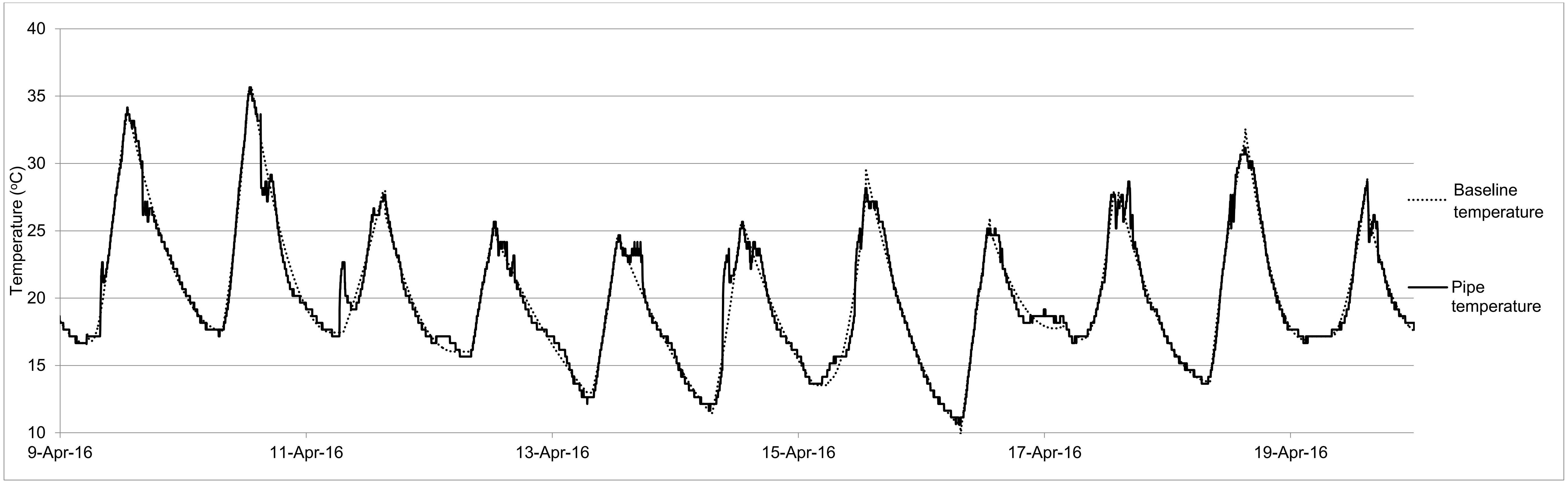


Figure E-1(a) Measured pipe temperature and estimated baseline temperature: Logger 1_1

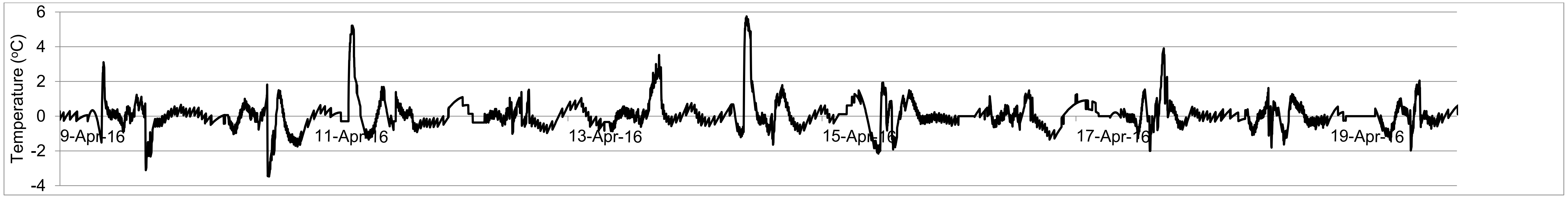


Figure E-1(b) Difference between pipe temperature and baseline temperature: Logger 1_1

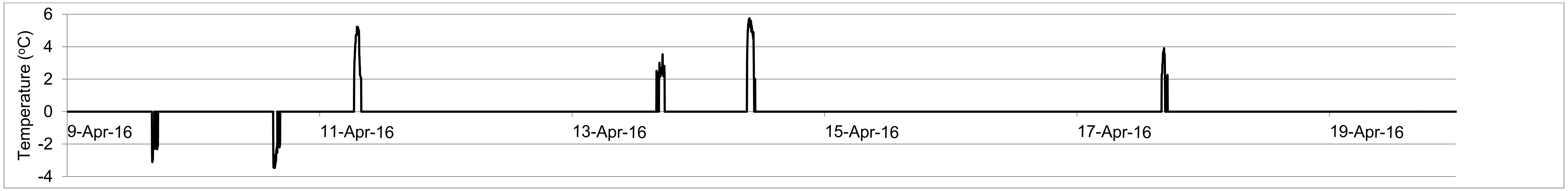


Figure E-1(c) Filtered difference between pipe temperature and baseline temperature: Logger 1_1

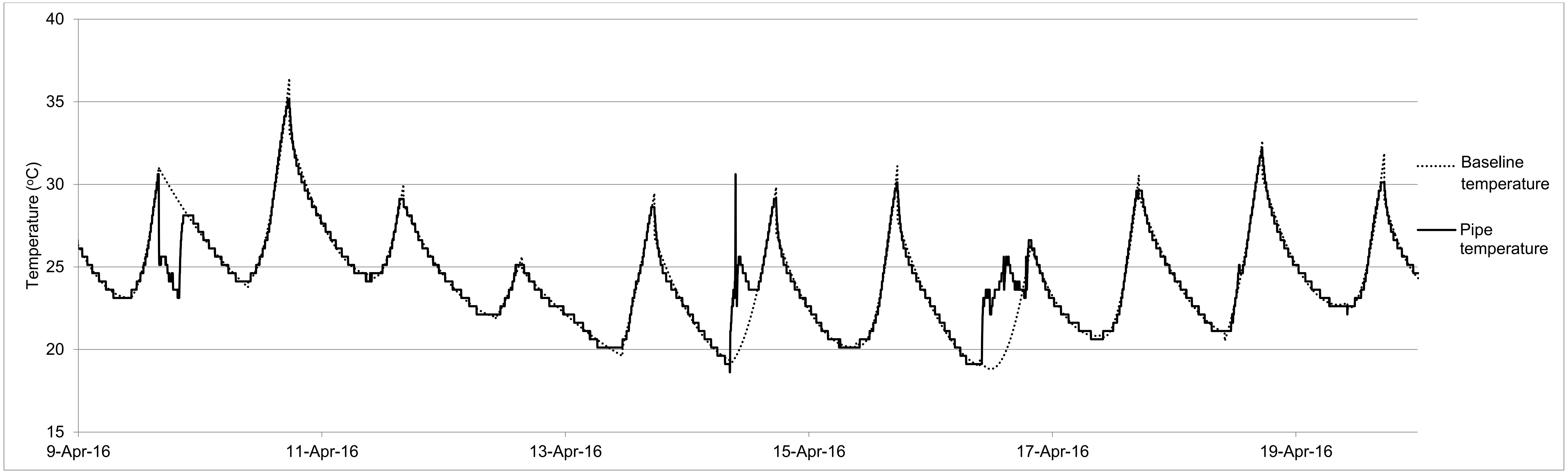


Figure E-2(a) Measured pipe temperature and estimated baseline temperature: Logger 1_2

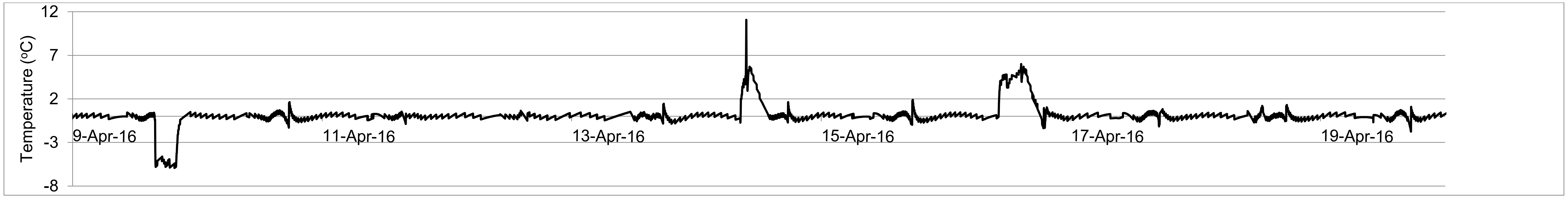


Figure E-2(b) Difference between pipe temperature and baseline temperature: Logger 1_2

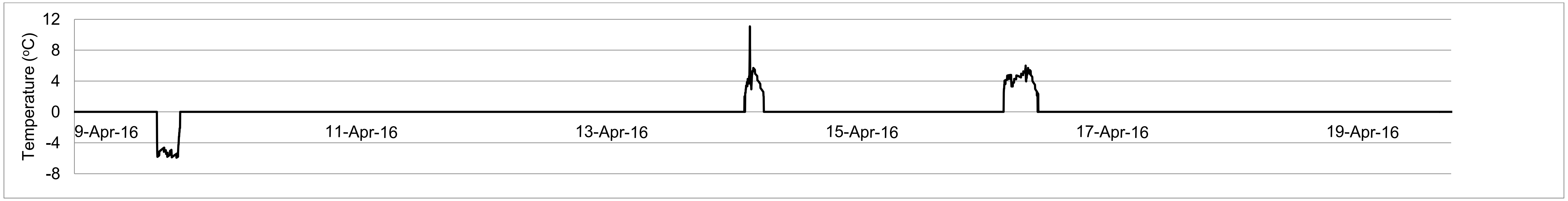


Figure E-2(c) Filtered difference between pipe temperature and baseline temperature: Logger 1_2

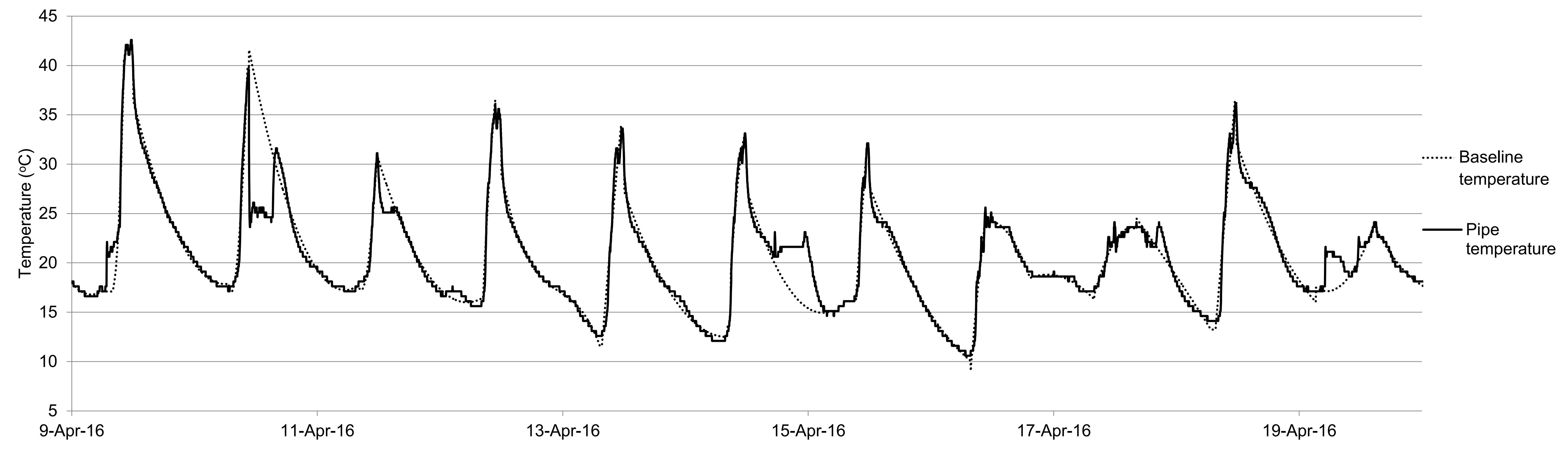


Figure E-3(a) Measured pipe temperature and estimated baseline temperature: Logger 1_3

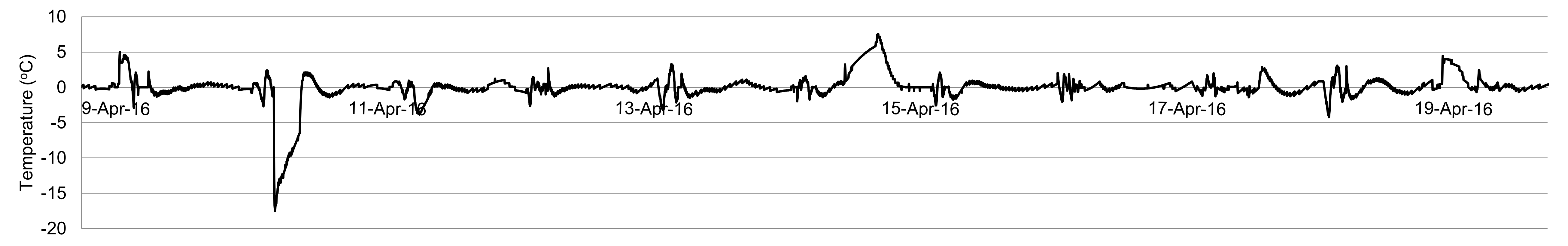


Figure E-3(b) Difference between pipe temperature and baseline temperature: Logger 1_3

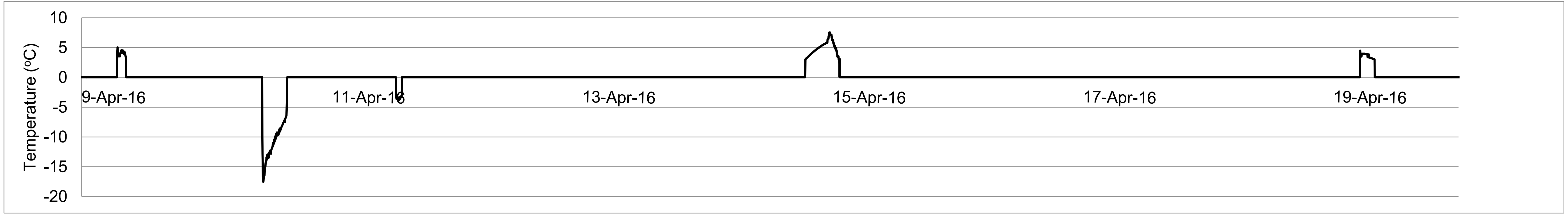


Figure E-3(c) Filtered difference between pipe temperature and baseline temperature: Logger 1_3

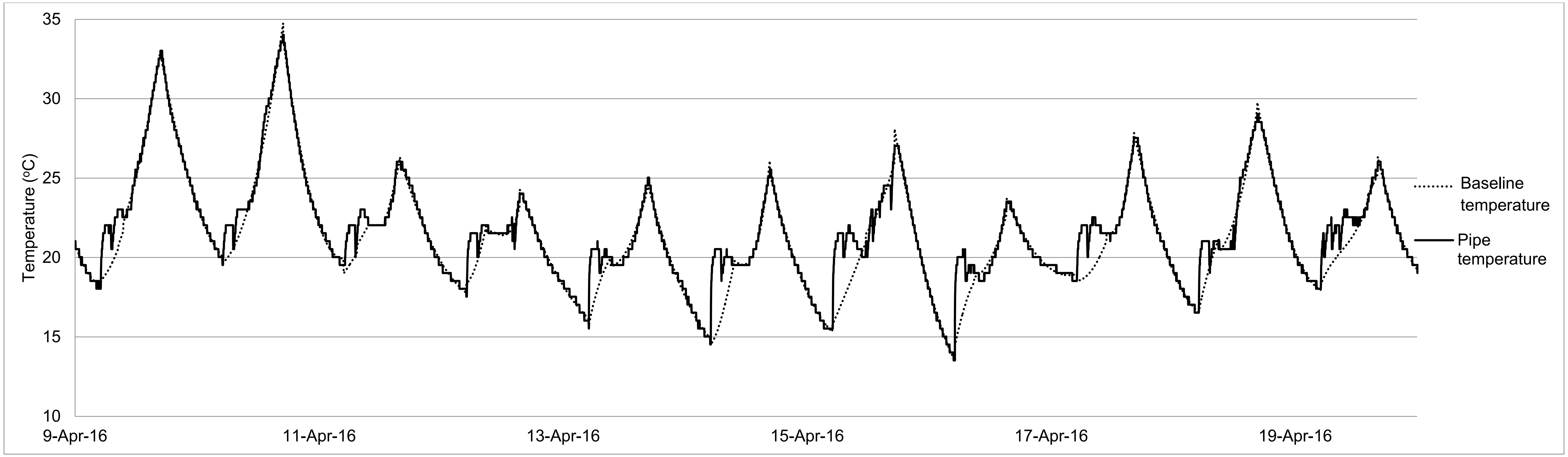


Figure E-4(a) **Measured pipe temperature and estimated baseline temperature: Logger 1_4**

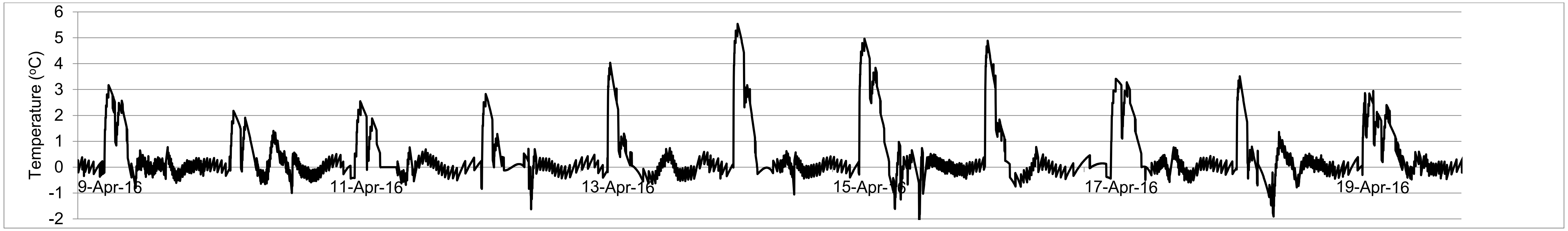


Figure E-4(b) **Difference between pipe temperature and baseline temperature: Logger 1_4**

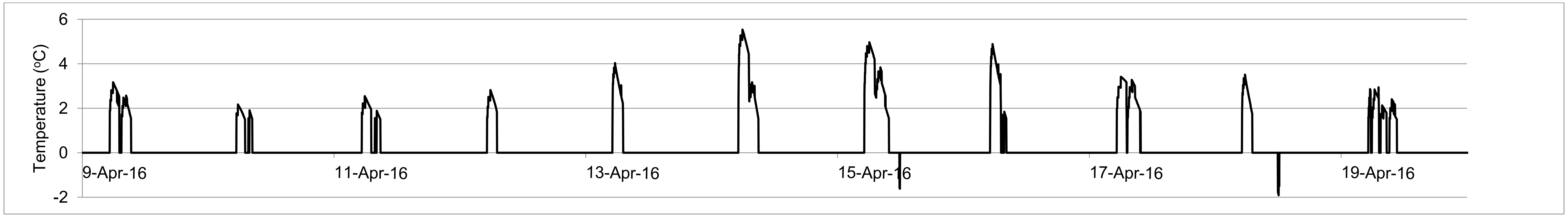


Figure E-4(c) **Filtered difference between pipe temperature and baseline temperature: Logger 1_4**

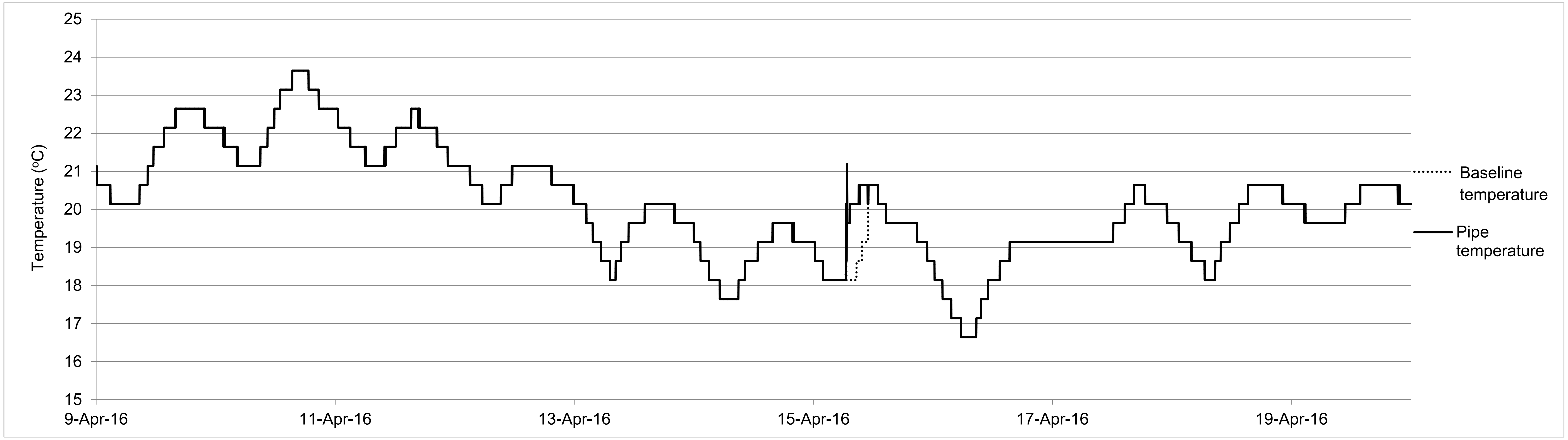


Figure E-5(a) Measured pipe temperature and estimated baseline temperature: Logger 2_1

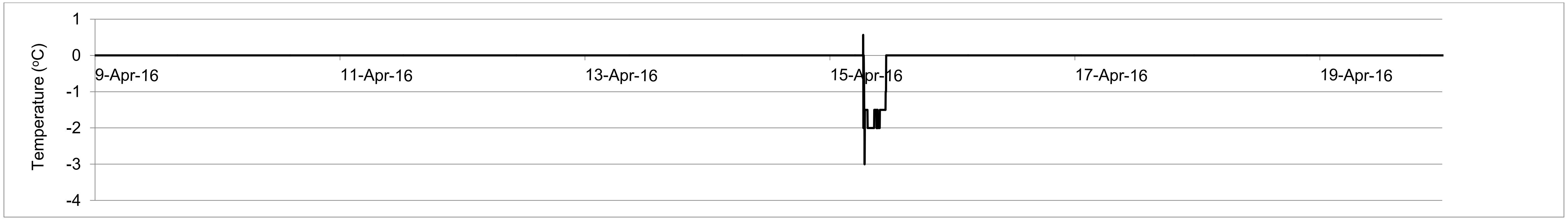


Figure E-5(b) Difference between pipe temperature and baseline temperature: Logger 2_1

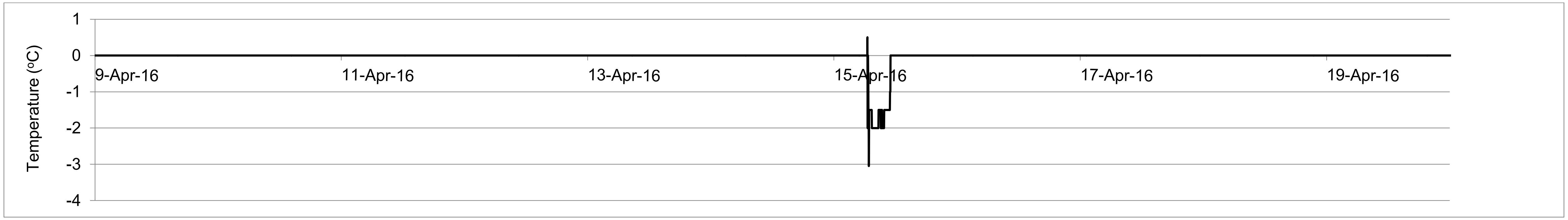


Figure E-5(c) Filtered difference between pipe temperature and baseline temperature: Logger 2_1

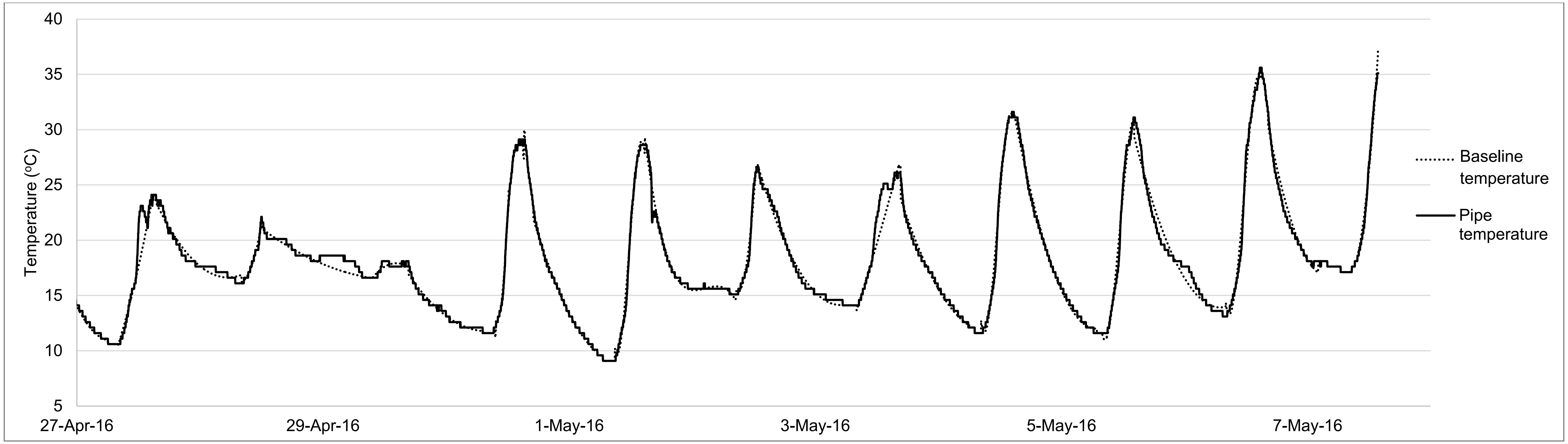


Figure E-6(a) Measured pipe temperature and estimated baseline temperature: Logger 2_1

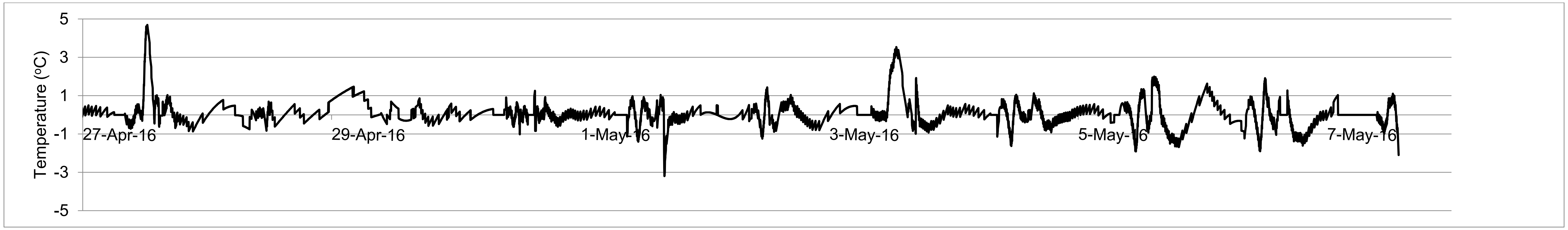


Figure E-6(b) Difference between pipe temperature and baseline temperature: Logger 2_1

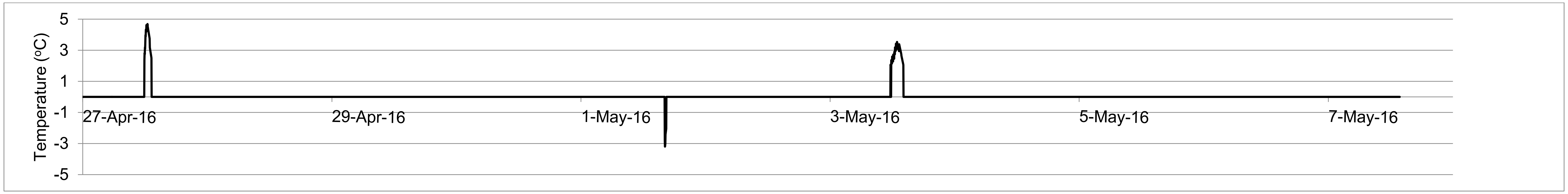


Figure E-6(c) Filtered difference between pipe temperature and baseline temperature: Logger 2_1

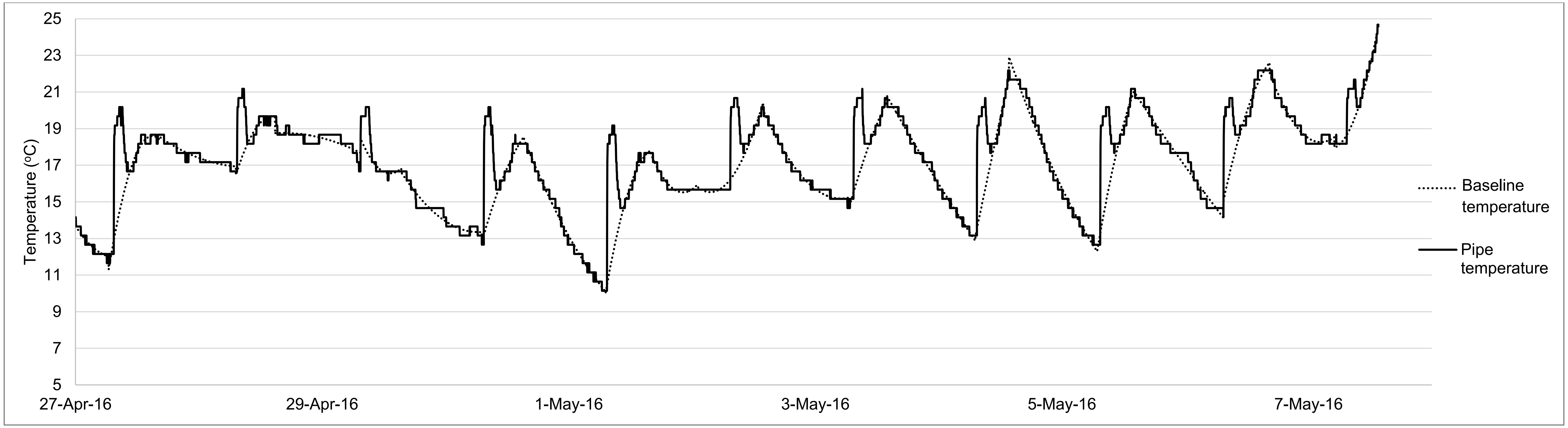


Figure E-7(a) Measured pipe temperature and estimated baseline temperature: Logger 2_2

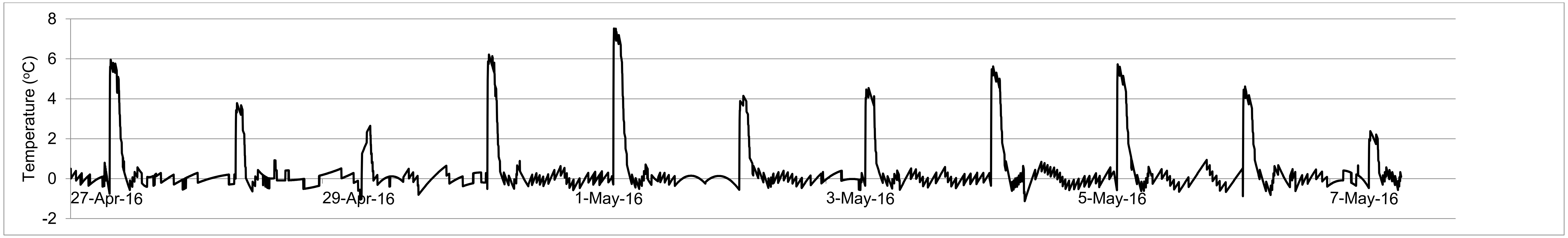


Figure E-7(b) Difference between pipe temperature and baseline temperature: Logger 1_2

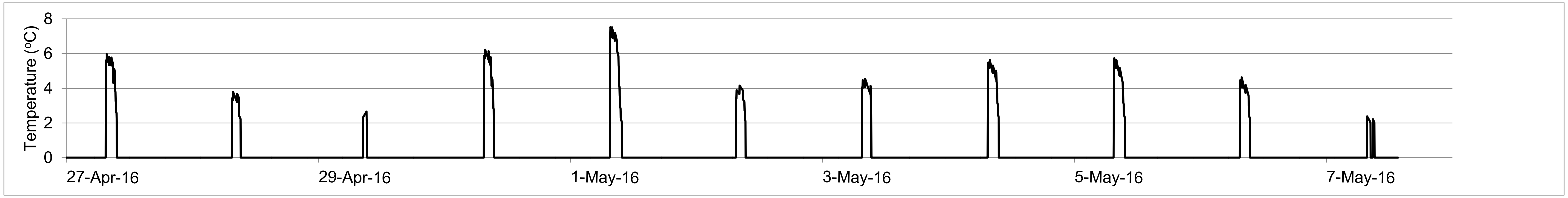


Figure E-7(c) Filtered difference between pipe temperature and baseline temperature: Logger 1_2

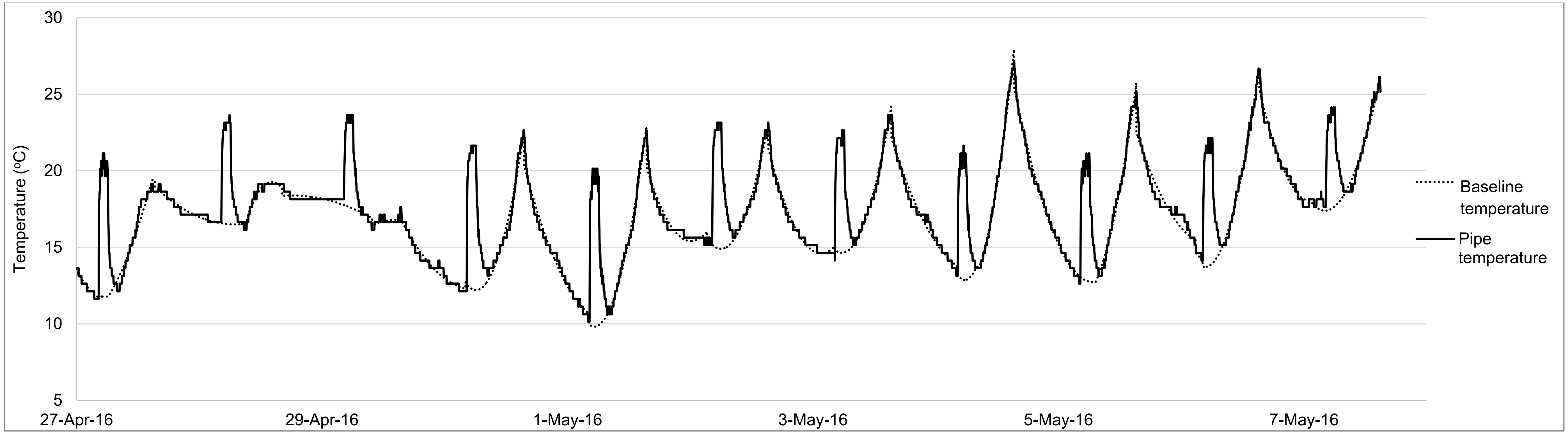


Figure E-8(a) Measured pipe temperature and estimated baseline temperature: Logger 2_3

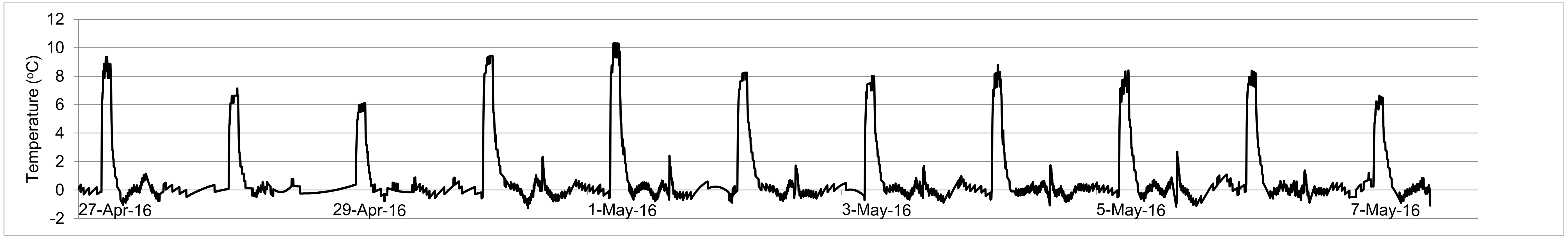


Figure E-8(b) Difference between pipe temperature and baseline temperature: Logger 2_3

Figure E-8(c) Filtered difference between pipe temperature and baseline temperature: Logger 2_3

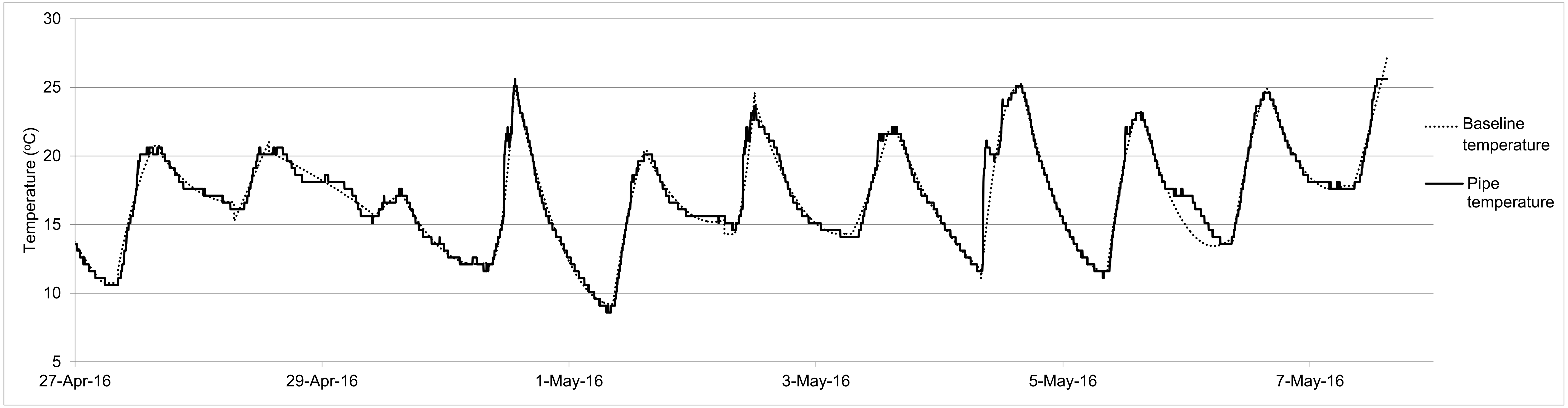


Figure E-9(a) Measured pipe temperature and estimated baseline temperature: Logger 2_4

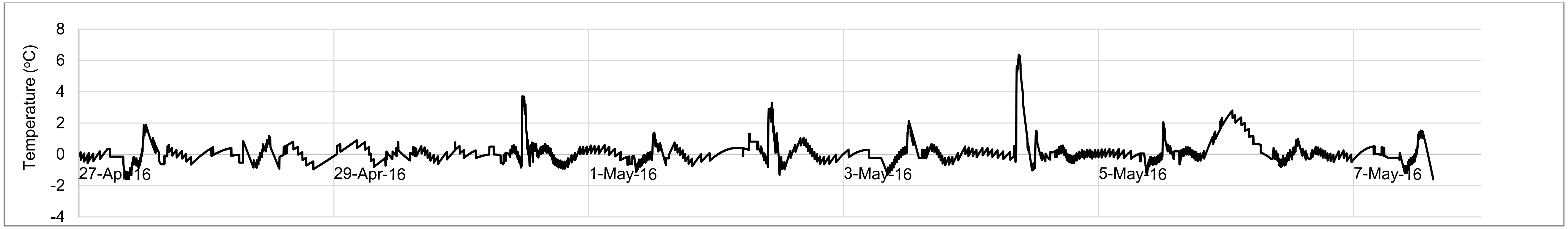


Figure E-9(b) Difference between pipe temperature and baseline temperature: Logger 2_4

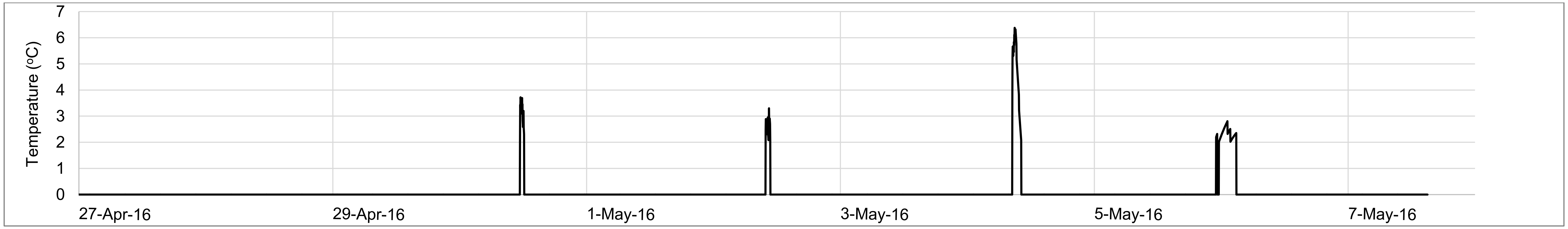


Figure E-9(c) Filtered difference between pipe temperature and baseline temperature: Logger 2_4

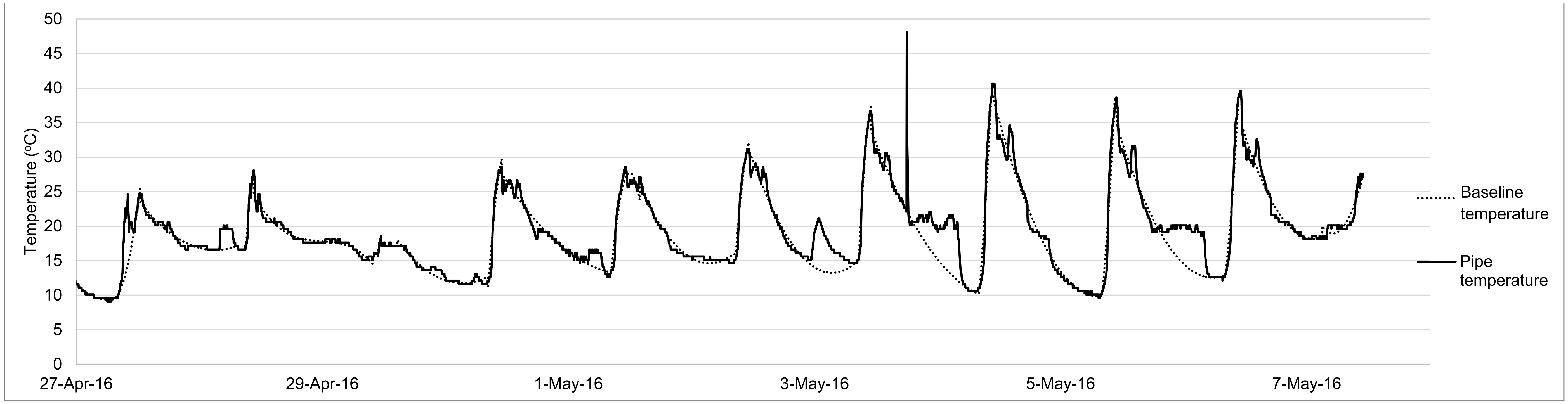


Figure E-10(a) Measured pipe temperature and estimated baseline temperature: Logger 2_5

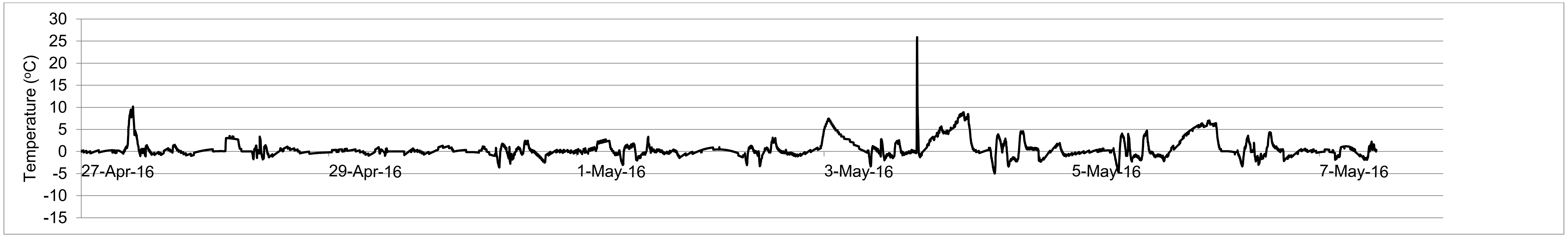


Figure E-10(b) Difference between pipe temperature and baseline temperature: Logger 2_5

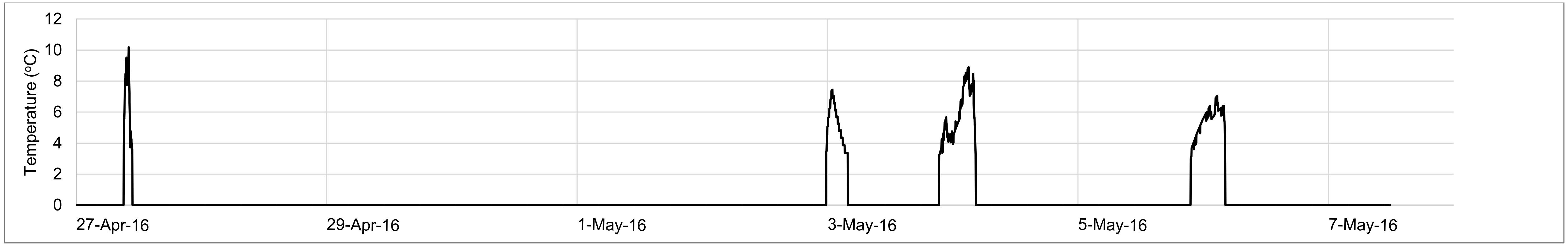


Figure E-10(c) Filtered difference between pipe temperature and baseline temperature: Logger 2_5

APPENDIX F

Measured groundwater temperatures

Table F-1 Measured groundwater temperatures: Group 1

Data logger code	Pumping event #	Start time		Stop time		Groundwater temperature (°C)
1_1	1	9-Apr	16:08	9-Apr	17:14	26.42
	2	10-Apr	15:12	10-Apr	16:28	28.02
	3	11-Apr	6:32	11-Apr	7:54	21.53
	4	13-Apr	16:02	13-Apr	17:34	23.32
	5	14-Apr	9:16	14-Apr	10:48	22.21
	6	17-Apr	16:06	17-Apr	17:12	27.09
1_2	7	9-Apr	15:52	9-Apr	20:16	24.51
	8	14-Apr	8:30	14-Apr	12:10	24.24
	9	16-Apr	10:12	16-Apr	16:48	23.91
1_3	10	9-Apr	6:50	9-Apr	8:32	21.36
	11	10-Apr	10:40	10-Apr	15:24	25.05
	12	11-Apr	12:18	11-Apr	13:24	25.56
	13	14-Apr	18:48	15-Apr	1:22	21.33
	14	19-Apr	5:06	19-Apr	7:54	20.87
1_4	15	9-Apr	5:16	9-Apr	7:04	21.73
		9-Apr	7:30	9-Apr	9:18	22.66
	16	10-Apr	5:24	10-Apr	7:02	21.95
		10-Apr	7:42	10-Apr	8:24	22.89
	17	11-Apr	5:18	11-Apr	7:04	21.78
		11-Apr	7:48	11-Apr	8:50	22.87
	18	12-Apr	5:12	12-Apr	7:04	21.31
	19	13-Apr	5:06	13-Apr	7:06	20.38
	20	14-Apr	5:06	14-Apr	8:54	20.02
	21	15-Apr	5:08	15-Apr	9:48	21.17
	22	16-Apr	5:06	16-Apr	7:08	19.83
		16-Apr	7:24	16-Apr	8:10	19.29
	23	17-Apr	5:16	17-Apr	7:08	21.71
		17-Apr	7:18	17-Apr	9:40	22.01
	24	18-Apr	5:08	18-Apr	7:04	20.79
	25	19-Apr	5:12	19-Apr	7:12	21.34
		19-Apr	7:34	19-Apr	8:40	21.85
		19-Apr	9:14	19-Apr	10:38	22.63
1_5	26	15-Apr	6:34	15-Apr	11:00	20.24

Table F-2 Measured groundwater temperatures: Group 2

Data logger code	Pumping event #	Start time		Stop time		Groundwater temperature (^oC)
2_1	27	27-Apr	11:52	27-Apr	13:12	22.56
	28	1-May	16:06	1-May	16:28	21.95
	29	3-May	11:38	3-May	14:06	23.75
2_2	30	26-Apr	14:15	26-Apr	15:51	24.28
	31	27-Apr	7:28	27-Apr	9:32	19.45
	32	28-Apr	7:32	28-Apr	9:06	20.63
	33	29-Apr	8:30	29-Apr	9:32	20.13
	34	30-Apr	7:28	30-Apr	9:24	19.3
	35	1-May	7:28	1-May	9:44	18.35
	36	2-May	7:30	2-May	9:18	20.23
	37	3-May	7:30	3-May	9:16	20.45
	38	4-May	7:28	4-May	9:32	19.68
	39	5-May	7:28	5-May	9:34	19.58
	40	6-May	7:30	6-May	9:24	20.16
2_3	41	27-Apr	4:22	27-Apr	6:14	17.23
	42	28-Apr	4:22	28-Apr	6:30	22.22
	43	29-Apr	4:22	29-Apr	6:38	22.43
	44	30-Apr	4:20	30-Apr	7:16	19.82
	45	1-May	4:20	1-May	7:02	18.25
	46	2-May	4:22	2-May	7:26	20.83
	47	3-May	4:22	3-May	6:56	20.68
	48	4-May	4:20	4-May	6:54	19.3
	49	5-May	4:20	5-May	7:00	19.21
	50	6-May	4:20	6-May	6:56	20.16
	51	7-May	4:22	7-May	7:02	22.45
2_4	52	30-Apr	11:24	30-Apr	12:10	21.14
	53	2-May	9:50	2-May	10:42	20.8
	54	4-May	8:30	4-May	10:10	20.34
	55	5-May	23:34	6-May	1:42	16.98
2_5	56	27-Apr	9:06	27-Apr	10:44	21.48
	57	2-May	23:44	3-May	3:50	19.8
	58	3-May	21:24	4-May	4:22	20.52
	59	5-May	21:36	6-May	4:12	19.68