University of Southern Queensland

Faculty of Health, Engineering and Sciences

GAB Water Cooling Systems for Municipal Supplies

A dissertation submitted by

Hayden Alexander Guse

In fulfilment of the requirements of

Courses ENG4111 and ENG4112 Research Project

Towards the degree of

Bachelor of Engineering (Civil)

Submitted: October, 2014

Abstract

Legislative specifications require water supply authorities in Queensland to deliver water at temperatures not exceeding 45 °C. Bores extracting water from the Great Artesian Basin can have water temperatures up to 100 °C. Hence municipal water suppliers that make use of hot artesian water are required to cool this water. To achieve this, a variety of cooling methods have been implemented throughout Queensland. The majority of the current cooling methods have proven to be quite wasteful of this valuable resource, while the systems themselves have proven to be quite costly.

The aim of this research was to investigate the existing cooling systems, determine whether Ground Heat Sink Pipe Loops (GHSPL) are a viable alternate cooling method and make recommendations for future cooling system designs. Ground Heat Sink Pipe Loops are pipes buried at shallow depths that utilise the naturally cool soil as a heat sink to dissipate the excess heat from the artesian water.

To determine the effectiveness of this alternate cooling method, a number of simple one-dimensional heat transfer models were written in MATLAB. Research found that an important design parameter for underground heat dissipation is soil thermal conductivity. With this in mind a number of experiments were conducted on an artesian water bore between Goondiwindi and St George, with the aim being to collect data so that the models could be iteratively used to determine the soil thermal conductivity. The models, along with an increased understanding of soil temperature relationships gained from experimentation were then used to produce a concept design.

This GHSPL design was completed for the township of Thargomindah, and found that with 200 mm nominal diameter polyethylene pipe and an integrated storage reservoir, there would be approximately 6.83 km of pipe buried at 450 mm depth to achieve the required cooling. This outcome is considered feasible based on system cost, and an improvement on current cooling methods, based on decreased water wastage. Further research into GHSPL cooling is required to better understand the complexities of system design prior to this technology being implemented.

University of Southern Queensland

Faculty of Health, Engineering and Sciences

ENG4111 & ENG4112 Research Project

Limitations of Use

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Hayden Guse

0061019343

____
Signature

____
Date

Acknowledgements

I would like to thank Dr Joseph Foley for his supervision, patience and time throughout this project. Without his guidance and encouragement this project would not be where it is now.

I would like to thank my colleague at Toowoomba Regional Council, Ian Ryan (formerly Queensland Department of Energy and Water Supply), for providing many excellent resources and contacts. I would also like to acknowledge his suggestions and feedback throughout this undertaking.

Thanks must go to Simon Orphant (Queensland Department of Natural Resources and Mines) for aiding in finding a suitable experimentation site. To Geoff and Virginia Phillips of “Tabooba”, thanks for your understanding and hospitality during the experimental phase of this project.

Finally I would like to thank my family and friends for their support and patience over the duration of this project, and throughout my degree.

Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
CD	Compact Disc
DNRM	Department of Natural Resources and Mines
ECA	Earth Coupled Analysis
GAB	Great Artesian Basin
GABSI	Great Artesian Basin Sustainability Initiative
GHSPL	Ground Heat Sink Pipe Loops
HDPE	High Density Polyethylene
MATLAB	Matrix Laboratory (computer program)
MDMM	Mean Day Maximum Month
NSW	New South Wales
OD	Outer Diameter
ORC	Organic Rankine Cycle
PC	Personal Computer
PE	Polyethylene
PE-X	Cross-linked Polyethylene
PH	Peak Hour
SI	Système International
SDR	Standard Dimension Ratio
USQ	University of Southern Queensland

Chapter 1 Introduction

'Now the stock have started dying, for the Lord has sent a drought;
But we're sick of prayers and Providence – we're going to do without;
With the derricks up above us and the solid earth below,
We are waiting at the lever for the word to let her go.
Sinking down, deeper down,
Oh, we'll sink it deeper down:
As the drill is plugging downward at a thousand feet of level,
If the Lord won't send us water, oh, well, we'll get it from the devil;
Yes we'll get it from the devil deeper down.'
Banjo Patterson – Song of the Artesian Water (1902)

There are many communities throughout Australia, particularly in Western Queensland, that utilise "hot" Great Artesian Basin water for municipal purposes. Legislative requirements and good asset management practice requires this water to be cooled, prior to entering a reticulated water supply. Existing cooling systems tend to have many disadvantages that may make them undesirable heading into the future. This chapter provides relevant background information that demonstrates why there is a need for an alternate water cooling system.

1.1 Great Artesian Basin

The Australian continent is commonly referred to as the 'driest inhabited continent on Earth' (Pigram 2006). This statement relates to the lack of surface water that is experienced over much of the continent. As a result of this lack of surface water there is a large reliance on groundwater across much of Australia (see Figure 1.1 below).

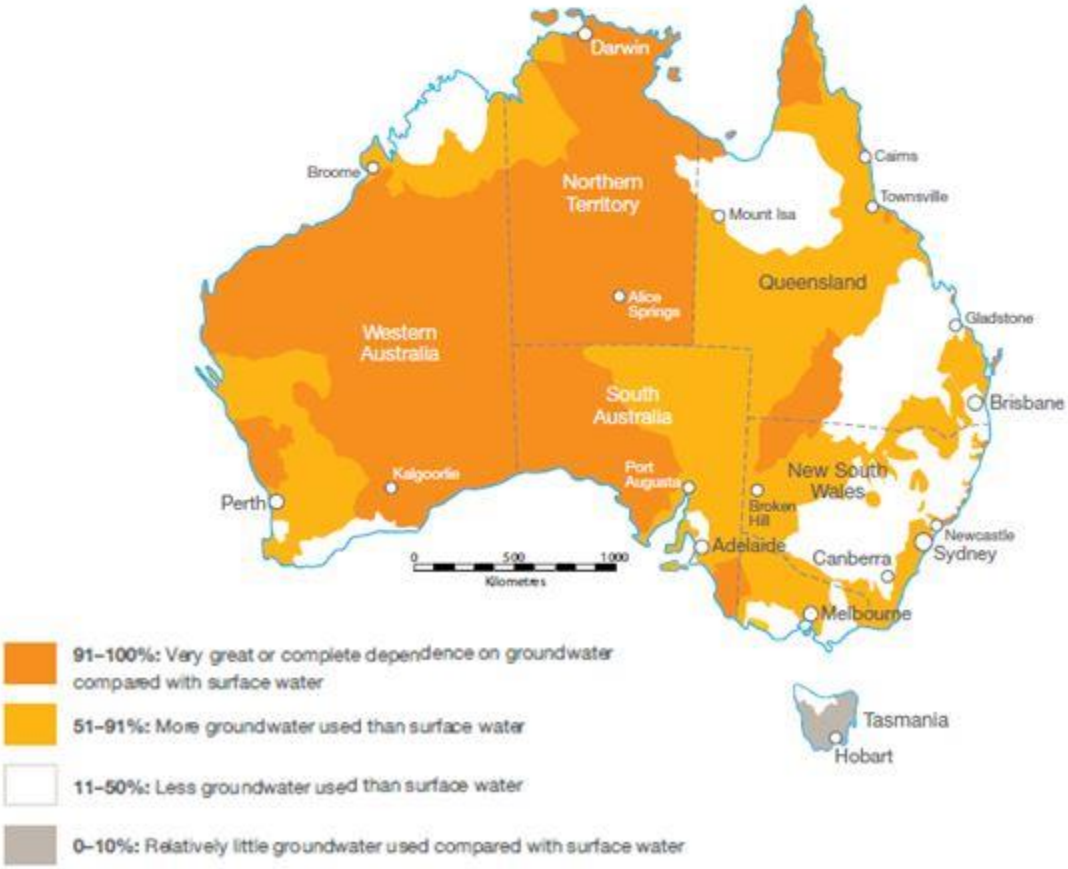

Figure 1.1. Comparative groundwater use in Australia (Harrington & Cook 2014, p. 9)

In contrast to the surface water situation, there are many large water bodies underlying the Australian continent. The largest of these is the Great Artesian Basin (GAB), which underlies 23% of the Australian continent. This natural sandstone aquifer is the world's largest artesian basin (covering over 1,700,00 km^2) and an important source of water for Queensland, New South Wales, South Australia and the Northern Territory (Cox & Barron 1998). Figure 1.2 shows the extent of the GAB.

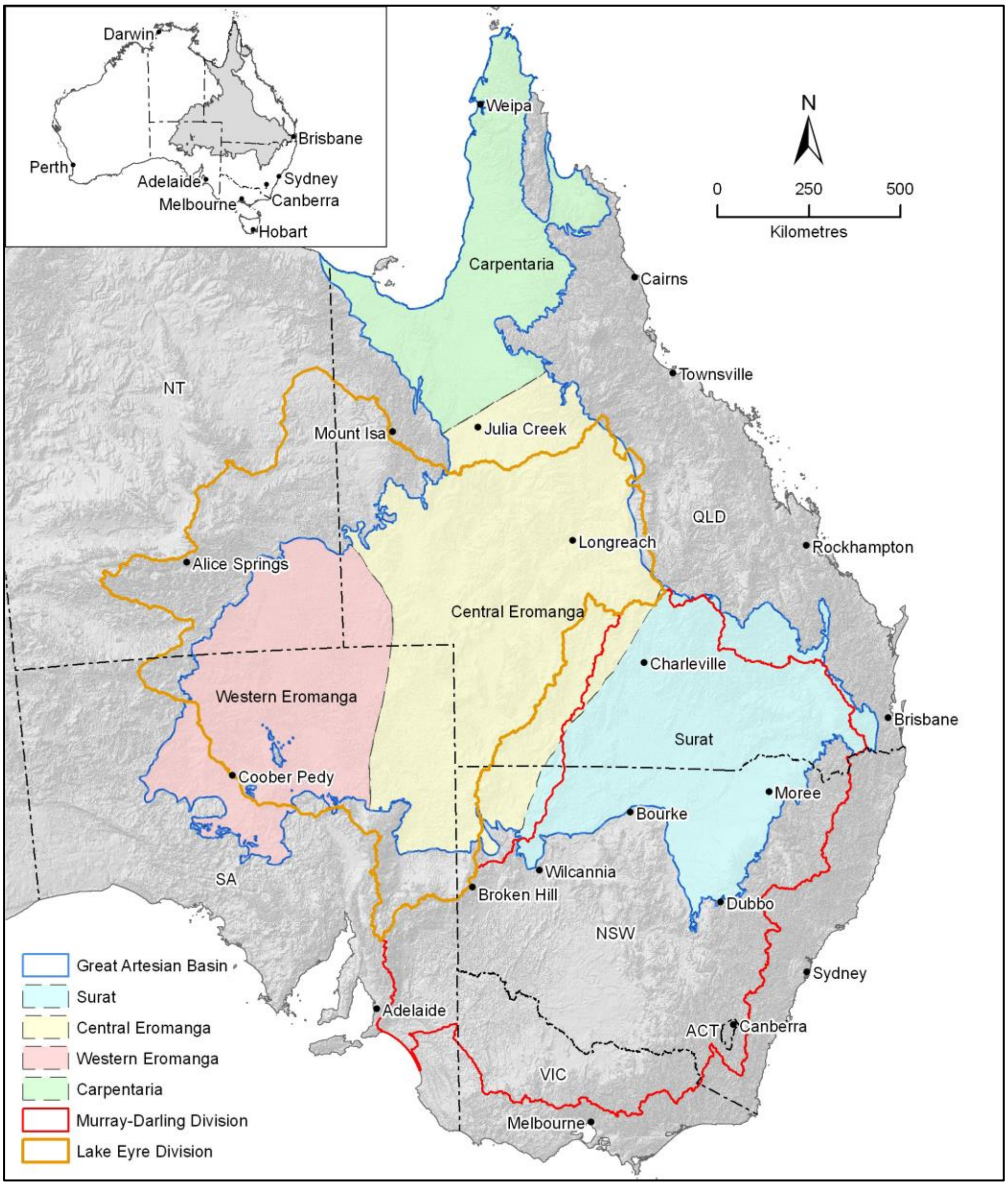

Figure 1.2. Extent of the Great Artesian Basin (Smerdon et al. 2012)

The largest use of GAB water comes from the agricultural sector (*Great Artesian Basin Resource Study Update* 2010). In comparison to the agricultural use, the extraction for municipal supply is quite small, though it still represents a significant volume of water. In 2005 Queensland alone used 32,471 ML of GAB water in municipal water supplies (*Great Artesian Basin Resource Study Update* 2010). Much of this usage can be attributed to Western Queensland townships that have no other potable water supply.

The GAB is confined between sedimentary layers of rock at depths of up to 3000 m (Cox & Barron 1998). The combination of the elevated earth temperatures at great depths, with the pressure exerted on the artesian aquifers, heats the groundwater to temperatures much higher than that experienced by surface water. This combination of depth and pressure means that the GAB supplies water to the surface at temperatures between 30 and 99 °Celsius.

The approximate extraction temperatures in some Western Queensland townships are:

- Winton 84 °C (Ryan, I 2014, pers. comm., 25 March)
- Thargomindah 86 °C (WorleyParsons 2010)
- Birdsville 98 °C (Ergon Energy n.d.)

These townships utilise three different cooling technologies in an attempt to cool the water prior to it entering the town reticulation system.

1.2 Water Cooling

The Queensland Plumbing and Drainage Act, 2002, is the legislation that regulates plumbing and drainage in the state of Queensland. Enabled under this Act is the Queensland Standard Plumbing and Drainage Regulation, 2003. Part 2 (Compliance with particular codes and standards) of this regulation sets out what documents must be followed when completing plumbing and drainage works in Queensland. Section 12 of Part 2 refers to the Plumbing Code of Australia which in turn covers the application of AS/NZS 3500.4:2003. As a result of this legislative reference, AS/NZS 3500.4:2003 Plumbing and Drainage – Heated Water Services, holds legislative power in the state of Queensland.

Amendment 2 to AS/NZS 3500.4:2003 was enacted in December 2010. Included in this amendment was a change to the maximum permissible water supply temperature. Clause ‘1.9.2: Sanitary fixture delivery temperature’ states (Standards Australia 2010):

> ‘All new heated water installations shall deliver heated water not exceeding’ –
> (a) ‘45 °C at the outlet of sanitary fixtures used primarily for personal hygiene purposes for the aged, the sick, children or people with disabilities in healthcare and aged care buildings, early childhood centres, primary and secondary schools and nursing homes or similar facilities for the aged, the sick, children or people with disabilities; and,’
> (b) ‘50 °C at the outlet of sanitary fixtures used primarily for personal hygiene purposes for all other situations.’

The above extract can be interpreted as any new water installation in Queensland cannot deliver water exceeding 45 °C if it may be used by a child, disabled, sick or elderly person for personal hygiene purposes. This temperature of 45 °C was presumably chosen to reduce the risks of burns to water users and those who work on water infrastructure. Hence as of December 2010, Queensland water suppliers should not be delivering reticulated water at temperatures greater than 45 °C.

This update to the Australian Standard means that those municipalities extracting GAB water at temperatures exceeding 45 °C are now legally required to cool this water to less than 45 °C before it enters the reticulation system. Water temperature variation (when extracted to the surface) across the GAB is shown in Figure 1.3 below.

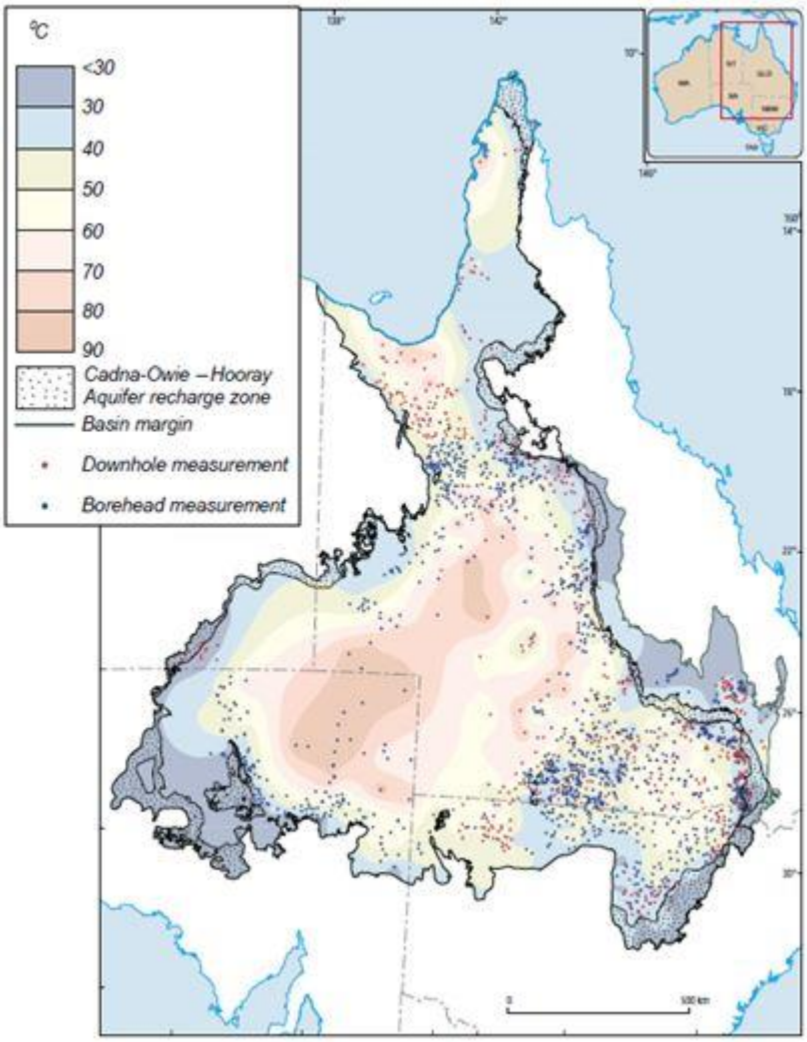

Figure 1.3. Great Artesian Basin water temperature distribution (Radke et al. 2000, p. 63)

In addition to the legislative requirements there are many other reasons as to why GAB water at elevated temperatures should be cooled. Increased asset life can be achieved by cooling the water to less than 45 °C. At elevated temperatures the useable life of plastic pipeline components (this may include the pipe itself, or other components such as rubber ring joints) rapidly decreases as the heat weakens the plastic. This effect is known as de-rating as it reduces the life of the plastic component, as well as reducing the pressure that it can operate under.

1.3 Current Cooling Methods

There are a number of methods employed by various municipalities to cool their artesian water supply. Many of the current methods have been found to be environmentally “unfriendly”, while others have been expensive to implement and maintain. Typical problems experienced include: large water losses, salinisation issues, high operating costs and maintenance issues.

There are a multitude of cooling methods that can be utilised to cool a body of flowing water. The town of Thargomindah utilises two submerged pipe cooling grids that operate in series (WorleyParsons 2010). This system experienced many problems and generally struggled to achieve the cooling that it was designed for. The ponds in which the cooling grids are submerged were found to have high ambient temperatures so dual cooling towers were installed to pre-cool the pond water.

This cooling system has posed many problems for Bulloo Shire Council. Difficulties include excessive water loss, mineral deposition (a third pond was constructed to store mineral accumulations), high operating costs and the fact that this system still struggles to achieve the cooling that is required under Queensland legislation. Maintenance also presents an issue as the dust storms experienced in this area add to sediment build up in the bottom of the ponds (Ryan, I 2014, pers. comm., 23 August).

Birdsville use a slightly different method of water cooling as the town runs an Organic Rankine Cycle (ORC) power plant off the hot artesian water. The power plant operates by passing two liquids through separate loops. The hot water flows through one loop, which is in contact with the second loop containing liquid Isopentane. The heat from the water evaporates the Isopentane into steam which runs a turbine and an alternator to supply AC electricity (Ergon Energy n.d.). During this process the water leaving the power plant has been cooled from approximately 98 °C to 80 °C, and this water then enters the town cooling ponds. The cooling ponds supply a plate heat exchanger which further cools the water before it enters the town reservoir (Diamantina Shire Council 2014).

The town of Winton also uses twin cooling ponds that are used in conjunction with a plate heat exchanger (Ryan, I 2014, pers. comm., 25 March). The plate heat exchanger has one loop containing water from a cooling pond, which then extracts heat from a separate loop containing the hot artesian water. The cooling pond water is circulated back into the ponds while the cooled artesian water passes into the town reservoir. This cooling method is effective, however two heat exchangers are required as every six weeks the exchangers must be deconstructed and cleaned of mineral depositions (WorleyParsons 2010).

The township of Richmond uses a different approach to the submerged cooling grid as only a single 110 mm polyethylene (PE) pipe is submerged in Lake Fred Tritton (WorleyParsons 2010). This man-made lake is primarily a tourist attraction but also acts as a heat sink for the bore water servicing the town. As the groundwater temperatures at Winton (less than 50 °C) are not on the same scale as those towns already discussed, this simple system is more than adequate for their cooling requirements (WorleyParsons 2010).

As discussed there are a variety of different methods utilised by water providers across Queensland to cool GAB water to less than 45 °C. Some methods are more effective than others, while all of the current methods have some drawbacks. All the systems described above utilise uncovered water bodies that are susceptible to large water losses and pose salinisation issues. The specific advantages and disadvantages of the current cooling methods can be found in Section 2.2.

1.4 Proposed Cooling Method

It has been proposed that a cheap, effective way to cool artesian water is to have the water flow through Ground Heat Sink Pipe Loops (GHSPL). Buried pipes have been used both deliberately, and incidentally, as a heat transfer medium in many applications. The ground around the pipes can either act as a heat sink or a heat source for the liquid flowing through the pipes. In the case of a GHSPL system, the surrounding soil is used as a heat dissipation medium. To achieve this, the naturally cooler soil at shallow depths (less than 2 m) is used as a sink to dissipate the heat from the artesian water. All that is required is an adequate length of pipe at an appropriate depth so that the amount of heat that is dissipated is appropriate for the situation.

1.5 Aims and Objectives

There is a great need to find an alternative cooling technique for municipal water supplies that extract from the Great Artesian Basin (GAB). The current techniques being used are far from perfect, and are generally quite expensive and wasteful of this limited natural resource.

The aim of this research is to investigate existing GAB water cooling systems and to determine the feasibility of in-ground pipe cooling systems. Should these systems be found viable, recommendations will be made for system design and implementation.

The objectives of this research are:

- Research the currently utilised GAB water cooling systems, focussing on those used for municipal supplies.
- Liaise with government staff to determine the performance of existing systems.
- Research and conduct modelling of in-ground pipe loop cooling systems.
- Take field measurements to calibrate the ground loop model.
- Evaluate the viability of in-ground pipe loop cooling systems, and if found to be viable, provide a concept design for this system.

- Provide recommendation(s) for future GAB water cooling systems for municipal supplies.

A complete set of project specifications for this research can be found in Appendix A.

1.6 Scope of Study

The scope of this study is to evaluate whether in-ground pipe cooling is viable to be implemented as a cooling system for municipal water supplies. The viability of such a system will be determined by the extent of pipe required and the system maintenance required to effectively cool the water of a typical municipality extracting from the GAB.

For the purposes of this study, Thargomindah, Queensland was chosen as the typical municipality. Horizontal in-ground pipe cooling systems utilising polyethylene (PE) pipe have been the focus of this research. The cost of implementing a vertical system precluded this option being extensively explored, while the low cost of PE pipe led to this material being the focus of this research.

1.7 Project Overview

This research project demonstrates why an alternative GAB municipal water cooling system is required, and tests the viability of one proposed alternative. In-ground pipe loop cooling has been suggested as an alternative “environmentally friendly” cooling method that may potentially be feasible. To make judgement on this feasibility a number of models have been used to theoretically determine the requirements of such a system. Due to a lack of published data in an Australian context experimentation was undertaken to measure a number of soil parameters. The models then underwent a calibration activity using actual measurements of underground pipe heat losses. Following this calibration, multiple system designs were simulated to determine an appropriate system layout. The size and layout of this system formed the basis of the judgement on the feasibility of such cooling systems. Recommendations for any municipalities that may choose to implement such a system in the future were also presented.

Chapter 2 Literature Review

This chapter reviews the relevant literature applicable to current municipal water cooling systems, as well as the proposed alternative. A thorough understanding of the relevant literature is essential to make an informed decision about the applicability of an alternate cooling technology.

2.1 Thermodynamics and Heat Transfer

An understanding of the basic concepts and underlying principles of thermodynamics and heat transfer is required to make recommendations for water cooling systems. There is a large amount of literature concerned with the subjects of thermodynamics and heat transfer, and a brief extract of this literature is presented below.

2.1.1 Basic Principles

Parker (2003, p. x) defines thermodynamics as:

> ‘The branch of physics which seeks to derive, from a few basic postulates, relations between properties of substances, especially those which are affected by changes in temperature, and a description of the conversion of energy from one form to another.’

Heat transfer can therefore be regarded as a sub-topic under the wider ranging subject of thermodynamics.

To achieve the aims of this research project, the viability of ground heat sink pipe loops (GHSPL) as an effective heat transfer system must be determined. Rogers and

Mayhew (1992) define heat as something that occurs when there is a temperature difference between a system and its surrounds. Hence for heat transfer to occur it is necessary to have a temperature difference. In the case of a GHSPL system, heat transfer is driven by the difference in temperature between the artesian water in the pipe network (heat source) and the soil surrounding the pipe network (heat sink).

Heat transfer occurs in three primary modes. These modes are conduction, convection and radiation. Heat in a GHSPL system will be transferred by a combination of conduction and convection, with the impact of radiation considered to be negligible. While the impact of radiation is often not considered in underground heat dissipation, it will also be briefly discussed to increase understanding of the other cooling methods that may be affected by this mode of heat transfer.

2.1.2 Conduction

Conduction can occur in all states of matter (solid, liquid and gas), and occurs as vibrating particles impact neighbouring particles (Rogers & Mayhew 1992). When a vibrating particle impacts another particle, a transfer of kinetic energy occurs, which corresponds to a heat transfer (ASHRAE 2005). The transfer of heat that occurs during conduction is quantified using Fourier’s Law of Conduction (ASHRAE 2005, p. 3.1) and this law is numerically illustrated below in Equation 2.1.

$$\ddot{q} = -k\frac{\partial t}{\partial x} \qquad (2.1)$$

where $\ddot{q}$ = heat flux [W/m^2]

k = thermal conductivity [W/m.K]

$\frac{\partial t}{\partial x}$ = temperature gradient [K/m]

For the case where a surface has uniform temperature and is subject to one-dimensional steady-state heat transfer, this equation becomes Equation 2.2 (ASHRAE 2005, p. 3.1).

$$q = -kA \frac{\partial t}{\partial x} \tag{2.2}$$

where
q = heat transferred [W]
A = cross-sectional area perpendicular to the x direction [m^2]
k = thermal conductivity [W/m.K]
$\frac{\partial t}{\partial x}$ = temperature gradient [K/m]

Equation 2.3 below is Fourier's Law applied to the case of a cylinder under 1-dimensional, uniform steady-state conductive heat transfer (ASHRAE 2005, p. 3.3).

$$q = \frac{2\pi k L (t_i - t_o)}{\ln(r_o/r_i)} \tag{2.3}$$

where
q = heat transferred [W]
k = thermal conductivity [W/m.K]
L = length of cylinder [m]
t_i = temperature at the internal face of the wall [K]
t_o = temperature at the external face of the wall [K]
r_i = internal radius [m]
r_o = external radius [m]

By making a number of assumptions, the above formula can be applied to the GHSPL system being evaluated. Assuming steady-state 1-dimensional heat transfer implies that conductive heat transfer is only occurring across the cylindrical surface and that the temperature gradient is the same at any radius. The first assumption that there is no longitudinal conductive heat transfer may not hold true, as there will be an appreciable temperature differential from one end of the pipe to the other. Though this may be the case it is still assumed to have negligible impact on the system. The second assumption of the same temperature gradient at any radius again may not hold true. The natural soil temperature may be variable around the pipe, which may make this assumption invalid (soil temperature distributions are further explored in Section 2.5.2).

2.1.3 Convection

Convection occurs because of a temperature gradient between a fluid and a solid boundary (Rogers & Mayhew 1992). There are two types of convection and these can be differentiated by the fluid motion. Forced convection occurs when the fluid is flowing due to external influences (water that is not stagnant) (ASHRAE 2005). Free (natural) convection occurs in a water body that does not have this external influence and may be noticeably flowing. In the latter case the water actually flows because of the variations in fluid density caused by the presence of the temperature gradient (ASHRAE 2005). Convection at the surface-fluid boundary is governed by Equation 2.4 (ASHRAE 2005, p. 3.2):

$$\ddot{q} = h\,(t_s - t_{ref}) \tag{2.4}$$

where
$\ddot{q}$ = heat flux [W/m^2]
h = convective heat transfer coefficient [$W/m^2.K$]
t_s = solid surface temperature [K]
t_{ref} = fluid reference temperature that defines h [K]

When the surface temperature and fluid temperature are uniform Equation 2.4 becomes Equation 2.5, which is commonly known as Newton’s Law of Cooling (ASHRAE 2005, p. 3.2):

$$q = h\,A_s\,(t_s - t_f) \tag{2.5}$$

where
q = heat transferred [W]
h = convective heat transfer coefficient [$W/m^2.K$]
A_s = surface area [m^2]
t_s = solid surface temperature [K]
t_f = fluid temperature [K]

The common difficulty with calculating convective heat transfer is determining the convective heat transfer coefficient. This coefficient is commonly calculated from dimensionless fluid flow numbers based on the flow regime. The importance of flow regimes will be further discussed in Section 2.6.1. The method used to calculate the convective heat transfer coefficient for this research is shown in Equation 2.6 (ASHRAE 2005, p. 3.13).

$$h = \frac{Nu\,k}{D} \qquad (2.6)$$

where h = convective heat transfer coefficient [W/m^2.K]
Nu = Nusselt number [dimensionless]
k = thermal conductivity [W/m.K]
D = pipe diameter [m]

2.1.4 Radiation

Radiation occurs due to the fact that all bodies above absolute zero temperature emit and absorb energy as electromagnetic waves (Rogers & Mayhew 1992). Radiation is most prominent for bodies exposed to the sun; hence a buried pipeline is influenced very little by radiative heat transfer. Equations 2.7 and 2.8 are the governing equations for radiative heat transfer between two black bodies (ASHRAE 2005; Rogers & Mayhew 1992).

$$q_1 = h_r A_1 (T_1 - T_2) \qquad (2.7)$$

where q_1 = heat transferred from body 1 [W]
h_r = radiative heat transfer coefficient [W/m^2.K]
$= \sigma\, \varepsilon_1 (T_1^2 + T_2^2)(T_1 + T_2)$ (2.8)
σ = Stefan-Boltzmann constant (5.67×10^{-8}) [W/m^2.K^4]
ε_1 = emissivity of body 1 [dimensionless]
A_1 = surface area of body 1 [m^2]
T_1 = temperature of body 1 [K]
T_2 = temperature of body 2 [K]

2.1.5 Combinations of Heat Transfer Modes

Many systems are subject to a combination of the three primary heat transfer modes. Reviewing Equations 2.2, 2.5 and 2.7, it can be seen that all the equations have common terms. For the case of steady-state, one-dimensional heat transfer where all transfer modes are occurring in series, the three heat transfer calculations can be combined. The method of combining these calculations comes from the fact that this situation is analogous to resistors in series in an electrical circuit (ASHRAE 2005). (see Equation 2.9 below).

$$R = \frac{L}{k\,A} + \frac{1}{h\,As} + \frac{1}{hr\,A1} \qquad (2.9)$$

where L = distance in the x direction [m]

all other variables are as previously defined

Equation 2.9 applies for a solid body subject to conduction, convection and radiation. This equation can be substituted into Equation 2.10, which in turn can be used to calculate the overall heat transfer occurring through the system (ASHRAE 2005).

$$q = \frac{\Delta T}{U} \qquad (2.10)$$

where q = heat transferred [W]

ΔT = temperature differential [K]

R = thermal resistivity [K/W]

2.2 Existing Cooling Systems and Cooling Technologies

As discussed in Section 1.3, there are many cooling systems and methods that are currently used in different applications across the world. This section will discuss those methods that have been identified as being utilised to cool GAB water.

2.2.1 Cooling Ponds and Submerged Cooling Grids

Cooling ponds and submerged cooling grids have been utilised in Queensland and other Australian states for many years. Submerged cooling grids have been used in both municipal water supply systems (Thargomindah), as well as in domestic water supply systems (Watt 2008), while cooling ponds are more common in municipal supplies.

Submerged cooling grids are medium to large pond or dam structures filled with water. Towards the bottom of the pond there will be a submerged pipe network consisting of a number of parallel pipes with a manifold on each end of the system (Watt 2008). The pipe networks are generally copper and are submerged under 1.3 m to 1.8 m of water (DWLBC 2006). The hot GAB water will enter through one manifold, flow through the pipe network, and exit through the other manifold at a lower temperature. Figure 2.1 below shows a submerged cooling grid system where the pond is yet to be filled.

Figure 2.1. Submerged domestic copper pipe cooling grid at "Tabooba" (pond yet to be filled)

Submerged cooling grids are subject to all three main heat transfer mechanisms, as well as the evaporative cooling effect. This evaporative cooling effect is due to the fact that a water particle in the pond will extract energy from its neighbouring particles in order to gain sufficient energy to change phase from liquid to gas. Thus the more water that evaporates, the more heat energy that is extracted from the bulk of the water body (further discussion of this concept is provided in Section 2.5.2).

Cooling ponds are small dams that are filled with "hot" water and left to cool. Cooling is primarily via the evaporative cooling effect described above. The cooled water will then be pumped from the pond to be used elsewhere (often to supplement other cooling systems, such as plate heat exchangers).

Advantages

- Generally an effective cooling method if designed correctly and regularly maintained
- Low ongoing costs
- Submerged cooling grids will cool sufficiently at flow rates of equal to, or less than, the design flow rate (DWLBC 2006)

Disadvantages

- Large water losses due to evaporation
- Water losses due to seepage
- Present a potential drowning hazard
- Susceptible to algal growth that will reduce system efficiency
- Susceptible to siltation and sedimentation issues
- Potentially large energy consumption when used in conjunction with other cooling methods
- Require regular maintenance to remove algal growth and other plant growth
- Ponds present salinity and scaling issues as the water evaporates
- Water from cooling ponds requires pumping and makes no use of any natural water pressure

Submerged cooling grids and cooling ponds are generally an effective method of cooling GAB water, but they present many other problems. With the finite GAB water supply under pressure from many industries, the loss of water from these systems compounds what is already a serious problem. Shown below in Figure 2.2, is a map quantifying evapotranspiration rates across the Australian continent.

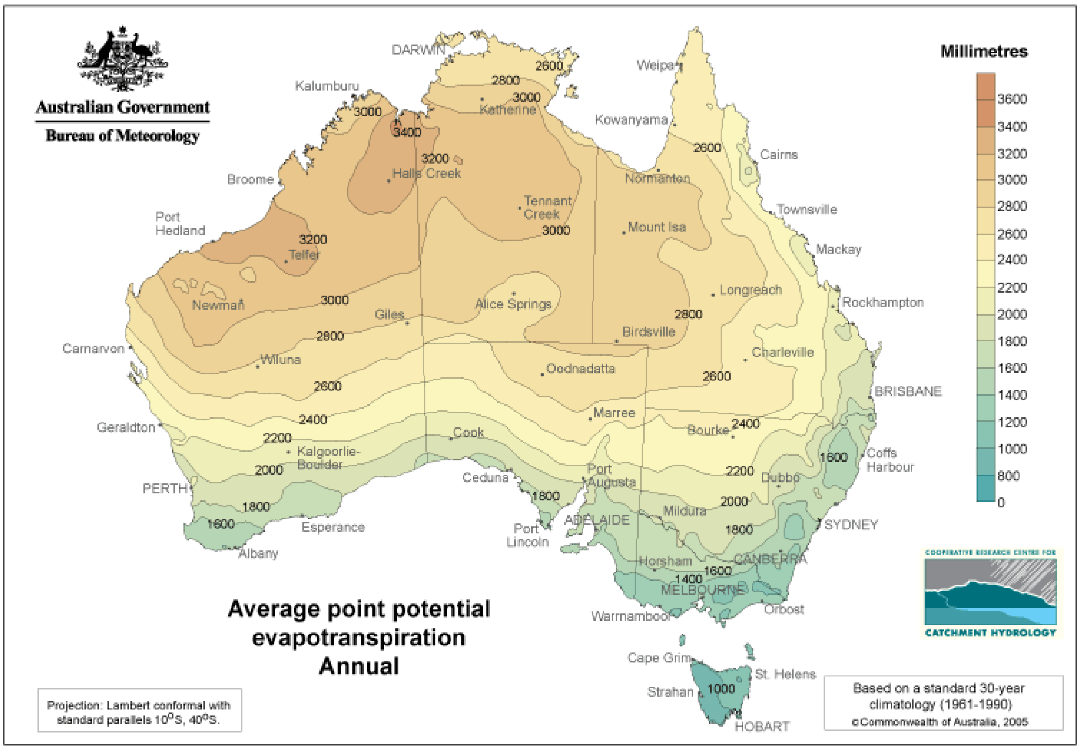

Figure 2.2.Average annual point potential evapotranspiration contours for Australia (Australian Bureau of Meteorology 2012)

As seen in Figure 2.2, most of the area within the Great Artesian Basin footprint is subject to high evapotranspiration losses (2000 to 3000 mm annually). The Australian Bureau of Meteorology (2012) suggests using average point potential evapotranspiration data to produce rough estimates of water losses from small water storages in arid environments, i.e. submerged cooling grids and cooling ponds. Areal imagery was used to measure the approximate surface area of the three ponds at Thargomindah. The evaporative losses were then estimated for this system by interpolating from the map above.

$$
\begin{aligned}
\text{Water loss} &= \text{Surface Area} \times \text{Evapotranspiration} \qquad (2.11)\\
&\approx 5{,}200\ \text{m}^2 \times 2.6\ \text{m/a}\\
&\approx 13{,}520\ \text{m}^3/\text{a}\\
&\approx 13.52\ \text{ML/a}
\end{aligned}
$$

With the Thargomindah water cooling system supporting a population of approximately 470 people (WorleyParsons 2010) this corresponds to an equivalent evaporative loss of approximately 28.77 kL per person per year. This is an extremely high loss (that does not consider seepage and other losses). Considering this water loss in combination with the evaporative losses from the cooling towers, and the associated long-term salinisation issues at this location, raises questions as to why cooling grids and ponds are in such high use. This sort of water cooling practice is unsustainable and placing pressure on GAB supplies.

2.2.2 Plate Heat Exchangers

Plate heat exchangers are used in many industries and are used for municipal water cooling in both Winton and Birdsville. In both of these municipalities plate heat exchangers are used in series with cooling ponds. Plate heat exchangers utilise a number of thin metal plates to separate two separate fluid loops (Rogers & Mayhew 1992). One loop will enter at significantly lower temperature than the other loop and heat will be transferred from the hot loop through the thin metal wall into the cool loop. The hot loop will therefore leave the system at much lower temperatures than it entered (after having transferred much of its heat to the other fluid loop).

In the case of the municipal plate heat exchangers, the cool loop is serviced by the cooling pond water. This water enters the plate heat exchanger, absorbs heat from the hot artesian water loop and then recirculates back into the ponds to again experience natural cooling. The other loop is directly fed from the town bore, with the hot water entering the heat exchanger, transferring its heat into the other loop, and then exiting at significantly lower temperature to the town reservoir.

Advantages

- Effective cooling method
- Well known technology (operates on the same principles as a car radiator)

Disadvantages

- Requires many pumps and associated electrical monitoring equipment, leading to appreciable ongoing costs
- When used in parallel with cooling ponds they have the same drawbacks as those mentioned in Section 2.2.1

2.2.3 Cooling Towers

Cooling towers utilise the evaporative cooling effect to cool a fluid, which dissipates the heat to the surrounding air. Thargomindah has dual submerged cooling grids that operate in series. The ponds in which the pipes are submerged have very low cooling efficiency so two cooling towers were installed to pre-cool the pond water.

Cooling towers are often gravity fed, with the water often cascading over a membrane to maximise the air-water interface (Cooling Technology Institute 2014). This process is often aided by the use of fans within the towers.

Advantages

- Effective cooling method
- Well-established technology

Disadvantages

- Large water losses due to evaporation
- Generally require large energy inputs (ongoing costs) and moderate installation costs

- Mineral build-up is prevalent due to evaporation of mineral rich artesian water
- When used in parallel with cooling ponds they have the same drawbacks as those mentioned in Section 2.2.1

2.3 Passive Ground Loop Heat Exchange

Passive ground loop heat exchange is a fluid heating and cooling technique that is widely used in the Northern Hemisphere. This method of heat exchange uses buried pipes to facilitate heat exchange between the enclosed fluid and the surrounding soil and rock.

2.3.1 Ground Source Heat Pumps

Ground source heat pumps are a well-established technology that is used for indoor heating and cooling applications over much of Europe and North America. While these systems are currently not designed for municipal water cooling, the principle on which these systems operate is the basis for the suggested alternative cooling method.

Horizontal ground source heat pumps utilise the naturally stable earth temperatures at depths of 1 m to 5 m underground, to heat and cool piped fluids (Florides & Kalogirou 2007). Pipes are buried at these shallow depths around and under buildings, with the pipe then extending up into the building walls. The fluid (often groundwater) circulates through the pipes, into the building where heat transfer occurs and then continues to circulate underground where a further a transfer of heat occurs. These systems use pipes of small diameter and minimal pipe thickness to maximise heat transfer. During summer the water will circulate from the naturally cooler ground into the building and absorb heat from the building. This heat is then dissipated into the ground. Conversely during winter the water will transfer heat from the warmer ground to the building. To increase the efficiency of these systems a second fluid that is a refrigerant, can be incorporated into the system to increase the heat transfer efficiency.

This technology is known as geoexchange in Australia and has had a limited uptake compared to the Northern Hemisphere. A number of geoexchange systems have been installed by the Department of Infrastructure Engineering at the University of Melbourne in order to try to promote the use of such systems (Johnston et al. 2012).

The underlying principle of these systems (when used in cooling mode) is to make use of the naturally stable soil temperatures as a heat sink. It is this principle that is being investigated to determine whether it could be exploited to achieve effective municipal water cooling.

2.3.2 Vertical Pipe Loops

Vertical pipe loops are one of the variations used in the ground heat exchanger component of a ground source heat pump system. Vertical pipe loop systems utilise vertical boreholes in which the piping is installed and looped. The fluid circulates through the pipe while exchanging heat to the surrounding soil. Holes of 150 mm diameter are drilled to depths of between 50 m to 150 m, with the pipes installed and then grouted in place (Arkins 2004). The basic concepts behind vertical pipe loops are shown in Figure 2.3.

Figure 2.3. Vertical pipe loop system (Klaassen 2006)

As discussed in Section 2.5.2, the thermal conductivity of air is extremely low so the grouting process is of upmost importance to achieve effective heat transfer. Bentonite clay is most commonly used for this application (Arkins 2004; Florides & Kalogirou 2007). Consideration must also be given to the location of the groundwater table when installing vertical pipe loop systems. The installation costs of these systems are generally higher than horizontal systems due to the larger boring costs.

2.3.3 Horizontal Pipe Loops

There are three principle variations of horizontal pipe loops that are used in underground heat exchange situations. Each of these three variations are detailed below.

Linear Pipe Loop Systems

Horizontal linear pipe networks consist of extended lengths of straight pipe buried at shallow depths. Shown below in Figure 2.4 is an illustration of a typical linear pipe loop system.

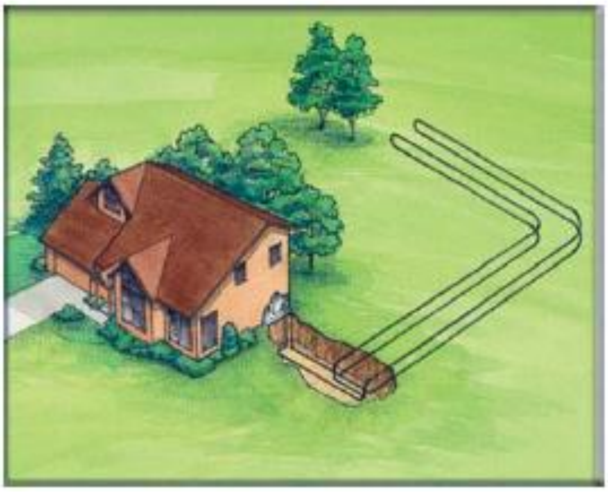

Figure 2.4. Horizontal pipe loop system (Klaassen 2006)

This option requires the largest land area of all possible underground pipe systems. Depending on the pipe material and installation method used, they can however be the cheapest option to install. The greatest advantage of these systems is the simple installation procedure.

Expanded Coil Pipe Loops

Horizontal expanded coil pipe loop systems operate on the same principle as the horizontal linear loop systems. The advantage of using expanded pipe coils are that less land is required to achieve the same amount of cooling (as more pipe can fit in each trench). Figure 2.5 below shows an illustration of a typical expanded coil pipe loop system.

Figure 2.5. Horizontal expanded coil pipe loop system (Klaassen 2006)

Difficulties can be experienced with expanded coil systems if the amount of pipe per trench is too high. This problem may lead to soil temperatures around the pipe elevating to such a level that heat transfer can no longer effectively take place.

Ponds

Horizontal pond loop systems are essentially the submerged cooling grids described in Section 2.2.1. Figure 2.6 shows an illustration of a horizontal pond loop.

Figure 2.6. Horizontal pond loop system (Klaassen 2006)

For the reasons explained in Section 2.2 submerged cooling grids (or horizontal pond loop systems) are not viewed as a sustainable cooling solution.

2.4 Modelling

There are many computation methods and computer programs that have been designed and used to model heat transfer in a buried pipe. There are commercial programs specifically designed to model heat transfer, there are programs used to simulate and design ground source heat pumps, and there are programs used to simulate pipe flow. Heat transfer can be assumed and modelled as one-dimensional or multi-dimensional, finite element and finite differencing approaches can be used, or simple hand calculations can be adopted.

In order to gain an understanding of the advantages and disadvantages of different modelling approaches a literature search was completed on ground heat transfer methodologies and modelling. A number of results found by this search contained valuable information on how similar problems had been approached in the past. Florides and Kalogirou (2007) present a thorough review of models and methods developed for ground heat exchange systems from the 1980s through to 2006. This review found that as the models increased in complexity the number and quality of the model outputs generally increased. In short, the simple models made a number of assumptions and described only the bare minimum (outlet temperature), while the more complex models gave a thorough understanding of the temperature distribution within the surrounding soil, as well as the expected output (water temperature at outlet). The more complex models made use of commercial software packages, often computational fluid dynamics programs such as TRNSYS and ANSYS FLUENT to be able to compute all required system properties (Florides & Kalogirou 2007).

As local governments and other water supply authorities (the organisations who would be looking at installing such systems) are unlikely to have access to these complex and expensive programs, a search for a simpler modelling methodology was conducted. There are a number of freeware and low-cost programs that have the ability to model underground pipe flow. Reducing the list to those that have the capability to concurrently simulate heat transfer and the number of options drastically reduces.

2.4.1 Earth Coupled Analysis

Earth Coupled Analysis (ECA) by Elite Software was identified as a commonly used program for sizing and costing ground source heat pumps for building heating and cooling applications (Elite Software 2012). This program costs US$395 but there is a demonstration version freely available (Elite Software 2012). ECA has an in-built library of American soil data, temperature data and equipment, which can be updated by the user. The user must enter some general design data (winter and summer heating and cooling loads and temperatures), configure the pipe loop layout (with or without a heat pump) and input head loss and costing data. The program will then use the ASHRAE calculation procedure (Elite Software 2012) to output the length of pipe required, and the total cost of the system.

The primary stumbling point with using this program is the fact that a number of features are intrinsically linked to the aim of designing a building heating and cooling system. Inputs required include the amount of heat to be removed from the building. These inputs could be worked around to determine heat loss over a pipe length, but this combined with the limitations of the demonstration version led to other options being investigated.

2.4.2 EnergyPlus

Another option that was identified was EnergyPlus energy simulation software. This software is published by the United States Department of Energy and is a HVAC design program (United States Department of Energy 2013a). EnergyPlus has been used in the design of ground source heat pumps for a number of years and there are free licenses available for the full program.

EnergyPlus has an in-built module capable of simulating heat transfer within a pipe (either buried or in the air). Input values required include soil surface temperatures, soil thermal conductivity and a convection coefficient (United States Department of Energy 2013b). The program then uses a finite differencing approach to model the transfer of heat into the soil. This is achieved by subdividing the pipe with a number of nodes, while the soil around the pipe is divided into a grid at each cross-section (United States Department of Energy 2013b). This calculation approach in effect minimises the error associated with assuming heat transfer does not occur longitudinally through the pipe (a key assumption of a one-dimensional model).

Finite differencing equations are then used to quantify the heat transfer occurring throughout the pipe length.

2.4.3 QPIPE

The Geo-Heat Center at the Oregon Institute of Technology has published a CD containing six spreadsheets and two Quick Basic programs that relate to heat transfer and direct use geothermal systems. One of the programs included is QPIPE, which is capable of calculating the heat transfer occurring in a buried pipe (Lienau 2012). The program can model multiple layers (a pipe, two layers of insulation, sand backfill, and the surrounding soil) in which it assumes all heat transfer is driven by the temperature difference between the soil surface and the fluid within the pipe (Lienau 2012). The CD containing this program costs US$7.50 and the program has been written in non-SI units.

Dimensions for the pipe, insulation and backfill are input, along with depth of burial, thermal conductivity values for all components, water and soil surface temperatures, water flow rate and pipe length (Lienau 2012). QPIPE uses an average water temperature in the pipe to determine the heat transfer occurring between the pipe and the soil. The outlet water temperature that has been calculated is then input back into the computation to provide an updated average water temperature (Lienau 2012). This is repeated five times before a final estimate of the outlet temperature is given. In order to calculate the heat loss the total thermal resistance for the system is computed and it is this along with the temperature difference, pipe length and fluid flow rate that determines the fluid temperature at the end of the pipeline (Lienau 2012).

2.4.4 GHD Design Spreadsheet

In 2007 GHD was commissioned by the New South Wales Department of Natural Resources to study the extent to which artesian water could be cooled by underground polyethylene pipe (Talayasingham 2007). In response GHD delivered a brief report and two spreadsheet models that could be used to determine the pipe length required to achieve a set outlet temperature. The two spreadsheet models differed in their assumptions (one assumed constant pipe wall temperature, while the other computed a variable wall temperature) but delivered similar outputs. These models were not verified by GHD but were based on theoretical heat transfer equations, solved by applying finite element methods (Talayasingham 2007).

Inputs into the spreadsheets include pipe dimensions, water and soil temperatures (including distance from pipe at which the temperature was taken), flow rate, soil and pipe thermal conductivity and pipe element length (Talayasingham 2007). Heat transfer equations are then applied to each pipe element. The outlet water temperature of each pipe element is then assigned as the inlet water temperature for the next pipe element. This process is continually repeated until the end of the spreadsheet is reached.

A number of properties such as water's specific heat capacity are assumed constant in the model, even though some of these properties may vary markedly with temperature. The Nusselt number of the flow is calculated based on whether the flow is laminar or turbulent (Reynolds number of 10^6 was used to discriminate between these flow regimes), with this number then used to determine the convective heat transfer coefficient (Talayasingham 2007). Similar to the QPIPE model a total thermal resistance is calculated by combining the convection and conduction occurring in the system. It is then this thermal resistance along with the temperature difference and flow rate that determines the heat transfer in each element.

2.4.5 James Hardie Design Method

James Hardie Pipelines (1997) presented an example calculation for determination of water outlet temperature when a pipeline is buried in saturated soil. This assumption of saturated soil means that convection calculations are being performed through the soil, rather than conduction calculations. The calculation method presented only uses a single steady state calculation, as no finite differencing or temperature averaging in used. This calculation method is only applicable to waterlogged soil, or for pipes submerged in water, hence application of this calculation method is limited to these applications.

Further discussion on these models can be found in Chapter 3.

2.5 Materials and Ground Conditions

As discussed in Section 2.1.2, conductive heat transfer depends on the thermal conductivity of the materials through which the transfer is occurring. In the case of buried pipe systems, conduction occurs through the pipe wall and then again through the surrounding soil.

2.5.1 Pipe Materials

There are a multitude of pipe materials available for use in buried pipelines. Copper piping has perhaps the highest thermal conductivity of the commonly used pipe materials, but is expensive, subject to corrosion and can easily be damaged (Banks 2012). Plastic piping is often used as it is cheap, resilient and easily installed. Of the common plastic pipe varieties polyethylene (PE) has the highest thermal conductivity. PE thermal conductivities tend to vary in the range of 0.37 to 0.47 W/m.K with high density polyethylene (HDPE) having greater thermal conductivity (Banks 2012; Iplex Pipelines 2009).

HDPE pipe has been used in many ground source heat pump applications overseas, as these systems are generally only exposed to low temperatures (mostly less than 45 °C). However as this technology is being adapted to be used with GAB water that may be extracted at up to 99 °C, a problem is presented. In high temperature applications a plastic pipe's pressure rating must be recalculated and the usable life of the pipe reduced. At the temperatures being investigated the design life of ordinary HDPE is likely to be less than 10 years (Iplex Pipelines 2009). This would mean that the pipe closest to the bore head (the section exposed to the highest temperatures) would have to be regularly replaced, unless another material is used.

Cross-linked polyethylene (PE-X) is an alternative to HDPE as it does not de-rate as quickly as HDPE at high temperatures (Iplex Pipelines 2009). PE-X pipes are currently more expensive than HDPE as they are a relatively new pipe material and do not have the same demand as ordinary PE. However as copper pipes are phased out due to high costs, the demand for PE-X pipes will increase and likely lead to a price drop.

2.5.2 Local Soil Conditions

Soil Thermal Conductivity

Soil thermal conductivity has been found to be highly influential in the design of ground heat exchange systems (Song et al. 2006). Increased thermal conductivity of the pipe material is beneficial, but small changes in soil thermal conductivity and soil temperature can have a large impact on system design.

The non-homogeneity of soil means that it is difficult to estimate soil thermal conductivity, especially where lengthy pipelines are involved. This being said there are a number of empirical relationships that attempt to relate common soil properties (such as dry density and moisture content) and/or soil classifications to thermal conductivity. Farouki (1986) presents a comprehensive selection of established empirical relationships used to determine soil thermal conductivity.

Though soil thermal conductivity can be measured, or can be estimated using empirical relationships, there are also some very general relationships that need to be considered. As stated in Florides and Kalogirou ‘Rocks that are rich in quartz, like sandstone, have a high thermal conductivity’ (2007). For example Quartzite has a thermal conductivity in the range of 5.5 – 7.5 W/m.K (Banks 2012). Banks (2012) also describes the best heat conducting soils as being dense, of low porosity and having high quartz content, whereas dry, porous sediments are regarded as the worst. As air has an extremely low thermal conductivity (0.024 W/m.K) and water has a moderately low thermal conductivity (0.6 W/m.K), it can be seen that some benefit may be gained by reducing the volume of air voids in soil. The inherent high thermal conductivity of silicate minerals cannot effectively be used where heat transfer has to occur across air voids (Singer & Munns 2002). By either compacting a porous soil or increasing the soil moisture content (until all air voids are replaced by water) the soil thermal conductivity can be greatly increased.

Soil Specific Heat Capacity

Another important parameter effecting heat transfer in soils is the specific heat capacity of the soil. Specific heat capacity is a measure of how much energy is required to heat a unit weight of a substance by 1 °C. Pure water has a specific heat capacity of 4.183 kJ/kg.K at 20 °C (Rogers & Mayhew 1995). The specific heat capacity of dry soil varies but is approximately one fifth that of water (Brady & Weil 2008). Due to this large relative difference in heat capacities it can be said that increasing the proportion of water in soil will in turn increase its specific heat capacity.

Soil temperature will be discussed shortly, but by increasing the specific heat capacity of a soil (by increasing its moisture content) will ensure that the soil temperature rises at a reduced rate (because more energy is required to increase the temperature of each unit weight of soil by 1 °C).

Enthalpy of Vaporisation

The enthalpy of vaporisation (also known as the latent heat of vaporisation) is the amount of energy per unit weight required to evaporate that substance. For water at 20 °C the enthalpy of vaporisation is 2453.7 kJ/kg (Rogers & Mayhew 1995). The energy that a water molecule in soil requires to evaporate can come from incoming solar radiation as well as the soil particles around it (Brady & Weil 2008). This taking of energy from surrounding particles in order to achieve vaporisation is known as the evaporative cooling effect (this effect has already been discussed in the context of cooling ponds in Section 2.2.1).

Soil Temperature

Another important soil parameter in the design of underground heat transfer systems is soil temperature. As presented in Section 2.1, heat transfer is governed by a temperature difference. As the water inside the pipes is at an elevated temperature, the cooler the surrounding soil is the quicker heat will be dissipated from the water.

There has been research published over many years (much of this research was conducted in the mid-20th century) on the temperature of Australian soils at varying depths. Research shows that from the surface to depths of around 15 m, the soil temperature steadily drops before rapidly increasing at depths of greater than 50 m (Kirkby & Gerner 2010). This particular research is quite applicable to vertical pipe loop cooling systems, but horizontal systems are installed at much shallower depths.

Buried pipes designed for heat transfer are generally installed at depths of between 0.3 and 2.0 m. This depth is used to get access to the cooler soil, to get as far away from the effects of daily and seasonal temperature variations, while still having ease of construction (Banks 2012; Florides & Kalogirou 2007).

The variation of soil temperature over time can be a difficult phenomenon to model. Soil surfaces and soil at shallow depths experience daily (diurnal) cyclical temperature variations as a result of daytime heating and night-time cooling (Marshall & Holmes 1988). The seasonal (annual) temperature variations experienced by soil are caused by variations in short-wave radiation coming from the sun (Marshall & Holmes 1988). The best example of an experimental study (in an Australian context) confirming the theory presented above was the work completed by West (1952) at Griffith, New South Wales. This work summarises eight years of soil temperature readings taken from bare soil at depths of up to 2.4 m. An extract of the data presented by West is shown below in Figure 2.7.

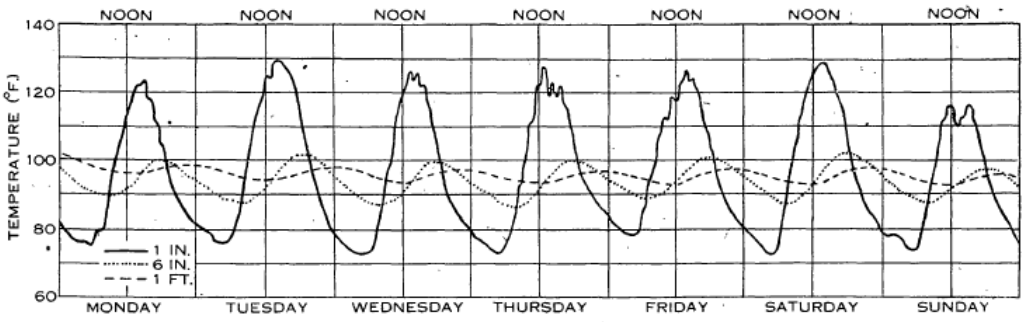

Figure 2.7. Griffith, NSW soil temperatures at 25 mm, 150 mm and 300 mm depths, January 16-22, 1939 (West 1952)

As seen above, during this week of summer in 1939 the temperature of the soil at 25 mm depth varied cyclically around a mean of approximately 36.7 °C (98 °F) with a range of approximately 31.7 °C (57 °F). The effect of this diurnal temperature variation decreases markedly as the depth is increased to 150 mm and 300 mm. The observed winter diurnal soil temperature variation is shown below in Figure 2.8.

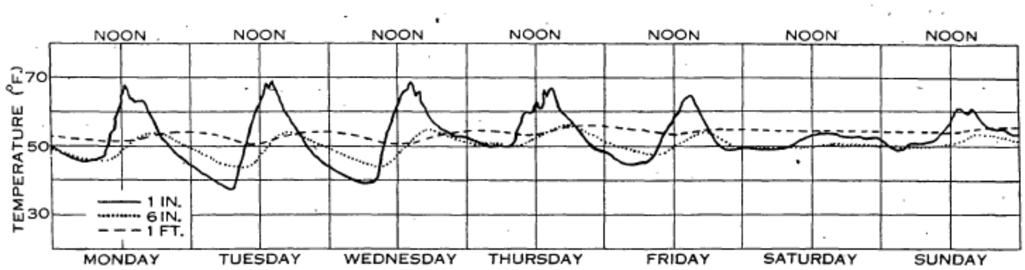

Figure 2.8. Griffith, NSW soil temperatures at 25 mm, 150 mm and 300 mm depths, July 20-26, 1936 (West 1952)

The above figure shows that the winter diurnal temperature variation is less intense than summer (as would be expected due to the decreased solar radiation during winter). It is interesting to note that the average temperature at 300 mm depth is slightly higher than the average at the surface at the surface for most of the observation period.

West (1952) also analysed the annual temperature variation in soil and fitted a theoretical sinusoidal function to the observed data. This is shown below in Figure 2.9.

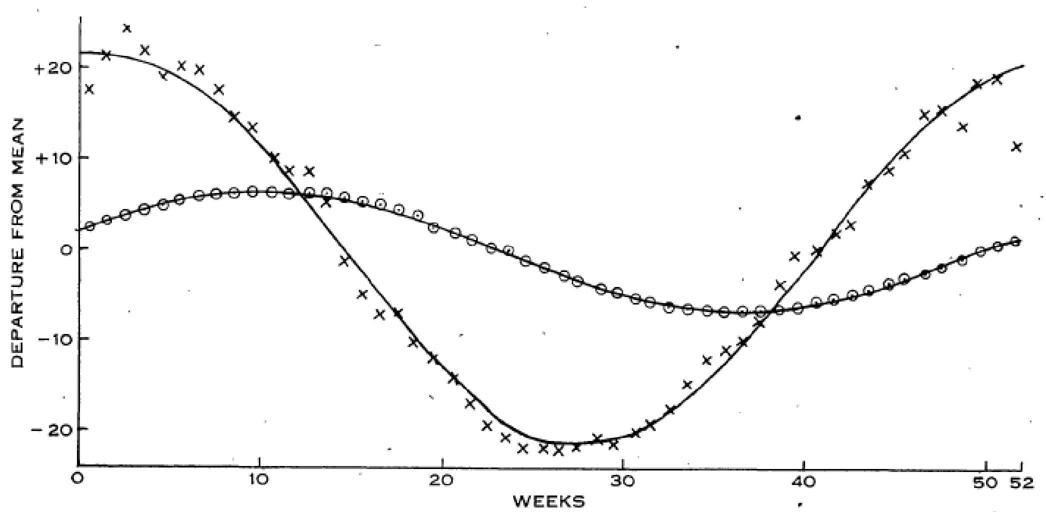

Figure 2.9. Griffith, NSW average annual soil temperatures at 25 mm (represented by crosses) and 2400 mm (represented by circles) depths (West 1952)

In summary, for soils at shallow depths (less than 2 m) the further away from the surface the less diurnal and annual temperature variation is experienced. The literature also suggests that soils from 300 mm to 2000 mm deep in the warm Australian climate would experience temperatures in summer much, much cooler than that experienced at the surface or in the air. Conversely soil temperatures at depth can be slightly warmer than at the surface during winter.

2.6 Hydraulics

To ensure that effective heat transfer occurs, and that water demand is met, the hydraulics of a GHSPL system must be understood.

2.6.1 Flow Regimes

There are three primary flow regimes that can be identified in fluid flow. Laminar flow is characteristic of low, slow flows where discrete “layers” develop in the flow. Turbulent flow on the other hand is characteristic of quick flows where eddies and currents develop. The third primary flow regime is transitional flow that occurs somewhere between laminar and turbulent flow. Flow type is identified by the dimensionless Reynolds number, which is the ratio of inertial forces to viscous forces (Nalluri & Featherstone 2009). Equation 2.12 below is the formula for calculating Reynolds number in a pipe (Nalluri & Featherstone 2009).

$$Re = \frac{\rho V D}{\mu} \qquad (2.2)$$

where Re = Reynolds number [dimensionless]

ρ = fluid density [kg/m^3]

V = fluid flow velocity [m/s]

D = pipe diameter [m]

μ = fluid dynamic viscosity [kg/m.s]

Heat transfer involving a flowing fluid is most effective in turbulent flows. This is because in laminar flows a boundary layer develops, which effectively shields the bulk of the fluid body from being exposed to the temperature difference present at the boundary. It is commonly accepted that laminar flow is present for Reynolds numbers of 2,000 or less, and turbulent flow is present for Reynolds numbers of 4,000 or more (Nalluri & Featherstone 2009; Chadwick, Morfett & Borthwick 2004). As mentioned in Section 2.1.3 the convective heat transfer coefficient, h, depends on the Nusselt number. Calculation of the Nusselt number depends on the flow regime because as stated earlier, the flow regime has dramatic effect on the efficiency of heat transfer. To ensure that turbulent flow is fully developed and that a boundary layer will not block the heat transfer, Reynolds numbers of greater than 10,000 will be considered to be indicative of turbulent flow for the purposes of this research. This methodology is consistent with the recommendation found in ASHRAE (2005).

2.6.2 Pipe Flow Considerations

Along with the flow regime there are a number of other considerations that must be taken into account when designing a GHSPL system. The system must be able to accommodate variable flow demands, so similar to the cooling grids already discussed it is likely that a number of pipes will be required to be installed in parallel. These pipes can be connected at either end by a manifold and the number of pipes receiving flow based on real-time water demand. This will allow each pipe to remain under the design flow rate, but still maintain turbulent flow where possible.

2.7 Experimental Procedures

To ensure that experimentation produces reliable results, an experimental methodology based on sound literature and current practice is required.

2.7.1 Temperature Measurement

There are many commercial devices readily available to determine the temperature of an object or substance. Some of the devices that were investigated for use in this research include:

Spear Thermometer

There are a number of options available when soil temperature at depth needs to be determined. Where temperature measurements are required at depths greater than about 100 mm there are few options that do not involve excavation. Excavation to place a contact thermometer or a stem thermometer is to be avoided where the excavation will be exposed to solar radiation. As discussed in Section 2.5.2, solar radiation has a large impact on soil temperature, hence excavating and exposing the soil to this heat source will introduce error into the measurement.

To get the most accurate temperature measurement the soil should be left undisturbed. Spear thermometers are temperature gauges attached to a metal probe that can come in lengths of greater than a metre. The probe at the end of the spear can be pressed into the substance that requires temperature measurement and the gauge at the top of the instrument read. This method of temperature measurement is regarded as being most accurate for soil depths of greater than 100 mm.

Digital Stem Thermometer

A digital stem thermometer can essentially perform the job of a spear thermometer and a contact thermometer. The majority of spear thermometers use dial gauges to convey the temperature reading where digital stem thermometers have the added precision of a digital display. Stem thermometers have a similar layout to spear thermometers, with the stem generally only extending up to a maximum of 200 mm. Hence these devices can be used to take shallow depth soil temperatures as well as taking temperature readings that any other contact thermometer can take.

Temperature Data Logger

A temperature data logger has the advantage of being able to record temperature with time, rather than just give an instantaneous temperature reading. These devices can make use of wireless internet technology to upload the recorded data to a PC or can be connected by cable (commonly through the USB port). Advances in microchip and battery technology mean that modern data loggers can take highly precise temperature readings at small time intervals over extended time periods. These devices have many applications but can easily be used to monitor soil temperature at depth over time.

Infrared Non-Contact Thermometer

Advances in laser technology have led to the development of infrared non-contact thermometers. These devices are extremely useful for situations where conventional contact thermometers may not be suitable. These devices are capable of delivering an instantaneous temperature reading with reasonable accuracy at the touch of a button. While the accuracy of these devices has improved in recent times, contact thermometers are still more popular (where access to the object or substance being measured can safely happen).

2.7.2 Flow Measurement

There are many empirical estimation techniques, simple and complex devices that are capable of determining flow rate in a conduit. Some of the methods investigated for use in this research are detailed below.

Physical Volume and Time Measurement

Perhaps the simplest method of determining the flow rate is to physically discharge the fluid into a container of known volume and measure the time it takes to fill. The volume divided by the time will give the water flow rate. Human error in starting and stopping the timer will have a large impact on the accuracy of the results so preferably a large volume would be used to minimise the impact of this error. Capturing all the flow when it is being discharged at pressure can also prove difficult. Wind and other environmental factors may also impact on the complete capture of water. Due to these errors and potential errors other flow measurement techniques were investigated.

California Pipe Method

The California Pipe method is an empirical method used to determine an estimate of the flow rate of water within a pipe. For water horizontally discharging freely into the air from a pipe of length greater than six times the pipe diameter, the discharge can be estimated by Equation 2.13 (United States Department of the Interior 2001):

$$Q = 4.685 \times (1 - \frac{a}{D})^{1.88} \times D^{2.48} \quad (2.3)$$

where Q = flow rate [m^3/s]

a = distance measured in the plane of the end of the pipe from the top of the internal surface to the water surface [m]

D = internal pipe diameter [m]

This method of flow rate measurement has been tested on pipes of 75 to 250 mm diameter and it has been found that results within 10% of actual flow can be expected where the pipe is flowing less than half full at the outlet (United States Department of the Interior 2001). A potential problem with using this method is determining an accurate value for a, while there is pressurised water flowing out the end of the pipe. Wind on-site would also likely cause the flow profile to change; hence the outlet would have to be shielded from wind effects.

The California Pipe Method is recommended not be used when the flow depth at the outlet is greater than half the pipe diameter. Where this occurs other empirical methods based the trajectory of the water flowing from the pipe should be used (United States Department of the Interior 2001). Similar to the physical time and volume measurement method, the California Pipe Method is a good back-up but another more accurate flow measurement method is preferred.

Venturis, Orifice Plates, Weirs and Propeller Flow Meters

Venturis, orifice plates, weirs and propeller flow meters are all commonly used methods of determining flow rate within a conduit. While varying accuracy can be achieved by each method, it can generally be said that if applied correctly, all of these methods have the ability to produce highly accurate results. The difficulty with these methods of flow measurement lies in the fact that these devices are required to be installed in, or on the end of the conduit containing the flowing fluid. Hence accurate date on pipe diameters and other pipeline properties need to be known so a correctly sized device can be brought to site. For this reason a flow measurement method that is easier to implement was sought after.

Ultrasonic Flow Meter

'An acoustic [ultrasonic] flowmeter is a non-mechanical, non-intrusive device which is capable of measuring discharge in open channels or pipes' (United States Department of the Interior 2001). Flow is measured by mounting a number of transducers on the pipe that send an acoustic signal through the pipe. The acoustic signal will be received by a transducer, potentially after reflecting off the pipe wall one or more times. Ultra-sonic pulses are sent in both directions along the pipe and the difference in travel time between the pulse travelling upstream and the pulse travelling downstream is used to calculate the flow velocity (Panametrics 1996). The flow rate within the pipe can then easily be calculated.

These highly expensive devices are extremely accurate (± 2% [United States Department of the Interior 2001]) and only require a large enough section of pipe to be exposed so the transducers can be attached. The fact that these devices can be fitted to a wide range of pipe sizes makes them ideal for non-intrusive flow measurement.

2.7.3 Dimension Measurement

Most experimental procedures require the measurement of a number of system dimensions. The following simple, commonly used devices were considered for dimension measurement.

Vernier Callipers

Vernier callipers are a popular measurement device for small objects. These devices are extremely precise and accurate when used correctly. Vernier callipers also have the advantage of being able to easily measure internal and external diameters which makes them ideal for comparing actual pipe dimensions to manufacturer specified dimensions.

5 m Measuring Tape

As vernier callipers are only capable of measuring small dimensions (maximum measurement is generally less than 200 mm) another instrument would be required for larger dimensions. A very common instrument for measuring dimensions is the measuring tape. Measuring tapes come in a number of lengths and a 5 m tape is a versatile instrument, though not as precise as some of the alternatives (steel rules).

Measuring Wheel (also known as Surveyor's Wheel)

For long distance measurement measuring wheels are amongst the most common pieces of equipment used. Measuring wheels work on the same principle as an odometer, where the rotation of the wheel is recorded and displayed as an equivalent distance travelled. The accuracy of this measurement method is conditional on the diameter of the wheel not changing (wear on the wheel contact surface will reduce reading accuracy) and friction being maintained between the wheel and the surface being measured. Due to ease of use, and relatively good accuracy over long distances, the measuring wheel is considered to be an appropriate piece of equipment to be used for measuring distances greater than 15 m.

2.7.4 Soil Sampling and Moisture Content Testing

Gaining an understanding of the local soil conditions at a test location can give insight into how the observed results at one location may transfer to another location.

Soil Sampling – Undisturbed Sampling

Undisturbed soil sampling is covered by Australian Standard AS1289.1.3.1 – 1999. Undisturbed soil samples are collected by pressing an open tube into the soil and extracting the tube when it is full of soil (Standards Australia 1999). As the volume of soil in the tube can easily be determined, and the mass of the full tube can be measured and compared to the mass of the tube when empty, the natural soil density can be determined. Another benefit is that undisturbed samples can often be used in place of disturbed samples were required.

Soil Sampling – Disturbed Sampling

Disturbed soil sampling is covered by Australian Standard AS1289.1.2.1 – 1998 (R2013). Disturbed samples are much more easily collected than undisturbed samples and simply require an adequate amount of soil to be placed in an appropriate sealable container (soil must be uniform in profile and from a constant depth). Where samples will be tested for moisture content the soil should be collected as soon as possible after excavation and monitored to ensure no mass is lost (Standards Australia 2013).

Soil Moisture Content – Oven Drying

An important soil property when considering heat transfer is the soil moisture content. Determination of soil moisture content by oven drying is covered by Australian Standard AS1289.2.1.1 – 2005. Soil moisture content can be determined by placing a soil sample in a container and placing the container in an oven at 105 to 110 °C for 16 to 24 hours (Standards Australia 2005). By measuring the mass of the empty container, container with moist soil, and container with dry soil, the moisture content of the soil can be accurately determined. Ideally after initial drying the sample should be placed back in the oven for an hour and the mass remeasured, with this repeated until the mass loss through drying is less than 0.1% between successive measurements (Standards Australia 2005).

Chapter 3 Model Selection and Methodology

To determine whether the proposed cooling solution is viable for municipal water supplies a well-developed modelling and simulation methodology must be enacted through a suitable model. This modelling must follow a logical sequence and come from well-established theory to enable an accurate determination of system feasibility to be determined. The modelling methodology should also extend to allow for further testing and optimisation, should the system be found viable.

3.1 Software Used

To determine the viability of Ground Heat Sink Pipe Loop (GHSPL) systems, a model was required to determine the length of pipe needed to achieve adequate cooling. The underlying heat transfer equations presented in Section 2.1 could be solved by hand and a system length determined, however this is computationally intensive. Greatest accuracy from these theoretical equations can be achieved by applying finite differencing to the pipe and minimising the segment length used in the finite difference.

3.1.1 Model Selection

For the purposes of this research two models are being utilised. As discussed in Section 2.4, there are a number of commercial computer programs available that are capable of quantifying the heat transfer in a buried pipe. Selection of a model to be used was based on quality of outputs, cost and ease of use. The design tool being used in this research could in the future be used by water supply authorities to generate concept and preliminary designs of water cooling systems, so cost and the platform on which the model is run was prioritised. Compared to the alternatives the commercial QPIPE software published by the Oregon Institute of Technology and the spreadsheets formulated by GHD were cheap and specifically designed for the underground heat transfer problem. The format of these models (Quick Basic program and spreadsheet) also gave the advantage of ease of use and installation. Both of the other programs mentioned in Section 2.4 were attempted to be used, but due to compatibility issues with the authors PC (EnergyPlus) or the fact that a work around would be required to make it work for this application (ECA), led to these models being abandoned. The James Hardie computation method was also used throughout this research, but the applicability of this model was generally an issue (assumes waterlogged soil conditions).

3.1.2 Model Adaptation

As presented in Section 2.4 there is a multitude of commercial software packages that could be used to determine GHSPL system viability. Once the two models were chosen for use they were analysed to determine where improvements could be made. The GHD model assumed a number of parameters had constant values where some of these actually vary with temperature. Tables of water properties at varying temperatures are easily found so these could be imported into a spreadsheet as a lookup table. Interpolation between values would however present a potential issue when input parameters are varied. The QPIPE program also had issues as the program code could be opened, but due to compatibility issues the program could not be run.

For this reason it was decided that the underlying equations of both models could be coded in MATLAB. MATLAB is an industry standard software program used for numerical computation and programming (Mathworks 2014). As previously stated, an aim of the modelling was to produce a simple, reliable design tool that could be used by water supply authorities. Should GHSPL systems be found to be commercially viable, and the MATLAB design tool verified, these MATLAB scripts could be coded in another language (as MATLAB is not likely to be used extensively in Western Queensland Councils) and distributed to aid in the design of GHSPL systems.

MATLAB Conversion and Model Improvements

GHD MATLAB Model

When converting the GHD model to a MATLAB script (from here on this model will be referred to as the GHD MATLAB model) a number of improvements were made to the original model with the aim of increasing the numerical accuracy of the model. The first major improvement was in converting from the spreadsheet to MATLAB. The original spreadsheet used 3.14 when a value of pi was required. By using the pi function in MATLAB, the accuracy of these calculations immediately increased in precision. The GHD MATLAB model was coded so that values of water density, specific heat, thermal conductivity and dynamic viscosity varied with water temperature. The original model assumed constant values for these properties, however this assumption does not hold true. Values for these properties presented in Rogers and Mayhew (1995) were input into a spreadsheet model, from which MATLAB interpolated values based on the water temperature. An example of why these properties cannot be assumed constant is shown below in the plot of the dynamic viscosity variance with temperature.

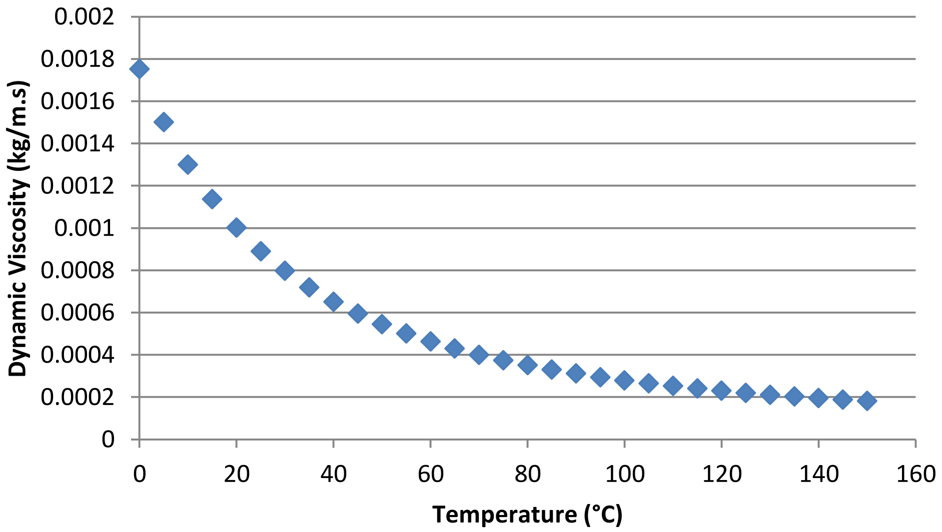

Figure 3.1. Dynamic viscosity of water over a range of water temperatures (Rogers & Mayhew 1995)

The original model differentiated laminar and turbulent flow when Reynolds number exceeded 10^6. This was modified in the MATLAB script to be 10,000 based on guidance given by ASHRAE (2005). Easy to use pop-up menus were produced so the model user could input all required system parameters. A default pipe length of 100,000 m was used in the model with the pipe segmented into 1 m lengths. The MATLAB script was written in such a way that as soon as the water temperature dropped below 45 °C all computations stopped and the length of pipe required displayed in the main window. This resulted in a model that runs in a matter of seconds (often milliseconds) and generates a length of pipe required to meet the legislative cooling requirements.

QPIPE MATLAB Model

The commercial software package known as QPIPE was coded into a MATLAB script in non-SI units as per the original program (from here on this model will be referred to as the QPIPE MATLAB model). In order to simplify the model for Australian users, a simple pop-up menu was created for inputs and all inputs have been specified in SI units. These inputs are then converted back to non-SI units so that the equations present in Lienau (2012) could be used. The original QPIPE model completed a single calculation followed by a further five iterations to give a final output temperature. To gain increased accuracy the number of computations was increased to 20 (though answer convergence often occurred much quicker than this) in the MATLAB script. The model then outputs the water temperature at the end of the pipe length to the main window (in SI units).

Both of the programs described above can be used to model horizontal GHSPL systems only. As discussed in Section 2.3, vertical cooling systems are quite commonly used. The models could be modified to model vertical GHSPL systems but this would require further extensive research and investigation and was not considered as part of this research.

3.1.3 Model Use

The two models already mentioned along with the James Hardie computation method (see further discussion in Section 3.2) were used throughout the modelling activities conducted. With the models ready to use, the process of how they were to be used needed to be determined. The development and use of the models that were chosen for this research project were guided by the flowchart shown below.

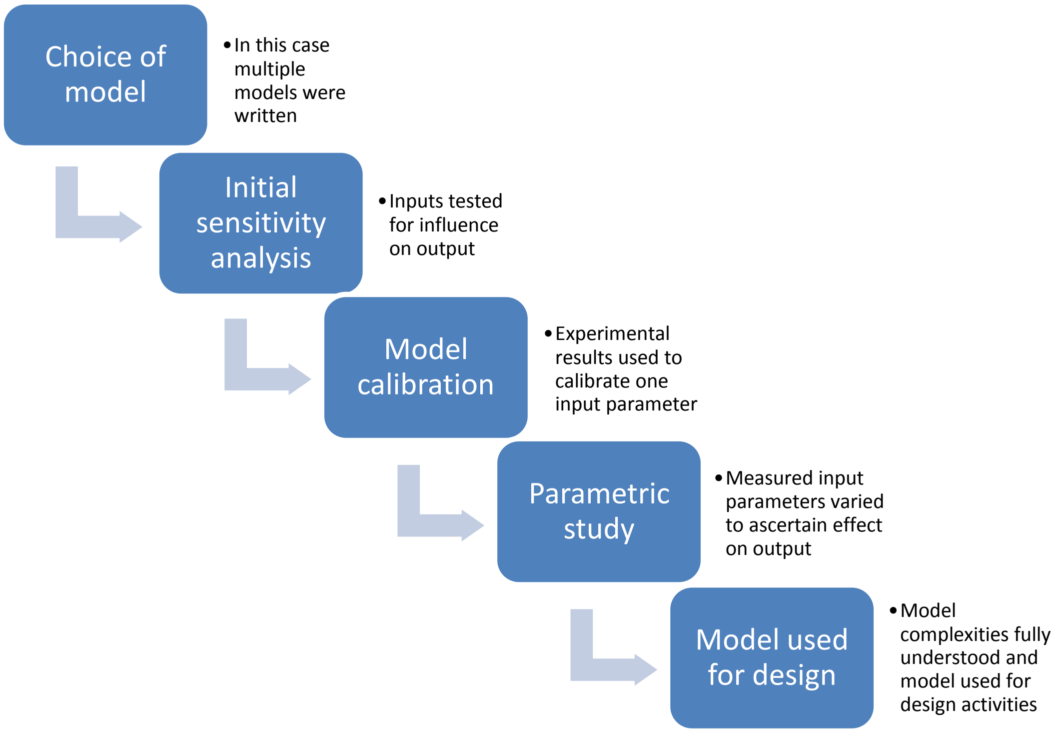

Figure 3.2. Model development flowchart

While the model use followed the general steps shown above, the actual modelling methodology can be found in Section 3.3.

3.2 Model Suitability

The models being used in this investigation have been based on models developed by other authors to simulate underground pipe heat transfer. The suitability of these models needs to be checked as these models have come from outside sources and have only been slightly modified and improved by the author. There are many equations and methodologies that can be used when simulating heat transfer in a buried pipe, and both models being used are reasonably simple representations of what can be a complex phenomenon.

In order to determine the suitability of the models, both were run on a number of simple computations with a range of input variables. The results of the models were compared and a range of input variables were then used to determine the stability of the models. The ultimate test of the model suitability was from comparing model outputs to actual measured data (see Section 5.2).

3.2.1 Model Comparison

GHD MATLAB Model

The GHD MATLAB model was coded using the underlying theory of one-dimensional convective and conductive heat transfer. The MATLAB script for this model can be found in Appendix B. The inputs required for this model are as follows:

- Pipe outer diameter (mm)
- Pipe wall thickness (mm)
- Backfill (soil) thickness (mm) *
- Water flow rate (L/s)
- Water entry temperature (°C)
- Soil temperature (°C)

- Pipe thermal conductivity (W/m.K)
- Soil thermal conductivity (W/m.K)

* Note. This thickness corresponds to the distance from the pipe wall that the soil temperature is measured at.

These inputs can easily be determined by anyone planning to install a cooling system. The pipe diameter and wall thickness can be determined from pipe manufacturer's catalogues. Small diameter pipes with minimal wall thickness are most suitable for heat transfer applications. The soil temperature can be estimated at a distance x mm from the pipe (where x is any distance), and these values input into the model. Note that it would not be entirely accurate to enter the soil surface temperature and pipe burial depth as this surface temperature would be influenced by heat transfer from the pipe and from solar radiation. The model cannot quantify solar radiation impacts; hence there would be some error in entering these values directly.

The water flow rate can be estimated from water usage data and water entry temperature measured at the bore head. The pipe thermal conductivity can again be found in pipe manufacturer's catalogues and the soil thermal conductivity experimentally determined or estimated using empirical formula. Hence the user should easily be able to quantify the input parameters and use the model to determine a pipe length that will achieve a water temperature of 45 °C.

QPIPE MATLAB Model

The MATLAB script for this model can be found in Appendix C. The inputs required for this model are as follows:

- Pipe internal diameter (mm)
- Pipe outer diameter (mm)
- Insulation outer diameter (mm)
- Jacket outer diameter (mm)
- Sand outer diameter (mm)
- Depth to pipe centre (mm) *

- Pipe thermal conductivity (W/m.K)
- Insulation thermal conductivity (W/m.K)
- Jacket thermal conductivity (W/m.K)
- Sand thermal conductivity (W/m.K)
- Soil thermal conductivity (W/m.K)
- Water entry temperature (°C)
- Soil temperature (°C)
- Water flow rate (L/s)
- Pipe length (m)

* Note. This thickness corresponds to the distance from the pipe wall that the soil temperature is measured at.

This model has similar inputs to the previous model but is much more versatile. Additional system components such as an imported backfill material can be included in the system analysis. Where the GHD model determines whether the flow is laminar or turbulent and relies on a number of water properties, this QPIPE model uses fewer calculations and does not discern between laminar and turbulent flow. To determine whether this model has been oversimplified it will need to be compared to measured results from a buried pipeline. As already discussed with the GHD MATLAB Model, all of these input values can easily be measured or estimated. Where the GHD MATLAB model outputs a pipe length required to achieve 45 °C water, this QPIPE MATLAB model outputs a water temperature based on the provided pipe length.

Model Output Comparison

The two models discussed above were run with the same inputs to determine how different the predicted output temperatures were. The following input parameters were held constant:

- Pipe internal diameter = 19.0 mm *
- Pipe outer diameter = 22.6 mm

- Insulation outer diameter = 22.6 mm *
- Jacket outer diameter = 22.6 mm *
- Sand outer diameter = 22.6 mm *
- Depth to pipe centre = 300 mm
- Pipe thermal conductivity = 0.38 W/m.K
- Insulation thermal conductivity = 0.38 W/m.K *
- Jacket thermal conductivity = 0.38 W/m.K *
- Sand thermal conductivity = 0.38 W/m.K *
- Soil thermal conductivity = 1.50 W/m.K
- Water entry temperature = 85 °C
- Soil temperature = 18 °C
- Water flow rate = 0.3 L/s

* Note. A pipe thickness of 1.8 mm was used in the GHD MATLAB model to get internal diameter equivalent to 19.0 mm. In the QPIPE MATLAB model the insulation, jacket and sand properties were kept at the same values as the pipe as the GHD MATLAB model does not have these inputs.

Three cases were input into the models. With the values above held constant, the following inputs were varied:

1. Pipe length 476 m, Soil temperature = 18 °C
2. Pipe length 575 m, Soil temperature = 25 °C
3. Pipe length 736 m, Soil temperature = 32 °C

The following table is a comparison of the water temperatures output by the GHD and QPIPE MATLAB models when provided the same inputs.

Table 3.1. GHD and QPIPE model comparison

Case	GHD Model Output	QPIPE Model Output
1	45 °C	47.21 °C
2	45 °C	46.39 °C
3	45 °C	44.97 °C

As seen above there is a slight variance between the two models with no distinct trend for one model to be more conservative than the other. Due to the slight differences in calculation method this variance was not unexpected. As the variance observed is not too significant, both models remained in use.

James Hardie MATLAB Model

There were three models originally being used for this research project. The third model was based on the computation method published by James Hardie Pipelines (1997). This method, like the QPIPE and GHD methods was coded into a MATLAB script file. The computation method presented by James Hardie Pipelines (1997) operates on the assumption of water charged ground. As the systems being investigated are primarily installed at shallow depths (very likely to be above the water table), in arid environments (most of the areas with “hot” GAB water could be described as arid), water charged ground conditions are unlikely to be encountered. For this reason there was limited modelling conducted using this method. As this was the case all results presented in this dissertation come from the GHD and QPIPE MATLAB models.

3.2.2 Model Stability

Varying the input parameters of both models across a wide range of values led to the discovery of instability within both models. Both models require the input of a soil temperature and a depth of soil around the pipe (essentially the pipe burial depth). Where a soil temperature has been measured close to the pipe and this temperature is input into the model, the distance to the pipe is modified to reflect this (even though the physical pipe depth has not changed, the distance over which the temperature gradient applies is now different). The temperature distribution in the soil approximates an exponential decay function as distance away from the pipe increases (see Figure 5.15). Where the soil temperature is input at a distance very close to the pipe (a burial depth in the order of millimetres, or a soil temperature reading taken very close to the pipe wall) both models give unreasonable temperature outputs (water temperature higher than the original input temperature). The QPIPE MATLAB model is most susceptible to this instability. Apart from this distinct instability (another instability was also observed in the QPIPE MATLAB model when large pipe lengths were used) both models perform quite well for a wide range of input variables.

3.3 Modelling Methodology

3.3.1 Initial Sensitivity Analysis

In order to gain an initial understanding of how sensitive the models were to changes in input parameters, a sensitivity analysis was conducted on both models. For the sake of brevity the results of the GHD MATLAB model sensitivity analysis are the only results that have been reproduced (both models had similar output changes based on the same input variance). The baseline input values used in the initial sensitivity analysis were as follows:

- Pipe outer diameter (OD) = 22.6 mm
- Pipe wall thickness = 1.8 mm
- Backfill (soil) thickness = 300 mm
- Water flow rate = 0.3 L/s
- Water entry temperature = 85 °C
- Soil temperature = 18 °C
- Pipe thermal conductivity = 0.38 W/m.K
- Soil thermal conductivity = 1.5 W/m.K

The above inputs gave a pipeline length of 476 m to cool the water to 45 °C. The above values were then varied by 10% to give the sensitivity analysis results. The results of this analysis can be found in Section 5.2.1. Discussion on the influence of different parameters on system design can be found in Section 7.1.3.

3.3.2 Model Calibration

With the initial sensitivity analysis completed the next step in the model development was to use the models to calibrate the model input parameters based on measured experimental results. Experimentation was conducted and a number of measurements were recorded for input into the MATLAB models (the experimental methodology for the calibration stage is presented in Section 4.1). All required modelling parameters were measured except for the soil thermal conductivity. The models had the measured input variables entered (the QPIPE MATLAB model was primarily used) and the soil thermal conductivity was iterated until the measured output temperature (at known system length) matched the model output. The results of the calibration activity can be found in Section 5.2.2. Discussion on the accuracy of this process can be found in Section 7.1.3.

3.3.3 Model Parametric Study

Following the calibration activity a parametric study was undertaken. With measured values for soil temperature at distance and soil thermal conductivity known, model inputs were varied to determine how these inputs affected the model output.

The initial sensitivity analysis that was conducted provided an indication of which input variables were most sensitive to the model result. The values used in this study were chosen at random and hence a full model parametric study was required to fully understand how model inputs affected the output. For the purpose of this study the GHD MATLAB model was used. To conduct this study there were four system parameters varied, soil temperature (which essentially has the same effect as changing burial depth), pipe flow rate (which changes the flow velocity and potentially alters the flow regime), the soil thermal conductivity and the pipe thermal conductivity. The default unchanged values for the other input parameters are shown below.

- Pipe outer diameter (OD) = 90.0 mm
- Pipe wall thickness = 4.30 mm
- Backfill (soil) thickness = 300 mm
- Water entry temperature = 85 °C

The parameters above that weren't varied were chosen as the effect of varying these are essentially the same as the parameters that are being varied. For example, varying the pipe diameter changes the flow velocity and potentially the flow regime, the same effect given by varying the flow rate. The results of the parametric study can be found in Section 5.2.3. Discussion on the results of this study can be found in Section 7.1.3.

3.3.4 GHSPL Concept Design

With the calibration exercise complete and a thorough understanding of how changes to the system alter the final output, the models were used to deliver a concept design for a GHSPL system for Thargomindah. The model inputs were adjusted where possible to try and provide the most efficient system design. The pipe length output from this design then gave an indication of the feasibility of implementing this alternate cooling method. This was used to determine system viability, and if found viable this output used as the basis for a concept design. The system concept design can be found in Chapter 6.

Chapter 4 Experimental Methodology

To determine whether the proposed cooling solution is viable for municipal water supplies the models must be used with accurate input data. With reliable input data an accurate determination of system viability can be made.

4.1 Field Testing Procedure

The models being used incorporate theoretical equations for heat transfer that require a number of inputs. The experimentation that has been conducted was aimed at determining accurate values for all the required inputs, as well as verifying the accuracy of the model calculations. In order to achieve the aims of the experimentation a carefully planned field testing procedure was required.

4.1.1 Reason for Experimentation

It is anticipated that flow rate data (water demand over time) will either be able to be sourced from water supply authorities (generally shire councils) or reasonably accurately estimated for the purpose of generating a concept design. Soil temperatures and thermal conductivities could be estimated using published empirical relationships.

Presented in **Error! Reference source not found.** are the initial sensitivity analysis results for one of the MATLAB models that have been written for the system design. It was found in this sensitivity analysis that two of the more influential system parameters are the soil temperature and the soil thermal conductivity. With this in mind, combined with the unknown accuracy of soil thermal conductivity empirical relationships when applied to Australian conditions, it has been decided that it would be extremely beneficial to conduct some on-site investigation into this parameter.

By collecting real-world data for soil temperature and thermal conductivity the degree of confidence associated with the system concept design will be greatly increased. Decisions can also be made about whether there is any significant benefit in trying to alter these parameters (by irrigating the pipeline for example) with the aim of reducing the pipe length required.

By taking measurements of these soil parameters while also monitoring a real buried pipe carrying artesian water of elevated temperature, the model can also be somewhat verified using the experimental results. In order to achieve all the goals mentioned above, a pipeline of significant length, buried at reasonable depth that carries water at elevated temperature (preferably significantly more than 45 °C) is required. The climate and geology at the test location would preferably be comparable to the towns already discussed (Thargomindah, Winton, Birdsville and Richmond) so that the results are appropriate to be used in a system design for one of these locations.

4.1.2 Experimental Location

The possible experimental sites identified for this research included:

- The University of Southern Queensland (USQ) – Toowoomba Campus "Agricultural Plot"
- Thargomindah, Queensland
- St George, Queensland

The advantages and disadvantages of each site are discussed below.

USQ "Agricultural Plot"

The "Agricultural Plot" at the USQ Toowoomba Campus has sufficient space for a pipeline to be buried and experimentation conducted. Using this site would allow complete control of the site to be had and would eliminate any travel involved with experimentation (as the author is based at USQ's Toowoomba Campus). The issues with using this site would be organising to have a sufficient length of pipe buried and providing a sufficient supply of hot water at a relatively constant temperature.

Thargomindah

The Queensland town of Thargomindah is supplied by Great Artesian Basin (GAB) water at temperatures of around 86 °C. Thargomindah has been adopted as the "typical municipality" for this study and hence system design for Thargomindah would be most accurate with soil temperatures and thermal conductivities that were actually measured in Thargomindah. The main drawback for experimenting at Thargomindah is that it is approximately 860 km west of Toowoomba. This means that significant time and expenses will be required to travel to the testing location (it is approximately a 12 hour drive or 3 hour flight from Toowoomba). If multiple trips were required (quite likely) there would be significant outlay to conduct the testing.

St George

St George, Queensland utilises GAB water for a number of applications and the majority of the bores in the region withdraw water at temperatures of approximately 60 °C. St George is the closest location to Toowoomba (approximately 370 km west of Toowoomba) that has GAB water at such elevated temperatures, so travel time and travel expenditure would be minimised. With the amount of agricultural activity that occurs in and around St George it is likely that a pipeline (either public or private) could be found where a constant flow rate of hot water could be organised for the duration of testing. St George is not as arid as Thargomindah but the climate and geology is likely to be a sufficient substitute for Thargomindah for the purpose of this research.

Locations Chosen

"Tabooba"

After evaluating all the available options it was decided that testing would be conducted on the "Tabooba" property bore, located approximately 75 km south-east of St George. The property bore is located just north of the Barwon Highway (State Route 85), with the exact location shown in Figure 4.1 below.

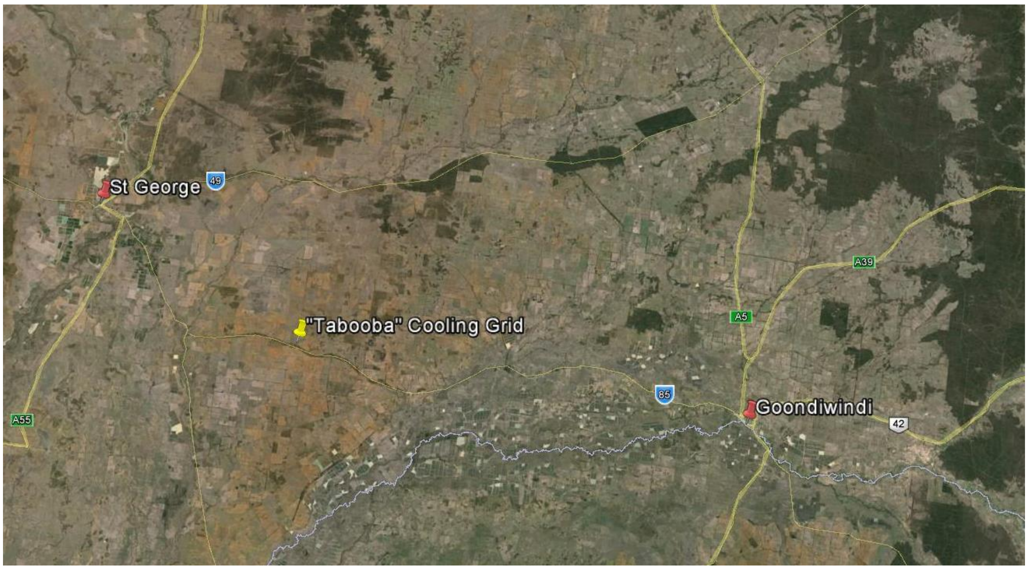

Figure 4.1. "Tabooba" location, just north of the Barwon Highway between Goondiwindi and St George (Google Earth 2014a)

This property has a bore that was sunk approximately 1.2 km into the GAB and has a maximum temperature of 63 °C at the surface (measure prior to capping and piping of the bore). As part of the Great Artesian Basin Sustainability Initiative (GABSI) this property replaced its bore drains with a submerged copper cooling grid and polyethylene pipe network for water distribution. In order to conduct testing, water would be diverted through the underground bypass line, instead of travelling through the submerged cooling grid (see Figure 2.1 for a photograph of the cooling grid). Both the bypass line and the cooling grid supply the distribution manifold (see Figure 4.2 below) that has a number of outlets servicing local tanks, troughs and properties, as well as having a number of currently unused outlets.

Figure 4.2. "Tabooba" distribution manifold

Shown above is the distribution manifold where the cooled artesian water enters to be distributed to local properties. The pipe closest to the camera is the incoming line from the cooling grid, while the nearest pipe on the left of the manifold is the incoming line from the bypass line. All other valves connect outgoing supply lines or currently unused outlets.

USQ "Agricultural Plot"

Due to time limitations a thorough study of underground soil temperature variation could not be completed on-site at "Tabooba". As a result subsequent testing of soil parameters was conducted at the USQ "Agricultural Plot" (see Figure 4.3 below). This testing conducted at this location was limited to soil temperature data at varying depths, and was collected to gain a larger data set.

Figure 4.3. USQ "Agricultural Plot" location on the north-eastern side of Handley Street in Darling Heights, Toowoomba (Google Earth 2014c)

4.1.3 Required Experimentation Outputs

For the reasons outlined above, "Tabooba" outside St George was chosen as the location of the experimentation phase of this research. Experimenting on an existing pipeline will be best as:

- Records of the pipe installation should include the pipe manufacturer, pipe material and nominal pipe size
  - From these values the pipe OD, wall thickness and thermal conductivity should be able to be found from the manufacturer's specifications

- Flow rate and water entry temperature will be able to be measured by incorporating a flow meter and thermometer into the start of the pipeline
- The water exit temperature can similarly be measured using a thermometer at any outlet
- The soil temperature at any displacement away from the pipe will also be able to be measured on-site and then input into the model

The only remaining input is the soil thermal conductivity. As measurement of this parameter requires highly specialist equipment it was decided that the models could be used to calibrate this parameter. The water temperature in the pipeline at a cross-section can be measured, while the temperature at different points in the soil at that cross-section can also be measured. It will be important that the soil be at a steady equilibrium state when experimentation occurs to ensure the measured results give an accurate representation of the system. Using theoretical heat transfer equations with the measured temperatures and distances will allow the soil thermal conductivity to be calculated. All the inputs required for the model will then be known and the model can be run. The shape of the soil temperature distribution will then be used as a “verification” of the model accuracy.

To gain a greater understanding of the importance of burial depth in the design of a Ground Heat Sink pipe Loop (GHSPL) system further data on soil temperature variability at depth was collected at the USQ “Agricultural Plot”. Collecting temperature data at a number of shallow depths, while also observing the temperature difference between grassed and bare earth areas ensured that an informed decision could be made on how to best implement such systems.

4.1.4 Safety and Risk

There is some inherent risk involved with all experimentation. The objective is to minimise this risk and make the experimentation as safe as possible. The experimentation involved with this research project was not viewed as high risk, but control measures were still implemented to minimise the risk that was present. The risk in all activities was evaluated using the following risk matrix.

Table 4.1. Generic risk matrix

		Severity of Consequence				
		Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain					
	Likely					
	Possible					
	Unlikely					
	Rare					

For the purpose of this research all activities were required to have measures put in place to reduce the risk so that it was in the green section of the risk matrix. Risk matrices for all activities, both before and after control measures were put in place can be found in Appendix D.

Travelling

As previously explained there was some travelling required to get to the experimentation site. To reduce the risk involved with this travel (undertaken by car), trips were be limited to daylight hours when the driver was well rested.

Hot Water

The pipeline on which the experimentation was undertaken delivered water at elevated temperatures. Contact with any water was limited to those times where it was absolutely necessary to be in contact. Gloves were used where contact was required with any material of elevated temperature. A first aid kit was also on-site to deal with any burns.

Excavations

The measurement of soil temperatures, pipe depth and pipe flow required access to the pipe to be gained by excavating soil around the pipe. Excavation was limited to locations where it is absolutely necessary, and the size of the excavations was kept as small as possible. Steel capped safety boots were worn at all times while excavating. The measurement of soil temperatures was completed with a spear thermometer pressed into the soil rather than excavating to take these measurements. All excavations were clearly designated and anyone likely to come into contact with these areas was made aware of the excavations. Excavations were be filled in as soon as possible after experimentation finished.

Dehydration

The climate in St George is much warmer than Toowoomba. Experimentation occurred during winter and spring but adequate water, sunscreen and sun safe clothing was still taken on-site to minimise the risk of dehydration and sunburn.

4.1.5 Resource Requirements

The majority of resources that have been required for this research have been freely available from the University of Southern Queensland. Additional resources were sourced for experimentation and these are outlined below. The resources used for non-experimental work include:

- PC with internet access, CD drive and Microsoft Office access
- University of Southern Queensland – Toowoomba Campus library
- MATLAB access

The resources used for the experimentation phase of this research included:

- Transportation
- Non-contact infra-red thermometer
- Cole-Parmer spear thermometer
- HOBO H08-002-02 temperature data logger
- Digital stem thermometer

- Panametrics TransPort^{TM} Model PT868 portable flowmeter
- Vernier calliper
- 5 m measuring tape
- Measuring wheel
- Shovel
- Mattock
- Manual post hole digger
- Straight edge
- Builder’s line and peg
- Hammer
- “Pile driver”
- Zip-lock bags (for soil samples)
- Digital scales
- 25 L esky
- 9 L bucket
- Laptop PC (for data logging capability)
- Chair
- Pen and paper
- Digital camera
- Gloves
- Raincoat
- Steel capped safety boots
- First aid kit, hearing protection, hat, sunglasses, sunscreen and water

As discussed in Section 2.7 the devices being used to take measurements are appropriate to the site conditions, and are widely used for these types of measurement. An ultra-sonic flow meter was used in the experimentation as the initial site visit revealed that the bypass line serves a distribution manifold with many outlets. Of the flow measurement techniques discussed in Section 2.7, the ultra-sonic flow meter was the only method capable of quantifying flows from all outlets. All other methods either required the bypass line to be taken off-line, so a measurement device could be installed or they could only quantify the flow being directly discharged to air at the distribution manifold site.

4.1.6 Methodology Used

The experimental methodology that was implemented was aimed at collecting accurate relevant data for input into the simulation models.

“Tabooba” Testing Methodology

There were two distinct testing methodologies implemented at the “Tabooba” test location. The first methodology was for the initial site visit while the second was for the full experimentation.

Initial Site Visit

The following methodology was implemented during the initial visit to “Tabooba”.

1. Travel to “Tabooba”.
2. Talk to the landholders to ascertain the general site layout, current use of the system, as well as any other relevant information.
3. Travel to the bore location and get familiarised with the site layout.
4. Take photographic evidence of all system components.
5. Measure and record the size of all system components using a vernier calliper (dimensions less than 200 mm), 5 m measuring tape and a measuring wheel.
6. Determine which valves switch flow between the submerged cooling grid and the underground bypass line.
7. Switch flow to the bypass line and flush the bore and bypass line for at least 60 seconds at moderate flow.
8. Take water temperature measurements at either end of the system using the digital stem thermometer.
9. Excavate soil near the approximate location of the bypass line and continue until the bypass line is found (if time permits).

10. Take measurements of soil temperature on the surface and at varying depths.
11. Re-cover any excavations prior to leaving the site.

Full Experimentation

The following methodology was implemented over the three days spent on-site at "Tabooba" to collect data for modelling purposes.

1. Get landholder to switch flow to the bypass line prior to travelling to site.
2. Travel to the bore location at "Tabooba".
3. Regularly measure and record temperature (using the digital stem thermometer), weather and water pressure data on each day of testing.
4. Using the digital stem thermometer regularly measure and record soil surface temperature readings on each day of testing.
5. Excavate a hole to 500 mm depth away from the bypass line.
6. Take a sample of soil from the excavation, seal in a zip-lock bag and place in an esky in the shade.
7. Measure the soil sample mass every 24 hours until the sample is tested to ensure no mass in being lost through water loss.
8. Place the temperature data logger in a sealed zip-lock bag and place this in the bottom of the hole.
9. Re-cover the hole with the excavation spoil and lightly compact.
10. Return to the excavation site at least 25 hours after Step 8 was completed and re-excavate the hole.
11. Remove the data logger and re-cover the hole with excavation spoil.
12. Offload the data logger measurements and save these to a PC.
13. Flush the bore and bypass line for at least 60 seconds at moderate flow prior to any water temperature measurements being recorded.
14. Input appropriate temperature parameters into the ultrasonic flow meter and install on the bypass line pipe where exposed at the distribution manifold.
15. Vary flow through the bypass line and record flow rate given by the flow meter.

16. Verify flow meter data by manually recording the time taken to fill a bucket of known volume.
17. Excavate at the approximate location of the bypass line until the pipe is uncovered.
18. Using the 5 m measuring tape measure and record the depth of the bypass line and take a soil sample from this site.
19. Repeat Steps 6 and 7 with this soil sample.
20. Using the measuring wheel measure and record the length of bypass line based on the approximate alignment given by the uncovered section of pipe.
21. Cover any excavations overnight.
22. Input appropriate temperature parameters into the ultrasonic flow meter and install on the bypass line pipe where exposed at the distribution manifold.
23. Adjust the gate valve on a free outlet to set a constant flow rate through the bypass line.
24. "Pile" holes at regular spacing both horizontally and vertically about the bypass line.
25. Measure and record water inlet and outlet temperature using the digital stem thermometer.
26. Record the flow rate at the start and end of data collection.
27. Using the spear thermometer and digital stem thermometer continue data collection by recording soil temperatures at the depths prepared in Step 24.
28. Analyse the results to determine whether equilibrium conditions were reached.
29. If results of Step 28 indicate that equilibrium was not reached repeat Steps 22 to 27.
30. Re-cover and compact all excavations and switch flow back to the submerged cooling grid prior to leaving the site.

USQ "Agricultural Plot" Testing Methodology

Testing at the University of Southern Queensland "Agricultural Plot" was primarily focussed on gaining an understanding of the spatial variation of soil temperatures. In order to gain this data the following methodology was used.

1. Measure and record temperature (using the digital stem thermometer) and weather data on each day of testing.
2. Using the digital stem thermometer measure and record temperature data for the soil surface on both bare patches and grassed areas.
3. Excavate a hole to 350 mm depth.
4. Place the temperature data logger in a sealed zip-lock bag and place this in the bottom of the hole.
5. Re-cover the hole with excavation spoil and lightly compact.
6. Return to site at least 25 hours after Step 4 was completed and re-excavate the hole.
7. Remove the data logger and re-cover hole with excavation spoil.
8. Offload the data logger measurements and save these to a PC.
9. Repeat Steps 3 to 8 at 500 mm depth and 650 mm depth.

4.2 Project Timeline

The timeline for this research project and the associated modelling and experimentation is shown on the following page.

Table 4.2. Project timeline

Milestone	Due Date	Achievement Date
Project Topic Allocation	12 March 2014	27 September 2013
Project Specification	19 March 2014	18 March 2014
Appropriate Model Chosen	5 May 2014	21 May 2014
Experimentation Location Chosen	26 May 2014	30 July 2014
Project Preliminary Report	4 June 2014	4 June 2014
Experimentation Completed	25 August 2014	3 September 2014
Model Calibration Completed	8 September 2014	16 September 2014
Partial Draft Dissertation	17 September 2014	17 September 2014
System Concept Design	6 October 2014	28 October 2014
Dissertation Submission	30 October 2014	30 October 2014

As seen above, there was some delay in finding an appropriate model and determining a suitable experimental location. These delays did not have a significant effect on the overall project timeline as all mandatory milestones were achieved.

Chapter 5 Results and Analysis

This chapter presents the results that have been gained from experimentation and modelling. Brief analysis of the results is presented which is followed by a discussion of these results in Chapter 7.

5.1 Experimental Results

A preliminary site investigation was held at “Tabooba” on 7^{th} August 2014 and this was followed by experimentation from the 1^{st} to the 3^{rd} of September 2014. The purpose of the initial preliminary investigation was to get familiar with the site layout and to plan for the actual experimentation. Following this visit, three days of experimentation was conducted to gain an understanding of the ground conditions on-site, as well as to collect data for use in the models. Further testing was then also conducted at the USQ “Agricultural Plot”.

5.1.1 Initial Site Visit

In order to gain an understanding of the site where testing would be occurring, a preliminary site investigation was conducted on August 7 2014. The author travelled to the site on the morning of the 7^{th} and spent approximately five and a half hours on-site familiarising and taking preliminary temperature measurements. The results from this investigation have not been presented as there was no formal data collection as such. The aim of the trip was to familiarise with the site layout and plan future experimentation. The purpose of the measurements taken was purely to verify what the author had heard about the site and to gain an understanding of the likely conditions during testing (see Figure 5.1 below). As a result of this initial site investigation a portion of the experimental methodology was altered to account for the observed site conditions (tough soil which resulted in difficulty in locating the bypass line).

Figure 5.1. The natural, relatively undisturbed terrain at "Tabooba"

The photograph above shows the ground conditions at “Tabooba” surrounding the bore and submerged cooling grid. This natural terrain could be described as “areas of natural woodland scattered between vast areas of grass tussocks and bare earth”. The bore head at “Tabooba” is shown in Figure 5.2.

Figure 5.2. Bore head at "Tabooba" and typical ground conditions

5.1.2 Site Experimentation

Experimentation was conducted at "Tabooba" over the period of Monday 1st September 2014 to Wednesday 3rd September 2014. Approximately seventeen hours were spent at the bore, setting up testing apparatus and taking and recording results.

The results that were collected can be broadly classified into three categories. The first set of results that was collected was concerned with determining a soil thermal conductivity value by iteratively using the models with the data collected. The second data set was concerned with determining soil temperature (both mean temperature and temperature variation) at depth. The third set of results was collected to understand the local soil conditions at the time of testing. All of these results have been presented below.

Soil Thermal Conductivity Calibration

The final results of the testing conducted on soil and water temperature and water flow rates are shown in Table 5.1 on the following page. This collection of results was primarily aimed at being used to determine the soil thermal conductivity on-site.

Table 5.1. "Tabooba" test results

"Tabooba" Testing - Day 3		
Date:	03/09/2014	
Test Start:	11.37 am	
Test Finish:	12.08 pm	
Weather:	warm, light westerly winds with moderate gusts	

	Start	**Finish**
Bore Head Water Temperature	56.8 °C	56.6 °C
Distribution Manifold Water Temperature	40.2 °C	40.0 °C
Flow Rate	0.280 L/s	0.285 L/s
Ambient Bare Earth Temperature	29.4 °C	31.1 °C
Ambient Air Temperature	19.6 °C	21.0 °C

Horizontal Distance from Pipe	**Temperature**
60 mm	22.5 °C
140 mm	21.0 °C
190 mm	20.0 °C
240 mm	19.0 °C
330 mm	18.0 °C
380 mm	17.5 °C
490 mm	17.0 °C

Vertical Distance from Pipe	**Temperature**
0 mm	34.5 °C
10 mm	30.6 °C
50 mm	25.9 °C
100 mm	22.0 °C
150 mm	19.0 °C
200 mm	18.0 °C
225 mm	17.9 °C
325 mm	19.0 °C

The collection of results shown above is from one of three separate tests conducted. These are the only results presented as they are the only data set considered reliable enough to be input into the models (see Section 7.1.1 for further discussion on this point).

The pipe properties on which the above measurements were taken are shown in Table 5.2. The outer diameter and thickness shown are based on the minimum specified dimensions given by Vinidex Pty Ltd (2014) who manufactured the pipe used at “Tabooba”. The pipe was measured on-site and the pipe dimensions were consistent with these values. The thermal conductivity value also was an approximation based on literature. Vinidex Pty Ltd (2014) state the thermal conductivity of their pipes is 0.40 W/m.K at 20 °C, but give no indication of how this varies with temperature. Iplex Pipelines (2009) specify that the thermal conductivity of their PE pipes varies essentially linearly from 0.47 W/m.K at 0 °C to 0.37 W/m.K at 70 °C. As the water in this pipeline varied from 40.1 °C to 55.2 °C a value of 0.38 W/m.K was adopted.

Table 5.2. “Tabooba” pipe properties (Vinidex Pty Ltd 2014)

"Tabooba" Pipe Properties	
Parameter	Value
Outer Diameter (OD)	90 mm
Thickness	4.3 mm
Burial Depth (to pipe centre)	395 mm
Length	162 m
Thermal Conductivity	0.38 W/m.K

Equation 2.10 was used to calculate the Reynolds number of the flow during testing. Using values for the water density and kinematic viscosity based on the average water temperature and the water properties given in Roger and Mayhew (1995), the Reynolds number of the flow was found to be approximately 7,700. As this value is less than 10,000 this would indicate that fully turbulent flow had not developed within the pipe at the time of testing (ASHRAE 2005).

Plots of the horizontal and vertical soil temperature variance given in Table 5.1 are shown in Figures 5.3 and 5.4.

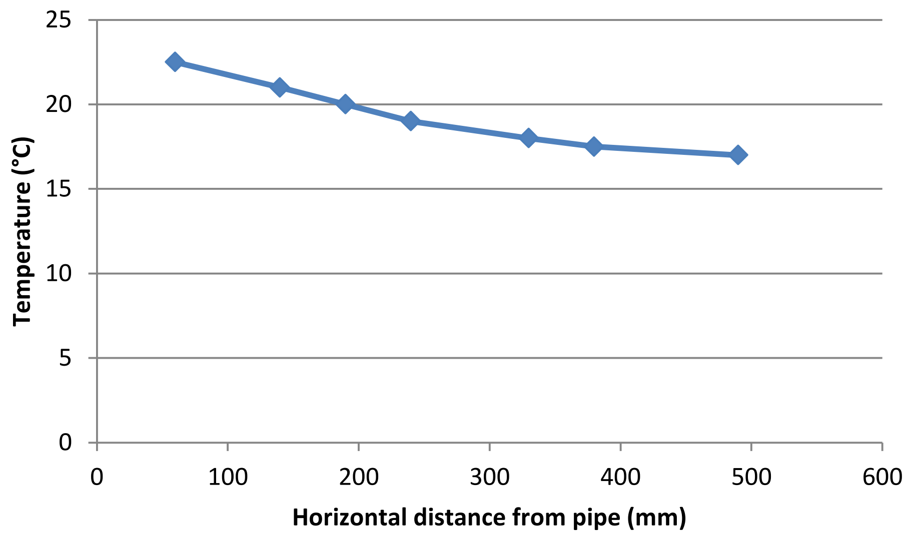

Figure 5.3. Soil temperature distribution moving horizontally away from the pipe

As seen above, the soil temperature drops in an almost linear fashion between 60 mm and 240 mm away from the pipe, before doing the same with a slight decrease in gradient up to 490 mm. The actual measured soil temperature at the pipe depth (350 mm to pipe obvert) not within the area of influence of the pipe was found to be 15.5 °C. Hence even at 490 mm horizontal displacement the water in the buried pipe was still influencing the soil temperature.

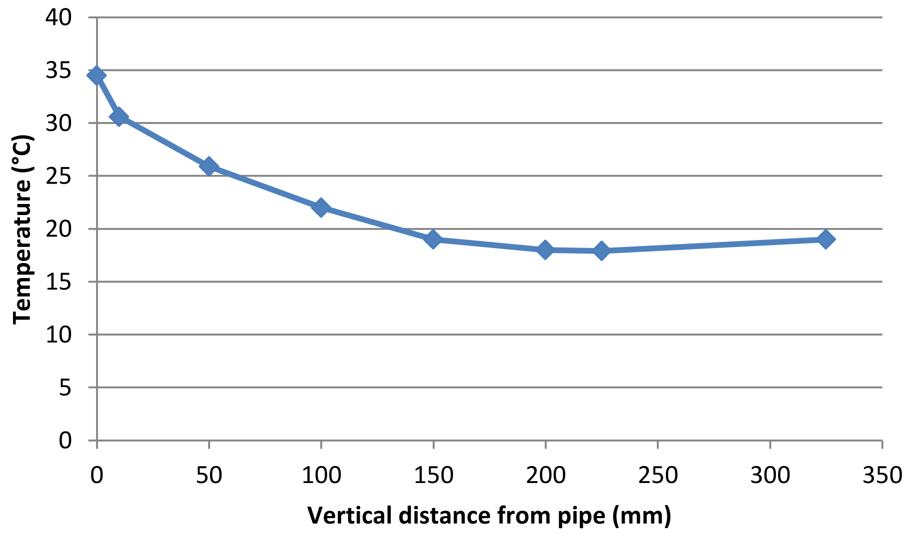

Figure 5.4. Soil temperature distribution moving vertically away from the pipe

The vertical soil temperature distribution mimics an exponential function until the last data point. At this point the temperature stops following the general trend of decreasing as the vertical displacement increases, and instead the temperature increases. Discussion on reasons why this has occurred can be found in Section 7.1.2.

Soil Temperature with Depth

Shown below is the variation of soil temperature at 500 mm depth over a 24 hour period. This test was conducted well away from any pipes, so as to gain an understanding of the ambient soil conditions without any unnatural outside influences.

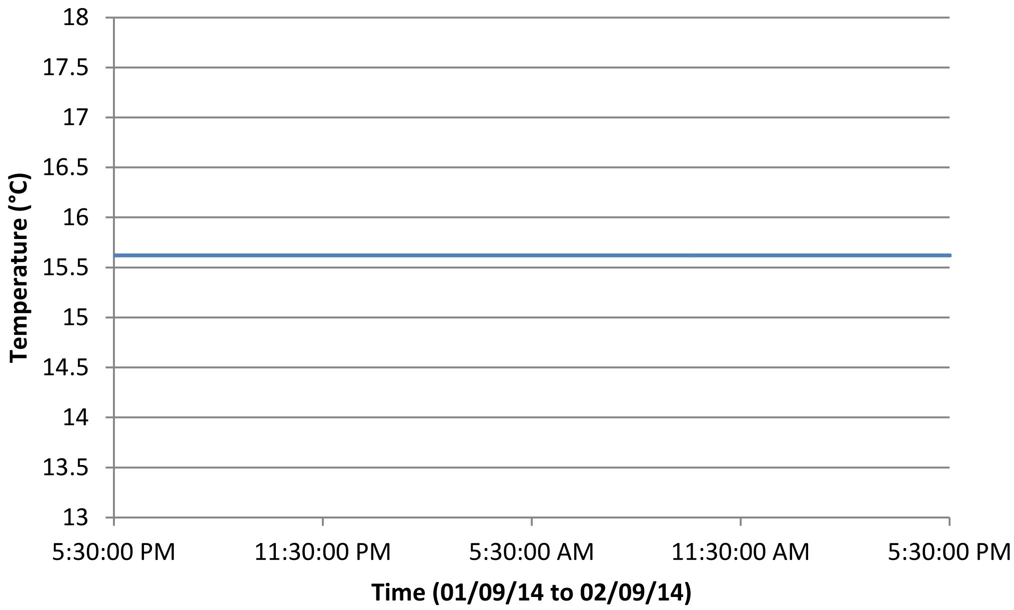

Figure 5.5. Soil temperature at "Tabooba" at 500 mm depth over a 24 hour period

As seen above, over the 24 hour period which the data logger was buried, the soil temperature stayed constant at 15.6 °C.

Other Soil Properties

In order to compare the soil thermal conductivity output from the model, to some of the empirical formula that have been published, a soil type needs to be established. The soil at depth on-site appeared to have high clay content and was quite moist around the pipeline depth (350 mm). The difference in colour between the natural soil surface and the soil at depth is shown in the figure below.

Figure 5.6. Difference between the soil natural surface and excavated soil

This photograph shows the difference between the soil found at depths greater than 150 mm (the darker reddish soil) and the soil on the surface (the pale brown-yellow soil). The pale soil from the surface displayed properties that would indicate it is mainly silt, while the darker soil at depth appeared to have high clay content. Further testing of the soil confirmed these initial thoughts as demonstrated below.

Figure 5.7. Soil sample rolled into a fine thread

Figure 5.7 shows that the moist soil that was sampled around the pipe depth was easily rolled into threads. This behaviour is characteristic of clay soil with medium to high plasticity (Vickers 1984). Figure 5.8 below shows “cracking clay” behaviour that was observed on-site in bare areas that had been recently inundated.

Figure 5.8. "Cracking clay" behaviour exhibited on-site

The behaviour observed above was typical of the larger bare patches on-site. With the soil type identified as being mainly clay, the soil samples that were collected were oven dried for 24 hours to determine the soil moisture content. The results of this testing is shown in Table 5.3.

Table 5.3. Soil moisture content results

Parameter	Soil Sample 1	Soil Sample 2
Location of sample	South of cooling grid (not near pipeline)	Cooling grid bypass line
Depth of sample	400 – 450 mm	250 – 300 mm
Measured moisture content	17.53%	13.88%

A number of empirical relationships used to estimate soil thermal conductivity also require the soil dry density. As soil samples that were collected were disturbed, a highly accurate measurement of the natural soil density could not be made. The disturbed samples taken were however used to give a dry density estimate of approximately 1600 kg/m^3.

5.1.3 Additional Experimentation

Due to various time constraints faced when at “Tabooba”, some soil profile data that was planned to be collected was not able to be measured. This data, mainly relating to the variability of soil temperature at depth, was collected at the University of Southern Queensland’s (USQ) – Toowoomba Campus “Agricultural Plot”.

As presented in the previous section, a temperature data logger was buried at “Tabooba” for a 24 hour period at 500 mm depth to measure the mean soil temperature and any variation. It was subsequently found that the temperature at this depth was constant over 24 hours and was substantially cooler than soil surface temperatures during the day. Additional data of this nature was sought to verify that there is a relatively constant soil temperature at 500 mm depth during spring, and to determine whether 500 mm is an optimal depth to bury a GHSPL system. To collect this data a temperature data logger was buried at USQ to record soil temperatures over a 24 hour period.

On-site experimentation was conducted at the USQ “Agricultural Plot” from Wednesday 10th September 2014 to Friday 10th October 2014. Approximately three and a half hours were spent on-site setting up the experimentation and recording experimental data. The general site conditions at the “Agricultural Plot” are shown below.

Figure 5.9. USQ "Agricultural Plot" ground conditions

Show in Figure 5.9 is the post hole digger used to excavate holes for data logger burial. Conditions at the “Agricultural Plot” could be described as a grassed paddock with patches of bare earth. The red earth that is uncovered in the bare patches is typical of the Toowoomba region.

The results of this experimentation are shown in Figures 5.10, 5.11 and 5.12.

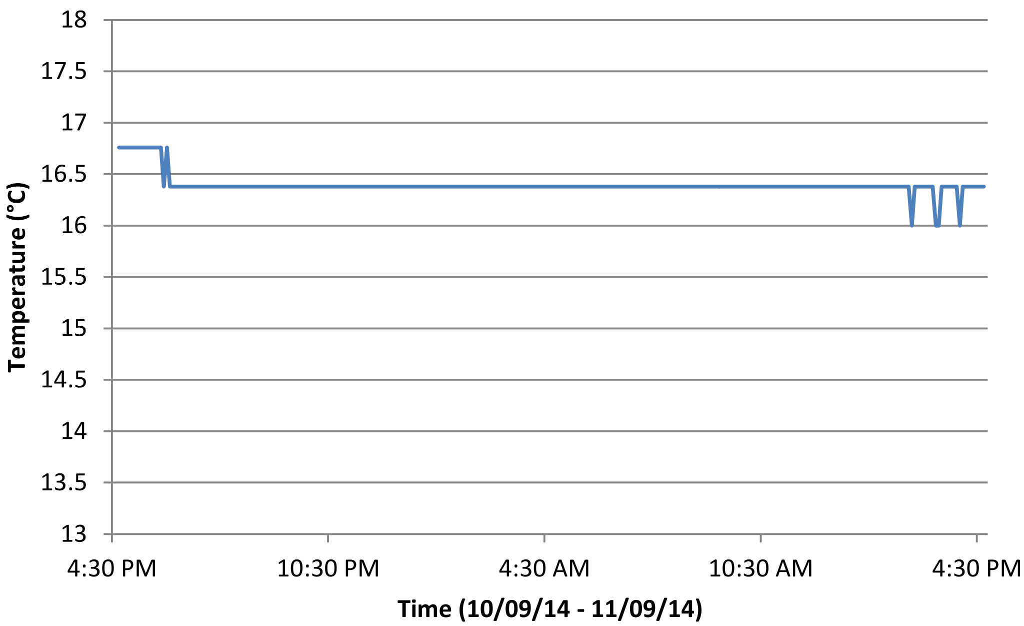

Figure 5.10. Soil temperature at USQ at 350 mm depth over a 24 hour period

As seen in Figure 5.10, after initially dropping to the ambient soil temperature of 16.38 °C the temperature of the data logger held mostly constant throughout the test. The temperature dropped to 16.0 °C between 2.30 pm and 4.30 pm, but on each occasion the drop was for at most two time periods (each time period being 5 minutes).

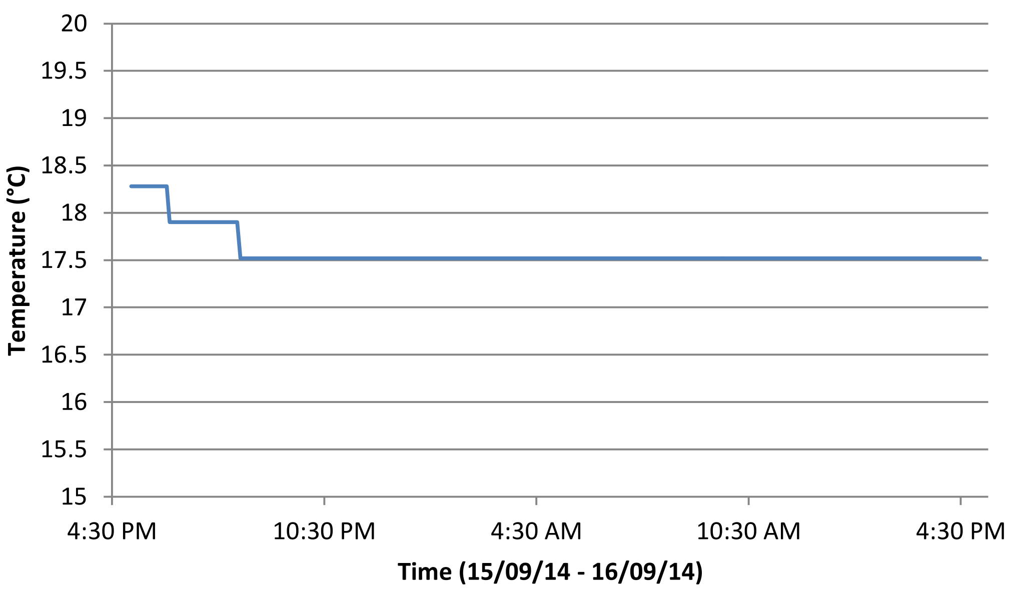

Figure 5.11. Soil temperature at USQ at 500 mm depth over a 24 hour period

At 500 mm depth after initially dropping to the ambient soil temperature of 17.52 °C the temperature of the data logger held constant throughout the test. This is similar to the previous results in that the ambient soil temperature had no variance over a 24 hour period.

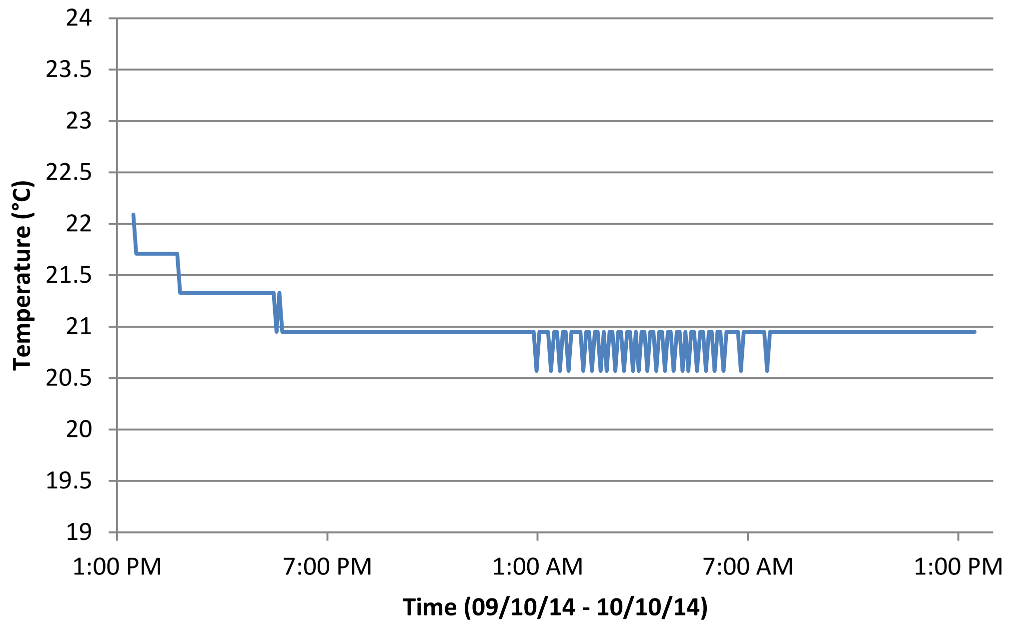

Figure 5.12. Soil temperature at USQ at 620 mm depth over a 24 hour period

As seen in Figure 5.12, after the data logger temperature settled to the initial ambient soil temperature there was little temperature variance, except in the early hours of October 10th. The data logger temperature then settled again at 20.95 °C for the remainder of the test.

Bare Earth Compared to Grass

While extracting the data logger on the 10th October 2014, a number of temperature readings were taken near the surface in both bare earth areas and grassed areas. Figure 5.13 below, shows the digital stem thermometer pressed 25 mm into the soil surface to get a temperature reading of a bare earth area.

Figure 5.13. Soil surface temperature measurement on a bare earth area

The results of this testing have been reproduced in Table 5.4.

Table 5.4. Bare earth temperatures compared to grassed areas

	Bare Earth	Grassed Area
Temperature (35 mm below surface)	38.9 °C	33.7 °C
Temperature (60 mm below surface)	33.4 °C	28.0 °C

As seen above, the soil temperature under the grassed areas was appreciably cooler than under the bare areas.

Soil Conditions

The soil observed at the USQ "Agricultural Plot" was typical of soil found across the Toowoomba region. There are two distinct soil types in and around Toowoomba known to locals as "red" and "black" soil. The soil at the "Agricultural Plot" was "red" soil (see Figure 5.13), and was quite dry while testing was occurring. The soil at USQ had far less clay content than "Tabooba", and was visibly less dense for the first 200 to 250 mm excavated.

5.2 Modelling Result

As depicted in Chapter 3, there were a number of steps that made up the modelling process. Results from the initial sensitivity analysis and parametric study have been reproduced below.

5.2.1 Initial Sensitivity Analysis

Below in Table 5.5 are the results of the initial sensitivity analysis that was conducted using the GHD MATLAB model. The pipe length prior to input variance was 476 m, with the initial parameter values given in Section 3.3.1.

Table 5.5. Initial model sensitivity analysis results

Parameter Varied	% Varied	Pipeline Length	Variance
Pipe OD	+ 10%	457 m	- 3.99%
	- 10%	498 m	+ 4.68%
Pipe wall thickness	+ 10%	485 m	+ 1.89%
	- 10%	467 m	- 1.89%
Backfill (soil) thickness	+ 10%	487 m	+ 2.31%
	- 10%	464 m	- 2.52%
Water flow rate	+ 10%	524 m	+ 10.08%
	- 10%	428 m	- 10.08%
Water entry temperature	+ 10%	538 m	+ 13.03%
	- 10%	406 m	- 14.71%
Soil temperature	+ 10%	498 m	+ 4.62%
	- 10%	456 m	- 4.20%
Pipe thermal conductivity	+ 10%	469 m	- 1.47%
	- 10%	485 m	+ 1.89%
Soil thermal conductivity	+ 10%	440 m	- 7.56%
	- 10%	520 m	+ 9.24%

As seen above, changes to the model inputs have varying degrees of impacts on the required pipeline length. It can be seen that the water flow rate, water temperature and soil thermal conductivity are the most sensitive model inputs.

5.2.2 Model Calibration

A calibrated soil thermal conductivity value was found by using the data collected during testing at “Tabooba” (the data presented in Section 5.1.2) as inputs in the chosen models. By initially using the GHD MATLAB model an estimate for the soil thermal conductivity of 1.95 W/m.K was produced. This value was found by iterating values of soil thermal conductivity to get the length of pipe output by the model to match the length of pipe that was measured on-site for the same output temperature (40.1 °C). The literature on soil thermal conductivity would suggest that this value is reasonably higher than what the author was expecting for this location and soil type (even though the soil was quite moist). For this reason a similar process was undertaken using the QPIPE MATLAB model.

The following values which came from Tables 5.1 and 5.2 were input into the QPIPE MATLAB model:

- Pipe ID = 81.4 mm
- Pipe OD = 90.0 mm
- Insulation OD = 90.0 mm
- Jacket OD = 90.0 mm
- Sand OD = 90.0 mm
- Depth to pipe centre = values in Table 5.1
- Pipe thermal conductivity = 0.38 W/m.K
- Insulation thermal conductivity = 0.38 W/m.K
- Jacket thermal conductivity = 0.38 W/m.K
- Sand thermal conductivity = 0.38 W/m.K
- Fluid temperature = 55.2 °C

- Ground temperature was iteratively determined
- Pipe flow rate = 0.2825 L/s
- Pipe length = 162 m

These values were used to iteratively determine a value for the soil thermal conductivity. As the theoretical soil temperature distribution with distance approximates an exponential function, the vertical temperature variation data was used (this data was previously presented in Figure 5.4). An initial estimate of the soil thermal conductivity of 1.90 W/m.K was input based on the results of the GHD MATLAB model. Next a depth to pipe centre was chosen from Table 5.1 (the initial data point was not used due to the model instability that was discussed in Section 3.2.2), and the ground temperature iterated until the model generated the water outlet temperature that was observed on-site (40.1 °C). This was repeated until all pipe depths were entered and the results were plotted against the observed site conditions. Figure 5.14 below shows the plot of the theoretical soil temperature distribution compared to the observed results with the soil thermal conductivity set at 1.90 W/m.K.

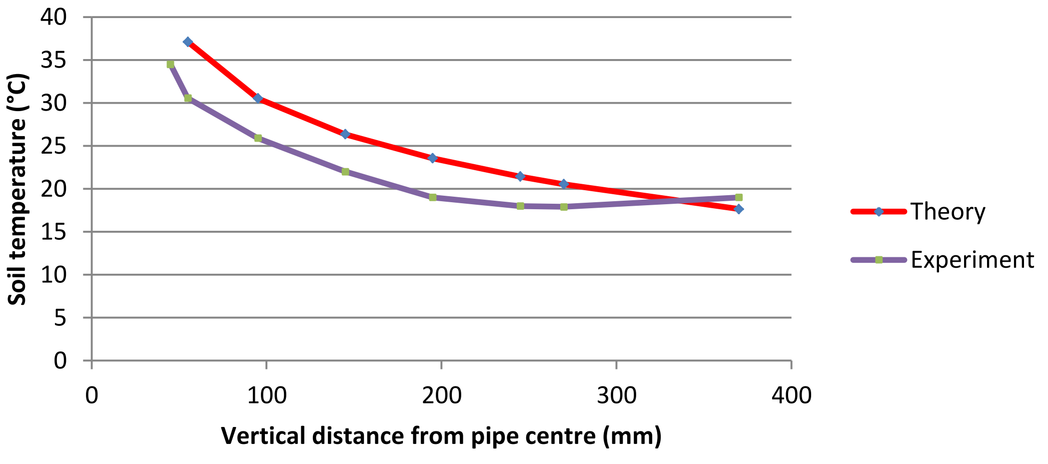

Figure 5.14. Theoretical results compared to experimental results (ksoil = 1.90 W/m.K)

As seen above, the fit of the theoretical data to the observed data is not acceptable. This indicated that a new value for the soil thermal conductivity needed to be used. In this manner the soil thermal conductivity was iteratively altered until the theoretical and observed results had a close fit. A selection of the iterations have been reproduced in Appendix E, with the final adopted value of the soil thermal conductivity being 1.60 W/m.K. The plot of the modelled soil temperature distribution compared to the observed soil temperature distribution at this thermal conductivity is shown in Figure 5.15.

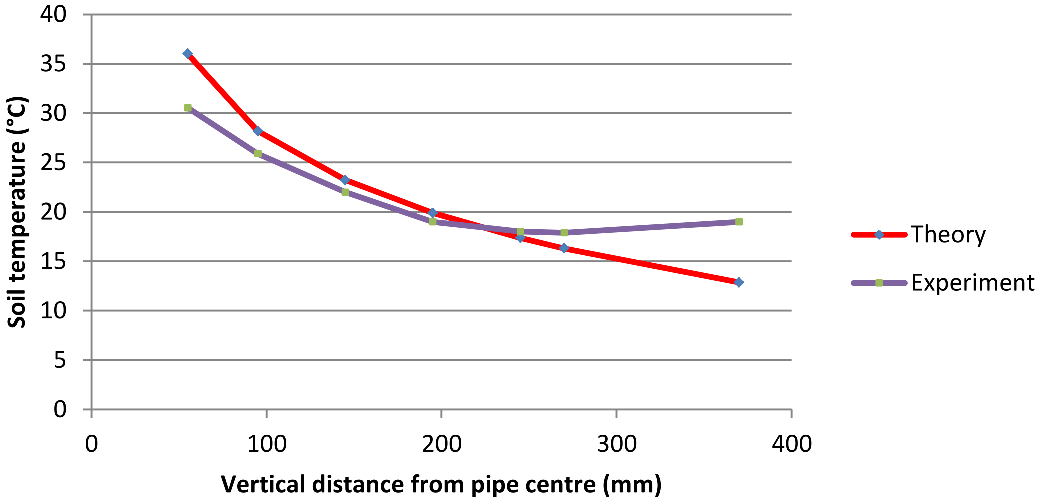

Figure 5.15. Theoretical results compared to experimental results (k_{soil} = 1.60 W/m.K)

As seen above, the results of this modelling would indicate that the soil thermal conductivity at "Tabooba" was approximately 1.60 W/m.K. To an ordinary observer the fit of the theory compared to the observed data that is shown above does not seem to be comprehensive, but the reasons why this fit is regarded as being the best is discussed in Chapter 7.

5.2.3 Model Parametric Study

The methodology of the parametric study was presented in Section 3.3.3. The input parameters that could not be varied (or could be varied but would have the same effect as varying another parameter) were held constant (see Section 3.3.3 for the values these parameters took). The results of the parametric study that was conducted using the GHD MATLAB model are shown below.

Table 5.6. Parametric study results

	Soil Temperature (°C)	Flow Rate (L/s)	Pipe Thermal Conductivity (W/m.K)	Soil Thermal Conductivity (W/m.K)	System Length (m)
Case 1	18	0.2	0.38	1.6	185
Case 2	25	0.2	0.38	1.6	223
Case 3	32	0.2	0.38	1.6	286
Case 4	18	0.9	0.38	1.6	824
Case 5	18	1.6	0.38	1.6	1464
Case 6	18	0.2	17	1.6	154
Case 7	18	0.2	380	1.6	154
Case 8	18	0.2	0.38	1	276
Case 9	18	0.2	0.38	2.2	144

The results presented above are important in understanding what needs to be prioritised when minimising the size of the GHSPL system required. Comparing Cases 2 to 9 to the baseline result (Case 1) gives a good indication of which parameters are most critical to the system design. As shown above, the flow rate (flow velocity) within the pipe has the greatest effect on system sizing. Soil temperature and soil thermal conductivity have moderate impacts, while the pipe thermal conductivity has minimal impact on the cooling system size.

Chapter 6 System Concept Design

The results presented in Chapter 5 indicate that Ground Heat Sink Pipe Loop (GHSPL) systems may be a viable alternative municipal water cooling method. To determine whether this is the case a system concept design was undertaken to provide guidance on the implementation of such a system. The Western Queensland town of Thargomindah was used as a case study for this design.

6.1 Design Considerations

For GHSPL to be implemented in a municipal water supply system a number of objectives need to be achieved. Some of these objectives will be discussed in detail while others were considered to be out of the scope of this project, hence further investigation or research would be required (recommendations for future research is covered in Section 8.2).

6.1.1 Key design considerations

Some of the key considerations of such a system would include:

- Achieving adequate temperature reduction under all flow conditions and flow rates (during peak demand water should still be delivered at 45 °C or less)
- Delivering potable water
- Not using overly large portions of land (system cost)
- Delivering water at sufficient pressure to all properties (minimum static head of 22 m is generally required)
- Addressing mineralisation issues

A prime consideration of the system design that affects most of the above points is the pipe material being used. The aim of this research is to determine a viable alternate cooling technology. To ensure that this alternative cooling technology will be considered alongside the existing cooling technologies, the costs of such a system needs to be competitive. In order to meet this requirement this research project has been primarily focussed on polyethylene (PE) pipes. PE pipes are cheap and readily available across Australia, as well as being easy to install and maintain. The heat transference properties of PE is not ideal, but as found in Section 5.2.3 the pipe thermal conductivity has little impact on system sizing (due to the small proportion of pipe material in any axial cross-section).

The major concern of using PE pipe in a water cooling system is the reduced component life when subject to high temperatures. Depending on the maximum water temperature at the installation location there are a number of options present. Assuming an 80 to 90 °C water temperature (typical of Thargomindah) the followings options are present:

1. Install an alternate pipe material for the initial length of pipe where the water temperature is highest
2. Accept that the design life of the pipe will not be as long as would normally be expected and continually monitor the pipe for failures (as well as having a regular replacement program)
3. Make use of a number of parallel pipe lengths so that all the pipe does not have hot water flowing through it at all times

With heat transfer being driven by a temperature difference, the higher the difference the more rapid the heat transfer. As seen in Figure 6.1 below, the temperature of water along a buried pipe length decreases at a decreasing rate as the water cools. This is a positive as it means that lesser lengths of pipe than what may be expected are subject to the highest water temperatures.

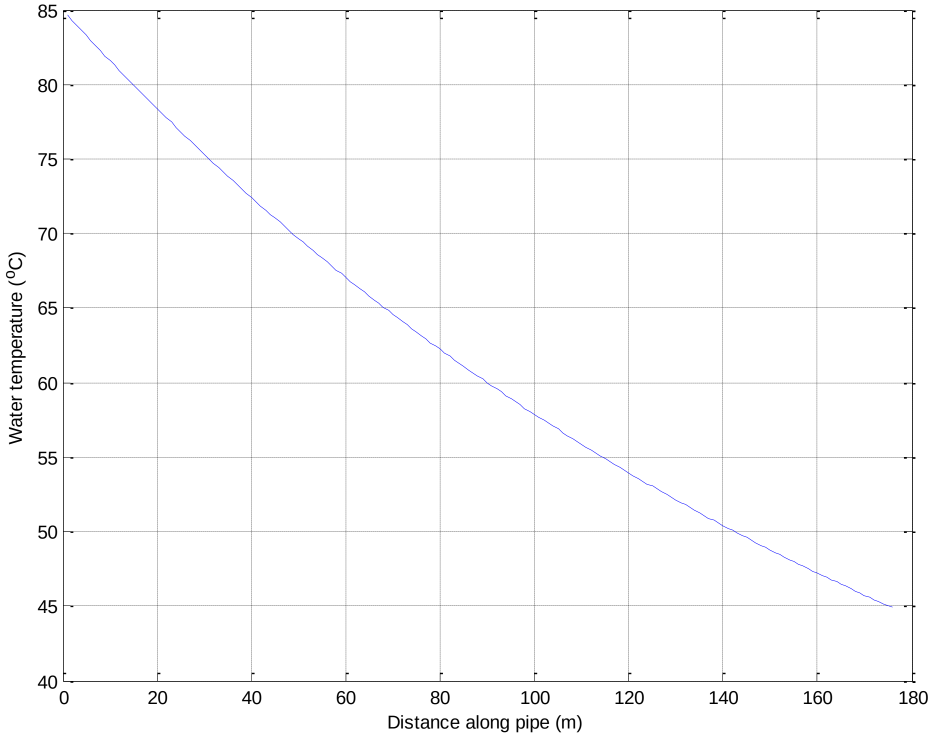

Figure 6.1. Simulated heat loss in a DN90 PE pipe

As per the key design consideration dot points, water pressure is a key consideration, for not only the minimum pressure head requirement, but also for pump selection and use. Where possible the naturally pressurised artesian water should be allowed to flow under its natural pressure in a GHSPL system. Head losses within the pipe network should be minimised to reduce the need for pumping and thus reduce the cost of the system. A full system analysis of head losses would need to be conducted as part of the design process to determine the pumping requirements.

6.1.2 Soil Conditions

The information presented in Section 2.5.2 has large implications on the design of any GHSPL system. As previously discussed, soil compaction has an impact on soil thermal conductivity, with a well compacted, low porosity soil most ideal for effective heat transfer. The depth at which the pipes are buried will impact the system as the mean soil temperature, as well as the temperature range experienced, is greatly affected by this depth. Soil compaction is often greater at depth and water retention at depth is much greater than at the surface, meaning that higher thermal conductivities are likely experienced at greater depths.

Perhaps the most important soil parameter is the soil moisture content. Increased soil moisture content has a threefold impact on the system as it effectively increases the soil thermal conductivity (to a certain point), increases the soil specific heat capacity and provides a natural cooling method through the evaporative cooling effect (see Section 2.5.2 for discussion on the enthalpy of vaporization). All of these impacts are positive with respect to a GHSPL system, hence some form of irrigation should be considered if installing such a system in a hot dry climate (most of the areas with GAB water that requires cooling could be described as having a hot dry climate).

Another consideration for GHSPL systems is ground cover. Ground coverage by grass and other vegetation plays a large role in reducing the amount of radiation received by the soil surface, which in turn ensures the soil stays cooler (this will be most noticeable at shallow depths). The ground cover effectively acts as an insulator and reduces the range of the daily temperature variation (see results in Section 5.1.3).

With all the above in mind a concept design for a GHSPL system was completed.

6.2 Concept Design

6.2.1 Design Data

As previously stated the system concept design is for the town of Thargomindah in Western Queensland. Knowing the location of the design gives an indication as to some of the input parameters that are required to design a GHSPL system. As identified in Sections 1.1 and 1.2 the artesian water at this location reaches the surface at approximately 86 °C and must be cooled to 45 °C before it can be discharged for human use. This gives the inlet water temperature and the required outlet temperature for system sizing.

All of the other design parameters can be somewhat controlled by the designer. The water flow rate will vary with time and the system will have to be designed for worst case flow rate. This parameter can however be managed by installing multiple parallel pipes. This will likely be required as flow velocity in water delivery pipelines is generally designed to not exceed 2.0 to 2.5 m/s. The pipe diameter can be varied to modify the flow velocity, while the pipe thickness will need to satisfy structural considerations. The burial depth and soil temperature parameters can be controlled to a limited extent, though a detailed on-site geotechnical analysis will be required to determine to what extent.

The pipe thermal conductivity is set by the pipe material chosen. As discussed in the previous section, polyethylene pipe has been the focus of this research due to its low cost and ease of installation. While the pipe thermal conductivity is known, the soil thermal conductivity cannot be stated with accuracy. Due to time constraints the author was unable to travel to Thargomindah to collect data that would have allowed determination of a soil thermal conductivity. Soil thermal conductivity was alternatively found for the “Tabooba” property between Goondiwindi and St George. The climate and environment at “Tabooba” is comparable to Thargomindah, but not as extreme. Without detailed knowledge of the soil properties at Thargomindah a soil thermal conductivity value will have to be estimated.

6.2.2 Design

The concept design of the GHSPL system for Thargomindah was undertaken with both models so the results of each simulation could be compared. It was important to use both models as the QPIPE MATLAB model can simulate additional parameters such as a sand backfill, which can provide more information than the GHD MATLAB model.

With the inlet water temperature and required outlet water temperature known the other model inputs needed to be specified. Such a cooling system needs to be delivering water for the whole year at temperatures less than 45 °C. Hence the system should be designed to the worst case soil conditions (summer) with the worst case flow conditions (peak hour flow).

The depth of burial of the pipe was assumed to be 450 mm with a maximum ambient soil temperature at this depth of 31.0 °C. This soil temperature was chosen as the mean maximum annual temperature at Thargomindah is 28.6 °C (Australian Bureau of Meteorology 2014). At 450 mm depth the soil temperature is expected to vary slightly over the course of the year, with the average soil temperature approximating the mean maximum annual temperature. The temperature of 31.0 °C was assumed to be the upper limit of the temperature variation at this depth. The inputs into the model were however set to 290.6 mm distance to pipe with soil temperature at 31.0 °C. Discussion on why this modified depth value was used can be found in Section 7.1.4.

The natural water pressure at Thargomindah determined the pipe thickness required. The pressure experienced at the town bore when it was first drilled was approximately 1200 kPa, which is equivalent to approximately 120 m head (Ryan, I 2014, pers. comm., 25 March). Assuming this pressure to still be present means that a polyethylene pipe of class PE100 PN20 is required (Vinidex 2014). The nominal working pressure of this pipe under standard conditions is stated as 200 m head, however using the Vinidex calculation method, when adjusting for elevated temperature and non-standard installation procedure (ploughing in) this reduces to approximately 145 m head. PE100 PN20 pipe corresponds to polyethylene with standard dimension ratio (SDR) of 9 (Vinidex 2014). With this known the pipe size can be chosen and the required pipe thickness will immediately be known.

Design Iteration 1

In the report that WorleyParsons prepared for the Queensland Department of Infrastructure and Planning (2010) it states that the current cooling system has been designed to cool flows of up to 32 L/s. Examining the Vinidex (2014) polyethylene pipe sizes, to convey 32 L/s and have a flow velocity of less than 2.0 m/s a minimum nominal pipe size of DN200 would be required (if not implementing parallel pipes). With SDR9 pipe the corresponding pipe thickness for DN200 is 22.4 mm. With the pipe thermal conductivity assumed as 0.38 W/m.K (the value that has been used throughout this research for polyethylene under elevated temperatures) the final input parameter required was the soil thermal conductivity. As there was no geotechnical data freely available for Thargomindah a value of 1.60 W/m.K was assumed. This value that was determined for the soil at “Tabooba” is a low to moderate soil thermal conductivity. It is assumed that by compacting the soil at the installation site, and keeping the soil moist, that this thermal conductivity can be maintained (whether or not this is assumption holds true will depend on the soil composition at Thargomindah). Excess or lack of quartz compared to the “Tabooba” site may lead to vastly different values.

The above input parameters were entered into the two models. The QPIPE MATLAB model determined the required system length to be approximately 42.85 km. The GHD MATLAB model determined the required system length to be approximately 42.97 km. This result would obviously rule out GHSPL as a viable alternate cooling technology as the cost to implement such a large system, as well as the amount of land required would be far too great.

The same design parameters were used with flow rates of 4.0 L/s to determine what system size would be required with 8 parallel pipes (each with a maximum flow of 4.0 L/s to give the 32 L/s capacity). This results in pipe lengths of between 5.3 and 5.4 km. This is appears much smaller than the single pipe, but when it is considered that there are 8 pipes of this length, no benefit is gained in terms of system size or cost.

With such a large system size being output a sanity check was conducted on this result. Due to the natural water pressure the whole pipe length will be flowing full. Calculating the volume of water that would then be contained within the 42.91 km pipe length (average of the two sizes) gave a value of approximately 814.9 m^3

(equivalent to 814.9 kL) of water. Daily water usage per person per day varies across Australia, with water usage highest in semi-arid and arid areas. The state of Western Australia has the highest average usage of 493 L/person/day (Planning Institute of Australia 2014). Assuming then that the average Thargomindah resident uses 550 L/person/day (slightly higher to be on the conservative side) with a total population of 470 (WorleyParsons 2010), then the average daily usage is approximately 258.5 kL/day. This figure should be on the conservative side as it is more than double the number of usual residents at Thargomindah which is 206 (Australian Bureau of Statistics 2013). Hence the pipeline described above would hold approximately 3.15 days of average supply. Such a large detention time in the pipeline would mean that all the water would be approaching, or would have reached the natural soil temperature (assumed worst case of 31.0 °C during summer) prior to discharge where water demand remains average. With this result in mind all the input parameters were reviewed.

The water inlet temperature and required outlet temperature have been supplied and hence are as accurate as possible. Pipe dimensions have been based on the assumed flow rate, while the pipe thermal conductivity and soil properties are all known or assumed based on previous experimental results and modelling. That leaves the flow rate as being and pipe size as being the only inputs that can be changed. The pipe size can be increased to reduce flow velocity and give the water more time to be exposed to the heat sink. This option should not be required as the calculations above indicate that the water will be in the pipe for a number of days under average flow conditions. Hence the flow rate that is being used must be responsible for such an unexpected outcome.

A flow rate of 32 L/s is very high when considering such a small population. This flow rate was likely assumed as the peak hour (PH) flow when the existing cooling system was designed. This flow if ever achieved will likely only last for a very short period, hence to design the system to this flow rate is not feasible.

Design Iteration 2

There is currently no storage reservoir in the Thargomindah water supply system which means that all system components delivering water must be designed to handle PH flows. By installing a storage reservoir, and placing the cooling system prior to this component, the design flow rates through the cooling system would only need to satisfy mean day maximum month (MDMM) flow. Different peaking factors are given for MDMM and PH flow, which means that the former flow can be approximated as being approximately 2.4 times smaller than the PH flow in arid areas (Department of Energy and Water Supply 2014). Hence an approximation for the design flow in the cooling system should a storage reservoir be installed, is 13.33 L/s. Preliminary modelling of this flow rate gives system sizes of 17.85 km (QPIPE MATLAB model) and 17.90 km (GHD MATLAB model). Again this system size seems overly large.

Re-examining the theory behind water supply schemes and it is found that in this industry all system components are sized based on the maximum flow conditions that are expected at that component. This deign method has been used thus far for this cooling system, however as long as the pipes are sized correctly for the maximum flow conditions the cooling system itself need not be designed to these flows. The cooling in the pipe is proportional to the time the water spends in the pipe; hence the time variability of flow needs to be considered, not just a single worst case flow rate (which is what is required in the case of conventional water supply design).

Design Iteration 3

Assuming the population and average daily usage figures previously stated are correct and applying the relevant peaking factors for an arid area (the upper values of the range was chosen in all cases) gives the average daily flow rate as 2.99 L/s, the MDMM flow rate as 5.09 L/s, the peak day flow rate as 5.98 L/s and the PH flow rate as 14.96 L/s (Department of Energy and Water Supply 2014). Two system designs were then tested using these figures, rather than the design flow rate quoted in the WorleyParsons report (2010). The first case assumed no storage reservoir and would be designed for a worst case of one hour PH flow followed by constant PD flow. The second case assumed installation of a storage reservoir; hence the required design flow was at MDMM conditions.

For the first scenario the modelling had to occur in two sections. With the flow velocity known (0.79 m/s) from the PH flow rate and pipe dimensions known (still assumed at DN200), the pipe length that would be travelled over a one hour period was modelled (approximately 2.84 km), and the water temperature at the end of this length then used as the input into the second pipe section at the lower flow rate. The system size for this case was calculated to be between 10.08 km (QPIPE MATLAB model) and 9.75 km (GHD MATLAB model). The second case described above was then input into the models. The system size for the case with the integrated storage reservoir was calculated to be between 6.82 km (QPIPE MATLAB model) and 6.84 km (GHD MATLAB model). These system sizes are much more reasonable than what was previously given.

Design Recommendation

With the flow rates quoted in design iteration 3 there were two system sizes determined. Both systems make use of DN200 size pipe, which could be reduced, however the low flow velocities in this size pipe are why the system size is so "small". A number of extra model simulations were run to try and "optimise" the systems presented above. For the case of the system without the storage reservoir by installing four parallel DN200 size pipes the flow rates could be halved and the total pipe length required would be approximately 15.7 km. Doing this for the case with the storage reservoir the amount of pipe required would stay the same (approximately 6.83 km).

The recommended concept design to come from this research is as follows:

- Install a water storage reservoir
- Install a GHSPL system to the following specifications:
    - Use PE100 SDR9 DN200 pipe

- Install four parallel pipe lengths, each length being 1.715 km (space pipes at least 1.5 m apart from each other)
- Install all pipe at 450 mm depth
- Connect the pipes at either end into a manifold
- Have the outlet manifold supplying the storage reservoir
- Regularly irrigate the GHSPL site and encourage grass growth (to maintain the assumed soil temperature and thermal conductivity)

As water supply systems need to be totally reliable and maintain continual supply, there would be benefit gained from installing additional parallel pipe lengths during the initial installation. As parallel pipes are being used, a flow regulation system could be used to have only the first pipe length used until the MDMM flow demand exceeds 1.2725 L/s. After this point flow will be allowed into further parallel lengths. This will maximise the life of the majority of the system (as the hot water reduces the pipe life), as not all pipes will be used at all times. By installing eight parallel pipe lengths rather than four, there is immediately more than enough capacity to be able to deal with the failure of one or more pipe lengths. This ensures the reliability of the system, as well as increases the return interval between needing to re-excavate the area for repairs or replacement.

It is not being recommended that the pipe material be changed, but should the water supply authority require more certainty regarding the system design life PE-X could be used for the initial lengths of the parallel pipes (where the highest temperatures are experienced. A pressure reduction valve prior to the system may also increase pipe life with the hot water.

Installation Location

Shown below in Figure 6.2, is the town of Thargomindah with the bore and current cooling system marked. It is anticipated that the location of the new cooling system would be kept as close as possible to the bore head to reduce overall system cost.

Figure 6.2. Town of Thargomindah (Google Earth 2014b)

Costing

WorleyParsons (2010) assumed a cost of $50 to $100 per metre of pipe for supply and installation when used for underground cooling. Examining more recent costings would suggest that these figures may need to be inflated, though due to the bulk nature of the work some cost reduction is likely (Rawlinsons Publishing 2014). Adopting a figure of $125 per metre of pipe gives an approximate system cost of $857,500 plus fittings and the storage reservoir. If the in-built contingency of eight parallel pipes is used, then this cost would double.

Community Benefits

As previously stated there is much benefit that can be gained from regularly irrigating the soil covering GHSPL systems and encouraging grass growth. This presents a unique opportunity for a town such as Thargomindah. In these arid areas where the artesian water is extracted at high temperatures there is often a lack of recreational facilities. With the system designed with the soil thermal conductivity and soil temperature values that assume the system is irrigated and grassed, this irrigated grassed area could be turned into a recreational facility. As these underground pipe networks do no suffer from the evaporation and seepage experienced by the current cooling methods, this water that is saved from these processes can be used to both improve the efficiency of the new cooling system, while providing the community with a recreational facility.

The recreational facility could be anything from a multi-purpose sporting field, a horse racing track, a golf fairway or any other grassed sporting facility. This facility would benefit the local community as they would get to use the new facility, while the social impact of having a community green area should not be discounted. The green area against the arid backdrop would also likely be popular with tourists, especially if it is developed as a golf fairway or horse racing track.

Issues Requiring Further Investigation

The system concept design that has been prepared was primarily concerned with determining what size GHSPL system would be required to be implemented at Thargomindah. As this research has been primarily concerned on the cooling aspects of such systems, great detail on a number of key considerations has not been provided. A detailed analysis of the water pressure (and head loss in the pipes), soil conditions, water quality and water usage would be required to size auxiliary system components such as the storage reservoir, pumps, water treatment plants and construction methods (the presence of rock may preclude the GHSPL system from being installed at the assumed depth).

6.2.3 System Benefits

When compared to the current cooling system in operation at Thargomindah (see Section 1.3), GHSPL provides a number of benefits:

1. Reduced system operational cost: Current yearly operational costs are in the order of $100,000 (Hayward, M 2014, pers. comm., 7 March)

2. Drastically reduced water losses: The evaporation and seepage losses discussed in Section 2.2.1 are no longer present
3. Increased public safety: there is no longer a drowning risk that is posed by the current cooling ponds
4. Decreased wild animal habitat: without open bodies of water there will be less chance of feral animals (pigs and kangaroos) being sighted in the town
5. Reduced maintenance considerations: the underground pipes do not need to have algal growth and other plant life removed as the current system does
6. Increased use of natural water pressure: less pumps would be required as there are no longer stagnant water bodies that require pumping into and out of a cooling tower

There are still a number of concerns with the operation of GHSPL systems. These concerns include:

1. Initial implementation costs: the system cost seems reasonably high, though ongoing costs will be minimal
2. System design life: these issues have been addressed in the design process
3. System efficiency over time: management of mineral build-up within the pipes and other system components will be required

6.3 Potential Design Applications

While this system concept design has been primarily aimed at supplying a small Western Queensland township, GHSPL systems are equally applicable to a number of other scenarios. The concept design completed in the previous section for Thargomindah is an example only. A full preliminary and detailed design would need to be conducted for this system prior to being implemented at Thargomindah. A complete design process, including data collection (accurate water demand data and local soil data) would be required for any other township investigating implementing such a system.

There are a large number of properties throughout Australia that extract GAB water at elevated temperature for potable and agricultural uses. Many of the existing systems gained funding through the Great Artesian Basin Sustainability Initiative (GABSI) to cap and pipe their bores, while many others also implemented small scale submerged copper cooling grids. The Queensland Department of Natural Resources and Mines (DNRM) were responsible for implementing the GABSI initiative. Such is the demand for GAB water cooling on a domestic scale, Queensland DNRM has a standardised cooling grid design. The problems associated with cooling grids have already been extensively documented, while those properties that are yet to be capped and piped (still have water supplied by bore drains) would experience the water loss and salinisation issues at a much larger scale. The results of this research are therefore likely to interest Queensland DNRM as this presents an alternative water cooling system that they could potentially implement (should the GABSI program receive further government funding in the future).

Chapter 7 Discussion and Implications

This chapter highlights critical information associated with the results reported in the previous two chapters, as well as the methodology used throughout the research. Sources of uncertainty and error are discussed as well as the mitigation measures implemented to reduce these.

7.1 Discussion

7.1.1 Methodology

Modelling Methodology

The methodology that was implemented during this project was sound, but could have been improved in a number of areas. The modelling methodology presented in Figure 3.2 and Section 3.3 ensured that the model was fully understood before it was run with experimental results and applied in a design situation. The careful model selection followed by the initial sensitivity analysis gave insight into the accuracy in which the model parameters needed to be specified. The next stage of modelling was to input the experimental results that were collected specifically for the models. The models were then iteratively used to determine the one system parameter that was not measured on-site. These measured results were then the subject of a parametric study to fully understand the relationships between the input variables and the model output. The model was then iteratively used to determine a concept design of a GHSPL system.

All stages of this methodology worked well and achieved what was originally envisaged. This broad modelling methodology is still viewed to be most appropriate for research of this manner. The more specific modelling methodologies used in the experimental verification and system design are also regarded as still being appropriate. The iterative process used to determine the soil thermal conductivity was the most appropriate way to determine this parameter, while the system design methodology consisted of inputting appropriate system parameters and re-analysing these values to improve the system design. This iterative design process aided in understanding of system intricacies, while performing a basic design optimisation.

Experimental Methodology

The experimental methodology of the initial site visit is viewed as being appropriate. The aims of this visit were to familiarise with the site, understand how the existing cooling system worked, determine how the site could be used to simulate a GHSPL system, while determining the likely variation in temperature data that would be experienced during full experimentation. These aims were achieved, hence the methodology was sound.

The methodology implemented during the full experimentation at “Tabooba” ensured that all the required measurements were taken, though the accuracy of some of these measurements could be improved. Improvements that could be made to the methodology employed at this site visit include:

- Taking undisturbed soil samples rather than disturbed samples so the natural soil density could be determined
- Flushing the underground pipe network for longer periods to ensure steady state or equilibrium conditions are achieved (the soil temperatures around the pipe do not change with time). To achieve this a flexible pipe or hose would be required to be attached to the distribution manifold and the water discharged to a number of different areas to avoid water logging the ground (to achieve complete steady state a large amount of water would need to be used over a long period)
- With the depth of the pipe known, the alignment could have been marked on the surface and the pipe recovered with soil to avoid direct radiation from the sun heating the pipe and the soil around it

- Further experiments could be conducted at varying flow rates to verify the value of soil thermal conductivity determined in the model

The methodology implemented during experimentation at the USQ "Agricultural Plot" ensured that where extra soil temperature data was required it was gained. The main concern with the methodology implemented for this testing was the fact that all the soil temperature at depth readings were taken from the same hole. These measurements were also taken over a period of approximately four weeks, which means that slight variations in air temperature and solar radiation were present in each test. To get the most accurate understanding of the variance of soil temperature at depth over time, three holes should have been dug in close proximity. A data logger could then be placed in each hole and soil temperature readings taken over the same time period. This improved methodology would ensure there is no uncertainty with the experimental results.

7.1.2 Experimentation

The experimental results presented in Section 5.1 need to be carefully examined to determine the accuracy and reliability of the results and any implications this would have on the overall project. All results presented in this dissertation were collected during the months of August, September and October. As the results were collected in late winter and early spring the soil temperature readings would not be close to the worst case temperature experienced during summer. While this does not make the results any less valid it should be kept in mind if conducting similar experimentation in the future.

"Tabooba" Experimentation

The results collected at "Tabooba" were recorded approximately two weeks after a rainfall event of approximately 30 mm (Australian Bureau of Meteorology 2014). This meant that the soil at depths of greater than approximately 200 mm were still quite moist. Digging holes was certainly easier during the second visit to site (the initial site visit was prior to this rain event and the soil was noticeably drier during this initial visit). Again this has little bearing on the accuracy of the results but should be considered during analysis of the results.

To avoid introducing unnecessary errors into the main data set, the hole in which the bypass line was unearthed was recovered overnight. Soil temperature readings in this area where also taken as far away as possible from this hole to try and capture soil with a more natural moisture level (as significant moisture loss would have occurred in the soil that was uncovered).

Water Temperature and Flow Rate Data

While the recorded bore head water temperature was between 56.6 °C and 56.8 °C the water entry temperature used for modelling was 55.2 °C. This value was used as the bore head temperature was measured at an outlet situated on the bore head. The water entering the bypass line was transferred from the bore head in an underground pipe into the pump shed (pipe nearest the camera in Figure 7.1 below) and through the pipe network in the pump shed prior to going underground again into the bypass line (pipe furthest from the camera in Figure 7.1). Various water temperature readings were taken at the outlet from the pump shed and on average the water from this outlet was 1.5 °C cooler than the water at the bore head. Hence the average bore head temperature had 1.5 °C subtracted and this gave 55.2 °C.

Figure 7.1. "Tabooba" pump shed houses dual pumps

The pump shed shown above was not mentioned in the experimental results as the pumps only come into operation when flow rates exceed a certain level (1 L/s for pump one and 3.5 L/s for pump two). As these flow rates were not exceeded during the experimental process, the pumps remained unused during these periods.

The flow rate at the distribution manifold was somewhat controlled by opening one gate valve and discharging water straight into the air. This was done to raise the flow rate as the "base flow" (flow being delivered by the other pipe outlets to tanks and troughs and properties) was quite low (generally reasonably constant between 0.1 L/s and 0.18 L/s). The "base flow" could not be controlled in any way (short of cutting off flow) but was reasonably constant during testing.

Soil Data

The soil temperature distributions both horizontally and vertically moving away from the buried pipe were shown in Figures 5.3 and 5.4 respectively. The theoretical temperature distribution of the soil in this situation is that of an exponential function. As seen in Figure 5.3, the observed horizontal temperature distribution was not of this nature but was closer to a linear distribution. This was an interesting result as it was somewhat unexpected. A temperature reading was taken at the pipe depth at another location not near the bypass line (though still in full sunshine in the same paddock) and the temperature at this point (or the natural temperature at this depth at this location) was recorded as 15.5 °C. There are a number of potential reasons as to why the horizontal temperature distribution did not follow an exponential decay down to 15.5 °C. The reason that is most likely is that the system had not reached equilibrium conditions yet. It is likely that the soil around the pipe was still heating up which is perhaps why the recording near the pipe do not show the exponential growth that was expected (there is further discussion on this equilibrium uncertainty presented below). Due to this unexpected result the horizontal temperature distribution data was not used as part of the modelling process.

The vertical temperature distribution showed a much more expected variance with distance (see Figure 5.4). A general exponential decay trend was observed as the reading progressed further away from the pipe. The obvious anomaly to this data set was the data point taken at the furthest distance from the pipe. This temperature reading was higher than the previous two readings and hence did not follow the general trend of the data. This anomaly is however easily explained. The theoretical models being used are assuming heat transfer between a heat source (the pipe) and a surrounding soil mass (that is essentially a heat sink). This model therefore assumes a single heat source. This assumption does not hold true in the observed data set as solar radiation being absorbed by the soil surface is a second heat source. The final data point in this data set is furthest from the pipe and was in fact taken at 25 mm below the soil surface. Hence this temperature reading would have been greatly influenced by this second heat source, more so than heat from the pipe 325 mm below. So it is this external influence that has caused this data point to break the theoretical temperature distribution trend. For this reason the final data point in this data set was essentially ignored during the modelling process and greater emphasis was placed on matching the model output to the temperature readings closer to the pipe.

The underground temperature data collected over 24 hours at 500 mm depth at “Tabooba” experienced no deviation in temperature. This would indicate that at this depth the soil temperature remains stable on a daily or weekly time scale. Based on the available literature on soil temperature at depth (see Section 2.5.2) this stable observed temperature may slightly increase and decrease throughout the year based on the season when testing occurs. The temperature observed at 500 mm depth was at least 5 °C cooler than the peak daytime air temperature and was significantly cooler than the peak soil surface temperature recorded on-site. This combined with the temperature stability would indicate that this may be a suitable depth for a GHSPL system to be buried at. However as there was no data to compare to (except for soil surface temperatures) a recommendation on an optimal system burial depth could not be made. For this reason extra data was collected on soil temperature variation at the University of Southern Queensland's (USQ) "Agricultural Plot".

Equilibrium Uncertainty

Over the three days on-site at "Tabooba", three data sets were collected for input into the model. The first two data sets were collected on the afternoon of the second day. Due to fading light these data sets were recorded fairly soon after flushing the bypass line. This meant that the temperatures recorded in the first data set were quite cooler than the second data set (taken approximately 40 minutes later). Due to the fact that the water and the soil were still warming up when these tests were conducted these results were not used in any model simulations.

The results that were reported in Table 5.1 were from testing on the morning of the third day on-site. These results were collected approximately 80 minutes after flushing the distribution manifold and getting the water at the outlet up to approximately 40 °C. For the next 80 minutes water was left flowing out the distribution manifold to maintain the soil being warmed by the hot water flow. The flow rate was then adjusted (slightly increased) just prior to testing beginning. As seen in Table 5.1 there was some variance between temperature readings taken at the start and end of the test. The water temperature at both the start and end of the pipeline held reasonably constant, while the air and soil surface temperatures rose as the day progressed.

A selection of soil temperature readings were repeated at the start and end of the test, and where differences were observed the average was adopted and provided in Table 5.1. The majority of the temperature readings at depth slightly increased (all were less than 1.0 °C difference) over time, meaning that at the time of testing equilibrium or steady state conditions may not have been achieved. This may have introduced some error into the results but this situation would be difficult to avoid if this test was to be repeated in the future.

Temperature measurements were taken over a period of approximately half an hour and in this time the air temperature on-site significantly increased. The increase in solar radiation as the test increased may have been responsible for some of the temperature differences recorded, though it is likely that this had little impact on some of the deeper measurements. As previously stated the pipeline had hot running water, at a similar flow rate to that used in the test, for approximately 80 minutes prior to any data being collected. This period of time was used to try and achieve equilibrium conditions around the pipe. This time period was chosen for a number of reasons:

1. At 80 minutes the measured rate of change of soil temperature close to the pipe had decreased significantly.
2. The distribution manifold was discharging straight into air to maintain the flow rate above 0.2 L/s. This water was flowing straight onto the ground and creating waterlogged conditions around the distribution manifold.
3. A significant amount of water had been used trying to achieve equilibrium conditions. The author was not comfortable "wasting" further water for a slight increase in accuracy and reliability of the results.

The baseflow (flows from the manifold that the author could not control) varied but were reasonably constant at 0.18 L/s during the morning of this testing. Earlier in the morning it was much lower than this as it was likely that the troughs and tanks that the system supplies were full, and little to no water was being used in the households that the system services. Hence overnight, particularly during the early morning prior to dawn, flow within the system would have likely been very low or had stopped. It is for this reason that a valve at the distribution manifold had to be turned on each morning to flush the system and raise the water temperature. At the start of each day the water at the distribution manifold would discharge at just over 20 °C, while the bore head would discharge significantly cooler water also. Hence to try to achieve equilibrium temperature conditions in the soil, significant volumes of water had to be used to raise the bore temperature and get this flowing through the full system.

The volume of water held in the bypass line itself was calculated to be approximately 1000 L. All of this water that had cooled overnight had to be discharged and replaced with hot bore water, and a continual flow maintained to heat the soil from its natural temperature of approximately 15.5 °C (measured at pipe depth well away from the bypass line) to around 30 °C which was measured around the pipe during testing. It is recommended that should future testing of this nature be conducted, a flexible pipe be connected to the distribution manifold so that the system can be flushed for longer periods without waterlogging and creating difficult conditions in one spot. Moving a hose or pipe around means that water could be discharged to different areas and the system could be flushed for longer periods. This improved experimentation would decrease the uncertainty about whether equilibrium (steady state) had been reached in the soil.

Error Sources

Critical analysis of the experimentation completed revealed that there were a number of potential sources of error within the test results.

One source of error came from the fact that the temperature measurements were taken by a number of instruments of varying precision. The digital stem thermometer being used recorded temperatures to 0.1 °C, while the spear thermometer dial gauge was in increments of 1.0 °C (meaning that temperatures could only be recorded to the nearest 0.5 °C). Hence some of the temperature measurements taken were not as precise as others. Human error would also be present in the reading of the dial gauge on the spear thermometer.

Like the temperature measurement, the distance measurement was conducted by instruments with varying levels of precision. The main source of error in the dimensions that were measured by these instruments would have been the human error in operating the measurement devices and making the readings.

Prior to experimentation, the digital stem thermometer, the spear thermometer and the temperature data logger were all used to measure the temperature of a common surface at the same time. The data logger and stem thermometer showed close correlation between readings while the stem thermometer was consistently 4 °C lower than the other two instruments. To counter the fact that this instrument had not been calibrated in recent times, all further readings from this instrument had 4 °C added.

During testing all temperature readings were left for at least 45 seconds for the device to settle. In most cases this time should have been sufficient to achieve a settled temperature measurement, however in some cases a longer time period may have been required.

The ultra-sonic flow meter that was used had an in-built program that required a number of inputs so the correct transducer spacing could be used. The transducer spacing depended on the pipe material and size and a number of temperature inputs. While the pipe material and size was known with certainty the actual temperatures during the tests had to be estimated using previously collected data. The wedge temperature (temperature of the surface where the transducers were in contact with the pipe) was input as 25.5 °C, while the fluid temperature in the pipe was estimated as 42.2 °C. With the acoustic pulses performing four traverses prior to being received, the transducer spacing was set at 143.0 mm. This spacing is applies only to these input values and is critical in the calculation of the flow velocity. The water temperature at the flow meter location was approximately 40.1 °C during testing, so there is some error involved with the flow rate measurement. This error is likely relatively small, but any future testing should ensure that more accurate input values are used.

A known error that was present in the data was due to the length of the pipeline at "Tabooba" being based on an educated estimate of the pipe alignment. No "As Constructed" plans were available for the water cooling system; hence measurement of the pipe length was conducted on an alignment that matched the memory of the property owner. As the system was installed a number of years ago (2007) there were only faint remains of where the pipe was ripped into the soil. Due to the uncertainty surrounding the alignment of this pipe the length that has been quoted is likely to only be within 10% of the actual value.

Potential error was introduced by having depth of the pipe being measured at a single location close to the distribution manifold. The bypass line being experimented on was ripped into the soil with a tyne attachment on a bulldozer; hence this depth is likely to be reasonably constant. However greater confidence in the depth that has been quoted would have been gained by unearthing the pipe in at least one other location and averaging the depth measurements.

The horizontal distances recorded away from the pipe are not likely highly accurate as a home-made "pile driver" was used to create a void in which the spear thermometer could be used. The driving of this device was completed with a sledge hammer and hence all the voids created cannot be guaranteed to be vertical. The displacements quoted in the results were measured at the soil surface; hence any deviations from vertical in the pile driving would make these measurements incorrect. Any future testing should use a spirit level to ensure that all measurements being quoted as horizontal or vertical displacements are actually so.

Where the temperature data logger was used to collect soil temperature readings, a hole was dug with a manual post hole digger with diameter approximately 400 mm. This created a hole in which the data logger could be placed (inside a zip-lock bag) and buried. The soil in which the data logger was buried was the excavated soil. The excavated soil was only left for minimal time periods prior to refilling the hole, but during this time the soil would have dried out and expanded. Hence when placed back in the hole this soil would not have had the compaction, or the moisture content of the surrounding soil. This likely introduced some error into the results from the data logger though this error is considered to be quite small.

Overall there were a number of errors that places some uncertainty over the accuracy of the data. Some of these errors were mitigated where possible, while others were either unavoidable or not considered prior to testing. Future experimentation could mitigate many more of these potential errors and improve the confidence in the results gained. Though the results have some uncertainty, no data set is perfect. There were a number of other data sets collected on-site that did not make it into this dissertation because of greater levels of uncertainty surrounding the accuracy of this data. The data that has been presented is the highest quality data that was collected and this data is regarded as being sufficiently accurate to be able to conduct modelling based on these results.

USQ "Agricultural Plot" Experimentation

Three shallow depths at the USQ "Agricultural Plot" had a data logger buried over a 24 hour period to make comparison between the temperature stability and relative temperature drop (compared to the soil surface) at these depths. The depths chosen for comparison were 350 mm, 500 mm, and 650 mm (due to tough ground conditions the final test was actually conducted at 620 mm rather than 650 mm). Based on the available literature on soil temperature at depth (see Section 2.5.2) 350 mm was regarded as the minimum burial depth. Any depth shallower than 350 mm would likely have natural soil temperature that is quite variable on both a daily and yearly scale and this would be detrimental to the operation of a GHSPL system. Depths below 650 mm were not tested as one of the benefits of being able to implement a polyethylene GHSPL system is the ease of installation by ripping the pipe into the soil. At depths much greater than 500 mm this installation method becomes less feasible and more expensive installation methods are required.

As seen in Figures 5.10, 5.11 and 5.12, the temperature of the data logger at each depth took some time to cool to the natural soil temperature. Once settled at the soil temperature there was then little to no variation in temperature for the remainder of the 24 hours. Where variation occurred it was always at most one temperature increment lower than the “constant” temperature (as the data logger measured temperature increments of degrees Fahrenheit). This means that on a daily level the temperature variation at all three depths is minimal to none. Based on the available literature on soil temperature at depth (see Section 2.5.2) the deepest soil depth is likely to have the least temperature variation over a full year. Hence there is limited daily temperature variation at all the depths tested, while annual temperature variation favours the deeper scenarios. Examining the temperature at which the data logger settled at, and it can be seen as the depth increased the temperature also increased. This trend was not expected as the literature suggests that for shallow depths, as the depth increases the temperature drops. It is only once medium depths between 1 m to 2.5 m are reached that this trend reverses. Some of the reasons why the temperature trend was opposite to what was expected may have been due to:

- The same location was used for all tests. The soil that was excavated and placed back into the hole may have been at lower moisture content than the surrounding undisturbed soil, which may have allowed this soil to heat up more quickly than the surrounds.
- There was approximately one month between the first test (350 mm depth) and the last test (620 mm depth). The average daytime temperature during this period was on the rise and hence the whole soil body may have been heating up due to the seasonal variation in solar radiation.
- The soil at USQ (which was quite dry) may act differently to other soils and have the temperature gradient reverse at much shallower depths
- Any combination of the above

The daily air temperature variations recorded at the USQ “Z Block” weather station during these tests are shown below.

Table 7.1. Air temperatures during soil temperature measurement at USQ "Agricultural Plot" (University of Southern Queensland 2014)

Test	Dates	Maximum Temperature	Minimum Temperature	Range
350 mm depth	10/09/14 - 11/09/14	22.6 °C	13.1 °C	9.5 °C
500 mm depth	15/09/14 - 16/09/14	24.2 °C	13.6 °C	10.6 °C
620 mm depth	09/10/14 - 10/10/14	23.4 °C	12.5 °C	10.9 °C

As seen above, the maximum, minimum and temperature range were reasonably similar for all of the tests conducted. Hence it is most likely that a combination of the points outlined above was why the soil temperature seemed to increase with increased depth below 350 mm.

From the results presented, and the literature available on soil temperature variation at depth, it would appear that depths of 350 mm to 500 mm would be appropriate for a GHSPL system installation. Ideally prior to implementing such a system further soil temperature testing would be conducted during the critical summer months. The soil temperatures recorded at these depths were 6 to 7 °C cooler than the maximum air temperature recorded during the test period. It would be favourable to observe what the differences are during the critical design period.

7.1.3 Modelling

There was a large amount of modelling conducted during this project. Comprehensive analysis and discussion of all modelling activities cannot be provided as not all modelling was presented in this dissertation. The sources of uncertainty in the modelling conducted was the primary focus of this section.

Model Comparison

The difference in outputs between the two models given in Section 3.2.1 was not unexpected. The differences in model computation methods means that some difference in output is inevitable. The GHD MATLAB model uses a varying rate of heat transfer along the pipe length, which is based on the segmenting of the pipe. The

QPIPE MATLAB model takes a different approach by assuming one heat transfer rate based on the average temperature within the pipe. Figure 6.1 shows the variance of temperature along the pipe length, and as the relationship is not linear this averaging used in the QPIPE model introduces some error. Though the models used different computation methods, the system sizes determined by the models in Section 6.2.2 had very little variation.

Initial Sensitivity Analysis and Model Parametric Study

As seen in Sections 5.2.1 and 5.2.3, the parameters input into the GHD MATLAB model had varying effects on the model output (pipe length required). The effect of these inputs is important, as these variables were required to be modified (where possible) to reduce the overall size of the GHSPL system required.

From the initial sensitivity analysis results presented in Section 5.2.1, it can be seen that the most sensitive input parameters are (in descending value):

1. Water entry temperature
2. Water flow rate
3. Soil thermal conductivity
4. Soil temperature
5. Pipe OD
6. Backfill (soil) thickness
7. Pipe wall thickness
8. Pipe thermal conductivity

From the above it can be seen that the water entry temperature, water flow rate, soil thermal conductivity and soil temperature all needed to be specified with certainty. Small changes in the precision of these inputs resulted in moderate changes in the model output. Hence for all modelling conducted after this sensitivity analysis these values were specified with as much certainty as possible, as incorrect values for these parameters could lead to the system being greatly over-designed or under-designed.

As seen in the results of the parametric study (see Section 5.2.3), the water entry temperature has the largest effect on the system length, yet this parameter will be fixed based on the installation site. The water flow rate has the second largest effect on pipe length and will vary with time based on water demand. The flow rate in the cooling system could potentially be controlled by having a number of pipe loops in parallel and turning loops on and off based on real time water demand (as was recommended in the concept design to manage the system size and design life). The soil thermal conductivity will be somewhat fixed based on the location of the installation. That being said the soil thermal conductivity is dependent on soil moisture content and density (as discussed in Section 2.5.2), and both these properties could be altered.

The parametric study revealed that the soil temperature has a moderate effect on pipeline length. This parameter could be varied by burying the pipe at a different depth in order to seek a lower temperature. The pipe OD can also be varied, but only to the extent that appropriate flow conditions are maintained within the pipe (flow velocity less than 2.0 to 2.5 m/s). The backfill (soil) thickness is the distance from the pipe that the soil temperature reading is taken, and hence cannot be manipulated to get a more positive outcome. The pipe wall thickness will vary based on the grade of pipe used and hence may be altered to achieve a smaller pipe length (though strength requirements will govern the range of possible variance).

The parameter having the least effect on the pipeline length was found to be the pipe thermal conductivity. This outcome was expected as the literature presented in Section 2.5.2 generally concluded that soil thermal conductivity had a much greater impact on system design than pipe material selection. Though a higher thermal conductivity will reduce the required pipe length, there will only be significant change with very large pipe thermal conductivity changes. Dramatic increases in pipe thermal conductivity (in the order of 1000 times) can be gained from using metal pipes rather than plastic. The parametric study shows that the significant expense of using metal pipe may be better spent on irrigating the pipeline to aid soil temperature and soil thermal conductivity as these parameters have a much greater impact on system sizing (though metal pipes or another alternative material may be required in systems where the water temperature is at the higher end of the scale to give adequate system life).

The most intriguing outcome of the parametric study was the effect of the varying flow rate. The range of flow rates simulated (0.2 L/s, 0.9 L/s and 1.6 L/s) had Reynolds numbers of 9,186, 41,337 and 73,487. The GHD MATLAB model assumes laminar flow for Reynolds numbers less than 10,000 and turbulent flow above this. This value of 10,000 was chosen as the delineation between the two flow regimes based on advice given in ASHRAE (2005), though 4,000 is commonly used (Nalluri & Featherstone 2009; Chadwick, Morfett & Borthwick 2004). The model then assigns a Nusselt number using one of two different formulas, the choice of formula dependent on the flow regime. This Nusselt number is then used to determine the convective heat transfer coefficient for the fluid within the pipe.

The change in Nusselt number and hence convective heat transfer coefficient (as the relationship between these parameters is linear) is quite dramatic when changing from laminar to turbulent flow. Depending on pipe dimensions, changes in convective heat transfer coefficient can be from 72 $W/m^2.K$ to 396 $W/m^2.K$ when going from a Reynolds number of 9,983 to 10,019. This increase in the convective heat transfer coefficient, that is a result of the turbulent flow having no laminar layers develop at the pipe boundary (which can act as a barrier to heat transfer occurring throughout the whole fluid section) was expected to be critical in the design of GHSPL systems (see discussion in Section 2.6.1). After extensive modelling was completed this was found to not be the case, in fact the opposite was often observed. Such is the effect of the flow velocity, when this is increased to get the flow into the turbulent region, the pipe length required for cooling increases. The convective component of the heat transfer in comparison to the conductive components through the pipe walls and into the soil is actually quite small. So the increase in convective heat flow is offset by the much larger effect of decreasing the time the water spends in the pipe. This was an interesting outcome of the research, and the experimentation conducted at “Tabooba” was completed under laminar flow conditions, yet the heat transfer in that system was still quite effective. It is likely that only under extremely slow flow conditions (very small Reynolds numbers) that the effect of laminar flow boundary layers preventing heat transfer will be observed.

Model Calibration

The calibration activity that was conducted to determine the soil thermal conductivity was based on iterative use of the QPIPE MATLAB model. After a number of iterations 1.60 W/m.K was adopted for the soil thermal conductivity. As seen in Figure 5.15, the fit of the experimental data to the observed data does not seem to be close. The reasons why this value was adopted were:

- As previously discussed, the experimentation was occurring as the soil was still heating. It is assumed that as this progressed the experimental temperatures recorded close to the pipe would have increased, giving a closer fit to the model output.
- The experimental results furthest from the pipe were taken quite close to the soil surface. As a result these measurements were receiving heat from the pipe below and the sun above. The models cannot handle this second heat source, so removing this would drop the temperature of the experimental results and move them closer to the model output.

User Experience

While both the models used are simple, easy to understand models, the user requires knowledge of the underlying model theory to effectively make use of these models. For example, consider a case where the user has a measured surface temperature and they wish to know what depth to bury their cooling system at. In this case the model could be initially run with an arbitrarily chosen depth and then again with a number of depth variations. The model will output that the shallower depth requires a smaller cooling system, even though the ambient soil temperature at the shallower depth may in fact be warmer than at the original system depth. This demonstrates why that with any model, even simple models such as those used in this research, complete understanding of the model purpose and underlying theory is required.

Model Performance

Overall the performance of the models was adequate for the purposes of this research. The models were used to iteratively output a soil thermal conductivity value based on measured experimental data. This model use was completed without any model validation. The theory on which the models are written is well established heat transfer theory. Heat transfer can be a complex phenomenon meaning that highly simplified models such as the ones being used may not always provide accurate results. Future work may be required to ensure the validity of these models by actually measuring soil thermal conductivity directly and comparing this to the values output by the models.

Model Assumptions

Both of the models being used could be described as one-dimensional models. Both models assume that no heat transfer occurs along the longitudinal axis of the pipe. It is assumed that the heat transfer is driven by a temperature difference between the fluid in the pipe and a single point axially displaced from the pipe. This assumption effectively places a circle around the pipe with every point on the circle radius assumed to be constant temperature. The heat transfer is therefore constant in every direction axially away from the pipe. This will not occur in real life as the temperature distribution of the soil, particularly in the vertical direction, may vary due to radiation influences. This means that every point on this imaginary circle will in fact have a different temperature. This difference in temperature gradient means that heat transfer will not be uniform throughout the soil profile (i.e. more heat will be transferred to the cooler soil areas). The only time when each point on this circle may have the same temperature is after the system has reached steady state, and the pipe is buried at sufficient depth to not be overly affected by solar radiation. As the flow within the pipe will continually change due to the natural diurnal water usage pattern, this steady state may not be reached for extended periods. The consequential result of this one-dimensional heat transfer assumption is that the model cannot handle the impact of a second heat source (solar radiation). Hence these models should only be used when the pipe is buried at appropriate depth such that the daily soil temperature does not vary significantly (i.e. should not be used for extremely shallow pipe burial).

7.1.4 System Concept Design

Preliminary modelling results would indicate that GHSPL systems are feasible where the peak water usage can be managed. As previously discussed the most important parameter in designing these systems is the flow velocity (essentially the water detention time). The longer the water stays in the pipe the more opportunity there is to transfer the fluid heat to the heat sink (soil), meaning that low velocities or long pipe lengths are required. As long pipe lengths add to the system cost, the preference is to lower the flow velocity by implementing larger pipe diameters or parallel pipe systems.

As mentioned in the previous chapter, it was assumed that the GHSPL system was to be buried at 450 mm depth, with the ambient soil temperature at this depth peaking at 31.0 °C in summer. For the reasons discussed above the user cannot just input a soil surface temperature and a depth when designing the system. Instead the ambient soil temperature at the burial depth can be used and the distance to this from the pipe where the soil returns to this temperature used as the displacement input (rather than burial depth). The experimentation at “Tabooba” found the natural soil temperature at the depth of pipe burial to be 15.5 °C (measured well away from the actual pipe, so as to not have this affecting the results). The model was then iteratively used to estimate a soil thermal conductivity for this location, with the result found to be 1.60 W/m.K. Inputting this thermal conductivity back into the model with the soil temperature at 15.5 °C and iterating for pipe displacement, led to 290.6 mm being found. This was the displacement of the soil temperature reading away from the pipe, were the modelled soil temperature matched the observed natural soil temperature. Essentially this was the models determination of the area of influence of the pipe on the surrounding soil. It is for this reason that 290.6 mm was used as the distance to the pipe in the concept design, rather than the actual pipe burial depth.

All the design iterations completed have been either based on flow data from another source (WorleyParsons 2010) that does not describe why this value was chosen, or from assumed flow values. As this was a concept design these parameter values were accepted, however to complete a preliminary and detailed design of such a system a detailed water demand analysis would be required to determine what the design flow rate should be. The concept design completed is a greenfield design based on a great number of assumptions. This concept was completed purely for the purpose of determining the feasibility of this alternate cooling technology.

From the system size output it would appear that this technology is feasible for implementation, especially in municipalities where the water temperature may not be as extreme as Thargomindah, or where the water demand is not overly large. The size and cost of the system seems quite large, though when compared to the implementation costs of current systems (in the order of $400,000 to $500,000 in the years 2007 and 2008) quoted in WorleyParsons (2010), the cost is put back into perspective. The system size that was found is of some concern, though it is hoped that with further research, and more reliable design data, a more refined concept or preliminary design would be able to be generated.

Assumptions

As previously detailed in Chapter 6, there were many assumptions used to develop the concept GHSPL system design for Thargomindah. There was a lack of design data freely available for this site, hence much of the data that was required to be input into the models had to be assumed.

The soil thermal conductivity for the Thargomindah concept design was assumed to be the same as that found for the “Tabooba” test site. The semi-arid environment at “Tabooba” is likely not as extreme as at Thargomindah, yet the proposed Thargomindah design would use soil compaction and regular irrigation (to try and raise the thermal conductivity to 1.60 W/m.K if not naturally so) to maintain the soil thermal conductivity as high as possible. Ultimately the soil composition at

Thargomindah will determine how close the actual thermal conductivity is to the assumed value, so without data on this a value had to be assumed. The value of 1.60 W/m.K is neither overly high nor low, so it is anticipated that the actual value should be close to the assumed value.

The soil temperature properties (temperature and distance to pipe) were assumed based on soil temperature literature and observations made during experimentation. The pipe was assumed to be buried at 450 mm depth which means that the soil temperature is likely reasonably constant with the maximum summer soil temperature a couple of degrees warmer than the annual mean maximum air temperature. For this reason this method of approximating the soil temperature was used.

The final major assumption in the design was of the system flow rate. Initial design used a design flow rate quoted by an external source (WorleyParsons 2010), however it was determined that this flow rate was likely a maximum possible flow rate that the bore can supply. This would mean that the system would not be required to continually operate under these conditions. A new flow rate was determined based on a daily water use assumption (which was based on actual flow data for Western Australia, much of which has a similar climate to Thargomindah) and peaking factors given in Queensland's water supply planning manual (Department of Energy and Water Supply 2014). Two system designs were made based on this flow assumption, the designs differing based on whether a storage reservoir would also be installed.

Design Outcome

Both the flow rates used in these designs were chosen based on conventional water supply theory, as well as trying to minimise system sizing while trying to ensure that adequate cooling is achieved under all flow conditions. The system designed may not always cool the water to the required temperature (the current system also has this problem), but it can be said with confidence that the return period between these system deficiencies will be quite large. The only way to ensure complete cooling during all flow situations is to design the system to the maximum bore flow rate and this is quite irresponsible and wasteful (the system would be so over-sized that it would essentially never reach capacity).

The concept designs that were reached (with and without a storage reservoir) are viewed as being appropriate cooling systems. The final flow rates that the systems were designed to are much lower than the alleged design flow rate of the current cooling system; however these designs are still viewed as being reliable cooling methods. The design with the integrated storage reservoir has a lower flow rate (flow which is based off an assumed daily use) as with the cooling system installed prior to the storage reservoir the actual worst case flow through the system will be reduced (the storage reservoir acts as a buffer during times of peak flow). Advantages of integrating a storage reservoir include having a central location to perform water treatment, as well as having extra cooling occur within the reservoir. The second design assumed PH flow for one hour followed by peak day flow thereafter. This was used as it is impractical to design a cooling system to continually cool a flow that may only occur for 5 minutes every year. A reliable cooling system can be designed by using much lower flow rates, due to the fact that flow demand continually changes throughout the day and year. This design without the storage reservoir is equally appropriate (though uses much more pipe), but it was recommended that a reservoir be installed.

As previously stated the designs that have been produced are not guaranteed to sufficiently cool the water supply every second of the system life; however the chance of the water demand being elevated for such long periods that the cooling system does not cool the water to 45 °C is sufficiently small. It should be remembered that the systems have been designed for worst case conditions that continue for at least an hour. For the majority of the day during peak consumption and the vast majority of time during non-peak water consumption the water will be supplied at temperatures much lower than 45 °C. For example if the average flow rate during night and early morning is 0.5 L/s the water will be cooled to 45 °C within the first kilometre of the pipeline and the remaining pipe length will be cooling the water to much lower temperatures. Essentially the water could reach the ambient soil temperature overnight and be discharged at this temperature in the morning until the whole pipe system has been flushed of this cool water. This natural storage contained within the pipe will ensure that the vast majority of time that water is discharged it will have temperatures less than 45 °C.

Mineralisation

One of the primary concerns with implementing GHSPL is mineralisation management. The current system at Thargomindah has two cooling ponds and a third pond just to manage the minerals evaporating out of the bore water. The photograph below shows deposits that have been left in one of the Thargomindah cooling towers.

Figure 7.2. Mineral deposits developed at the base of one of the cooling towers at Thargomindah (Ryan, I 2014, supplied photograph, 25 March)

To implement an underground pipe network to effectively promote heat transfer there cannot be substantial mineral build-up occurring at the pipe walls. The build-up will reduce the flow area which will increase flow velocities and hence decrease the efficiency of the cooling system. The photograph below shows an extreme case of mineral build-up on the walls of a pipe that was installed at Winton.

Figure 7.3. Mineral build-up on the inside of a pipe at Winton (Ryan, I 2014, supplied photograph, 25 March)

The location of experimentation also showed less extreme mineralisation issues. The water at "Tabooba" was not noticeably high in total dissolved solids, but had a reasonably distinct smell that was exacerbated at higher temperatures. The photograph below shows staining on a sink at "Tabooba" that can likely be attributed to the minerals present in the water.

Figure 7.4. Staining on a sink at "Tabooba" due to water with a high mineral content

This mineralisation due to high total dissolved solids in the artesian water has the potential to cause large issues with the proposed cooling system. As the dissolved solids often precipitate out as the water cools, and this is occurring within the buried pipes, maintenance for any issues that arise will be difficult. For this reason preventative measures rather than maintenance is the preferred option.

Analysis of water samples at any location where water is being cooled will be required to determine what minerals are causing the deposition issues. It is likely that water hardness is quite high (high levels of dissolved Calcium and Magnesium). Should hardness be the issue treatment methods include water softening or ion exchange (Aravinthan & Yoong 2014). Further proposed water treatment methods without the results of a detailed water analysis would just be speculation. Complete water treatment design for these cooling systems was not in the original project scope, hence why it has not been investigated in detail.

7.2 Consequential Effects

This research or more specifically the outcomes of this research are likely to have some implications for Great Artesian Basin (GAB) water suppliers across Queensland. The outcomes of this research are also likely to interest the agricultural community who also tend to cool their hot GAB supplies. This research was aimed at determining the viability of Ground Heat Sink Pipe Loops (GHSPL) for municipal supplies. As stated above, GHSPL systems have been judged to be feasible, depending on the particular site being investigated for implementation.

With this alternate technology being regarded as feasible, this research may be used to educate those who hold an interest in municipal water cooling (or domestic water cooling). It is hoped that further research will be conducted on the application of GHSPL to this problem so that confidence in this cooling method will increase. Appendix F contains ethical considerations of this research.

Chapter 8 Conclusions and Future Work

8.1 Conclusions

The aim of this research project was to investigate existing GAB water cooling systems and to determine the viability of in-ground pipe loop cooling systems. This aim has been achieved by implementing a structured project methodology. Relevant background information was sought from Local Governments and water supply authorities. Literature on current cooling systems was consulted and an alternate cooling method determined. Experimentation and modelling was then conducted to determine the performance of this alternate cooling system. Using the simulation models a concept design was prepared for the town of Thargomindah. This design demonstrated that implementation of such systems would be feasible, and that many benefits can be gained from such systems.

Key outcomes of this research include:

- Determining that the current cooling methods being used in municipal water supplies are generally expensive and extremely wasteful of this valuable natural resource
- Determining that simple one-dimensional heat transfer models can be used to iteratively determine values for soil thermal conductivity with close correlation to observed soil temperature measurements
- Observing that mineral content in artesian water can potentially cause problems by having the dissolved solids deposit out as the water is cooled
- Determining that Ground Heat Sink Pipe Loops (GHSPL), which are an adaptation of the commonly used ground source heat pumps that are widely applied to building heating and cooling in the Northern Hemisphere, are a viable and feasible alternate water cooling technology

- Determining that GHSPL may be able to be applied in Western Queensland townships that are required to cool their municipal water supplies

8.2 Suggestions for Further Work

There were a number of topics encountered during this project that were outside the scope of research but will potentially contribute to the future design and understanding of GHSPL systems.

Soil thermal conductivity and temperature data at shallow depths for the Australian continent is not as well documented as it is in major North American and European countries. A thorough understanding of soil conditions is required prior to implementing a GHSPL system. Knowledge of whether some of the empirical relationships and rules of thumb that have been developed for soils in the Northern Hemisphere hold true in Australian conditions would be extremely useful to further the knowledge of, and confidence in, GHSPL systems.

Further documentation of the effects of using soil as a heat sink over long time periods needs to be completed. The effects of looping the underground pipe network and the proximity in which parallel pipes can be to other pipes has little formal documentation.

Little consideration was given in this research to a formal structural design of the pipe network (thrust blocks and other structural considerations). Prior to implementing such a system this design would need to be completed.

As mentioned throughout this dissertation, GHSPL systems can be implemented as either horizontal or vertical systems. The bulk of this research was focussed on horizontal systems (as the simulation models chosen could not simulate vertical systems without substantial modification); hence investigation into vertical systems in an Australian water cooling context could be conducted. It was initially assumed that as Australia does not have the land area pressures experienced by other nations implementing underground pipe networks for heat transfer, that horizontal systems would both be appropriate and cheaper than the vertical alternatives. A thorough review of vertical options would be required to test this hypothesis. An analysis of head loss within vertical and horizontal GHSPL systems would also be required to understand the pumping requirements of both systems.

The effect of mineral deposition due to high mineral content was discussed in some length in this dissertation. Due to the variability of artesian water quality throughout Australia, detailed investigation into the options for countering this issue was not conducted. This mineral deposition issue presents an interesting challenge, because whether GHSPL systems are adopted, or other alternative systems are used, there will still be this issue present.

Further research should also be conducted into water cooling methods that can utilise this waste heat, whilst not wasting vast amounts of water.

References

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) 2005, *ASHRAE Handbook - Fundamentals (2005) [SI Edition]*, ASHRAE, Atlanta, Georgia.

Aravinthan, V & Yoong, E 2014, *ENV4203 Public health engineering: Study book*, University of Southern Queensland, Toowoomba.

Arkins, C 2004, *An Introduction to Ground Source Heat Pump Systems*, design note, Australian Institute of Architects, Canberra, viewed 4 June 2014, <http://www.environmentdesignguide.com.au/pages/content/tec--technology/tec-6-an-introduction-to-ground-source-heat-pump-systems.php>.

Australian Bureau of Meteorology 2012, *Average annual point potential evapotranspiration map*, Australian climate data, Australian Bureau of Meteorology, Victoria, viewed 17 September 2014, <http://www.bom.gov.au/jsp/ncc/climate_averages/evapotranspiration/index.jsp?maptype=6&period=an>.

Australian Bureau of Meteorology 2014, *Climate Data Online*, Daily Climate Statistics, Australian Bureau of Meteorology, Victoria, viewed 21 August 2014, <http://www.bom.gov.au/climate/data/>.

Australian Bureau of Statistics 2013, *2011 Census QuickStats*, census data, Australian Bureau of Statistics, Belconnen, ACT, viewed 30 October 2014, <http://www.censusdata.abs.gov.au/census_services/getproduct/census/2011/quickstat/0>.

Banks, D 2012, *An introduction to thermogeology: ground source heating and cooling*, 2nd edn., Wiley-Blackwell, Chichester West Sussex.

Brady, NC & Weil, RR 2008, *The nature and properties of soils*, 14th edn., Prentice Hall, Harlow.

Chadwick, AJ, Morfett, JC & Borthwick, M 2004, *Hydraulics in civil and environmental engineering*, Spon Press, London.

Cooling Technology Institute 2014, *What is a (wet, atmospheric) cooling tower?*, Cooling Technology Institute, Houston, Texas, viewed 3 June 2014, <http://www.cti.org/whatis/coolingtowerdetail.shtml>.

Cox, R & Barron, A (Eds) 1998, *Great Artesian Basin Resource Study*, Great Artesian Basin Consultative Council, Manuka ACT.

Department of Energy and Water Supply 2014, *Planning guidelines for water supply and sewerage*, Queensland Government, Brisbane.

Diamantina Shire Council 2014, Diamantina Shire Council, Bedourie, Queensland, viewed 4 June 2014, <http://www.diamantina.qld.gov.au/water>.

DWLBC 2006, *GAB Well Maintenance Field Guide for Artesian Wells*, Department of Water, Lands and Biodiversity Conservation and South Australian Arid Lands Natural Resources Management Board, South Australia.

Elite Software 2012, *ECA – Earth Coupled Analysis*, Elite Software, Texas, viewed 23 October 2014, <http://www.elitesoft.com/web/hvacr/ecaw.html>.

Engineers Australia 2010, *Code of Ethics*, Engineers Australia, Barton, ACT, viewed 10 May 2014, <http://www.engineersaustralia.org.au/sites/default/files/shado/About%20Us/Overview/Governance/codeofethics2010.pdf>.

Ergon Energy n.d., *Birdsville Organic Rankine Cycle geothermal power station*, Ergon Energy, Townsville, QLD, viewed 30 May 2014, <https://www.ergon.com.au/__data/assets/pdf_file/0008/4967/EGE0425-birdsville-geothermal-brochure-r3.pdf>.

Farouki, OT 1986, *Thermal Properties of Soils*, Series on Rock and Soil Mechanics: Volume 2, Trans Tech Publications, Clausthal-Zellerfeld, Germany.

Florides, G & Kalogirou, S 2007, 'Ground heat exchangers—A review of systems, models and applications', *Renewable Energy*, vol. 32, no. 15, pp. 2461-78.

Google Earth 7.1.1 2014a, *Tabooba Cooling Grid 28°26'01.67" S, 149°18'49.34" E, elevation 214 m*, Google Earth, Australia, viewed 17 September 2014, <http://www.google.com/earth/index.html>.

Google Earth 7.1.1 2014b, *Town of Thargomindah 27°59'28.94" S, 143°49'30.96" E, elevation 133 m*, Google Earth, Australia, viewed 28 October 2014, <http://www.google.com/earth/index.html>.

Google Earth 7.1.1 2014c, *USQ Ag Plot 27°36'26.89" S, 151°55'53.97" E, elevation 693 m*, Google Earth, Australia, viewed 17 September 2014, <http://www.google.com/earth/index.html>.

Great Artesian Basin Resource Study Update 2010 (draft), Great Artesian Basin Coordinating Committee, Manuka ACT.

Greene, D 1997, *Towards sustainable engineering practice: engineering frameworks for sustainability*, Institution of Engineers, Barton ACT.

Harrington, N & Cook, P 2014, *Groundwater in Australia*, National Centre for Groundwater Research and Training, Australia, viewed 30 May 2014, <http://www.groundwater.com.au/resources>.

Iplex Pipelines 2009, *Polyethylene Pipe and Fittings*, Product Systems Technical Information, Iplex Pipelines, Chatswood, NSW, viewed 4 June 2014, <http://www.iplex.com.au/iplex.php?page=lib&lib=1>.

James Hardie Pipelines 1997, *POLIplex polyethylene pipe design textbook*, James Hardie Pipelines, New South Wales.

Johnston, I, Narsilio, G, Colls, S, Valizadeh Kivi, A, Payne, D, Wearing-Smith, M & Noonan, G 2012, 'Direct Geothermal Energy Demonstration Projects for Victoria, Australia', *Proceedings of the New Zealand Geothermal Workshop 2012*, held November 19 - 21, Auckland, New Zealand, pp. unknown.

Kirkby, AL & Gerner, EJ 2010, *Heat flow interpretations for the Australian continent: Release 1*, Geoscience Australia, Canberra.

Klaassen, CJ 2006, *Geothermal Heat Pump Systems: GeoExchange Technology*, Iowa Energy Center, Iowa, viewed 4 June 2014, <http://www.michigan.gov/documents/CIS_EO_KC-MAY06-Workshop_159640_7.pdf>.

Lienau, PJ 2012, *QPIPE*, QPIPE software documentation, Geo-Heat Center, Oregon, viewed 4 June 2014, <http://geoheat.oit.edu/software/qpipe.pdf>.

Marshall, TJ & Holmes, JW 1988, *Soil Physics*, 2nd edn., Cambridge University Press, New York.

Mathworks 2014, Mathworks, Massachusetts, USA, viewed 30 May 2014, <http://www.mathworks.com.au/products/matlab/>.

Nalluri, C & Featherstone, RE 2009, *Nalluri & Featherstone's civil engineering hydraulics : essential theory with worked examples*, 5th edn., Wiley-Blackwell, Oxford.

Panametrics 1996, *TransPort™ Model PT868 Portable Flowmeter: User's manual*, Panametrics, Massachusetts.

Parker, SP 2003, *McGraw-Hill dictionary of engineering*, McGraw-Hill, New York.

Paterson, AB 1902, *Rio Grande's last race and other verses*, Angus and Robertson, Melbourne.

Pigram, JJ 2006, *Australia's water resources: from use to management*, CSIRO Publishing, Collingwood, Victoria.

Planning Institute of Australia 2014, *Water and Planning*, Planning Institute of Australia, Barton, ACT, viewed 28 October 2014, <http://www.planning.org.au/policy/water-and-planning>.

Radke, BM & Ferguson, J & Cresswell, RG & Ransley, TR & Habermehl, MA 2000, *Hydrochemistry and implied hydrodynamics of the Cadna-owie - Hooray Aquifer, Great Artesian Basin, Australia*, Bureau of Rural Sciences, Canberra.

Rawlinsons Publishing 2014, *Rawlinsons Australian construction handbook*, 32nd edn., Rawlinsons Publishing, Perth, Western Australia.

Rogers, GFC & Mayhew, YR 1992, *Engineering thermodynamics: work and heat transfer : [SI units]*, Longman, Burnt Mill, England.

Rogers, GFC & Mayhew, YR 1995, *Thermodynamic and transport properties of fluids: SI units*, B. Blackwell, New York, USA.

Singer, MJ & Munns, DN 2002, *Soils: An Introduction*, 5th edn., Prentice Hall, New Jersey.

Smerdon BD, Ransley TR, Radke BM & Kellett JR 2012, *Water resource assessment for the Great Artesian Basin*, A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment, CSIRO Water for a Healthy Country Flagship, Australia.

Song, Y, Yao, Y & Na, W 2006, 'Impacts of Soil and Pipe Thermal Conductivity on Performance of Horizontal Pipe in a Ground-source Heat Pump', *Renewable Energy Resources and a Greener Future Vol.VIII-11-1: Proceedings of the sixth international conference for Enhanced Building Operations*, held November 6 - 9 Shenzhen, China, pp. unknown.

Standards Australia 1999, *Methods of testing soils for engineering purposes – Method 1.3.1: Sampling and preparation of soils – Undisturbed samples – Standard method*, AS 1289.1.3.1–1999, Standards Australia, Sydney, viewed 23 October 2014, <http://www.saiglobal.com/online/autologin.asp>.

Standards Australia 2005, *Methods of testing soils for engineering purposes – Method 2.1.1: Soil moisture content tests – Determination of the moisture content of a soil – Oven Drying Method (Standard method)*, AS 1289.2.1.1–2005, Standards Australia, Sydney, viewed 23 October 2014, <http://www.saiglobal.com/online/autologin.asp>.

Standards Australia 2010, *Plumbing and Drainage – Heated Water Services*, AS/NZS 3500.4:2003, Standards Australia, Sydney, viewed 30 May 2014, <http://www.saiglobal.com/online/autologin.asp>.

Standards Australia 2013, *Methods of testing soils for engineering purposes – Method 1.2.1: Sampling and preparation of soils – Disturbed samples – Standard method*, AS 1289.1.2.1–1998 (R2013), Standards Australia, Sydney, viewed 23 October 2014, <http://www.saiglobal.com/online/autologin.asp>.

Talayasingham, J 2007, *Report for Borewater Cooling: Study on Heat Transfer from Buried Polyethylene Pipe Work*, Report for NSW Department of Natural Resources, GHD, Sydney.

United States Department of Energy 2013a, *EnergyPlus Energy Simulation Software*, United States Department of Energy, Office of Energy Efficiency and renewable Energy, Washington, viewed 23 October 2014, <http://apps1.eere.energy.gov/buildings/energyplus/>.

United States Department of Energy 2013b, *EnergyPlus Engineering Reference*, United States Department of Energy, Office of Energy Efficiency and Renewable Energy, Washington, viewed 23 October 2014 <http://apps1.eere.energy.gov/buildings/energyplus/pdfs/engineeringreference.pdf>.

United States Department of the Interior 2001, *Water Measurement Manual*, 3rd edn, technical publication, United States Department of the Interior, Bureau of Reclamation, Washington, viewed 22 October 2014, <http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/chap14_12.html>.

University of Southern Queensland 2014, *Weather station data*, data file, University of Southern Queensland, Faculty of Health, Engineering and Sciences, Toowoomba, viewed 22 October 2014, <http://foesweather.usq.edu.au/>.

Vickers, B 1984, *Laboratory work in soil mechanics*, Granada, London.

Vinidex Pty Ltd 2014, Vinidex Pty Ltd, North Rocks, NSW, viewed 20 October 2014, <http://www.vinidex.com.au/ >.

Watt, AT 2008, ‘Validation of cooling grid model and testing of alternatives’, Bachelor Thesis, University of Southern Queensland, Toowoomba.

West, ES 1952, 'A Study of the Annual Soil Temperature Wave', *Australian Journal of Scientific Research, Series A: Physical Sciences*, vol. 5, pp. 303-14.

WorleyParsons 2010, *Water Supply Cooling Study: Reference Document*, Report for Queensland Department of Infrastructure and Planning, WorleyParsons, Brisbane.

Appendix A – Project Specification

University of Southern Queensland

FACULTY OF HEALTH, ENGINEERING AND SCIENCES

SCHOOL OF CIVIL ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR:	**HAYDEN GUSE**
TOPIC:	GAB WATER COOLING SYSTEMS FOR MUNICIPAL SUPPLIES
SUPERVISOR:	Dr. Joseph Foley
ENROLMENT:	ENG4111 – S1, 2014 ENG4112 – S2, 2014
PROJECT AIM:	To investigate existing GAB water cooling systems and determine the viability of in-ground pipe loop cooling systems, and make recommendations for future designs.

PROGRAMME: **Issue A, 19th March 2014**

1. Research the currently utilised GAB water cooling systems, focussing on those used for municipal supplies.
2. Liaise with government staff to determine the performance of existing systems.
3. Research and conduct modelling of in-ground pipe loop cooling systems.
4. Take field measurements to calibrate the ground loop model.
5. Evaluate the viability of in-ground pipe loop cooling systems, and if found to be viable, provide a concept design for this system.
6. Provide recommendation(s) for future GAB water cooling systems for municipal supplies.

As time permits,

7. Conduct system testing on existing GAB water cooling systems.
8. Test the concept design of the pipe loop cooling system.

AGREED:

______________________ (Student) ______________________ (Supervisor)

___ /___ /2014 ___ /___ /2014

Appendix B – GHD MATLAB Model Code

```
%% BURIED PIPE HEAT TRANSFER MODEL
%
% Author: Hayden Guse
% Date: 2014
%
% This script file has been based on a report and spreadsheet model
% prepared by GHD for the NSW Department of Natural Resources. The
% reference for the original work is shown below:
%
 % Talayasingham, J 2007, Report for Borewater Cooling: Study on Heat
 % Transfer from Buried Polyethylene Pipe Work, Report for NSW Department of
 % Natural Resources, GHD, Sydney.
 %
 clear;
 clc;
 %
 % This model solves the buried pipe heat transfer problem using finite
 % differencing. The pipeline is segmented into discrete elements with heat
 % loss calculated for each element. The outlet temperature of each element
 % is then used as the inlet temperature for the next element.
 %
 %------------------------------------------------------------------------
 %% IMPORTING WATER PROPERTY DATA
 %
 % The spreadsheet being called on below contains tables of water properties
 % at temperatures between 0.01 and 150 degrees Celsius.
 %
 Water_Prop = xlsread('Water_Property_Data.xls', 'Water_Properties');
 water_temp_th = Water_Prop(:,1);             % degrees Celsius
 water_density_th = Water_Prop(:,5);          % kg/m3
 water_spec_heat_th = Water_Prop(:,7);        % J/kg.K
 water_therm_con_th = Water_Prop(:,9);        % W/m.K
 water_dyn_visc_th = Water_Prop(:,11);        % kg/m.s
 %
 %------------------------------------------------------------------------
 %% SOLVING PIPE LENGTH BASED ON INPUTS
 %
 range = false;
 while ~ range
 %
 prompt={'Enter the pipe outer diameter (mm):',...
     'Enter the pipe thickness (mm):',...
     'Enter the backfill thickness (mm):',...
     'Enter the flow rate (L/s):',...
     'Enter the water entry temperature (^oC):',...
     'Enter the backfill temperature (^oC):',...
     'Enter the pipe thermal conductivity (W/m.K):',...
```

```
    'Enter the backfill thermal conductivity (W/m.K):'};  % Required inputs
name='Model Input Parameters';
numlines=2;
defaultanswer={'200.0','22.4','290.6','32.0','85.0','31.0','0.38','1.6'};
options.Resize='off';
options.WindowStyle='normal';
options.Interpreter='tex';
%
% Pop-up requesting user input
%
answer=inputdlg(prompt,name,numlines,defaultanswer,options);
%
% Loop to account for someone hitting cancel on the pop-up menu
%
if isempty(answer)
    choice = menu('Please choose an option','     Re-run program     ',...
             '     Exit     ');
%
    if choice == 1
    close all, clc
%
    elseif choice == 2
    close all, clc
    range = true;
%
    end
%
else
%
range = true;
%
% Convert input strings to numbers
%
[pipe_o_dia] = str2num(answer{1})/1000;
[pipe_thick] = str2num(answer{2})/1000;
[backfill_thick] = str2num(answer{3})/1000;
[flow_rate] = str2num(answer{4})/1000;
[entry_temp] = str2num(answer{5});
[soil_temp] = str2num(answer{6});
[pipe_therm] = str2num(answer{7});
[backfill_therm] = str2num(answer{8});
%
% Based on the provided inputs, the other required values are calculated
%
pipe_i_dia = pipe_o_dia - (2*pipe_thick);        % m
pipe_area = pi*(pipe_i_dia^2)/4;                 % m^2
velocity = flow_rate/pipe_area;                  % m/s
pipe_element = 1;                                % 1 m segments
total_pipe_length = 0:pipe_element:100000;       % 100,000 m default length
conv_area = 2*pi*(backfill_thick+(pipe_o_dia/2))*pipe_element;      % m^2
wall_cond_resis = (log((pipe_o_dia/2)/(pipe_i_dia/2)))/...
                  (2*pi*pipe_therm*pipe_element);      % K/W
```

```
soil_cond_resis = (log((backfill_thick+(pipe_o_dia/2))/(pipe_o_dia/2)))/...
                  (2*pi*backfill_therm*pipe_element);     % K/W
%
% Variables required for each pipe element
%
exit_temp = entry_temp*ones(1,length(total_pipe_length));  % degrees Celsius
ave_wall_temp = ones(1,length(total_pipe_length));         % degrees Celsius
dyn_visc_bulk = ones(1,length(total_pipe_length));         % kg/m.s
dyn_visc_wall = ones(1,length(total_pipe_length));         % kg/m.s
water_density = ones(1,length(total_pipe_length));         % kg/m^3
water_spec_heat = ones(1,length(total_pipe_length));       % J/kg.K
Reynolds = ones(1,length(total_pipe_length));              % dimensionless
Prandtl = ones(1,length(total_pipe_length));               % dimensionless
Nusselt = ones(1,length(total_pipe_length));               % dimensionless
water_therm_con = ones(1,length(total_pipe_length));       % W/m.K
conv_heat_trans_coeff = ones(1,length(total_pipe_length)); % W/m^2.K
conv_resis = ones(1,length(total_pipe_length));            % K/W
tot_coeff = ones(1,length(total_pipe_length));             % K/W
energy_trans = ones(1,length(total_pipe_length));          % W
mass_flow = ones(1,length(total_pipe_length));             % kg/s
%
% Initial pipeline conditions
%
dyn_visc_bulk(1,1) = interp1(water_temp_th,water_dyn_visc_th,entry_temp);
ave_wall_temp(1,1) = (entry_temp + soil_temp)/2;
dyn_visc_wall(1,1) =
interp1(water_temp_th,water_dyn_visc_th,ave_wall_temp(1,1));
water_density(1,1) = interp1(water_temp_th,water_density_th,entry_temp);
water_spec_heat(1,1) = interp1(water_temp_th,water_spec_heat_th,entry_temp);
Reynolds(1,1) = water_density(1,1).*velocity.*pipe_i_dia./dyn_visc_bulk(1,1);
water_therm_con(1,1) = interp1(water_temp_th,water_therm_con_th,entry_temp);
Prandtl(1,1) = water_spec_heat(1,1).*dyn_visc_bulk(1,1)./water_therm_con(1,1);
%
if Reynolds(1,1) >= 10000
    Nusselt(1,1) = 0.023*(Reynolds(1,1)^0.8).*(Prandtl(1,1)^0.3);
else
    Nusselt(1,1) = 1.86*(((Reynolds(1,1).*Prandtl(1,1))./...
                   (pipe_element/pipe_i_dia))^(1/3))*...
                   ((dyn_visc_bulk(1,1)./dyn_visc_wall(1,1))^0.14);
end
%
% The above if statement allows the Nusselt number calculation to be based
% on whether there is laminar or turbulent flow occurring within the pipe
% element.
%
conv_heat_trans_coeff(1,1) = Nusselt(1,1).*water_therm_con(1,1)./pipe_i_dia;
conv_resis(1,1) = 1/(conv_heat_trans_coeff(1,1).*conv_area);
tot_coeff(1,1) = conv_resis(1,1) + wall_cond_resis(1,1) + soil_cond_resis(1,1);
energy_trans(1,1) = (entry_temp-soil_temp)./tot_coeff(1,1);
mass_flow(1,1) = water_density(1,1).*pipe_area*velocity;
exit_temp(1,1) = entry_temp - (energy_trans(1,1)./(mass_flow(1,1).*...
                 water_spec_heat(1,1)));
```

```
%
% Looping to solve for each successive element
%
for i = 2:length(total_pipe_length);
%
dyn_visc_bulk(1,i) = interp1(water_temp_th,water_dyn_visc_th,exit_temp(1,i-1));
ave_wall_temp(1,i) = (exit_temp(1,i-1) + soil_temp)/2;
dyn_visc_wall(1,i) = interp1(water_temp_th,water_dyn_visc_th,ave_wall_temp(1,i));
water_density(1,i) = interp1(water_temp_th,water_density_th,exit_temp(1,i-1));
water_spec_heat(1,i) = interp1(water_temp_th,water_spec_heat_th,exit_temp(1,i-1));
Reynolds(1,i) = water_density(1,i).*velocity.*pipe_i_dia./dyn_visc_bulk(1,i);
water_therm_con(1,i) = interp1(water_temp_th,water_therm_con_th,exit_temp(1,i-1));
Prandtl(1,i) = water_spec_heat(1,i).*dyn_visc_bulk(1,i)./water_therm_con(1,i);
%
     if Reynolds(1,i) >= 10000
         Nusselt(1,i) = 0.023*(Reynolds(1,i).^0.8).*(Prandtl(1,i).^0.3);
     else
         Nusselt(1,i) = 1.86*(((Reynolds(1,i).*Prandtl(1,i))./...
                        (pipe_element/pipe_i_dia))^(1/3))*...
                        ((dyn_visc_bulk(1,i)./dyn_visc_wall(1,i))^0.14);
     end
%
conv_heat_trans_coeff(1,i) = Nusselt(1,i).*water_therm_con(1,i)./pipe_i_dia;
conv_resis(1,i) = 1/(conv_heat_trans_coeff(1,i).*conv_area);
tot_coeff(1,i) = conv_resis(1,i) + wall_cond_resis + soil_cond_resis;
energy_trans(1,i) = (exit_temp(1,i-1)-soil_temp)./tot_coeff(1,i);
mass_flow(1,i) = water_density(1,i).*pipe_area*velocity;
exit_temp(1,i) = exit_temp(1,i-1) - (energy_trans(1,i)./(mass_flow(1,i).*...
                 water_spec_heat(1,i)));
%
    if exit_temp(1,i) < 45
        break
    end
%
% The above statement stops calculations when the pipeline temperature
% drops below 45 degrees Celsius.
%
end
%
% Calculation and display of where the temperature first drops below 45
% degrees Celsius.
%
pipe_length_req = min(find(exit_temp<45)).*pipe_element;            % m
fprintf('\nThe pipe length required to get water temperature less than '),
fprintf('45%cC is ', char(176)),disp([num2str(pipe_length_req), ' m.']),
fprintf('\n\n')
%
end
%
```

```
end
%
%-----------------------------------------------------------------------------
```

Appendix C – QPIPE MATLAB Model Code

```
%% QPIPE PROGRAM
%
% Author: Hayden Guse Date: 2014
%
% The QPIPE program was converted to a MATLAB script as the original
% program was not compatible with Windows 7. There are a few differences
% between the original and the MATLAB file due to differences in the coding
% language, but the same computation method has been retained. The
% reference for the original work is shown below:
 %
 % Lienau, PJ 2012, QPIPE, QPIPE  software documentation, Geo-Heat Center,
 % Oregon, viewed 4 June 2014, <http://geoheat.oit.edu/software/qpipe.pdf>.
 %
 clear;
 clc;
 %
 %--------------------------------------------------------------------------
 %% DESCRIPTION
 %
 % This program computes buried pipe heat loss per lineal foot, total heat
 % loss, and total temperature drop.
 %
 % VARIABLE KEY:
 % ID, OD, IN, CO, SA   =   Pipe dimensions for carrier pipe, insulation,
 % jacket and sand
 % Z   =   Depth buried to pipe centre
 % PTC, ITC CTC, STC, ETC   =   Thermal conductivity of pipe, insulation,
 % jacket, sand and soil
 % TF, TG   =   Temperature of fluid and ground surface
 % Q   =   Flow rate
 % L   =   Pipe length
 % TTD   =   Temperature drop
 % TX   =   Exit temperature
 % DN   =   Density
 %
 %--------------------------------------------------------------------------
 %% INITIALISATION
 %
 prompt={'Enter the pipe internal diameter (mm):',...
     'Enter the pipe outer diameter (mm):',...
     'Enter the insulation outer diameter (mm):',...
     'Enter the jacket outer diameter (mm):',...
     'Enter the sand outer diameter (mm):',...
     'Enter the depth to pipe centre (mm):'};          % Required inputs
 name='Model Input Parameters 1';
 numlines=1;
 defaultanswer={'155.2','200.0','200.0','200.0','200.0','290.6'};
```

```
options.Resize='on';
options.WindowStyle='normal';
options.Interpreter='tex';
%
% Pop-up requesting user input
%
answer=inputdlg(prompt,name,numlines,defaultanswer,options);
%
ID = str2num(answer{1})*0.03936996;
OD = str2num(answer{2})*0.03936996;
IN = str2num(answer{3})*0.03936996;
CO = str2num(answer{4})*0.03936996;
SA = str2num(answer{5})*0.03936996;
Z = str2num(answer{6})*0.03936996;
%
prompt={'Enter the pipe thermal conductivity (W/m.K):',...
    'Enter the insulation thermal conductivity (W/m.K):',...
    'Enter the jacket thermal conductivity (W/m.K):',...
    'Enter the sand thermal conductivity (W/m.K):',...
    'Enter the soil thermal conductivity (W/m.K):',...
    'Enter the fluid temperature (^oC):',...
    'Enter the ground temperature (^oC):',...
    'Enter the pipe flow rate (L/s):',...
    'Enter the pipe length (m):',};          % Required inputs
name='Model Input Parameters 2';
numlines=1;
defaultanswer={'0.38','0.38','0.38','0.38','1.60','85.0','31.0','32.0','42967'};
options.Resize='on';
options.WindowStyle='normal';
options.Interpreter='tex';
%
% Pop-up requesting user input
%
answer=inputdlg(prompt,name,numlines,defaultanswer,options);
%
% Convert input SI unit strings to non-SI numbers
%
PTC = str2num(answer{1})/1.730735;
ITC = str2num(answer{2})/1.730735;
CTC = str2num(answer{3})/1.730735;
STC = str2num(answer{4})/1.730735;
ETC = str2num(answer{5})/1.730735;
TF = (str2num(answer{6})*(9/5))+32;
TG = (str2num(answer{7})*(9/5))+32;
Q = str2num(answer{8})*15.850323;
LP = str2num(answer{9})*3.28083;
%
%--------------------------------------------------------------------------
%% HEAT LOSS COMPUTATION
%
R = (log(OD/ID)/(PTC) + log(IN/OD)/(ITC) + log(CO/IN)/(CTC) +...
    log(SA/CO)/(STC) + log((2*Z)/SA + sqrt((((2*Z)/SA)^2)-1))/(ETC))/(2*pi);
```

```
K = 1;
%
% Initial pipeline iteration
%
H(1,K) = (TF - TG)/R;
TH(1,K) = H(1,K).*LP;
DN(1,K) = 61.5 - ((TF - 120).*0.01667);
FLOW(1,K) = DN(1,K).*Q.*8.0178;
TTD(1,K) = TH(1,K)./FLOW(1,K);
TX(1,K) = TF - TTD(1,K);
%
% Looping to iterate the output temperature 20 times
%
for K = 2:20
     TA(1,K) = (TF + TX(1,K-1))./2;
     H(1,K) = (TA(1,K) - TG)./R;
     TH(1,K) = H(1,K).*LP;
     DN(1,K) = 61.5 - ((TA(1,K) - 120).*0.01667);
     FLOW(1,K) = DN(1,K).*Q.*8.0178;
     TTD(1,K) = TH(1,K)./FLOW(1,K);
     TX(1,K) = TF - TTD(1,K);
end
%
% Determine the temperature at the end of the pipeline and display the
% answer in SI units
%
EXIT_T = (TX(1,end) - 32).*(5/9);       % degrees C
fprintf('\nThe water temperature at the end of the specified pipe length'),
fprintf(' is '),fprintf(num2str(EXIT_T)),fprintf('%cC.', char(176)),
fprintf('\n\n')
%
%-------------------------------------------------------------------------
```

Appendix D – Risk Matrices

Key:

B = risk before control measures were implemented

A = risk after control measures were implemented

A full list of the control measures that were implemented can be found in Section 4.1.4.

Travelling

Table D.1. Risk matrix for travel to experimental site

		Severity of Consequence				
		Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain					
	Likely					
	Possible					
	Unlikely				B	
	Rare				A	

Hot Water

Table D.2. Risk matrix for working with hot water

		Severity of Consequence				
		Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain					
	Likely		B			
	Possible					
	Unlikely	A				
	Rare					

Excavations

Table D.3. Risk matrix for creating and working near excavations

		Severity of Consequence				
		Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain					
	Likely			B		
	Possible					
	Unlikely	A				
	Rare					

Dehydration

Table D.4. Risk matrix for potential dehydration on-site

		Severity of Consequence				
		Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain					
	Likely					
	Possible					
	Unlikely		B			
	Rare	A				

As seen above, all of the control measures that were implemented reduced the risk of the experimentation to an acceptable level.

Appendix E – Soil Thermal Conductivity Calibration

Shown below is a sample of the soil thermal conductivity iterations that were conducted. For each iteration shown the fit between the experimental and the observed data was judged not to be appropriate. Hence iteration continued until the appropriate value of 1.60 W/m.K was found (see Section 5.2.2).

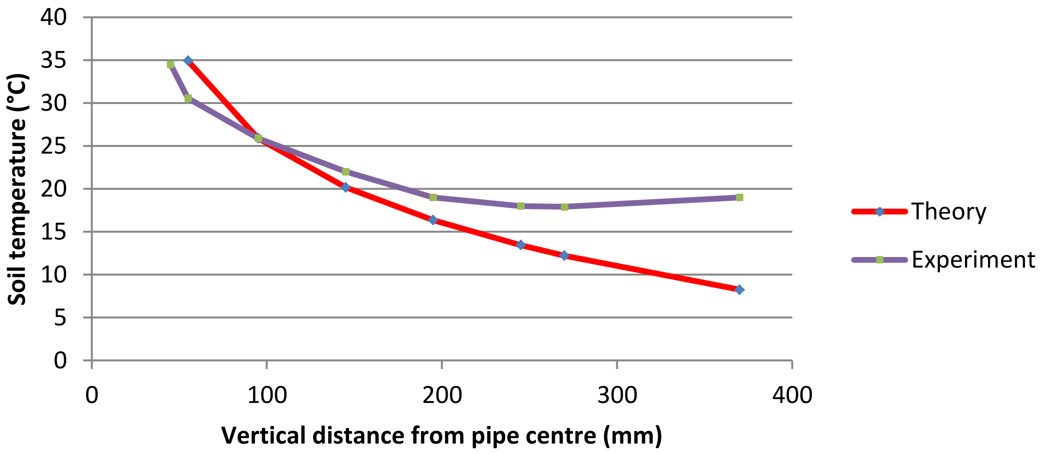

Figure E.1. Theoretical results compared to experimental results (ksoil = 1.388 W/m.K)

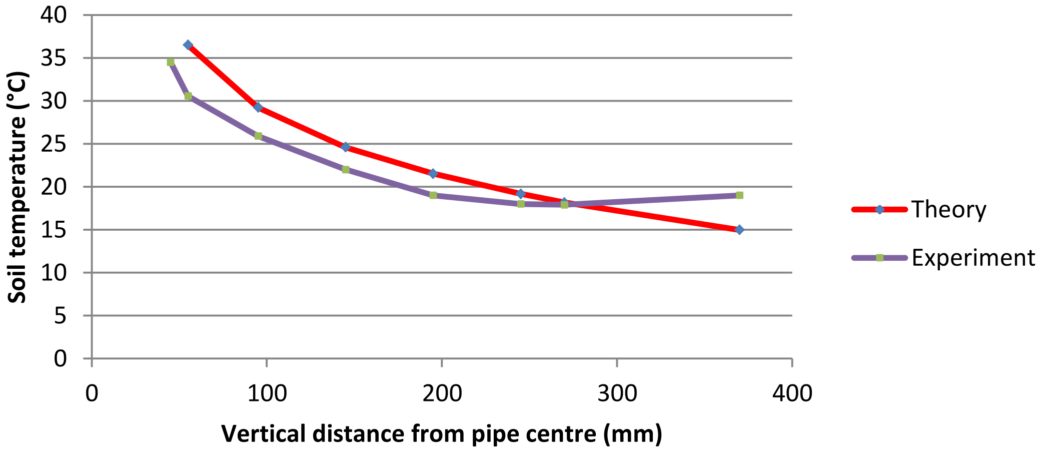

Figure E.2. Theoretical results compared to experimental results (ksoil = 1.72 W/m.K)

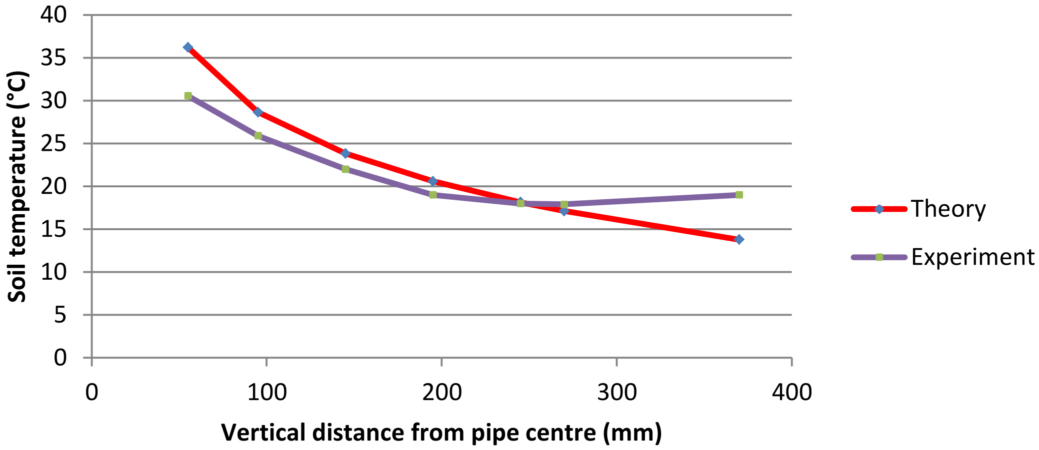

Figure E.3. Theoretical results compared to experimental results (ksoil = 1.65 W/m.K)

Appendix F – Ethical Considerations

Ethically this research has no notable dilemmas. The 'Engineers Australia Code of Ethics' (2010) has two elements that relate specifically to the environment. These elements are as follows:

> 4.2 'Practise engineering to foster the health, safety and wellbeing of the community and environment'
>
> 4.3 'Balance the needs of the present with the needs of future generations'

Both of these elements are being achieved by this research. Some of the current cooling methods employed by water supply authorities are reasonably environmentally "unfriendly" as they waste vast quantities of water. As a result a primary concern of the proposed alternative method was to ensure that it is achieving, at the very least, non-worsening of the current situation. The alternative being proposed would appear to have a much better environmental outcome as it will have negligible water losses compared to the current systems. The proposed alternative will also not experience the cooling pond issues of: salinisation, weed growth, algal growth and providing a water source for wild (pest) animals.

In the same way that the elements of the 'Engineers Australia Code of Ethics' are achieved, the key Engineers Australia sustainability document titled, Towards sustainable engineering practice: engineering frameworks for sustainability (Greene, D 1997) is also achieved. This document sets out ten aspects of sustainability that Australian engineers should be working to. All of these ten actions can be achieved by the alternative cooling system suggested in this research.