UNIVERSITY OF CAPE TOWN

MASTERS THESIS

Analysing Stormwater Temperature at Site-Specific Discharge Points along the Liesbeek River, South Africa

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in the

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UNIVERSITY OF CAPE TOWN

Abstract

Faculty of Science

Department of Earth and Geographical Science

Masters of Science

Analysing Stormwater Temperature at Site Specific Discharge Points along the Liesbeek River, South Africa

by Annesley CRISP

Increased urban development has resulted in increased impervious land-cover and the removal of natural vegetation. The continued anthropic modification of the Earth's surface towards an urban state, has had profound effects on the surrounding natural systems (Thompson et al., 2008). Consequently, recent studies have highlighted a strong link between expanding urbanisation and thermal impacts on streams and rivers draining urban catchments (Roa-Espinosa et al., 2003; Arrington, 2003; Herb et al., 2009b). Anthropogenic perturbations such as thermal pollution can adversely disturb the natural thermal regime of a river (Boothe and Bledsoe, 2009). An important source of thermal pollution is thermally enriched stormwater runoff. During a rainfall event, runoff temperature is elevated as it makes contact with, and passes over surfaces which have a large heat storage capacity, such as pavements, roofs and roads (Young et al., 2013). However, the extent of impervious surfaces and resulting thermal pollution produced by them is poorly understood, although it is thought to be a major contributor to stream degradation.

Previous research has focused on investigating the thermal effects of removing riparian vegetation. Additionally, a recent research approach has been to develop models of the urban surface-water-atmosphere systems. Finally, research in the field of fresh-water ecology has investigated the effects of temperature on aquatic biota. Water temperature affects all aspects of freshwater ecosystems and plays an important role in regulating physical and biological characteristics of a river (Olsen et al. 2011). Consequently, any

anthropogenic modification to temperature can have devastating effects on the ecological functioning of a river and biodiversity of species within the river habitat.

Important findings by Young et al. (2013) suggest the need for a detailed study of stormwater temperature changes in relation to rainfall events, at a catchment scale. Furthermore, data is required to show the point source effects of stormwater runoff from impervious surfaces on the temperature of the receiving water body. Therefore, the aim of this study is: To determine the extent and risk of thermal pollution at site specific discharge points, along the Liesbeek River. In order to achieve this aim, variables which cause temperature variations needed to be identified.

The primary research method makes use of Thermocron iButton Temperature Loggers. These were placed in four stormwater outlet pipes, which frequently discharge event-based stormwater runoff into the Liesbeek River. Additionally, iButton loggers were placed in the river channel, to provide a reference temperature to compare stormwater discharge temperature. In addition, hourly rainfall and air temperature was acquired from the South African Weather Service (SAWS) and was used in conjunction with the iButton temperature data.

Results from this study are compiled in three sections. Firstly, a Geographic Information System desktop analysis was undertaken. "Parcel Areas" were selected to provide contextual knowledge of the area in which stormwater runoff was passing over. Next, collated data was graphically presented. Temperature was plotted against event variables, in order to visualize temperature dynamics over the course of an event. Finally, a statistical regression model was used to test the type of relationship existing between stormwater temperature and event variables.

Combined findings include, statistically significant evidence of thermal loading at all stormwater outlet sites. It was established that the average temperature of stormwater discharge, over the course of a rainfall event, will be between 0.7°C to 1.9°C warmer than average river water temperature. Furthermore, event variables such as ambient air temperature, duration of rainfall, amount of rainfall, and time of day, show significant relationships with stormwater temperature. These relationships are supported by the literature. Finally, parcel characteristics such as the length of the stormwater pipe network, parcel area landuse, length of road network, and overall parcel area size, can aid observed temperature explanations. However, a more detailed analysis is required to understand their specific influence on stormwater temperature.

Overall, stormwater discharge at these four outlet sites should be considered as a source of thermal pollution. Additionally, the cumulative effect of multiple discharge sites along the river will have serious implications for overall river functioning. Solutions may lie within the concept of Sustainable Urban Drainage Systems. This new approach to urban water management indirectly supports thermal mitigation opportunities. In conclusion, elevated stormwater runoff and subsequent thermal enrichment of urban rivers should receive increased recognition as a contaminant of concern. Furthermore, it is vital to monitor temperature as a water-quality indicator, for functioning river and stream health.

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I would like to dedicate this Masters dissertation to my family. There is no doubt in my mind that without their continued kindness, support and encouragement from my parents and sister, I could not have completed this process. I am greatly indebted to their endless love and patience, which contributed significantly to the success of this research.

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List of Abbreviations

ARI	Auto Correlation Structure
CTM	Critical Thermal Maximum
EPT	Ephemeroptera, Plecoptera, Trichoptera taxa
GPS	Global Positioning System
LPL	Longest Pipe Length
MINUHET	Minnesota Urban Heat Export Tool
PND	Pipe Network Density
SAWS	South African Weather Service
SDI	Strategic Development System
TES	Thermal Enrichment of Stormwater
T_{opt}	Thermal Growth Optimum
TSS	Total Suspended Solids
TURM	Thermal Urban Runoff Model
UILT	Upper Incipient Lethal Temperature
USB	Universal Serial Bus (Cable System)
WEP	Water and Energy Transfer Process
WSUD	Water Sensitive Urban Design

Chapter 1

Introduction

1.1 General Background

Today, approximately 54 per cent of the world's population lives in urban areas, a proportion that is expected to increase to 66 per cent by 2050 (United Nations, 2014). Projections suggest that much of the expected urban growth will take place in countries of the developing regions, particularly Africa. As a result, these countries will face numerous challenges in meeting the needs of their growing populations, including housing, infrastructure, transportation, energy and water (Paul and Meyer, 2001).

The continued anthropic modification of the Earth's surface towards an urban state, has had profound effects on the surrounding natural systems (Thompson et al., 2008a). Urban development has changed the local climate, hydrology, and the water quality among other impacts. Consequently, managing urban areas and building sustainable cities has become one of the grand development challenges of the 21st century.

Increased urban development has resulted in increased impervious land cover and the removal of natural vegetation and upsetting the natural "hydrologic balance". For example, there is a noticeable reduction in infiltration, and an increase in the volume and rate of runoff, which occurs during rainfall events (Boothe and Bledsoe, 2009; Brown et al., 2005). Consequently, recent studies have highlighted a strong link between expanding urbanisation and thermal impacts on streams and rivers draining urban catchments (Shanahan, 1984; Hough, 1995; Roa-Espinosa et al., 2003; Arrington, 2003; Herb et al., 2009b).

Water temperature fluctuations occur naturally (Caissie, 2006). Similarly, river temperature variability exists on temporal (daily, seasonal) and spatial scales, within a catchment. However, anthropogenic perturbations such as thermal pollution, deforestation and climate change, can adversely disturb the natural thermal regime of a river or stream (Boothe and Bledsoe, 2009).

An important source of thermal pollution is thermally enriched stormwater runoff. During a rainfall event, runoff temperature is elevated as it makes contact with, and passes over surfaces which have a large heat storage capacity, such as pavements, roofs and roads (Young et al., 2013). During warmer days, stormwater runoff which flows over these artificial surfaces can reach temperatures above those observed in the natural environment (Sabouri et al., 2013; Sabouri, 2013). Thompson et al. (2008b), argue that the extent of impervious surfaces and resulting thermal pollution produced by them is poorly understood, although it is thought to be a major contributor to stream degradation.

Recognizing temperature as a contaminant is by no means a new concept. Research conducted as early as 1967, highlighted the concern of thermal pollution on receiving water systems (Davidson and Bradshaw, 1967; Pluhowski, 1970). Extensive studies exist on investigating the thermal effect of removing riparian vegetation from rivers and streams (Kinouchi, 2007; Rutherford et al., 1997a; Kinouchi et al., 2007) According to Galli (1991), there has been an observed long term increase in average stream temperatures globally, and this can be attributed to the influence of humans on their surroundings.

More recently, a common research approach has been to develop models of the urban surface-water-atmosphere systems. For example, the model developed by Roa-Espinosa et al. (2003) included a thermal component for impervious areas. Modelling heat transfer from warm surfaces to runoff water is one way of assessing the contributions of various factors to the overall rise in river water temperature (Roa-Espinosa et al., 2003). However, there are multiple factors which may significantly affect water temperature, e.g. solar radiation, air temperature, relative humidity, wind speed, the temperature and amount of rainfall or runoff, and the temperature and amount of ground water entering the river or stream. Hence, evaluating the complex relations between these variables, across differing scales (global climatic conditions affecting, surface-water energy transfers) can be extremely challenging (Todd et al., 2008). Nevertheless, developing thermal models does provide a useful tool for urban planners, managers, and the engineering community to be able to better manage the impact of large urban development on receiving water systems.

Additionally, research in the field of fresh-water ecology has investigated the effects of temperature on aquatic biota (Quinn et al., 1994; Richardson et al., 1994; Poff et al., 2002; Herb et al., 2007a; Ross-Gillespie, 2014). Notable emphasis has been placed on studying the effects on fish species such as Salmonids, because of an economic concern relating to decreasing populations (Simmons, 1986; Bartholow, 1991; McCullougg, 2003; Jones, 2008). However, a common theme emerging in all these studies is the recognition of the importance of temperature as a water-quality indicator, for functioning river and stream health.

According to Olsen et al. (2011) water temperature affects all aspects of freshwater ecosystems and the role it plays in regulating many physical and biological characteristics of a river. Firstly, temperature influences the health and survival of all aquatic organisms. It can be considered a limiting factor for biological activity as it controls metabolic rates and reproductive activities. Almost all aquatic biota have sensitive physiological optimum temperature ranges and thermal tolerances (Ross-Gillespie, 2014). Hence, increasing the overall temperature of a stream or river can disrupt the aquatic ecosystem, diminish populations, and threaten river functioning (Herb et al., 2009b; Jones et al., 2012). Moreover, intermittent thermal shocks, such as heated stormwater discharge into a river channel, can be a source of acute stress on aquatic organisms where death can be instantaneous (Coutant, 1970; Olsen et al., 2011; Ross-Gillespie, 2014).

Water temperature also controls physical characteristics of a river, such as the solubility of organic chemicals, nutrient concentrations and oxygen concentrations (Vannote et al., 1980; Poole and Berman, 2001; Gu and Li, 2002; Rostgaard and Jacobsen, 2005; Caissie, 2006; Young et al., 2013; Ross-Gillespie, 2014). For example, cool water can hold more oxygen than warm water which affects certain species of aquatic invertebrates, and therefore fish that have high oxygen needs are only found in cooler water. Furthermore, temperature influences the rate of photosynthesis by algae or aquatic plants. As water temperature rises, the rate of photosynthesis increases provided there is sufficient nutrient availability (Dodds, 2002).

Natural seasonal and daily variations of water temperature are important determinants which shape aquatic communities and their distribution, as highlighted by the River Continuum Concept (Vannote et al., 1980). Furthermore, temperature regulates ecological processes and determines the overall health of a river system (Bunn and Arthington, 2002; Jackson et al., 2007; Ross-Gillespie, 2014). Consequently, any anthropogenic modification to flow or temperature can have devastating effects on the ecological functioning of a river and biodiversity of species within the river habitat.

Anthropogenic sources of thermal pollution will be exacerbated by future climate change predictions. Daily temperature range shifts, seasonal temperature fluctuations and changes in precipitation patterns, also impact on river temperature regimes. There is growing concern about the need to reduce the negative effects of conventional urban management, and simultaneously to protect the ecological health of the water system (Young et al., 2013). According to Wong & Brown (2008), new thinking and practice in sustainable urban drainage systems (SUDS) can build resilience towards addressing these future climatic uncertainties and help to mitigate impacts on surface water bodies (Brown et al., 2008).

1.2 Stormwater Discharge: A Source of Thermal Pollution

Stormwater runoff which discharges into a receiving river or stream is considered to be a significant source of thermal pollution in urban catchments (Verspagen, 1996; VanBuren et al., 2000; Li and James, 2004; Herb et al., 2008). This form of pollution occurs when rainfall falls on impervious landcover with elevated surface temperatures. This condition and consequences might be obvious yet there is a significant gap in research in understanding the dynamic thermal behaviour of stormwater and variability over the course of a rainfall event (Young et al., 2013).

Temperature regimes in response to rainfall events were studied by Young et al. (2013). This research, which was conducted in New Zealand, examined temperature data from two rainfall events and compared rural and urban catchments. Important findings from the four urban monitoring sites included a measurable (0.2-1.2° C) first flush increase in river water temperature for both rain events. In the post first flush period, river water temperature remained elevated above that of ambient conditions. It can be deduced that a substantial thermal load is available for transfer from connected impervious surfaces, over a long period of time. Further analysis did however show that eventually after prolonged rainfall, surface temperatures cooled and runoff temperature reached equilibrium with river water temperature (Young et al., 2013).

In contrast, data collected from one of the rain events, which occurred at night-time, showed no apparent thermal influence from impervious surfaces on river water temperature. It was concluded that air temperature (and thus rainfall temperature) has a more significant influence on river water temperature in the absence of solar heating (Mohseni and Stefan, 1999; Young et al., 2013).

The research also concluded that river water temperature in response to stormwater runoff inputs varied according to a number of factors that include time of day, air temperature, amount of rainfall and stream baseflow temperature. Additional findings indicated that stormwater runoff inputs gave rise to a homogenous river landscape because of a reduced diurnal variation during days with rainfall. However, during certain high volume rainfall events, the river was exposed to short-term thermal shock loading. The river habitat at the site of stormwater discharge was largely devoid of life because of these intermittent thermal shocks. Although it is difficult to solely blame these ecologically sterile patches on the effect of elevated temperature, it is suggested that the result is a combination of high temperatures, oxygen depletion, eutrophication and increased algal blooms. Compounding the problem is the nature of stormwater flows which occur in 'pulses' in which aquatic biota is compromised in its ability to assimilate unpredictable environmental conditions (Bevelhimer and Bennett, 2000; Department of Water Affairs and Forestry, 2005).

Although the research by Young et al. (2013) was invaluable in providing reliable baseline information, significant research gaps remain. The study and data were not able to show the point source effects of stormwater runoff from impervious surfaces on the temperature of the receiving water body. Their research highlighted the need for a detailed study of stormwater temperature changes in relation to rainfall events at a catchment scale (monitoring sites were selected across multiple catchments in New Zealand). Furthermore, temperature data were recorded over 15 minute time intervals which was a significant limitation for thermal changes occurring at a narrow temporal scale. Finally, temperature loggers were placed in the river channel and monitored river water temperature and its subsequent changes. The data were representative of a mixing of stormwater inputs from the entire catchment above making it impossible to differentiate individual thermal contributors.

It can be deduced that if monitoring occurred at specific stormwater point discharge sites, along a single river, this data would provide valuable information on the individual impacts of thermal shock loading. This would be more useful at determining the overall thermal effects of stormwater runoff on urban streams or rivers.

This research aimed to isolate stormwater discharge as a component of total thermal pollution into the Liesbeek River. Methods from previous studies have monitored river water temperature changes and not specifically the individual contributions of stormwater inputs, and this raises a question about the thermal shock loading of a single stormwater pipe network. The question can be answered by determining factors that affect the heating of stormwater (such as surface type), and the possibility of attributing thermal loading to specific variables (such as amount or duration of rainfall). In this study the aim is to examine the "behaviour" of stormwater temperature inputs over the course of selected rainfall events and to quantify the effects of thermal loading on the receiving water system.

1.3 Research Question

This research seeks to address the research opportunity identified in Young et al (2013) which was undertaken by measuring temperatures of event-based stormwater discharge at representative sites along the Liesbeek River, Cape Town. It is expected that thermal shock loading will be pronounced at these discharge sites.

The main research question is:

What causes temperature variations at site specific discharge points along the Liesbeek River?

The study aimed at identifying changes which might occur over the course of a rainfall event and to understand the impact of thermal shock loading from stormwater inputs that arise from elevated temperatures from impervious surfaces. This study could contribute to improved overall protection of aquatic ecosystems and inform future urban river management.

1.4 Aim

The aim of this study is:

To determine the extent and risk of thermal pollution at site specific discharge points, along the Liesbeek River.

In South Africa, formalised urban landscapes are drained by stormwater infrastructure that discharges directly into river channels. This study seeks to determine the relative temperature contribution of this discharge to the receiving water body, the Liesbeek River, and to quantify the thermal impact it has on the overall river temperature. The study will identify a range of variables which interact and influence discharge temperature dynamics, and evaluate the significance and risk. Overall this study aims to inform urban water sensitive management objectives in order to protect receiving rivers from temperature loading resulting from stormwater discharge. The following objectives were developed in order to meet the aim of this study:

- to measure temperature of stormwater discharge
- to analyse data collected over a reasonable time-period during a representative range of rainfall events.
- to determine statistically significant temperature differences between each monitoring site and the instream river water temperature
- to identify material elements and factors which have an influence on stormwater temperatures
- to evaluate the risks of thermal pollution from the empirical evidence
- to recommend appropriate management that could be used to reverse any warming trends within the study site area or at a larger catchment scale.

1.5 Literature Overview

Over time, increased ambient water temperature of urban streams and rivers has been witnessed globally (Kinouchi et al., 2007). The permanent warming of rivers has become a serious concern around the word. Many nations have now included temperature thresholds in their national water policy, and added thermal pollution mitigation techniques to their stormwater management protocol (Young et al., 2013).

Firstly, the study examines literature on the thermal regime of rivers. Understanding natural temperature dynamics of a river is critical for assessing the risk which thermal pollution might impose . Therefore, the scope of this study has a particular focus on urban stormwater discharge, which is considered as a significant source of thermal pollution. This source of pollution arises from stormwater runoff which flows over heated artificial surfaces and becomes thermally loaded (Herb et al., 2008).

Therefore, one future concern regarding the continued enrichment of urban rivers is that predicted increases in urbanisation could mean potential increases in catchment imperviousness. This will result in rivers becoming more susceptible to heated stormwater inputs. Exacerbating this problem is that temperature has yet to be recognised as a contaminant of concern. Moreover, there is limited available information which sets out temperature thresholds and research which should inform these thresholds is seriously lacking (Young et al., 2013).

A recent concept known as Water Sensitive Urban Design (WSUD) has been highlighted as an appropriate, alternative approach to site design and development, in cities (Brown et al., 2008). WSUD conceptually does not directly discuss the effects of thermal enrichment of urban rivers. However, in practice, certain mitigation devices do advocate for maintaining river baseflows and improved infiltration. Furthermore, water sensitive urban design includes retaining natural areas and introducing pervious surfaces. Literature suggests that in order to reduce the effects of thermal enrichment infiltration should be promoted within the catchment (Dorava et al., 2003a). Additionally, increased shading, increased river baseflows and a reduction in impervious surfaces will improve a river's buffering capacity against thermal pollution (Walsh, 2004). Thus, it would seem that the WSUD approach indirectly advocates for mitigation of thermal enrichment (Young et al., 2013; Walsh et al., 2005a). This study aims to later scrutinize literature on mitigation approaches, and to evaluate their effectiveness with regard to thermal enrichment.

Furthermore, literature on factors which affect the temperature of stormwater discharge will be unpacked. This is important for providing explanation behind the observed trends in this study's findings. Likewise, previous research, such as key models, which have been developed to predict urban thermal dynamics, will be unpacked. This is necessary to understand the complex interactions of variables which affect stormwater temperature (Nelson and Palmer, 2007).

The specific rationale of this research is to provide improved understanding of stormwater discharge, as a source of thermal pollution. Additionally, the study aims to quantify the extent of thermal loading, and assess the risk it imposes on receiving river systems. This is based on the premise that adverse ecological impacts occur due to increased river temperature (Ross-Gillespie, 2014; Olsen et al., 2011). This is discussed further in section 2.3. Finally, methodological limitations and solutions will be discussed, so that continued research within this theme is possible.

1.6 Research Design Overview

During a rainfall event in Cape Town, and the Liesbeek Valley where this study was conducted, stormwater runoff is typically collected in catchpits and conveyed via stormwater infrastructure and thus removed away from built-up areas. The surface runoff drains areas with a high percentage of connected impervious land-cover. The temperature of this water is elevated by these artificial surfaces and is considered a substantial contributor of thermal enrichment of the Liesbeek River. Stormwater discharges directly into the main river channel at various point sources of discharge.

Four stormwater pipe outlets were selected as monitoring sites, and are located in the middle-to-lower reaches of the catchment. The four pipe outlets frequently discharge event-driven stormwater into the river. This stormwater drains the surrounding area of two of the oldest urbanised suburbs of Cape Town, namely Mowbray and Observatory.

The temperature of the stormwater discharge, as it enters the river, was measured using *Thermocron iButton Loggers*. These sensors were placed within the pipeline near the outlet. The primary research method makes use of *Thermocron iButton Loggers* (referred to as iButton loggers hereafter). These sensors are programmed to capture and record continuous temperature data at selected intervals. In addition hourly rainfall and air temperature was acquired from the South African Weather Service (SAWS) and was used in conjunction with the iButton temperature data. The meteorological data was recorded at the weather station located within the study area at the South African Astronomical Observatory, Cape Town.

Results from this study are compiled in three sections. Firstly, a Geographic Information System desktop analysis was undertaken. This was to provide contextual knowledge of the environment these iButtons had been placed in. The GIS analysis was used to inform explanations of temperature trends, observed in the data. Next, collated data was graphically presented using MATLAB. Stormwater temperature was plotted against event variables, in order to visualize temperature dynamics over the course of an event. Observed temperature trends were discussed with reference to the literature.

Finally, a statistical regression model was used to test the type of relationship existing between stormwater temperature and event variables. The significance of each was assessed.

Combined findings are discussed with reference to the literature, in order to evaluate the risk each stormwater pipe outlet imposes on the receiving Liesbeek River.

1.7 The Liesbeek River: Study Area

The Liesbeek River displays attributes of a degraded river system in the lower reaches. The State of Rivers Report (2005) graded the present health of the middle and lower Liesbeek as 'fair' quality. The lower stretches offer a poor diversity of aquatic habitat and where tolerant or opportunistic species dominate. In part this is due to high stormwater inflows, high point and non-point source pollutant concentrations and low summer base flows. In contrast the upper reaches of the Liesbeek River are less degraded. The upper reaches are surrounded by relatively low density residential housing and other low intensity land use. These upper stretches provide a buffering capacity to the middle-lower more degraded river stretches. Figure 1.1 below illustrates the Liesbeek River catchment and the four monitoring sites situated in the lower reaches.

Figure 1.1: Study Area: The Liesbeek River Catchment

The middle-to-lower reach of the river catchment encompass the growing suburbs of Cape Town with a large proportion of the catchment comprising impervious surfaces. In addition, approximately 70% of the Liesbeek River has been canalised. The urban management history of waterways in Cape Town is characterized by efforts to address flooding risks. To this end, formal urban areas are serviced with an extensive series of stormwater networks that were designed to drain cities from "nuisance" surface water. In many cities stormwater was, and still is, viewed as a health risk and flood hazard with little or no focus on its ecological importance (Paul and Meyer, 2001). Subsequently, a suite of negative impacts arose from conventional urban stormwater drainage. Typically, concentrated thermally enriched stormwater runoff, which is washed off from impervious surfaces, and directly discharged into the main river channel, posing a threat to aquatic and riparian systems (Paul and Meyer, 2001; Walsh et al., 2005)

Figure 1.2 shows the number of stormwater outlets per 50m length of Liesbeek river. The middle to lower stretch of the Liesbeek show a higher density of stormwater discharge outlet points compared to the upper reaches. This stretch of river receives runoff draining urbanised land-cover with a mixture of land-use zones including residential housing and apartment blocks, commercial offices, recreational sportsfields and small, light industries.

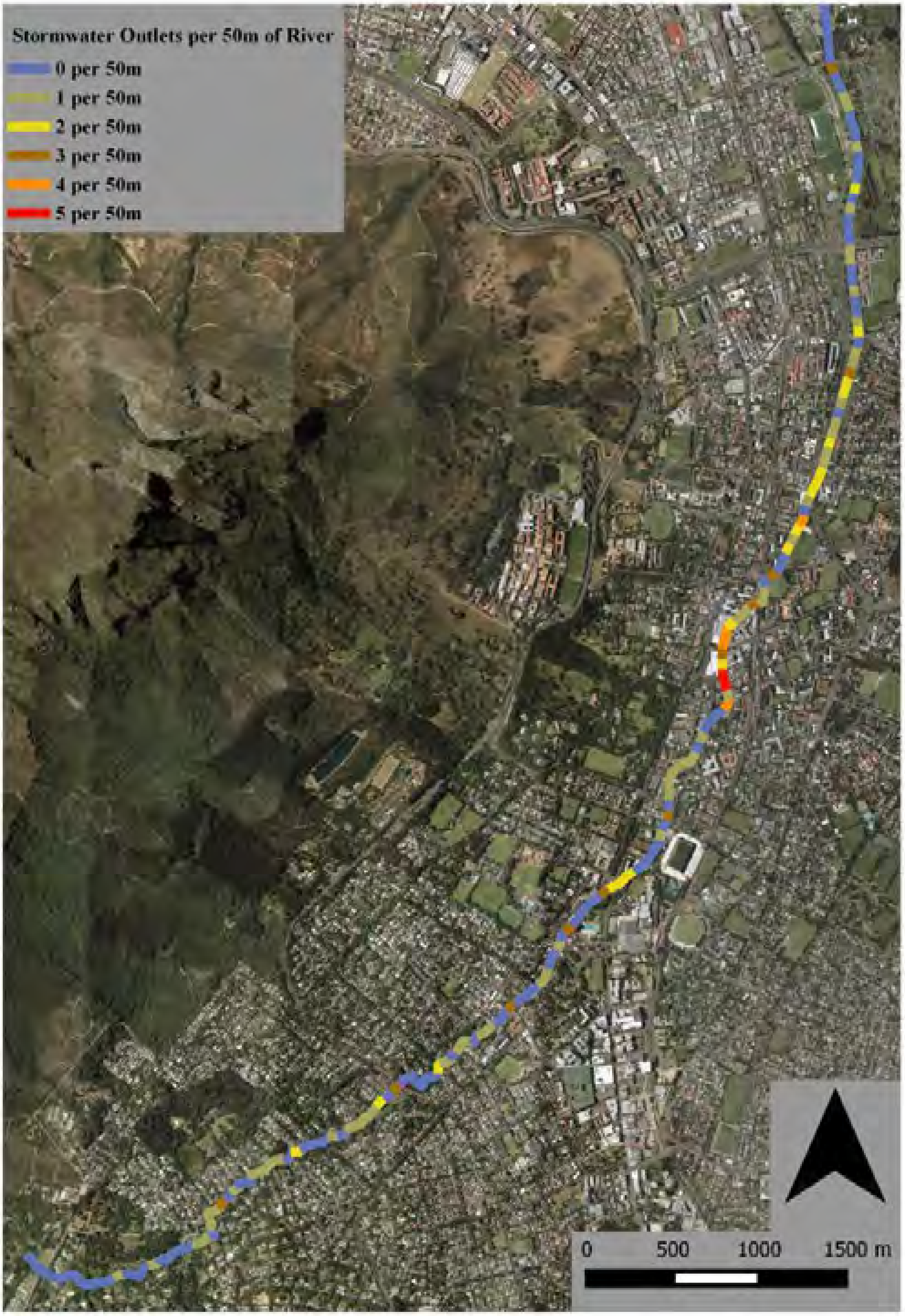


Figure 1.2: Stormwater Outlet Density Along the Liesbeek River: Number of Stormwater Pipe Outlets per 50m Length of River

The Liesbeek River has experienced a steady increase in ambient water temperature over the last 20 years. Galli (1991), states that "the increase in stream temperatures was related to the degree of imperviousness of the contributing area", by a factor of 0.09°C for every 1% increase in impervious area (Galli, 1991), on page 188. Figure 1.3 illustrates the increasing temperature trend for the Liesbeek River. The figure shows river temperature monitoring; which took place from 1988 to 2002, and in the months May through to September. The headwater site which is situated at Kirstenbosch Gardens not far from the source of the river which is on the eastern face of Table Mountain, is relatively unaffected by thermal impacts and thus displays a constant trend in temperature, over time. However, the downstream monitoring site, which is situated in the mid-to-lower reaches of the river, shows a noticeable increasing temperature trend. This stretch of river is surrounded by urban land use and over time increased urbanisation and impervious coverage has occurred and is a potential cause for the rise in ambient river temperature as suggested earlier.

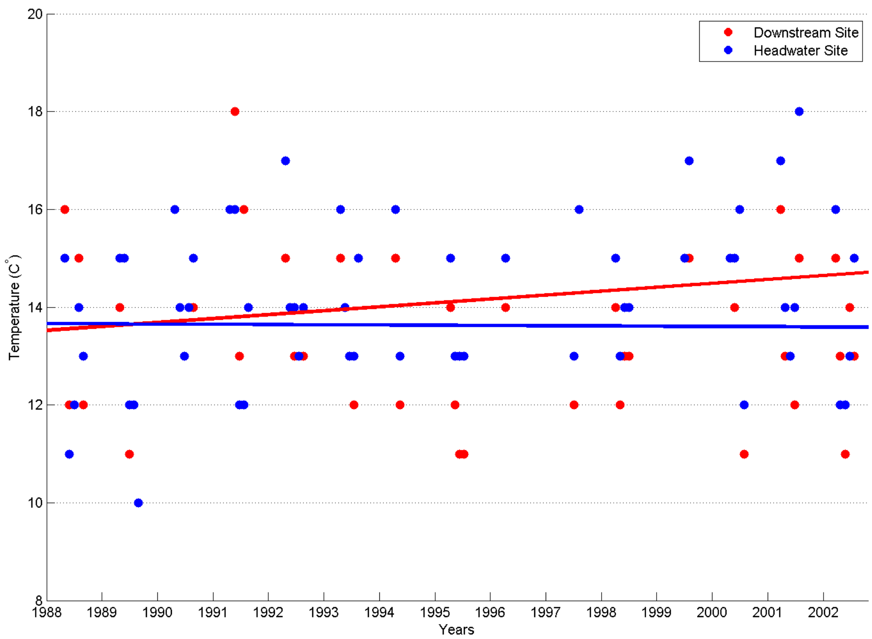


Figure 1.3: Ambient river temperature trends, for two sites along the Liesbeek River, Monitoring occurred over the months of May to September and from 1988 to 2003

In general, the mid-lower river stretches of the Liesbeek River, would naturally experience warmer temperatures. This is due to their shallower nature and less riparian shading compared to the headwater reaches. However, thermally enriched stormwater inputs are exacerbating the natural trend. This stretch of river now experiences wider temperature ranges, higher maximum temperatures and frequent thermal shocks (Department of Water Affairs and Forestry, 2005).

The following chapter discusses the thermal regime of rivers. Furthermore, factors which might affect this sensitive regime such as sources of thermal pollution are discussed in detail. The chapter draws particular focus to stormwater runoff, which is considered as a significant source of thermal pollution. Finally, the implications of disturbing the thermal regime are highlighted and techniques suggested to mitigate the effects of thermal pollution are scrutinised by evaluating their effectiveness.

Chapter 2

Literature Review

2.1 Thermal Regime of Urban Rivers

The natural thermal regime of a stream or river is affected by atmospheric conditions, topographic characteristics, stream discharge and streambed characteristics. These factors are summarized in Figure 3.1, which has been adapted from Caissie (2006).

Atmospheric conditions are responsible for changing water temperature in the heat-exchange process at the water-surface interface. As ambient air temperature above the water surface increases, there is an increase in ambient water temperature of the river which permeates from the surface to lower depths. This is considered the single greatest factor in the natural increase in water temperature (Bartholow, 1991). Thermal stratification occurs in calm weather conditions where warmest temperatures are found at the surface and deeper layers become cooler (Jones et al., 2012). However, studies have shown that the relationship between air temperature and water temperature are not necessarily linear (Caissie, 2006). This is due to influences by groundwater at low air temperatures or from evaporative cooling at high air temperatures: these factors act to regulate water temperature. It was found that using a logarithmic relationship between air and water temperature is more appropriate. The heat/energy exchange occurring at the air-water surface is a result of temperature differences between the atmosphere and river. When river water temperature correlates with air temperature it is known to be at equilibrium.

Solar radiation is major source of thermal input, especially to an un-shaded body of water (Young et al., 2013). Consequently, natural riparian vegetation acts as shading from high solar radiation, and this can have a significant cooling effect on water temperature. Additional factors affecting water temperatures are evaporation, relative humidity and local wind speed. Furthermore, precipitation can influence water temperature. Depending on the amount and temperature of the rainfall, this will influence cooling or warming of water temperature. Topography or geographical setting also plays an important role in the thermal regime of rivers, as this influences atmospheric conditions. The aspect, altitude and latitude of a river together influence ambient river temperature patterns. For example, a headwater stretch situated on a north or south facing slope, might influence upland stream temperature (Caissie, 2006).

Another factor influencing the thermal regime of a river is discharge, which refers to the inflows and outflows of a river system. These influence the heating capacity or cooling (through mixing) of water temperature. This is dependent on the volume and temperature of river inflows and outflows. For example, stormwater runoff discharging into a river can have either a cooling or heating effect on river temperature, depending on its thermal load.

Finally, streambed characteristics and the heat exchange processes which occur at the streambed-water interface are additional factors influencing the thermal regime of a river. Temperature is influenced by groundwater contributions and energy exchanges which occur at the sediment-water interface. However, these energy transfers are less well understood.

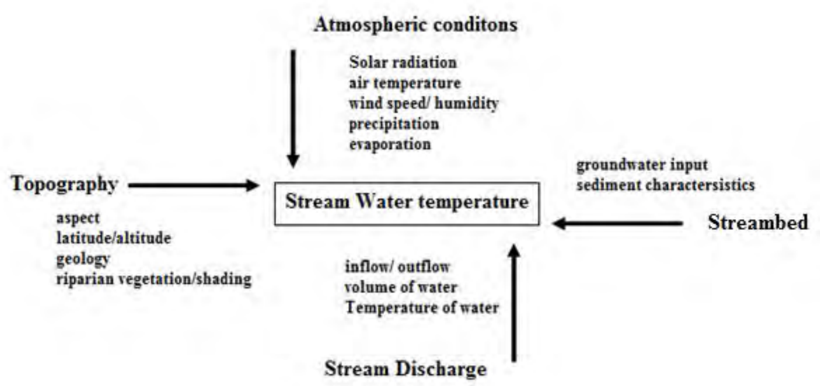


Figure 2.1: Factors influencing the thermal regime of rivers, adapted from (Caissie, 2006)

In addition to the factors mentioned above, river temperature regimes will exhibit spatial and temporal variability. In terms of spatial variability, it is generally accepted that mean daily water temperature increases in a downstream direction (as stream order increases). Headwater streams will be closest to groundwater temperature and will thereafter increase downstream. However, the increase in water temperature is not linear and the rate of increase is generally greater for small streams compared to large rivers (Caissie, 2006).

On a temporal scale, water temperature varies following a sinusoidal cycle. Water temperature reaches a daily minimum in the early morning (at sunrise) and a daily maximum in late afternoon to early evening. Furthermore, the daily temperature range (minimum-maximum) is different for different stream sizes. Ranges are generally small for small headwater steams as temperature is more dominated by groundwater. For larger streams, ranges can be greater, because temperature is dominated by atmospheric conditions. Similar to the daily temperature cycle, streams and rivers also experience an annual/seasonal temperature cycle, with the lowest water temperatures occurring at the start of spring and the end of autumn (Webb and Walling, 1993).

In contrast, urban rivers display noticeably different thermal regimes. This is due to anthropogenic activities and perturbations occurring within the catchment. Changes to the environmental factors summarized in Figure 2.1, result in significant changes to the thermal regime of a river or stream. Most notably sources of thermal pollution can exacerbate environmental factors. For example, increased impervious coverage in the catchment, will limit infiltration of stormwater runoff. This in turn will reduce the cooling effect of groundwater inputs into the river. This might cause changes to daily water temperature ranges (i.e. reduced amplitude between daily minimum and maximum temperature).

The removal of indigenous and riparian vegetation within the urban catchment has significant adverse effects on the thermal regime of a river or stream. Many studies have confirmed the direct increase in stream temperature, due to increased solar radiation, from the removal of shading (Rutherford et al., 1997a). If the removal of riparian vegetation occurs in the headwater streams it can have severe consequences for the entire river stretch. Elevated temperatures can persist for many hundreds of meters downstream. With the absence of a cooling factor, such as groundwater recharge or shading, increased temperatures are not able to "shed" the added heat, but continue to warm.

Another noticeable change to the natural thermal regime is the loss of spatial temperature variability along the longitudinal profile and across the water column (Poole and Berman, 2001). This is due to anthropogenic changes to stream discharge. For example, during a rain event, stormwater is heated as it passes over artificial surfaces. Warmer inflow will directly change the water temperature at the point of discharge i.e. the water column becomes uniform in temperature. Additionally, the cumulative effect of many discharge points will cause river temperature to increase across the longitudinal profile. Heated stormwater discharge has the capacity to influence large portions of a river system. If the river channel has been shortened (through channel engineering) then the dilution capacity of the river is reduced.

Finally, the impact of anthropogenic induced climate change will affect atmospheric factors which influence the thermal regime of rivers. Increased evaporation and changes to precipitation patterns, as well as expected increases in air temperature will undoubtedly influence river water temperature. Changes will be both temporal and spatial, significantly affecting the ecological functioning of the river system.

Anthropogenic perturbations modify the thermal regime of rivers and streams and as a result will affect aquatic resources and their functioning. Urban rivers exhibit thermal characteristics which can be summarized as follows (Bevelhimer and Bennett, 2000):

- Increased ambient water temperature
- Decreased thermal variability, spatial and temporal
- Increased occurrences of thermal shocks
- Daily and seasonal temperature range shifts
- Reduced dilution/buffering capacity
- Reduced groundwater temperature regulation

In order to improve understanding of the thermal regime of urban rivers, this requires the identification of sources of thermal pollution, which occur in the catchment. These are discussed in detail in the following section.

2.1.1 Sources of Thermal Pollution

Urbanisation results in increased stream or river temperature which includes increased daily maximum temperatures and increased frequency in the number of days where natural stream temperature is exceeded. This is due, in part, to the formation of the urban heat island, or localised areas of heat storage (e.g. warmer ambient air temperatures near urban centres) (USEPA, 2008). However, there are many other aspects of urbanisation which contribute to additional stream warming. According to Young et al (2013) thermal pollution is:

> "The degradation of water quality by any process which changes its ambient water temperature" (Young et al., 2013:5).

The paper by Young et al. (2013) continues to express that unlike other contaminants found in urban streams or rivers, which are well understood and their effects have been extensively managed for, elevated water temperature is not widely recognised as a type of contamination (Young et al., 2013). In an urban area there is a wide range of sources generating thermal pollution. The three main sources for consideration are reduced natural vegetation cover, increased impervious land cover and industrial/wastewater inputs" (Bartholow, 1991; LeBlanc et al., 1997; Nelson and Palmer, 2007).

- **Reduced natural vegetation cover:** across the catchment, means there will be reduced shading which leads to increased solar radiation reaching the water surface.
- **Industrial/Wastewater inputs:** can lead to the direct discharge of warmer effluents into streams and rivers.
- **Increased impervious land cover:** will lead to higher rates and volumes of stormwater runoff, this runoff is heated as it comes into contact with warm artificial surfaces eventually discharging into the main river channel.

In addition to higher stormwater flows mentioned above, increased impervious land cover also prevents infiltration and groundwater recharge. Groundwater recharge is vital for mitigating high water temperatures, especially in summer when rains are absent. The shallow baseflows in an urban river are more susceptible to thermal effects than deeper waters, charged with cool groundwater (Mills and Williamson, 2008).

Changes in flow volumes and runoff velocities can erode and widen downstream channels. Lower river depths and lower flow rates, caused by stream bank erosion, sediment loading and widening, all allow streams to be more quickly influenced by higher ambient air temperatures and solar heating. Furthermore, increased erosion and sediment loading, entering the river, can cause increased turbidity. According to Schueler (1987), who found that turbid rivers or streams are known to be warmer, as sediment particles allow more of the sun's energy to be absorbed by the water, this increases ambient water temperature independently from other inputs (Schueler, 1987).

Finally, a contentious source of thermal pollution is runoff that is diverted into stormwater retention ponds. These devices were thought to be examples of Best Management Practices for urban streams (BMPs). However, research has shown that ponds can act as sinks, increasing water retention time and warming (Jones and Hunt, 2010; Sabouri et al., 2013). Moreover, lack of appropriate shading over these ponds can increase temperature further (Schueler, 1987; Smith, 2006; Jones and Hunt, 2010; Young et al., 2013). Extensive research has been done on stormwater detention ponds and their effect on temperature enrichment. Additionally, research is already underway investigating mitigation techniques to remedy the effect of stream heating from stormwater detention devices. Some examples of this research include papers by Lieb and Carline (2000), Marsalek (2002), Maxted et al. (2005), Herb et al. (2009), Jones and Hunt (2010), Arseneau et al. (2010) and by Sabouri (2013).

This research aims at analysing the temperature of stormwater discharge and asserts that urban landscapes are substantial contributors of thermal pollution in urban streams and rivers (Schueler, 1987; Galli, 1991; Smith, 2006; Young et al., 2013). Stormwater runoff is absorbed and transfers heat energy as it passes over impervious surfaces, over parts where heat storage capacity is relatively high such as roofs, pavements and roads. In order to drain this runoff away from city developments, it is collected by catchpits and conveyed via piped networks (reticulation). These pipes then discharge stormwater directly into the main river channel, at multiple sites along the river. However, relatively little is known about event-based stormwater temperatures and the degree to which it impacts on receiving rivers (Young et al., 2013). Furthermore, the unique nature of each rain-event which varies with the amount of rainfall, duration of rainfall and ambient air temperature, adds to the complexity of the analysis. The interaction of these variables differs for differing rain-events.

As part of a new approach to water management, there is an increased advocacy for a focus on improving stormwater quality. There is now growing international recognition that water temperature be included in the water quality index and should be monitored more closely (Young et al., 2013). Current South African regulations and monitoring protocol do not directly recognise temperature as a contaminant of concern.

The most common direct and indirect sources of thermal pollution, impacting on urban hydrology, have been mentioned above. These are applicable to many cities around the world. Each city would have context specific sources of thermal pollution, which would need unique investigation, as is the case for the Liesbeek River, Cape Town. In order to quantify the effect of stormwater as a source of thermal pollution, it is necessary to understand the factors which might affect the temperature of stormwater discharge.

2.2 Factors Affecting Stormwater Discharge Temperature

A number of factors influence stormwater runoff temperature in the urban landscape, including evidence of both heating and cooling factors. These are discussed below with reference to local examples and international literature.

2.2.1 Land Use Type and Catchment Development

Catchment development has a significant impact on the extent of thermal heating (Pluhowski, 1970; Galli, 1991; LeBlanc et al., 1997). Stormwater temperature increases as runoff passes over heated impervious surfaces, these surfaces are heated by incoming solar radiation. In the United States, the effect of catchment development on water temperature has been widely studied, with a number of empirical models developed to characterise the effects of catchment imperviousness on cold water receiving environments (Shanahan, 1984; Roa-Espinosa et al., 2003; Arrington, 2003; Herb et al., 2009b).

Galli, (1990) pioneered research in summertime average stream temperature and catchment imperviousness. Although a correlation in imperviousness-to-water temperature was reported, there are a number of variables influencing the relationship. For example, local meteorological conditions make it difficult to predict the extent of thermal effects in urban streams. Although these studies illustrated that stream temperatures typically increase with increasing watershed imperviousness; there are currently few models available which can predict the magnitude of these increases (Young et al., 2013).

As catchment imperviousness increases streams become more susceptible to stormwater runoff inputs. Furthermore, even at relatively low catchment imperviousness, frequency of exceedences, in terms of stream temperature standards still increased. In other words, even small changes to the landscape translate to pronounced impacts on stream temperature dynamics (Young et al., 2013) .

In Dane County, Wisconsin, recorded runoff temperatures from urban impervious areas were as high as 29°C (Arrington, 2003; Roa-Espinosa et al., 2003). Dane County is located in a temperate climate zone, with average summer peak ambient air temperature of 27°C, and average summer lows of 14°C. In comparison, Cape Town experiences average winter peak air temperatures of 20°C and average winter lows of 10°C. However, unlike Dane County which experiences summer rainfall, Cape Town has a Mediterranean climate with winter rainfall occurring during the months of May to September.

Catchment development and increased impervious land cover also contributes to increased flooding and erosion. High volumes of stormwater carrying sediment loads can be heated further due to greater energy transfers. In addition, high stormwater flows may indicate reductions in groundwater recharge (Young et al., 2013). Stream baseflows are important as a diluting factor to reduce higher runoff temperatures. Unfortunately, in South Africa, the impacts of increased catchment imperviousness on the receiving water environment are not well understood. Cape Town, specifically the study area in which this research takes place, has experienced increases in urban development and densification. The area encompasses a range of land use zones including; residential, recreational, rail and road transport and commercial business.

2.2.2 Surface Type

During a rainfall event or storm, heat is transferred to the water that falls as precipitation on these surfaces (Dorava et al., 2003a). The type of material used in construction of urban surfaces has a significant influence on stormwater runoff temperature increases, through heat transfer. Differences exist in thermal conductivity and reflectivity of different types of urban surfaces. In addition, factors such as air temperature, solar radiation and shading can all influence the amount of heat transferred from the surface to stormwater runoff.

Solar reflectance is the main determinant of the maximum surface temperature of material, where highly reflective surfaces maintain cooler temperatures (Young et al., 2013). Heat from solar radiation may concentrate near the surface or be transferred downward in the material, to be re-released at night. Thermal emmitance, which is the amount of heat a surface will radiate per unit area, at a given temperature, is also an important factor when considering stormwater temperature increases. High emittance surfaces give off heat more readily therefore these types of surfaces will reach thermal equilibrium at lower temperatures compared to surfaces with low thermal emmitance (Herb et al., 2007a). Asphalt surfacing, which is typically found in urban river catchments, has a low reflectivity and high absorption capacity of solar radiation. Surface temperatures of this material have been known to reach 60°C (Asaeda et al., 1996; Jones and Hunt, 2009). These findings were supported by Thompson et al (2008), which further reported that average asphalt runoff temperature is strongly dependant on initial asphalt temperature at the start of a rain event.

Continued research in this field by Janke et al. (2009), found that heat transfers from urbanised areas to streams are more sensitive to rain density, rainfall duration and antecedent pavement temperature. Rather than less influential physical parameters such as slope, roughness and the length of paved surface (Sabouri et al., 2013). Using computer generated models a considerable amount of research has been completed in thermal enrichment of stormwater runoff by paved surfaces (Galli, 1991; Picksley and Deletic, 1999; Verspagen, 1996; VanBuren et al., 2000; Jia et al., 2001; Haq and James, 2002; Roa-Espinosa et al., 2003; Herb et al., 2007a; Herb et al., 2007b; Thompson et al., 2008a; Herb et al., 2009a). For summative purposes, the research is presented in Table 2.1 below.

Researchers	Model Description	Abbreviation
Verspagen (1996)	This model used the "decade method" to estimate the temperature of surface runoff from paved surfaces. Results reported mean runoff temperature as a linear function of initial pavement temperature, before wetting	***
Picksley and Deletic (1999)	This model developed a statistical analysis using graphical observations of thermal trends, analysis of the event mean temperature (EMT), and analysis of thermal exponential decay theory	***
Jia et al. (2002)	The Water and Energy Transfer Processes model (WEP) predicts changes in water and energy budgets associated with land use changes in urbanized and partially-urbanized watersheds	The WEP model
Haq and James (2002)	The Thermal Enrichment of Stormwater model (TES) is a direct application of Verspagen's work. This model is characterized for a big difference made in calculation of the Reynolds Number	The TES model
Herb et al. (2006)	Developed the Minnesota Urban Heat Export Tool (MINUHET) which is an analytical model capable of simulating the flow of stormwater surface runoff and its associated heat content for small watersheds	The MINUHET model
Roa-Espinosa et al. (2003)	The Thermal Urban Runoff model (TURM) is a model for determining runoff temperature for typical urban areas. The model is event based, its major limitation is the rainfall events are treated with uniform intensity as a consequence of using the Soil Conservation Service (SCS) curve number method for prediction of runoff hydrographs	The TURM model

Table 2.1: Previous Research Regarding Thermal Enrichment of Stormwater Runoff by Paved Surfaces, and Their Associated Computer Models

Roa-Espinosa et al. (2003), modelled the heat transfer from warm surfaces to runoff waters. It provides a good assessment of the contributions of various factors to the overall rise in water temperature. The Thermal Urban Runoff Model (TURM) was developed to predict runoff temperature increases by calculating the heat transfer between heated impervious urban areas and surface runoff. TURM outputs found that in general, hot paved surfaces receiving rainfall initially released energy through evaporation, but then as rainfall intensity increased, high temperature runoff was generated (Roa-Espinosa et al., 2003).

The original model by Herb et al. (2006) and further developed by Herb et al (2007a), simulated surface runoff temperature and heat export for ten terrestrial covers, including concrete, pavement (asphalt), commercial roof (asphalt/gravel), residential roof (asphalt shingle), lawn, tall grass, forest, crop (corn and soybeans), and bare soil, as well as an un-shaded wet detention pond, a reservoir and a vegetated pond (Herb et al., 2006; Herb et al., 2007a; Young et al., 2013). Average runoff temperature ranged from 21.5°C for a forest cover, to 24.9°C for concrete. More importantly, the average maximum runoff temperature ranged from 22.9°C for a forest to 28.7°C for asphalt. Pavement (asphalt) commercial roofs, bare soil, the wet detention pond, and lakes/reservoirs were all found to give runoff temperatures high enough to "significantly impact stream temperature" (Herb et al., 2006; Herb et al., 2007a). Interestingly, the variation in runoff temperatures between land uses was not large. However, it is important to keep in mind that even small temperature differences can cause severe thermal impacts on stream biota.

Table 2.2 below summarizes runoff temperature and surface type according to research by Herb et al. (2007a). The study was conducted in Albertville, Minnesota. While the climate in Albertville is not directly comparable to Cape Town (average summer temperatures in Albertville are more similar to average winter temperatures in Cape Town) the table still provides a good comparison of the relative ranking of runoff temperatures from different surfaces.

Surface Type	**Average Runoff Temperature ± Std. Dev. °C**	**Peak Runoff Temperature ± Std. Dev. °C**
Asphalt	24.5 ± 3.1	28.7 ± 3.5
Bare Soil	24.5 ± 2.5	27.1 ± 2.8
Commercial Roof (Asphalt/Gravel)	24.4 ± 4.4	29.6 ± 4.8
Concrete	24.9 ± 2.8	28.6 ± 3.2
Grass (Short)	22.0 ± 1.2	23.4 ± 1.8
Grass (Long)	22.0 ± 1.3	23.6 ± 2.0
Forest	21.5 ± 1.2	22.9 ± 1.9
Residential Roof (Asphalt Shingle)	20.6 ± 3.1	24.0 ± 3.6

Table 2.2: Runoff Temperature and Surface Type adapted from Herb et al. (2007a)

From Table 2.2 above, the surfaces which produce the highest runoff temperatures are concrete and asphalt (Asaeda et al., 1996; Kevern et al., 2009; Wardynski et al., 2013). However, according to Herb et al. (2007b) these results can vary depending on the nature of each rainfall event. Thompson et al. (2008) found that runoff temperatures from heated surfaces initially exhibit a short-term temperature increase, and then cool as the rainfall event progresses. This research which was conducted in Wisconsin, United States, found that summer asphalt surface temperatures immediately prior to rainfall were approximately 43.6°C and decreased by 12.3°C over sixty minutes, as rain cooled the surface. Initial heated runoff temperatures from the asphalt averaged 35°C, decreasing by an average of 4.1°C at the end of the event.

Referring to Table 2.2, bare soil runoff temperatures can be comparable to asphalt. However, the thermal load which bare soil exports is less than asphalt. Soil exports 32% less heat per unit area than asphalt due to the reduction in runoff volume as a result of infiltration (Herb et al., 2007a; Herb et al., 2007b; Chapman et al., 2008). The runoff temperatures observed from roofs was dependent on the type of material it was made from, and therefore its ability to absorb and store heat energy, otherwise known as thermal mass.

Residential roofs (asphalt shingle) exhibited lower runoff temperatures compared to commercial roofs. It was concluded that residential roofs have a lower thermal mass and cool quickly during a rainfall event (Herb et al., 2007a; Herb et al., 2007b; Young et al., 2013). However, commercial roof made from asphalt or gravel, produced much higher peak runoff temperatures, of up to 29.6°C ± 4.8°C. It was speculated that the large surface area of the roofs was contributing to the resulting thermal load. Chapman et al. (2008) observed that residential roofs exported 70% less heat per unit area than commercial roof, due to its lower thermal mass. The research also found that asphalt surfaces export less heat than concrete (despite the black colour of asphalt compared to the white colour of concrete) which was due to asphalt having a lower thermal mass. There is currently no data available to directly compare the heating effects of residential versus commercial roofs in Cape Town. Depending on which material is denser in structure this will result in a greater heat export, per unit area. Increasing the solar reflectivity of any surface, through coatings or pigmentation to reflect solar energy, can greatly moderate surface temperature (USEPA, 2008).

Finally, it is evident that vegetated surfaces generate substantially lower runoff temperatures, and export less heat per unit area compared to pavement (LeBlanc et al., 1997; Rutherford et al., 1997a; Sponseller et al., 2001; Herb et al., 2007a). Furthermore, vegetated surfaces have a smaller range difference between peak and average runoff temperatures and a smaller standard deviation range. This indicates that runoff temperatures are more consistent and have a narrow range of variation. Different vegetation types produced similar runoff temperatures (Herb et al., 2007a).

It is clear that surface-type has a significant effect on stormwater runoff temperatures. Material characteristics and properties affect thermal mass and heat export rates. It is important to note the scale at which heat transfer is occurring. Many studies have analysed the individual contribution of a single surface-to-water transfer, for example the contribution of heat per m^2 of concrete to water runoff. Results are then multiplied by the amount of area covered in concrete to better understand the total heat transfer.

Additional research has looked at a larger scale and studied a more generalised land parcel, and its associated heat transfer. For example, the temperature of stormwater discharge at an outlet point would be representative of a mixture and accumulation of surface type transfers. At this scale it is difficult to identify whether a surface is acting as an "energy absorber" or "energy emitter". In this case differing rainfall event variables such as, time of day, the amount, intensity and duration of rainfall, will produce a different total heat transferred result each time. When modelling urban heat dynamics, uncertainties increase with increasing scale, a large variety of interacting variables need to be accounted for in the model, furthermore, flexibility is needed within the model to allow for their differing responses (Shanahan, 1984).

It can be concluded that during a rainfall event, as rain passes over urban landuse, surface-type can be considered the single most important contributor to runoff temperature. However, there are additional factors which influence stormwater temperature, which are shading and climate. These are discussed respectively in the section to follow.

2.2.3 Shading and Climate

When considering a pre-developed state, natural vegetation would have been abundant. However, after human settlement and the subsequent removal of catchment vegetation, stream and river temperatures were adversely affected. The lack of shading and its effect on temperature has been identified as a key stressor by a number of authors including; Burton & Likens (1973), Quinn et al. (1994), Rutherford et al. (1999) and Mills (2008).

Over a longitudinal distance, river temperature can change drastically, especially when riparian vegetation is removed from headwater river stretches. Research by Burton & Likens (1973) found that stream water temperature increased by approximately 5°C along stretches where riparian vegetation had been experimentally removed. Similarly, Galli (1990) noted an increase of 0.83°C per 30.5 metres of a poorly shaded reach. Whilst riparian shading does not directly influence stormwater temperature inputs, a long stretches where there are high temperature inputs from stormwater, these will be exacerbated by lack of shading.

Herb et al (2007a) found that emergent vegetation shading a pond can reduce runoff temperature by up to 6°C compared to an un-shaded pond. Hence, this indicates that even moderate shade levels may be sufficient at restoring baseline stream temperatures. Further research has been done regarding the effects of restoring shade on certain species assemblages. Preferences for riparian shade are strongly species-specific and additional variables such as distance from the coast and differences in cover along a longitudinal gradient, will all influence species assemblage (Kelly, 2010).

It has been found that measuring shade can be highly variable, and difficult to accomplish in an un-biased way. It is therefore not a strong indicator of the effects of thermal heating in streams. It is important to note that shading does not have to be provided by vegetation, but that buildings in conjunction with topography and aspect also provide shading. Not only do they provide shade to a river or stream stretch, but also to urban surfaces, which stormwater may pass over (Rutherford et al., 1997a).

In accordance with this idea, Sabouri et al. (2013) conducted research relating to the cooling effect of underground stormwater pipes on stormwater runoff temperature. Using a combination of runoff monitoring and modelling the study found that the longest storm sewer pipe length (LPL) and the storm sewer pipe network density (PND) are the two key parameters that control the cooling effect of the underground sewer system. Analysis showed that if LPL increased from 345m to 966m this resulted in a runoff temperature drop by 2.5°C (Sabouri et al., 2013).

Climate plays a significant role in predicting surface runoff temperatures; in particular, determining air and rainfall temperature (Roa-Espinosa et al., 2003). Ambient air temperature has a greater influence on stream temperature, even more so than flow (Galli, 1991). In a natural river environment stream temperature can decrease as a result of a drop in air temperature which accompanies most rainfall events. Herb et al (2009) found that climate parameters such as air temperature, dew point temperature, and solar radiation, prior to a rainfall event are more important factors in determining runoff temperature than parameters such as length and slope of impervious surfaces. However, pavement thermal parameters, such as specific heat and thermal conductance, have an overarching influence on initial runoff temperature.

As a rainfall event continues over time, the amount and intensity of rainfall becomes an important contributing factor (Galli, 1991). The instantaneous heat export rate which is "the rate at which heat energy is delivered to a receiving stream, from a rainfall event, at any given time," is strongly related to the instantaneous change in stream temperature (Herb et al., 2007b). This rate is an important measure in determining total thermal pollution. According to Herb et al. (2007a) and Herb et al. (2007b) rainfall events with a high heat export rate have several characteristics in common:

- They will occur in the afternoon
- They are preceded by warm sunny weather which results in high surface temperatures
- They have runoff temperatures above 20°C
- The event will have relatively low total rainfall but with a rapid onset

Hence, afternoon rainfall with small total precipitation, but high initial runoff temperatures (from passing over warm pavements), will contribute a significant proportion to the entire rainfall event heat export. In contrast, increases in stream temperature were not observed during steady, light precipitation, suggesting that urban surfaces had time to cool during the event (Galli, 1991).

Cape Town is situated in a winter rainfall region, where ocean-derived cold-fronts bring passing rain. If the event coincides with high ambient air temperatures (mid-afternoon) and is relatively low volume and low intensity, this could result in high runoff temperatures and subsequent thermal pollution reaching the Liesbeek River. Cape Town receives frequent rainfall events throughout the winter months June, July and August. However, the heat export from rainfall events would be highest in the seasonal transitioning months (either May or September). The Liesbeek River's susceptibility to thermal enrichment from stormwater heating would be greatest in these months, due to higher ambient air temperatures and higher solar radiation. Furthermore, baseflows in these months would be lower and its buffering capacity reduced, exacerbating thermal effects, as stormwater would make up a significant portion of the total river flow.

It is important to recognize a single rainfall event with high runoff temperatures may cause significant effects due to 'thermal shock'. Schueler (1987) referred to these as 'thermal pulses', which in warmer months can exacerbate the magnitude of thermal heating, due to low groundwater flows. During spring or autumn in Cape Town, these 'pulses' can have severe effects on stream biota which are more accustomed to slower heating of water through increases in ambient temperature.

Lieb & Carline (2000) measured rapid stream water temperature increases of up to 6.6°C per hour, following storm events in the United States. This exceeded the recommended 1.1°C increase per hour limit, which was specified by the Pennsylvania Department of Environmental Protection, for the maintenance of aquatic life in cold-water streams. Temperature exerts a significant influence over many aspects of riverine ecosystem functioning. Consequently, altering stream temperature regimes can have serious negative impacts (Bunn and Arthington, 2002) . The subsequent impacts, which heated stormwater has on receiving rivers and streams are discussed further in the section below. Understanding the thermal requirements for a functioning river is an essential component of informed water management.

2.3 The Impacts of Heated Stormwater

A number of studies have been carried out investigating the effects of elevated stream temperature on macroinvertebrates and fish (Richardson et al., 1994; Quinn et al., 1994; Poff et al., 2002; Walsh, 2004; Ross-Gillespie, 2014). Water temperature strongly influences stream ecosystem structure and function and is considered the primary underlying variable driving or constraining a range of biotic and abiotic processes in streams (Nelson and Palmer, 2007) .

Water temperature not only controls physical characteristics of a river, such as the solubility of oxygen, or the rate of photosynthesis (Dodds, 2002; Young et al., 2013). These physical properties indirectly but significantly affect ecological functioning of a river. However, emphasis must be placed on the direct impact temperature can have on aquatic biota. As most aquatic species are poikilotherms (cold-blooded) their internal body temperature varies according to their immediate environment. Consequently, water temperature can have a substantial influence on their biology. Hence, most aquatic biota have sensitive physiological optimum temperature ranges and thermal tolerances (Ross-Gillespie, 2014).

Olsen et al (2011), developed acute and chronic water temperature criteria for native aquatic biota in New Zealand. The criteria can be summarized and Olsen et al. (2011) recommends water temperatures of less than 20°C in 'upland streams' and temperatures less than 25°C in lowland streams. This would ensure that the most sensitive native taxa are protected. While this criterion is not directly transferrable to the South African context, the significance of this research highlights the need to understand thermal requirements of biota as an essential component of informed urban water management (Olsen et al., 2011).

A noticeable gap exists in researching species specific aquatic thermal tolerances. The study by Olsen et al (2011) analysed data for a few species only. The criterion which was established was therefore calculated with a low level of confidence. Using methodology developed by Todd et al. (2008), Olsen's study identified two types of water temperature criteria for aquatic biota. Firstly, acute criteria, have the main objective of protecting species from the lethal effects of short-lived high temperatures. Secondly, chronic criteria, have the objective to protect species from sub-lethal effects of elevated temperatures, hence it provided guidance of the thermal conditions that are suitable for the growth and reproduction of species (Young et al., 2013; Todd et al., 2008; Olsen et al., 2011).

Acute criteria are established using the 'upper incipient lethal temperature' (UILT) value, which is defined as the temperature at which death occurs almost instantaneously. Because species have the ability to acclimatise and therefore extend their upper tolerance limit, the UILT value is variable. The UILT initially increases with increasing acclimatization temperature, but only up to a certain point. Past this point mortality will occur. Bevelhimer and Bennett (2000) recognised that regulatory criteria were based on constant temperatures. However, large daily fluctuations in water temperature can result in significantly different impacts. Currently, there is poor understanding of thermal stress in fish in thermally dynamic environments, due to limited data availability (Bevelhimer and Bennett, 2000). It has been noted that more reliable acute criteria need to be established for a range of species, furthermore, experimental results conducted in most laboratory studies may reflect an over estimation of the real thermal tolerance level of species. This is due to the limitations of replicating the natural environment (Cox and Rutherford, 2000).

Chronic criteria are established using the upper thermal growth optimum (T_{opt}) which includes the UILT and preferred temperature parameters. Or the Critical Thermal Maximum (CTM) is used as the basis for chronic criteria which is defined as the temperature at which an organism's movement becomes disorganised and would be unable to escape the condition of warm temperature (Olsen et al., 2011; Young et al., 2013) . Chronic criteria have been widely researched for key fish species. However, currently, there is no suitable data available for macroinvertabrate species (Cox and Rutherford, 2000).

The absence of certain aquatic biota from streams and rivers can be the result of high water temperatures (Quinn and Hickey, 1990; Quinn et al., 1994; Rutherford et al., 1997a). Fish species tend to select stream temperatures where physiological functions operate at maximum efficiency (Richardson et al., 1994). Although they can survive outside of these temperatures physiological and behavioural changes can affect survival and reproductive success. Furthermore, fish species show a developmental shift in their temperature preference. For example, adult fish species may prefer cooler water temperatures compared to their juvenile life stage (Simmons, 1986; Boubée et al., 1991; Richardson et al., 1994).

Likewise, macroinvertebrate species are considered to have low thermal tolerances and are more sensitive than fish species, resulting in their absence from streams occurring sooner (Department of Water Affairs and Forestry, 2005; Young et al., 2013) High water temperatures occur when headwater stream-side vegetation is removed. This may enhance in-stream primary productivity, resulting in changes to the trophic structure of benthic macroinvertebrate communities. Sponseller et al (2001) reported a significant decrease in abundance and diversity of macroinvertebrate taxa as a result of thermal pollution (Sponseller et al., 2001). Both acute and chronic criteria had to be adapted, by introducing a margin of safety. This was to ensure temperatures were appropriate for the protection of all macroinvertebrate taxa (Ross-Gillespie, 2014).

Few studies exist, regarding thermal tolerances of aquatic biota, applicable to the South African context. A recent and important study by Ross-Gillespie (2014), titled "Effects of water temperature on life-history traits of selected South African aquatic insects", provided valuable information for Lestagella penicillata (Ephemeroptera), Aphanicercella spp. (Plecoptera) and Chimarra ambulans (Trichoptera), or EPT taxa, and how they are driven by environmental and genetic factors, in six rivers situated in the south-western Cape Province. Upper and lower thermal tolerance limits for egg development, as well as the optimum temperature ranges for growth of each species, provided some of the first fundamental information necessary for informing thermal guidelines for water management policy.

Important findings from the study include; the temperature range for optimum growth were found to be 13-21.5°C for L. penicillata, 11.5°C-14.5°C for Aphanicercella spp., and 14.3°C-21.5°C for C. ambulans. Furthermore, the effects of thermal parameters on egg-hatching showed that L. penicillata and particularly C. ambulans were warm adapted, while the Aphanicercella was cold adapted (Ross-Gillespie, 2014).

Most notably, the study stressed that the data presented illustrated strong differences in individual thermal regimes of South African rivers. Therefore generalised thermal guidelines, made at a national-scale, would not be appropriate for management purposes. Aquatic thermal tolerance criteria would need to be conceived at a regional or even local scale, in order to ensure ecological protection. It is apparent, that significantly more research is needed in this field. Such information is essential to inform decision-making (Ross-Gillespie, 2014).

Arguably, water temperature could be considered as the most important master variables of a river. Natural seasonal and daily variations of water temperature are important determinants which shape aquatic communities and their distribution, (Vannote et al., 1980). However anthropogenic sources of thermal pollution will impact on aquatic communities, altering their distribution, abundance, diversity, and growth (Hocutt et al., 1994; Kelly, 2010; Olsen et al., 2011). Furthermore, the degree to which temperature impacts stream biota is generally dependent on the magnitude of the temperature organisms are exposed to, the duration of exposure and the frequency of exposure. Additionally, the spatial extent of temperature exposure also impacts on stream biota (Arseneau et al., 2010).

As the aforementioned criteria suggest, thermal pollution can have both acute and chronic consequences on aquatic biota. With respect to heated stormwater discharge, this type of pollution can cause both acute and chronic costs to biota. The associated high temperatures of stormwater, passing over impervious surfaces, at the beginning of a rainfall event, and discharging directly into the river, will expose aquatic ecosystems to short-term thermal shocks. The temperature of discharging water could be equivalent to the UILT of certain species, resulting in death of these species at the point of discharge. Alternatively, due to frequent inputs of heated water, species with the ability to escape will abandon the polluted area with knock-on effects on other aquatic biota. This could potentially leave patches of sterile aquatic environment along the river stretch. Furthermore, continuous exposure to thermal shocks and high daily thermal variations may cause thermal stress in species, resulting in reduced growth rates or reproductive productivity.

Chronic stress on aquatic biota may occur, if discharge input points change the thermal structure of the river across the longitudinal profile (i.e. less thermal variation exists due to a high number of input points across the entire river channel). Over time, the slow increase in ambient river temperature due to increased catchment development (and thus impervious surfaces), will undoubtedly affect the growth and reproductive success of many species. Furthermore, the new river environment will favour more-tolerant species skewing ecosystem communities. Most urban streams and rivers are considered degraded because of the absence of important indicator species, such as sensitive EPT taxa. The "urban stream syndrome" summarizes global river degradation as the effect of urban development on aquatic ecosystems which are unable to cope with anthropogenic interferences (Department of Water Affairs and Forestry, 2005; Walsh et al., 2005).

2.4 Stormwater Mitigation Techniques

Current stormwater management addresses stormwater quantity and quality. Therefore, multiple stormwater treatment devices have been developed to mitigate water quality and water quantity concerns associated with development. Water quality typically focuses on nutrients, the presence of heavy metals and total suspended solids (TSS). Quantity concerns predominantly focus on reducing peak flow rate, using control measures such as detention and retention devices.

Historically, temperature has not been viewed as a stormwater contaminant, and in South Africa it is currently not included in water monitoring protocol (Department of Water Affairs and Forestry, River Health Programme, 2005). Although temperature has received increasing attention as a significant issue, urban water management mitigation options have generally not been selected with temperature in mind. According to Young et al.(2013) in many cases the effects of these "approved" management systems on runoff temperature are largely unknown.

Popular stormwater mitigation devices used are wet ponds, and more recently a shift from ponds to more natural systems such as wetlands has occurred. These devices are based to a large extent on biological treatment mechanisms. Additional devices used for stormwater mitigation are; dry ponds, sand filters, soakholes, infiltration trenches, pervious paving and tree pits, swales, filter strips, rainwater tanks and living roofs. It is evident that many of these devices have yet to be introduced into the South African context. Literature on their effectiveness is largely based on international case studies.

It has been recognised that thermal enrichment should have been taken into account when designing stormwater management systems. Most systems do not include specific temperature measures or limits which need to be adhered to. The most logical attempt at addressing stormwater temperature effects would be to reduce the area of contributing surfaces, thus, avoiding thermal enrichment. Another obvious solution would be to shade existing "at risk" areas, and reduce their thermal effect. Finally, temperature effects can be managed by integrating temperature moderating practises to treat thermal pollution. Furthermore, management should prevent thermally enriched stormwater discharge from entering directly into freshwater streams and rivers.

An extensive study by Young et al. (2013) addresses a variety of stormwater management practises and demonstrates how they operate in the context of thermal enrichment. In summary, the paper highlights a few concerns. Firstly, traditional paving, used for roads, roofs and footpaths, contributes a significant portion of urban surfacing. Most notably, impervious asphalt and concrete make up most of a community's land cover (USEPA, 2008). These artificial surfaces can record temperatures unseen in the natural world. Young et al. (2013) suggest mitigation techniques such as shading these surfaces, replacing them with pervious surfacing and introducing "cool pavements", which are surfaces with a high albedo (solar reflectance). Jones (2008), found that a light coloured chip seal may have similar cooling effects to a mature tree canopy.

Wet ponds have been used in the past extensively as a stormwater management device. They are however a controversial approach for capturing runoff. Detention times for runoff vary according to how long a particulate contaminant will take to settle. The design of these devices does not address temperature effects. Extensive research has found that wet ponds are a source of thermal pollution (Galli, 1991; Jones and Hunt, 2010; Kieser et al., 2004). Thermal enrichment of these ponds is generally a combination of incoming solar radiation, extended detention time and inadequate shading, (Chapman et al., 2008; Galli, 1991; Maxted et al., 2005; VanBuren et al., 2000; Lieb and Carline, 2000). Furthermore, sediment accumulation in these ponds also acts to absorb radiation, exacerbating heating (Schueler, 1987). In order to remedy the effect of thermal enrichment of these devices Young et al (2013) suggest infiltration as a better approach to reduce peak flow rates.

Infiltration is the optimum temperature mitigation method, for thermally sensitive catchments. This not only directly reduces thermal enrichment of stormwater, but it further increases the integrity of the river and its buffering capacity to further thermal inputs. Additional ways of increasing a river's buffering capacity are planting trees and maintaining base flows. It is important to note, especially when considering the Liesbeek River, that contaminants found in stormwater be treated before infiltration is attempted. Furthermore, the water table level needs to be investigated before infiltration devices are implemented. Infiltration devices include; pervious paving, biorentention ponds, soak holes and swales.

An additional option for reducing thermal effects on stormwater runoff is to retrofit current management devices. This could include encouraging conveyance of water into underground pipes, as these can have a significant cooling effect (Sabouri et al., 2013), or careful re-designing of the outlet point of wet ponds, so that discharge water is drawn from lower, cooler levels of the pond (Jones and Hunt, 2009).

Finally, a more recent concept known as Water Sensitive Urban Design (WSUD) is an appropriate alternative approach to site design and development. WSUD does not directly discuss the effects of thermal enrichment. However, it does identify that reduction in baseflow is a serious concern, and that infiltration is an important component of sustainable stormwater management. Water Sensitive Urban Design includes retaining natural areas and reducing impervious surfaces. Therefore, these mitigation approaches also promote mitigation from thermal enrichment (Walsh, 2004; Walsh et al., 2005a).

Some popular WSUD management practises, which also limit elevated runoff temperatures are;

- Shading;
- Using lighter reflective colours for paving and construction material;
- Promotion of infiltration using permeable pavement;

- Use of stormwater pipe materials with a higher convective heat transfer coefficient to dissipate heat into the ground and
- Cooling trenches (Coutant, 1970; Arrington, 2003).

Finally an important mitigation approach, specifically relevant to the Liesbeek River catchment, would be to address the "first flush" runoff. This runoff which would be most affected by heating from impervious surfaces can compromise receiving water temperatures greatly. This initial volume of water can easily be re-routed through an infiltration or sub-surface device. Furthermore, discharging this runoff to reticulation via an underdrain will aid cooling (Sabouri et al., 2013; Young et al., 2013).

Recognising temperature as a water quality pollutant is critical for meeting sustainable resource management objectives. New features of urban design are rapidly emerging which challenge historic thinking. WSUD advocates for a shift towards strategies which can handle complexity and uncertainty. Such design must establish cities of resilience, ones which are able to meet the future challenges of climate change (Brown et al., 2008; Grimm et al., 2008).

Chapter 3

Methodology

3.1 Introduction to Methodology

The data, collected over 4 months, were collated and graphs for each rainfall event were built using MATLAB. Observations and inferences could then be made, with respect to appropriate literature. Important research questions arose, such as, are there any noticeable trends occurring at each site and for each rain event. Similarly, are there any apparent differences occurring at each site and for each rain event, and can these be explained using current theories.

Next, a desktop Geographical Information Systems (GIS) analysis was undertaken to visually and spatially understand the monitoring sites in the context of their urban surroundings. This was necessary to aid graphical explanations. GIS maps were generated and illustrated 'Parcel Areas' which bound the stormwater pipe network and outlet. The maps represented the outlet and corresponding parcel area which was representative of the 'area drained' during each rain event. The GIS analysis was possible using layers provided by the 2011 City of Cape Town geospatial dataset. In each parcel area, specific quantitative and visual data were needed to help explain temperature trends, which included land-use zones, stormwater pipe network length, number of catchpits, parcel area size, and length of road network.

Finally, a statistical model was built using the program R. Data was averaged for all the stormwater pipe outlets and across all rain events, in order to investigate generalised relationships between variables affecting stormwater discharge temperature and their significance.

3.2 Study Area and Monitoring Sites

The study area is situated in the Liesbeek River Catchment, which can be seen in Figure 1.1. The Liesbeek River is characteristic of an urban river as the majority of the most highly intensive commercial uses are located in all reaches, with high densities found in the mid-to-lower areas of the basin. The study site can be found in a largely developed portion of the city, with over 90% impervious surface coverage. This area includes highways, parking lots and buildings, all of which generate large volumes of stormwater and urban pollutants. The chosen study area falls in the mid-to-lower reaches of the Liesbeek River and incorporates the suburbs of Rosebank and Observatory, Cape Town. This river section is partially canalised with sections of soft and hard banks. A small section of riparian rehabilitation has taken place along the Observatory stretch of river. However, the Rosebank river stretch is fully canalised, using concrete slabs lining the banks and base. The Rosebank river stretch is fully canalised, using concrete slabs lining the banks and base.

The current major impacts to the middle and lower reaches of the Liesbeek River include the removal of indigenous riparian vegetation which has been replaced by invading alien plants such as kikuyu, poplars and wattle. There is an abundance of alien fish such as carp, catfish and tilapia in the lower stretches of the river. These alien fish out-compete indigenous species in terms of food and habitat. Furthermore, predation has caused the near disappearance of indigenous Cape galaxias. Urban development in the densely populated suburbs of Rosebank and Observatory, has meant canalising the river with a resultant loss of goods and services (ability to process and dilute waste). Finally, poor water quality in these stretches of river is a result from wastewater discharges, stormwater runoff and litter disposal. This reduces ecosystem functioning and poses a risk to human health. Table 3.1 below summarizes the current state of the Liesbeek River, in particular the Middle and Lower River stretches.

River Health Indices	Lower Liesbeek	Middle Liesbeek	Upper Liesbeek
Index of Habitat Integrity (IHI)	Fair/Poor	Fair/Poor	Natural
Water Quality	Fair	Poor	Natural
South African Scoring System (SASS)	Poor	Fair	Natural
Fish Index (FI)	Fair	Good	Natural
Riparian Vegetation (RVI)	Poor	Fair	Natural

Table 3.1: Liesbeek River Health (Table adapted from: Department of Water Affairs and Forestry, River Health Programme, 2005)

River Health Category	Ecological Perspective	Management Perspective
Natural (N)	No or negligible modification from natural	Relatively little human interaction
Good (G)	Biodiversity and integrity largely intact but ecosystems essentially in good state	Some human-related disturbance but ecosystems essentially in good state
Fair (F)	Sensitive species may be lost; tolerant or opportunistic species dominate	Multiple disturbances associated with the need for socio-economic development
Poor (P)	Mostly tolerant species; alien invasion, disrupted population dynamics; organisms often diseased	High human densities or extensive resource exploitation
Unacceptable (U)	Critical modifications; almost complete loss of natural habitat and species; severe alien invasion	Very high human density and/or resource exploitation

Table 3.2: Key for Liesbeek River Health Table 3.1 (Table adapted from: Department of Water Affairs and Forestry, River Health Programme, 2005)

The study area was selected because it is bound by the same micro-climate and experiences the same weather characteristics. The Liesbeek River is considered to be relatively short longitudinally. Although, surprisingly, it flows across different local climatic zones, each stretch exposed to different weather characteristics such as the amount of rainfall, ambient air temperature, wind speed and evaporation. The South African Weather Service has a meteorological station located in Observatory which provided additional specific weather data variables, to be used alongside the collected temperature data, in order to build the analysis. Therefore, within the Liesbeek River catchment there was a necessity for the selected monitoring sites to be geographically close to each other, and the weather station located in Observatory. This was so that the influence of weather variables remained constant at each site.

Four monitoring sites were selected within the study area. These sites corresponded to four stormwater pipe outlets, which discharge stormwater directly into the river channel. The stormwater pipes were selected because of their connection to the main river channel and because of their accessibility. This was important as the iButtons had to be manually planted inside each pipe outlet. Figure 3.1 below shows the stormwater pipe outlet monitoring points along the Liesbeek River, and Table 3.3, Table 3.4 and Table 3.5 show site photographs of the stormwater pipe outlets with a short description of each.

In order to analyse the temperature of the stormwater discharge relative to the river temperature, six iButton loggers were placed in the main river channel and monitored river water temperature. River water temperature was the reference which the stormwater temperature would be measured against. These six iButton loggers were placed upstream, instream and downstream of the stormwater pipe outlets.

Figure 3.1: Monitoring Sites: Four Stormwater Pipe Outlet points, along the Liesbeek River, Observatory and Rosebank, and the Observatory Weather Station (Created by A. Crisp, Quantum GIS Development, 2009)

Site	Description	Temperature Monitoring Site
Site 1 Stormwater Pipe Outlet - 1 "Observatory" 33°56′32.1″S 18°28′37.9″E	The most downstream site, situated just off Liesbeek Parkway Road. This river section has soft banks and base, riparian restoration is currently taking place. At this point the river is approximately 5m wide and 1m in depth. This pipe outlet discharges stormwater which is run-off falling over the suburb of Observatory, Cape Town, situated near the base of Table mountain the outlet drains into the Western river boarder.	 
Site 2 Stormwater Pipe Outlet - 2 "Observatory" 33°56′39.5″S 18°28′37.8″E	The stormwater pipe outlet is situated under a major highway intersection, where the N2 meets the M5 highway. This river section is heavily canalised, concrete slabs line both the bank and base of the river. At this point the river is approximately 4m wide and 0.2m in depth. This pipe outlet also discharges stormwater from the suburb of Observatory, however the pipe network drains mostly the N2 highway which runs perpendicular to the River on the Western river boarder.	 

Table 3.3: Stormwater Pipe Outlet Monitoring Sites 1 & 2

Site	**Description**	**Temperature Monitoring Site**
Site 3 Stormwater Pipe Outlet - 3 "Rosebank" 33°57′07.4″S 18°28′36.8″E	The stormwater pipe outlet is set back slightly from the river and is channelled into the river. This river section is canalised, Concrete slabs line both the bank and base of the river. At this point the river is approximately 5m wide and 0.3m in depth. This pipe outlet discharges stormwater from the suburb of Rosebank, and drains the western boarder of the river	 
Site 4 Stormwater Pipe Outlet - 4 "Rosebank" 33°57′08.0″S 18°28′34.8″E	The stormwater pipe outlet is <10m upstream from Site 3. It discharges into the same canalised river stretch. Concrete slabs line both the bank and base of the river. At this point the river is approximately 5m wide and 0.3m in depth. This pipe outlet discharges stormwater from the suburb of Rosebank, and drains the eastern boarder of the river.	 

Table 3.4: Stormwater Pipe Outlet Monitoring Sites 3 & 4

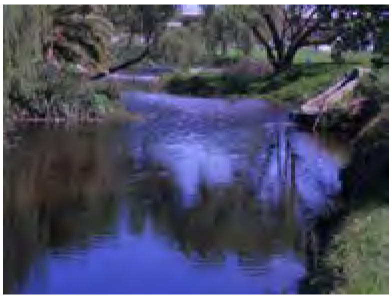
Site	Description	Temperature Monitoring Site
River Reference Sites	Six iButtons were placed in the main river channel, in order to measure ambient river temperature. In descending order from most upstream to the most downstream: **Rosebank Site:** One iButton was placed upstream $(100m)$ from stormwater pipe outlet 4 One iButton was placed in-stream between stormwater pipe outlets 3 and 4 $(< 20m)$ One iButton was placed downstream $(100m)$ from stormwater pipe outlet 3 **Observatory Site:** One iButton was placed upstream $(100m)$ from stormwater pipe outlet 2 One iButton was placed in-stream between stormwater pipe outlets 1 and 2 $(< 20m)$ One iButton was placed downstream $(100m)$ from stormwater pipe outlet 1	 

Table 3.5: River Reference Sites

3.3 iButton Temperature Loggers

This study provided the first opportunity to test the use of iButton technology for collecting stormwater discharge temperature, during rainfall events in Cape Town.

Previously iButton loggers have not been applied to measure stormwater discharge. They have, however, been used to measure tidal inundation regimes. Additionally, they are being used in the Mediterranean Sea, to monitor the temperature environment of the Mediterranean's Posidonia Oceanica. Recent research sponsored by the Innovative Pavement Research Foundation, installed Thermochron iButton loggers into airfield pavements at the Des Moines International Airport. These iButton loggers were being used to monitor the temperature history of fresh concrete during construction. Finally, iButton loggers are used extensively in the transportation and packaging industries, to ensure produce is kept at standardized temperatures (Tully, 2007). Although iButton loggers are a relatively new addition to the research world, their accuracy and effectiveness is exceptional. These iButton loggers are highly recommended as equipment for future scientific temperature studies, and provide a suitable cheaper alternative to temperature probes.

The Thermochron iButton logger is a thermometer and real-time clock encased in a stainless steel capsule, 16mm in diameter, 5mm thick and weighs approximately 3g. Recordings taken by the iButton are user defined and stored in the form of temperature values. These can later be uploaded using an adapter cable with USB port, onto a personal computer. The specific software package bought with the iButtons, namely *Coldchain Thermodynamics* was used for initial configuring, uploading data and initial collating and basic analysis.

Table 3.6 illustrates and describes general characteristics of the iButton, the waterproof silicone enclosure and the associated iButton software and accessories.

Initial trial testing of alternative deployment methods was conducted to establish the best approach for gathering useful data. Once this was completed, the formal testing began and proceeded over four months during the winter rainfall season of 2015 (end of May to the end of September). Ten iButton loggers were used to measure stormwater discharge temperature and instream river temperature. These iButtons were selected as a monitoring device because they are accurate and durable sensors, which require little maintenance and are relatively inexpensive. A continuous monitoring protocol was established and is further described below.

Item Characteristics	Item
Maxim iButton - Temperature Logger • **Sensors:** One internal sensor • **Measuring Range:** $-5°C$ to $+26°C$ • **Measuring Accuracy:** $\pm1°C$ • **Measuring Resolution:** $0.125°C$ • **Memory capacity:** 2048 Samples • **Size:** 16 mm diameter x 5 mm depth • **Software:** ColdChain Thermodynamics • **Features:** Extremely Small, durable and can record in frozen temperature range.	
iButton Sinking Silicone Enclosure • **Use:** Protection and waterproofing • **Size:** 29 mm height x 21 mm depth • **Specifications:** The lowest cost waterproof enclosure for the iButton data loggers. This enclosure is constructed from neutral coloured silicone. this produces a lightweight, two part enclosure that protects the data logger at pressures up to 0.5 bar or depths of 5 m.	
iButton Adapter Cable • **Adapter cable:** PC interface, used to connect the iButtons to a Computer via a USB port.	
ColdChain Thermodynamics Software • **Software:** Fully featured Management system for interfacing the Maxim iButtons and accessing, displaying, downloading and reporting on temperature readings. This version of the software supports all standard features for logger control, data export and reporting. This version is perfect for research purposes and/or low volume use. The software features automatic start and download control modes and features reporting, graphing and data export capabilities. The software is also compliant with international standards.	

Table 3.6: Items Used for Temperature Monitoring (Table adapted from: Fairbridge Technologies, 2010)

3.4 Methodological Design

3.4.1 Accuracy Test

Firstly, a bench test was conducted to ensure accuracy of each of the ten iButton loggers. These would be used to record data in the field. A beaker was filled with 100ml of water, with a known temperature. Eight iButtons were configured, using the ColdChain Thermodynamic software. A recording interval was set to capture temperature readings every minute for a period of 15 minutes. They were placed in their waterproof enclosure Table 3.6 and then placed in the beaker of water. Along with the iButtons, an electronic thermometer was placed in the beaker. At every minute, equal to the interval of the iButtons, the temperature of the water was recorded using the thermometer. It was verified that the iButtons were reading accurate water temperature when compared to the thermometer, and within their specified limits. This concluded the accuracy testing.

3.4.2 Fieldwork

'Wire holders' were designed and attached to the inside the four selected stormwater pipe outlets. It was necessary for the stormwater pipes to be dry in order to glue the wire holder inside the concrete pipe. The glue used was a two-part epoxy adhesive, specifically for concrete. This required 24 hours to set. Figure 3.2 below illustrates the wire holder which secured the iButton logger within the stormwater pipe.

The design of the wire holders needed to ensure the iButton would not be lost during rainfall events, but also that the iButton could be retrieved after rain events. Stored temperature data on the iButton had to be manually uploaded to a personal computer after every rain event. Each predicted rain event prompted fieldwork. The process for fieldwork is summarized in the steps below:

1. **Configuring and activating** each iButton using ColdChain Thermodynamics software, this involved setting a mission start and end time (according to the predicted rain event) and setting the sample time interval, which was 3 minutes (for every rain event).

2. **Preparing** each of the ten iButtons, this included labelling them, placing them in the silicone waterproof enclosure and securing a zip cable

around each one. The six river reference iButton loggers were then attached to bricks, refer to Figure 3.3 below, in order for them to be placed into the river and not drift away.

3. **Travelling** to each site, stormwater pipe outlets 1 & 2 were situated in Observatory (site 1) and stormwater pipe outlets 3 & 4 were situated in Rosebank (site 2).
4. **Deployment**: each of the four iButton loggers was placed in the wire holder in the stormwater pipe outlet. The remaining six iButton loggers, each attached to a brick, were placed in the river, (upstream, instream and downstream of each site). Where possible placement of these was in the middle of the main channel, in order to avoid measurement bias from the warmer stream edges and from thermal stratification.
5. **Collection**, after each rain-event all ten iButton loggers were collected and cleaned.

After collection the iButton loggers were then individually placed in the socket of the USB adapter cable, so that the recent temperature data could be uploaded onto a personal computer, the stored data could then be deleted off the iButton logger and it would be ready for configuration once again.

Figure 3.2: The wire holder securing the iButton in the Stormwater pipe outlet

Figure 3.3: iButton attached to brick for deployment into the Liesbeek River

3.4.3 Data Collection

Over the course of four months (May – September 2015), temperature data was collected after each rain event. Data was uploaded from each iButton and stored in the ColdChain Thermodynamics program; refer to Appendix C which illustrates a working example of the software user-interface. The data was categorized into files corresponding to the date of the rainfall event. Once fieldwork concluded, the data set was exported into Microsoft Excel 2010, which allowed for convenient data manipulation.

3.4.4 Graphing

Separate spreadsheets were created in Excel. Each one represented individual rain events, each spreadsheet combined all necessary variables including iButton temperature data, river reference temperature data, rainfall and ambient air temperature (see Appendix D: Raw Data). It is important to note that data collected from all six iButtons placed in the river was averaged. This provided a single reference data set, in order to compare stormwater temperature.

After basic 'cleaning' of the raw data, it was exported to MATLAB to generate graphs. MATLAB allowed for a standard template to be created which could be applied to each individual set of data from each rainfall event. This streamlined the data processing aspect of the project. Refer to Appendix D which represents the template code. For each graph temperature was plotted against time (x-axis) and rainfall amount (second Y-axis), ambient temperature and the river reference temperature were include in the graph.

In total 14 graphs were completed. However, five selected graphs are presented and are discussed in detail in Chapter 4 below. Additionally, hourly cumulative temperature was mathematically calculated measuring area under the curve of the MATLAB graphs. This is presented alongside the five selected graphs in Chapter 4.

3.4.5 Geographic Information Systems: Desktop Analysis

Stormwater temperature data were analysed in the context of the surrounding land use. Hence, a basic geographical information systems (GIS) desktop analysis was undertaken.

GPS coordinates were taken at each of the stormwater outlet points and uploaded to a new GIS project. Layers were provided by The Department of Strategic Development Information (SDI) and Geographic Information System (GIS) Department. These layers were then added to the project, these reflected characteristics of the area around each stormwater outlet point. The following layers were used to build a full analysis of the study area: stormwater and associated infrastructure including piped network and catchpits (2005), road layer (2011), buildings layer, aerial photograph overlay (2014), the Liesbeek River and catchment boundary (2011) and City of Cape Town Zoning layer (2013).

Next, new shapefile layers were created. Each shapefile layer was labelled as a “parcel area” and represented the “area-drained” by the corresponding stormwater outlet point. Each parcel area layer was manually drawn by tracing around the stormwater pipe network attached to the stormwater outlet point. The parcel area was necessary to perform intersection analysis of different layers with the individual parcel area layers. For example, parcel area 1 layer was intersected by the catchpit layer, to give the number of catchpits falling within this parcel area. It could then be deduced that stormwater pipe outlet 1, situated in Observatory had 136 catchpits on its pipe network. Correspondingly, parcel area 2, 3 and 4 could also be intersected with the catchpit layer.

This intersection analysis was performed using a number of layers, to build information about the characteristics found in each parcel area. This would provide a basic understanding of the 'type of area' being drained during a rain event, and the subsequent stormwater discharge temperature at the outlet point.

The zoning layer provided information about the types and size of different land-use zones falling within the parcel area, and an indication of the type of surface. Similarly, the length of road network was calculated in each parcel area and was a proxy for the approximate amount of asphalt surface. Maps were composed and presented in section 4.2 below. These maps visually represent each parcel area. Tables were created and highlighted quantitative information of each parcel area. This concluded the GIS desktop analysis component of the project.

3.4.6 Statistical Testing

The data from each Excel spreadsheet was further summarized, in order to make it appropriate for statistical testing. Ambient air temperature and rainfall amount were measured hourly at the Observatory Weather Station. Therefore, iButton temperature data needed to correlate to this time interval. The mean, median, minimum and maximum temperature, per hour, for each hour of rainfall, was calculated. This was done for each stormwater pipe and each of the 13 rain events. Additionally, the mean, median, maximum and minimum per hour, for each hour of rainfall, was calculated for the river reference temperature. Refer to Appendix E which is the prepared data for statistical testing.

Two descriptive statistical tests were carried out. These were necessary to show measures of central tendency, measures of variability and minimum and maximum values. These tests formed the basis of the initial description of the data, as part of a more extensive statistical analysis. Firstly, *Box and Whisker* plots were produced, to provide a simple summary about the collected data. Each plot represented the spread of data collected for each stormwater pipe outlet and the river reference temperature, for all 13 rain events. The box shows the spread of data including the median, and whiskers represent the minimum and maximum temperature data observed.

Secondly, a Tukey Range test was performed at the 95% confidence level. This is a single step multiple comparison test. The mean temperature of each stormwater pipe outlet was tested against the mean temperature of every other stormwater outlet, and against the mean river reference temperature. This test provided a comparative analysis of each site.

The statistical modelling program 'R' was used for an in-depth analysis of stormwater temperature. A generalized least squares model was built. The model used mean, hourly, stormwater temperature as a function of explanatory variables. These variables were mean, hourly air temperature, mean hourly river temperature (reference temperature), amount of rainfall (mm), duration of rainfall (hours), cumulative rainfall and time of day.

The model used a simple auto correlation structure (AR1 process) to account for correlation of previous temperature values, i.e. that measurements from the same location and a single rain event are correlated, and are in series. Refer to appendix F for the specific "R" code.

Model output results would include regression coefficients between stormwater temperature and tested variables. This would offer an indication of the statistical relationships between stormwater temperature and tested variables. Finally, output scatter plots will graphically illustrate the regression model showing relationships between dependent (stormwater temperature) and explanatory variables. This regression model provided statistical control and is important because it isolates the role of one variable from all of the others in the model.

During the course of fieldwork and as the research project progressed, it became apparent that certain limitations existed within the methodology. Furthermore, general project concerns were experienced. These are included, in order to provide guidance towards future development of this research, and are discussed in detail below.

3.5 Limitations with Methodology

3.5.1 Field Work

One serious limitation experienced during the course of fieldwork, was two cases of theft. iButton loggers were taken from the field and thus data for these events was not captured. This occurred on the 26^{th} May 2015 where one iButton was taken from site 1 and on the 29^{th} June 2015 where both iButton loggers from site 1 and 2 were taken. Due to the fact that the iButton loggers had to be collected after every rain event, so that data could be manually uploaded to a personal computer, this meant the iButton loggers could not be permanently fixed within the stormwater pipe. This made them vulnerable to the public, and every rain event were at risk of being taken. A few solutions addressing this problem could include camouflaging the loggers and trying not to draw attention to the placement of them. A more expensive solution could be to purchase loggers which can transmit data, and therefore eliminate the manual component of collecting data. These loggers could then be permanently fixed within the pipe. This in fact could be a positive suggestion for more reliable long term river temperature monitoring.

An additional fieldwork concern, was the ability to accurately predict rain events. The nature of weather is that it is unpredictable, and it was sometimes not feasible to attempt fieldwork late at night or in the early hours of the morning. Realistically, it was expected that a few rain events would be missed and loggers would not be in place in time to collect data. This only occurred on a few occasions, as the prediction of rain events improved, especially when frontal systems passing over Cape Town became more consistent in the mid-winter months.

It was noticed early on during fieldwork, when collecting the iButton loggers from within the pipe outlet, after a rain event, leaves, vegetation and sometimes litter had washed over the iButton or become caught on the wire holder which fastened the iButton in situ. This was concerning because temperature recordings could have been affected by these interferences. Site 3 and 4 in Rosebank, were the areas where this issue was most problematic. The surrounding area was mostly residential, with large amounts of loose vegetation available to be washed into the stormwater pipes. It was assumed at high runoff rates this litter would have been flushed through quite quickly and therefore would affect data recordings. However, at low runoff rates the issue would be more pronounced. One solution during placement of the iButtons, was to clear any visible vegetation from in and around the outlet point. Furthermore, to ensure the iButton was set as 'streamline' as possible to the bottom of the pipe in order to minimise litter becoming caught in the wire holder.

Finally, on some occasions prior to a rainfall event and when visiting the Observatory monitoring site, it was observed that grey water was flowing at outlet pipes 1 and 2. This was hugely concerning as it was impossible to trace its source. The assumption was that it was an illegal temporary connection, in which grey water was being disposed of directly into the river. On these occasions the iButton logger would not be placed, or if possible would be placed out of the stream flow of the grey water. An important point to highlight would be that for these events, iButton loggers would be recording temperature of mixed grey water and stormwater discharge, once rainfall had started. In this case the relative thermal load would be greater. Stormwater pipe outlets were selected because of their accessibility and safety of the area. For future improvement it would be advisable to ensure there is no contamination from grey water flow, and select stormwater pipes accordingly.

3.5.2 Data Analysis

Once the iButton logger had been configured to take temperature recordings every 3 minutes, this automatically set a limit on the possible number of recordings the logger could store, when set at this time interval. The number of stored recordings was 2048. This was not a major limitation. However, careful planning was required when setting the start and end time on for each iButton logger. Each rain event was predicted to have a different duration and so the recordings had to be set in order to capture the entire rainfall event. What worked well, and would be a good future suggestion for further research, would be to complete a pilot test at the start of the project. This would enable the researcher to understand what time interval was best suited and would yield the most number of stored recordings, without losing accuracy at larger time intervals. Literature suggests 2-10 minute temperature monitoring intervals are most appropriate for monitoring stormwater (Young et al., 2013).

When beginning data analysis it became clear there were a few concerns, and it is important to highlight them in order to improve future research projects of a similar nature. Firstly, when developing the Geographical Information System analysis, the layers provided by The Department of Strategic Development Information (SDI) and the Department of Geographic Information System (GIS) of the City of Cape Town, were not representative of a single year. Furthermore, some were significantly outdated, for example the stormwater pipe network was updated in 2005. The most recent layer used was land use zoning information from 2013. However this was overlayed on layers from earlier years. Unfortunately, many South African geographical records are outdated and inaccurate, because of this reason the weight of the GIS analysis changed from initially hoping to provide a detailed analysis, to only being able to provide a more generalised analysis of the surrounding area and its characteristics. The results should be considered with low confidence and only partially aid explanatory observations. For future research, it is imperative that GIS records used are up to date and accurately reflect the current environmental characteristics.

Similarly, an additional data concern was the weather data provided by the South African Weather Service (SAWS). This data was averaged and in hourly time intervals. Rainfall amount and ambient air temperature were given as an average, hourly recording, during the rainfall event. This did not match the 3 minute time interval which the iButton loggers were recording at. This was a significant limitation when statistically analysing the data. Stormwater temperature data had to be averaged hourly in order for all data to be consistent and testable. This meant that observing subtle changes in temperature would not be possible, results reflected changes in temperature and variable relationships over hour time frames. The solution to this limitation could be to install a personal meteorological station within the study, one which monitors weather variables at the same time interval as the iButton loggers are configured. Changes in rainfall amount and ambient temperature could then be correlated to changes in stormwater temperature data. Picksley and Deletic et al. (1999) used a tipping bucket rain gauge (0.2mm/tip), to record rainfall amount and intensity, of rainfall on site. The recording process was initiated by the first tip of the rain gauge. This would be advisable for future application. However, this study experienced limitations in ambient air recordings, similar to this project. Weather data for their study was provided by local meteorological stations in the form of daily, mean, maximum and minimum, therefore the actual air temperature was unknown at the onset of rain (Picksley and Deletic, 1999). Air temperature is considered a significant driving factor of stormwater temperature. This study accounted for that.

Finally, an important gap in the research was that river water flow was not recorded in this study, nor was stormwater discharge rate at the pipe outlet. Flow monitoring devices are significantly more expensive than iButton temperature loggers. Realistically, it was not financially possible to place a flow device in each stormwater outlet pipe, with the additional risk of theft. Furthermore, the instream river flow monitoring device (placed by the City of Cape Town in the Liesbeek River) was situated outside of the study area and therefore was not reliable as a predictor of peak flow. Within the scope of this study rainfall amount was sufficient to use as an indicator of flow, i.e. peak flow rate would occur shortly after peak rainfall but pervious and vegetated surfaces (and other SUDS) could delay peak flow significantly. However, investigating the relationship between flow and stormwater temperature, over time, would be an important addition to future research development. As with many scientific research studies, limitations exist because of real life challenges. Whether these might be financial or contextual challenges related to the study. It is important to acknowledge their effect on research results. This will highlight areas where methodology can be improved so that research can progress.

Chapter 4

Results and Discussion

4.1 Introduction to Results

Temperature data was collected from four different monitoring sites. Two sites situated along the Observatory section of river and two sites situated along the Rosebank river section were selected. Monitoring sites were established at four stormwater pipe outlets, in which an iButton temperature logger was placed inside to capture temperature readings. During the course of a rain event data was captured in 3 minute time intervals. This was achieved for 14 rain events in total, over the months May to September 2015. In addition, temperature data of the river was monitored using six iButton loggers (set at 3 minute intervals). These were placed in the river channel along the entire Rosebank-Observatory section. Data was averaged for all six iButton loggers: this provided a temperature reference variable. Finally, meteorological data including ambient air temperature and rainfall amount (provided hourly) were used for analysis.

The following results aim to analyse stormwater temperature at four discharge sites, along the Liesbeek River.

Firstly, each parcel drainage area for the four outlet sites is discussed with reference to the GIS desktop analysis and maps generated. Parcel area characteristics are explained to provide contextual analysis for each monitoring site.

Secondly, observations were presented and discussed with reference to the literature, for five selected rain events. Five events were selected out of 14 for summative purposes. These five events are characteristically different. They represent different variables such as, time of day, amount of rainfall, duration of event, and month of the year (refer to Appendix H for all event graphs).

Finally, statistical results, generated from the model built in R, which averaged data from all events (hourly), are presented and discussed, with reference to the literature.

4.2 Parcel Area Characteristics

At each of the four monitoring sites, the stormwater pipe outlet which discharges directly into the river drains a corresponding 'parcel area'. A GIS desktop based analysis was used to identify these parcel areas and to provide basic characteristics for each area.

Figure 4.1 is the generated map identifying each parcel area. Additionally Table 4.1 includes information regarding the size of each parcel area, the length of the stormwater pipe network draining the parcel, the number of catchpits found in each area and the length of road network within the parcel area.

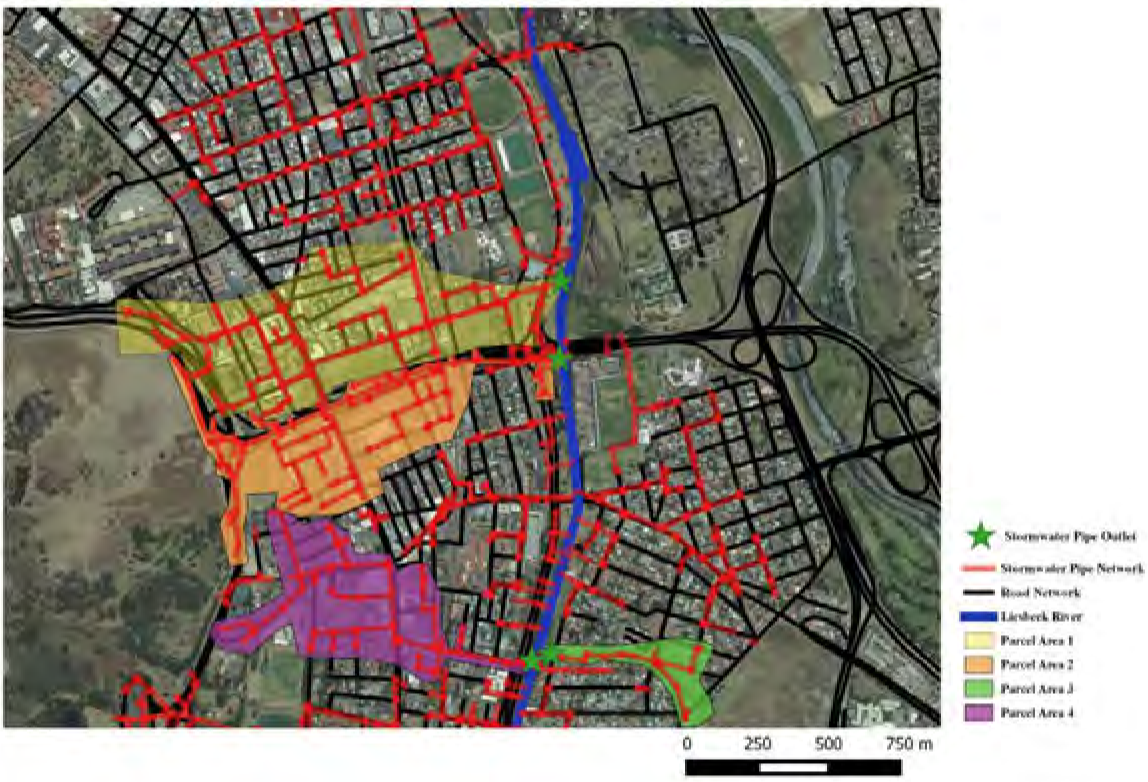


Figure 4.1: Parcel Areas 1,2,3 & 4: Representing the 'Area-Drained'during a rainfall event and discharging into the Liesbeek river at the corresponding outlet points (Created by A. Crisp Using Quantum GIS Development (2009))

Parcel	Length of Stormwater Pipe Network (m)	Number of Catchpits	Length of Road Network (m)	Area (m^2)
1	6286	136	8372	368917
2	5322	145	6817	227085
3	880	21	1060	49284
4	3223	86	4037	198016

Table 4.1: Parcel Area Characteristics (Tabel statistics taken from Quantum GIS Development (2009))

Each of the defined parcel areas has unique characteristics, in terms of its size, the length of stormwater pipe network falling within each area, and the type of land-use found in each area (Figure 4.1). Parcel areas 1, 2 and 4 all drain runoff along the western border of the Liesbeek River. Parcel area 3 represents runoff drained along the eastern boarder of the River.

Parcel area 3 covers the smallest area 49,000m^2. Parcel area 1 covers the largest area of 36,800m^2. Parcel areas 2 and 4 are similar in area size, 22,700m^2 and 19,800m^2 respectively. The stormwater pipe network length is longest in parcel area 1 and is approximately 6km long. This would be expected as it is covers the largest area. The length of the stormwater pipe network in parcel area 2 is approximately 5km. In parcel area 3 it is 880 metres, and in parcel area 4 it is approximately 3km. The number of catchpits in parcel area 2 is 145. This area has the most counted. Parcel area 3 has 21 counted catchpits.

The road network is longest in parcel area 1, and is roughly 8km. Therefore it can be assumed that the road surfacing (asphalt) is greatest in this area. Similarly, parcel area 2 has large road coverage, approximately 6.8km total length. It is important to note that only length of road was measured and not width. Parcel area 2 incorporates a large national highway which extends perpendicular from the Liesbeek River. Parcel area 3 has 1km of road this is the smallest asphalt coverage. Parcel area 4 has just over 4km of road network length.

Parcel area 1 is the largest in size. It would be expected that stormwater discharge temperature would be the highest at the discharge outlet point in this parcel area, compared to the temperature at the other discharge outlet points. Due to the larger surface area, it can be assumed that thermal energy transfers from surface to runoff would be greater. Therefore runoff in parcel area 1 would carry a greater thermal load. Runoff in parcel area 3 would have the least thermal load, as it is the smallest drainage area and therefore discharge temperature would be lowest at this outlet point, compared to temperature at the other outlet points.

4.2.1 Parcel Area Zoning

The GIS desktop analysis continued by looking more closely at the land-use zones found in each parcel area. This was achieved using City of Cape Town zoning layers (2013), and were 'clipped' accordingly to fall within each parcel area. The zoning layers which were used provided a high-level, generalised representation of area characteristics. The objective of this analysis was to increase insight into the type of surfacing and activities occurring in each parcel area. A more direct method would be simply to analyse satellite images of the area and confirm ambiguous examples by site inspection.

Figure 4.2, Figure 4.3, Figure 4.4, and Figure 4.5, illustrate the maps generated, showing detailed zoning for each area. Table 4.2 provides a summary of zoning information.

Figure 4.2: Parcel Area 1- Zoning (Created by A. Crisp Using Quantum GIS Development (2009))

Within parcel area 1 there are multiple land-use zones, and the area has the largest range of zones. The largest portion of area zoned is general residential within parcel area 1 and covers an area of 105 000m^2 . The second largest area zoned is general commercial. There is a high percentage of undefined zoning, within this parcel area. However, from the overlayed aerial photograph, most of the undefined areas appear to be open land. The parcel area also has a large portion of area zoned as community facilities which are grass covered fields or parks, and a public swimming pool. A general characteristic of this parcel area is mixed land use zones.

Figure 4.3: Parcel Area 2- Zoning (Created by A. Crisp Using Quantum GIS Development (2009))

Parcel area 2 has a high portion of undefined land use. The aerial photograph was used to infer the type of landuse existing in these places. Most notably was the existence of university residence and academic buildings, a sports field and a high school. A large percentage of the parcel area is zoned as general residential, and covers an area of 44 400m^2. Finally, in both parcel area 1 and 2 there is a railway line which runs parallel to the River. A few general characteristics of this parcel area include high residential and high transport coverage. Parcel areas 1 and 2, fall within the suburb of Observatory. This is a densely developed area a number of different land use zones and associated activities occur in this relatively small area, for example, educational, commercial, residential and recreational. Observatory can be considered a transitioning suburb.

Figure 4.4: Parcel Area 3- Zoning (Created by A. Crisp Using Quantum GIS Development (2009))

Parcel area 3 is completely zoned as residential land use. With a total 32 000m^2 zoned as residential. Two undefined areas are visible in Figure 4.4. On closer inspection these two areas are public open space. This parcel area falls in the suburb of Rosebank, which is a residential suburb, mostly made up of single dwelling residential properties, and many plots also include small garden areas. Parcel area 3 includes a public park which provides a buffer zone to the River. With reference to Figure 4.4 the stormwater discharge outlet is set back from the main river channel. The general characteristic of this parcel area is residential land use.

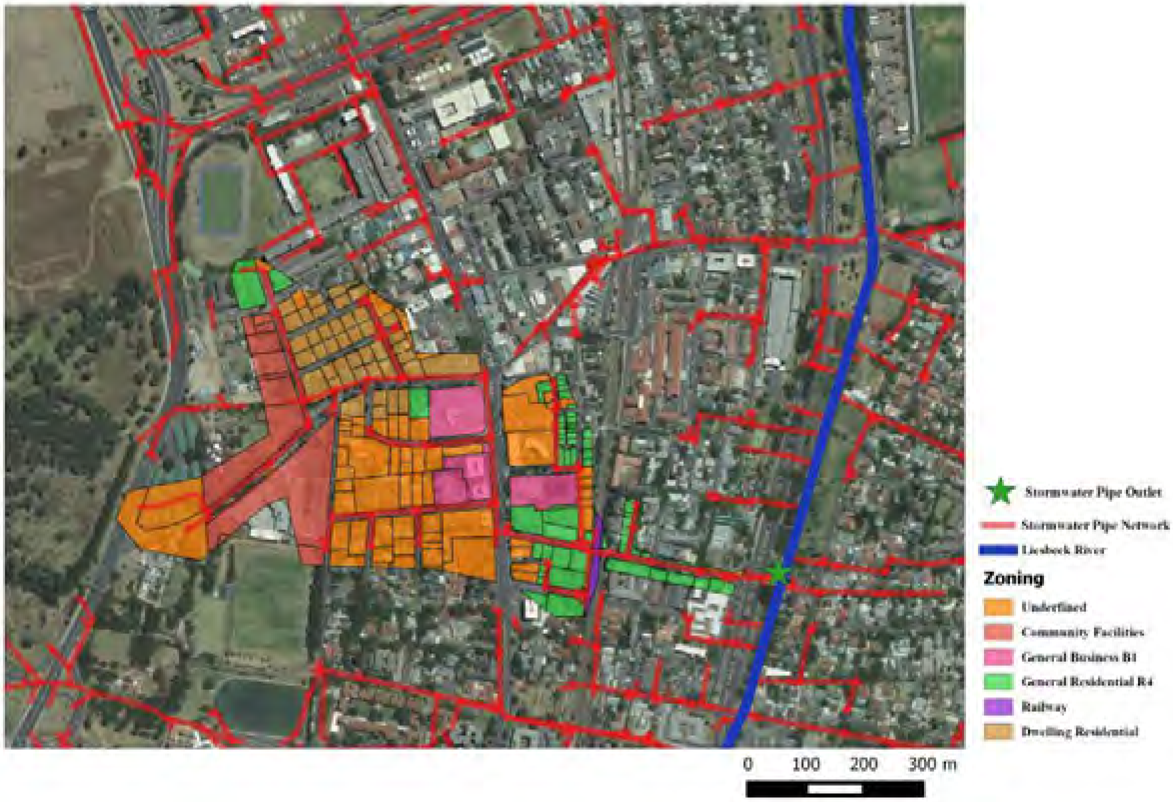


Figure 4.5: Parcel Area 4- Zoning (Created by A. Crisp Using Quantum GIS Development (2009))

Figure 4.5 illustrates parcel area 4. This parcel area also falls within the suburb of Rosebank. There is a high proportion of residential zoned land use, in total covering 75 700m^2 within this parcel. General business and community facilities zones can also be seen in this parcel area. Using the aerial photograph it was possible to determine that the large portion of undefined area was mostly residential. This would have to be added to the residential coverage total. Parcel area 4 can considered mixed land use.

It is important to note, the entire area of each parcel was not zoned. The last row in Table 3.5 reflects this. It was calculated that 86% of parcel area 1 was zoned. Therefore 14% was unaccounted for. 73% of parcel area 2 was zoned with a discrepancy of 27%, which was the largest area unaccounted for. In parcel area 3, 80% of the area was zoned with a discrepancy of 20%. Finally, 84% of parcel area 4 was zoned, therefore, 16% was unaccounted for. This error adds to the inaccuracy of truly understanding the characteristics of each parcel area.

Zone	1	2	3	4
Community Facilities (m^2)	29131	3651	0	35493
General Business (m^2)	6429	3624	0	17868
General Commercial (m^2)	38155	0	0	0
General Residential (m^2)	105094	444416	32072	51598
Single Dwelling Residential (m^2)	9684	1000	0	24163
Government (m^2)	18786	0	0	0
Streets (m^2)	597	138	0	166
Public Open Space (m^2)	0	0	3008	0
Railway (m^2)	6951	4293	0	1529
Undefined (m^2)	100962	108698	4545	35825
Sum of Zoned Area (m^2)	315789	165820	39625	16642
Zoned Area (%)	86	73	80	84

Table 4.2: Land-Use Zones Found in Each Parcel Area

4.3 Data Presentation and Observations

Observations are summarized for each rainfall event in Table H.1 below, with corresponding dates, and the hours in which rain fell. This table gives a visual representation of the differences in types of rainfall events, for example some occurred in the early hours of the morning when river and air temperature is expected to be lowest (Event 11 and 12). Rain events 1, 3, and 13 occurred in the afternoon to early evening when river and air temperature is expected to be highest. The duration of rainfall (in hours) also differs across each event. For example event 7 was 2 short hours of intense rainfall. However, event 8 was a prolonged rainfall event lasting 9 hours in total.

Event 2 was omitted from the analysis because of the limited amount of rainfall, in which less than 1mm of rain fell per hour. This decision was based on previous studies ((Picksley and Deletic, 1999; Herb et al., 2007b)), which suggest that less than 1mm of rainfall per hour is not sufficient to measure discharge at an outlet point. Furthermore, the data from this event was erratic and unreliable. It was therefore disregarded from this analysis and statistical testing.

It is important to note that rainfall was summed for every hour and was recorded as a single data entry. Consequently, how the rain fell in reality, over the course of 60 minutes is not shown. For example, Event 1 on 26th May, shows the onset of rain starting at 11am, this however would have been an amount (0.4mm) of rainfall which fell between the hours of 10am and 11am.

Event	1.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
Date	26th May	3rd June	16th June	23rd/24th June	28th/29th June	11th July	17th July	23rd July (1)	23rd July (2)	30th July	4th August	10th September	29th/30th September
01:00:00 AM				*	*					*	*		*
02:00:00 AM			*		*			*		*	*		
03:00:00 AM			*	*	*			*		*	*		*
04:00:00 AM			*	*				*		*	*		*
05:00:00 AM			*	*				*		*	*		*
06:00:00 AM										*			*
07:00:00 AM			*		*					*			*
08:00:00 AM			*		*								*
09:00:00 AM												*	*
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11:00:00 AM	*			*								*	
12:00:00 PM	*	*	*									*	
01:00:00 PM	*	*	*	*								*	
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09:00:00 PM				*		*	*						*
10:00:00 PM				*		*	*		*				*
11:00:00 PM			*	*	*		*		*				
12:00:00 AM				*	*		*		*				*

Table 4.3: Summary showing all rain events, $*$ marks where rain occurred. Temperature Data was collected on all these occasions. See Appendix H for Enlarged Version of Table (Created by A. Crisp (2016))

Table H.1, shows data for the five rain events that were selected. These were event 1, 3, 7, 8 and 12. These 5 rain events were specifically selected as they represent different scenarios and conditions in which stormwater temperature was monitored. Observations of the data are presented below. In each graph, stormwater discharge temperature for each stormwater pipe (1-4) was plotted against time of day and rainfall amount. Ambient air temperature and average river temperature are also plotted on the graph. The following explanations for each event highlight the dynamic behaviour of temperature over the course of a rainfall event with respect to the literature.

4.3.1 Rainfall Event 1: 26th May 2015

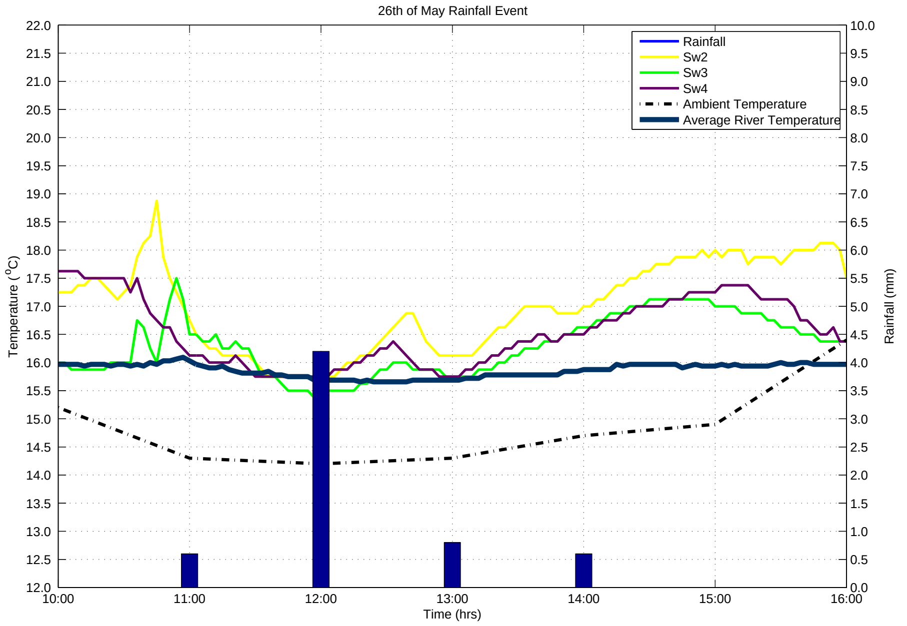

Figure 4.6: Rainfall Event 1 on 26th May 2015, note the absence of data for stormwater pipe 1

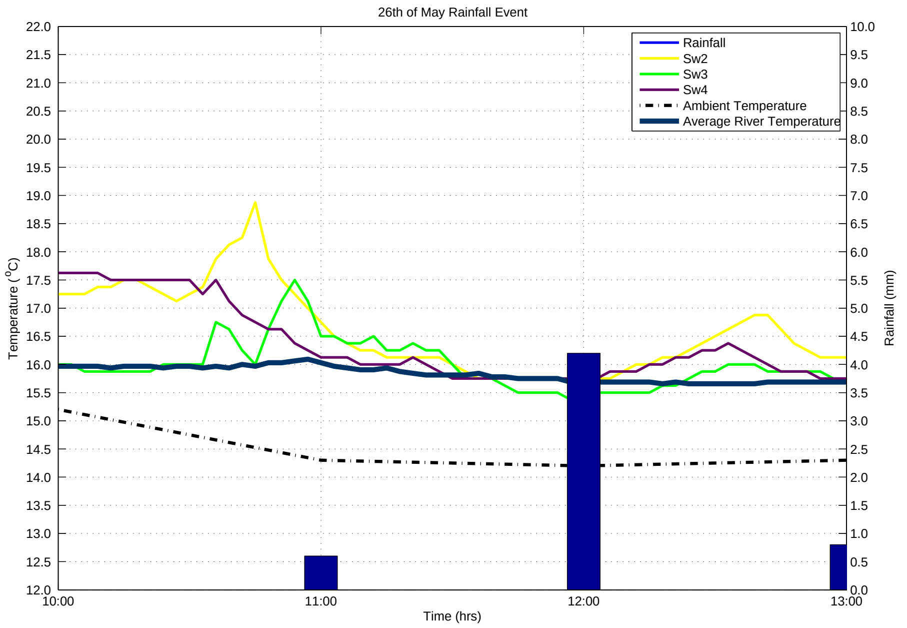

Figure 4.7: A closer look at Stormwater temperature at the onset of rainfall, Event 1

Due to theft of the iButton placed in stormwater pipe 1, this temperature data is missing. Nevertheless, this event provided valuable stormwater temperature data, worth analysis. The rainfall event occurred on 26^{th} May 2015. Rain lasted 4 hours in total, with the maximum rainfall occurring between 11am and 12noon. Over 4mm of rain fell in this hour. The event occurred over midday. Therefore, due to the morning sunlight hours, it is expected that solar radiation would have heated urban surfaces within the study area.

The sharp drop in ambient air temperature by 1°C, from 10am to 11am, illustrates the beginning of the rain event (Picksley and Deletic, 1999). The onset of rainfall began during the 10am hour interval (note this is recorded on the 11am hour) Figure 4.6. Therefore, approximately 0.6mm of rain fell between 10am and 11am.

Just before 11am, there is a noticeable increase or "spike" in stormwater temperature, and this is evident at two of the three stormwater pipe outlets. This spike could be attributed to the "first flush" temperature increase (Young et al., 2013). The theory presented by Young et al. (2013), explains that a high level of heat transfer from urban surface to stormwater runoff will occur at the onset of rain. Therefore, stormwater runoff becomes thermally loaded and will be higher than ambient and river water temperature. This is seen in Figure 4.7 which represents a zoom on the first two hours of rainfall. Stormwater outlet 2, experiences the highest temperature spike, and is close to 19°C at 10:50am. Stormwater outlet 3 at 10:00am measures roughly the same temperature as river temperature. This is interrupted by two temperature "spikes". The first at 10:40 and is 16.8°C. The second spike at 10:55 is significantly higher, measuring 17.5°C. The temperature logger placed in stormwater outlet 4, records a smaller spike in temperature, and is also around 17.5°C, similar to outlet pipe 3.

At 11am stormwater temperature rapidly decreases, and is evident at all outlet sites. Stormwater temperature reaches equilibrium with river temperature just after 11:30am. The rapid decrease in discharge temperature occurs as peak rainfall occurs. Analysis by Young et al. (2013) suggests that after prolonged or intense rainfall surface temperatures are cooled. Runoff temperature begins to correlate to actual rain temperature, as wetted surfaces are cooled and have a lowered thermal emittance (amount of heat a surface will radiate per unit area, at a given temperature) (Young et al., 2013). The observed decrease in discharge temperature, from 11am, at each outlet point, could be attributed to this notion.

Remarkably, average river temperature does not show any significant response to heated stormwater inputs, as a whole. River water temperature (represented by the blue line in all the graphs) remained constant and elevated above ambient air temperature. This is because of the high specific heat capacity of water. One might expect to see an increase in river temperature due to the cumulative effect of heated stormwater discharging from all outlet points upstream from the study area. However, the effect would be closely related to the amount of rainfall and thus runoff which the river received. Because this event was relatively moderate, where peak rainfall was just 4mm, and total rainfall was approximately 6mm over 4 hours, the amount and rate of runoff would have been small. As the rain event progressed, dilution of any heat inputs would have occurred and this will have resulted in a relatively constant average river temperature.

Average ambient air temperature begins to climb around 2pm, after the rain event has ended. It increases above river water temperature. At this point, air temperature will equal recordings by the iButton temperature loggers as runoff is no longer discharging at the outlet site.

An interesting observation from this rain event is the second temperature "spike" occurring at 12:30pm. All stormwater outlet pipes recorded a similar trend. This second temperature pulse can be explained with reference to the increased amount of rainfall. Peak rainfall occurring in the hour from 11am-12noon would result in increased runoff. This runoff could be derived from a greater area extent, i.e. new areas within the catchment would now be experiencing surface runoff (from the greater rainfall) and therefore a second wave of heat transfer may have taken place. This stormwater would have been directed to the discharge outlets, the "spike" in temperature would register with a lag effect.

However, another explanation behind the second temperature increase could be related to the type of surfaces which stormwater runoff is flowing over. Roofs, roads and pavements together contribute significantly to heated stormwater water runoff. According to Herb et al. (2007a), conventional roof materials can absorb solar radiation and retain heat for a considerable period of time. Metal roofs in particular have very high conductivity and attain high temperatures, thus posing a risk for thermal pulse loading. Concrete or slate roof tiles do not heat up as much but can store heat for much longer time periods and therefore it can slowly release over the course of a rain event (Herb et al., 2007a; Sabouri et al., 2013; VanBuren et al., 2000; USEPA, 2008). It would be difficult to confirm the specific surface type responsible for the second temperature pulse, or if in fact it is a combined result of all surface types with increased rainfall which is contributing to the increased discharge temperature. It is important to note, that the trend occurs at all 3 stormwater outlets, meaning it is a localised factor influencing stormwater temperature. An explanation for this double spike in temperature could be that the first is the result of runoff from the roads and other ground-level surfaces, while the second peak is from the building roofs, from which the water needs to be channelled through the buildings' own rainwater systems e.g. gutters, downpipes. The South African stormwater approach is directly associated with removing rainwater from roads as efficiently as possible. All other sources of water entering the piped network are secondary and would therefore take much longer to reach the system.

Stormwater outlet pipe 2 experiences the highest temperature pulses and therefore the largest range in temperature recordings over the entire event. This outlet is situated along the Observatory stretch of river. Stormwater pipe outlets 3 and 4, which are situated in Rosebank, both track a similar trend over the course of the rain event.

4.3.2 Rainfall Event 2: 3^{rd} June 2015

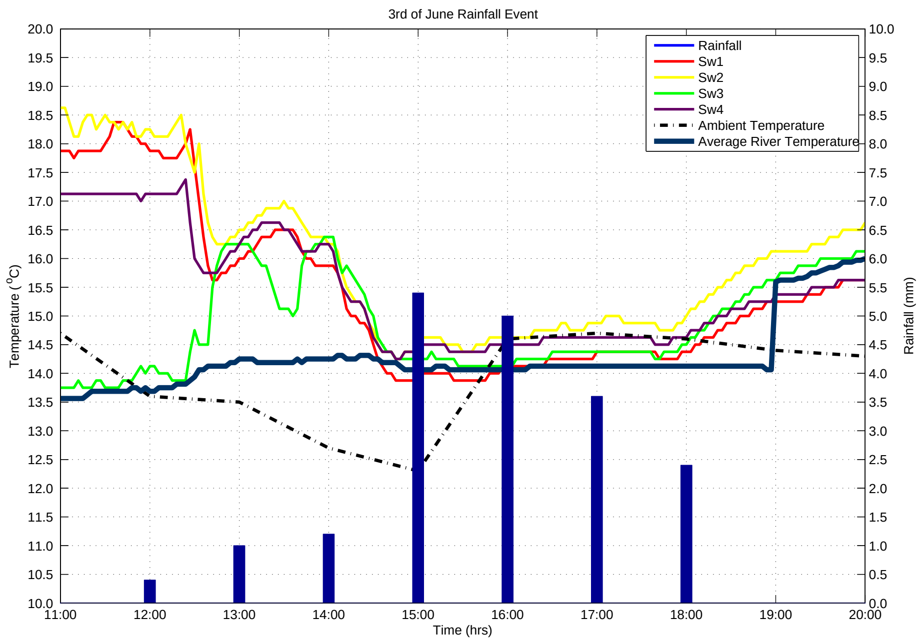

Figure 4.8: Rainfall Event 2 on 3^{rd} June 2015

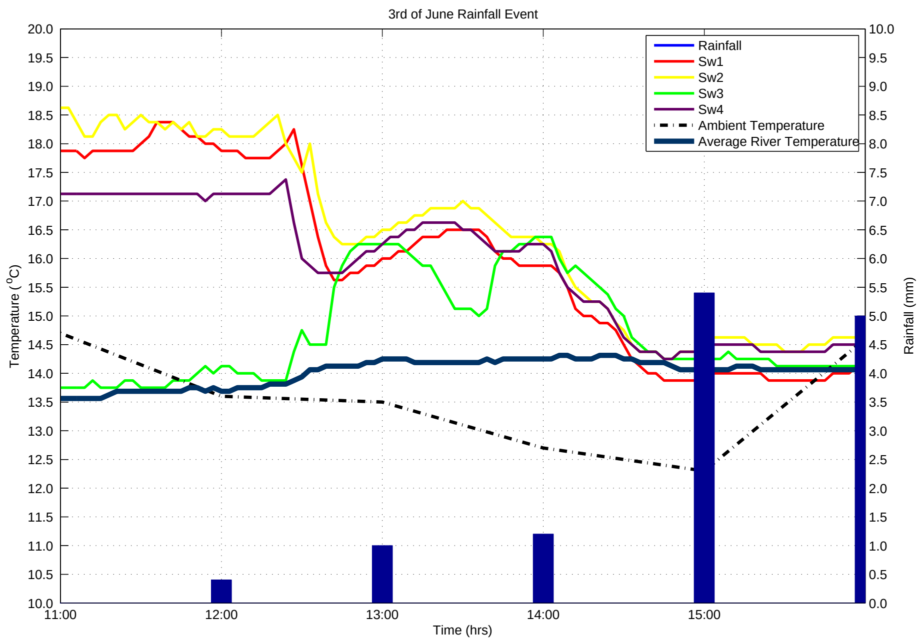

Figure 4.9: A closer look at Stormwater temperature at the onset of rainfall, Event 2

This rainfall event occurred on 3^{rd} of June 2015. The onset of rain occurred between 11am and 12 noon: the noticeable drop in ambient air temperature confirms this. This event also occurred over midday, similar to event 1. However, the amount of rainfall for this event was much greater, and was 19mm in total. Furthermore, the duration of the event lasted 7 hours in total. The 'first flush' temperature increase is observed in the second hour of rainfall. This could be because at the onset of rain only 0.4mm fell between 11am and 12noon. This might not have been a substantial enough amount of rainfall for runoff to be discharged at the outlet sites. Therefore, during the second hour of rainfall, once an additional 1mm of rain had fallen, runoff experienced surfaces heat transfers and was recorded at the outlet sites.

There is a second pulse in stormwater temperature, observed over the hours of 1pm and 2pm. This trend is evident at all 4 outlet sites, with slight differences occurring at stormwater outlet site 3 (represented by the light green line). The noticeable "bulge" in stormwater temperature from 1pm to 2pm is visible in Figure 4.8. Due to the increased rainfall amount and the time of day, substantial heat transfer could be taking place in the catchment, from surfaces to stormwater runoff. This is confirmed by the significant difference between ambient air temperature (13°C) and discharge temperature, which are not correlated.

This increase in discharge temperature could again be attributed to artificial surface areas which release heat more slowly. Young et al. (2013) suggest the characteristics of different surface types have a significant influence on the heating of stormwater. Runoff temperatures observed in their analysis, were based on the material's ability to absorb, store and release heat energy, otherwise known as thermal mass. Additionally, runoff temperatures can vary depending on the nature of each rainfall event. Consequently, the witnessed increase in stormwater temperature on this occasion could be the interaction of many surface types. However, it would likely be asphalt and concrete contributed significantly to increased stormwater temperature, on this occasion (Asaeda et al., 1996; Kevern et al., 2009; Wardynski et al., 2013).

Similar to the previous rain event 1, there is a rapid drop in stormwater temperature, during the hour of peak rainfall. This occurred between 2pm and 3pm and was 5.4mm of rain in total. All outlet temperature loggers recorded this rapid drop. At 3pm stormwater temperature reaches equilibrium with river water temperature.

A notable difference compared to event 1, was the significant rise in average river water temperature. This increase from 13.5°C-14.2°C occurred at 12:30pm, and remained steadily constant at this increased temperature. This could be attributed to a number of factors, such as higher solar radiation occurring on this day. One important inference would be to assume this increase was a response to increased temperature inputs along the entire Liesbeek River, from stormwater discharge points upstream of the study area. However, a suit of temperature loggers placed along the entire river stretch upstream of the study area would be needed. The single upstream temperature logger which was placed and the captured data were not reliable to confirm this inference. Furthermore, the rise in river water temperature correlates to the second pulse in stormwater discharge temperature.

As the rain event progresses ambient air temperature begins to rise, with a peak at 3pm in the afternoon. Stormwater discharge temperature reaches equilibrium with ambient air temperature. This would be because ambient air temperature exerts a strong effect on the temperature of rainfall and thus runoff temperature, once surfaces have cooled and heat transfers are no longer occurring.

4.3.3 Rainfall Event 3: 11th July 2015

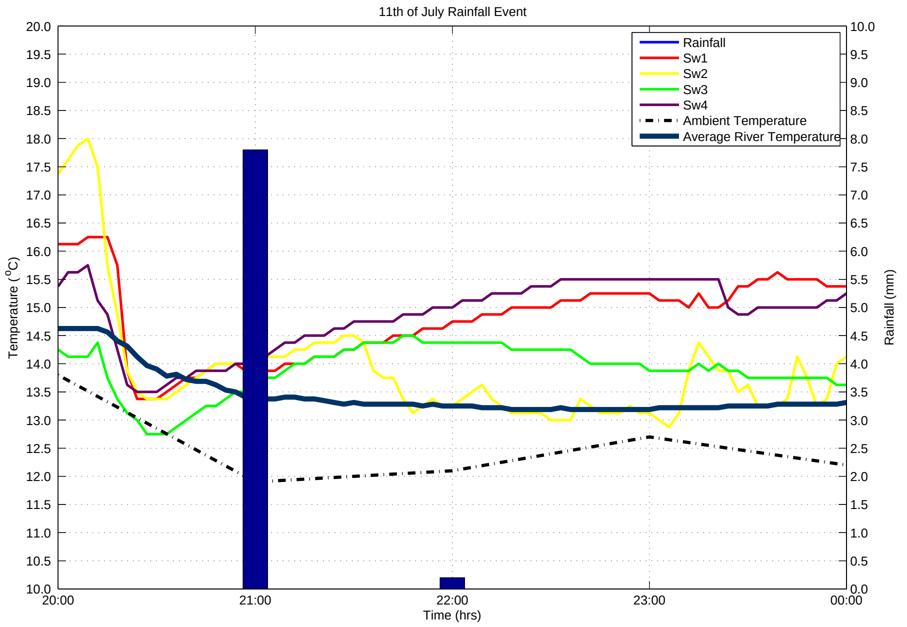

Figure 4.10: Rainfall Event 3 on 11th July 2015

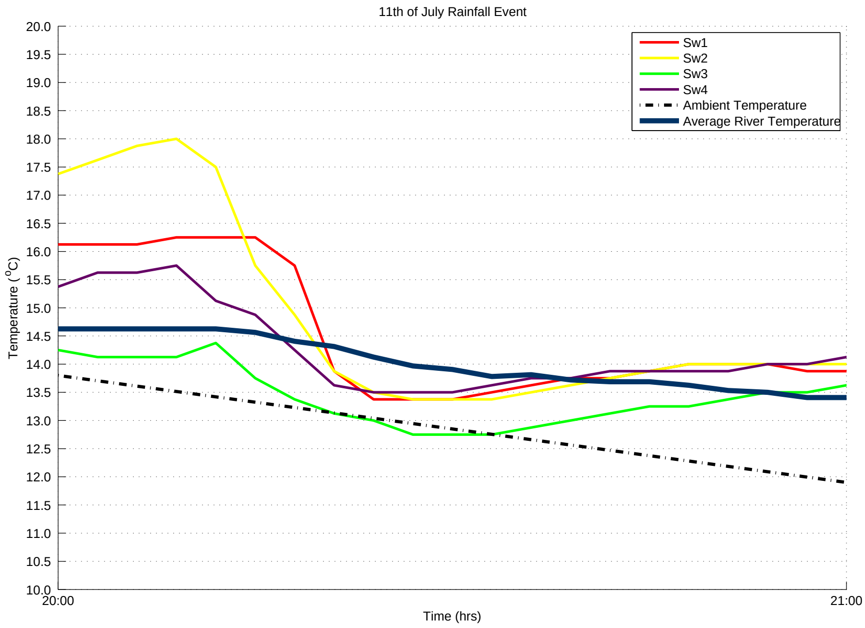

Figure 4.11: A closer look at Stormwater temperature at the onset of rainfall, Event 3

Rainfall event 3, which occurred on the 11th July 2015, was a short intense rain event, where 7.8mm of rain fell in just one hour, from 8pm to 9pm. This event represented an evening rain event. According to Young et al. (2013), this time of day can be the most potential risk for river thermal enrichment due to stormwater runoff, as all surfaces within the catchment have had time to warm (Young et al., 2013). Figure 4.11 illustrates a zoom of the 1 hour of rainfall. Note the "rainfall bar" in dark blue, has been removed in order to see stormwater temperature trends over the 60 minutes. Ambient air temperature starts to decrease at 8pm, from 13.7°C to 12°C illustrating the beginning of the rainfall storm.

All stormwater pipe outlets illustrate a small "spike" before a rapid decrease in temperature. With the exception of stormwater outlet pipe 3, the other outlet sites record higher runoff temperatures than river water temperature, at the onset of rainfall. The rapid decrease in stormwater discharge temperature, to below river water temperature, can be attributed to the high rainfall amount and runoff rate. Surface-to-stormwater heat transfers would not be visible at a 3 minute time interval. This is due to the reduced contact time rainfall has on surfaces. Runoff will quickly be diverted into stormwater pipes and discharged rapidly into the river. Due to the nature of this event, runoff would have subsided soon after 9pm, without any prolonged heat pulses from urban surface transfers.

In contrast to event 2, average river water temperature over the course of this rain event did not show any response to thermal influence from impervious surfaces. River temperature decreased at the onset of rainfall, and tended towards ambient air temperature. This highlights the notion that air temperature is a more significant driver of river water temperature, in the absence of solar heating (Young et al., 2013; Mohseni and Stefan, 1999).

Interestingly, stormwater outlet pipe 3, situated in Rosebank, records discharge temperatures below river water temperature, for the entire duration of the event. The catchment parcel for outlet 3 most closely resembles a natural regime, with mostly residential and gardens areas. By 8pm, many of the surfaces in this area may have already cooled to ambient levels, depending on materials. For example, a metal roof loses its heat very quickly after sunset. A possible explanation would be the temperature of the rain itself was probably several degrees colder than the river temperature. The rainfall temperature could be a useful measurement to capture in future research. This reflects a strong correlation between runoff temperature and ambient air temperature at this site. Runoff flowing over this area might still have become thermally loaded due to heat transfers from impervious surfaces. However, overall the temperature of runoff in this area never exceeded river water temperature. This discharge outlet, during this event, would be considered acceptable in terms of thermal pollution levels.

4.3.4 Rainfall Event 4: 17^{th} July 2015

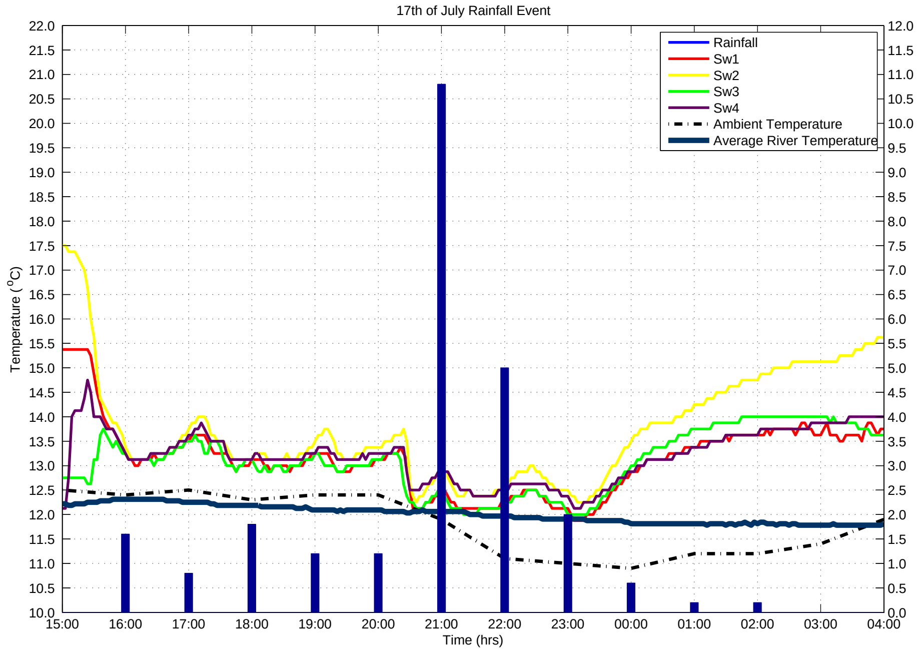

Figure 4.12: Rainfall Event 4 on 17^{th} July 2015

Rainfall event 4 occurred on 17^{th} July with the onset of rain at 3pm. This rain event occurred in the late afternoon after substantial hours of solar radiation. In total, 25.5mm of rain fell over the course of 11 hours. Peak rainfall occurred between 8pm and 9pm, with over 10mm of rain falling in this hour. This event represents a characteristic winter rainfall event, which occur frequently in Cape Town. The event was considerably prolonged, and rain was continuous for all 11 hours.

A noticeable trend, among all the stormwater outlet pipes, is that discharge temperature pulses continuously as rainfall pulses. Each line in Figure 4.12 which represent temperature recordings closely tracks all the others. This means each outlet shared a similar response to rainfall, for the duration of the event.

There is an evident "spike" in discharge temperature in stormwater pipes 3 and 4, situated in Rosebank. This occurred within the first hour of rainfall from 3pm to 4pm, and suggests a first flush temperature spike, resulting from surfaces which may readily give up heat energy. However, stormwater pipe outlets 1 and 2 showed no apparent temperature spike at the onset of rain. Runoff temperature rapidly decreased at 4pm, and is evident at all outlets. However it remains above ambient air temperature. This suggests thermal loading could be responsible for maintaining runoff temperature above ambient air temperature. From 4pm to 8pm there is a series of temperature pulses, as rainfall progresses: in total 6.6mm of rain fell in the first 4 hours.

Between 8pm and 9pm, peak rainfall occurs, with over 10mm of rain falling in this hour. At this point ambient air temperature rapidly drops below river water temperature. Likewise, stormwater discharge temperature at all outlet pipes drops. This is because ambient air temperature drives actual rainfall temperature, and therefore runoff temperature. Shortly after peak rainfall around 8:30pm stormwater discharge temperature reaches equilibrium with river water temperature. However, between 9pm and 11pm, an additional 7mm of rain fell during this hour and resulted in two secondary temperature pulses. Although runoff temperature was reduced (from previous peak rainfall) the temperature pulses are still noticeable, and are above ambient and river water temperature. This suggests urban surface emittance is still responsive to additional rainfall. Surfaces can store and transfer heat over a prolonged period of time, maintaining elevated stormwater runoff temperatures. Alternatively, the secondary temperature pulses, after peak rainfall, could suggest new surface areas are becoming wetted within a greater extent of the catchment, due to the cumulative effect of rainfall. The pulses could be a result of a positive knock-on effect: increased rainfall leads to increased runoff, which leads to greater surface area where heat transfers take place.

Average river water temperature remains constant, for the duration of the event, around 12°C. However, there is a slight rise in river water temperature in the first hour of rainfall. This could signify a response to the first flush temperature inputs from stormwater discharge. This can significantly influence river water temperature, especially since river flow has not peaked. Ambient air temperature remains elevated above river water temperature for the first 5 hours of the event. Therefore ambient air temperature will exert a strong influence on runoff temperature, exacerbating thermal loading. Herb et al (2009) found that climate parameters such as air temperature and solar radiation, prior to a rainfall event are more important factors in determining runoff temperature than parameters such as length and slope of impervious surfaces. However, pavement thermal parameters, such as specific heat and thermal conductance, have an overarching influence on initial runoff temperature (Galli, 1991; Roa-Espinosa et al., 2003; Herb et al., 2007b).

4.3.5 Rainfall Event 5: 4^{th} August 2015

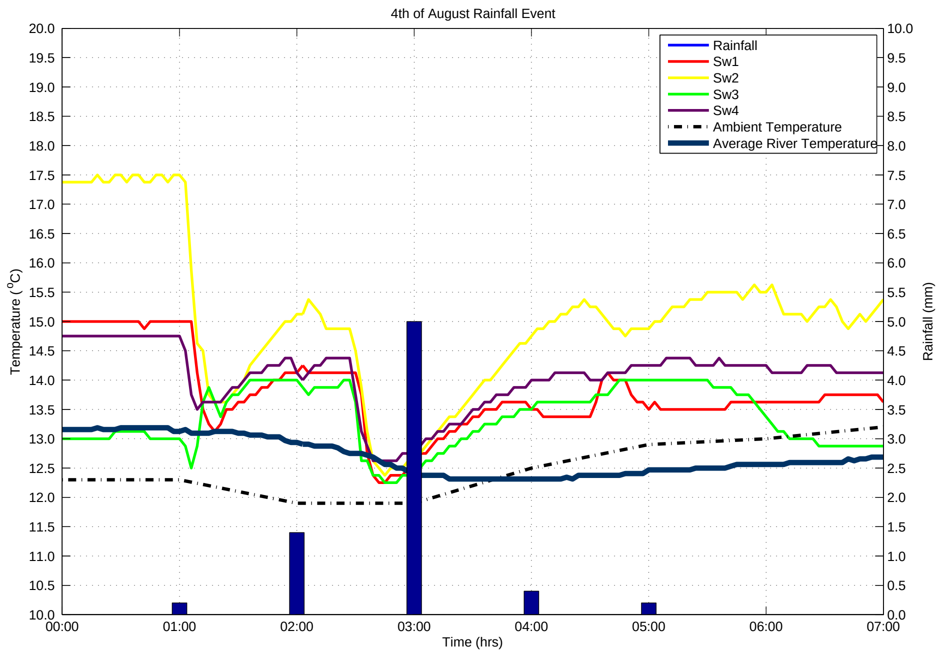

Figure 4.13: Rainfall Event 4 on 4^{th} August 2015

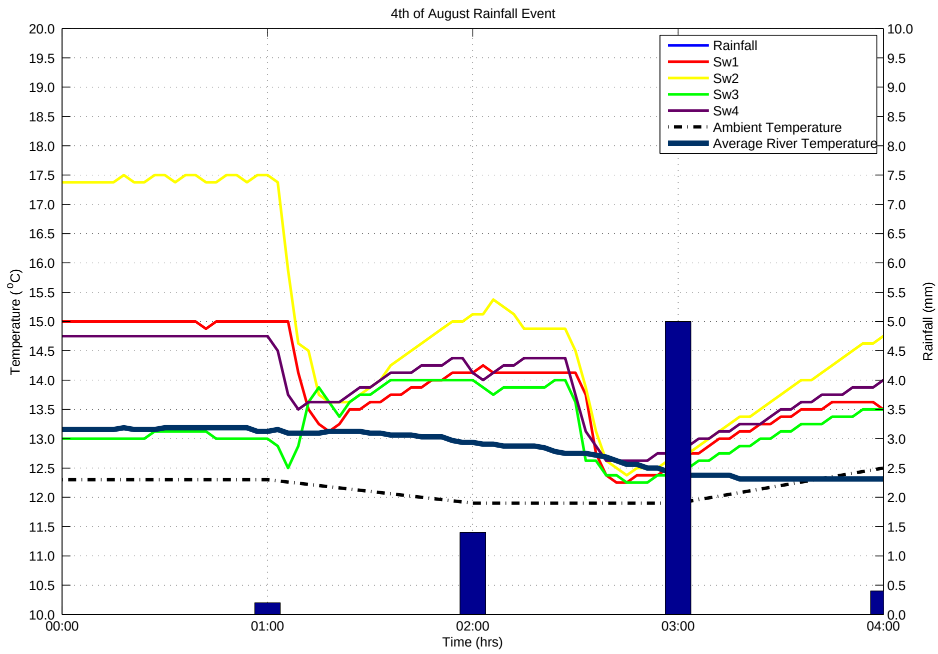

Figure 4.14: A closer look at Stormwater temperature at the onset of rainfall, Event 5

Event 5 occurred on 4^{th} August 2015, with the onset of rain occurring at midnight, The duration of rain lasted for 5 hours. This event represented an example of an early morning rain event. In the first hour less than 0.4mm of rain fell, which would not have produced substantial runoff to be recorded at the discharge outlet points. Hence, only in the second hour of rainfall, from 1am to 2am where an additional 1.4mm of rain had fallen can trends be seen in stormwater temperature.

There is a sharp drop in stormwater temperature at pipe outlets 1, 2 and 4 at 1am. This signified the onset of rainfall. Stormwater temperature at outlet pipe 3 shows an initial drop below river water temperature and then climbs. Discharge temperature recordings at outlet 3 then follows the same response as the other outlet points.

Runoff temperature between 1:30am and 2:30am was recorded as substantially higher than river water temperature and ambient air temperature. This is clearly shown in Figure 4.14. Furthermore, the elevated temperature is sustained for this entire hour. Pipe outlet 2 recorded the highest runoff temperatures in this time period. The increase in discharge temperature, at all pipe outlets, suggests evidence of thermal loading on stormwater runoff. This highlights that urban surfaces can retain heat for prolonged periods of time and can be released to stormwater runoff even in the early hours of the morning. The amount of heat exported to runoff from impervious surfaces can be based on a number of factors, including solar radiation, wind speed, maximum air temperature. It could be inferred that previous weather conditions, during the daylight hours before this storm would have been favourable towards a high heat export capacity, i.e. high solar radiation and low wind speed. Peak rainfall occurred between 2am and 3am, where 5mm of rain fell in this hour. At this point stormwater discharge temperature rapidly decreases and it reaches equilibrium with river water temperature. It then continues to decrease below river water temperature. This would be because ambient air temperature exerts a stronger force on runoff temperatures, after surfaces have cooled and heat transfers have subsided. Ambient air temperature remains lower than river water temperature at the beginning of the rain event. It then begins to climb after peak rainfall. Average river water temperature follows an opposite trend to air temperature. The river temperature shows no response to stormwater inputs. It remains relatively constant during the start of the rainfall event and then decreases as peak rainfall occurs. Due to the fact that it is early morning, river temperature will be tending towards the daily minimum. It is not apparent from Figure 4.13 that the daily river temperature cycle has been affected. However, a more detailed analysis of the in-river data as well as the inlets, using additional temperature loggers would be required to confirm this. It is important to remember the temporal regime of a river is superimposed over smaller time scale temperature fluctuations (Webb and Walling, 1993; Caissie, 2006).

Graphical observations provide valuable information regarding stormwater temperature dynamics, during a rainfall event. Changes occurring in time can be seen clearly, including trends which may develop. In almost all rain events, outlet pipe 3 recorded slightly differing temperature data. Outlet pipes 1, 2 and 4 recorded very similar responses to rainfall. The explanations provided above, give a good understanding of temperature dynamics of the individual outlet pipes, river water temperature and ambient air temperature. Furthermore, they distinguish the unique and variable nature of each rain event, including factors such as, differences in rainfall amount, time of day and duration of rainfall.

In the following section, data from all 13 rain events was statistically interrogated for significance. Statistical analysis is an important component of scientific analysis. It provides understanding of general trends and relationships which exist between variables. In this case mean hourly stormwater temperature was tested as a function of explanatory variables against mean river water temperature, which was the reference variable. Key findings are presented in the following section (4.4).

4.4 Statistical Analysis

Two descriptive statistical tests were carried out. These were necessary to show measures of central tendency, measures of variability and minimum and maximum values.

Figure 4.15, the Box and Whiskers diagram, summarizes data for all 13 rain events, and shows mean hourly stormwater discharge temperature at outlet sites 1,2,3 and 4. The box shows the spread of data including the median, and whiskers represent the minimum and maximum temperature data observed. "V" in Figure 4.15 represents the mean hourly river water temperature, and is used as a temperature reference in order to compare mean hourly stormwater temperature.

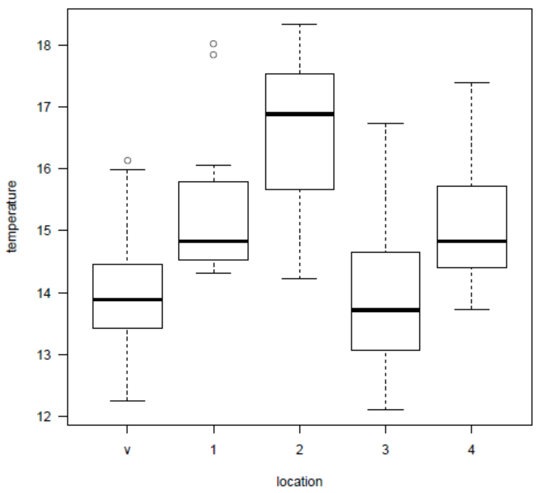

Figure 4.15: Box and Whiskers Diagram

From Figure 4.15 it is clear that mean hourly stormwater discharge temperature at outlet sites 1,2, and 4 is significantly higher than mean hourly river water temperature (V), for all rain events. Stormwater outlet 2 shows the highest mean hourly temperature recorded, and is approximately 17°C.

Stormwater pipe outlets 1 and 4 share similar mean temperature, which is approximately 14.8°C. However, stormwater outlet 3 shows a greater data spread. At this site, the maximum temperature recorded was approximately 17°C and the minimum temperature recorded was 12°C, whereas at outlet site 1 the maximum mean hourly temperature recorded was 16°C and the minimum temperature was 14.2°C. At outlet site 4 there is a larger temperature range, in response to rainfall.

Mean river water temperature, which represents the temperature reference, is approximately 14°C. River water temperature also has a large data spread, however daily temperature cycles govern maximum and minimum temperatures, river water temperature would be primarily influenced by air temperature, however, one would expect rainfall temperature to also have a smaller but significant influence. Outlet pipe 3 exhibits the closest mean hourly temperature recordings when compared to mean river water temperature recordings. The mean temperature at outlet site 3 is approximately 13.7°C. This is less than mean river water temperature and could be attributed to the ambient temperature of the rainfall. However, the spread of temperature recordings is greater at outlet site 3 when compared to river water temperature recordings. Maximum temperature at outlet site 3 is approximately 16.8°C. This observed maximum temperature would be considered a response to rainfall. Thermal loading of stormwater runoff would result in higher maximum temperature being recorded at this site.

A Tukey Range test was performed at the 95% confidence level: Figure 4.16 graphically shows this test. The mean temperature of each stormwater pipe outlet was tested against the mean temperature of every other stormwater outlet, and against the mean river reference temperature. This test provided a comparative analysis of each site.

Some important findings from this test include the noticeable difference in temperature recorded at outlet site 2, when compared to river temperature (V). This supports the previous finding that stormwater outlet 2 shows the highest temperature differences when compared to the river reference. The difference is positive, and represents increased temperatures observed at outlet pipe 2. The temperature difference between these two data sets is approximately +2°C, but can be as great as +4°C difference.

A second notable finding is that when mean stormwater temperature at outlet site 3 is compared to the river reference temperature, there is almost no difference observed. Positive differences exist between outlet sites 1 and

4, when compared to the river reference site. The mean temperature difference is approximately +1°C, for both outlet sites when compared to the river reference.

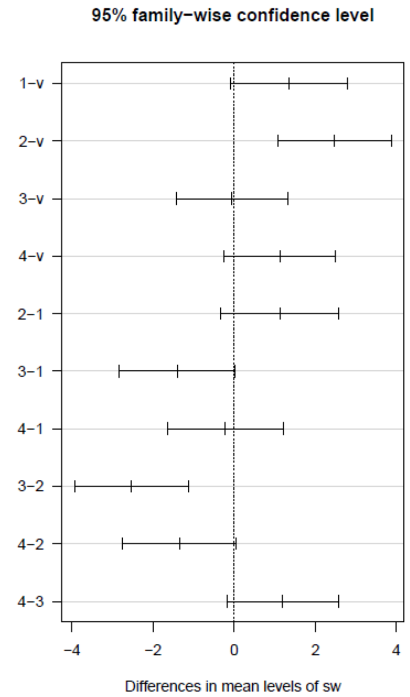

Figure 4.16: Comparative Analysis of Each Outlet Site, Including the River Reference Temperature: Tukey Range Test

The statistical modelling program 'R' was used for an in depth analysis of stormwater temperature. A generalized least squares model was built. The model used mean, hourly, stormwater temperature as a function of explanatory variables. These variables were; mean, hourly air temperature, mean hourly river temperature (reference temperature), amount of rainfall (mm), duration of rainfall (hours), cumulative rainfall and time of day.

The model used a simple auto correlation structure (AR1 process) to account for correlation of previous temperature values, i.e. that measurements from the same location and a single rain event are correlated, and are in series. Model output results can be seen in Table 4.4. Regression coefficients and their corresponding p-values, between stormwater temperature and tested variables, are given. Also included are standard errors of linear regression and corresponding t-values.

Coefficients	Value	Std. Error	t-value	p-value
Intercept	12.6694	0.4318	29.3407	0.0000
Sw1	1.2355	0.3185	3.8792	0.0001
Sw2	1.9912	0.3136	6.0958	0.0000
Sw3	0.7043	0.3073	2.2918	0.0222
Sw4	1.4141	0.3073	4.6014	0.0000
Ambient	0.1013	0.0280	3.6162	0.0003
Rain.hour	0.0002	0.1178	0.0184	0.9853
Rain.cum	-0.1039	0.0111	-9.3444	0.0000
Hour	0.0812	0.0164	4.9399	0.0000
$\sin(\text{time.hour}/24 * 2 * \pi)$	-0.2889	0.09620	-3.0027	0.0028
$\cos(\text{time.hour}/24 * 2 * \pi)$	-0.2319	0.0962	-2.4120	0.0161

Table 4.4: Model outputs: Stormwater temperature as a function of explanatory variables

From Table 4.4 The p-value calculated for stormwater temperature at outlet pipes 1,2 and 4 is < 0.05, this confirms that stormwater temperature measured at outlets 1,2 and 4 is significantly different from the predictor variable, which is river water temperature. Stormwater temperature at outlet 3 has a calculated p-value of 0.02. This confirms that stormwater temperature at outlet 3 is not strongly different from river water temperature.

Regression coefficients represent the mean change in the response variable for one unit of change in the predictor variable, while holding other predictors in the model constant. The regression coefficient for stormwater outlet 1 is 1.24°C. This shows that for all rainfall events, mean hourly stormwater temperature measured at outlet pipe 1 was 1.24°C higher than river water temperature. Similarly, stormwater temperature measured at outlet pipe 2 showed a significant difference in temperature compared to the river water temperature. The regression coefficient for temperature at outlet pipe 2 was 1.91°C. This means that mean hourly stormwater runoff, measured at outlet 2, was 1.91°C higher than river water temperature for all rain events. This was the highest recorded significant difference. Outlet pipe 4 also measured a significant difference. The regression coefficient for outlet 4, shows that mean, hourly stormwater temperature was 1.41°C higher than river water temperature.

Additional significance is observed for the effect of mean hourly ambient air temperature on mean hourly stormwater temperature $P < 0.05$ (Table 4.4). Furthermore, cumulative rainfall, time of day, and the duration of the rain event (hours) are statistically significant and show a strong relationship with stormwater temperature.

The relationships between the dependent (stormwater temperature) and explanatory variables are better illustrated using scatter plots, these are presented and discussed further (Figure 4.17).

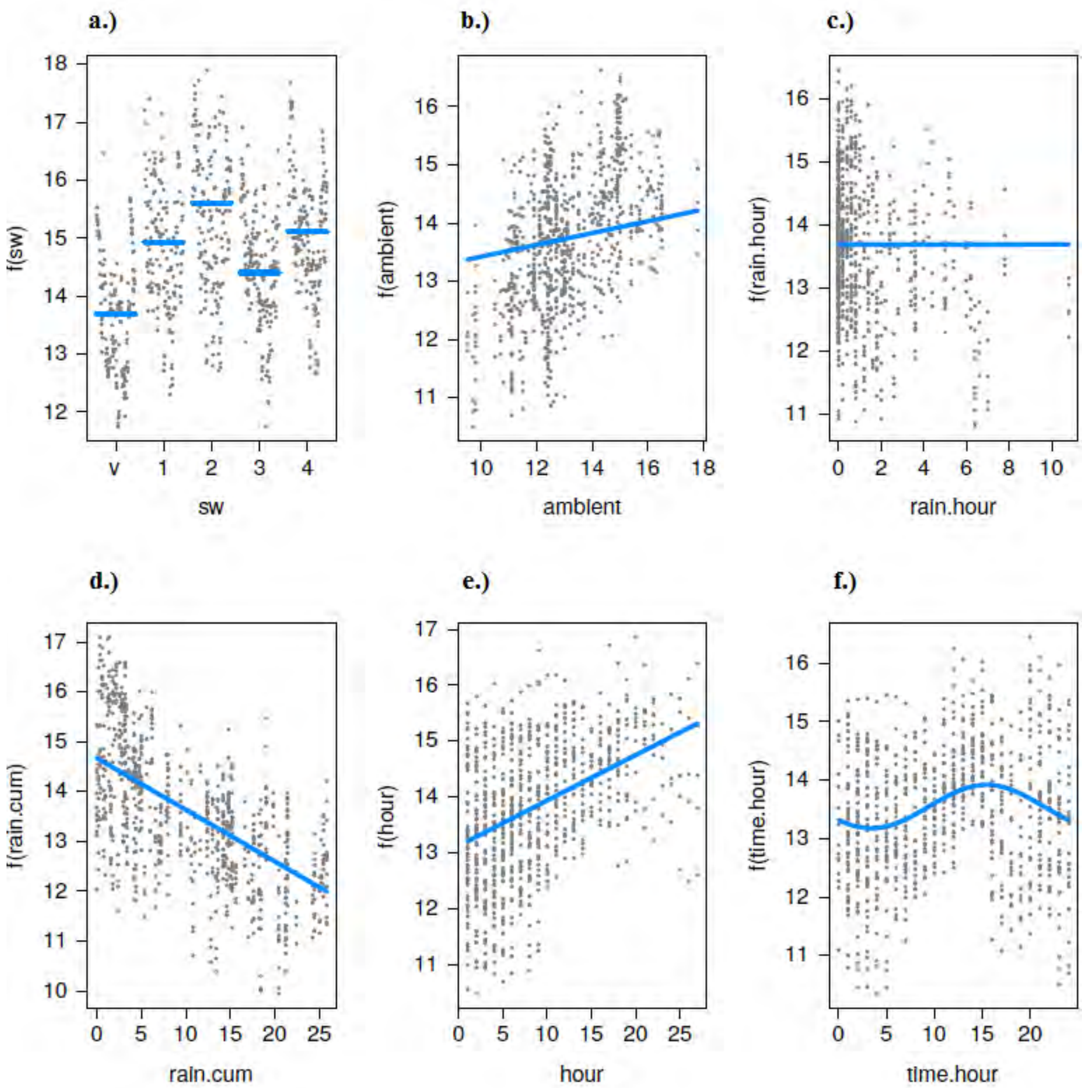

Figure 4.17: Scatter plots showing Stormwater Temperature as a Function of Event Variables

Figure 4.17a, shows key relationships between all stormwater outlet pipes and the river reference. The plot shows mean, hourly stormwater temperature as a function of outlet location (1, 2, 3, and 4) and the river reference (v). The mean trend line has been identified within the spread of data. It is clear to see that all stormwater outlet sites have a higher mean temperature when compared to mean river temperature. Stormwater temperature at outlet site 2 is significantly higher than river temperature, and is the highest observed difference. The relationship between mean stormwater temperature at outlet sites 1 and 4 is similar. Additionally, these two outlet sites are significantly higher than mean river temperature. Outlet site 3 shows the closest relationship to mean river temperature, but still measures higher than river temperature. The higher mean temperatures observed at the outlet discharge sites could be attributed to thermal loading. Runoff which passes over impervious surfaces is heated. This runoff is said to be a source of thermal pollution and will be higher in temperature than the receiving body of water.

Figure 4.17b, shows a positive linear relationship between mean hourly stormwater temperature and mean hourly ambient temperature. This means that as ambient air temperature increases so stormwater temperature increases. This is observed at all sites. This relationship would be expected, as ambient air temperature exerts a strong influence on rainfall temperature and therefore on runoff temperatures. The temperature of discharging stormwater at each outlet site will be strongly correlated to ambient air temperature, regardless of other variables. From Table 4.4, for every 1°C increase in ambient air temperature, stormwater temperature will increase by 0.1°C.

Figure 4.17c, shows stormwater temperature as a function of rainfall per hour. There is no apparent relationship between these two variables. This is confirmed by the high p value ($P > 0.05$) in Table 4.4. The graph suggests that rainfall per hour does not affect stormwater temperature. This is an acceptable finding as there was high variability in each rain event, in terms of rainfall amount per hour and duration of event. This variability was too great in order for the model to recognise a strong relationship. Only from graphical observations (section 4.3) was it possible to observe that in the first or second hour (depending on the amount of rainfall) stormwater temperature showed evidence of thermal loading. Furthermore, graphical observations illustrated that during the hour of peak rainfall stormwater temperature rapidly decreased.

Figure 4.17d, shows stormwater temperature as a function of cumulative rainfall. The linear relationship is strongly negative. This means that stormwater temperature decreases as total rainfall amount increases. In other words, as rainfall amount accumulates over the duration of the event, there is an observed decrease in stormwater temperature. This relationship is expected. Increased rainfall will mean reduced runoff temperature, as surfaces are cooled over the course of the event.

Figure 4.17e, shows stormwater temperature as a function of time (duration of rain event). The plot shows a strong positive linear regression, meaning that stormwater temperature increases with increasing event duration. This plot does not show a true representation of a linear relationship between these two variables and should be disregarded due to data density concerns. There is a large scatter visible in the range of 0-5 hours. However, the data spread is not evident as the duration of event increases. For example, between the 12-20 hour time range there is a lack of data falling in the lower quartile. This will result in a shift in the mean which will incorrectly produce a linear relationship. Stormwater temperature cannot infinitely increase with increasing event duration. This in fact contradicts Figure 4.17d, which showed that cumulative rainfall resulted in a decrease in stormwater temperature.

Finally, Figure 4.17f, shows stormwater temperature as a function of time of day. This means that stormwater temperature is strongly affected by time of day, and this effect follows a sinusoidal pattern (natural daily temperature cycles). This relationship is expected. This means that stormwater temperature is still governed by the natural laws of temperature cycles. In other words, observed stormwater temperature would be higher for a rain event occurring mid afternoon, than if an identical event were to occur early morning. This is due to the strong influence ambient air temperature has on rainfall temperature and thus runoff temperature.

4.5 Key Findings

4.5.1 Key Findings from Graphical Observations

A number of key findings from the graphical observations presented in section 4.3 can be discussed further. Firstly, differences and similarities in stormwater temperature exist between outlet pipes. Most notably, stormwater outlet pipe 2 recorded the highest temperatures for all events (1-5). Stormwater pipe outlet 3 recorded the lowest temperatures, for all events (1-5). These two strong differences can be directly correlated to the parcel area characteristics.

In section 4.2, Table 4.1 identifies parcel area 3, which is the area drained and discharges at outlet pipe 3, as the smallest area (49000m^2). Additionally, the length of stormwater pipe is considerably smaller than all other pipe networks (880m) and the number of catchpits is far less (21). The observed lower temperatures measured at this site could be associated with the fact that the area is significantly smaller. It will receive lower volumes of runoff and therefore carry less thermal load (Thompson et al., 2008a). Unfortunately, this study did not measure discharge at the outlet of each pipe and so this theory would need to be further investigated, by measuring the relative volume of water discharging at each outlet point to assess the effects of volume on stormwater temperature.

The landuse within parcel area 3 is a combination of general residential and public open space. Figure 4.4 illustrates the "low-impact" nature of surfacing found within this parcel area (Herb et al., 2007a). The area is bound by two public parks, offering infiltration and has high tree coverage (found in residential gardens) providing shading to surfaces within the parcel area (Rutherford et al., 1997a). In addition, the road network was shorter than in the other three parcels, therefore asphalt coverage would be reduced. All these factors combine to provide favourable thermal mitigation conditions for stormwater runoff (Young et al., 2013). Hence, the lower temperatures are recorded at this site. It is important to note that even though the area displays favourable attributes, temperature recordings at outlet site 3, on many occasions measured higher than river water temperature. For example, during event 1 a clear "first flush" temperature spike is visible in Figure 4.6 and measures close to 17.5°C. During Event 2, stormwater outlet pipe 3 shows two temperature pulses measuring 16.5°C (Figure 4.9), in response to pulsing rainfall. This means that the receiving water environment, at this outlet point, is still subjected to frequent thermal shocks. Thermal shocks are known to have devastating effects on aquatic biota (Olsen et al., 2011). In contrast, stormwater outlet pipe 2 recorded extremely high temperatures. On one particular event discharge measured 19°C (event 1, 26^{th} May 2015). Parcel area 2, which drains into outlet pipe 2, has significantly different characteristics in comparison to parcel area 3. This could explain the differences in stormwater temperature recordings. Firstly, the area is much larger (368,900m^2), the pipe network is considerably longer (6286m) and the number of catchpits is 136. This means that the area will receive larger volumes of runoff, which has drained a more expansive surface area. Thus, runoff will carry a higher thermal load (Thompson et al., 2008a). Moreover, the landuse characteristics of this parcel area are more varied. There is evidence of community facilities, general residential and general business zones (Figure 4.3). This will equate to more paving, roofs, and concrete structures, all of which have a high thermal mass index (Asaeda et al., 1996; Kevern et al., 2009; Wardynski et al., 2013).

Additionally, parcel area 2 has an extensive road network, approximately 7km in length (Table 4.2). This is a significant feature of parcel area 2, a large contribution of this total length is attributed to the national highway and this stretch of extensive road drains directly into outlet pipe 2. The length of road could be used as a proxy for the amount of asphalt present in the area. According to Herb et al. (2007a), asphalt surfaces exhibit very high heat export temperatures. It could be assumed that high stormwater discharge temperatures are directly related to runoff draining a large surface area of potentially very hot asphalt road. A more detailed study would need to confirm the specific contribution of thermal loading provided by this national highway. Furthermore, it is important to note the lack of shading of the highway in comparison with narrow roads, shaded by buildings and/or trees could contribute to higher discharge temperatures.

In general, parcel area 2 has more roofs, concrete pavements and road coverage. This would result in higher runoff temperatures (Thompson et al., 2008b). The project did not provide enough detail to measure how each of these surfaces respond to rainfall. For example, to investigate if asphalt heat exports result in the "first flush" spike or if concrete heat exports result in prolonged temperature pulses. This could be valuable research for prioritising the selection of thermal mitigation devices for "high risk" areas.

Stormwater temperature recordings measured at outlet pipes 1 and 4 are characteristically very similar, across all rainfall events. Theses similarities can be explained with reference to the two parcel areas, which also display similar attributes (Table 4.2; Table 3.5; Figure 4.2; Figure 4.5. However, parcel area 1 is measured as the largest area (368,900m^2), and has the longest stormwater pipe and road network. One would question why the temperatures measured at outlet 1 were not therefore the highest. This could be attributed to a number of factors. Temperature interactions which occur as runoff flows over surfaces are complex and variable. Furthermore, with differing event variables such as amount of rainfall and ambient air temperature, will result in differing responses in runoff temperature, within parcel areas. Most importantly, the type of material and distribution of surface type will play a determining role in heat transfers and therefore runoff temperatures. For example, runoff which initially flows over a warmed concrete surface and becomes thermally loaded may dissipate some of this heat if it then subsequently flows over or infiltrates a vegetated surface (Herb et al., 2007a). A final assertion is developed from theory presented by Sabouri et al. (2013), which suggests that the length of sewer pipe network can have a cooling effect on stormwater temperature. The stormwater pipe network is approximately 6km long and could explain the lower observed stormwater temperatures at outlet 1, when compared to outlet 2 which has a network 5km long and outlet 4 which has a pipe network 3km long.

Overall, a general temperature trend, which can be observed at all stormwater outlet pipes, is seen with the onset of rainfall. Noticeable "first flush temperature spikes" are witnessed in events 1, 2 and 3. These spikes can be attributed to thermal loading of stormwater runoff from heated impervious surfaces (Caissie, 2006).

Events 4 and 5, illustrate examples of temperature pulses at the onset of rain. This is attributed to stored thermal heat which is released as rainfall progresses (Herb et al., 2007b). These thermal pulses correlate to rainfall pulses. However, soon after peak rainfall, surfaces will be significantly cooled and heat transfers from surface-to-runoff will be reduced (Herb et al., 2009a).

Depending on the time of day, whether it is mid-afternoon or early evening; stormwater temperatures measured higher than temperatures recorded in the early morning or later evening. This can be explained due to the strong influence ambient air temperature exerts on runoff, and therefore stormwater discharge temperatures (Mohseni and Stefan, 1999). Furthermore, in the late afternoon surfaces have had longer solar radiation exposure time, and have not yet started to cool (Herb et al., 2007b). General temperature trends, observed at all outlets can be summarized;

- During the hour of peak rainfall, stormwater temperature rapidly drops and generally reaches equilibrium with river water temperature (Picksley and Deletic, 1999).
- Ambient air temperature will exert a strong influence on stormwater temperature, once heat transfers have subsided (Mohseni and Stefan, 1999).
- Average river water temperature showed a response to "first flush" temperature spikes: it displayed a small increase soon after the onset of rain (events 1, 2 and 4) (Young et al., 2013).

- Event 3, which represented a short, intense rain event, did not show evidence of thermal loading. This could be due to time-scale concerns. Temperature changes in response to intense rainfall would need to be monitored at smaller time intervals. Another explanation suggests that the rate of runoff and rapid drainage would not allow surface-water contact time and therefore reduce heat export rates.

- Event 4, which represented a prolonged rainfall event, where runoff rates were slower, will result in temperature pulses. All surfaces would be wetted simultaneously in small parcel catchment areas, but the runoff rate and volume would vary, depending on surface characteristics (e.g. perviousness, roughness) reaching saturation at differing rates, including man-made systems (gutters, etc.). The diversity in surface type would result in temperature pulses. This is different from the largely homogenous surface type found in the parcel 2 catchment area. An additional explanation is that surfaces can retain and release heat over prolonged periods of time. Surface-water contact time will be greater allowing for "longer temperature pulses" as opposed to "shorter temperature spikes".

4.5.2 Key Findings from Statistical Analysis

A number of key findings from the statistical analysis (section 4.4) can be summarised, and discussed further. Firstly, differences in stormwater temperature at all four outlet pipes can be confirmed by Figure 4.15 and Figure 4.16. These figures illustrate mean hourly stormwater temperature, for all 13 events. The observed temperatures are all higher than river water temperature, thereby, confirming that thermal loading of stormwater runoff will elevate discharge temperature (VanBuren et al., 2000).

Output results, generated by the generalized least squares regression model (Table 4.4) quantify these elevations; stormwater outlet pipe 1 demonstrated a mean temperature which was 1.2°C higher than mean river water temperature, stormwater outlet pipe 2 demonstrated a mean temperature which was 1.9°C higher than river water temperature, stormwater pipe outlet 3 demonstrated a mean temperature which was 0.7°C higher than river water temperature, and stormwater pipe outlet 4 demonstrated a mean temperature difference which was 1.4°C higher than river water temperature.

Figure 4.18 below, summarizes the relationship between outlet pipes relative to the river. This regression analysis is slightly different from Figure 4.17

as it uses "change in temperature" as a function for explanatory variables. The scatter plot illustrates a positive change in mean hourly temperature, for all outlet points, relative to river water temperature. In other words all outlet pipes, for all 13 rain events, recorded higher mean temperatures, relative to the river. This confirms that all four outlet pipes exhibited higher mean temperatures, which would therefore impose a thermal risk to the receiving river.

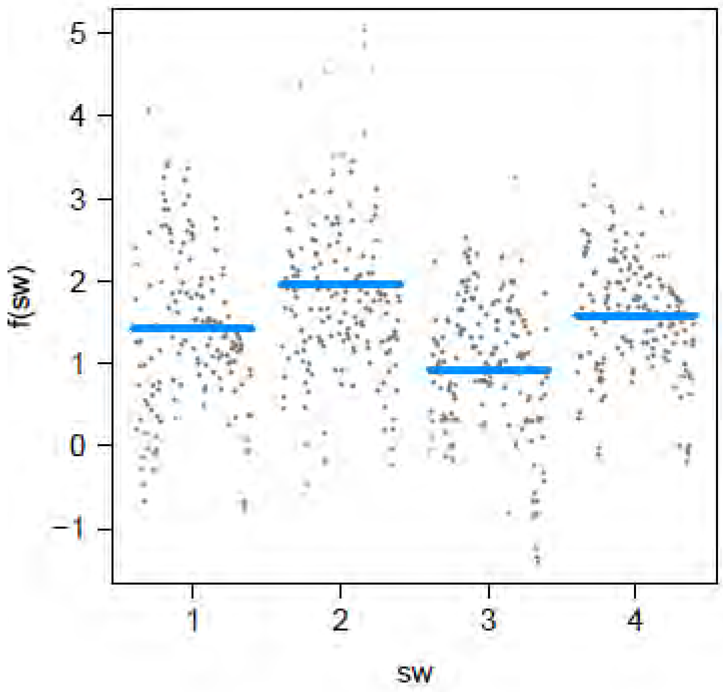

Figure 4.18: Scatter Plot Showing Change in Temperature Relative to River Water Temperature

When considering the explanatory event variables, additional findings from the statistical regression model analysis include;

- Cumulative rainfall and stormwater temperature have a negative linear relationship: as rainfall accumulates it is expected that stormwater temperature will decrease. This is most noticeable after peak rainfall (Picksley and Deletic, 1999).

- Ambient air temperature and stormwater temperature have a positive linear relationship. As mean ambient air temperature increases so mean stormwater temperature increases. This is expected as ambient air temperature exerts a strong influence on rainfall temperature and thus runoff temperature. This is especially true after surface-water heat transfers have subsided and runoff tends towards air temperature (Mohseni and Stefan, 1999).

- The time of day and stormwater temperature have a sinusoidal relationship. Stormwater temperature is still independently governed by natural daily temperature cycles (Caissie, 2006).
- Stormwater temperature measured at outlet 3 was closest to river water temperature. This site could be considered as a reference site. Furthermore, characteristics of this area could be investigated as potential mitigation methods for "high risk areas", in order to reduce stormwater heating.

Chapter 5

Conclusions

5.1 General Conclusions

The findings presented in this study, which are supported by current literature, suggest that mean stormwater temperature is highest at the onset of rainfall, which is due to "first flush" temperature spikes (Young et al., 2013). In addition, temperature pulses can occur, but will not be as elevated as initial runoff temperature (Picksley and Deletic, 1999; Young et al., 2013). Stormwater heating is attributed to thermal loading of runoff, which flows over impervious surfaces (Herb et al., 2008). However, ambient air temperature exerts a strong influence on stormwater temperature, after surface-water heat transfers have subsided (Picksley and Deletic, 1999). Stormwater temperatures are expected to decrease throughout the course of an event, and the sharpest decrease will be initiated by peak rainfall (Herb et al., 2007b). Furthermore, temperature reaches equilibrium after some time, usually soon after peak rainfall. Finally, differing thermal trends can occur, depending on variables such as; time of day, event duration, ambient air and amount of rainfall (Thompson et al., 2008a).

Thermal pollution is considered to be the degradation of water quality by any process which changes its ambient water temperature (Young et al., 2013). All outlet points demonstrated higher stormwater temperatures relative to the receiving river. This has been quantitatively shown, and provides a baseline for understanding the contribution of thermal loading at specific discharge sites. These outlet points should therefore be viewed as sources of thermal pollution.

In order to evaluate the risk imposed on the Liesbeek River, by these outlet points, it is important to consider certain characteristics of rain events. Findings from this study suggest that time of day, ambient air temperature, amount of rainfall and duration of event, influence the degree of stormwater heating. Shorter rain events which occur at midday, and the early evening, demonstrated the highest observed stormwater temperatures. These heated inputs were also delivered in the form of temperature "spikes". These types of rain events would therefore be a concern to aquatic biota which are sensitive to thermal shocks (Olsen et al., 2011).

More prolonged rain events that occurred at night or early morning demonstrated elevated stormwater temperatures. However, heat inputs were delivered in the form of temperature pulses. These types of storms would affect aquatic biota sensitive to chronic temperature changes (Olsen et al., 2011).

Water temperature is considered as one of the most important master variables governing river functioning. Natural seasonal and daily variations of water temperature are important determinants which shape aquatic communities and their distribution, (Vannote et al., 1980). Furthermore, temperature regulates ecological processes and determines the overall health of a river system (Bunn and Arthington, 2002; Jackson et al., 2007; Ross-Gillespie, 2014). Consequently, any anthropogenic modification to a river's thermal regime can have devastating effects on the ecological functioning of a river (Poole and Berman, 2001).

The impacts of heated stormwater, discharging directly into the Liesbeek River, will likely result in exclusion of a range of fish and invertebrate species that cannot survive high temperature shocks or pulses. Furthermore, it could have sub-lethal effects on more tolerant species, certainly by exposing species to higher daily temperature fluctuations and prolonged sub-optimal temperatures (Olsen et al., 2011). With the absence of ecosystem goods and services provided by aquatic communities, the river ultimately loses functioning, possibly to an irreversible point.

The implication of these project findings is that stormwater should be recognised as a source of thermal contamination. A more serious concern is that currently stormwater temperature is not directly acknowledged as a contaminant of concern (Young et al., 2013). Furthermore, there is limited available information regarding temperature thresholds. In addition, research informing these thresholds is also lacking (Ross-Gillespie, 2014). This research should include river-specific temperature requirements for aquatic biota.

This study highlighted that "parcel area" characteristics can help to explain temperature differences occurring at each outlet site. However, a more detailed study is required to understand the varying degree of thermal pollution observed at each site. Overall, outlet pipe 2 can be categorised as imposing a very high risk on the receiving river. This would be related to the effect of the large road network in this parcel area. The extensive asphalt surfacing has a high heat export and elevates runoff temperatures, resulting in the observed high discharge temperatures (Thompson et al., 2008b).

Outlet pipes 1and 4 can be grouped, and considered as high risk sites. This would be due to the extent of mixed land-use within each parcel area. Heat transfers from multiple different surface-types can have a cumulative heat effect on runoff temperature (Young et al., 2013). The presence of public open space and vegetated areas, evident in both parcel areas may help to moderate discharge temperatures at these outlet sites. In addition, the cooling effect of stormwater pipe length may exert a mitigating influence on temperature (Sabouri et al., 2013).

Outlet site 3 could be considered as imposing a moderate risk on the receiving Liesbeek River. Temperatures observed at this discharge site were closest to river temperature and therefore did not raise concern regarding excessive thermal enrichment. Within the parcel area, there is evidence for stormwater infiltration opportunities and evidence of shading over artificial surfaces. These are attributes of residential zoned areas. Additionally, the relative size of parcel area 3 and therefore amount of runoff derived from this area, was much smaller, resulting in lower observed temperatures (Young et al., 2013). Parcel site 3 exhibits traits which are supported by Water Sensitive Urban Design principles. WSUD advocates for increased infiltration and retaining natural vegetation to promote on-site treatment of stormwater runoff. This approach set out by WSUD also addresses mitigation of thermal enrichment and thus could be enhanced across the catchment as a valuable solution (Young et al., 2013).

It is important to note that thermal pollution can occur from a number of factors including stormwater runoff flowing over impervious surfaces, but not disregarding the effects of reduced shading, channel modification, or reduced groundwater inputs. All these sources are important factors in determining changes to the thermal regime of urban rivers (Caissie, 2006). Stormwater discharge was isolated for the scope of this study. However, findings from this study should not be viewed in isolation, nor should they overlook the combined interactions and effects of multiple sources of thermal pollution.

This leads to the concern of cumulative effects of multiple sources of thermal pollution. Anthropogenic activities within the catchment can exacerbate thermal enrichment. For example, the relative thermal contribution of four stormwater outlet pipes would be easily buffered by the receiving river, providing the river catchment has sufficient shading, or that baseflows were not altered (Young et al., 2013) . The removal of vegetation and subsequent replacement with impervious surfaces has a three-fold thermal impact on the river system, firstly, reduction in shading, secondly, reduced infiltration and thirdly, enhanced thermal loading to stormwater runoff. With expected future increases in urbanisation and development within urban catchments, during an age of uncertain climate responses, it is imperative that temperature be included, as an important water quality index, which is subject to strict regulation and monitoring.

5.2 Future Research Development

This research project provided the first opportunity to monitor stormwater discharge temperature at site-specific discharge points along the Liesbeek River. The unique opportunity to undertake such a project was a privilege. However, it also provided the opportunity to present recommendations and future development, to aid research within this theme.

Firstly, the study monitored four different outlet sites. Whilst this provided a baseline indication of thermal contributions, it might be more appropriate to focus on a single pipe network, as a "detailed, individual" study of thermal loading. Specific variables and their effect could be highlighted, and an understanding of their relationships to stormwater temperature would be improved. For example, monitoring temperature at outlet pipe 2 coupled with a detailed study of parcel drainage might help to better understand the contribution of road/asphalt temperature loading to stormwater runoff. This could provide valuable data for future thermal modelling of the catchment.

A significant challenge with the study was the manual collection and deployment of Thermocron iButton loggers. A valuable suggestion would be to develop an iButton which could transmit real time data, with activation and deactivation achieved remotely. This would enhance the ease of monitoring and would eliminate difficulties associated with advanced prediction of weather events. Furthermore, iButton loggers which are permanently placed in-field, could "double-up" as a research and monitoring tool, for improved urban water management.

A few noticeable gaps, which arose after the completion of this study, are:

- Investigating the dilution or buffering capacity of the river. This estimate would greatly enhance knowledge of the actual thermal contribution of stormwater discharge, and not just the relative contribution.
- Additionally, the necessity for a smaller monitoring time-interval was apparent. Ambient air and rainfall amount were measured in hourly time intervals, whereas, iButton loggers were set to measure temperature in 3 minute sample intervals. This discrepancy meant that accuracy was lost at smaller time scales by averaging stormwater temperature (to become hourly). A better approach would be to monitor meteorological variables at the same time interval as water temperature monitoring (a suggested 3 minute interval is best). This would provide maximum detail in temperature response trends and changes. Due to the nature of rain events which can be rapid and runoff which is drained quickly, smaller time-intervals are more appropriate.
- Furthermore, discharge was not measured at outlet pipes. Flow rate was not monitored due to the expense and risk of placing flow monitoring devices in-field. However, flow is an important variable necessary for understanding temperature dynamics. Future studies would benefit from measuring discharge at the outlet site, alongside other variables, as it is provides a proxy for what is occurring at the catchment scale. Furthermore, the relationship between temperature and flow was not investigated and could shed light for instance on thermal loading occurring at low flow, moderate flow and high flow scenarios.
- Similar to the omission of flow monitoring, the cooling effect that the length of stormwater pipe network has on stormwater temperature, was not investigated. This would be extremely interesting to study, as it may provide future mitigation opportunities, especially for countries which still currently have extensive networks in place.
- The Geographic Information System (GIS) analysis raised concerns associated with accuracy and was another challenge which arose during this study. The GIS desktop analysis was severely hindered by "out of date" layers. This meant that recent changes to the parcel area landscape were not yet visible in the GIS layer database. Aerial photographs helped to ameliorate some of this inaccuracy. However,

future recommendations would be to undertake a personal detailed mapping analysis of a single parcel area, one which is detailed enough to highlight surface type and coverage. This would provide improved parameters for future urban heat-surface modelling.

- Finally, this study conducted fieldwork over 4 months. However data was captured from just a single season. An improvement would be to increase the size of the data set by conducting fieldwork over multiple seasons. This would be possible with remotely transmitting iButton loggers (as mentioned above). Furthermore, sporadic rain events occurring in summertime would likely produce very interesting results in terms of thermal loading of stormwater. Moreover, an increased data set will mean improved statistical modelling and would enhance the scientific integrity of the results.

The aforementioned recommendations and future developments were discussed with specific reference to this study. However, over the course of answering this research question, additional and alternative research study opportunities presented themselves. These are noteworthy, as within any scientific field, research is expansive and infinite.

One suggestion for a future research topic would be to look at the interplay of temperature and other water quality contaminants. For example, the effect of nutrient loading coupled with elevated river water temperatures, might provide a more holistic interpretation of actual exposure to aquatic biota. Instead of researching contaminants in isolation, research aimed at investigating their combined effect on river functioning, would be a more current and realistic representation of urban river issues. It would likely provide evidence for changes to be made to certain contaminant thresholds that would have been too conservative in the past.

Another research area, which requires informed scientific findings and is currently lacking in the South African context, would be to undertake river-specific biotic analyses, in conjunction with urban temperature monitoring studies, for example, a study which investigates aquatic community structure and function, in response to stormwater temperature dynamics. This would improve understanding of the effects of stormwater heating on aquatic biota, provide information for the development of species specific temperature criteria and inform management of important temperature thresholds.

This follows onto a final research opportunity, one which could look at the aquatic response to thermally rehabilitated areas. A positively-focused scientific study would motivate future urban river rehabilitation. There are a number of successful restoration projects currently underway, globally, and these would have been informed by an initial, scientifically designed pilot study. The opportunities discussed above are suggestions for continued development within the theme of urban thermal regimes, an area which is sure to gain attention in the face of changing climates and future resource uncertainties.

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Appendix A

Weather Data

LEGEND
The rainfall (in mm) as reported on the hour is the total of the rainfall reported over the previous hour
*** indicates that data is missing or is unavailable in the current month
--- indicates that data is unavailable or was not requested
A blank indicates that no rain was recorded over the previous hour
= indicates that the average is unreliable due to missing hourly values
The 'tot' coloumn represents the total rainfell reported from 00:00 to 23:00

HOURLY DATA : Rain(mm) - May 2015

S A ASTRONOMICAL OBSERVATORY - Climate Number:0020866 9 Lat:-33.9330 Lon:18.4770 Height:15 m (Extracted 2015/06/08 08:19)

DD	h01	h02	h03	h04	h05	h06	h07	h08	h09	h10	h11	h12	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24	tot
1															0.2										0.2
2																									0.0
3																									0.0
4						0.2																			0.2
5												2.4													2.4
6																									0.0
7																									0.0
8																									0.0
9																									0.0
10																									0.0
11																									0.0
12																									0.0
13																					6.0	0.4		0.2	6.6
14	1.0	0.4	0.6		0.2																				2.2
15																						0.4	1.8	2.2	4.4
16	0.4	0.4	1.8	1.8													0.2								4.6
17																									0.0
18																									0.0
19													1.0												1.0
20							0.2																		0.2
21																									0.0
22																									0.0
23												0.2													0.2
24																									0.0
25																					0.2		0.4		0.6
26		0.2			1.0						0.6	4.2	0.8	0.6											7.4
27																									0.0
28																									0.0
29																				0.6	0.6	0.2		0.8	2.2
30		0.4	0.6					1.0		0.2	0.6												0.6		3.4
31	0.2					0.4								0.6	2.4										3.6
tot																									**39.2**

LEGEND
The temperature (in °C) as reported on the hour
The reading at h00 can either be interpreted as the last reading of the previous day or the first reading of the current day
*** indicates that data is missing or is unavailable in the current month
--- indicates that data is unavailable or was not requested
= indicates that the average is unreliable due to missing hourly values
The 'avg' column indicates the average temperature for the day and is calculated as the average of the daily maximum and minimum temperatures
The 'mx' column indicates the highest temperature (maximum temperature) reported on the day
The 'mxtm' column reports the time of the occurrence of the highest temperature of the day
The 'mn' column indicates the lowest temperature (minimum temperature) reported on the day
The 'mntm' column reports the time of the occurrence of the lowest temperature of the day

HOURLY DATA : Temperature (C) - May 2015

S A ASTRONOMICAL OBSERVATORY - Climate Number:0020866 9 Lat:-33.9330 Lon:18.4770 Height:15 m (Extracted 2015/06/08 08:19)

DD	h01	h02	h03	h04	h05	h06	h07	h08	h09	h10	h11	h12	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24	avg	mx	tm	mn	tm
1	15.4	14.8	14.1	13.5	13.2	12.3	11.9	12.4	13.8	16.4	17.1	17.6	19.8	19.8	19.9	20.8	18.7	17.5	16.2	15.8	15.2	14.8	14.0	13.7	16.3	20.8	1545	11.8	0710
2	14.1	14.3	14.6	14.8	14.6	14.2	14.2	14.9	16.4	17.2	19.8	17.9	19.6	19.9	23.4	22.1	20.7	16.2	15.4	15.4	15.1	14.9	14.3	13.9	18.6	23.5	1502	13.8	0005
3	13.9	13.3	12.9	12.3	13.0	13.8	13.8	14.5	15.5	18.6	18.9	20.5	20.0	20.4	20.6	20.3	20.1	18.0	17.5	16.4	15.8	15.5	16.2	15.6	16.9	21.5	1216	12.2	0402
4	14.8	14.6	14.3	14.6	14.6	14.1	14.3	15.2	16.3	17.7	19.0	19.1	19.8	22.1	23.1	22.9	21.9	19.5	19.0	19.0	19.0	18.8	18.4	18.4	19.0	24.0	1435	14.0	0545
5	17.9	17.8	16.6	15.9	15.6	15.7	15.9	16.1	17.2	16.7	17.6	17.0	18.1	17.5	18.0	19.0	17.9	17.0	16.1	16.0	15.2	14.9	15.1	15.0	17.3	19.7	1535	14.8	2155
6	15.6	14.9	14.6	14.8	14.2	14.6	14.6	15.5	17.3	18.6	18.4	19.3	19.4	19.3	19.5	18.8	18.0	16.5	16.2	16.2	15.8	15.7	15.5	15.6	17.1	20.1	1233	14.1	0501
7	15.4	16.1	15.2	15.7	15.2	15.0	15.0	16.5	18.4	20.0	20.5	22.2	23.1	24.6	25.6	25.6	23.7	21.1	19.1	18.7	17.4	16.5	16.0	15.7	20.3	26.0	1450	14.6	0625
8	16.4	15.3	14.3	13.7	13.4	14.1	14.3	14.6	17.6	19.7	22.1	25.8	25.7	26.5	23.5	21.8	19.1	16.3	16.2	16.0	15.7	15.6	15.6	16.3	20.1	26.9	1320	13.3	0450
9	17.7	18.1	17.9	17.8	17.8	17.8	17.5	17.6	17.9	18.4	19.5	21.0	19.7	20.4	20.6	20.1	19.4	18.4	17.9	17.6	17.4	17.2	17.5	17.3	18.6	21.1	1148	16.1	0021
10	16.9	16.7	16.8	18.3	18.4	18.1	18.0	18.2	18.8	19.8	20.6	22.3	20.7	17.6	21.2	20.8	19.2	18.7	18.4	17.9	17.5	17.3	18.2	17.3	19.6	22.6	1211	16.6	0157
11	16.8	16.7	17.6	17.8	17.9	17.4	15.7	16.7	17.2	17.9	19.4	20.4	21.8	22.6	22.1	20.6	19.2	18.4	20.1	20.3	19.0	18.9	18.4	18.6	19.4	23.1	1350	15.6	0645
12	18.1	17.5	18.1	18.2	18.3	17.1	17.0	15.8	19.2	22.4	24.7	26.2	27.5	28.2	28.2	27.7	25.2	21.6	19.2	16.9	16.3	15.5	15.1	14.1	21.3	28.5	1446	14.1	2400
13	13.3	13.2	12.9	13.1	12.8	13.2	13.5	13.6	14.2	15.1	16.9	18.7	19.2	17.9	18.2	18.2	16.7	15.7	14.9	14.9	15.1	15.1	15.1	14.9	15.9	19.2	1248	12.7	0454
14	14.6	14.6	14.3	14.1	14.1	14.0	13.3	13.0	13.9	15.8	17.6	18.5	18.0	20.8	18.2	17.3	17.6	15.7	14.2	12.4	12.7	12.9	11.7	11.2	16.1	20.9	1358	11.2	2400
15	10.6	10.0	10.1	10.6	11.0	11.1	10.4	11.4	12.6	14.0	15.4	15.4	15.8	15.4	15.2	14.9	15.0	14.7	14.6	14.8	14.6	13.9	12.4	12.2	12.9	15.9	1130	9.8	0210
16	12.7	12.9	12.8	13.1	12.8	12.6	12.8	13.1	13.8	14.9	17.1	18.0	19.2	20.6	20.4	20.3	18.2	16.5	15.2	14.9	14.8	15.5	15.3	15.4	16.5	20.8	1545	12.2	0005
17	15.0	14.3	13.5	12.6	12.0	10.7	10.4	11.3	14.2	18.5	20.3	22.7	25.7	25.6	26.4	24.8	22.9	19.2	17.5	16.2	17.9	17.5	18.2	16.6	18.8	27.5	1443	10.1	0622
18	14.5	14.3	14.3	13.8	15.4	14.9	14.2	14.9	15.8	18.4	20.4	21.7	21.3	20.0	19.8	18.4	17.0	16.0	15.8	15.9	17.2	17.2	17.2	16.9	17.6	21.9	1150	13.4	0746
19	16.7	16.2	15.6	15.7	15.5	15.2	14.9	15.0	15.3	15.5	15.8	16.8	16.5	19.0	19.0	19.0	17.6	14.6	14.1	13.6	13.4	14.0	15.1	15.7	16.6	19.9	1544	13.3	2038
20	16.0	16.1	14.0	12.7	12.4	11.9	11.6	11.4	11.4	12.7	15.6	17.4	19.0	19.7	21.3	23.4	18.2	16.4	15.5	14.1	13.5	13.2	13.1	13.5	17.3	23.4	1600	11.1	0835
21	13.5	13.1	13.1	13.2	13.1	13.0	12.9	12.7	13.9	16.3	16.8	18.7	19.2	19.5	18.7	18.8	18.3	17.3	16.5	16.2	16.5	16.7	17.1	17.6	16.9	21.3	1333	12.6	0439
22	17.4	16.8	18.0	16.9	17.3	17.4	15.0	13.7	16.2	19.4	24.9	26.1	28.5	29.5	29.7	23.1	23.6	18.5	17.7	17.9	18.4	17.1	17.1	18.4	21.9	30.2	1433	13.7	0753
23	17.4	15.2	15.4	14.7	14.3	14.4	14.6	15.2	15.2	16.0	16.2	16.5	17.0	18.8	17.5	17.5	17.2	16.7	16.5	15.7	15.4	15.0	15.1	14.5	16.5	18.9	1349	14.1	0514
24	14.4	14.1	14.1	14.3	14.3	13.8	14.1	14.1	14.7	15.0	15.5	16.7	18.4	19.0	18.2	17.1	16.5	16.1	15.2	14.6	14.7	14.2	13.9	14.0	16.6	19.6	1346	13.7	0216
25	14.4	14.3	14.3	14.5	14.6	14.5	15.0	14.5	15.5	15.7	16.5	17.0	17.4	17.6	17.4	16.8	15.9	15.3	15.7	15.6	14.9	14.9	14.4	14.4	15.9	17.9	1433	14.0	0005
26	14.6	14.4	14.4	14.0	13.7	14.4	14.6	14.0	14.7	15.2	14.3	14.2	14.3	14.7	14.9	16.4	15.6	15.3	15.2	15.2	15.4	15.6	15.7	15.7	15.1	16.5	1604	13.6	0453
27	15.4	15.1	14.9	14.4	14.3	13.9	13.7	13.7	14.0	16.1	16.8	18.4	19.6	18.8	19.3	19.2	17.6	16.1	16.1	15.1	14.9	15.1	15.1	15.5	16.8	19.8	1445	13.7	0655
28	15.7	15.5	15.6	15.5	15.1	15.4	15.2	14.9	15.1	15.7	16.3	17.5	18.1	17.6	17.3	17.0	16.4	16.5	16.0	15.5	15.6	15.7	15.1	14.5	16.3	18.1	1255	14.5	2400
29	14.3	14.3	13.9	14.4	14.3	13.5	13.5	12.8	13.7	15.2	15.7	16.2	16.9	16.5	16.7	16.2	16.1	15.6	15.3	14.9	15.0	15.0	15.0	15.0	15.1	17.4	1318	12.8	0817
30	14.9	15.2	14.9	15.1	15.0	14.8	14.9	14.4	14.9	15.6	16.5	17.8	15.7	17.1	17.6	17.0	17.1	15.4	14.4	13.8	13.2	13.6	12.9	12.3	15.3	18.2	1208	12.3	2400
31	12.3	12.4	12.2	12.3	12.3	12.1	12.1	12.5	12.6	13.0	14.6	15.2	14.0	13.2	12.5	13.8	13.1	13.0	12.9	13.0	13.0	12.8	13.0	12.8	13.8	15.7	1150	11.9	0017
avg	**15.2**	**14.9**	**14.7**	**14.6**	**14.5**	**14.4**	**14.2**	**14.3**	**15.4**	**16.8**	**18.1**	**19.1**	**19.6**	**20.0**	**20.1**	**19.7**	**18.5**	**16.9**	**16.3**	**15.8**	**15.7**	**15.5**	**15.4**	**15.2**	**17.3**	**21.3**		**13.3**	

Figure A.1: May Weather Data

LEGEND
The rainfall (in mm) as reported on the hour is the total of the rainfall reported over the previous hour
*** indicates that data is missing or is unavailable in the current month
--- indicates that data is unavailable or was not requested
A blank indicates that no rain was recorded over the previous hour
= indicates that the average is unreliable due to missing hourly values
The 'tot' coloumn represents the total rainfell reported from 00:00 to 23:00

HOURLY DATA : Rain(mm) - June 2015																									
S A ASTRONOMICAL OBSERVATORY - Climate Number:0020866 9 Lat:-33.9330 Lon:18.4770 Height:15 m (Extracted 2015/07/02 09:13)																									
DD	**h01**	**h02**	**h03**	**h04**	**h05**	**h06**	**h07**	**h08**	**h09**	**h10**	**h11**	**h12**	**h13**	**h14**	**h15**	**h16**	**h17**	**h18**	**h19**	**h20**	**h21**	**h22**	**h23**	**h24**	**tot**
1				0.2																					0.2
2								0.2	1.0	2.6	4.2	3.0	3.4	1.4	0.2										16.0
3						0.4	0.4	0.2				0.4	1.0	1.2	5.4	5.0	3.6	2.4		0.2					20.2
4							0.2	0.2																	0.4
5																									0.0
6																									0.0
7																									0.0
8																									0.0
9																									0.0
10																									0.0
11																									0.0
12																									0.0
13																									0.0
14		0.2																							0.2
15							0.2	0.2	0.4	1.0															1.8
16		0.2	4.0	1.8	3.4		3.6	0.6				1.2	0.2	0.2					1.8	0.6			0.6		18.2
17	0.2																								0.2
18																									0.0
19																									0.0
20																									0.0
21																									0.0
22																									0.0
23																					0.4	2.4	2.2	6.0	11.0
24	3.6		5.2	1.4	0.2					2.8	0.2		1.4							0.2			0.4		15.4
25												0.4													0.4
26																									0.0
27																									0.0
28						0.2																	1.0	3.4	4.6
29	6.2	2.8	0.8				0.2	0.6		0.6					0.2										11.4
30																									0.0
tot																									**100.0**

LEGEND
The temperature (in °C) as reported on the hour
The reading at h00 can either be interpreted as the last reading of the previous day or the first reading of the current day
*** indicates that data is missing or is unavailable in the current month
--- indicates that data is unavailable or was not requested
= indicates that the average is unreliable due to missing hourly values
The 'avg' column indicates the average temperature for the day and is calculated as the average of the daily maximum and minimum temperatures
The 'mx' column indicates the highest temperature (maximum temperature) reported on the day
The 'mxtm' column reports the time of the occurrence of the highest temperature of the day
The 'mn' column indicates the lowest temperature (minimum temperature) reported on the day
The 'mntm' column reports the time of the occurrence of the lowest temperature of the day

HOURLY DATA : Temperature (C) - June 2015																													
S A ASTRONOMICAL OBSERVATORY - Climate Number:0020866 9 Lat:-33.9330 Lon:18.4770 Height:15 m (Extracted 2015/07/02 09:14)																													
DD	**h01**	**h02**	**h03**	**h04**	**h05**	**h06**	**h07**	**h08**	**h09**	**h10**	**h11**	**h12**	**h13**	**h14**	**h15**	**h16**	**h17**	**h18**	**h19**	**h20**	**h21**	**h22**	**h23**	**h24**	**avg**	**mx**	**tm**	**mn**	**tm**
1	12.7	12.5	12.4	12.3	12.2	12.0	12.3	12.4	12.5	13.0	13.4	13.5	13.5	13.9	14.7	14.5	14.6	14.1	14.1	14.3	14.6	14.9	14.9	15.0	13.6	15.2	2340	12.0	613
2	14.7	14.9	15.1	15.4	15.4	15.4	16.6	15.6	15.0	14.5	13.8	14.1	13.9	14.3	14.7	16.1	15.5	15.9	14.1	14.5	13.9	13.6	13.4	13.2	14.9	16.7	703	13.2	2345
3	12.9	12.7	12.7	12.6	12.6	12.1	11.9	11.8	12.4	13.8	14.7	13.6	13.5	12.7	12.3	14.6	14.7	14.6	14.4	14.3	14.8	15.3	15.3	15.2	13.6	15.4	2240	11.7	639
4	14.8	15.0	14.8	14.5	14.2	14.1	13.3	13.7	14.9	15.4	16.0	16.7	17.1	17.1	17.4	17.2	15.9	14.4	14.0	13.8	13.6	13.4	13.0	12.7	15.1	17.6	1409	12.5	2322
5	12.2	10.8	11.9	11.6	9.5	8.2	8.1	8.4	12.0	15.2	18.1	16.6	18.2	17.9	17.2	16.4	16.0	15.2	13.2	12.1	11.9	11.5	11.1	10.4	13.2	18.4	1320	8.0	635
6	10.1	10.2	9.2	9.0	10.6	10.9	10.8	11.4	14.3	16.4	16.7	18.0	17.9	18.5	17.9	16.9	15.7	14.5	14.7	14.6	15.0	15.0	14.5	14.0	13.9	19.0	1406	8.7	343
7	13.3	13.5	12.3	12.5	11.3	13.5	13.6	14.0	15.6	17.3	18.2	18.9	20.4	20.6	20.2	19.1	17.1	14.9	14.9	14.6	13.6	11.9	10.3	10.3	15.7	21.6	1330	9.8	2320
8	10.5	9.1	8.2	8.4	9.0	9.3	11.5	12.3	14.5	15.9	17.1	19.4	20.5	21.2	20.0	17.5	16.9	15.8	16.2	15.9	15.7	16.4	16.0	16.7	14.8	21.5	1408	8.1	309
9	16.5	16.1	16.2	16.4	16.7	16.9	15.1	10.9	14.3	18.6	21.2	23.1	24.8	25.3	24.6	24.8	21.7	20.0	20.4	20.3	18.3	20.6	16.1	14.6	18.3	25.6	1432	10.9	759
10	13.3	13.2	12.8	13.0	13.3	12.8	13.2	13.6	13.7	14.0	15.3	15.8	16.8	16.5	16.3	19.0	17.0	14.6	14.7	17.1	15.0	13.3	12.7	12.1	15.8	19.5	1605	12.1	2400
11	11.6	12.1	11.1	10.9	10.4	10.1	11.3	11.8	12.5	12.9	16.6	17.8	18.2	17.5	18.2	18.5	17.9	15.7	15.3	15.5	14.6	13.8	13.2	12.2	14.4	18.7	1635	10.0	556
12	11.8	11.1	11.4	11.3	11.3	11.1	11.2	10.6	10.7	11.2	11.1	13.8	16.7	18.3	17.9	17.9	18.6	15.4	16.3	16.1	16.0	14.9	13.6	13.1	14.7	18.9	1437	10.5	843
13	12.2	12.4	12.2	11.9	12.3	13.0	13.0	12.7	12.8	12.8	12.5	15.9	17.9	17.8	18.4	17.6	15.1	13.5	13.1	13.4	13.5	13.4	12.8	12.7	15.4	19.0	1312	11.9	416
14	13.4	13.4	13.5	13.5	13.8	13.8	13.6	13.7	13.5	14.8	14.9	16.5	16.3	15.5	15.7	15.8	15.4	15.1	15.0	14.9	14.9	15.4	15.2	15.3	14.8	16.8	1252	12.7	21
15	14.4	14.8	14.9	14.8	14.5	13.9	13.9	13.0	12.8	13.1	13.4	14.3	15.3	14.7	14.8	14.9	14.7	14.3	14.0	13.7	13.6	13.6	13.2	13.3	14.3	15.7	1315	12.8	852
16	13.2	13.0	12.9	13.0	13.3	13.7	12.7	13.3	14.0	16.1	16.3	15.4	15.7	15.4	15.8	16.2	15.4	14.4	14.7	14.3	14.3	13.5	12.5	13.0	14.2	16.9	1242	11.5	632
17	12.4	12.6	13.0	13.0	13.0	12.2	12.0	12.1	13.7	15.2	16.7	16.5	16.9	18.1	18.4	18.0	17.4	13.8	12.2	11.1	10.9	9.6	9.9	10.1	14.3	19.0	1525	9.5	2213
18	8.7	8.9	9.5	9.7	9.7	8.9	8.4	8.1	11.0	13.4	14.6	16.2	16.3	16.5	16.6	15.8	15.5	13.5	12.5	11.9	12.3	12.6	11.7	11.2	12.6	17.0	1316	8.1	759
19	10.2	9.6	9.5	12.8	13.3	13.7	13.8	14.0	15.0	15.8	16.6	17.1	18.0	17.6	17.3	16.8	15.8	14.3	14.0	13.8	13.4	13.8	13.5	12.1	13.6	18.0	1314	9.1	240
20	10.8	10.7	9.6	9.0	9.5	8.4	8.4	9.0	11.2	16.5	19.3	21.9	23.4	24.1	22.6	20.3	17.0	14.9	14.0	13.9	14.1	13.6	13.3	13.0	16.6	25.1	1325	8.2	610
21	13.0	13.0	13.1	13.2	13.2	13.0	12.9	12.4	13.8	15.1	16.2	16.9	17.3	17.6	17.7	16.8	15.4	13.4	13.0	13.0	12.6	12.7	13.0	13.0	15.3	18.2	1435	12.4	755
22	13.0	12.4	11.6	11.0	10.2	9.9	9.5	9.2	11.4	12.6	13.8	16.2	13.8	13.9	13.6	14.4	13.8	13.9	13.9	14.0	14.1	13.7	13.5	13.7	13.0	17.0	1223	9.0	806
23	13.5	13.3	13.4	13.2	13.2	12.7	12.5	11.9	12.5	13.7	14.7	16.2	15.4	16.0	15.4	15.3	15.1	14.9	14.9	14.6	12.8	12.1	12.4	12.5	14.2	16.5	1146	11.9	807
24	12.7	13.1	12.3	13.0	12.9	13.5	13.3	13.3	13.9	11.9	12.5	14.1	12.4	14.9	14.9	15.2	13.8	12.9	12.7	11.3	10.3	10.6	10.3	9.8	12.6	15.3	1601	9.8	2358
25	9.4	9.1	8.4	8.0	7.1	6.9	6.8	7.1	10.0	12.3	14.6	13.3	15.2	15.1	13.4	13.7	13.6	12.7	11.7	11.9	11.9	11.1	10.6	11.4	11.1	15.5	1256	6.6	706
26	10.3	11.5	11.8	11.5	11.9	11.6	11.6	12.1	12.9	13.9	14.5	14.9	14.5	14.9	15.2	14.9	13.7	12.9	13.0	13.0	13.0	12.7	12.4	12.2	12.7	15.4	1427	9.9	108
27	11.5	11.9	11.6	11.6	11.3	9.3	10.1	10.2	11.9	14.1	15.7	16.5	16.5	15.9	17.0	15.9	16.2	13.8	14.0	13.6	13.3	13.4	13.0	11.8	13.3	17.6	1215	9.0	629
28	12.1	12.1	12.0	12.0	12.0	11.6	11.7	11.9	12.1	12.8	14.3	14.9	15.7	15.6	15.4	14.8	15.4	14.1	13.3	13.4	13.3	13.3	11.5	11.2	13.6	15.9	1308	11.2	2356
29	11.1	11.1	11.1	11.0	11.4	11.7	11.2	11.1	12.0	13.0	14.1	15.0	15.4	16.4	16.6	17.2	15.7	13.4	12.6	13.0	11.9	11.4	10.5	10.3	14.0	17.7	1540	10.3	2250
30	9.2	8.8	8.2	8.6	10.0	9.6	8.8	8.1	8.4	10.1	11.9	16.5	17.0	17.8	17.9	17.0	16.0	14.1	13.8	13.5	13.3	13.3	13.3	13.4	13.1	18.1	1435	8.1	250
avg	**12.2**	**12.1**	**11.9**	**12.0**	**12.0**	**11.8**	**11.8**	**11.7**	**12.8**	**14.2**	**15.3**	**16.3**	**16.8**	**17.1**	**16.9**	**16.8**	**15.9**	**14.5**	**14.2**	**14.0**	**13.7**	**13.5**	**12.9**	**12.7**	**14.2**	**18.1**		**10.3**	

Figure A.2: June Weather Data

LEGEND
The rainfall (in mm) as reported on the hour is the total of the rainfall reported over the previous hour
*** indicates that data is missing or is unavailable in the current month
--- indicates that data is unavailable or was not requested
A blank indicates that no rain was recorded over the previous hour
= indicates that the average is unreliable due to missing hourly values
The 'tot' coloumn represents the total rainfell reported from 00:00 to 23:00

HOURLY DATA : Rain(mm) - July 2015																									
S A ASTRONOMICAL OBSERVATORY - Climate Number:0020866 9 Lat:-33.9330 Lon:18.4770 Height:15 m (Extracted 2015/08/03 11:04)																									
DD	h01	h02	h03	h04	h05	h06	h07	h08	h09	h10	h11	h12	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24	tot
1																									0.0
2																									0.0
3																									0.0
4																									0.0
5																									0.0
6																									0.0
7																									0.0
8								0.4																	0.4
9																									0.0
10																									0.0
11														0.4							7.8	0.2		0.2	8.6
12	0.4		0.4			0.4	0.4	0.2																	1.8
13	0.2	0.2	0.4																						0.8
14																									0.0
15																									0.0
16																		0.2							0.2
17						0.2		0.2	0.4	0.2						1.6	0.8	1.8	1.2	1.2	10.8	5.0	2.0	0.6	26.0
18	0.2	0.2																							0.4
19																									0.0
20																									0.0
21																									0.0
22																									0.0
23		0.8	3.6	6.2	3.6												0.8	0.8	1.4	0.4		3.6	6.4	7.0	34.6
24														0.2	0.4	0.4									1.0
25																									0.0
26																									0.0
27																									0.0
28																									0.0
29										0.2														0.2	0.4
30	0.8	0.8	2.6	6.4	2.0	1.8	6.6																		21.0
31																									0.0
tot																									**95.2**

LEGEND
The temperature (in °C) as reported on the hour
The reading at h00 can either be interpreted as the last reading of the previous day or the first reading of the current day
*** indicates that data is missing or is unavailable in the current month
--- indicates that data is unavailable or was not requested
= indicates that the average is unreliable due to missing hourly values
The 'avg' column indicates the average temperature for the day and is calculated as the average of the daily maximum and minimum temperatures
The 'mx' column indicates the highest temperature (maximum temperature) reported on the day
The 'mxtm' column reports the time of the occurrence of the highest temperature of the day
The 'mn' column indicates the lowest temperature (minimum temperature) reported on the day
The 'mntm' column reports the time of the occurrence of the lowest temperature of the day

HOURLY DATA : Temperature (C) - July 2015																													
S A ASTRONOMICAL OBSERVATORY - Climate Number:0020866 9 Lat:-33.9330 Lon:18.4770 Height:15 m (Extracted 2015/08/03 11:04)																													
DD	h01	h02	h03	h04	h05	h06	h07	h08	h09	h10	h11	h12	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24	avg	mx	tm	mn	tm
1	13.3	13.3	13.3	13.2	13.0	12.9	12.8	12.9	13.6	14.4	15.1	15.5	16.3	16.3	15.8	15.6	14.6	13.8	13.9	13.8	13.8	13.8	14.1	13.8	14.6	16.5	1317	12.7	710
2	13.3	13.0	12.6	12.8	12.5	12.3	12.7	12.6	13.5	14.7	15.6	16.1	16.5	16.2	15.8	16.1	15.4	14.6	14.3	13.9	13.5	13.5	13.6	13.6	14.2	16.7	1244	11.7	633
3	13.1	13.3	12.7	11.2	11.7	10.6	10.3	10.6	12.2	14.8	17.4	18.5	20.0	20.0	20.0	17.9	16.3	15.1	14.9	14.8	13.9	13.8	13.3	13.2	15.3	20.5	1345	10.1	645
4	13.0	13.0	11.1	9.5	10.1	8.7	7.8	8.0	10.6	12.5	16.1	19.5	19.9	20.5	19.5	18.2	16.1	15.3	15.2	15.1	15.0	14.8	14.6	14.0	14.1	20.5	1401	7.7	715
5	14.4	14.6	14.2	14.3	14.1	14.1	13.9	13.9	15.2	15.6	16.2	17.0	17.2	17.2	17.0	16.9	15.3	14.5	14.3	14.4	14.3	14.3	14.2	14.3	15.7	17.6	1510	13.8	742
6	14.9	15.0	14.8	15.1	15.2	14.8	14.4	14.7	14.4	16.6	18.1	20.1	20.6	22.2	22.3	21.5	20.4	16.8	17.5	17.0	17.1	16.9	17.5	16.5	17.8	22.5	1450	13.1	840
7	16.8	13.2	12.6	13.2	12.9	13.4	13.0	12.3	16.0	17.3	22.0	24.6	25.1	24.3	24.9	19.6	16.3	15.0	15.0	14.6	14.3	14.2	14.3	14.2	18.7	25.2	1252	12.2	754
8	14.1	13.7	13.5	13.4	13.5	13.5	13.5	13.3	13.8	14.6	16.0	15.8	18.7	18.1	17.8	16.6	17.3	15.4	14.9	14.9	14.6	14.7	14.8	14.7	16.4	19.5	1247	13.3	741
9	14.7	14.8	14.8	14.6	14.9	15.1	14.9	14.7	15.2	16.5	17.4	18.0	18.7	19.5	19.5	18.7	17.6	16.8	16.7	16.2	16.2	15.9	15.4	15.2	17.2	19.9	1535	14.5	407
10	15.4	15.2	15.5	15.4	15.4	15.4	15.2	14.0	16.2	18.4	20.8	22.7	24.0	25.5	25.7	25.6	21.0	18.4	16.8	15.5	14.2	14.1	13.3	13.1	19.5	26.0	1452	13.0	2332
11	13.2	13.2	13.1	13.5	12.0	13.7	13.9	14.1	13.9	14.5	14.3	14.3	14.3	14.8	14.6	14.3	14.1	14.0	13.7	13.8	11.9	12.1	12.7	12.2	13.4	15.0	1350	11.7	2030
12	12.8	11.9	11.6	11.8	12.1	12.2	10.3	11.5	11.9	12.4	12.8	13.6	14.5	14.1	14.1	14.7	12.9	11.4	11.1	10.2	9.4	9.3	8.7	8.0	11.4	14.8	1245	8.0	2400
13	8.5	9.0	8.5	7.5	7.5	6.3	6.9	6.7	8.8	10.5	13.6	14.1	13.8	12.5	12.3	12.7	12.2	10.6	10.5	10.6	10.5	10.0	10.1	10.3	10.8	15.2	1442	6.3	601
14	10.8	11.0	11.1	10.8	11.3	10.9	11.2	11.2	11.7	13.3	13.5	14.9	16.1	16.5	16.9	16.1	15.8	12.7	11.9	10.7	9.6	8.4	7.4	7.3	12.3	17.6	1249	7.0	2356
15	7.7	6.5	6.7	6.7	6.7	5.9	6.1	6.3	8.9	10.8	12.4	14.1	14.9	14.7	15.0	13.7	13.1	13.0	12.4	12.4	12.4	12.2	11.6	11.4	10.4	15.6	1420	5.2	610
16	10.1	9.6	10.1	9.0	9.8	9.6	9.7	9.8	10.1	11.1	11.8	13.1	14.0	15.0	14.1	13.5	12.3	12.2	12.5	12.4	11.9	11.7	12.1	12.0	12.0	15.0	1400	9.0	358
17	11.8	12.2	12.4	12.6	12.6	12.4	12.4	12.0	12.1	12.1	12.5	13.1	13.0	12.8	12.5	12.4	12.5	12.3	12.4	12.4	11.9	11.1	11.0	10.9	12.1	13.2	1217	10.9	2250
18	11.2	11.2	11.4	11.9	11.8	11.2	11.6	11.4	13.2	14.0	14.6	16.2	17.8	19.6	17.9	17.3	17.0	14.4	13.1	11.8	11.7	11.7	11.0	10.8	15.7	20.6	1417	10.7	2334
19	10.5	11.4	11.6	11.2	10.8	9.8	10.0	10.4	11.6	12.9	11.9	13.4	15.5	15.2	15.8	15.5	14.9	13.4	13.0	12.3	11.3	11.1	10.6	11.2	13.0	16.3	1447	9.7	534
20	12.0	13.2	12.8	12.9	13.0	13.0	12.7	12.7	12.7	14.4	14.1	14.3	15.3	15.6	15.2	14.5	13.8	13.4	13.0	13.0	12.7	12.2	12.5	12.1	13.8	16.2	1250	11.3	5
21	12.2	12.0	11.6	11.4	10.6	10.7	11.4	11.6	12.7	13.9	14.8	15.7	16.4	16.8	16.8	16.3	15.2	14.1	14.0	13.5	14.0	14.0	14.3	14.2	13.8	17.1	1424	10.5	511
22	14.3	14.1	13.9	13.6	13.8	13.8	13.6	13.7	14.5	14.4	14.9	16.9	16.9	17.3	16.6	15.2	14.1	13.7	13.5	13.4	13.5	13.5	13.1	13.2	15.4	17.7	1314	13.0	2310
23	12.5	13.1	12.9	12.4	11.9	12.1	12.1	11.8	12.7	13.5	14.4	14.1	14.8	14.4	12.7	12.7	11.4	11.2	11.0	10.7	10.5	9.8	9.7	9.8	12.4	15.1	1240	9.6	2225
24	9.5	9.8	10.3	9.9	10.1	9.9	9.7	9.5	10.6	12.2	13.3	12.0	13.1	12.7	11.9	12.5	12.8	12.4	12.9	12.6	12.9	12.4	12.6	12.7	11.5	13.6	1112	9.4	816
25	12.5	12.2	12.6	12.5	12.5	12.6	12.5	12.5	13.4	14.6	15.4	15.1	15.7	16.2	15.6	14.8	14.2	12.8	12.5	12.4	12.4	12.4	12.2	12.0	14.3	16.5	1405	12.0	2400
26	11.7	11.5	11.0	9.8	9.8	11.3	10.9	10.9	12.4	13.8	15.0	17.2	18.6	18.4	18.7	19.3	17.0	13.2	11.6	11.2	11.1	11.1	11.1	11.1	14.4	19.5	1558	9.3	448
27	10.8	10.6	10.0	9.8	9.9	9.3	9.4	9.9	12.2	14.1	14.7	15.7	16.2	16.1	16.0	15.6	14.9	12.6	12.2	11.9	12.3	12.5	12.6	12.5	12.9	16.5	1312	9.3	718
28	12.5	12.7	12.5	12.3	12.9	12.4	12.6	12.3	13.5	14.1	14.8	15.4	16.0	15.9	16.0	15.4	14.5	12.8	12.0	11.6	11.0	10.5	10.9	10.7	13.4	16.5	1345	10.3	2145
29	10.4	11.8	11.2	11.4	11.2	11.0	10.0	9.8	9.6	11.2	11.7	12.2	12.2	12.4	12.4	12.9	12.3	12.2	12.0	11.9	11.8	11.5	11.9	11.1	11.3	13.2	1552	9.3	728
30	10.8	11.1	11.1	11.1	11.5	11.6	12.4	13.7	13.5	13.9	15.0	15.2	15.4	16.1	16.0	14.5	13.6	12.3	11.8	11.0	11.0	10.7	9.7	9.6	12.9	16.4	1411	9.5	2348
31	9.9	11.1	9.9	8.9	7.5	7.7	7.5	7.7	9.0	9.9	11.1	13.0	13.3	13.7	14.4	13.5	13.2	11.6	11.6	10.9	10.2	9.8	8.8	8.5	11.0	14.7	1436	7.3	721
avg	**12.2**	**12.2**	**12.0**	**11.7**	**11.7**	**11.6**	**11.5**	**11.5**	**12.6**	**13.8**	**14.9**	**15.9**	**16.6**	**16.8**	**16.6**	**15.9**	**14.9**	**13.6**	**13.3**	**12.9**	**12.6**	**12.4**	**12.2**	**12.1**	**13.9**	**17.5**		**10.4**	

Figure A.3: July Weather Data

LEGEND
The rainfall (in mm) as reported on the hour is the total of the rainfall reported over the previous hour
*** indicates that data is missing or is unavailable in the current month
--- indicates that data is unavailable or was not requested
A blank indicates that no rain was recorded over the previous hour
= indicates that the average is unreliable due to missing hourly values
The 'tot' coloumn represents the total rainfell reported from 00:00 to 23:00

HOURLY DATA : Rain(mm) - August 2015																									
S A ASTRONOMICAL OBSERVATORY - Climate Number:0020866 9 Lat:-33.9330 Lon:18.4770 Height:15 m (Extracted 2015/09/01 15:24)																									
DD	h01	h02	h03	h04	h05	h06	h07	h08	h09	h10	h11	h12	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24	tot
1																									0
2																									0
3																									0
4	0.2	1.4	5	0.4	0.2			0.2		0.4			0.2												8
5																									0
6																									0
7																									0
8																									0
9																									0
10																									0
11																									0
12																0.6	0.8	1.2							2.6
13						0.6	0.2	1.8			1	0.2					2	1.4	0.2		0.2				7.6
14																									0
15																					0.2	2.8	5.2	4.4	12.6
16	3.4	1.4	1.2	0.4	0.4	0.2	0.2	0.2	0.2																7.6
17																									0
18																									0
19																									0
20																									0
21					-																				0
22																									0
23																									0
24																								0.6	0.6
25	1.6	1.6	1.4	0.4	0.4	1																			6.4
26																									0
27																									0
28																									0
29																									0
30																				0.2	1.4	0.8	0.2	0.8	3.4
31	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
tot																									**48.8**

LEGEND
The temperature (in °C) as reported on the hour
The reading at h00 can either be interpreted as the last reading of the previous day or the first reading of the current day
*** indicates that data is missing or is unavailable in the current month
--- indicates that data is unavailable or was not requested
= indicates that the average is unreliable due to missing hourly values
The 'avg' column indicates the average temperature for the day and is calculated as the average of the daily maximum and minimum temperatures
The 'mx' column indicates the highest temperature (maximum temperature) reported on the day
The 'mxtm' column reports the time of the occurrence of the highest temperature of the day
The 'mn' column indicates the lowest temperature (minimum temperature) reported on the day
The 'mntm' column reports the time of the occurrence of the lowest temperature of the day

HOURLY DATA : Temperature (C) - August 2015																													
S A ASTRONOMICAL OBSERVATORY - Climate Number:0020866 9 Lat:-33.9330 Lon:18.4770 Height:15 m (Extracted 2015/09/01 15:24)																													
DD	h01	h02	h03	h04	h05	h06	h07	h08	h09	h10	h11	h12	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24	avg	mx	tm	mn	tm
1	8.2	8	7.5	6.8	6.1	5.9	6.1	5.8	9.6	13.7	15.5	17.2	17.6	18.7	20.1	17.9	16	13.1	12.3	12.2	12.1	12.1	11.9	11.7	12.9	20.3	1442	5.5	751
2	10.7	10.3	10.3	10.3	9.5	8.7	8.6	8.8	12.7	16.2	19.8	22.9	23.6	25.6	26.5	26.8	19.3	16.5	15.5	14.1	13.2	12.4	12.2	12.2	18.1	27.7	1618	8.5	614
3	11.5	10.9	12.4	15.7	14.9	12.7	12.9	14.5	14.9	14.1	13.3	13.9	13	13.3	13.9	13.8	13.8	13.5	13.4	13.1	12.8	12.6	12.5	12.3	13.3	15.7	414	10.8	206
4	12.3	11.9	11.9	12.5	12.9	13	13.2	13.5	13.5	14.1	14.5	14.6	15.4	16.1	15.5	14	13.6	13.6	13.8	14.1	13.3	13.2	12.5	12.4	14.3	16.6	1334	11.9	251
5	12.2	12.2	12.3	12.2	11.5	12	11.9	11.9	12.4	13.9	15.6	16.4	17	18.1	19	18.7	19.2	14.9	13.5	12.6	12.6	12.3	12	12.2	15.4	19.2	1535	11.5	455
6	12.7	11.3	10.1	10.5	10.1	9.5	8.5	9.3	12.8	17	20.1	24	25.1	25.7	27	27.9	26.2	18.5	16.4	15.1	14.2	12.7	12	11.9	18.2	27.9	1600	8.5	655
7	11.2	10	9.9	11.4	10.6	8.8	8.5	8.7	11.3	15.6	18.3	20.4	17.1	20.8	19.5	18.6	19	14.3	12.8	11.8	11.2	10.9	10.6	10.2	14.9	21.6	1350	8.2	726
8	9.7	8.5	8.4	7.9	7.4	7.9	8.2	7.6	8.1	10.6	14	16.7	18.7	18.8	18.4	18	17	15.4	15.1	14.7	13.9	14	13.6	13.6	13.6	20.1	1425	7.1	520
9	13	12.2	11.1	11.6	11.1	10.5	9.9	10.1	13.5	13.8	15.3	15.5	15.9	14.5	14.9	13.6	13.6	12.2	11.5	11.1	10.9	11.3	10.9	10.7	13.3	17	1122	9.6	739
10	10.6	10.8	11.1	11.2	11.3	11.4	11.2	11.6	12.8	13.6	14.6	15.4	15.7	16.2	15.7	15.7	14.7	13.3	12.8	12.8	12.7	12.4	12	11.9	13.5	16.6	1230	10.4	29
11	11.7	10.8	9.6	10.8	9.3	9	9.6	9.1	10.8	13.3	14.8	18.1	18.6	18.5	18	17.8	16.8	15.7	15.4	13.9	12.7	12.5	12.9	13.2	14.2	19.6	1332	8.7	549
12	14.5	14.6	17.2	18.3	18.2	15.8	14.2	13.8	13.5	13.5	14.6	15.1	16.2	15.3	14.5	13.7	13.6	13.2	12.7	12.8	12.5	12.5	12.3	12.2	15.6	19	509	12.1	2355
13	12.2	12.1	12.2	12	12.4	12.1	12.5	13	13.1	13.5	13.1	13.8	13.9	13.8	13.7	13.4	12.9	12.7	12.4	12.2	12.6	13.2	12.7	12.4	13.1	14.1	1238	12	354
14	12.2	12.3	12	12	12	12	12.1	12.2	12.7	13.9	15.4	15.9	17.4	18.8	19.2	18.7	21.7	15.9	13.6	12.9	12.2	11.5	11.3	11.7	16.4	21.7	1700	11.1	2318
15	11.5	12.8	12.4	11.9	11.7	12	12.7	12.9	13.3	14	14.7	15.1	14.9	14.2	13.9	13.7	13.2	13.1	12.6	12.5	12.2	12	12.2	11.8	13.2	15.1	1153	11.3	23
16	11.8	11.9	11.6	11.4	11.4	11.4	11.1	11.4	11.3	12	13.3	14.7	15.5	15.7	15.4	15.2	14.7	13.8	13.3	13.3	13.1	12.8	12.8	12.8	13.6	16	1340	11.1	700
17	13.2	12.7	13	13.8	13.8	13.8	14.1	14.5	15.5	16.2	17.2	17.5	17.9	17.7	17.3	16	15.1	14.1	14.3	14.3	14	14	14	14	15.6	18.5	1342	12.6	34
18	13.8	13.7	13.8	13.8	14	14.1	13.2	13.1	13.3	13.5	13.4	14.6	15.2	14.6	14.9	15.1	14.4	13.2	12.8	12.9	13.2	13.2	12.7	12.8	13.9	15.6	1239	12.3	2333
19	13	12.7	12.5	12.8	12.7	12.7	12.9	13.7	14.6	15.7	16.6	17.1	17.6	17.5	17.1	17	16	14.8	14.3	14.5	14.4	14.4	13.8	14.5	15.3	18.1	1337	12.4	225
20	13.8	13.8	13.8	13.8	13.9	14.1	14.3	15.6	16.8	18.2	20.5	22	21.6	22.2	22.9	22.7	21.5	18.5	16.9	17.1	18.3	17.8	17.6	17.3	18.6	23.6	1514	13.7	254
21	17.2	16.7	15.5	14.8	13.6	12.8	12.3	15.5	17.8	20.2	22.1	23.3	24.3	24.5	25.4	22.6	21.4	18.6	17.8	18.1	17.9	17.8	17.3	16.9	18.8	25.4	1500	12.2	655
22	17	17	16.3	16.2	15.1	14.8	14.9	16.7	17.6	19.3	21.1	22.2	22.6	23.8	22.7	21.4	20	18.6	18.2	17.9	18.9	20.5	19.8	18.6	19.3	24.2	1413	14.4	713
23	17.4	16.8	14.5	14.3	14.3	14.4	13.9	13.8	14.5	16	16.3	18	17.6	16.6	18.8	19	17.9	16.1	13.9	13.8	14	14.2	14	14	16.5	19.3	1606	13.7	723
24	13.8	13.9	13.6	13.3	13	12.7	12.4	12.6	13.2	13.8	14.7	15.1	16.2	16.6	17	17	17	15.9	14.6	14.3	14.1	14.3	14	13.5	15.3	18.3	1424	12.3	647
25	13	12.9	13	13	13.2	13.3	13.3	13.3	13.8	15.4	15.9	16.6	18.1	18.6	18.4	19.5	19.4	16.7	15.3	14.1	13.5	13.1	12.7	11.9	16	20.1	1605	11.9	2400
26	11.6	11.2	10.6	10.3	10.4	10.2	10.1	10.6	14.1	17.6	18.6	19	19.5	19.4	18.3	18.1	17.3	16	15.6	15.7	15.4	15.2	15.4	14.9	15	20	1344	10	624
27	15.1	15	15	15	15	14.8	14.9	15.2	15.7	16.8	17.4	18.5	20.7	20.3	19.6	18.2	17.3	16.8	15.8	15.7	15.1	14.9	14.3	14.1	17.9	21.8	1415	14.1	2320
28	13.8	13.8	14.3	13.7	13.8	14	13.9	14.1	14.9	14.9	14.7	15.3	16	15.3	15.1	15	14.6	14.5	14.2	14.1	14.1	14	14.1	14.1	15.1	16.6	1226	13.6	413
29	13.7	14.1	14	13.3	13.5	13.9	13.5	13.5	14	15	15.9	17	17.7	17.4	17.5	17	16.4	15	14.6	14.5	14.4	14.4	14.3	14.4	15.8	18.4	1328	13.2	729
30	14.3	14.1	14	14	14.1	14.1	14.2	14.3	14.2	13.9	14.3	15.1	15.8	16.3	16.1	15.1	14.5	13.8	13.7	13.5	13.3	13.3	13.5	13.7	15.1	16.9	1434	13.3	2156
31	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-					
avg	**12.9**	**12.6**	**12.5**	**12.6**	**12.4**	**12.1**	**12**	**12.4**	**13.5**	**15**	**16.2**	**17.4**	**17.9**	**18.2**	**18.2**	**17.7**	**16.9**	**15.1**	**14.3**	**14**	**13.8**	**13.7**	**13.4**	**13.3**	**15.4**	**19.5**		**11.3**	

Figure A.4: August Weather Data

LEGEND
The rainfall (in mm) as reported on the hour is the total of the rainfall reported over the previous hour
*** indicates that data is missing or is unavailable in the current month
--- indicates that data is unavailable or was not requested
A blank indicates that no rain was recorded over the previous hour
= indicates that the average is unreliable due to missing hourly values
The 'tot' coloumn represents the total rainfell reported from 00:00 to 23:00

HOURLY DATA : Rain(mm) - September 2015																									
S A ASTRONOMICAL OBSERVATORY - Climate Number:0020866 9 Lat:-33.9330 Lon:18.4770 Height:15 m (Extracted 2015/10/02 13:01)																									
DD	**h01**	**h02**	**h03**	**h04**	**h05**	**h06**	**h07**	**h08**	**h09**	**h10**	**h11**	**h12**	**h13**	**h14**	**h15**	**h16**	**h17**	**h18**	**h19**	**h20**	**h21**	**h22**	**h23**	**h24**	**tot**
1														0.2											0.2
2																									0.0
3																									0.0
4																									0.0
5																									0.0
6																									0.0
7							1.2		0.8	0.2											1.0	0.4			3.6
8			0.4																						0.4
9																									0.0
10									2.6	0.6	0.4	0.4	0.2	0.2	0.4										4.8
11																									0.0
12																									0.0
13																									0.0
14																				0.2					0.2
15						0.2	0.4	0.8	2.6	1.4															5.4
16																									0.0
17																									0.0
18																									0.0
19																									0.0
20																									0.0
21																									0.0
22																									0.0
23																									0.0
24																									0.0
25																									0.0
26					0.4	0.4	0.8	0.2		1.4	0.2														3.4
27													0.2		0.2	1.0	0.2								1.6
28																									0.0
29																				0.4	0.4	1.0		0.2	2.0
30	0.8		0.2	0.4	1.6	4.4	0.8	1.4	0.8					1.8	0.6										12.8
tot																									**34.4**

LEGEND
The temperature (in °C) as reported on the hour
The reading at h00 can either be interpreted as the last reading of the previous day or the first reading of the current day
*** indicates that data is missing or is unavailable in the current month
--- indicates that data is unavailable or was not requested
= indicates that the average is unreliable due to missing hourly values
The 'avg' column indicates the average temperature for the day and is calculated as the average of the daily maximum and minimum temperatures
The 'mx' column indicates the highest temperature (maximum temperature) reported on the day
The 'mxtm' column reports the time of the occurrence of the highest temperature of the day
The 'mn' column indicates the lowest temperature (minimum temperature) reported on the day
The 'mntm' column reports the time of the occurrence of the lowest temperature of the day

HOURLY DATA : Temperature (C) - September 2015																													
S A ASTRONOMICAL OBSERVATORY - Climate Number:0020866 9 Lat:-33.9330 Lon:18.4770 Height:15 m (Extracted 2015/10/02 13:01)																													
DD	**h01**	**h02**	**h03**	**h04**	**h05**	**h06**	**h07**	**h08**	**h09**	**h10**	**h11**	**h12**	**h13**	**h14**	**h15**	**h16**	**h17**	**h18**	**h19**	**h20**	**h21**	**h22**	**h23**	**h24**	**avg**	**mx**	**tm**	**mn**	**tm**
1	13.4	13.6	13.5	13.2	12.9	13.0	12.9	13.2	15.7	16.0	17.5	17.5	17.8	17.6	17.3	16.8	16.1	14.7	13.8	13.4	13.2	12.7	12.8	12.7	15.4	18.3	1307.0	12.5	2336
2	12.5	12.6	12.5	12.7	12.8	12.8	12.5	13.4	15.4	16.1	17.0	17.3	17.4	17.6	18.1	17.0	16.6	15.4	14.6	14.0	13.9	13.8	14.0	14.3	15.2	18.1	1251.0	12.3	244
3	14.4	14.1	13.7	13.8	13.6	13.6	14.4	15.7	16.7	18.6	18.7	19.0	21.0	21.9	22.5	22.7	22.4	20.8	19.2	18.4	17.4	16.5	16.1	16.2	18.3	23.1	1451.0	13.5	327
4	16.2	16.0	14.9	13.9	12.4	11.1	10.6	13.1	17.3	20.5	22.3	23.2	25.3	26.7	24.8	24.6	23.3	20.9	17.8	16.5	16.2	17.0	17.2	18.2	19.2	27.9	1431.0	10.5	704
5	18.6	17.9	13.6	12.5	11.9	12.2	11.5	13.9	18.7	23.0	26.2	29.2	29.7	30.4	30.7	30.8	26.7	23.3	19.6	20.1	20.6	19.5	18.6	17.8	21.5	31.7	1630.0	11.3	644
6	17.5	15.9	15.1	15.1	17.2	20.0	19.7	20.6	21.6	23.8	24.1	22.4	18.0	15.8	16.6	16.4	15.0	13.8	13.7	13.9	13.9	14.2	14.1	14.0	19.3	25.0	1039.0	13.6	1829
7	14.0	13.8	13.8	13.3	12.8	12.9	12.9	13.3	13.6	14.6	16.0	17.4	17.1	16.7	16.5	16.2	17.5	16.7	14.1	13.7	13.0	12.5	12.7	12.8	15.6	18.7	1721.0	12.4	2115
8	12.6	12.1	12.2	12.1	12.2	11.9	11.3	12.4	13.2	14.6	16.2	16.7	17.0	17.7	18.5	17.6	17.4	15.9	14.2	13.3	12.7	12.0	10.9	10.1	14.3	18.5	1459.0	10.1	2351
9	9.8	9.5	9.7	10.2	10.1	10.0	10.0	11.6	13.8	14.6	15.7	16.9	17.2	16.0	17.0	16.0	15.0	14.5	14.2	13.9	14.2	13.6	13.5	13.2	13.9	18.3	1248.0	9.5	201
10	13.3	13.2	13.1	13.1	13.1	13.1	12.6	12.7	11.5	11.3	11.3	12.4	12.2	12.1	13.1	15.0	14.2	14.3	12.7	12.7	13.2	12.9	12.5	12.7	13.1	15.0	1602.0	11.1	918
11	12.7	12.8	12.8	12.8	12.8	12.5	12.6	13.8	15.1	16.5	19.0	20.3	20.2	21.4	20.9	20.1	19.5	18.4	17.4	16.8	16.3	16.0	15.7	15.5	17.3	22.1	1429.0	12.4	146
12	15.3	14.0	14.2	13.8	14.2	13.8	13.7	14.8	15.7	17.4	18.1	19.8	20.1	19.9	19.8	19.8	18.5	17.6	17.0	16.9	16.3	15.9	15.7	15.5	17.1	20.6	1524.0	13.5	714
13	15.2	15.3	15.6	15.9	16.2	16.4	16.1	16.7	17.5	21.3	22.7	23.6	25.9	27.0	26.7	27.8	26.5	24.0	20.1	21.0	21.7	18.6	17.3	16.5	21.4	27.8	1601.0	15.1	54
14	17.7	18.4	17.0	21.2	18.9	24.0	27.1	23.9	24.7	21.5	18.2	22.4	23.3	21.9	19.8	17.6	15.0	15.1	16.7	15.6	14.8	14.6	14.4	14.4	20.9	27.3	643.0	14.4	2344
15	14.4	14.7	14.4	14.5	14.4	14.6	14.6	14.4	14.5	14.6	14.9	15.2	17.3	17.0	18.7	18.6	17.3	17.0	16.2	15.1	15.1	14.9	14.9	14.0	16.6	19.2	1533.0	14.0	2359
16	13.6	13.2	14.0	13.8	14.0	13.9	13.5	14.7	15.6	16.9	18.5	18.3	19.3	19.7	19.3	18.1	17.3	16.2	14.8	14.6	14.5	14.4	14.2	14.0	16.4	19.8	1411.0	13.0	127
17	14.1	13.9	13.9	13.7	13.1	13.1	13.0	14.3	15.4	16.5	17.1	17.6	17.8	18.4	18.1	17.0	16.9	15.7	14.7	14.3	14.2	13.8	13.6	13.4	15.8	18.7	1327.0	12.9	639
18	13.3	12.9	13.0	13.0	12.9	13.0	13.0	14.5	15.7	17.2	18.4	19.1	18.9	19.0	19.4	19.8	18.2	16.9	15.4	15.0	14.9	14.7	14.4	14.1	16.4	20.0	1225.0	12.8	155
19	14.1	14.0	14.0	13.8	13.5	13.3	13.8	15.2	16.6	19.3	19.2	20.3	21.8	22.7	23.6	23.2	23.4	22.2	19.8	18.6	17.9	17.8	17.7	17.2	18.6	24.0	1637.0	13.3	557
20	18.0	18.3	18.8	15.1	14.4	14.3	14.8	15.1	17.0	20.2	23.0	24.7	28.8	28.2	25.2	23.0	17.8	16.2	14.2	14.4	14.9	15.1	13.9	14.0	21.8	30.2	1334.0	13.3	2335
21	13.8	13.0	13.3	13.9	14.1	13.8	14.1	14.0	14.7	15.4	16.8	17.0	17.6	16.5	16.6	16.2	15.5	14.6	14.3	14.0	14.5	14.0	13.1	13.2	15.4	17.8	1309.0	12.9	222
22	13.2	13.2	13.0	12.7	12.3	12.5	12.5	12.5	14.3	16.2	17.1	17.8	18.8	19.0	20.0	19.2	17.8	16.1	16.0	15.7	14.8	14.4	14.1	14.1	16.2	20.1	1501.0	12.3	517
23	14.0	13.4	12.8	12.8	12.2	12.2	12.1	13.3	16.1	17.9	18.4	19.1	19.7	20.5	21.2	21.3	21.8	17.8	17.3	16.0	15.1	14.5	14.1	13.5	17.2	22.5	1620.0	11.9	549
24	13.1	13.1	12.4	12.1	12.0	12.7	13.0	14.0	17.0	16.2	16.5	17.0	18.0	19.0	18.1	17.9	18.1	16.8	15.6	14.6	14.2	14.0	14.0	13.8	15.4	19.0	1359.0	11.9	534
25	13.8	14.0	14.1	14.4	14.6	14.7	14.8	15.1	16.2	17.3	18.0	18.4	19.3	19.7	20.1	20.9	19.8	20.1	17.2	17.3	16.6	16.6	15.2	14.8	17.8	21.7	1544.0	13.8	28
26	14.9	15.2	14.8	14.6	14.5	13.5	13.3	13.5	13.6	13.5	14.8	16.0	15.1	15.3	15.4	15.1	15.1	15.0	14.6	14.6	14.6	14.8	14.7	14.7	14.6	16.1	1159.0	13.1	727
27	14.2	14.1	13.8	13.5	13.4	13.3	13.3	13.8	15.7	16.7	16.7	18.3	19.4	18.9	15.7	13.6	15.1	14.8	13.9	13.8	13.4	13.3	13.4	13.8	16.6	20.4	1321.0	12.7	631
28	13.7	13.5	13.6	13.8	13.5	13.6	13.1	15.9	16.8	16.3	17.5	17.1	20.1	20.2	20.6	19.1	18.2	17.0	15.4	14.8	14.6	14.2	13.4	12.2	16.9	21.7	1323.0	12.2	2358
29	12.4	12.3	11.6	11.3	12.0	11.6	11.5	12.6	14.9	15.7	16.2	16.2	16.8	16.6	16.0	15.0	14.7	13.6	13.3	12.7	12.6	12.3	12.4	12.4	14.1	17.0	1315.0	11.1	352
30	12.5	12.5	12.5	12.4	12.4	11.9	11.7	11.8	12.7	14.0	16.5	16.5	16.4	12.7	14.9	16.0	14.5	13.8	13.7	13.5	13.1	12.8	13.0	12.8	14.6	17.6	1127.0	11.6	644
avg	**14.2**	**14.0**	**13.7**	**13.6**	**13.5**	**13.6**	**13.7**	**14.5**	**15.9**	**17.1**	**18.1**	**18.9**	**19.6**	**19.5**	**19.5**	**19.1**	**18.2**	**17.0**	**15.7**	**15.3**	**15.1**	**14.7**	**14.4**	**14.2**	**16.9**	**21.3**		**12.5**	

Figure A.5: September Weather Data

Appendix B

GIS: Methodology for Density Map

To quantify the effect of stormwater influx into the Liesbeek river Figure 1.1, the number of stormwater outlets for any given length of the river was calculated using a GIS desktop analysis (Quantum GIS Development, 2009). It was decided to represent outlets per 50m stretch of river as a valuable representation of stormwater outlet density.

The first step consisted of splitting the main river layer into 50m sections, assigning a unique ID to every section. Next, each stormwater outlet into the river was digitised with a point. This required using the stormwater pipe layer (2005), this data was generally clearly defined, except for the classification of features as inlet or outlet. This was not distinguishable from the attribute table. It was therefore decided to manually select all possible outlet points which fell nearest to the river. It was assumed that outlet points are usually located close to the river, whereas inlet points are typically further away.

The next step was to spatially join the attributes of the river sections to the points. This gave every point an assigned unique ID of the river section it was closest to. The attribute table of "points by River section ID" was then summarized. i.e. a count of how many times an ID appeared gave a total number of storm water outlets for each 50m section of river. A table join based on the section ID to join the summary table back into the river sections layer was then done. This meant that each section now had an attribute showing the number of stormwater outlets for that section. Finally, the entire river layer was symbolised by "outlets per section" field. This was then categorised by a colour gradient to visually show the number of outlets per 50m segment of river. For example blue meant 0 outlets per 50m segment and red reflected 5 outlets per 50m segment of river.

Appendix C

Working Example of ColdChain Interface

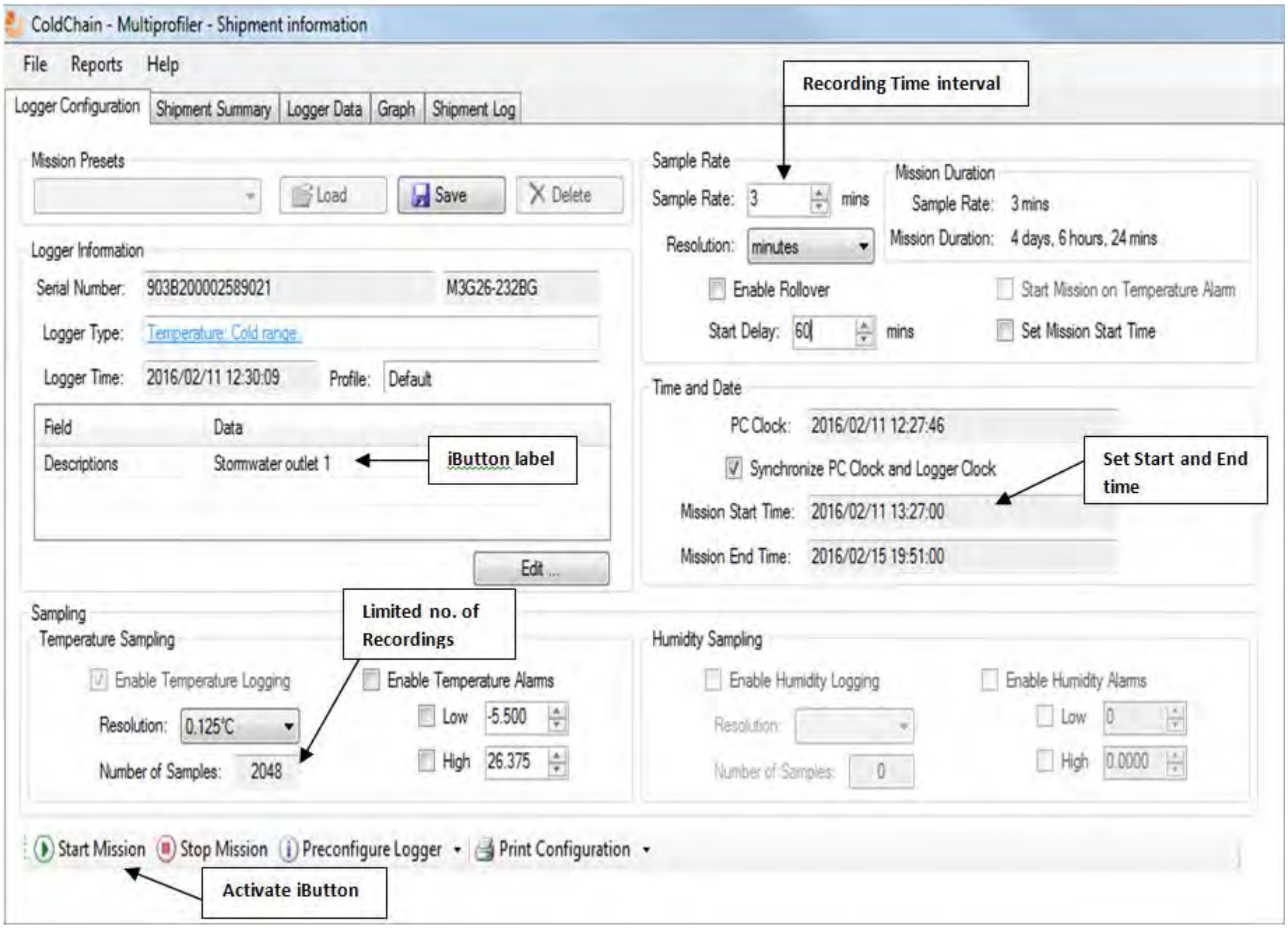

Figure C.1: ColdChain Thermodynamics software interface: showing activation of iButton temperature Logger

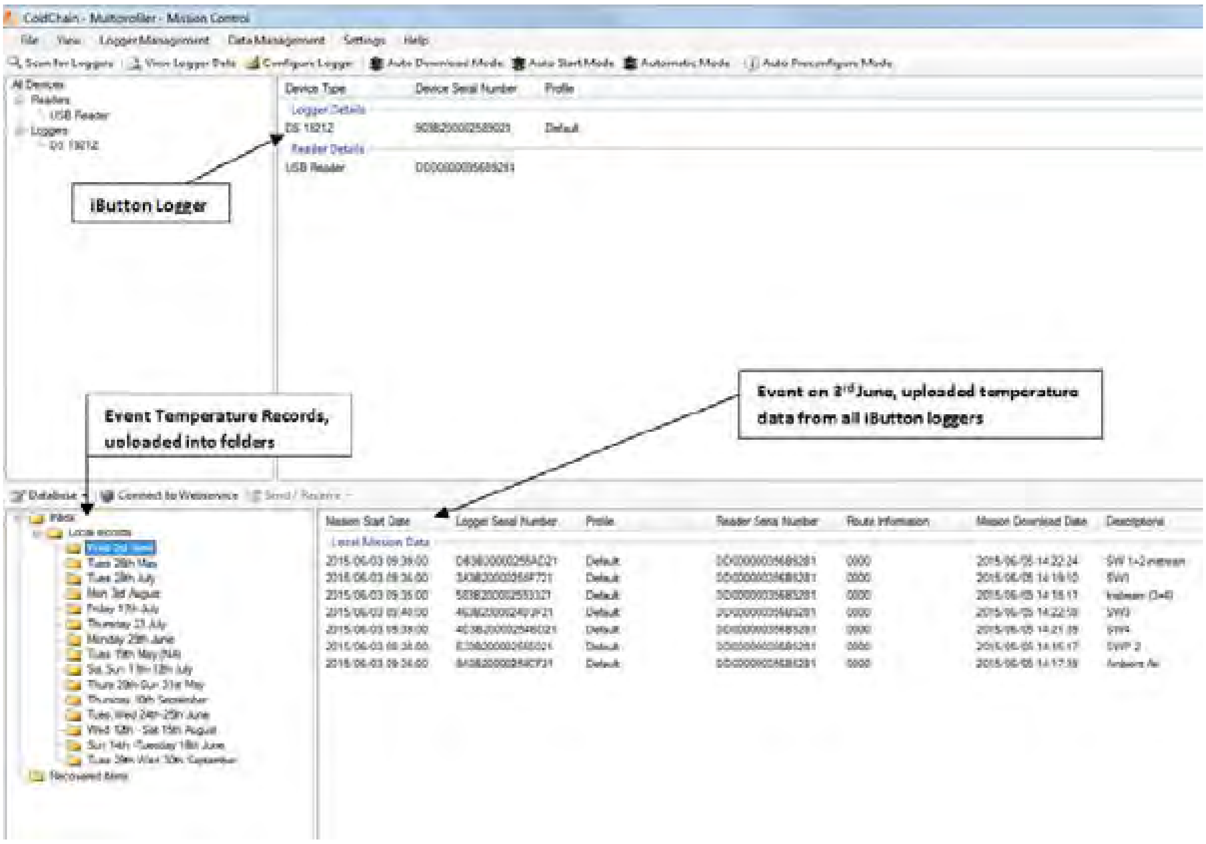

Figure C.2: ColdChain Thermodynamics software interface: showing initial upload of temperature data

Appendix D

Matlab Code Template

Data Entry

```
clear all
```

Variable Values (added as vectors)

```
sw1 = []; % Storm Water Pipe Outlet 1

sw2 =[]; % Storm Water Pipe Outlet 2

sw3 = []; % Storm Water Pipe Outlet 3

sw4 = []; % Storm Water Pipe Outlet 4

river_average_temp = []; % River Water Temperature

ambient = []; % Ambient Air Temperature

r = []; % Rainfall per hour
```

Graphing

```
% Start Time and End Time of Rainfall Event

StartTime = %24;
EndTime = %48;

x = StartTime/24:1/480:EndTime/24;
```

Rainfall Bar Graph (plotted on x-axis and secondart y-axis)

```
[ax,p,b] = plotyy(x,r,x,r,'plot','bar');
linkaxes(ax,'x')
xlim(ax(1),[StartTime/24 EndTime/24]);
xlim(ax(2),[StartTime/24 EndTime/24]);
datetick(ax(1),'x', 'HH:MM');
datetick(ax(2),'x', 'HH:MM');
set(ax(1),'xtick',[]);
set(ax(2),'xtick',[]);
set(ax,{'ycolor'},{'k';'k'});
set(b,'BarWidth',2.5);

hold on
```

Line Graphs of Storm Water Pipe Outlets(plotted on x-axis and y-axis)

```
plot(x, sw1,'color',[1 0 0]);
datetick('x', 'HH:MM')

hold on

plot(x, sw2,'color',[1 1 0]);
datetick('x', 'HH:MM')

hold on

plot(x, sw3,'color',[0 1 0]);
```

```
datetick('x', 'HH:MM')

hold on

plot(x, sw4,'color',[0.4 0 0.4]);
datetick('x', 'HH:MM')

hold on

set(findall(gca, 'Type', 'Line'),'LineWidth',2); % Set Line Thickness of
Line Graphs

hold on
```

Line Graphs of Ambient Air Temperature and River Water Temperature(plotted on secondary x-axis and y-axis, due to different vector lengths of input values as compared to storm water outlet temperature values)

```
xx = StartTime/24:1/24:EndTime/24;

aa = plot(xx, ambient,'-.','color',[0 0 0]);
datetick('x', 'HH:MM')
set(aa,'LineWidth',2.5);

hold on

c = plot(x, river_average_temp,'color',[0 0.2 0.4]);
datetick('x', 'HH:MM')
set(c,'LineWidth',4);

hold on
```

Set Axis Limits

```
axis([StartTime/24,EndTime/24,10,20])
```

Set X-axis Time Interval to be Displayed

```
step=1/24;  % 1 Hour Interval
debut = StartTime/24;
fin = EndTime/24;

set(gca, 'XTick', [debut:step:fin]);
datetick(ax(1),'x','HH:MM','keeplimits','keepticks');
datetick(ax(2),'x','HH:MM','keeplimits','keepticks');
```

Set Y-Axis Limits to be Displayed

```
sstep=0.5;
ddebut = 10;
ffin = 20;

y = 10:0.5:20;

set(gca,'YTick',[ddebut:sstep:ffin]);
set(gca,'yticklabel',sprintf('%.1f |',y));
```

Set Secondary Y-Axis Limits to be Displayed

```
ssstep=0.5;
dddebut = 0;
fffin = 10;
yy = 0:0.5:10;

ylim(ax(2),[dddebut fffin]);

set(ax(2),'YTick',[dddebut:ssstep:fffin]);
set(ax(2),'yticklabel',sprintf('%.1f |',yy));
grid on;
```

Calculation of Area Under Various Curves

sw1

```
X = StartTime:1:EndTime; % 30 min Time Range for Calculations

N = 20; % 30 min Time Intervals

Y1 = sw1(1:N:length(sw1));

z1 = cumtrapz(X,Y1);
```

sw2

```
Y1 = sw2(1:N:length(sw2));

z2 = cumtrapz(X,Y1);
```

sw3

```
Y2 = sw3(1:N:length(sw3));

z3 = cumtrapz(X,Y2);
```

sw4

```
Y2 = sw4(1:N:length(sw4));

z4 = cumtrapz(X,Y2);
```

Average River Temperature

```
Y3 = river_average_temp(1:N:length(river_average_temp));

z5 = cumtrapz(X,Y3);
```

Final Area Determination (area under desired curved subtracted from area under river water temperature curve)

```
Area1 = z1 - z5;
```

```
hold on

Area2 = z2 - z5;

hold on

Area3 = z3 - z5;

hold on

Area4 = z4 - z5;

hold on

display(Area1);
display(Area2);
display(Area3);
display(Area4);
```

Cumulative Rainfall Determination, Time Period and Ambient Temperature

```
Rainfall = r(1:N:length(r));
River_Average_Temp = river_average_temp(1:N:length(river_average_temp));

Time_Period = X;
Ambient_Temperature = ambient;
```

Graph Labels

```
xlabel('Time (hrs)');
ylabel(ax(1),'Temperature ( ^{o}C)')
ylabel(ax(2),'Rainfall (mm)')
title('_____date Rainfall Event'); %i.e. 8th of February
legend('Rainfall ','Sw1 ','Sw2','Sw3','Sw4','Ambient Temperature','Average
River Temperature');
```

Output Graphs As PDF Documents

```
u=gcf;
set(u,'PaperOrientation','landscape');
set(u,'PaperPosition', [1 1 28 19]);
print(gcf, '-dpdf', 'Graph_Date.pdf'); %i.e. 8th_February
movefile('3rd_June.pdf','Graphs'); %i.e. 8th_February
```

Appendix E

Statistical Data

Table Number		Hourly Data																			
	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
1.0	1	NO DATA				17.5313	17.3750	17.0000	18.8750	16.2625	16.0000	15.8750	17.5000	17.2188	17.5000	16.2500	17.6250	15.9812	15.9688	15.9375	16.0938
	2					16.0313	16.0625	15.7500	16.7500	15.9938	16.1250	15.3750	16.5000	15.8938	15.8125	15.7500	16.1250	15.8375	15.8125	15.6875	16.0313
	3					16.2500	16.1875	15.6250	16.8750	15.7438	15.8125	15.5000	16.0000	15.9875	15.9375	15.7500	16.3750	15.6766	15.6875	15.6563	15.6875
	4					16.6500	16.8125	16.1250	17.0000	16.1187	16.1250	15.7500	16.6250	16.2188	16.3125	15.7500	16.5000	15.7719	15.7813	15.6875	15.8438
	5					17.5562	17.6250	17.0000	18.0000	16.9812	17.0625	16.6250	17.1250	16.9563	17.0000	16.5000	17.2500	15.9359	15.9531	15.8750	15.9688
	6					17.9563	18.0000	17.7500	18.1250	16.6938	16.6875	16.3750	17.0000	17.0063	17.1250	16.3750	17.3750	15.9625	15.9688	15.9375	16.0000

Note: In the column labelled B, the value 1 corresponds to the first hour of the test etc. i.e. 1 = 10:00 to 10:57; 2 = 11:00 to 11:57 etc.

Table Number		Hourly Data																			
	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
2.0	1	17.8438	17.6250	16.8750	19.2500	18.2688	18.5000	17.0000	19.3750	16.7312	16.3750	16.1250	17.6250	17.3875	16.8750	16.6250	18.3750	15.8662	15.9000	15.7000	15.9250
	2	17.0250	17.0625	16.6250	17.5000	17.1563	17.0625	16.8750	17.6250	17.4812	17.5000	16.8750	17.6250	16.9187	16.8750	16.5000	17.5000	15.6100	15.6000	15.5500	15.7000
	3	16.5500	16.3750	15.7500	17.5000	17.9312	17.9375	17.3750	18.2500	16.8188	16.6250	16.3750	17.6250	17.9063	17.8750	17.5000	18.2500	15.5750	15.5750	15.5500	15.6000
	4	15.4875	15.5625	15.2500	15.7500	16.3500	16.1250	16.1250	17.2500	16.2312	16.2500	16.1250	16.3750	18.2063	18.2500	18.1250	18.2500	15.5550	15.5500	15.5250	15.6000
	5	17.4187	17.5625	15.3750	18.2500	17.5750	17.5000	16.8750	18.7500	16.4625	16.1250	15.8750	17.3750	17.5250	17.3750	16.7500	18.2500	15.5175	15.5250	15.4750	15.5500
	6	16.0625	15.8750	15.6250	17.2500	17.9375	17.9375	17.6250	18.2500	16.5437	16.3750	16.2500	17.3750	17.6625	17.7500	17.2500	18.0000	15.4750	15.4750	15.4750	15.4750
	7	16.3625	16.0000	15.6250	17.8750	17.0375	16.8125	16.1250	18.6250	16.3750	16.3750	16.2500	16.7500	17.7563	18.0000	17.1250	18.1250	15.4600	15.4500	15.4500	15.4750
	8	16.6187	16.7500	15.8750	17.6250	17.6563	17.7500	17.1250	18.0000	16.3687	16.3750	16.2500	16.5000	17.7563	17.7500	17.3750	18.0000	15.4325	15.4250	15.3750	15.4750
	9	15.7125	15.0625	15.0000	17.0000	17.5625	17.6250	17.2500	17.8750	16.2750	16.2500	16.1250	16.3750	17.8000	17.8125	17.6250	18.0000	15.3238	15.3250	15.2750	15.3750
	10	15.1438	15.1250	15.0000	15.3750	17.5813	17.6250	17.3750	17.7500	16.3562	16.3750	16.2500	16.3750	17.9875	18.0000	17.8750	18.0000	15.2063	15.2000	15.1750	15.2750
	11	15.3188	15.2500	15.1250	15.6250	17.5188	17.5000	17.2500	17.7500	16.1563	16.1250	16.0000	16.3750	18.0188	18.0000	18.0000	18.1250	15.1150	15.1250	15.0750	15.1750
	12	15.0625	15.0000	15.0000	15.2500	17.4063	17.3750	17.0000	17.7500	15.8313	15.8125	15.7500	16.0000	18.0000	18.0000	18.0000	18.0000	15.0525	15.0500	15.0500	15.1000
	13	16.4812	16.6250	15.1250	16.8750	17.0875	17.0000	16.6250	18.1250	16.6438	16.8750	15.5000	17.3750	16.6313	16.5000	16.1250	18.0000	15.0712	15.0750	15.0250	15.1250
	14	14.8875	14.7500	14.6250	16.0000	17.3687	17.4375	16.3750	17.8750	16.8813	16.9375	16.2500	17.5000	17.3938	17.3750	17.0000	17.7500	15.0200	15.0250	14.9750	15.0500
	15	16.2500	16.4375	15.5000	16.8750	16.8375	16.8750	16.1250	17.8750	16.0688	16.1250	15.3750	16.6250	16.3750	16.3125	15.6250	17.7500	15.0275	15.0500	14.9750	15.0500
	16	15.9938	15.8750	15.5000	16.6250	17.9125	18.0000	17.3750	18.2500	16.8687	16.8750	16.5000	17.1250	17.2688	17.3125	16.8750	17.5000	15.0863	15.0750	15.0500	15.1750
	17	16.0500	16.1250	15.6250	16.6250	18.2063	18.2500	17.8750	18.5000	16.4125	16.3750	16.3750	16.5000	17.6875	17.7500	17.5000	17.7500	15.2300	15.2250	15.1750	15.3000
	18	16.6062	16.6250	16.2500	16.8750	18.0313	18.0000	17.8750	18.2500	16.2750	16.2500	16.1250	16.3750	17.8625	17.8750	17.7500	18.0000	15.3963	15.4000	15.3250	15.4750

Table Number		Hourly Data																			
	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
3.0	1	18.0188	17.9375	17.7500	18.3750	18.3438	18.3750	18.1250	18.6250	13.8313	13.7500	13.7500	14.1250	17.1187	17.1250	17.0000	17.1250	13.6563	13.6875	13.5625	13.7500
	2	17.0063	17.6875	15.6250	18.2500	17.4375	17.8750	16.2500	18.5000	14.7312	14.4375	13.8750	16.2500	16.5063	16.3750	15.7500	17.3750	13.9375	13.9063	13.6875	14.1875
	3	16.2125	16.1875	15.8750	16.5000	16.6687	16.6875	16.3750	17.0000	15.8063	15.9375	15.0000	16.3750	16.3875	16.3750	16.1250	16.6250	14.2188	14.2188	14.1875	14.2500
	4	14.6438	14.6250	13.8750	15.8750	14.9875	14.8125	14.2500	16.2500	15.0938	15.0625	14.2500	16.3750	14.9313	14.7500	14.2500	16.2500	14.2188	14.2500	14.0625	14.3125
	5	13.9500	14.0000	13.8750	14.1250	14.5375	14.5000	14.3750	14.6250	14.1875	14.1250	14.1250	14.3750	14.4438	14.5000	14.3750	14.5000	14.0719	14.0625	14.0625	14.1250
	6	14.1938	14.2500	14.1250	14.2500	14.7375	14.7500	14.6250	14.8750	14.3000	14.3125	14.1250	14.3750	14.5750	14.6250	14.5000	14.6250	14.1094	14.1250	14.0625	14.1250
	7	14.3438	14.3750	14.2500	14.3750	14.8750	14.8750	14.7500	15.0000	14.3688	14.3750	14.2500	14.5000	14.6000	14.6250	14.5000	14.6250	14.1250	14.1250	14.1250	14.1250
	8	14.8313	14.8750	14.3750	15.2500	15.6000	15.6250	15.0000	16.1250	15.1250	15.1250	14.5000	15.6250	15.0250	15.0625	14.6250	15.2500	14.1188	14.1250	14.0625	14.1250
	9	15.4187	15.3750	15.2500	15.6250	16.2813	16.2500	16.1250	16.5000	15.9125	15.9375	15.6250	16.1250	15.4875	15.5000	15.3750	15.6250	15.7750	15.7656	15.5938	15.9688

Table Number		Hourly Data																			
	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
4.0	1	14.3188	14.3750	14.0000	14.6250	14.2188	13.9375	13.7500	15.3750	14.2063	14.2500	14.1250	14.3750	14.9812	15.0000	14.7500	15.1250	14.4516	14.4375	14.4375	14.4688
	2	14.2250	14.1250	14.0000	14.7500	13.8063	13.7500	13.6250	14.0000	14.1062	14.0625	14.0000	15.0000	15.0938	14.8750	14.7500	16.2500	14.4375	14.4375	14.4375	14.4375
	3	15.0063	14.1875	13.2500	17.8750	14.4625	14.1250	13.5000	16.5000	14.1750	14.1250	13.3750	15.1250	14.4500	14.1250	13.6250	16.0000	14.3500	14.4063	14.0625	14.4375
	4	13.7000	13.7500	13.3750	14.0000	14.0000	14.0625	13.5000	14.2500	13.6625	13.7500	13.3750	13.8750	13.9000	13.8750	13.6250	14.0000	13.8359	13.8125	13.7188	14.0313
	5	13.8063	13.8125	13.2500	14.3750	14.1250	14.0625	13.5000	14.7500	13.6938	13.5625	13.3750	14.2500	13.9375	13.8125	13.6250	14.3750	13.6375	13.6406	13.5625	13.7188
	6	14.1250	14.1875	13.3750	14.7500	14.6750	14.6875	13.7500	15.5000	14.0938	14.0625	13.5000	14.7500	14.3562	14.3750	13.7500	14.8750	13.5203	13.5313	13.5000	13.5625
	7	14.1813	14.8750	12.7500	15.5000	14.6813	15.3750	13.1250	16.0000	14.0875	14.1875	13.0000	15.1250	14.0813	14.1875	13.1250	15.0000	13.4875	13.5000	13.3438	13.5313
	8	13.1687	13.0625	12.6250	14.0000	13.7438	13.5625	13.1250	14.7500	13.1938	13.0625	12.8750	13.8750	13.4812	13.4375	13.0000	14.1250	13.1281	13.0938	12.9688	13.3438
	9	14.9313	14.8750	14.1250	15.7500	15.4500	15.5000	14.7500	16.0000	14.4063	14.4375	13.8750	14.7500	14.4500	14.5000	14.1250	14.6250	12.9281	12.9375	12.9063	12.9688
	10	15.8375	15.8125	15.5000	16.2500	16.2563	16.2500	16.0000	16.3750	15.0063	15.0000	14.8750	15.1250	14.9000	14.8750	14.7500	15.1250	12.9406	12.9375	12.9063	12.9688
	11	16.4375	16.4375	16.0000	17.2500	16.0562	16.1250	15.2500	16.3750	15.0250	15.0000	14.8750	15.1250	15.2875	15.2500	15.1250	15.5000	13.0469	13.0313	13.0000	13.1250
	12	16.6812	16.4375	16.0000	18.3750	15.5875	15.6250	14.5000	16.8750	14.7813	14.7500	14.3750	15.2500	15.2063	15.2500	14.6250	15.7500	13.2172	13.2188	13.1563	13.2813
	13	16.4937	16.5000	15.7500	17.1250	16.1187	16.1250	15.5000	17.0000	14.9812	15.0000	14.6250	15.3750	15.4500	15.5000	14.8750	15.8750	13.3734	13.3906	13.2813	13.4375
	14	16.7312	16.7500	16.0000	17.1250	16.0688	16.1250	15.7500	16.3750	15.1625	15.1250	15.0000	15.3750	15.4187	15.3750	15.2500	15.8750	13.5359	13.5625	13.4375	13.5938
	15	16.3875	16.4375	15.7500	17.0000	16.0437	16.0625	15.5000	16.3750	15.3625	15.3750	15.1250	15.6250	15.6875	15.7500	15.5000	15.8750	13.5922	13.5938	13.5625	13.5938
	16	17.0750	17.0625	16.6250	17.5000	15.6563	15.6250	15.1250	16.0000	15.6000	15.6250	15.5000	15.6250	15.8750	15.8750	15.8750	15.8750	13.5500	13.5625	13.4688	13.5938
	17	16.7563	16.7500	15.7500	17.5000	15.2563	15.3125	14.3750	16.0000	15.3562	15.3750	15.1250	15.5000	15.9812	16.0000	15.8750	16.0000	13.4016	13.3750	13.3125	13.5000
	18	15.9313	15.9375	15.5000	16.5000	14.3875	14.3750	13.8750	15.0000	14.4812	14.5000	14.0000	15.0000	15.9688	16.0000	15.8750	16.0000	13.2094	13.2188	13.1250	13.3125
	19	14.6563	14.5000	13.0000	17.0000	14.2375	14.1875	13.6250	15.6250	14.7438	14.8750	14.0000	15.7500	14.5313	14.3125	13.7500	16.0000	13.0844	13.0938	13.0625	13.1250
	20	15.5375	15.6250	15.1250	15.8750	15.1188	15.1250	14.0000	16.0000	15.2563	15.3125	15.0000	15.5000	15.1500	15.1250	14.7500	15.3750	13.0422	13.0313	13.0000	13.0938
	21	15.4750	15.5000	15.0000	15.8750	14.5563	14.3125	13.6250	15.6250	15.4187	15.5000	15.1250	15.5000	15.5625	15.6250	15.3750	15.6250	12.9844	12.9844	12.9688	13.0000
	22	15.3625	15.6250	14.5000	16.1250	14.1625	14.1250	13.3750	15.2500	14.7625	14.6875	14.6250	15.1250	15.7312	15.7500	15.6250	15.7500	12.9859	13.0000	12.9688	13.0000
	23	14.7000	14.6250	14.1250	16.2500	14.3562	13.9375	13.2500	16.1250	14.7813	14.6250	14.3750	15.1250	15.1188	15.0000	14.2500	15.7500	12.9656	12.9688	12.9375	12.9688
	24	14.3063	14.2500	14.1250	14.6250	14.1938	14.1250	13.6250	15.1250	15.2813	15.2500	15.1250	15.3750	15.3625	15.3750	15.0000	15.6250	12.9672	12.9688	12.9375	13.0000
	25	13.8438	13.8750	13.5000	14.1250	13.1938	13.1250	12.8750	13.7500	15.0563	15.1250	14.6250	15.2500	15.5250	15.5000	15.3750	15.6250	12.9688	12.9688	12.9688	12.9688
	26	13.7188	13.7500	13.5000	14.0000	12.9563	12.9375	12.8750	13.1250	15.3813	15.3125	15.1250	15.7500	15.3938	15.3750	15.2500	15.6250	12.9688	12.9688	12.9688	12.9688
	27	13.6125	13.6875	13.1250	14.0000	13.1000	13.1250	12.8750	13.2500	15.6750	15.7500	15.5000	15.7500	15.2688	15.2500	15.0000	15.5000	12.9688	12.9688	12.9688	12.9688

Table Number		Hourly Data																			
	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
5.0	1	15.4625	15.5000	15.0000	15.7500	18.2500	18.2500	18.2500	18.2500	14.6500	14.7500	14.3750	14.7500	14.9000	14.8750	14.6250	15.1250	14.1016	14.0938	14.0625	14.1250
	2	15.4313	14.6875	14.5000	18.2500	16.0375	15.3125	14.7500	18.2500	14.5813	14.6875	13.7500	15.3750	14.9812	14.7500	14.6250	15.7500	14.0469	14.0625	13.9375	14.0625
	3	13.8438	13.7500	13.3750	14.5000	14.0813	14.0000	13.6250	14.7500	14.2063	14.0625	13.8750	15.0000	14.0250	13.8750	13.7500	14.8750	13.4688	13.4375	13.1250	13.8750
	4	13.3750	13.1250	13.0000	14.0000	13.6625	13.4375	13.2500	14.2500	13.5437	13.2500	13.1250	14.1250	13.7312	13.5000	13.3750	14.2500	12.9203	12.8906	12.7500	13.0938
	5	12.9750	12.8750	12.7500	13.3750	13.4187	13.3125	13.2500	14.0000	13.0563	13.0000	12.8750	13.3750	13.4625	13.3750	13.2500	13.7500	12.7203	12.7188	12.7188	12.7500
	6	14.0125	13.9375	13.5000	14.6250	14.5750	14.5000	14.0000	15.2500	13.9313	13.9375	13.3750	14.3750	14.2750	14.2500	13.8750	14.6250	12.7094	12.7188	12.6875	12.7500
	7	14.3688	14.7500	12.6250	15.1250	15.1000	15.5000	12.8750	15.8750	14.1188	14.5000	12.7500	14.6250	14.3625	14.7500	12.8750	14.8750	12.7453	12.7500	12.7188	12.7500
	8	12.9000	12.9375	12.2500	13.6250	13.4938	13.5000	12.6250	14.5000	12.9375	12.8750	12.3750	13.6250	13.2688	13.2500	12.7500	13.8750	12.5797	12.5625	12.5000	12.6875
	9	13.4688	13.5625	12.8750	13.8750	14.0500	14.1250	13.3750	14.6250	13.4375	13.3750	12.8750	14.0000	13.5563	13.5625	13.1250	14.0000	12.4578	12.4688	12.4063	12.5000
	10	14.2688	14.3125	13.8750	14.5000	14.9812	15.0000	14.5000	15.3750	14.2063	14.2500	13.7500	14.5000	14.1875	14.2500	13.8750	14.3750	12.3547	12.3438	12.3125	12.4063
	11	14.7312	14.7500	14.5000	15.1250	15.5688	15.5625	15.3750	15.7500	14.5938	14.6250	14.5000	14.6250	14.5563	14.6250	14.3750	14.6250	12.2688	12.2813	12.1875	12.3125
	12	15.2688	15.2500	15.0000	15.5000	15.8625	15.8750	15.6250	16.0000	14.4000	14.3750	14.2500	14.5000	14.7312	14.7500	14.6250	14.8750	12.1875	12.1875	12.1875	12.1875
	13	15.6313	15.6250	15.5000	15.7500	14.6500	14.5000	14.2500	15.5000	13.8875	13.8750	13.5000	14.3750	14.9812	15.0000	14.8750	15.0000	12.1344	12.1250	12.1250	12.1875
	14	13.7438	12.9375	12.5000	16.1250	13.3750	13.1250	12.7500	14.2500	13.2500	13.1875	12.5000	14.3750	13.7312	13.5000	12.8750	14.8750	12.1672	12.1563	12.1250	12.2188
	15	14.3875	14.4375	13.3750	15.1250	14.3813	14.4375	13.1250	15.2500	13.6625	13.7500	13.1250	14.1250	14.1438	14.2500	13.3750	14.6250	12.1594	12.1875	12.0938	12.1875
	16	15.3438	15.3125	15.0000	15.8750	15.5063	15.4375	15.2500	15.8750	14.4187	14.5000	14.1250	14.5000	14.7500	14.7500	14.5000	15.0000	12.1609	12.1563	12.0938	12.2188
	17	16.3750	16.3750	15.8750	16.8750	15.4750	15.3125	14.7500	16.1250	14.3188	14.3750	14.1250	14.3750	14.6875	14.6250	14.5000	15.3750	12.4078	12.4219	12.2188	12.5313
	18	16.3500	16.3125	16.1250	17.1250	16.0125	16.0000	15.3750	16.7500	14.1062	14.1250	14.0000	14.2500	15.4625	15.5000	15.2500	15.6250	12.6469	12.6563	12.5313	12.7188
	19	16.0750	16.1250	15.6250	16.3750	14.7000	14.5625	14.1250	15.3750	13.8438	13.8750	13.7500	14.0000	15.5437	15.5625	15.2500	15.7500	12.7531	12.7500	12.7188	12.8125

Hourly Data

Table Number	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
6.0	1									13.3750	13.3750	12.7500	13.7500	14.4063	14.3750	14.0000	15.2500	13.7063	13.7500	13.6250	13.7500
	2									13.0125	12.8750	12.7500	13.5000	13.9500	14.1875	13.0000	14.6250	13.6000	13.6250	13.5000	13.6250
	3									12.8438	12.8125	12.3750	13.2500	12.7375	12.7500	12.5000	12.8750	13.3000	13.3125	13.0000	13.5000
	4									12.6813	12.6250	12.5000	13.0000	12.7750	12.7500	12.5000	13.0000	12.7875	12.7500	12.7500	13.0000
	5									13.2125	13.1250	13.0000	13.6250	13.1250	13.0000	13.0000	13.5000	12.7563	12.7500	12.7500	12.8750
	6									13.8188	13.8750	13.2500	14.0000	14.0000	14.0000	13.6250	14.2500	12.8063	12.7500	12.7500	12.8750
	7	NO DATA				NO DATA				12.9250	12.8750	12.8750	13.1250	14.2813	14.2500	14.1250	14.5000	12.5375	12.5000	12.3750	12.7500
	8									12.9625	13.0000	12.8750	13.0000	14.0813	14.0000	13.8750	14.2500	12.2688	12.2500	12.2500	12.3750
	9									12.8625	12.8750	12.7500	13.0000	13.7750	13.7500	13.5000	14.0000	12.2063	12.2500	12.1250	12.2500
	10									12.7875	12.7500	12.7500	12.8750	14.4500	14.6250	13.5000	14.8750	12.1062	12.1250	12.0000	12.1250
	11									12.8938	12.8750	12.8750	13.0000	14.4187	14.4375	14.2500	14.5000	12.1188	12.1250	12.0000	12.1250
	12									13.2000	13.2500	13.0000	13.3750	14.1313	13.9375	13.7500	14.6250	12.1938	12.2500	12.1250	12.2500
	13									13.5938	13.6250	13.3750	13.8750	14.5188	14.6250	14.0000	14.7500	12.4063	12.3750	12.2500	12.5000
	14									14.1125	14.1250	13.8750	14.2500	14.8063	14.8750	14.6250	14.8750	12.6563	12.6250	12.6250	12.7500

Hourly Data

Table Number	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
7.0	1	14.5625	13.9375	13.3750	16.2500	14.8625	14.0000	13.3750	18.0000	13.4187	13.3125	12.7500	14.3750	14.2688	13.8750	13.5000	15.7500	14.0578	13.9375	13.4063	14.6250
	2	14.2500	14.2500	13.8750	14.6250	13.9563	14.1250	13.1250	14.5000	14.1750	14.2500	13.6250	14.5000	14.6188	14.6875	14.1250	15.0000	13.3219	13.2969	13.2500	13.4063
	3	15.0375	15.0000	14.7500	15.2500	13.2125	13.1250	13.0000	13.6250	14.2063	14.2500	14.0000	14.3750	15.3500	15.3750	15.0000	15.5000	13.2031	13.1875	13.1875	13.2500
	4	15.3063	15.3750	15.0000	15.6250	13.5500	13.4375	12.8750	14.3750	13.8188	13.8125	13.6250	14.0000	15.2000	15.0625	14.8750	15.5000	13.2469	13.2500	13.1875	13.2813

Hourly Data

Table Number	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
8.0	1	14.6563	15.0625	13.3750	15.3750	15.6750	15.8125	13.6250	17.5000	13.0750	12.9375	12.6250	13.7500	13.7312	13.9375	12.1250	14.7500	12.2531	12.2500	12.1875	12.3125
	2	13.2000	13.1250	13.0000	13.5000	13.2875	13.2500	13.1250	13.6250	13.2000	13.1250	13.0000	13.5000	13.2625	13.2500	13.1250	13.5000	12.2984	12.3125	12.2500	12.3125
	3	13.2875	13.2500	12.8750	13.6250	13.5250	13.5000	13.1250	14.0000	13.2625	13.2500	12.8750	13.6250	13.4313	13.5000	13.1250	13.8750	12.2125	12.1875	12.1875	12.2500
	4	13.0375	13.0000	12.8750	13.2500	13.2000	13.1875	13.1250	13.3750	12.9938	13.0000	12.8750	13.1250	13.1563	13.1250	13.1250	13.2500	12.1516	12.1563	12.0938	12.1875
	5	13.0437	13.0000	12.8750	13.2500	13.3813	13.3750	13.1250	13.7500	13.0250	13.0000	12.8750	13.2500	13.2188	13.2500	13.1250	13.3750	12.0906	12.0938	12.0625	12.0938
	6	12.7312	12.8125	12.1250	13.3750	13.0375	13.1250	12.2500	13.7500	12.6625	12.4375	12.1250	13.2500	12.9438	12.8750	12.5000	13.3750	12.0641	12.0625	12.0313	12.0938
	7	12.1938	12.1250	12.1250	12.5000	12.4938	12.4375	12.3750	12.8750	12.1250	12.1250	12.0000	12.3750	12.5313	12.5000	12.3750	12.8750	12.0156	12.0000	11.9688	12.0625
	8	12.3188	12.3750	12.1250	12.5000	12.7375	12.7500	12.5000	13.0000	12.3375	12.3750	12.1250	12.5000	12.5625	12.6250	12.3750	12.6250	11.9297	11.9375	11.9063	11.9688
	9	12.2250	12.1250	11.8750	12.7500	12.6687	12.5000	12.2500	13.3750	12.3063	12.1875	12.0000	12.8750	12.4313	12.3750	12.1250	12.8750	11.8813	11.8750	11.8438	11.9063
	10	13.1438	13.1250	12.8750	13.3750	13.8688	13.8750	13.5000	14.1250	13.3813	13.3750	13.0000	13.7500	13.1250	13.1250	12.8750	13.3750	11.8125	11.8125	11.8125	11.8125
	11	13.5437	13.5000	13.3750	13.6250	14.5188	14.5000	14.2500	14.7500	13.8688	13.8750	13.7500	14.0000	13.5313	13.5625	13.3750	13.6250	11.8094	11.8125	11.7813	11.8438
	12	13.7188	13.7500	13.6250	13.8750	15.0188	15.0000	14.7500	15.1250	14.0000	14.0000	14.0000	14.0000	13.7625	13.7500	13.6250	13.8750	11.8016	11.8125	11.7813	11.8438
	13	13.6687	13.6250	13.5000	13.8750	15.3188	15.2500	15.1250	15.6250	13.8250	13.8750	13.6250	14.0000	13.9438	14.0000	13.8750	14.0000	11.7828	11.7813	11.7813	11.8125

Hourly Data

Table Number	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
9.0	1	14.6062	14.7500	13.0000	15.3750	15.8313	15.6250	13.2500	17.7500	13.6000	13.6250	13.2500	13.8750	14.4938	14.3750	13.3750	15.5000	13.5146	13.5000	13.4583	13.5417
	2	13.3000	13.1875	12.8750	13.8750	13.5375	13.5000	13.1250	14.1250	13.5188	13.5000	13.2500	13.7500	13.7688	13.8750	13.3750	14.0000	13.3604	13.3750	13.2917	13.4167
	3	13.0750	13.1250	13.0000	13.2500	13.5813	13.5000	13.5000	13.7500	13.4250	13.3750	13.2500	13.7500	13.5750	13.5000	13.5000	13.8750	13.2833	13.2917	13.1667	13.3333
	4	12.9187	12.8750	12.8750	13.0000	13.3500	13.3750	13.2500	13.5000	13.1188	13.1250	13.0000	13.2500	13.3063	13.2500	13.2500	13.5000	13.0250	13.0417	12.8333	13.1667
	5	13.2813	13.3125	12.8750	13.7500	13.8688	13.8750	13.3750	14.5000	13.5563	13.5625	13.1250	14.0000	13.5938	13.6250	13.2500	13.8750	12.7313	12.7292	12.6667	12.8333
	6	13.9688	14.0000	13.7500	14.1250	14.4812	14.5000	14.3750	14.6250	14.1188	14.1250	14.0000	14.2500	14.0750	14.1250	13.8750	14.2500	12.6917	12.7083	12.6667	12.7083

Hourly Data

Table Number	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
10.0	1	14.4938	14.5625	14.1250	15.0000	14.7625	15.0625	2.8750	15.3750	12.4625	12.5000	12.3750	12.5000	14.5625	14.6250	14.1250	14.8750	13.4146	13.4167	13.3333	13.5000
	2	14.3438	14.3125	14.1250	15.0000	14.2563	14.0625	13.2500	16.2500	13.1750	12.6875	12.5000	14.5000	14.7250	14.7500	14.3750	15.1250	13.1646	13.1667	13.0417	13.2917
	3	14.2750	14.2500	14.2500	14.3750	14.7937	14.8125	14.6250	14.8750	14.4938	14.5000	14.3750	14.6250	14.3500	14.3750	14.2500	14.3750	13.0104	13.0000	12.9583	13.0833
	4	14.0063	14.0625	13.6250	14.2500	14.5500	14.6875	14.0000	14.8750	14.1500	14.0625	13.7500	14.5000	14.0750	14.0000	13.7500	14.3750	12.9875	13.0000	12.9167	13.0000
	5	13.6563	13.6250	13.5000	13.8750	14.1062	14.1250	13.8750	14.2500	13.9812	14.0000	13.8750	14.1250	13.9125	13.8750	13.7500	14.1250	12.8938	12.8958	12.8333	12.9583
	6	14.1875	14.2500	13.8750	14.3750	14.0437	14.0000	13.7500	14.5000	14.1500	14.1250	14.0000	14.2500	14.4563	14.5000	14.2500	14.6250	12.6917	12.6875	12.5833	12.7917
	7	13.3625	14.3125	11.6250	14.5000	13.5563	13.8125	11.8750	14.7500	13.3063	13.6875	12.2500	14.0000	13.5063	14.0000	12.0000	14.7500	12.4979	12.5417	12.2917	12.5833
	8	11.3688	11.3125	11.0000	11.7500	11.7813	11.7500	11.5000	12.1250	11.7688	11.6250	11.5000	12.2500	11.7438	11.7500	11.5000	12.1250	11.7875	11.7917	11.2917	12.2500
	9	10.7813	10.7500	10.6250	11.0000	11.3438	11.3750	11.1250	11.6250	11.2250	11.2500	11.1250	11.3750	11.3625	11.3750	11.2500	11.5000	10.9729	10.9375	10.7917	11.2917
	10	11.7000	11.7500	10.8750	12.3750	12.4875	12.5625	11.5000	13.3750	12.1625	12.1875	11.3750	12.8750	12.1250	12.1875	11.5000	12.6250	10.7833	10.7917	10.7500	10.7917
	11	12.8438	12.8750	12.5000	13.1250	13.8688	13.8750	13.3750	14.2500	13.3500	13.3750	13.0000	13.6250	12.9187	12.9375	12.6250	13.1250	10.6417	10.6458	10.5417	10.7500

Hourly Data

Table Number	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
11.0	1	14.4313	14.3750	14.3750	14.5000	16.8875	16.8750	16.6250	17.0000	12.1062	12.1250	12.0000	12.2500	13.9875	14.0000	13.8750	14.0000	12.4688	12.4688	12.4688	12.4688
	2	14.6188	14.6250	14.3750	14.8750	17.0188	17.0000	16.8750	17.2500	11.9812	12.0000	11.8750	12.0000	14.2875	14.2500	14.0000	14.6250	12.4203	12.4219	12.3750	12.4375
	3	12.5625	12.3750	12.0000	14.7500	13.0813	12.7500	12.3750	16.2500	12.7375	12.7500	11.5000	13.0000	12.4812	12.5000	12.2500	13.1250	12.1297	12.1563	11.7500	12.3750
	4	12.4125	12.5000	11.5000	13.0000	12.7937	12.8750	11.6250	13.6250	12.5813	12.8750	11.6250	13.2500	12.4938	12.6875	11.6250	13.2500	11.5234	11.4688	11.4063	11.7500
	5	11.5875	11.5000	11.3750	12.0000	11.7875	11.7500	11.6250	12.1250	11.6125	11.6250	11.3750	11.8750	11.8562	11.8125	11.7500	12.1250	11.3547	11.3438	11.3125	11.4063
	6	11.4250	11.3750	11.1250	12.0000	11.8000	11.6250	11.2500	12.6250	11.4750	11.3750	11.1250	12.1250	11.7563	11.6875	11.5000	12.2500	11.2109	11.2344	11.0938	11.2813
	7	12.2813	12.2500	12.0000	12.5000	12.8813	12.8750	12.2500	13.2500	12.3813	12.3750	11.8750	12.8750	12.3938	12.3750	12.1250	12.6250	11.1453	11.1563	11.0938	11.1563
	8	11.6750	11.7500	11.3750	12.0000	11.9875	12.1250	11.6250	12.2500	11.6250	11.6875	11.3750	11.7500	12.0188	12.0000	11.8750	12.1250	11.2422	11.2500	11.1563	11.3125
	9	12.4187	12.5000	11.8750	12.8750	12.9563	13.0625	12.1250	13.6250	12.4438	12.4375	11.7500	13.0000	12.4563	12.5000	12.1250	12.7500	11.2859	11.2813	11.2500	11.3438
	10	13.2438	13.2500	12.8750	13.5000	13.9063	13.8750	13.6250	14.1250	13.4250	13.4375	13.1250	13.7500	12.8625	12.8750	12.6250	13.0000	11.1516	11.1563	11.0313	11.2500

Hourly Data

Table Number	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
12.0	1	14.9938	15.0000	14.8750	15.0000	17.4250	17.3750	17.3750	17.5000	13.0375	13.0000	13.0000	13.1250	14.7500	14.7500	14.7500	14.7500	13.1703	13.1719	13.1250	13.1875
	2	13.9000	13.8125	13.1250	15.0000	14.6750	14.5000	13.6250	17.5000	13.6375	13.8125	12.5000	14.0000	14.0188	14.0625	13.5000	14.7500	13.0766	13.0938	12.9375	13.1563
	3	13.4250	14.1250	12.2500	14.2500	13.9750	14.6875	12.3750	15.3750	13.2063	13.6875	12.2500	14.0000	13.5500	13.8750	12.6250	14.3750	12.7359	12.7500	12.4375	12.9375
	4	13.2563	13.3125	12.6250	13.6250	13.6875	13.6875	12.7500	14.6250	13.0313	13.0625	12.5000	13.5000	13.4125	13.4375	12.8750	13.8750	12.3313	12.3125	12.3125	12.3750
	5	13.6062	13.5000	13.3750	14.1250	15.0188	15.0000	14.7500	15.3750	13.7438	13.6250	13.5000	14.0000	14.1000	14.1250	14.0000	14.2500	12.3578	12.3750	12.3125	12.4063
	6	13.5437	13.5000	13.5000	13.6250	15.3438	15.3750	14.8750	15.6250	13.8938	14.0000	13.5000	14.0000	14.2875	14.2500	14.2500	14.3750	12.5047	12.5000	12.4688	12.5625
	7	13.6875	13.6875	13.6250	13.7500	15.1813	15.1250	14.8750	15.6250	12.9750	12.8750	12.8750	13.3750	14.1625	14.1250	14.1250	14.2500	12.6078	12.5938	12.5625	12.6875

Table Number	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
13.0	1	15.5250	15.8750	13.7500	16.0000	17.0750	17.7500	14.0000	18.1250	14.2813	14.3750	13.8750	14.6250	15.2000	15.7500	14.0000	16.2500	14.1375	14.1875	14.0000	14.2188
	2	14.1813	14.1250	13.8750	14.6250	14.5875	14.5625	14.0000	15.2500	14.4750	14.4375	13.8750	15.1250	14.6313	14.6250	14.1250	15.1250	13.9125	13.9063	13.8750	14.0000
	3	15.0188	15.1250	14.6250	15.2500	15.8750	16.0000	15.2500	16.3750	15.1313	15.1250	14.8750	15.2500	15.6188	15.6250	15.1250	16.0000	13.9250	13.9375	13.8750	13.9375
	4	15.1125	15.1250	14.8750	15.3750	16.0688	16.0000	15.7500	16.6250	15.1687	15.0625	14.8750	15.7500	15.5813	15.5000	15.3750	15.8750	14.0078	14.0000	13.9063	14.1250
	5	15.5750	15.6250	15.3750	15.7500	16.1625	16.2500	15.8750	16.3750	15.7625	15.8125	15.3750	16.0000	16.1938	16.2500	15.8750	16.3750	14.2312	14.2188	14.1250	14.3125
	6	15.7688	15.7500	15.5000	15.8750	16.3562	16.4375	15.6250	17.2500	15.1188	15.1250	15.0000	15.3750	16.2750	16.3750	16.0000	16.5000	14.4109	14.4063	14.3125	14.4688
	7	15.8313	15.8750	15.6250	15.8750	16.5750	16.6250	16.3750	16.7500	14.9375	14.9375	14.8750	15.0000	16.3375	16.3750	16.1250	16.5000	14.5703	14.5938	14.4688	14.6250
	8	15.8562	15.8750	15.7500	15.8750	16.1000	16.0625	15.6250	16.7500	14.8938	14.8750	14.7500	15.0000	16.4625	16.5000	16.3750	16.6250	14.7016	14.6875	14.6250	14.7813
	9	15.5188	15.5000	15.1250	15.7500	15.6188	15.6250	14.8750	16.1250	15.1563	15.1250	15.0000	15.2500	16.4063	16.3750	16.2500	16.6250	14.8484	14.8594	14.7813	14.8750

Table Number	B	Sw1 (°C)				Sw2 (°C)				Sw3 (°C)				Sw4 (°C)				River Temperature (°C)			
		Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
14.0	1	16.0625	15.8750	15.7500	16.8750	15.9063	15.8125	15.5000	16.7500	15.0437	15.0000	14.8750	15.2500	15.7125	15.1875	15.0000	17.0000	16.1297	16.1250	16.0625	16.1875
	2	16.8500	16.8125	16.7500	17.0000	16.0875	15.8750	15.6250	16.8750	14.7813	14.7500	14.6250	14.8750	16.2063	16.1875	15.5000	17.0000	16.0000	16.0000	15.9688	16.0313
	3	16.6687	16.8750	16.1250	17.1250	17.1438	17.1250	16.3750	18.1250	15.0688	14.8125	14.6250	15.6250	17.0625	17.0000	16.7500	17.6250	15.8688	15.8750	15.7813	15.9688
	4	16.4438	16.5000	16.1250	16.6250	16.9063	16.8750	16.5000	17.2500	14.7250	14.5625	14.0000	15.5000	16.8000	16.8125	16.3750	17.1250	15.7203	15.7188	15.6875	15.7813
	5	16.5813	16.6250	16.5000	16.6250	16.3750	16.3750	16.2500	16.6250	14.0188	14.0000	13.8750	14.1250	16.0938	16.1250	16.0000	16.2500	15.5875	15.5781	15.5625	15.6563
	6	16.5250	16.5625	16.2500	17.0000	16.9750	17.0000	16.3750	17.8750	14.3938	14.3125	14.0000	14.8750	16.8375	16.8750	16.2500	17.3750	15.5359	15.5313	15.5000	15.5625
	7	16.4250	16.5000	16.2500	16.6250	16.5562	16.6250	16.3750	16.8750	14.5875	14.4375	14.2500	15.0000	16.6687	16.6250	16.3750	17.0000	15.4563	15.4375	15.4375	15.5313
	8	16.4750	16.5000	16.3750	16.6250	16.1938	16.2500	15.8750	16.5000	13.9500	13.8750	13.7500	14.2500	16.2813	16.3125	16.1250	16.3750	15.3813	15.3750	15.3750	15.4375
	9	16.5125	16.5000	16.3750	16.6250	16.4375	16.4375	16.0000	16.8750	13.8750	13.8750	13.7500	14.1250	16.5375	16.5000	16.1250	17.2500	15.3422	15.3438	15.2500	15.3750
	10	15.9812	16.0000	15.0000	16.8750	16.5500	16.3750	15.7500	17.6250	15.5437	15.8750	14.1250	16.5000	16.1500	16.1875	15.6250	16.6250	15.2516	15.2500	15.2500	15.2813
	11	13.9750	13.7500	13.5000	14.8750	14.4375	14.3125	13.7500	15.6250	15.0063	14.8125	14.5000	16.3750	14.4625	14.3125	13.8750	15.5000	15.1250	15.1563	14.9063	15.2500
	12	14.0188	14.0000	13.8750	14.2500	14.6625	14.6250	14.2500	15.0000	15.0188	15.0000	14.6250	15.5000	14.6313	14.5000	14.3750	15.1250	14.7719	14.7813	14.6875	14.8750
	13	13.8813	13.9375	13.3750	14.3750	14.8562	15.0625	14.1250	15.5000	15.2188	15.4375	14.5000	15.7500	14.5437	14.5000	14.1250	15.1250	14.6484	14.6563	14.5938	14.6875
	14	13.9625	14.0000	13.6250	14.3750	14.9938	15.0000	14.3750	15.6250	15.0000	15.0000	14.6250	15.5000	14.6625	14.6250	14.1250	15.2500	14.5281	14.5313	14.5000	14.5938
	15	14.7813	14.8125	14.3750	15.1250	16.1812	16.1875	15.7500	16.6250	15.6000	15.6250	15.5000	15.7500	15.6938	15.7500	15.3750	16.0000	14.4953	14.5000	14.4688	14.5313
	16	15.3562	15.3750	15.1250	15.5000	16.6625	16.6250	16.3750	17.0000	15.3813	15.3750	15.3750	15.5000	16.1375	16.1250	16.0000	16.2500	14.6625	14.6406	14.5313	14.8125
	17	15.7063	15.7500	15.5000	15.8750	16.7375	16.7500	16.5000	16.8750	15.4438	15.5000	15.3750	15.5000	16.3875	16.3125	16.1250	16.7500	15.0531	15.0313	14.8438	15.2813
	18	15.8375	15.8750	15.7500	16.0000	16.5813	16.5625	16.2500	16.8750	15.4812	15.5000	15.3750	15.5000	16.7250	16.7500	16.3750	16.8750	15.4078	15.4063	15.3125	15.4688
	19	15.9812	15.8750	15.2500	16.8750	16.9000	16.8750	15.2500	18.2500	16.2250	15.5625	15.5000	17.5000	16.8313	16.8750	16.2500	17.5000	15.4484	15.4688	15.3750	15.5000
	20	16.5250	16.5625	16.2500	16.6250	17.1313	17.1250	16.7500	17.3750	17.4500	17.5000	17.3750	17.5000	16.8875	16.8750	16.6250	17.0000	15.3719	15.3438	15.3438	15.4375
	21	16.5063	16.5000	16.1250	16.6250	17.4688	17.5000	17.3750	17.6250	17.0625	17.0625	16.6250	17.5000	16.9312	17.0000	16.7500	17.0000	15.3375	15.3438	15.3125	15.3438
	22	15.8000	15.8125	15.3750	16.3750	17.1875	17.2500	16.5000	17.6250	16.2625	16.2500	16.0000	16.6250	16.9125	16.8750	16.6250	17.1250	15.2969	15.2969	15.2500	15.3438

Table Number	Date
1.0	26th May 2015
2.0	29th and 30th May 2015
3.0	3rd June 2015
4.0	16th June 2015
5.0	23rd and 24th June 2015
6.0	29th June 2015
7.0	11th and 12th of July 2015
8.0	17th July 2015
9.0	23rd July 2015 (Rainfall event 1)
10.0	23rd July 2015 (Rainfall event 2)
11.0	30th July 2015
12.0	4th August 2015
13.0	10th September 2015
14.0	29th and 30th September 2015

Figure E.1: Excel Statistical Data

Appendix F

R Code

```
### crisp.R
### November 2015
### ===========================================================================

setwd("C:/Users/Annesley/Desktop/R STATS DATA/DATA SET 2")

### ---- some data manipulation

library(reshape)
library(stringi)
library(FSA)
library(visreg)

temps <- read.csv("crisp.csv", header = TRUE, skip= 2)
head(temps)
names(temps)

temp2 <- read.csv("crisp2.csv", header = TRUE)
head(temp2)
names(temp2)

temp2$time.hour <- as.numeric(substr(temp2$Time, 1, 2))
ampm <- stri_sub(temp2$Time, -2, -1)
temp2$time.hour <- ifelse(ampm == "PM" & temp2$time.hour < 12, temp2$time.hour + 12, temp2$time.hour)
temp2$time.hour <- ifelse(ampm == "AM" & temp2$time.hour == 12, temp2$time.hour + 12, temp2$time.hour)

dim(temp2)
dim(temps)

dat1 <- merge(temp2, temps, by.x = c("event", "hour"), by.y = c("table.number", "hour"),
              all = TRUE)
names(dat1)
head(dat1)
dim(dat1)


## put all temperatures into one variable 'value'

#dat <- melt(temps, id.vars = c(1, 2), measure.vars = 3:22, variable_name = "var")
#dat[1:20, ]

dat <- melt(dat1, id.vars = c(1:3, 8:13), measure.vars = c(4:7, 14:33), variable_name = "var")
dat[1:20, ]


## add another variable indicating where temperature from
dat$sw <- substr(dat$var, 3, 3)
dat$sw <- as.factor(dat$sw)            # change to categorical variable
dat$sw <- relevel(dat$sw, "v")         # set river as reference category

## add another variable indicating which statistic
v2 <-   strsplit(as.character(dat$var), split = ".", fixed = TRUE)
dat$stat <- sapply(v2, function(x) x[2])

names(dat)
head(dat)
dat$value <- as.numeric(dat$value)

### ----- some exploratory plots

plot(value ~ hour, data = subset(dat, stat == "mean"), col = as.numeric(sw),
     las = 1, ylab = "temperature", xlab = "hours since rain event")

hist(value ~ sw, data = subset(dat, stat == "mean"))

### -----

## differences in mean temperature only one hour after rain event

pdf("onehourmeanboxplots.pdf")
plot(value ~ sw, data = subset(dat, stat == "mean" & hour == 1), las = 1,
     xlab = "location", ylab = "temperature")
dev.off()

m1 <- lm(value ~ sw, data = subset(dat, stat == "mean" & hour == 1))
summary(m1)

a1 <- aov(value ~ sw, data = subset(dat, stat == "mean" & hour == 1))
summary(a1)

TukeyHSD(a1)

pdf("onehourmeantukey.pdf", height=8, width=5)
```

```
plot(TukeyHSD(a1), las = 1)
dev.off()


###

## -----

m2 <- lm(value ~ sw + ambient + time.hour + rain.hour + rain.cum + hour,
        data = subset(dat, stat == "mean"))
summary(m2)



par(mfrow = c(2, 3))
visreg(m2)

## residual checks
par(mfrow = c(2, 2))
plot(m2)




###

dat$ser <- as.factor(paste(dat$sw, dat$event))
dat$ser

library(nlme)

m3 <- gls(value ~ sw + ambient + rain.hour + rain.cum + hour +
                sin(time.hour / 24 * 2 * pi) + cos(time.hour / 24 * 2 * pi),
        correlation = corAR1(form = ~ 1 | ser),
        data = subset(dat, stat == "mean" & hour > 0 & !is.na(value)))
summary(m3)


m4 <- gls(value ~ sw + ambient + rain.hour + rain.cum +
                sin(time.hour / 24 * 2 * pi) + cos(time.hour / 24 * 2 * pi),
        correlation = corAR1(form = ~ 1 | ser),
        data = subset(dat, stat == "mean" & hour > 0 & !is.na(value)))
summary(m4)

m5 <- gls(value ~ sw + ambient + rain.hour + rain.cum + hour,
        correlation = corAR1(form = ~ 1 | ser),
        data = subset(dat, stat == "mean" & hour > 0 & !is.na(value)))
summary(m5)

m6 <- gls(value ~ sw + sw:hour + ambient + rain.hour + rain.cum + hour +
        sin(time.hour / 24 * 2 * pi) + cos(time.hour / 24 * 2 * pi),
        correlation = corAR1(form = ~ 1 | ser),
        data = subset(dat, stat == "mean" & hour > 0 & !is.na(value)))
summary(m6)

m7 <- gls(value ~ sw + ambient + rain.hour + I(rain.hour^2) + rain.cum + hour +
    sin(time.hour / 24 * 2 * pi) + cos(time.hour / 24 * 2 * pi),
        correlation = corAR1(form = ~ 1 | ser),
        data = subset(dat, stat == "mean" & hour > 0 & !is.na(value)))
summary(m7)



m8 <- gls(value ~ sw + ambient + rain.hour + rain.cum + sw:rain.cum + hour +
        sin(time.hour / 24 * 2 * pi) + cos(time.hour / 24 * 2 * pi),
        correlation = corAR1(form = ~ 1 | ser),
        data = subset(dat, stat == "mean" & hour > 0 & !is.na(value)))
summary(m8)

dim(subset(dat, stat == "mean" & hour > 0 & !is.na(value)))


AIC(m3, m4, m5, m6, m7, m8)
#subset(dat, stat == "mean" & hour > 0)$value

par(mfrow = c(2, 3))
visreg(m3)
visreg(m4)



### maximum

m3.max <- gls(value ~ sw + ambient + rain.hour + rain.cum + hour +
        sin(time.hour / 24 * 2 * pi) + cos(time.hour / 24 * 2 * pi),
```

```
        correlation = corAR1(form = ~ 1 | ser),
        data = subset(dat, stat == "max" & hour > 0 & !is.na(value)))
summary(m3.max)


m4.max <- gls(value ~ sw + ambient + rain.hour + rain.cum +
                sin(time.hour / 24 * 2 * pi) + cos(time.hour / 24 * 2 * pi),
        correlation = corAR1(form = ~ 1 | ser),
        data = subset(dat, stat == "max" & hour > 0 & !is.na(value)))
summary(m4.max)

m5.max <- gls(value ~ sw + ambient + rain.hour + rain.cum + hour,
        correlation = corAR1(form = ~ 1 | ser),
        data = subset(dat, stat == "max" & hour > 0 & !is.na(value)))
summary(m5.max)


AIC(m3.max, m4.max, m5.max)
#subset(dat, stat == "mean" & hour > 0)$value

par(mfrow = c(2, 3))
visreg(m3.max)
visreg(m4.max)



### minimum

m3.min <- gls(value ~ sw + ambient + rain.hour + rain.cum + hour +
    sin(time.hour / 24 * 2 * pi) + cos(time.hour / 24 * 2 * pi),
        correlation = corAR1(form = ~ 1 | ser),
        data = subset(dat, stat == "min" & hour > 0 & !is.na(value)))
summary(m3.min)


m4.min <- gls(value ~ sw + ambient + rain.hour + rain.cum +
                sin(time.hour / 24 * 2 * pi) + cos(time.hour / 24 * 2 * pi),
        correlation = corAR1(form = ~ 1 | ser),
        data = subset(dat, stat == "min" & hour > 0 & !is.na(value)))
summary(m4.min)

m5.min <- gls(value ~ sw + ambient + rain.hour + rain.cum + hour,
        correlation = corAR1(form = ~ 1 | ser),
        data = subset(dat, stat == "min" & hour > 0 & !is.na(value)))
summary(m5.min)


AIC(m3.min, m4.min, m5.min)
#subset(dat, stat == "mean" & hour > 0)$value

par(mfrow = c(2, 3))
visreg(m5.min)
visreg(m3.min)



cor(dat[, c(2, 4:9, 11)], use = "pairwise.complete.obs")
```

Appendix G

Graphs

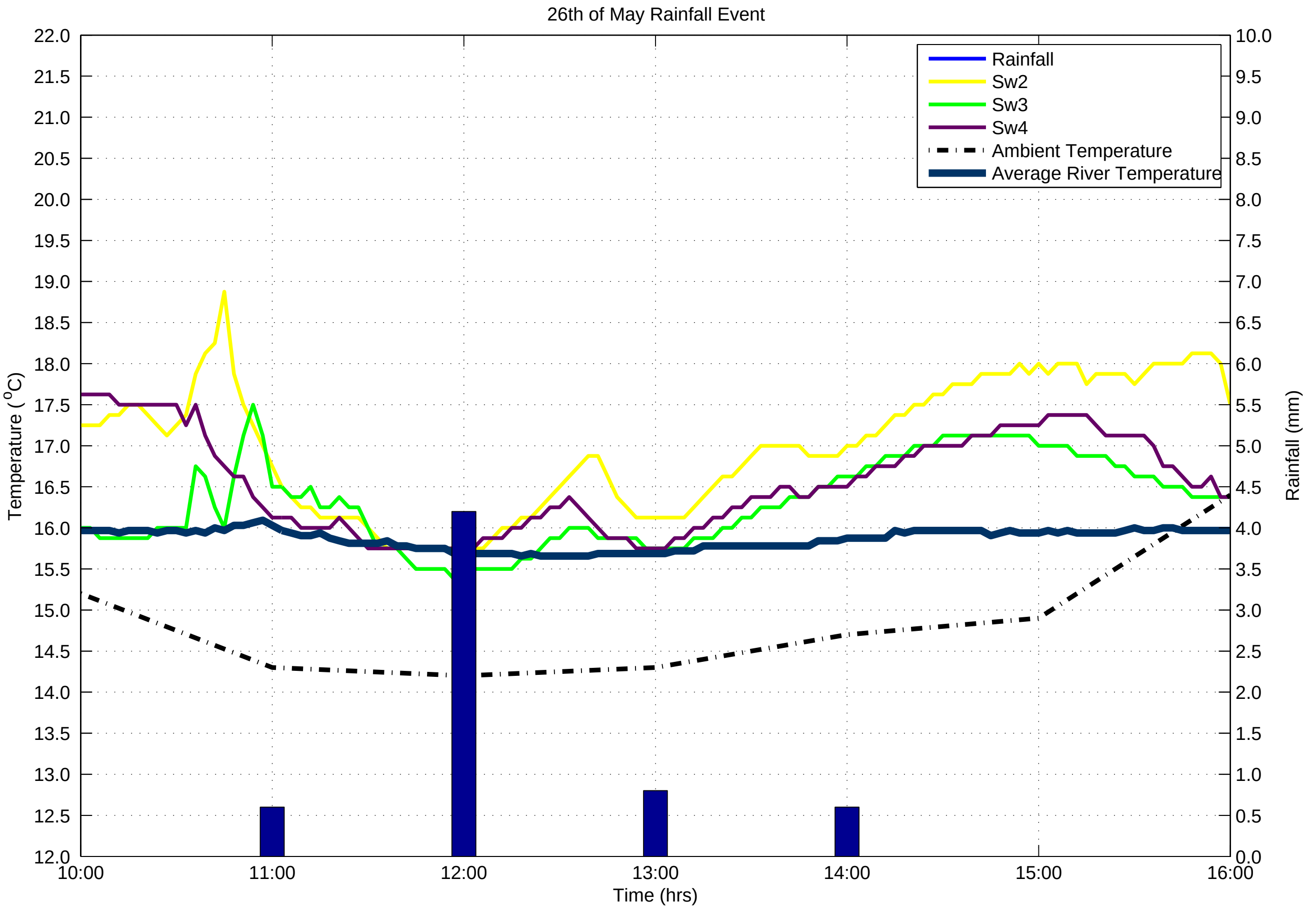

Figure G.1: 26th May Rainfall Event

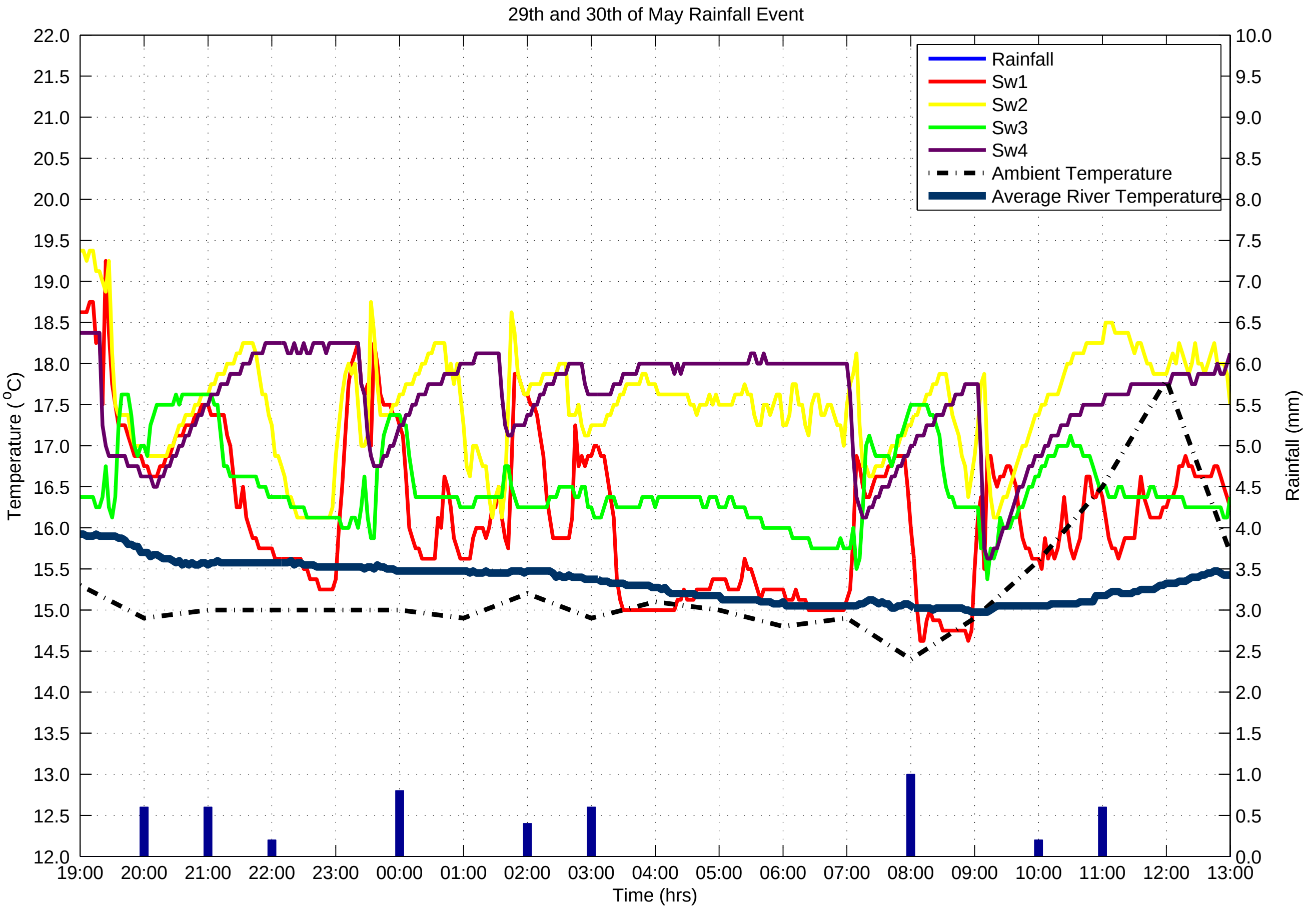

Figure G.2: 29th and 30th May Rainfall Event

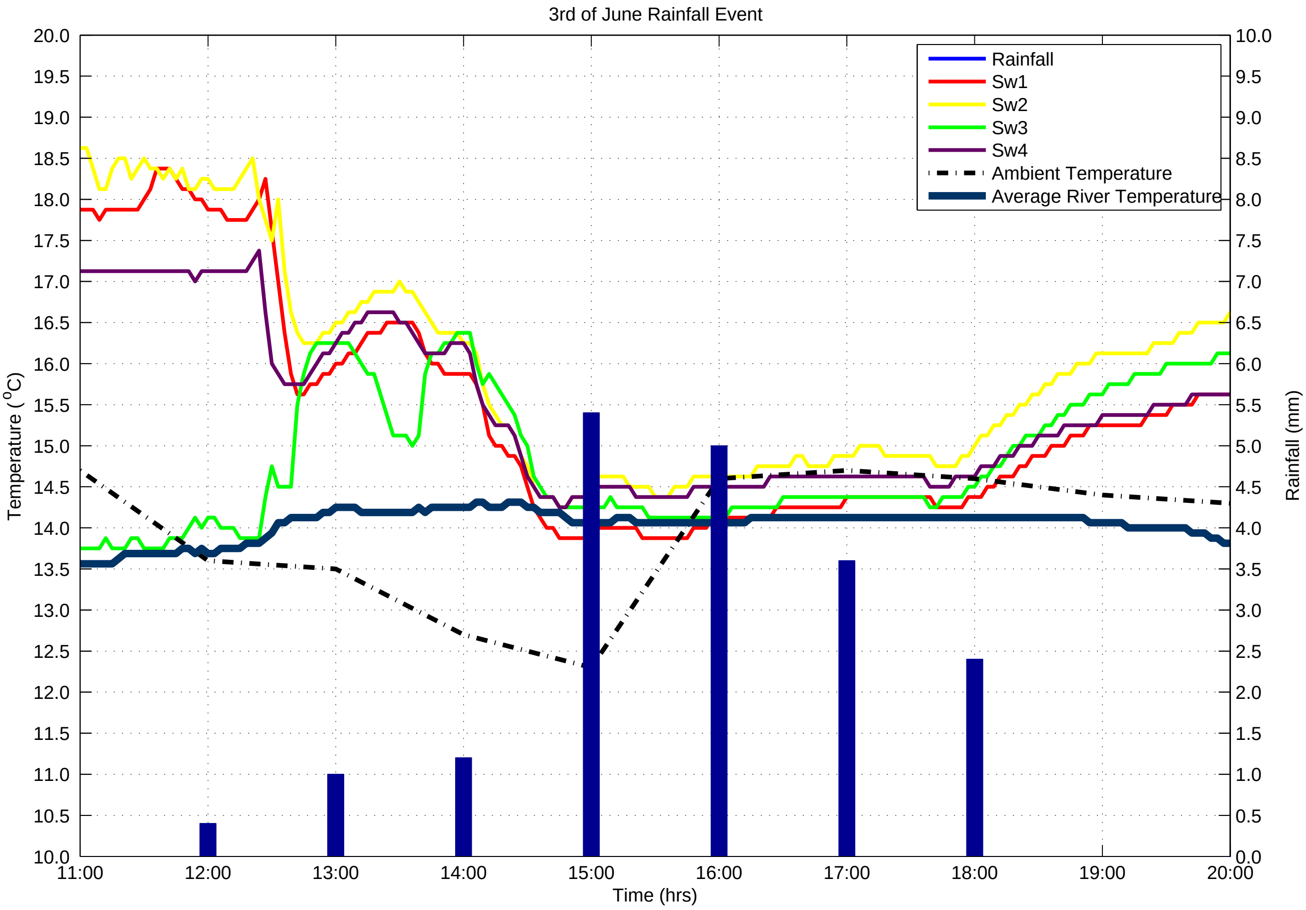

Figure G.3: 3rd June Rainfall Event

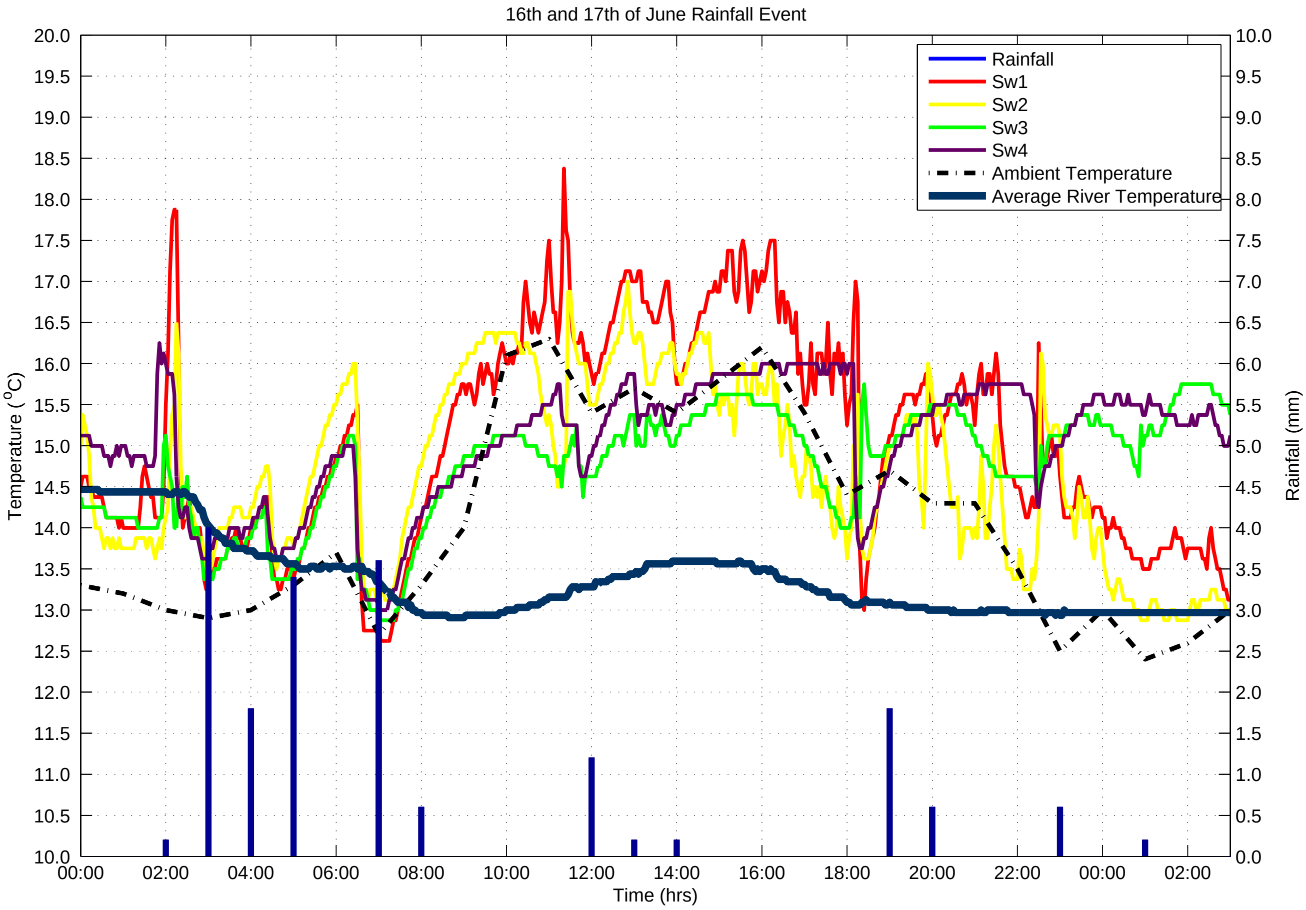

Figure G.4: 16th and 17th June Rainfall Event

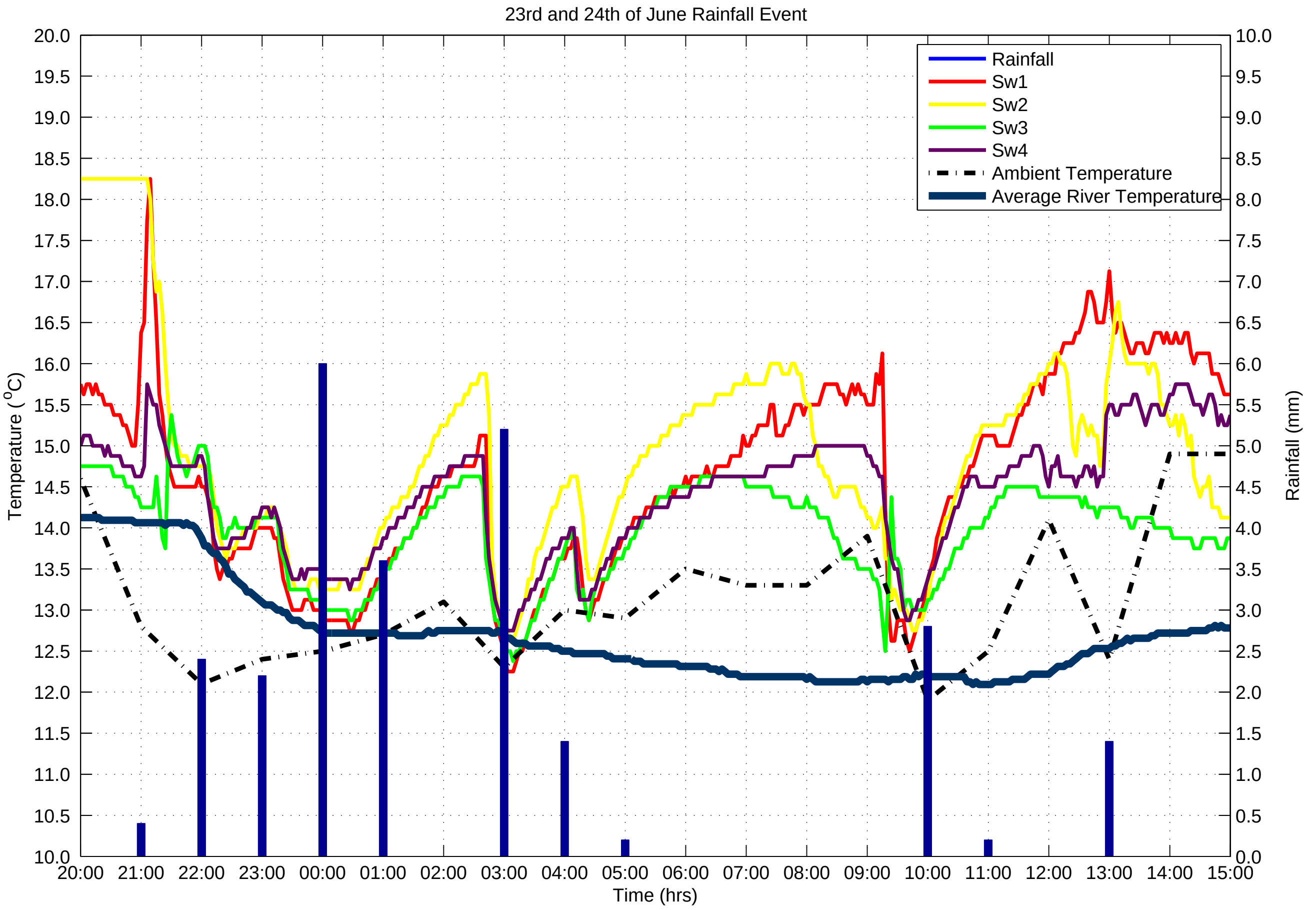

Figure G.5: 23rd and 24th June Rainfall Event

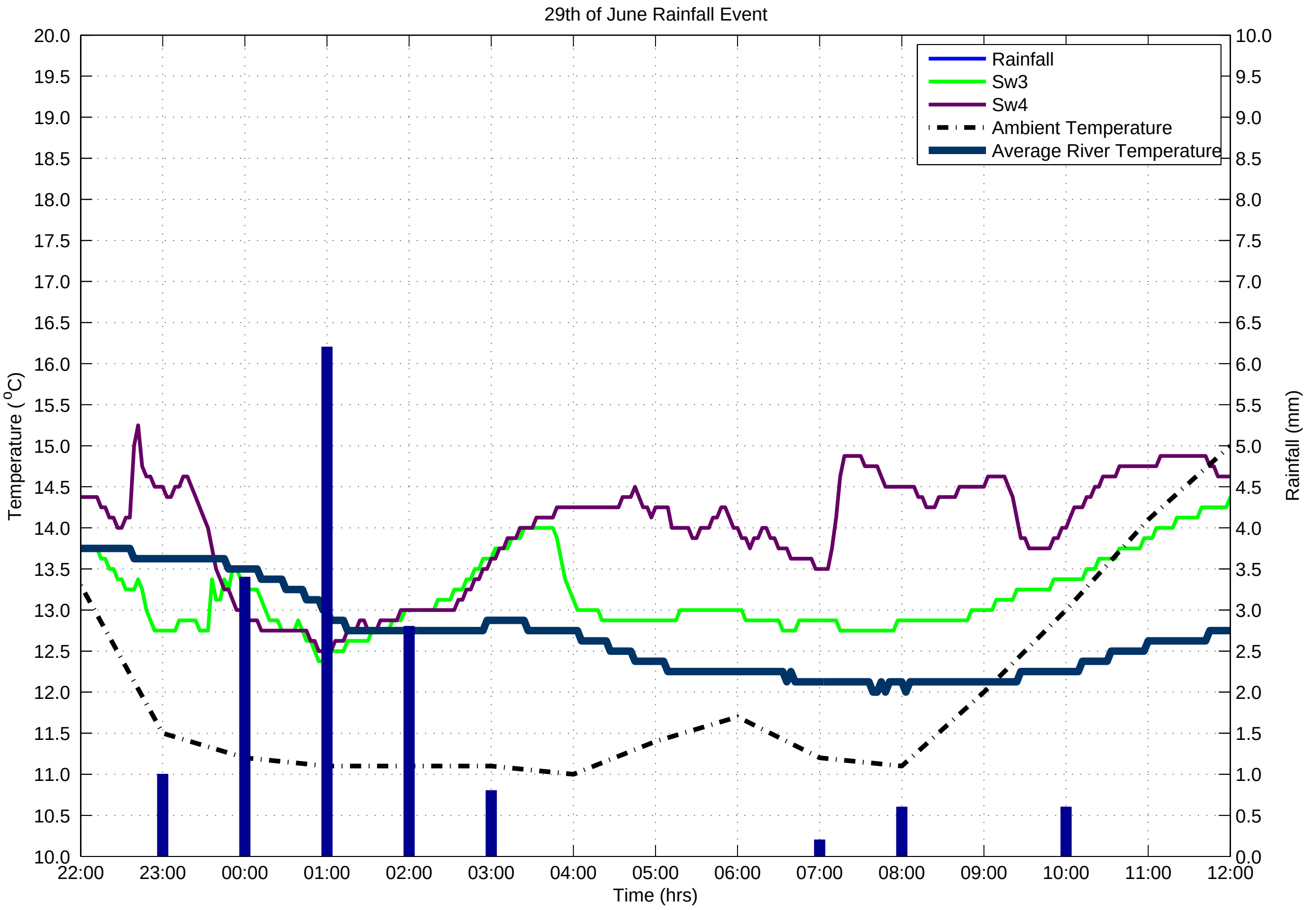

Figure G.6: 29th June Rainfall Event

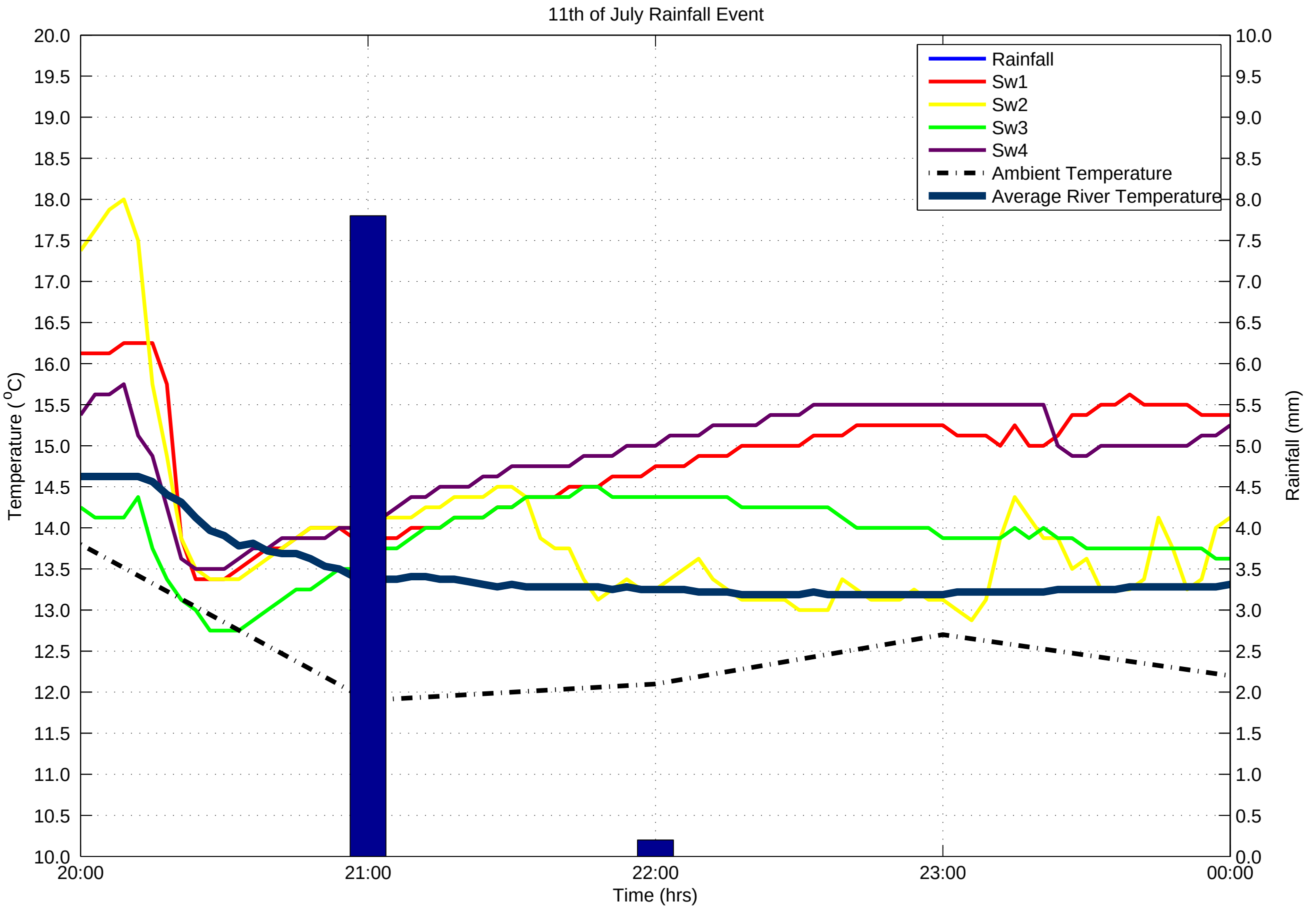

Figure G.7: 11th June Rainfall Event

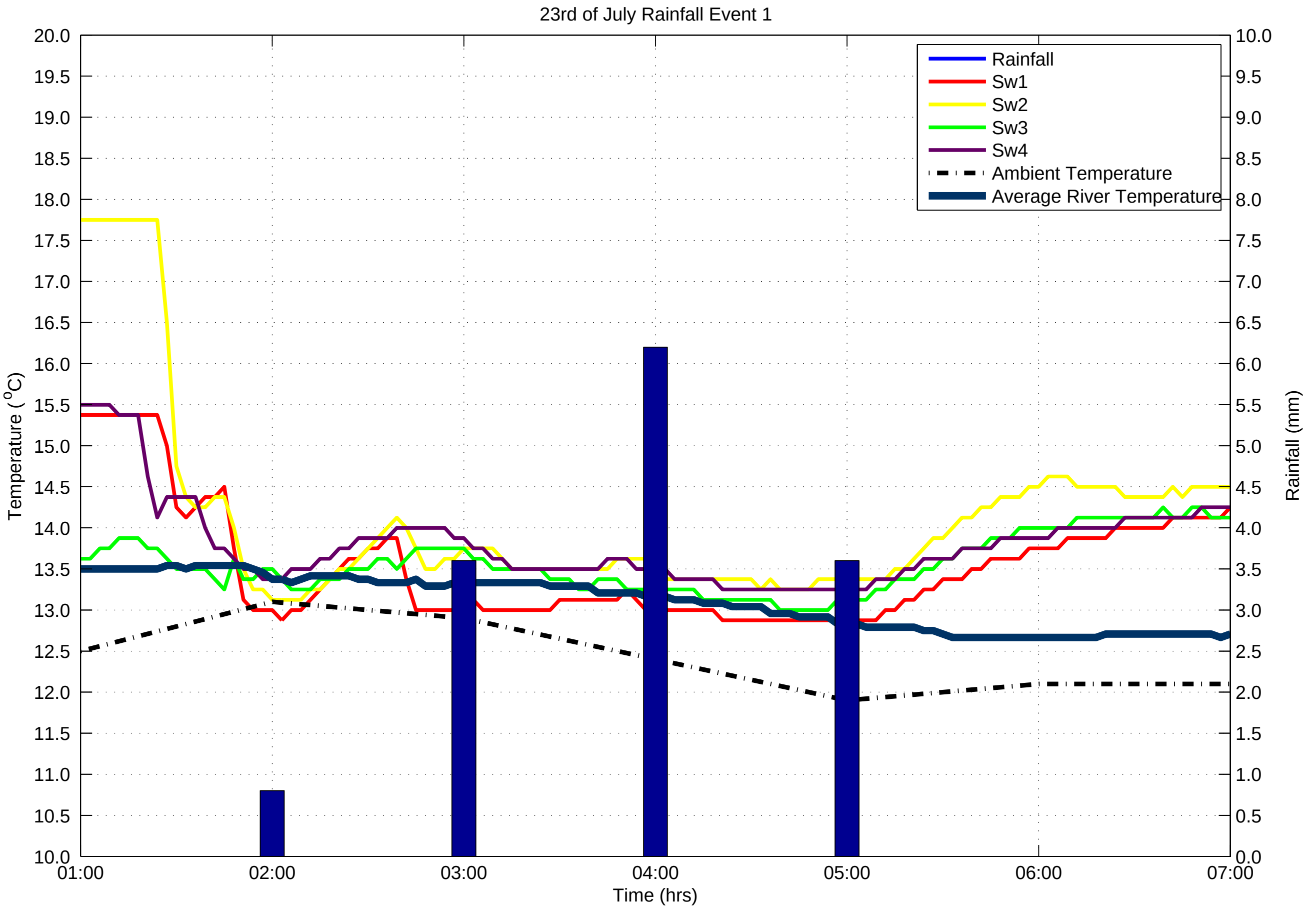

Figure G.8: 23rd July Rainfall Event 1

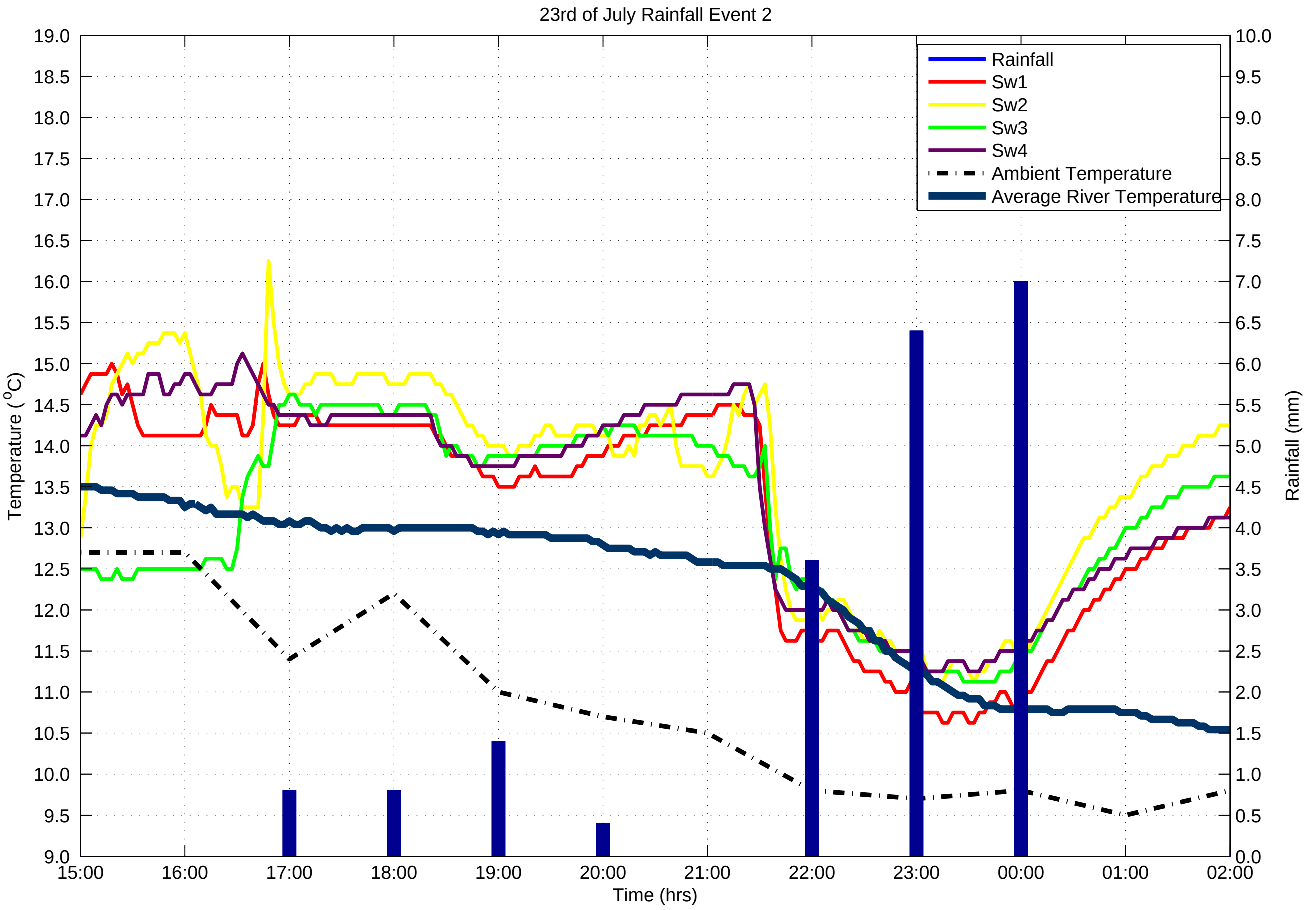

Figure G.9: 23rd July Rainfall Event 2

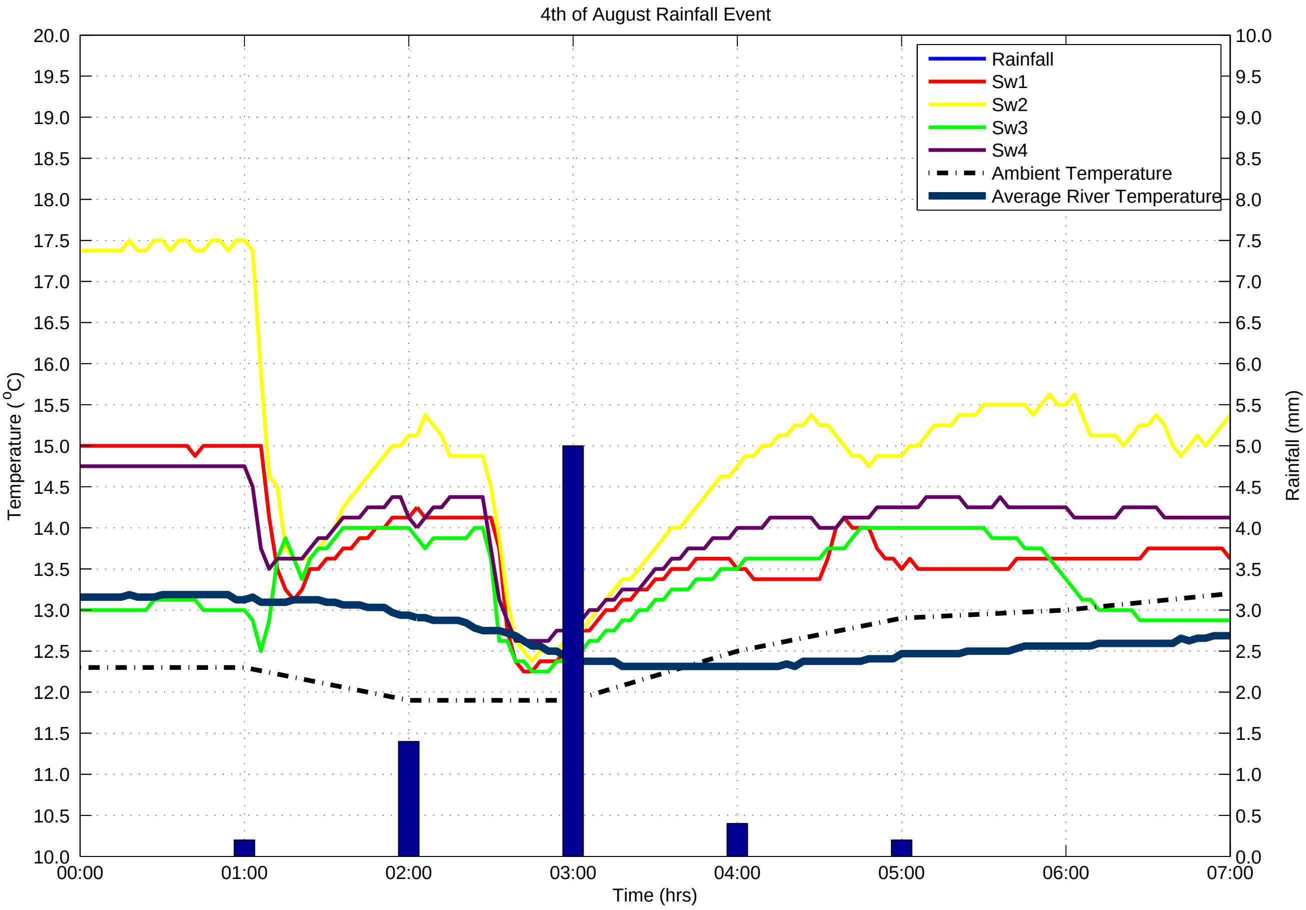

Figure G.10: 4th August Rainfall Event

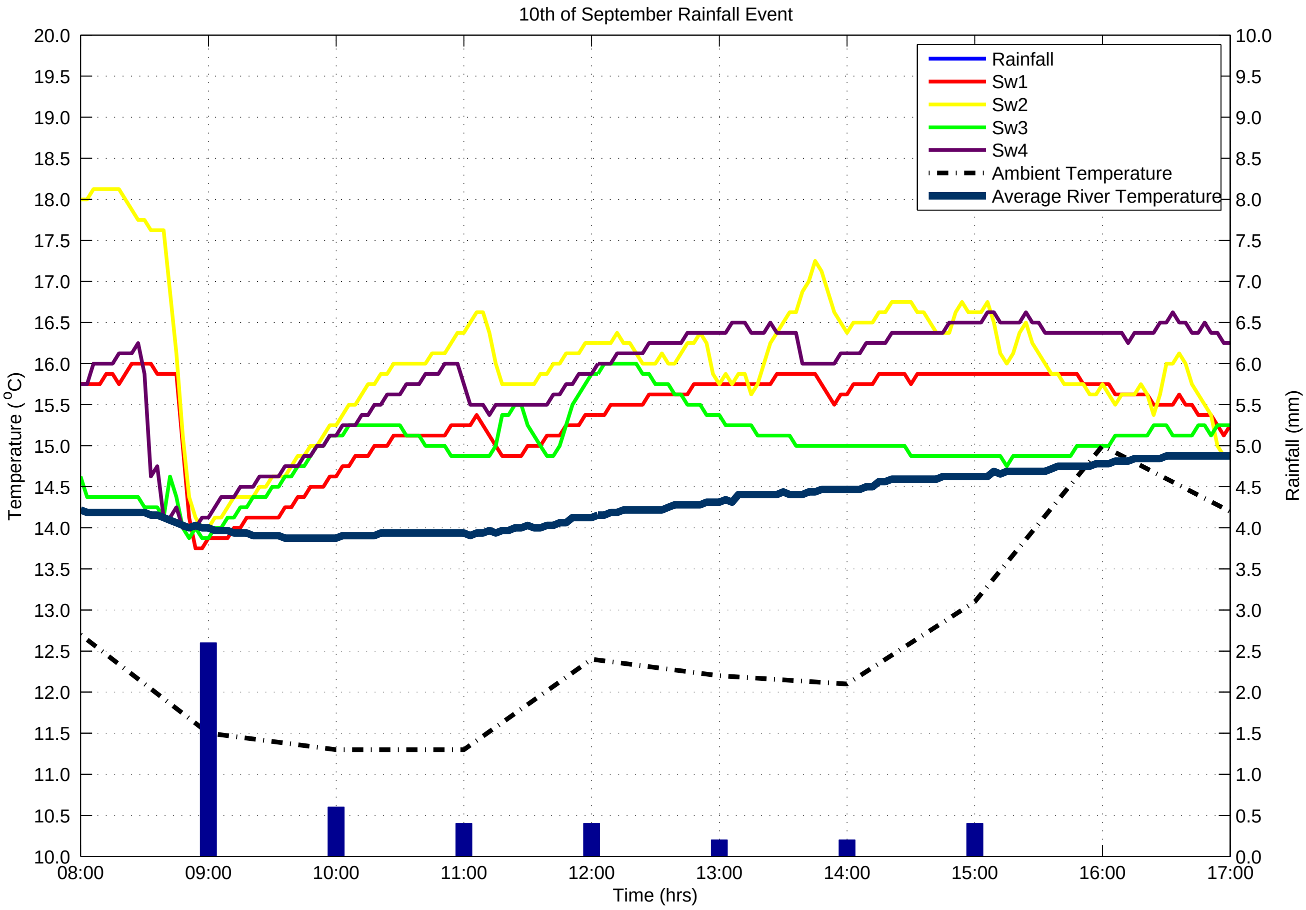

Figure G.11: 10th September Rainfall Event

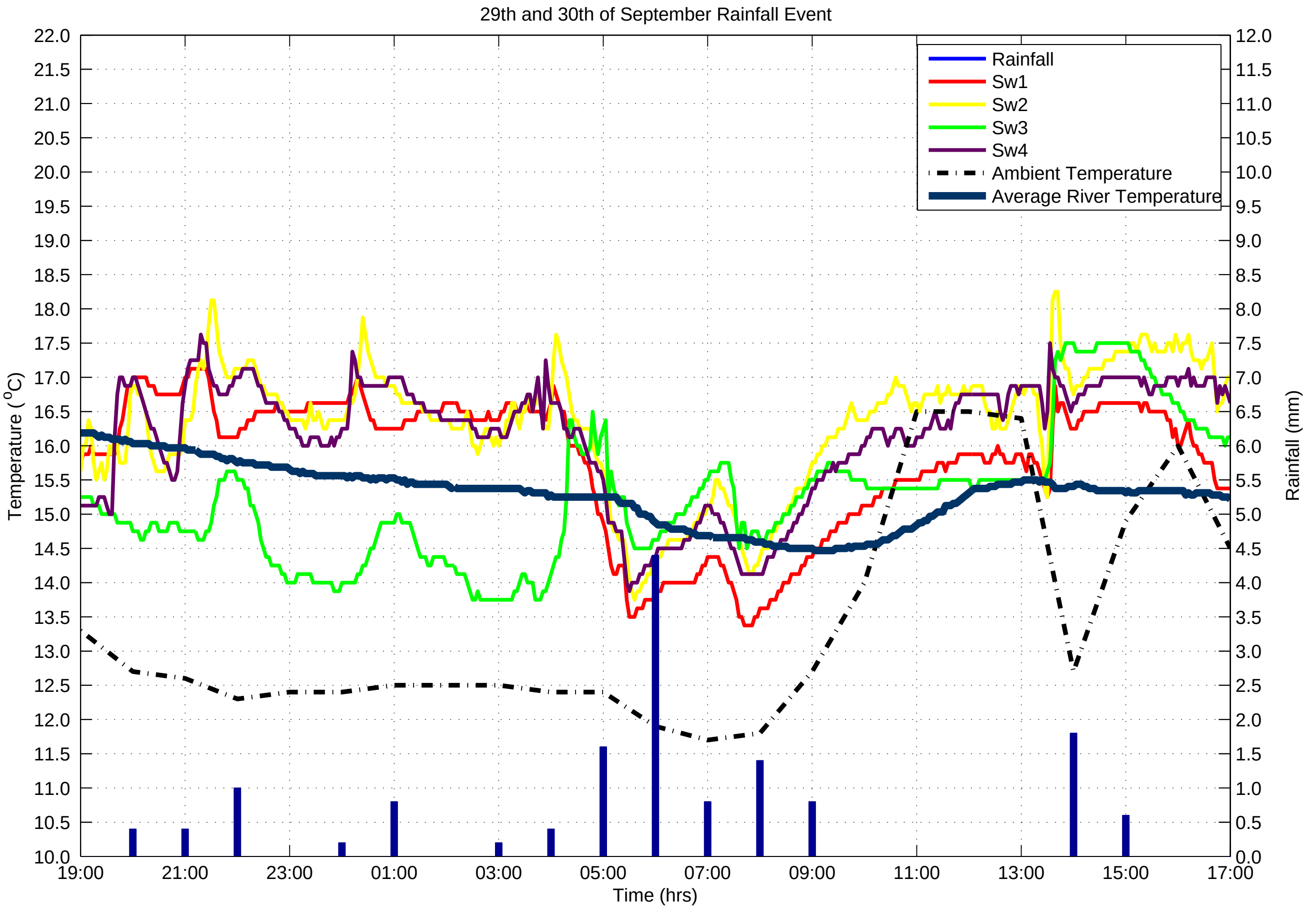

Figure G.12: 29th and 30th September Rainfall Event

Appendix H

Table 4.3 Enlarged

Event	1.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
Date	26th May	3rd June	16th June	23rd/24th June	28th/29th June	11th July	17th July	23rd July (1)	23rd July (2)	30th July	4th August	10th September	29th/30th September
01:00:00 AM				*	*					*	*		*
02:00:00 AM			*		*			*		*	*		
03:00:00 AM			*	*	*			*		*	*		*
04:00:00 AM			*	*				*		*	*		*
05:00:00 AM			*	*				*		*	*		*
06:00:00 AM										*			*
07:00:00 AM			*		*					*			*
08:00:00 AM			*		*								*
09:00:00 AM												*	*
10:00:00 AM				*	*							*	
11:00:00 AM	*			*								*	
12:00:00 PM	*	*	*									*	
01:00:00 PM	*	*	*	*								*	
02:00:00 PM	*	*	*									*	*
03:00:00 PM		*											*
04:00:00 PM		*					*						
05:00:00 PM		*					*		*				
06:00:00 PM		*					*		*				
07:00:00 PM		*	*				*		*				
08:00:00 PM			*				*		*				*
09:00:00 PM				*		*	*						*
10:00:00 PM				*		*	*		*				*
11:00:00 PM			*	*	*		*		*				
12:00:00 AM				*	*		*		*				*

Table H.1: Summary showing all rain events, $*$ marks where rain occurred. Temperature Data was collected on all these occasions. See Appendix H for Enlarged Version of Table

Appendix I

Revisions Report

Table A: Revision Report, July 2016

Revision Number	Changes	Reason	Section/Page/Paragraph /Line
ABSTRACT			
1.	'Have' to 'Has'	Grammatical	Abstract/ Page ii/ Para 1/ Line 3
CHAPTER 1			
2.	'Have' to 'Has'	Grammatical	Section 1.1 / Page 1/ Para 2/ Line 2
3.	'Which' to 'That'	Grammatical	Section 1.1 / Page 3/ Para 3 / Line 6
4.	'Are being' to 'Will be'	Grammatical Logic	Section 1.1 / Page 4 / Para 2 / Line 1
5.	'reaches' to reach and 'encompasses' to 'encompass'	Grammatical	Section 1.7 / Page 12 / Para 1 / Line 1
6.	'Figure 1.2shows' to 'Figure 1.2 shows'	Formatting Inserted space	Section 1.7 / Page 12 / Para 2 / Line 1
7.	'Stretches' to 'Stretch' 'shows' to 'show'	Grammatical	Section 1.7 / Page 12 / Para 2 / Line 2
CHAPTER 2			
8.	'(Caissie, 2006)' to 'Caissie (2006)'	Grammatical	Section 2.1 / Page 16 / Para 1 / Line 4
9.	'permeate' to 'permeates'	Grammatical	Section 2.1 / Page 16 / Para 2 / Line 4
10.	'temperatures, these factors' to 'temperatures: these factors'	Grammatical Insert colon	Section 2.1 / Page 16 / Para 2 / Line 12
11.	'The removal of vegetation' to 'The removal of indigenous vegetation'	Missing Word	Section 2.1 / Page 18 / Para 4 / Line 1
12.	'where stream temperature' to 'where natural stream temperature'	Missing Word	Section 2.1.1 / Page 20 / Para 1 / Line 3
13.	'Page 5 (Young et al., 2013)' to '(Young et al., 2013: 5)'	Reference Formatting	Section 2.1.1 / Page 20 / Para 2 / Line 10

Revision Number	Changes	Reason	Section/Page/Paragraph /Line
14.	'there are a wide' to 'there is a wide'	Grammatical	Section 2.1.1 / Page 20 / Para 3 / Line 5
15.	'runoff is absorbs' to 'runoff is absorbed'	Grammatical	Section 2.1.1 / Page 21 / Para 3 / Line 4
16.	'interaction these' to 'interaction of these'	Missing Word	Section 2.1.1 / Page 21 / Para 3 / Line 14
17.	'(1990))' to '(1990)'	Removed duplicate bracket	Section 2.2.1 / Page 23 / Para 1 / Line 1
18.	Deleted space before full stop '. Dane' to '. Dane'	Formatting	Section 2.2.1 / Page 23 / Para3 / Line 3
19.	'However, unlike Dane County which experiences summer rainfall, Cape Town has a Mediterranean….'	Added Clarification	Section 2.2.1 / Page 23 / Para 3 / Line 6
20.	'due greater' to 'due to greater'	Missing Word	Section 2.2.1 / Page 23 / Para 4 / Line 3
21.	'In Cape Town' to 'Cape Town'	Deleted Word	Section 2.2.1 / Page 23 / Para 4 / Line 8
22.	'Using computer generated models a considerable amount of research has been completed in thermal enrichment of stormwater runoff by paved surfaces.'	Re-word Sentence	Section 2.2.2 / Page 24 / Para 3 / Line 5
23.	'cover, and' to 'cover, to'	Grammatical	Section 2.2.2 / Page 26 / Para 1 / Line 8
24.	'However, it is important to keep in mind that even small temperature differences can cause severe thermal impacts on stream biota.'	Re-word sentence	Section 2.2.2 / Page 26 / Para 1 / Line 14
25.	'more alike' to 'more similar'	Wording	Section 2.2.2 / Page 26 / Para 2 / Line 4
26.	From Table 2.2 above (Herb et al. 2007a)	Formatting Table Numbers	Section 2.2.2 / Page 26 / Para 3 / Line 1
27.	Table Heading: 'Table 2.2 Runoff Temperature and Surface Type adapted from Herb et al. (2007a)'	Reference	Section 2.2.2 / Page 26 / Table 2.2
28.	'roof' to 'roofs'	Grammatical	Section 2.2.2 / Page 27 / Para 3 / Line 8

Revision Number	Changes	Reason	Section/Page/Paragraph /Line
29.	'…concrete) this was' to '…..concrete), which was'	Grammatical	Section 2.2.2 / Page 27 / Para 3 / Line 11
30.	However, depending on which material is denser in structure this will result in a greater heat export per unit area.	Re-wording sentence	Section 2.2.2 / Page 27 / Para 3 / Line 14
31.	'solar energy can…' to 'solar energy, can…'	Grammatical Comma inserted	Section 2.2.2 / Page 27 / Para 3 / Line 17
32.	'temperature, they are' to 'temperature which are'	Grammatical	Section 2.2.2 / Page 28 / Para 3 / Line 4
33.	'temperature inputs, from' to 'temperature inputs from'	Grammatical Deleted comma	Section 2.2.3 / Page 29 / Para 1 / Line 8
34.	'from stormwater these' to 'from stormwater, these'	Grammatical Inserted comma	Section 2.2.3 / Page 29 / Para 1 / Line 8
35.	'Hence, indicating' to 'Hence, this indicates'	Grammatical participle to verb	Section 2.2.3 / Page 29 / Para 2 / Line 3
36.	'…sewer system, analysis' to '…sewer system. Analysis'	Grammatical full stop and new sentence	Section 2.2.3 / Page 29 / Para 4 / Line 6
37.	'and is strongly' to 'is strongly'	Grammatical deleted word	Section 2.2.3 / Page 30 / Para 2 / Line 4
38.	'temperatures, (from…' to 'temperatures (from…'	Grammatical deleted comma	Section 2.2.3 / Page 30 / Para 3 / Line 2
39.	'enrichment, from…' to 'enrichment from…'	Grammatical deleted comma	Section 2.2.3 / Page 30 / Para 4 / Line 9
40.	'and it's' to 'and its'	Grammatical deleted apostrophe	Section 2.2.3 / Page 31 / Para 1 / Line 2
41.	'criteria' to 'criterion'	Grammatical Plural to singular	Section 2.3 / Page 32 / Para 2 / Line 6
42.	'Firstly, acute criteria, which have' to 'Firstly, acute criteria have'	Grammatical Deleted word	Section 2.3 / Page 32 / Para 3 / Line 6
43.	'Short, lived' to 'short-lived'	Grammatical Hyphenated	Section 2.3 / Page 32 / Para 3 / Line 7
44.	'chronic criteria, which have' to 'chronic criteria have'	Grammatical Deleted word	Section 2.3 / Page 32 / Para 3 / Line 8

Revision Number	Changes	Reason	Section/Page/Paragraph /Line
45.	'ability to acclimate' to 'ability to acclimatise'	Grammatical	Section 2.3 / Page 32 / Para 4 / Line 3
46.	'increasing acclimation' to 'increasing acclimatization'	Grammatical	Section 2.3 / Page 32 / Para 4 / Line 5
47.	'criteria needs to' to 'criteria need to'	Grammatical Plural	Section 2.3 / Page 33 / Para 1 / Line 4
48.	'Critical thermal maximum' to 'Critical Thermal Maximum'	Grammatical Capital letters	Section 2.3 / Page 33 / Para 2 / Line 3
49.	'criteria, this is' to 'criteria which is'	Grammatical Sentence structure	Section 2.3 / Page 33 / Para 2 / Line 4
50.	'(Richardson et al., 1994) although they…' to ' (Richardson et al., 1994). Although they…'	Grammatical new sentence	Section 2.3 / Page 33 / Para 3 / Line 5
51.	'Each species provided' to 'each species, provided'	Grammatical insert comma	Section 2.3 / Page 34 / Para 1 / Line 10
52.	'with knock affects on' to 'with knock-on effects on'	Grammatical	Section 2.3 / Page 35 / Para 1 / Line 10
53.	'currently not part monitoring protocol.' to 'it is currently not included in water-monitoring protocol'	Grammatical Re-word Sentence	Section 2.4 / Page 36 / Para 1 / Line 2
54.	'protocol (...).' to 'protocol (Department of Water Affairs and Forestry, River Health Programme, 2005).'	Reference included	Section 2.4 / Page 36 / Para 1 / Line 2
55.	'Although, temperature' to 'Although temperature'	Grammatical Deleted Comma	Section 2.4 / Page 36 / Para 1 / Line 3
56.	'roofs. Although it is' to 'roofs. It is'	Grammatical Deleted word	Section 2.4 / Page 36 / Para 2 / Line 6
57.	'footpaths contributes' to 'footpaths, contributes'	Grammatical Inert Comma	Section 2.4 / Page 36 / Para 4 / Line 4
58.	'(solar reflectance)' to '(solar reflectance).'	Grammatical Insert full stop	Section 2.4 / Page 36 / Para 4 / Line 10

Revision Number	Changes	Reason	Section/Page/Paragraph /Line
59.	'stormwater management device, they are' to 'stormwater management device. They are'	Grammatical New sentence	Section 2.4 / Page 37 / Para 1 / Line 2
60.	'act' to 'acts'	Grammatical Plural	Section 2.4 / Page 37 / Para 1 / Line 11
59.	'stormwater management device, they are' to 'stormwater management device. They are'	Grammatical New sentence	Section 2.4 / Page 37 / Para 1 / Line 2
60.	'act' to 'acts'	Grammatical Plural	Section 2.4 / Page 37 / Para 1 / Line 11
61.	'radiation exacerbating' to 'radiation, exacerbating	Grammatical Inert comma	Section 2.4 / Page 37 / Para 1 / Line 11
62.	'stormwater it further increases' to 'stormwater, but it further increases'	Grammatical Re-word sentence	Section 2.4 / Page 37 / Para 2 / Line 3
63.	'(Sabouri et al., 2013). Careful re-designing' to '(Sabouri et al., 2013), or careful re-designing'	Grammatical Re-word sentence	Section 2.4 / Page 37 / Para 3 / Line 4
64.	'and Cooling trenches' to 'Cooling trenches'	Grammatical Lower case	Section 2.4 / Page 38 / Final bullet point / Line 10
65.	'impervious surfaces and can compromise' to 'impervious surfaces can compromise'	Grammatical Deleted word	Section 2.4 / Page 38 / Para 2 / Line 4
66.	'or sub-surface device, even discharging' to 'or sub-surface device. Furthermore, discharging'	Grammatical New sentence	Section 2.4 / Page 38 / Para 2 / Line 6
67.	'pollutant, in the age of cities and urbanisation is critical' to 'pollutant is critical'	Grammatical Deleted words	Section 2.4 / Page 38 / Para 3 / Line 1

Revision Number	Changes	Reason	Section/Page/Paragraph /Line
68.	'resilience. Ones' to 'resilience, ones'	Grammatical Comma instead of full stop	Section 2.4 / Page 38 / Para 3 / Line 6
CHAPTER 3			
69.	'trends, these' to 'trends, which'	Grammatical	Section 3.1 / Page 39 / Para 2 / Line 10
70.	'road network etc.' to 'road network.'	Grammatical Deleted word	Section 3.1 / Page 39 / Para 2 / Line 12
71.	'out compete' to 'out-compete'	Grammatical Insert hyphen	Section 3.2 / Page 40 / Para 2 / Line 5
72.	'Observatory, have' to Observatory, has'	Grammatical	Section 3.2 / Page 40 / Para 2 / Line 8
73.	'Liesbeek River in' to 'Liesbeek River, in'	Grammatical Insert comma	Section 3.2 / Page 40 / Para 2 / Line 13
74.	Table Reference (Table adapted from: Department of Water Affairs and Forestry, River Health Programme, 2005)	Reference	Section 3.2 / Page 41 / Table 3.1 and Table 3.2
75.	'Created by A. Crisp, Quantum GIS Development, 2009'	Source of Satellite Figure: Reference	Section 3.2 / Page 43 / Figure 3.1
76.	Table Reference: (Table adapted from: Fairbridge Technologies, 2010)	Reference	Section 3.3 / Page 48 / Table 3.6
77.	'Deployment,' to 'Deployment:'	Grammatical inserted colon	Section 3.4.2 / Page 50 / Para 3 / Line 1
78.	'All data' to 'The data'	Grammatical Plural	Section 3.4.3 / Page 51 / Para 1 / Line 5
79.	'in depth' to 'in-depth'	Grammatical hyphen	Section 3.4.6 / Page 54 / Para 2 / Line 1
80.	'study area. One which' to 'study, one which'	Grammatical comma	Section 3.5.2 / Page 57 / Para 2 / Line 12
81.	'A study by Picksley and Deletic et al. (1999)' to 'Picksley and Deletic (1999)'	Grammatical	Section 3.5.2 / Page 57 / Para 2 / Line 15

Revision Number	*Changes*	*Reason*	*Section/Page/Paragraph /Line*
82.	‘study did experienced limitations’ to ‘study experienced limitations’	Grammatical	Section 3.5.2/ Page 57 / Para 2 / Line 19
83.	‘Recorded in this study. As well as’ To ‘recorded in this study, nor was’	Grammatical Sentence structure	Section 3.5.2 / Page 58 / Para 1 / Line 2
84.	‘i.e. peak flow rate would occur shortly after peak rainfall ’ to ‘i.e. peak flow rate would occur shortly after peak rainfall but pervious and vegetated surfaces (and other SUDS) could delay peak flow significantly.	Grammatical	Section 3.5.2 / Page 58 / Para 1 / Line 10
85.	‘However, investigating the relationship’ to ‘However, investigating these relationships’	Grammatical	Section 3.5.2 / Page 58 / Para 1 / Line 11
86.	stormwater (young et al.,2013) was deleted	Grammatical Reference deleted	Section 3.5.2 / Page 58 / Floating Reference
87.	Deleted paragraph	Deleted duplication	Section 3.5.2 / Page 58 / Para 2
88.	Deleted pages	Deleted pages duplication	Section 3.5.2 / Page 59 and Page 60
		CHAPTER 4	
89.	‘temperature data of the river were monitored’ to ‘temperature data of the river was monitored’	Grammatical Singular	Section 4.1 / Page 61 / Para 1 / Line 8
90.	‘in the river channel across the’ to ‘in the river channel along the’	Grammatical wording	Section 4.1 / Page 61 / Para 1/ Line 9
91.	‘six iButton loggers, this’ to ‘six iButton loggers: this’	Grammatical Insert colon	Section 4.1 / Page 61 / Para1 / Line 11
92.	‘parcel drainage area, for’ to ‘parcel drainage area for’	Grammatical Deleted comma	Section 4.1 / Page 61 / Para 3 / Line 1

Revision Number	***Changes***	***Reason***	***Section/Page/Paragraph /Line***
93.	Figure 4.1: Reference: Created by A. Crisp Using Quantum GIS Development (2009)	Inserted Reference	Section 4.2/ Page 63/ Figure 4.1
94.	'in terms of their size, the length' to 'in terms of its size, the length'	Grammatical	Section 4.2 / Page 63/ Para 1 / Line1
95.	'the western boarder' to 'the western border'	Grammatical	Section 4.2 / Page 63 / Para 1 / Line 4
96.	The zoning layers which were used provided a high-level, generalised representation of area characteristics. The objective of this analysis… A more direct method would be simply to analyse satellite images of the area and confirm ambiguous examples by site inspection.	Insert Justification	Section 4.2.1 / Page 64 / Para 4
97.	'Rosebank, this is' to 'Rosebank, which is'	Grammatical	Section 4.2.1 / Page 66 / Para 2 / Line 4
98.	'provides as a buffer' to 'provides a buffer'	Grammatical Deleted word	Section 4.2.1 / Page 66/ Para 2 / Line 6
99.	'residential land use' to 'residential land use.'	Grammatical Insert Full stop	Section 4.2.1 / Page 66/ Para 2/ Line 9
100.	Paragraphs moved to below image 4.5	Paragraphs moved	Section 4.2.1 / Page 67 / Para 1 and Para 2
101.	'of 27%, this' to 'of 27%, which'	Grammatical	Section 4.2.1 / Page 67 / Para 2 / Line 4
102.	'hours where rain fell' to 'hours in which rain fell'	Grammatical	Section 4.3 / Page 69/ Para 1 / Line 2
103.	'morning where river' to 'morning when river'	Grammatical	Section 4.3 / Page 69/ Para 1 / Line 4
104.	'evening where river' to 'evening when river'	Grammatical	Section 4.3/ Page 69/ Para 1/ Line 6

Revision Number	***Changes***	***Reason***	***Section/Page/Paragraph /Line***
105.	Table 4.3 reference: (Created by A. Crisp (2016))	Reference	Section 4.3 / Page 70 / Table 4.3
106.	Deleted paragraphs duplication	Deleted Paragraphs duplication	Section 4.3 / Page 70 / Paragraphs 1 and 2
107.	‘and this is evident at all three stormwater pipe outlets’ to ‘ and this is evident at two of the three stormwater pipe outlets’	Justification	Section 4.3.1 / Page 72/ Para 3/ Line 2
108.	The ‘ “spike:’ to the “spike”	Insert inverted comma	Section 4.3.1 / Page 74 / Para 1/ Line 9
109.	‘stormwater outlets. Meaning’ to ‘stormwater outlets, meaning’	Grammatical Inserted Comma	Section 4.3.1 / Page 74 / Para 2/ Line 15
110.	An explanation for this double spike in temperature could be that the first is the result of runoff from the roads and other ground-level surfaces, while the second peak is from the building roofs, from which the water needs to be channelled through the buildings' own rainwater systems e.g. gutters, downpipes. The South African stormwater approach is directly associated with removing rainwater from roads as efficiently as possible. All other sources of water entering the piped network are secondary and would therefore take much longer to reach the system.	Explanation Added	Section 4.3.1/ Page 74 / Para 2 / Line 16
111.	‘11am and 12noon, the’ To ‘11am and 12 noon: the	Grammatical Inserted Colon	Section 4.3.2 / Page 76 / Para 1/ Line 2

Revision Number	Changes	Reason	Section/Page/Paragraph /Line
112.	'types, has a significant' to 'types have a significant'	Grammatical	Section 4.3.2 / Page 76 / Para 3/ Line 3
113.	However, a suit of temperature loggers placed along the entire river stretch upstream of the study area would be needed. The single upstream temperature logger which was placed and the captured data were not reliable to confirm this inference.	Explanation	Section 4.3.2/ Page 77 / Para 1/ Line 8
114.	'begins to rise, at 3pm' to 'begins to rise, with a peak at 3pm'	Grammatical	Section 4.3.2 / Page 77 / Para 2 / Line 1
115.	'temperature. Once surfaces' to 'temperature, once surfaces'	Grammatical Cont. sentence comma inserted	Section 4.3.2 / Page 77/ Para 2/ Line 5
116.	Error, Figure 4.11 replaced	Figure Error Fig. 4.11 replaced	Section 4.3.3 / Page 78/ Figure 4.11
117.	The catchment parcel for outlet 3 most closely resembles a natural regime, with mostly residential and gardens areas. By 8pm, many of the surfaces in this area may have already cooled to ambient levels, depending on materials. For example, a metal roof loses its heat very quickly after sunset. A possible explanation would be the temperature of the rain itself was probably several degrees colder than the river temperature. The rainfall temperature could be a useful measurement to capture in future research.	Explanation added	Section 4.3.3 / Page 79 / Para 2/ Line 3

Revision Number	***Changes***	***Reason***	***Section/Page/Paragraph /Line***
118.	'was consistent for all' to 'was continuous for all'	Grammatical	Section 4.3.4 / Page 80/ Para 1/ Line 7
119.	'recordings, all closely track each other.' to 'closely tracks all the others.'	Grammatical	Section 4.3.4/ Page 80 / Para 2/ Line 3
120.	'there are a series' to 'there is a series'	Grammatical	Section 4.3.4/ Page 81/ Para 1/ Line 6
121.	'progresses, in total' to 'progresses: in total'	Grammatical Insert colon	Section 4.3.4/ Page 81 / Para1/ Line 7
122.	'knock on effect, increased' to 'knock-on effect: increased'	Grammatical Insert hyphen and colon	Section 4.3.4/ Page 81 / Para 2/ Line 17
123.	'event around' to 'event, around'	Grammatical Insert comma	Section 4.3.4 / Page 81 / Para 3 / Line 2
124.	'12midnight' to 'midnight'	Grammatical Deleted number	Section 4.3.5/ Page 83 / Para 1/ Line 2
125.	'fell, this would' to 'fell, which would'	Grammatical	Section 4.3.5 / Page 83/ Para 1/ Line 4
126.	'trends can be seen in stormwater temperature.' To 'can trends be seen in stormwater temperature.'	Grammatical	Section 4.3.5 / Page 83/ Para 1/ Line 6
127.	'day light' to 'daylight'	Grammatical	Section 4.3.5/ Page 84 / Para 1 / Line 8
128.	However, a more detailed analysis of the in-river data as well as the inlets, using additional temperature loggers would be required to confirm this.	Explanation added	Section 4.3.5 / Page 84/ Para 1 / Line 24
129.	'section data' to 'section, data'	Grammatical Comma inserted	Section 4.3.5 / Page 85 / Para 1/ Line 1
130.	'was 12°C. Whereas' to 'was 12°C, whereas'	Grammatical Comma cont. sentence	Section 4.4 / Page 86 / Para 1/ Line 8

Revision Number	Changes	Reason	Section/Page/Paragraph /Line
131.	‘This means that at outlet site 4 there are larger temperature fluctuations, in response to rainfall.’ to ‘At outlet site 4 there is a larger temperature range, in response to rainfall.’	Grammatical Re-word sentence	Section 4.4 / Page 86 / Para 1 / Line 10
132.	‘and this would not be a response to rainfall.’ To ‘river water temperature would be primarily influenced by air temperature, however, one would expect rainfall temperature to also have a smaller but significant influence.’	Expanded Explanation	Section 4.4/ Page 86 / Para 2/ Line 4
133.	‘Outlet pipe 3, exhibits the closest mean, hourly temperature recordings when compared to mean river water temperature recordings.’ To ‘Outlet pipe 3 exhibits the closest mean hourly temperature recordings when compared to mean river water temperature recordings.’	Grammatical Deleted commas	Section 4.4 / Page 86 / Para 2 / Line 4 and 5
134.	‘(this is less than mean river water temperature)’ to ‘This is less than mean river water temperature and could be attributed to the ambient temperature of the rainfall.’	Expanded Explanation	Section 4.4 / Page 86/ Para 2 / Line 7
135.	‘confidence level, Figure’ to ‘confidence level: Figure’	Grammatical Insert colon	Section 4.4 / Page 86/ Para 3/ Line 1
136.	‘findings, from’ to ‘findings from’	Grammatical Deleted comma	Section 4.4 / Page 86 / Para 4/ Line 1
137.	‘rainfall events, mean, hourly, stormwater’ to ‘rainfall events, mean hourly stormwater’	Grammatical Deleted commas	Section 4.4 / Page 88/ Para 2/ Line 4

Revision Number	***Changes***	***Reason***	***Section/Page/Paragraph /Line***
138.	(Table ??) to (Table 4.4)	Inserted table number	Section 4.4 / Page 88/ Para 3/ Line 2
139.	‘stormwater, at each’ to ‘stormwater at each’	Grammatical Deleted comma	Section 4.4/ Page 90 / Para 2 / Line 7
140.	‘From Table 4.4 for’ to ‘From Table 4.4, for’	Grammatical Insert comma	Section 4.4 / Page 90/ Para 2/ Line 8
141.	‘Although’ the plot to ‘The plot’	Grammatical Deleted word	Section 4.4 / Page 91 / Para 1/ Line 2
142.	‘The plot demonstrates a sinusoidal relationship’ sentence deleted	Deleted Sentence	Section 4.4 / Page 91 / Para 2 / Line 2
143.	‘than if the exact same event’ to ‘than if an identical event’	Grammatical	Section 4.4 / Page 91 / Para 2 / Line 8
144.	Title Heading Change 4.5 Discussion Continued To 4.5 Key Findings	Heading Change	Section 4.5 / Page 91 / Heading 4.5
145.	‘lower temperatures, measured’ to ‘lower temperatures measured’	Grammatical Delete comma	Section 4.5.1/ Page 92/ Para 1 / Line 5
146.	‘associated to the’ to ‘associated with the’	Grammatical	Section 4.5.1 /Page 92/ Para 1/ Line 5
147.	‘In addition, the road network length is considerably short therefore’ to ‘In addition, the road network was shorter than in the other three parcels, therefore’	Grammatical Sentence re-structure	Section 4.5.1 / Page 92/ Para 2/ Line 6
148.	‘length (Table **??**).’ to ‘length (Table 4.2).’	Table number inserted	Section 4.5 / Page 93 / Para 2 / Line 2

Revision Number	**_Changes_**	**_Reason_**	**_Section/Page/Paragraph /Line_**
149.	‘One significant feature of the total road network is a large contribution of the length is in fact a national highway. This stretch of extensive road is drained into outlet pipe 2.’ To ‘This is a significant feature of parcel area 2, a large contribution of this total length is attributed to the national highway and this stretch of extensive road drains directly into outlet pipe 2.’	Grammatical Re-worded sentence	Section 4.5 / Page 93/ Para 2/ Line 2
150.	‘asphalt surface exhibit’ to ‘asphalt surfaces exhibit’	Grammatical plural	Section4.5 / Page 93 / Para 2/ Line 6
151.	‘Furthermore, it is important to note the lack of shading of the highway in comparison with narrow roads, shaded by buildings and/or trees could contribute to higher discharge temperatures.’	Additional explanation	Section 4.5 / Page 93 / Para 2 / Line 9
152.	‘Table **??**’ to ‘Table 4.2’	Table Number inserted	Section 4.5.1 / Page 93 / Para 4 / Line 4
153.	‘variables such as, amount’ to ‘variables such as amount’	Grammatical Deleted comma	Section 4.5.1/ Page 94 / Para 1/ Line 2
154.	‘events1, 2 and 3’ ‘events 1, 2 and 3’	Grammatical Insert space	Section 4.5.1 / Page 94 / Para 2 / Line 3
155.	‘time of day whether’ to ‘time of day, whether’	Grammatical Comma inserted	Section 4.5.1 / Page 94 / Para 3 / Line 1
156.	‘Additional, general temperature’ to ‘General temperature’	Grammatical Deleted word	Section 4.5.1 / Page 94 / Para 3 / Line 7
157.	‘temperature spikes, it displayed’ to ‘temperature spikes: it displayed’	Grammatical Insert colon	Section 4.5.1 / Page 95/ First bullet point
158.	‘would not allow reduce surface-water’ to ‘would not allow surface-water’	Grammatical Deleted word	Section 4.5.1 / Page 95 / Second bullet point

Revision Number	Changes	Reason	Section/Page/Paragraph /Line
159.	'Newly wetted areas will increase thermal loading, there will be a delay before this runoff reaches the discharge site.' To 'All surfaces would be wetted simultaneously in small parcel catchment areas, but the runoff rate and volume would vary, depending on surface characteristics (e.g. perviousness, roughness) reaching saturation at differing rates, including man-made systems (gutters, etc.). The diversity in surface type would result in temperature pulses. This is different from the largely homogenous surface type found in the parcel 2 catchment area.'	Expanded Explanation	Section 4.5.1 / Page 95 / Third bullet point
160.	'water temperature. Thereby, confirming' to 'water temperature, thereby, confirming'	Grammatical Comma and cont. sentence	Section 4.5 2/ Page 95 / Para1 / Line 6
161.	'relationship, as rainfall' to 'relationship: as rainfall'	Grammatical Insert colon	Section 4.5.2 / Page 96/ Bullet Point 1
149.	'One significant feature of the total road network is a large contribution of the length is in fact a national highway. This stretch of extensive road is drained into outlet pipe 2.' To 'This is a significant feature of parcel area 2, a large contribution of this total length is attributed to the national highway and this stretch of extensive road drains directly into outlet pipe 2.'	Grammatical Re-worded sentence	Section 4.5 / Page 93/ Para 2/ Line 2
150.	'asphalt surface exhibit' to 'asphalt surfaces exhibit'	Grammatical plural	Section4.5 / Page 93 / Para 2/ Line 6
151.	'Furthermore, it is important to note the lack of shading of the highway in comparison with narrow roads, shaded by buildings and/or trees could contribute to higher discharge temperatures.'	Additional explanation	Section 4.5 / Page 93 / Para 2 / Line 9
152.	'Table **??**' to 'Table 4.2'	Table Number inserted	Section 4.5.1 / Page 93 / Para 4 / Line 4

Revision Number	Changes	Reason	Section/Page/Paragraph /Line
153.	‘variables such as, amount’ to ‘variables such as amount’	Grammatical Deleted comma	Section 4.5.1/ Page 94 / Para 1/ Line 2
154.	‘events1, 2 and 3’ ‘events 1, 2 and 3’	Grammatical Insert space	Section 4.5.1 / Page 94 / Para 2 / Line 3
155.	‘time of day whether’ to ‘time of day, whether’	Grammatical Comma inserted	Section 4.5.1 / Page 94 / Para 3 / Line 1
156.	‘Additional, general temperature’ to ‘General temperature’	Grammatical Deleted word	Section 4.5.1 / Page 94 / Para 3 / Line 7
157.	‘temperature spikes, it displayed’ to ‘temperature spikes: it displayed’	Grammatical Insert colon	Section 4.5.1 / Page 95/ First bullet point
158.	‘would not allow reduce surface-water’ to ‘would not allow surface-water’	Grammatical Deleted word	Section 4.5.1 / Page 95 / Second bullet point
159.	‘Newly wetted areas will increase thermal loading, there will be a delay before this runoff reaches the discharge site.’ To ‘All surfaces would be wetted simultaneously in small parcel catchment areas, but the runoff rate and volume would vary, depending on surface characteristics (e.g. perviousness, roughness) reaching saturation at differing rates, including man-made systems (gutters, etc.). The diversity in surface type would result in temperature pulses. This is different from the largely homogenous surface type found in the parcel 2 catchment area.’	Expanded Explanation	Section 4.5.1 / Page 95 / Third bullet point
160.	‘water temperature. Thereby, confirming’ to ‘water temperature, thereby, confirming’	Grammatical Comma and cont. sentence	Section 4.5 2/ Page 95 / Para1 / Line 6
161.	‘relationship, as rainfall’ to ‘relationship: as rainfall’	Grammatical Insert colon	Section 4.5.2 / Page 96/ Bullet Point 1

Revision Number	Changes	Reason	Section/Page/Paragraph /Line
CHAPTER 5			
162.	‘rainfall, this is due’ to ‘rainfall, which is due’	Grammatical	Section 5.1 / Page 98 / Para 1/ Line 3
163.	‘(Young et al., 2013) All’ to ‘(Young et al., 2013). All’	Grammatical Inserted full stop	Section 5.1 / Page 98 / Para 2 / Line 3
164.	‘highest, observed’ to ‘highest observed’	Grammatical Deleted comma	Section 5.1 / Page 99 / Para 1 / Line 4
165.	‘would concern aquatic biota’ to ‘would affect aquatic biota’	Grammatical	Section 5.1 / Page 99 / Para 2/ Line 4
166.	‘service provided’ to ‘services provided’	Grammatical plural	Section 5.1/ Page 99/ Para 4 / Line 7
167.	‘network, in this’ to ‘network in this’	Grammatical Deleted comma	Section 5.1 / Page 100/ Para 1/ Line 6
168.	‘temperatures, at these’ to ‘temperatures at these’	Grammatical Deleted comma	Section 5.1 / Page 100 / Para 2 / Line 6
169.	‘In Addition, the’ to ‘In addition, the’	Grammatical Lower case	Section 5.1/ Page 100/ Para 2/ Line 6
170.	‘system. Firstly, reduction’ to ‘system, firstly, reduction’	Grammatical Comma and cont. sentence	Section 5.1 / Page 101 / Para 1/ Line 8
171.	study, are: bullet points inserted	Bullet points inserted	Section 5.2 / Page 102 / Bullet points inserted
172.	‘were measure’ to ‘were measured’	Grammatical Tense	Section 5.2 / Page 102/ Second bullet point/ Line 2

Revision Number	***Changes***	***Reason***	***Section/Page/Paragraph /Line***
173.	‘Similarly, to the omission’ to ‘Similar to the omission’	Grammatical	Section 5.2 / Page 102/ Fourth bullet point/ Line 1
174.	‘associated to accuracy’ to ‘associated with accuracy’	Grammatical	Section 5.2 / Page 102 / Fifth bullet point/ Line 2
175.	‘would be, to undertake’ To’ would be to undertake’	Grammatical Deleted comma	Section 5.2/ Page 103/ first bullet point/ Line 4
176.	‘Nevertheless, an increased’ to ‘Moreover, an increased’	Grammatical	Section 5.2 / Page 103 / Second bullet point/ Line 7
177.	‘studies. For example’ to ‘studies, for example’	Grammatical Insert comma and cont. sentence	Section 5.2 / Page 103 / Para3 / Line 4
178.	‘,globally and’ to ‘,globally, and’	Grammatical Inserted Comma	Section / Page 104 / Para 1 / Line 4

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APPENDICES			
1.	Appendix C- Replaced Figure – Working Example of ColdChain Interface	Corrected Duplication	Page 124
2.	Added Appendix I – Revisions Report	Additional Appendix	Page 153