A Climate Adaptation Plan: Identifying Thermal Refugia for Salmonids in the Tsolum River

by

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Approval

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Abstract

Stream temperatures in the Pacific Northwest are increasing due to climate change, resulting in thermal stress for salmonids. Groundwater is a cooler source of water into streams, providing thermal refugia. The goal of this Applied Research Project was to identify groundwater input areas in the Tsolum River, using temperature loggers to trace the thermal signal of groundwater. A total of 28 water temperature loggers and 2 air temperature loggers were deployed within the watershed in the summer of 2019. Results showed that 12 sites may be influenced by groundwater input. Restoration/management actions such as riparian planting, gravel bar live staking, and restrictions on groundwater withdrawal are recommended to decrease stream temperatures. This study demonstrated that temperature loggers can be deployed within streams to identify areas of groundwater input. The identification of thermal refugia within the Tsolum River and other salmonid-bearing streams will help to protect salmonids from climate change impacts.

Keywords: Thermal Refugia; Tsolum River; Groundwater; Climate Adaptation

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Looking upstream at W18-2019 in the Tsolum River on July 5, 2019.

Chapter 1.

Introduction

Temperature is a significant contributor to stream habitat quality, as increasing temperatures can lead to reductions in native salmonid populations (Poole et al. 2001). Even an increase in temperature as small as 2-3°C has been shown to impair salmonid fitness throughout their thermally sensitive life stages (Poole et al. 2001). Further, it is likely that climate change will exert a dramatic adverse effect on Pacific salmon and their habitats (Beechie et al. 2012). Mean air temperatures in the Comox Valley region are expected to increase by 1.5°C by the 2050s, compared to 1961-1990 baseline temperatures (Pacific Climate Impacts Consortium 2012). At the same time, mean summer precipitation in the Comox Valley region is expected to decrease by 17%, with winter and spring snowfall decreasing by 36% and 52%, respectively (Pacific Climate Impacts Consortium 2012). Although it has been shown that there is the potential for Pacific salmon species to adapt and acclimate to increasing water temperatures, there is a limit to this adaptability and the rate of temperature change may be higher than the adaptation capacity of salmonids (Munoz et al. 2015). As such, mitigating against increases in stream temperatures will be crucial to the survival of salmon in the Pacific Northwest (PNW; Munoz et al. 2015).

Regressional analyses for the PNW have shown that one of the primary components that influences thermal regimes in the summer is baseflow index (the amount of groundwater influence; Mayer 2012). Groundwater tends to be a cooler input of water into the stream in the summer and a warmer input of water into the stream in the winter (Risley et al. 2010; Mayer 2012). The average annual temperature of shallow groundwater (between 10 to 25 m deep) is typically 1-2ºC higher than the average annual air temperature for the area (Heath 1983). Since the average annual air temperature at the Comox A weather station is 10ºC, it is expected that the average annual groundwater temperature for the area should be 11-12ºC (Government of Canada 2019a). Due to the stable temperatures, groundwater discharges into streams are key components of appropriate thermal habitat for aquatic organisms, including fish (Chu et al. 2008). Groundwater impacts the reproduction, habitat use, productivity, behaviour, and mobility of fish (Power et al. 1999). Areas of the stream that have groundwater input are considered thermal refugia for cold water species, such as salmon and trout (Chu et al. 2008). Fish actively search for these thermal refugia in both the summer and winter months (Power et al. 1999; Mayer 2012). For example, it has been shown that juvenile coho are more abundant in areas of groundwater input in the interior of BC compared to areas without groundwater input (McGrath & Walsh 2012). These thermal refugia may allow cold water fish species to survive the effects of climate change (Briggs et al. 2018). Drone surveys have shown that thermal patterns (both warming and cooling) in streams are typically constant throughout multiple years of surveys, indicating that areas of cool water (thermal refugia) typically persist throughout time (Faux et al. 2001).

Native salmonids in the PNW are cold-blooded fish, and as such, water temperature affects their distribution, health, and survival by controlling their behaviour and physiology (Poole et al. 2001). Temperatures that exceed species-specific thresholds of salmonids can negatively affect their abundance and health, and can even cause mortality (Poole et al. 2001). Therefore, salmon utilize the temporally and spatially heterogeneous conditions of streams in which they live to regulate their body temperature to stay within their thermal tolerances (Poole et al. 2001). Restoration actions that decrease temperatures within the stream and create thermal refugia for fish will likely be the most successful and effective as the climate changes and stream and air temperatures continue to increase (Beechie et al. 2012). The temperature thresholds for each of the Pacific salmon species are listed in Table 1.1 (Beechie et al. 2012).

Table 1.1 Temperature thresholds (°C) for Pacific salmon species.

Life Stage	Threshold Level	Chinook	Chum	Coho	Pink	Sockeye
Adult migration	Lethal threshold	22	21	21	-	-
Adult holding and spawning	Optimal threshold	14.5	12.8	15.6	-	-
Incubation and early fry development	Upper threshold	14.5	10	12	12	12.5
	Optimal Threshold	14.8	15	17	-	-
Juvenile	Lethal threshold	-	21	23	-	20
Rearing	Upper zero net growth	24	19.8	23.4	21	-

Beechie et al. 2012 – Data for table from Bjornn and Reiser 1991, Eaton and Scheller 1996, McCullogh et al. 2001, and Richter and Kolmes 2005.

1.1. Study Area

This temperature study was conducted on the Tsolum River, which is located in Courtenay, British Columbia, on the east coast of Vancouver Island (Figure 3.1). The Tsolum River is approximately 30 km long, originating on Mount Washington and flowing into the Puntledge River in Courtenay, slightly upstream of the K'ómoks estuary (Hamilton et al. 2008; Phippen & Obee 2012). The Tsolum River watershed is 248 km^2 (Metherall 2019). There are multiple tributaries that feed into the Tsolum River, including Murex Creek, Portuguese Creek, Headquarters Creek, and Dove Creek (Phippen & Obee 2012). There are a number of lakes and swamps in the upper and mid-watershed that contribute to the river flow and act as water storage areas (Metherall 2019). These include Regan Lake, Blue Grouse Lake, Anderson Lake, Little Lost Lake, Dover Lake, Lost Lake, and McKay Lake (Metherall 2019). The Tsolum River watershed is within the K'ómoks First Nation Unceded Traditional Territory, and was a source of plentiful food and resources for thousands of years prior to European settlement and logging (D.R. Clough Consulting 2014).

The land within the watershed is mostly privately owned, with the lands upstream of Headwaters Creek mainly owned by forestry companies and the land between Headquarters Creek and Dove Creek mainly owned by private residents for agricultural and residential use (Phippen & Obee 2012). Closer to the Comox harbour, the land surrounding the Tsolum River and its tributaries is mainly higher density residential and commercial land use (Phippen & Obee 2012).

The lower section of the Tsolum River watershed is within the Coastal Western Hemlock (Eastern very dry maritime, variant CWHxm1) biogeoclimatic zone and becomes the CWHxm2 variant at an elevation of approximately 400 m (Phippen & Obee 2012). Above an elevation of 600 m, the biogeoclimatic zone is CWHmm2, which is the windward moist montane variant (Phippen & Obee 2012). Higher up in the watershed, the biogeoclimatic zones are the Mountain Hemlock (windward moist montane variant, MHmm1) above 800 m, and the Coastal Mountain-heather Alpine (CMAunp) above 1,200 m in elevation (Phippen & Obee 2012). The upper watershed is within the Leeward Island Mountains (LIM) ecoregion and the lower watershed is within the Nanaimo Lowland (NAL) ecoregion (Phippen & Obee 2012).

There are four aquifers within the Tsolum River watershed, of which two are unconsolidated aquifers, comprising of sand and gravel (Aquifers 408 and 952), one is a bedrock aquifer (Aquifer 413), and one is a confined aquifer comprising of sand and gravel layers between glacial till (Tsolum Aquifer TS-2; Metherall 2019). Aquifer 408 consists of Quadra sand, which is well-sorted sand with some silt and gravel that was deposited in the area prior to the Fraser Glaciation (Clague 1976). This Quadra sand overlies marine and fluvial sediments deposited prior to the glacial period, and is overlain by till from the Fraser Glaciation (Clague 1976). Aquifer 952 consists of Capilano sediments, which are sands and gravels that were deposited in the region from fluvial outwash from the Vancouver Island mountain ranges, after the glacial period (Metherall 2019). Aquifers 408, 952, and 413 cover almost 20% of the Tsolum River watershed, with Aquifer 408 comprising the largest proportion (Figure 1.1). The Tsolum Aquifer TS-2, located on the east side of the Tsolum River overlaps with Aquifer 408 (closer to the surface) in some locations (Metherall 2019). There are two locations where it appears that the Tsolum Aquifer TS-2 may interact with the Tsolum River, potentially allowing for groundwater input in these locations. These two locations (W8-2019 and W16-2019) were selected as temperature monitoring sites as explained in Appendix A.

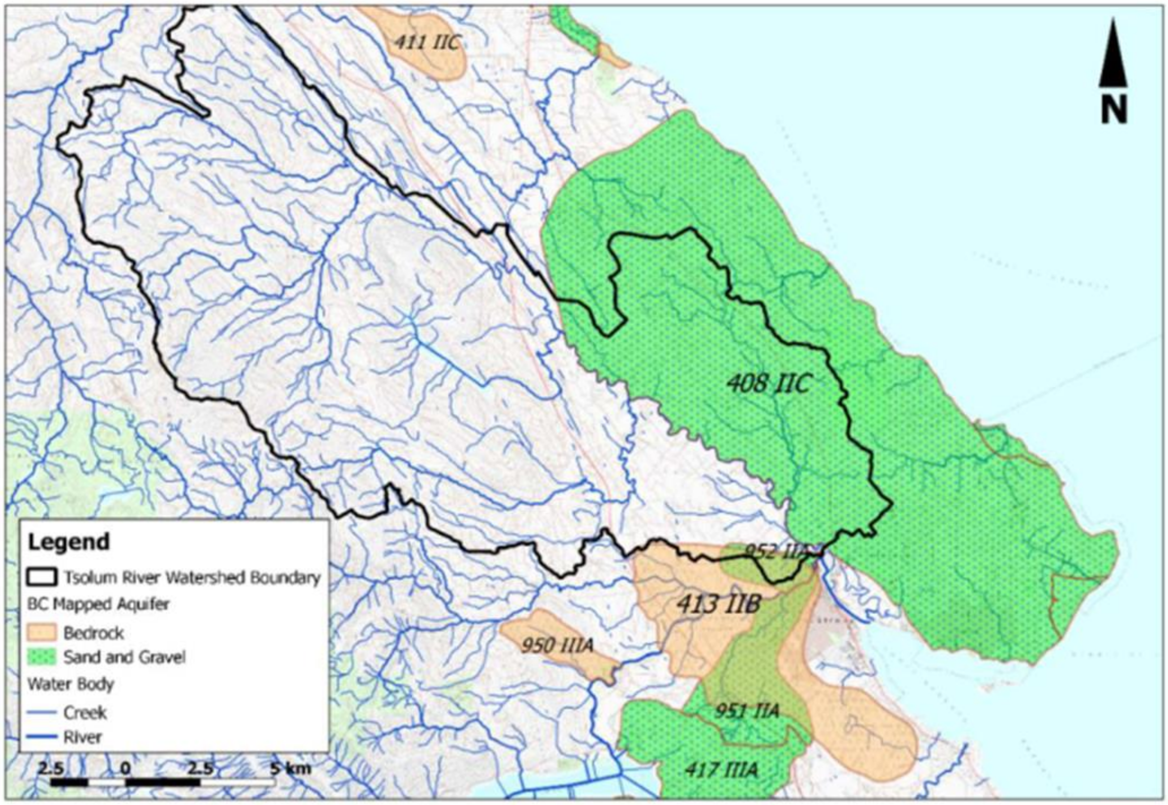

Figure 1.1 **Aquifers near the Tsolum River watershed, including Aquifers 408, 413, and 952 within the boundaries of the watershed according to iMap BC (Metherall 2019).**

The majority of flowing springs in the Tsolum River watershed are located within the Portuguese subwatershed, indicating that there are likely areas within Portuguese Creek that are influenced by groundwater input (Metherall 2019). The aquifer boundary assessment conducted by GW Solutions did not show any flowing springs directly adjacent to the Tsolum River (Metherall 2019). Previous flow and temperature measurements conducted in 2015 in the Tsolum River indicated that there may be groundwater inputs in the lower reaches of the river, which exhibit cooler water temperatures (Metherall 2019).

There are 500 groundwater wells within the boundaries of the watershed, with the deepest wells located on the east side of the river (Figure 1.2; Metherall 2019). The majority of groundwater wells within the watershed are relatively shallow (maximum depth of 20 m), where groundwater is extracted from surficial layers of sand and gravel rather than bedrock (Metherall 2019).

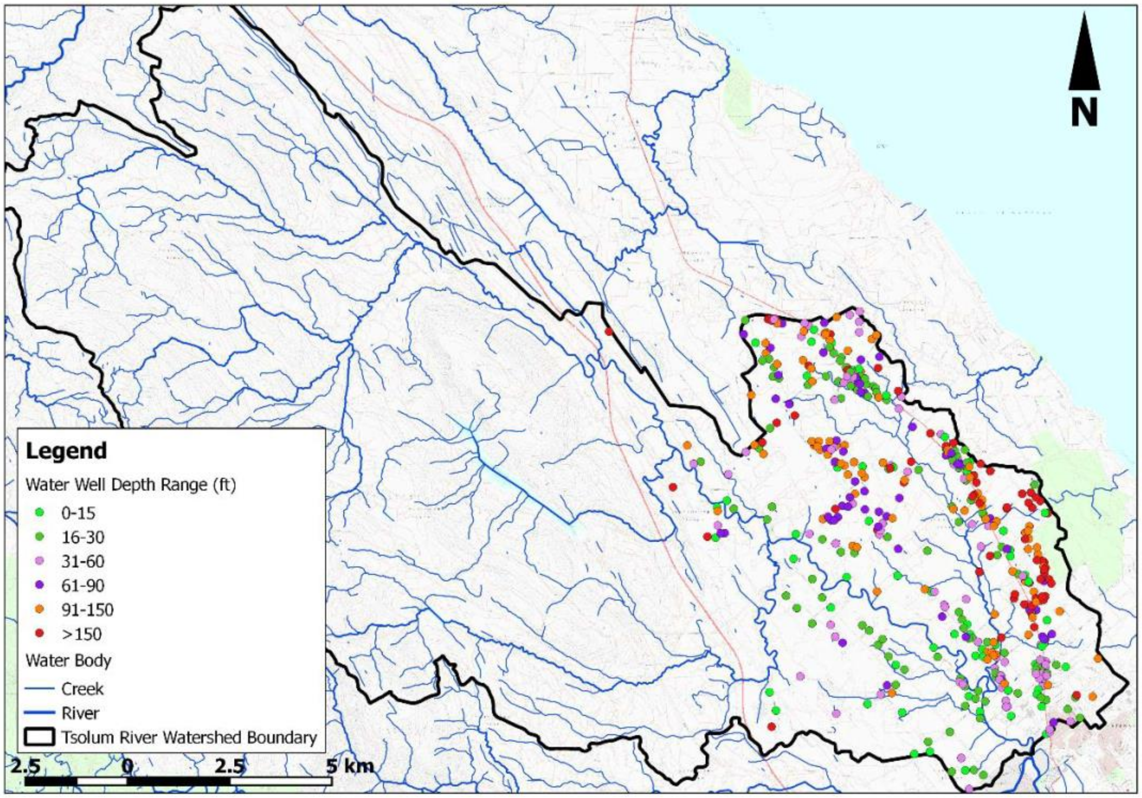

Figure 1.2 Groundwater wells located in the Tsolum River watershed (Metherall 2019).

As shown in Figure 1.2, most of the groundwater wells adjacent to the Tsolum River are shallow (0-15 m deep) and are located in the lower reaches of the channel, downstream of Headquarters Creek (Metherall 2019). As part of a groundwater study between Fanny Bay and Campbell River in 1979, multiple springs were identified to the east of the Tsolum River and around Portuguese Creek between the layers of thin marine-veneer and till (Zubel 1979). These springs have low flow, however the flow was determined to be adequate for domestic groundwater usage (Zubel 1979).

Precipitation in the form of rain is usually highest through the fall and winter months and lowest in the summer months in the Comox Valley, which is characteristic for the Coast Mountains and Island Physiographic Range (Figure 1.3; Moore et al. 2010; Government of Canada 2019a). The lowest flows in the river are typically in August and September, and as such, flows are augmented from Wolf Lake to maintain critical flow levels for salmonids (Phippen & Obee 2012).

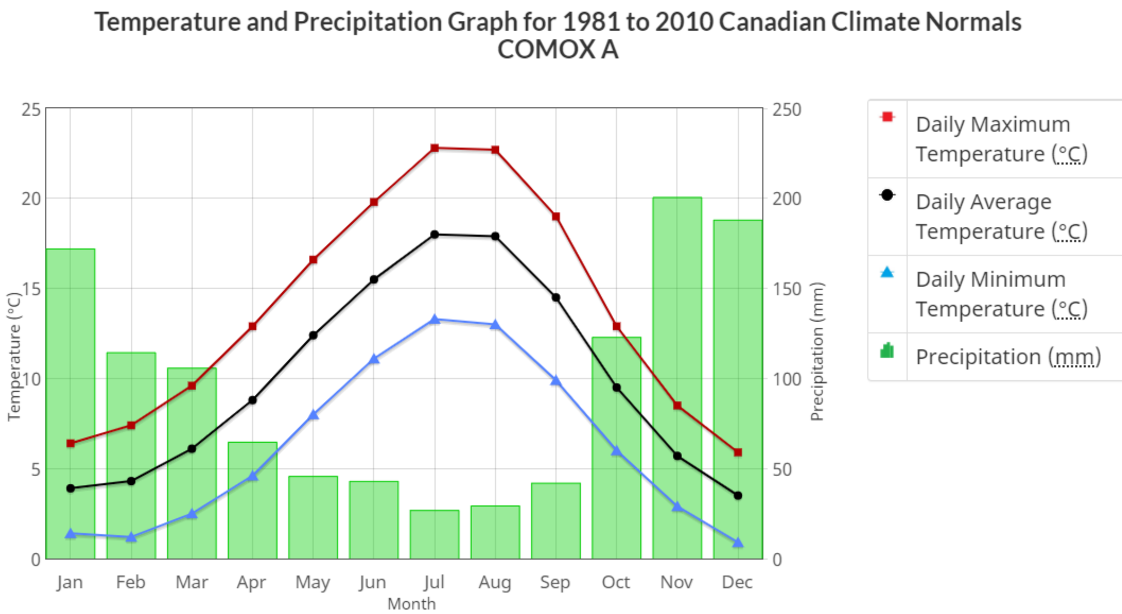

Figure 1.3 1981 to 2010 Canadian Climate Normals for the Comox A Station showing precipitation and temperature data (Government of Canada 2019a).

The watershed has multiple salmonid-bearing tributaries including Dove Creek, Murex Creek, Headquarters Creek, Hell Diver Creek, Constitution Creek, and Portuguese Creek (Spooner 2016). All five Pacific salmon species are present in the Tsolum River watershed, with pink salmon (*Oncorhynchus gorbuscha*) being the most common, followed by coho salmon (*O. kisutch*) and chum salmon (*O. keta*; Spooner 2016). Resident and anadromous rainbow and cutthroat trout (*O. clarkii*), Dolly Varden (*Salvelinus malma*), and three-spined stickleback (*Gasterosteus aculeatus*) are also present within the watershed (Phippen & Obee 2012). As such, the Tsolum River has an important fisheries value.

1.2. Historical and Current Conditions

There were declines in the salmon stocks in the Tsolum River by 1985, resulting from clear cut logging activity, development, and the Mount Washington copper mine (Campbell 1999; Hamilton et al. 2008). Logging that occurred in the 1950s increased peak flows and sediment input to the stream, causing redds to be smothered and benthic invertebrates to be killed (Campbell 1999). Vegetation removal from logging has been found to increase peak flows due to decreased evapotranspiration rates and altered snow accumulation (Jones & Grant 1996). Additionally, logging roads can alter flow pathways, by decreasing subsurface flows and increasing surface flows, resulting in increased delivery of storm water to stream channels (Jones & Grant 1996). The Tsolum River was dredged in the 1940s, with gravel removed from the lower reaches to construct the runway at the Canadian Forces Base (Campbell 1999). This resulted in a loss of spawning gravel for salmonids (Campbell 1999). Additionally, in 1985, it was discovered that acid mine drainage from the abandoned Mount Washington copper mine that operated from 1964 until 1967, as well as acid treatment for leaching copper from the ore on-site in the late 1970s had contaminated the watershed and resulted in a further decline of the salmon stocks (Campbell 1999). The Mount Washington mine site was remediated in 2009, decreasing copper levels and resulting in an increase in salmonid abundance (Spooner 2016). However, there are still many concerns for salmonids in the Tsolum River, specifically regarding high temperatures and low flows during the summer months.

Temperature was listed as one of the limiting factors to pink salmon production in the Tsolum River (Campbell 2010), and is likely also a limiting factor to the production of other Pacific salmonid and trout species. There are several possible factors that may be contributing to an increase in water temperature of streams within the Tsolum River watershed including water extraction, releasing water from Wolf Lake to increase downstream flows (flow augmentation), and the loss of riparian vegetation.

Both surface water and groundwater are being extracted from the Tsolum River, tributaries, and aquifers within the Tsolum River watershed (Phippen & Obee 2012). This may be increasing stream temperatures since the surface area to volume ratio of the stream increases as water is removed, leading to additional heat transfer between the atmosphere and stream surface (Risley et al. 2010). Stream temperatures may also increase when groundwater is removed since there is a loss in cool groundwater buffering the stream's temperature (Risley et al. 2010). There are 67 water licenses within the Tsolum River watershed, of which 56 are for surface water withdrawal and 11 are for groundwater withdrawal (Metherall 2019). The annual allowable withdrawal amount for all of these licenses combined is 287,668,004 m^3 (Metherall 2019). Of this total, 2,437,027 m^3 is for consumptive use and 285,230,977 m^3 is for non-consumptive use, as it is for Wolf Lake flow augmentation (Metherall 2019). Of the consumptive amount, 554,521 m^3 is for surface water extraction and 1,882,506 m^3 is for groundwater extraction (Metherall 2019). 53% of the surface water licenses are for irrigation, 32% are for domestic usage, and the remaining licenses are for livestock, conservation, and water storage (Metherall 2019). The groundwater licenses are primarily for domestic use (73%), with the remaining licenses for irrigation and water storage (Metherall 2019). All of these licenses holders are located in the lower reaches of the river, downstream of the Highway 17 crossing (Figure 1.4). Hoses and water pumps were visible within the river during the 2019 study, especially in the lower reaches where a greater number of residences and farms were located.

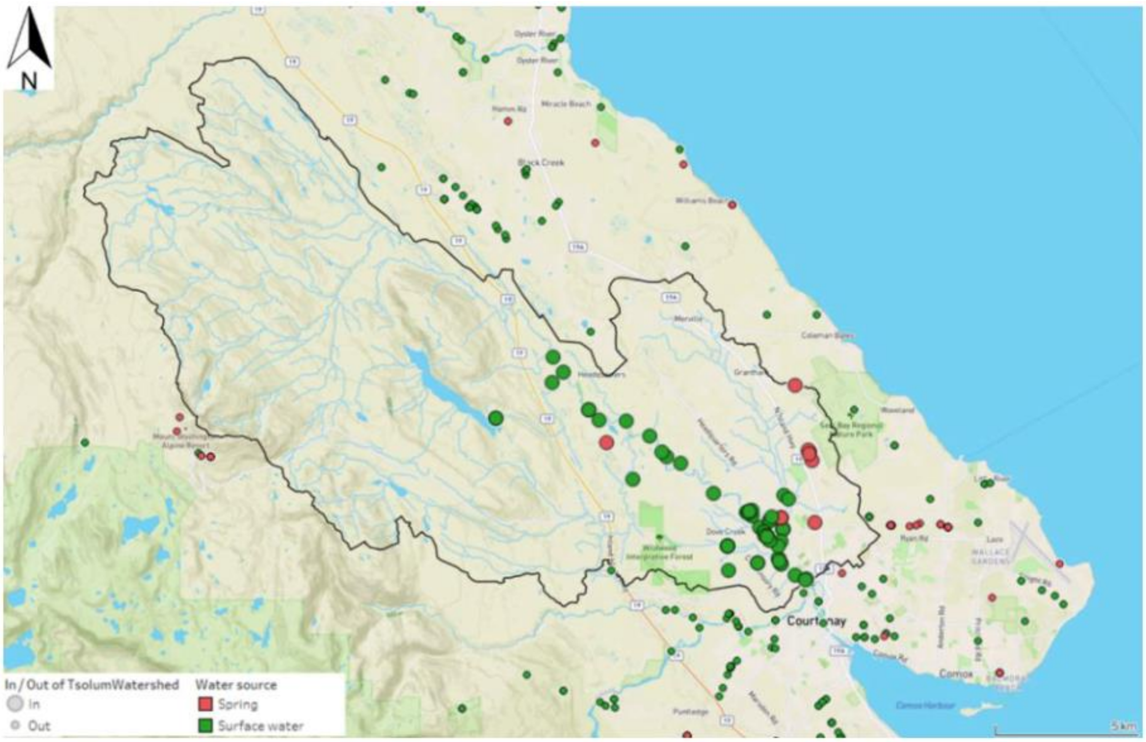

Figure 1.4 Surface water and groundwater (spring) water licenses within and outside the Tsolum River watershed (Metherall 2019).

The majority of water extraction occurs during the warm and dry summer months, when flows are naturally lower (Metherall 2019). July and August have the highest consumptive water usage, at an estimated 163,410 m^3 for each month, based on allowable extraction amounts (97% of this is surface water and 3% is extracted from springs, for both July and August; Metherall 2019). A Water Allocation Restriction was implemented for the Tsolum River by the Ministry of Forests, Lands, and Natural Resources Operations and Rural Developments (FLNRORD) in 1953, only allowing surface water to be extracted from the river when the mean monthly flow is greater than 60% of the mean annual discharge (MAD), which coincides with the high rainfall experienced on the coast from October to May each year (Riddell & Bryden 1996; FLNRORD 2016). This only applies to licenses issued after 1953 however, and many of the current licenses were issued prior to the implementation of the Water Allocation Restriction, allowing them to extract water during the summer months (W. White 2020, Tsolum River Restoration Society, Courtenay, BC, personal communication). According to the Water Allocation Restriction for the Tsolum River, new surface water licenses will not be issued unless the licensee creates water storage on their lands (FLNRORD 2016; Metherall 2019).

The majority of water licenses, by volume of water, are under Fisheries and Oceans Canada (DFO). These licenses permit DFO to withdraw water from Wolf Lake in order to supplement periods of low flow along the mainstem of the Tsolum River (Phippen & Obee 2012). The goal is to maintain flows at a minimum of 10% of the MAD, which is the minimum flow required for fish (Riddell & Bryden 1996; Phippen & Obee 2012). Wolf Lake is 1.6 km^2 and is located in the centre of the Tsolum River watershed, approximately 15 km northwest of Courtenay (Gooding 2009). There is a concrete dam and spillway at the southeast end of the lake. Water is released from the spillway into a constructed by-pass channel approximately 40 m west of the outlet structure of the lake (Gooding 2009). This by-pass channel connects with Headquarters Creek approximately 40 m downstream of the lake, flowing southeast for 6 km before connecting with the Tsolum River (Gooding 2009).

Surface water is typically released from Wolf Lake during the late summer through to early fall, when precipitation increases (Phippen & Obee 2012). The dates of water release depend on the water levels in the river each year (J. Amos 2019, Puntledge River Hatchery, Courtenay, BC, personal communication). In 2019, water was released from Wolf Lake from July 29 to the end of November (J. Amos 2019, Puntledge River Hatchery, Courtenay, BC, personal communication). The intent of augmentation is to provide between 0.8 and 0.99 cubic metres/second (cms) at the Water Survey Canada (WSC) Tsolum River near Courtenay 08HB011 Station (Spooner 2016). In August and September, approximately 48% of the Tsolum River discharge below the Headquarters Creek confluence comes from the flow augmentation from Wolf Lake (Metherall 2019).

Riparian vegetation in the Tsolum River watershed has been reduced over time due to historical logging activities (Spooner 2016). Riparian vegetation is impacted by the expansion of urban and agricultural land use in the lower watershed, adjacent to the Tsolum River (Spooner 2016). Between the late 1800s and 1964, the majority of the riparian vegetation along the Tsolum River and tributaries within the watershed was removed (Gooding 2010). A reduction in riparian vegetation often decreases shading, exposing a greater area of the surface water to solar radiation, resulting in increased stream temperatures (Poole & Berman 2001). Riparian vegetation also protects streams from wind, decreasing the convective heat transfer between the stream and air (Erickson & Stefan 2000).

1.3. Past Temperature Studies

Temperature data in the Tsolum River watershed was collected from 1996 to 2003 by W.E. McLean from the Habitat Enhancement Branch of DFO in the Pacific Region (TRRS N.D.). This was done to determine the effects of elevated stream temperatures on the growth and maturation of salmonids and their eggs (TRRS N.D.). Temperatures were studied by deploying Onset temperature loggers in four monitoring locations, which were the Wolf Lake outlet, the Headquarters Creek hatchery site, the Yew Tree site (100 m upstream of the confluence of Headquarters Creek and the Tsolum River), and the old pink counting fence site in the Lower Tsolum River (TRRS N.D.). Temperatures were logged every 15 minutes at these six locations (TRRS N.D.).

Temperature was also measured in the Tsolum River as part of water quality sampling conducted by the British Columbia Ministry of Environment (MoE) from 2009 to 2011 (Phippen & Obee 2012). This was conducted to determine background water quality of the Tsolum River in order to set the water quality objectives under Section 5(e) of the Environmental Management Act. Temperature was monitored at one location, 500 m downstream of Murex Creek in the Tsolum River (Phippen & Obee 2012). Water temperatures at this location exceeded both the provincial aesthetic drinking water guidelines (15°C) as well as the aquatic life guidelines (+/- 1°C from optimal thermal thresholds for the salmonid species present with the lowest thermal threshold) during the low-flow summer months (Phippen & Obee 2012; Ministry of Environment and Climate Change Strategy 2017; Ministry of Environment and Climate Change Strategy 2019).

The maximum temperature recorded was 20°C during this study period (Phippen & Obee 2012).

The water quality objective that was established for the Tsolum River, based on the 2009 to 2011 study results, was that the average weekly temperature of the Tsolum River should be no greater than 16°C (Phippen & Obee 2012). The maximum optimal rearing temperature for coho, cutthroat trout, and Dolly Varden, which are all present within the river during the entire year, is 16°C (Ministry of Environment and Climate Change Strategy 2019). It is for this reason that the water quality objective was set as 16°C (Phippen & Obee 2012). The sampling location for the 2009 to 2011 study was in the upper watershed and results indicated that temperatures in this location were higher than the water quality objective of 16°C (Phippen & Obee 2012). However, salmonids usually spawn lower in the watershed, and it is common for stream temperatures to increase longitudinally from the headwaters downstream (Caissie 2006; Phippen & Obee 2012). Therefore, it was suspected that temperatures were above the 16°C target for water quality in the lower watershed, which is of concern to spawning and rearing salmonids.

1.4. Thermal Regime in Streams

There are many factors that affect the thermal regime of a stream, including atmospheric conditions, landform and topography, streamflow, and the streambed composition and processes (Figure 1.5; Caissie 2006). Atmospheric conditions greatly influence stream temperatures because they impact the exchange of heat at the water's surface (Caissie 2006). The hydrology of a stream controls its response to atmospheric changes, which can result in an increase or decrease in stream temperatures. The location of the stream along a longitudinal profile as well as the exchange of water between the streambed and water column, also impact the response (Caissie 2006). Some of the key physical parameters that affect stream temperatures are wind speed and humidity, solar radiation, sediment thermal conductivity, stream depth, and groundwater upwelling (Figure 1.5; Pilgrim et al. 1998; Caissie 2006).

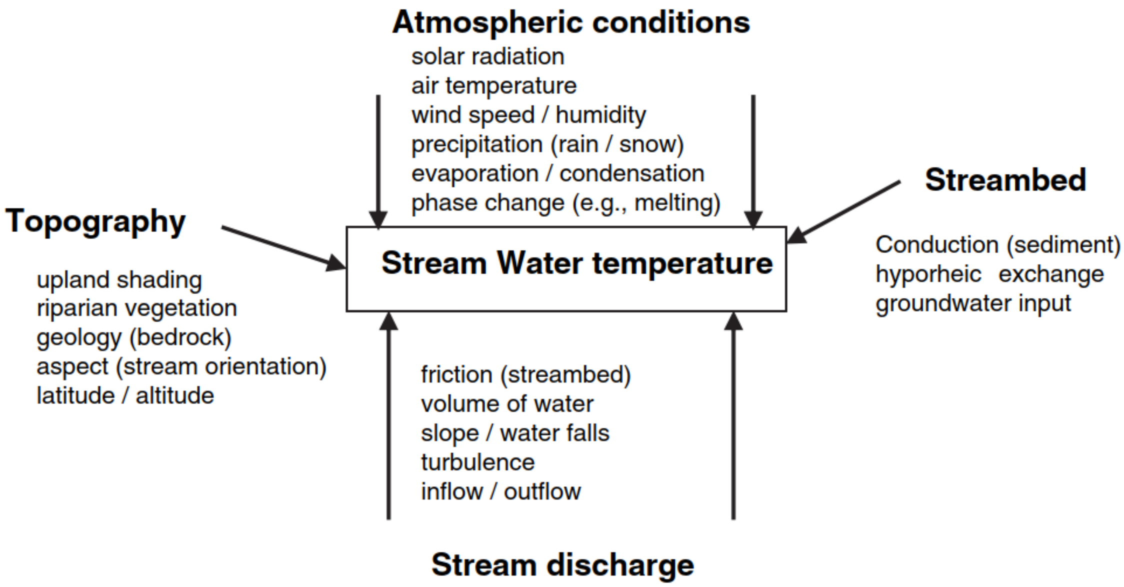

Figure 1.5 Factors that contribute to the thermal regime of a stream (Caissie 2006).

Heat from the atmosphere interacts with the water surface through conduction, convection, and advection, with convection being the process by which atmospheric heat gets transferred into the stream, thereby influencing the stream temperature (Poole & Berman 2001). Advection is the process by which heat energy is transferred to streams from inputs of external water sources, such as groundwater and tributaries (Tague et al. 2007). Groundwater from deep reservoirs interact with streams as cold water springs, emerging in high volumes (Tague et al. 2007). Conversely, groundwater from shallower layers can result in more diffuse, subsurface flow, contributing less cold water to the stream system (Tague et al. 2007).

Water temperatures are typically less sensitive to changes in air temperatures in areas where groundwater interacts with the stream, meaning air temperatures cannot be used to predict water temperatures accurately in these locations (Mackey & Berrie 1991). When streams are sufficiently mixed and heat is predominantly transferred to the stream from the atmosphere, water and air temperatures are highly correlated (Erickson & Stefan 2000). This relationship is disrupted when there is an upstream dam holding back water and releasing it at various times or when groundwater or wastewater is discharging into the stream (Erickson & Stefan). Typically, temperatures in streams that have large groundwater contributions are relatively unresponsive to changes in atmospheric conditions (Driscoll & DeWalle 2004; Briggs et al. 2018). In contrast, temperatures in streams that have no or minimal groundwater contributions are directly linked to atmospheric conditions, with stream temperatures changing as air temperatures change (Driscoll & DeWalle 2004). As such, the relationship between air and water temperatures can signal whether there are groundwater inputs at a site.

Understanding how groundwater and surface water interact in a stream is crucial for managing and protecting water quality (Kalbus et al. 2006). Groundwater can either flow into a stream from the hyporheic zone (gaining) or flow from the stream into the hyporheic zone (losing; Kalbus et al. 2006). These processes are inconsistent along the longitudinal profile of a stream, such that some reaches are gaining and others are losing (Kalbus et al. 2006). The depth of the water table affects whether the stream will be gaining or losing, and the water table depth changes with precipitation volumes (Kalbus et al. 2006). Although a reach may be gaining at one time in the year, it could become a losing reach during a dry time of the year as the water table elevation decreases (Kalbus et al. 2006). There are many methods that can be used to determine where groundwater and surface water interactions occur within a stream including water movement with seepage meters, temperature measurements, and streamflow measurements (Kalbus et al. 2006).

1.5. 2019 Temperature Study

The primary goal of this study was to determine whether air or groundwater regulates the temperature at various locations within the Tsolum River. Identifying areas in the stream that are influenced by groundwater can inform management decisions regarding water use and restoration activities. These areas can be protected and possibly restored, allowing salmonids to use these areas during rearing and spawning. This would increase the likelihood of their survival as stream temperatures increase with climate change (Briggs et al. 2018). This Applied Research Project (ARP) aimed to identify thermal refugia in the Tsolum River, in order to proactively protect and potentially restore these areas, thereby providing temperature resilience for salmonids in the watershed.

Phase 1 of the Tsolum River Agricultural Watershed Plan states that groundwater plays a crucial role within the Tsolum River watershed and makes up 75%

of the water use within it (Metherall 2019). However, the interaction between groundwater and surface water is not fully understood (Metherall 2019), which is why this study is important. The recommendations for Phase 2 of the Tsolum River Agricultural Watershed Plan include identifying areas where there are groundwater and surface water interactions (Metherall 2019). The findings of this ARP can complement the Phase 2 Agricultural Watershed Plan.

Chapter 2.

Research Goals and Objectives

Goal 1: Determine whether air or groundwater regulates the temperature in various locations within the Tsolum River.

> ***Objective 1.1:*** Identify areas in the stream that are primarily affected by groundwater discharge, with the aim of mapping out these critical areas that can potentially serve as thermal refugia for salmonids.
>
> ***Objective 1.2:*** Identify areas in the stream that are lacking in riparian shading.
>
> ***Objective 1.3:*** Create a climate adaption/restoration plan for the Tsolum River Restoration Society (TRRS) with the aim of mapping potential thermal refugia, recommending future temperature studies, and proposing restoration treatments should they be necessary.

Goal 2: Determine economical and efficient ways of locating groundwater/surface water interactions in a stream.

> ***Objective 2.1:*** Test various methodologies for identifying groundwater input areas that may be used on other salmonid-bearing streams.

Chapter 3.

Methods

3.1. Temperature Monitoring

3.1.1. Reconnaissance and Site Selection

Desktop and field reconnaissance of the lower 18 km of the Tsolum River was conducted to determine locations where groundwater may be interacting with the Tsolum River. Maps showing flowing springs, groundwater wells, and local aquifers were studied and discussions were undertaken with TRRS members, landowners, and hydrogeologists at GW Solutions. Once potential areas of groundwater input were identified, ground-truthing was conducted by walking along sections of the river, assessing the banks and substrate, looking for bubbles coming up from the stream bottom, and looking for signs of seepage. A handheld thermometer was used in areas where there was suspected groundwater input, since the small-scale thermal variability common in streams is easiest to assess using a hand-held thermometer (Dunham et al. 2005). At each location where temperature was measured during the reconnaissance surveys, depth, GPS coordinates, and photographs were also collected to assess the feasibility of installing a temperature data logger in that location. Additionally, snorkel surveys were conducted at various times throughout the field season to identify locations where additional loggers could be installed.

3.1.2. Water Temperature Monitoring

Since temperature is often used as a tracer to identify areas of groundwater-stream exchange, TidbiT™ v2 loggers (herein referred to as loggers) were used to measure temperatures at various locations within the watershed (Objective 1.1; Karan et al. 2017). This is an effective method for determining areas of groundwater seepage since there are notable differences between surface water temperatures that vary daily and seasonally, and groundwater temperatures that are nearly constant throughout the day and year (Karan et al. 2017). These loggers are accurate to within +/- 0.21ºC and are waterproof to 305 m (Onset Computer Corporation 2018). Loggers were installed at

28 monitoring locations within the Tsolum River and associated tributaries and two monitoring locations within the Cowichan River. Rivers are typically thoroughly vertically mixed, with relatively constant temperatures between the streambed and surface (Caissie 2006). Therefore, loggers were not installed in a dual-logger system (one logger at the streambed-water interface (SWI) and one logger near the surface), as in a similar study (Karan et al. 2016). Instead, one logger was installed at the streambed at each site. Installing only one logger at each location maximized spatial coverage since twice as many loggers could be installed throughout the watershed. One exception was made to test whether there were differences between temperatures at the streambed and at the surface. As described in Appendix A, W24-2019 and W12-2019 (see Section 3.1.5 for explanation of site naming convention) were installed in the same location at different depths to test whether stream temperatures were different at various depths. The loggers were all installed in areas where it appeared that they would remain wetted throughout the summer.

Each logger was attached to a piece of 2.5 cm thick white cutting board (as shown in Photo 2), which were designed by Ted Sweeten (DFO) and manufactured by Industrial Plastics. These white inserts with the loggers attached were then bolted into a 17.8 cm long section of white PVC pipe (5.1 cm diameter), using a bolt, nut, and nylon locking nut (as shown in Photos 1, 3, and 4). The PVC pipe was used to protect the logger from crushing, abrasions, and solar radiation impacts (Dunham et al. 2005). White PVC housings were used since they do not absorb solar radiation, which could artificially increase water temperatures (Dunham et al. 2005). The PVC sections were cut with a table saw and had ten 6 mm diameter holes drilled into them. Two of these holes were drilled through one end of the PVC, allowing the bolt to pass through and be locked into place (as shown in Photos 1, 3, and 4). The other eight holes were drilled into the centre of the PVC pipe to provide water flow-through (Dunham et al. 2005; U.S. Environmental Protection Agency 2014). The exchange of water through the PVC pipe was critical since the temperature readings could be biased if there was not proper flow-through (Dunham et al. 2005).

Rebar (3.2 cm diameter) was pounded into the substrate with a rebar pounder at each monitoring location. Rebar was the preferred installation method since there was minimal large wood that the loggers could be cabled to and the substrate was primarily composed of silt, sand, and clay (Heck et al. 2018). The rebar was installed protruding from the water, so that it could be easily located, with orange safety caps placed on top (Heck et al. 2018). The depths of the rebar in the substrate varied depending on the length of rebar and substrate type, however, they were all pounded into the substrate until they could not be easily removed.

The PVC pieces with the loggers inside were then attached to the bottom of the rebar at the SWI with a zip tie. They were oriented with the PVC opening facing downstream, to further allow for water flow-through. However, some of the loggers shifted sideways (opening facing closer to right or left banks) between downloads. To ensure that this shifting did not impact the temperature due to a change in water flow-through, a second logger was installed directly above W26-2019 (see Section 3.1.5 for explanation of site naming convention). The second logger was called “sideways test at W26-2019”, and its opening was facing the left bank instead of downstream as the opening for W26-2019 was. The “sideways test at W26-2019” logger was left in this location for 10 days to compare the temperatures with the different orientations. The average temperatures of the two loggers were the same (18.6ºC), therefore the shifting of the loggers throughout the study was not determined to affect recorded stream temperatures. A time series graph showing the temperature of both loggers is presented in Appendix B.

A second installation method was employed for deeper pools, where rebar installation was not possible. In these cases, the PVC pipes with the loggers inside were zip-tied to bricks and were dropped in the pools, with chains attaching them to the bank to prevent them from moving downstream. The chains were locked to a tree on the bank to discourage tampering or removal. Three water loggers were installed using this methodology (W22-2019, W23-2019, and W24-2019; see Section 3.1.5 for explanation of site naming convention). One PVC pipe piece with a logger inside (W21-2019; see Section 3.1.5 for explanation of site naming convention) was attached beneath a piece of large woody debris on the right bank using a chain and lock. The remaining 26 loggers were installed using the rebar method, as described above.

Photo 1 - PVC pipe with bolt and spacer prior to logger insertion.

Photo 2 - Logger attached to white insert that was installed inside PVC pipe.

Photo 3 - PVC pipe with flow-through holes; white insert with logger bolted into top holes of PVC pipe.

Photo 4 - White insert with logger bolted into top holes of PVC pipe.

Additional data was collected at each logger, including:

- Wetted width at the transect where the logger was located
- Stream depth at the logger

- Surface water temperature (when possible; thermometer was broken for a period of time)
- Time the logger was retrieved from the water
- Time the logger was redeployed in the water
- Condition of the logger

The wetted width and depth were measured during each download to gain an understanding of how the stream morphology was changing over time. Times when the logger was out of the water were removed from the analysis by assessing the time retrieved and redeployed at each logger.

3.1.3. Air Temperature Monitoring

Two loggers (A1-2019 and A2-2019; see Section 3.1.5 for explanation of site naming convention) were installed along the banks of the Tsolum River, in the lower portion of the study area (Figure 3.1). These air temperature loggers were used to compare air temperature and water temperature at each site to better understand how responsive stream temperatures were to air temperatures (U.S. Environmental Protection Agency 2014).

Both of the air loggers were installed within the same section of stream (at the property at the end of Stephen Road; Figures 3.1 and C-5 in Appendix C), across from each other on the left and right banks. A1-2019 was installed on an open gravel bar on the right bank, with 6.5% riparian vegetation cover. A2-2019 was installed on the left bank, beneath bushes and trees with 99.8% riparian vegetation cover. Each water temperature logger in the Tsolum River watershed was assigned to an air temperature logger, depending on the percent cover measured at the logger. Water temperature loggers with less than 50% cover were compared to A1-2019 and water temperature loggers with greater than 50% cover were compared to A2-2019 (Table 4.5). Both of the loggers were installed inside Gill-style Onset RS1 solar radiation shields, which were mounted to rebar pounded into the gravel bar and bank (Photos 5 and 6).

Photo 5 – A1-2019 installed within solar radiation shield on exposed gravel bar, looking south.

Photo 6 – A2-2019 installed within solar radiation shield along covered bank, looking southwest.

The distance between the air temperature loggers and water temperature loggers that they were compared to ranged from 0.3 km away (W23-2019) to 18 km away (W18-2019; see Section 3.1.5 for explanation of site naming convention). The difference in elevation between the air temperature loggers and the farthest water temperature logger (W18-2019) was 92 m. Correlations conducted between air and water temperatures in streams in Minnesota found that the quality of the correlation was not dependent on the distance between the air and water temperature stations, as long as the elevations were similar (Pilgrim et al. 1998). In the Pilgrim et al. (1998) study, the distances between measurement stations ranged from 1.6 km to 232 km and the elevations ranged from 200 m to 400 m above mean sea level (Pilgrim et al. 1998). These distance and elevation ranges did not have an effect on the correlation between air and water temperatures (Pilgrim et al. 1998). The distances and elevations between water and air loggers installed for this ARP were less than for the Minnesota study, therefore it is assumed that the distances between water and air monitoring locations did not affect the results of this study.

3.1.4. Logger Accuracy Check, Deployment, and Downloads

The accuracy of the loggers was checked prior to deployment and after collection (Onset Computer Corporation 2020). Loggers were all submerged in a cooler containing crushed ice and distilled water, and were left until the temperature of the ice bath reached its lowest point (approximately 0-1°C). The loggers were hung by a string inside the cooler to prevent them from touching the sides or bottom of the cooler, as suggested by an Onset employee. The ice bucket temperature was taken with a handheld thermometer, ensuring the temperature was close to 0°C. When the loggers were removed from the ice bath, the data was read by the Onset Hoboware Pro version 3.7.16 software and the lowest temperature was recorded from the ice bath submersion. The loggers were considered accurate and could be used as long as the lowest temperature was +/- 0.21°C of 0°C (Onset Computer Corporation 2018), which was the case for all of the loggers both pre- and post-deployment.

Loggers were launched using the Onset Hoboware Pro version 3.7.16 software prior to installation. The recording interval was set to 15 minutes for all loggers deployed. This interval was used since a shorter sampling period has a greater chance of capturing diurnal variations in a stream, and therefore the actual thermal regime (Dunham et al. 2005). The loggers were set to a delayed start for the day they were deployed, several hours after installation was expected to be complete to ensure they were in the correct location when they began recording. The temperature data from the loggers was downloaded every two to three weeks from each monitoring location, using an Optic USB base station in the field.

3.1.5. Temperature Logger Naming Convention

Each logger was named with a prefix of W or A, for water or air, respectively. A number followed, indicating the order in which the loggers were deployed. Finally, a dash and the year (2019) was added so that this study can be repeated in the future with loggers installed in the same locations. An example of this naming convention is W1-2019, which was the first water logger installed. A1-2019 was the first air logger installed. There were 30 water temperature loggers, called W1-2019 to W30-2019 and two air temperature loggers, called A1-2019 and A2-2019.

3.1.6. Research Sites

The monitoring locations were primarily established in the lower Tsolum River, with one location in the upper Tsolum River (serving as a control site), as well as several monitoring locations within tributaries. Previous temperature studies conducted have shown that temperatures in the upper Tsolum River (at the confluence of Headquarters Creek and upstream) are cooler than in lower sections of the watershed, therefore the lower portion of the river was the focus of this study (Campbell 2010). Sites descriptions, average depth, and site selection rationale are presented in Table A-1 in Appendix A.

Two loggers were also installed using the rebar method in the Cowichan River watershed in August 2019. During a snorkel swim of the Cowichan River in July 2019, cold water was identified by sight and feel at the confluence of Bear Creek and the Cowichan River. Since obvious signs of groundwater had not been observed in the Tsolum River, two loggers were installed within the Cowichan River watershed to test whether the methodology was able to identify areas of groundwater influence. One was installed in Bear Creek near the confluence of the Cowichan River (W29-2019) and one was installed in the Cowichan River, approximately 85 m upstream of the confluence with Bear Creek (W30-2019).

Figure 3.1 shows the locations of the water and air temperature loggers within the Tsolum River watershed. Figures C-1 to C-6 in Appendix C show close-up views of each labeled water temperature logger within the Tsolum River watershed. Figure 3.2 shows the locations of the water temperature loggers within the Cowichan River watershed.

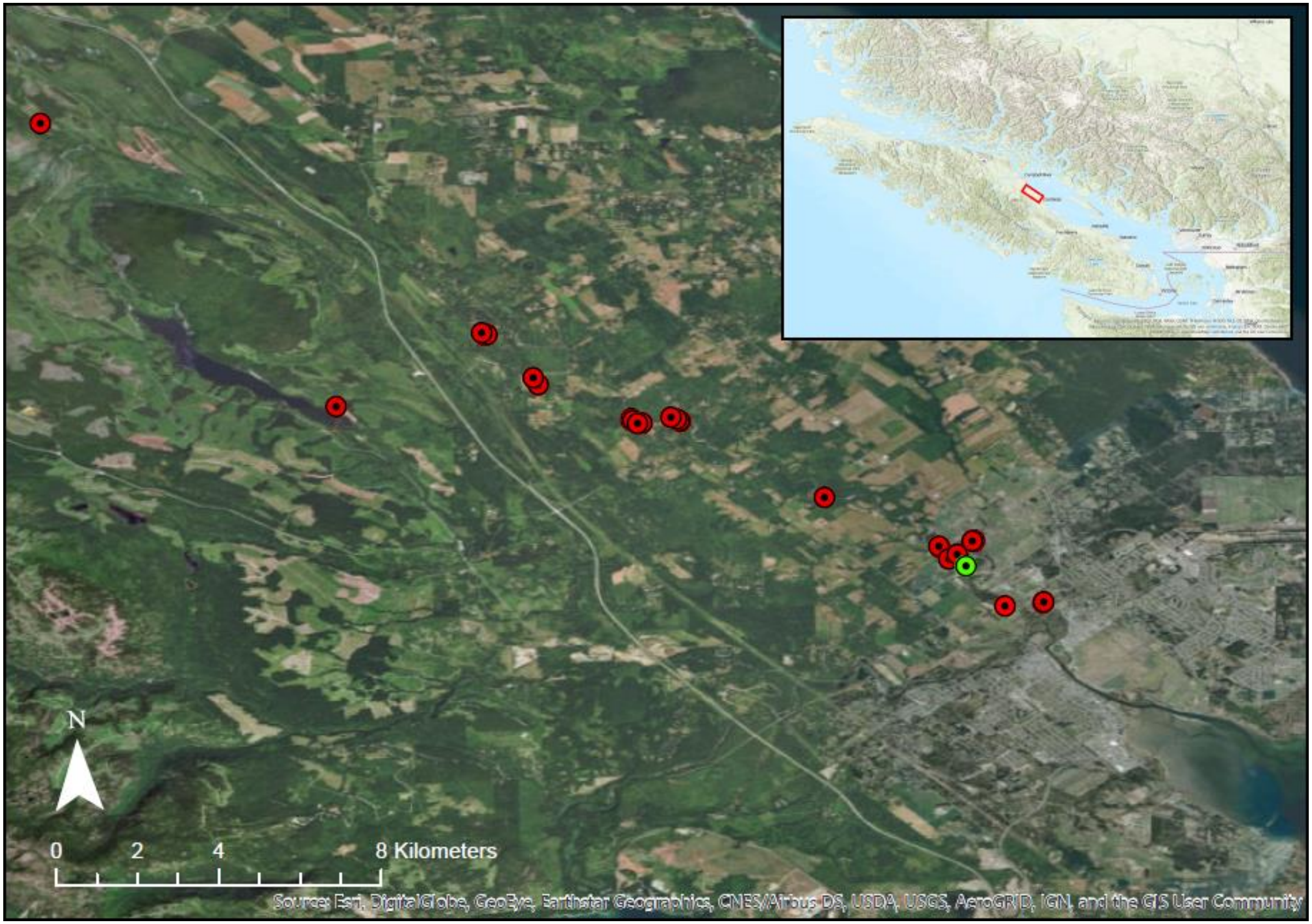

Figure 3.1 **Temperature monitoring locations within the Tsolum River watershed, upstream of the K'ómoks estuary. Red markers indicate water temperature loggers and green markers indicate air temperature loggers. The inset box in the top right shows the location of Courtenay, BC (Esri 2009).**

Figure 3.2 **Water temperature monitoring locations within the Cowichan River watershed. Red markers indicate water temperature loggers. The inset box in the top right shows the location of the Cowichan River, BC (Esri 2009).**

3.1.1. GPS Coordinates and Photographs

GPS coordinates were collected at each monitoring location, at the time of the temperature logger set-up. A hand-held GPS unit (Garmin 4S) was used to determine the latitude and longitude of the monitoring locations. Photographs of the temperature logger set-up and the logger in the four cardinal directions were taken at each of the monitoring locations during every site visit. These photos capture the characteristics and condition of the channel planform and the condition of the riparian vegetation at each logger location.

3.1.2. Temperature Logger Removal and Data Analysis

All loggers were removed from the rivers/tributaries from September 7 to 11, 2019. Temperatures were compared throughout the study area by comparing the means for the study period (by using the average of monthly means; Figure 4.1), monthly means (Table 4.1), and daily means (Figures 4.2 and 4.3) from July 18 to September 8, 2019 when all loggers were recording temperatures. Daily total precipitation values were compared to daily mean temperatures (Figure 4.3).

Simple linear regressions can be used to model the relationship between air and stream temperatures. The relationship between air and water temperatures is strongest using monthly averages and weakest using daily averages (Erickson & Stefan 2000). Since this study was conducted over 3 months, the relationship could not be assessed on a monthly scale, therefore the weekly scale was used. At temperatures between 0°C and 20°C, the relationship between air and water temperature has been shown to be linear (Mohseni & Stefan 1999). This relationship departs from linearity and levels off when air temperatures exceed 25°C due to evaporative heat loss at higher temperatures (Erickson & Stefan 2000). Since the average summer air temperatures in the Comox Valley did not exceed 25°C and did not drop below 0°C, the relationship between air and water temperatures was linear and could be used to understand the thermal regime of the river.

Weekly means for water temperature and air temperature were compared using a linear regression model in R version 3.6.1 (2019; Webb et al. 2008). Four assumptions needed to be met before linear regressions could be conducted which were: (1) the relationship between the independent and dependent variables were linear, (2) the residuals were homoscedastic, (3) the observations were independent, and (4) the data was normally distributed (Boston University

School of Public Health 2016). Each pair of water and air temperature loggers were plotted to determine whether the relationship appeared to be linear. Kolmogrov-Smirnov (KS) tests were conducted on the weekly means of both the water and air temperatures for each water/air temperature logger pair to check that the data was normally distributed (Table D-1 in Appendix D). Kolmogrov-Smirnov tests were also conducted on the residuals of the comparison between the weekly means of water and air temperatures for each water/air temperature logger pair to check that the residuals were normally distributed (Table D-2 in Appendix D). Additionally, a Breush-Pagan test was conducted on the residuals of the comparison between the weekly means of water and air temperatures for each water/air temperature logger pair to check that the residuals were homoscedastic (Table D-2 in Appendix D). These assumptions were met, therefore linear regressions were performed.

The significance of the linear regression models were tested for each air/water temperature logger pair. The null hypothesis was that there was not a significant relationship between water and air temperatures, suggesting that air temperature is not the primary driver of stream temperature in that location. The alternative hypothesis was that there was a significant relationship between water and air temperatures, suggesting that air temperature is the primary driver of stream temperature in that location. If p-values were less than the significance value of 0.05, then the null hypothesis was rejected and if p-values were greater than the significance value of 0.05, then there was a failure to reject the null hypothesis. There was the potential for type I errors to occur (falsely rejecting a true hypothesis) since multiple hypothesis tests were conducted (Benjamin & Yekutieli 2001). The p-values were therefore adjusted to minimize this risk (Benjamin & Yekutieli 2001).

Along with a p-value, the linear regression models produced a slope and an intercept for each air/water temperature logger pair (Table 4.2). Typically, the slope will be gentle and the intercept will be large when graphically comparing air and surface water temperatures if groundwater is contributing to the temperature of the stream (Driscoll & DeWalle 2004). Lower slopes indicate that air is not a driving force in the determination of water temperature (Webb 1992 in Erickson & Stefan 2000). If groundwater is not contributing to the temperature of the stream, then the slope will be steep and the intercept will be close to zero on a graph (Driscoll & DeWalle 2004). Slopes versus intercepts were plotted for the weekly stream/air linear regressions, to determine whether the stream temperature at each site was more likely to be influenced by atmospheric conditions or by groundwater input (Figure 4.6; Driscoll & DeWalle 2004).

Another way in which the stream/air temperature relationship was assessed at each site was by evaluating the slopes of the trendlines from the time series graphs presented in Appendix E. These trendline slopes indicate the rate of change of both water and air temperatures throughout the study period, visually showing the dependency of water temperature on air temperature.

As a final analysis step, self-organizing maps (SOM) were used to examine whether there was the potential for groundwater influence at each of the Tsolum River watershed monitoring sites. The SOM-Toolbox implemented in Mathworks® MATLAB was used for the analysis (Vatanen et al. 2015). Self-organizing maps use unsupervised learning in an artificial neural network to identify patterns in data, and characterize monitoring sites according to these patterns (Chartrand et al. 2015). As a result, SOM is a type of clustering analysis commonly used on large datasets (Chartrand et al. 2015). A principle component analysis (PCA) was first conducted to determine the number of principle components that explain a majority of the variance in the water temperature data. Consequently, a SOM with 4 nodes was developed to identify characteristic water temperature response curves for the 51-day monitoring period across all of the monitoring sites.

The daily means from the historical temperature loggers ("Lower Tsolum" and "Yew Tree") were compared to the daily means of W17-2019 and W28-2019, respectively, which were installed in these locations to provide a comparison of stream temperatures over time. These means were compared for the days when W17-2019 and W28-2019 overlapped with the historical temperature measurements. The means of daily means from June 25 to July 16 were compared between W17-2019 and the "Lower Tsolum" measurements from 1998-2002. The means of daily means from July 19 to September 7 were compared for W28-2019 and the "Yew Tree" measurements from 1998 to 1999.

Air temperature loggers were not installed near the Cowichan River watershed loggers (W29-2019 and W30-2019), therefore the North Cowichan Environment Canada weather station was used for air temperature comparisons. The North Cowichan weather station is located approximately 18 km northeast of the water loggers, and is the closest weather station with hourly historical air temperature data. Due to the limited amount of temperature data (only four full weeks), linear regressions between stream and air temperatures were not conducted. Instead, the analysis of the Cowichan River watershed loggers was based solely on a visual assessment of the time series graphs between the water and air temperatures and average temperatures throughout the study period.

3.2. Stream Discharge Measurements

Stream discharge was measured using a FlowTracker 2® flow meter (herein referred to as flow meter) and estimated using the velocity-area method (Karan et al. 2017). These measurements were conducted on a monthly basis from June to August at six locations (Figure 3.3). The locations chosen were at the confluence of the three tributaries entering the Tsolum River within the study area (Headquarters Creek, Dove Creek, and Portuguese Creek) and downstream of these confluences in the Tsolum River. A measurement of the bankfull width and depth was required to calculate the cross-sectional area at the point of discharge measurement. A measuring tape was stretched across the stream at the transects where velocity was measured, and velocity measurements were taken at a minimum of 20 panels across each transect. The flow meter was also used to measure the depth of the stream at each velocity measurement location. Figure 3.3 shows the locations of the flow monitoring stations within the Tsolum River watershed.

The discharge from the WSC hydrometric station (Tsolum River near Courtenay 08HB011 Station) was also assessed since these measurements were conducted on a daily basis.

Figure 3.3 **Flow monitoring locations within the Tsolum River watershed. Yellow markers indicate sites where flow measurements were conducted throughout the sampling periods (Esri 2009).**

3.3. Riparian Vegetation Assessment

The percentage of riparian cover at each temperature monitoring location was determined using a spherical hand-held densiometer (Objective 1.2; McKee 2009). The assessment was completed once during the field season, at the end of August. The canopy cover percentage was captured in four directions at each logger; upstream, left bank, downstream, and right bank. The percent cover in these directions was also taken at the left bank, centre, and right bank of the transect where the logger was located. The number of shaded dots in each direction was recorded and these were averaged and multiplied by 0.26 to compute the percent cover, as per streamkeeper field procedures (Streamkeepers 2009). The densiometer measurements were conducted by the same person each time, closing one eye and holding the densiometer approximately 30 cm above the surface of the water (Rhode Island Department of Environmental Management 2011).

Riparian assessments throughout the Tsolum River mainstem and the salmonid-bearing tributaries within the watershed were conducted as part of a Fish Habitat Assessment Program (FHAP) by D.R. Clough Consulting in the fall of 2014. The Tsolum River mainstem and its tributaries were broken down into reaches for the FHAP and riparian assessments. Riparian conditions were recorded for each reach, including plant community type and dominant species present, the bank slope and stability, and the width of the riparian area away from the river (D.R. Clough Consulting 2014). The percent crown cover in each reach was assigned a rating of 1, 3, or 5 which was assigned to a result of good, fair, or poor, respectively. This ranking system follows the Vancouver Island Urban Salmonid Habitat Program Assessment and Mapping Procedures Manual (Michalski et al. 2000 in D.R. Clough Consulting 2014). Each logger location was assigned to one of the reaches from the FHAP, comparing the 2014 FHAP riparian assessment results to the percent cover measured at the 2019 study sites (Table 4.6). The percent cover measured at each logger transect during the 2019 study was calculated by averaging the left bank, right bank, and centre densiometer measurements (Table 4.6). In several cases, the densiometer measurement at the logger was used in the average rather than the centre measurement due to the prohibitive stream depth.

3.4. Methodology Testing to Identify Groundwater

The comparison of water and air temperatures using continuously-recording loggers was the primary method used to located groundwater in the Tsolum River watershed. Three other methods were tested as per Objective 2.1 to determine efficient and economical ways to locate groundwater in salmonid-bearing streams. These include specific conductance measurements, longitudinal temperature measurements, and forward-looking infrared radar (FLIR) drone surveys.

3.4.1. Specific Conductance Measurements

Specific conductance measurements were taken at each of the loggers once in August 2019 using a YSI 556 handheld multi-parameter probe. Specific conductance is electrical conductivity (EC) that has been standardized to 25ºC, which is the parameter that was measured by the YSI probe (U.S. Geological Survey 2019). Increases in specific conductance in a stream can signal areas of groundwater input since groundwater usually has higher levels of dissolved solids and therefore elevated specific conductance values compared to surface water (LakeSuperiorStreams 2009). Specific conductance was therefore measured to provide an additional line of evidence for groundwater input, and to test whether this methodology is successful in determining where groundwater is entering the stream.

3.4.2. Longitudinal Temperature Measurements

One method to locate groundwater upwelling areas within a stream is by distributed temperature sensing (DTS), which is a fibre optic (FO) cable that continuously measures stream temperatures over long distances (Birkham et al. 2014). A study was conducted in British Columbia's Elk Valley to determine the capability of the FO DTS in identifying areas of groundwater input to the stream (Birkham et al. 2014). The cable was installed along a 350 m section of the river, with temperature measurements collected every meter (Birkham et al. 2014). This study determined that the FO DTS was able to identify cooler areas of the stream caused by groundwater upwelling (Birkham et al. 2014). This method produced longitudinal temperature results, with the ability to record frequent temperatures along the length of the study area.

The FO DTS method was cost-prohibitive and could not be tested for this ARP, however it prompted the idea of measuring stream temperatures longitudinally down the Tsolum River with a high spatial resolution. This test was conducted on August 14, 2019, using two loggers simultaneously measuring temperatures at one second intervals. One logger was attached to a float so that it would stay on the surface (called Surface-2019), recording surface water temperatures (Photo 7). A second logger was attached to a fishing weight so that it would drag along the bottom (called Streambed-2019), recording stream bed temperatures (Photo 8). Both of these loggers were installed within the same PVC sections used for all other loggers in this study. A string was attached between the bottom and top loggers and they were dragged down the river by a swimmer, keeping them in a vertical line with each other (Photo 9). These loggers were dragged for a distance of 746 m, starting approximately 8 m downstream of W20-2019 and ending approximately 16 m downstream of W23-2019 (Figure 3.4). A GPS track was created using the handheld Garmin GPS, with the time of each track segment recorded to correlate stream temperatures and locations.

		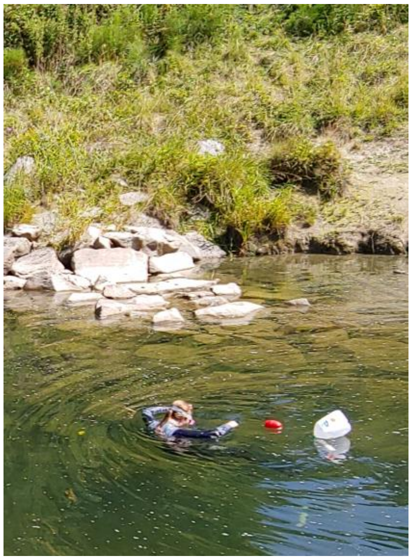
Photo 7 – Surface-2019 logger in PVC pipe attached to float.	Photo 8 – Streambed-2019 logger in PVC pipe attached to fishing weight.	Photo 9 – Loggers being dragged through the river one on top of the other.

Figure 3.4 Location of longitudinal temperature survey conducted on August 14, 2019. Yellow markers indicate points marked on GPS showing survey route (Esri 2009).

3.4.1. Forward-Looking Infrared Radar Drone Survey

A FLIR drone was flown over multiple sections of the Tsolum River on July 29, 2019. The aim of this survey was to test whether this type of drone survey could identify temperature hotspots as well as cool sections of the river, potentially indicating areas of groundwater upwelling. Dr. Eric Saczuk flew a DJI Mavic 2 Enterprise Dual drone (Photos 10 and 11) to test its capabilities of measuring temperatures within the stream. Five distinct sections of the river were selected for the survey based on their potential for groundwater input (called Segments 1-5; Figure 3.5). Four batteries were used, with a battery life of approximately 22 minutes each. The battery life dictated the length of the river that was able to be surveyed. The drone was flown in a single line downstream, following the thalweg in each section surveyed. Both colour (RGB) and thermal images were captured at many points along the drone flight for each section surveyed.

	
Photo 10 - DJI Mavic 2 Enterprise Dual drone on landing pad.	Photo 11 - DJI Mavic 2 Enterprise Dual drone on landing pad within the Tsolum River.

Figure 3.5 **Locations of drone survey conducted on July 29, 2019. Pink markers indicate start and end points of each surveyed segment (Esri 2009).**

3.5. Wolf Lake Physiochemical Sampling

Water that is released from Wolf Lake for downstream flow augmentation is surface water, spilling out of the concrete dam at the southeast corner of the lake (Gooding 2009). This has led to concerns that the released surface water may have high temperatures, potentially increasing water temperatures in Headquarters Creek and the Tsolum River downstream (N. Wiens 2018, Tsolum River Restoration Society, Courtenay, BC, personal communication). For this reason, W25-2019 was installed directly downstream of the spillway in the by-pass channel to assess the temperature of the water being released from Wolf Lake. There is the potential to release hypolimnetic water rather than epilimnetic water from the lake, providing cooler water for augmentation (K. Ashley 2018, British Columbia Institute of Technology, Rivers Institute, Burnaby, BC, personal communication). If dissolved oxygen (DO) levels are below the lethal threshold for salmonids in the hypolimnion of Wolf Lake however, water being pumped from the hypolimnion into Heaquarters Creek could be deleterious to fish (Marshall et al. 2002).

As such, a preliminary study was conducted on August 9, 2019 in Wolf Lake to measure temperature and DO concentrations at various depths in two locations of the lake. The first sampling location (called N-2019) was estimated to be in the deepest part of the lake according to bathymetry maps. The second sampling location was in a shallower section of the lake closer to the dam and weir, located southeast of N-2019 (called S-2019). The starting locations of both N-2019 and S-2019 are shown in Figure 3.6. A small aluminum boat was used to access these sampling locations. The boat driver attempted to keep the boat stationary during measurements since an anchor was not used, however the boat drifted approximately 12 m and 67 m at N-2019 and S-2019, respectively. A YSI 556 handheld multi-parameter probe was used to measure temperature and DO at 0.5 m intervals from the surface down to 20 m at N-2019, as this was the cable length of the probe. Temperature and DO measurements were also taken from the surface to the lake bottom at S-2019 (9 m depth).

Figure 3.6 **Location of physiochemical water sampling in Wolf Lake. Orange markers indicate starting points of sampling at N-2019 and S-2019 on August 9, 2019 (Esri 2009).**

Chapter 4.

Results

4.1. Temperature Results

4.1.1. Comparison between 2019 Water Temperature Loggers

Mean monthly temperatures from July 18 at 12:00 pm to September 8 at 8:45 am (inclusive) were compared for each location (Table 4.1). This was the time period when all 28 Tsolum River watershed loggers were recording temperatures and could be compared.

Table 4.1 Mean monthly temperatures from July 18 to September 8.

Site	Average Temperature (°C)		
	July	**August**	**September**
W1-2019	18.9	19.2	18.5
W2-2019	18.8	18.9	18.1
W3-2019	18.8	18.9	18.2
W4-2019	18.2	18.8	18.1
W5-2019	18.0	19.0	18.7
W6-2019	18.1	18.9	18.6
W7-2019	18.9	19.1	18.5
W8-2019	19.2	19.3	18.6
W9-2019	20.4	20.4	19.6
W10-2019	18.1	18.4	17.7
W11-2019	20.4	20.4	19.5
W12-2019	20.7	20.6	19.6
W13-2019	18.9	19.1	18.5
W14-2019	18.7	19.2	18.6
W15-2019	18.4	19.0	18.5
W16-2019	19.9	20.0	19.1
W17-2019*	---	---	---
W18-2019	16.4	16.5	16.0
W19-2019	18.3	18.9	18.5
W20-2019	17.8	17.8	15.8
W21-2019	20.1	20.1	19.2
W22-2019	20.2	20.2	19.1
W23-2019	19.8	20.2	19.4
W24-2019	20.7	20.6	19.6
W25-2019	20.9	21.9	21.4
W26-2019	19.2	19.3	18.6
W27-2019	19.2	19.3	18.6

W28-2019	18.1	18.2	17.8

*W17-2019 was lost prior to July 17, 2019.

The average of monthly means for each site for the same time period (July 18 at 12:00 pm to September 8 at 8:45 am) is presented in Figure 4.1. This shows that temperatures typically increased in a downstream direction.

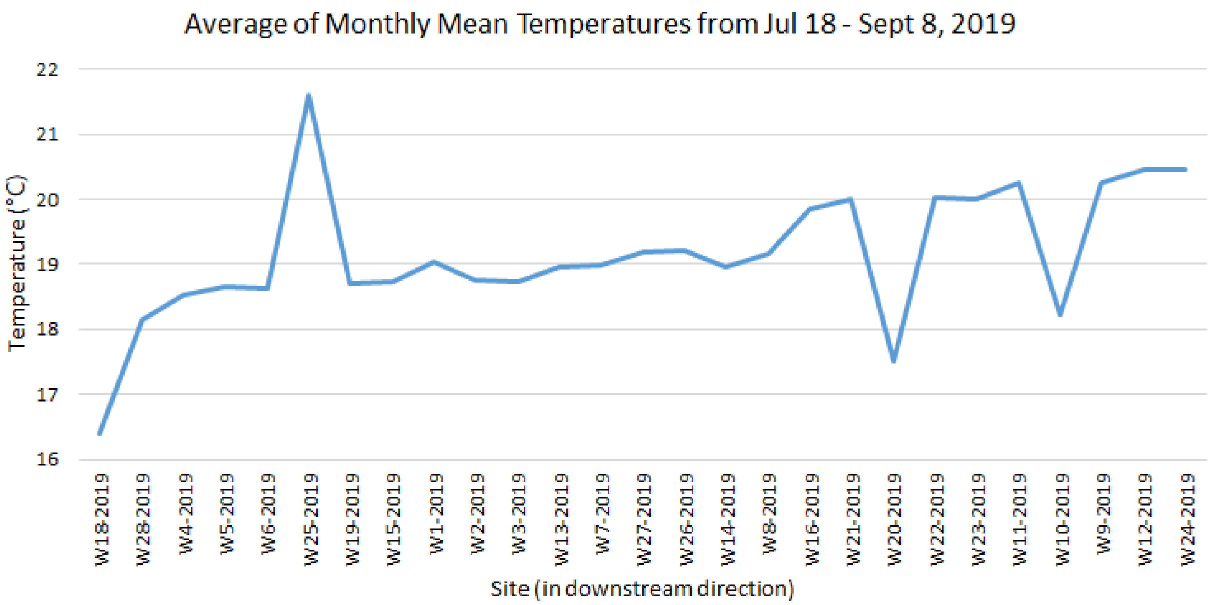

Figure 4.1 Mean water temperatures over study period (average of monthly means) from July 18 to September 8, 2019.

The mean daily temperatures were also compared between each location from July 19 to September 7, 2019. These dates where chosen so that the average of each complete day could be computed, with all loggers recording temperatures on the same days. Figure 4.2 shows a boxplot with the median of the daily means, as well as the variation around these daily means for each logger.

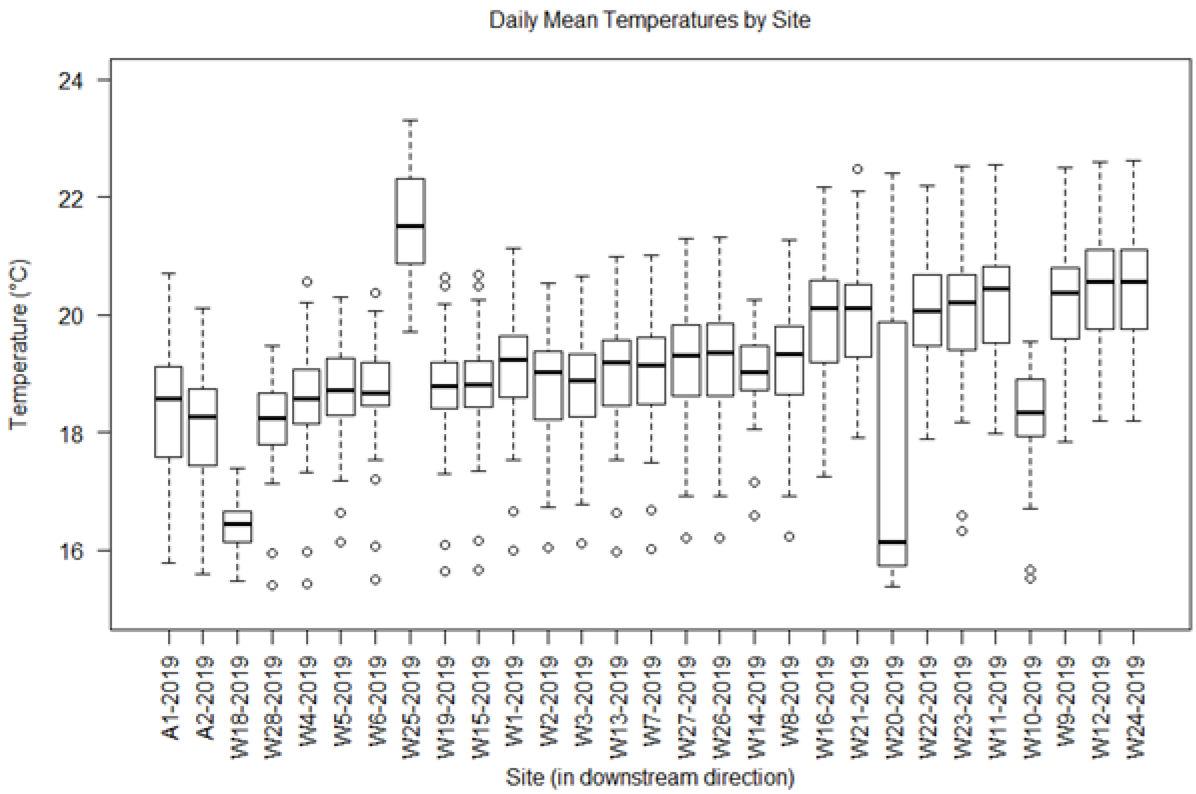

Figure 4.2 Boxplot showing daily medians and variation surrounding mean temperatures from July 19 to September 7, 2019.

Figure 4.3 shows the thermal gradient of the mean daily temperatures from July 19 to September 7 for the 27 water temperature loggers. The precipitation volumes for the same days are presented to the right of the thermal gradient graph.

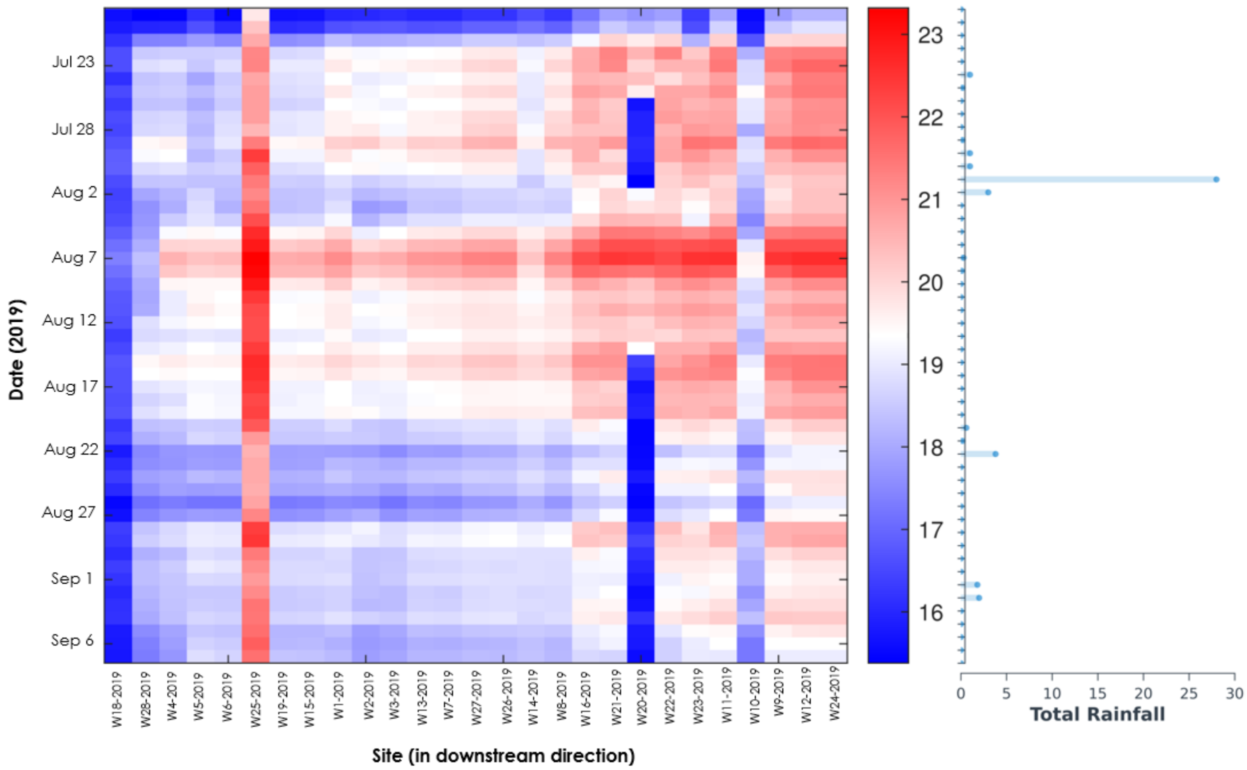

Figure 4.3 Thermal gradient of mean daily temperatures and total daily precipitation volumes from July 19 to September 7, 2019.

Water temperature variance across the 27 monitoring locations can be explained by the first four principal components (Figure 4.4), with a majority (78%) explained by the first principal component. The latter result indicates that the water temperature responses across a majority of the 27 monitoring locations are generally similar in their time-dependent shape. The underlying similarity is evident in the four SOM nodes (Figure 4.5), with one exception (discussed in more detail below).

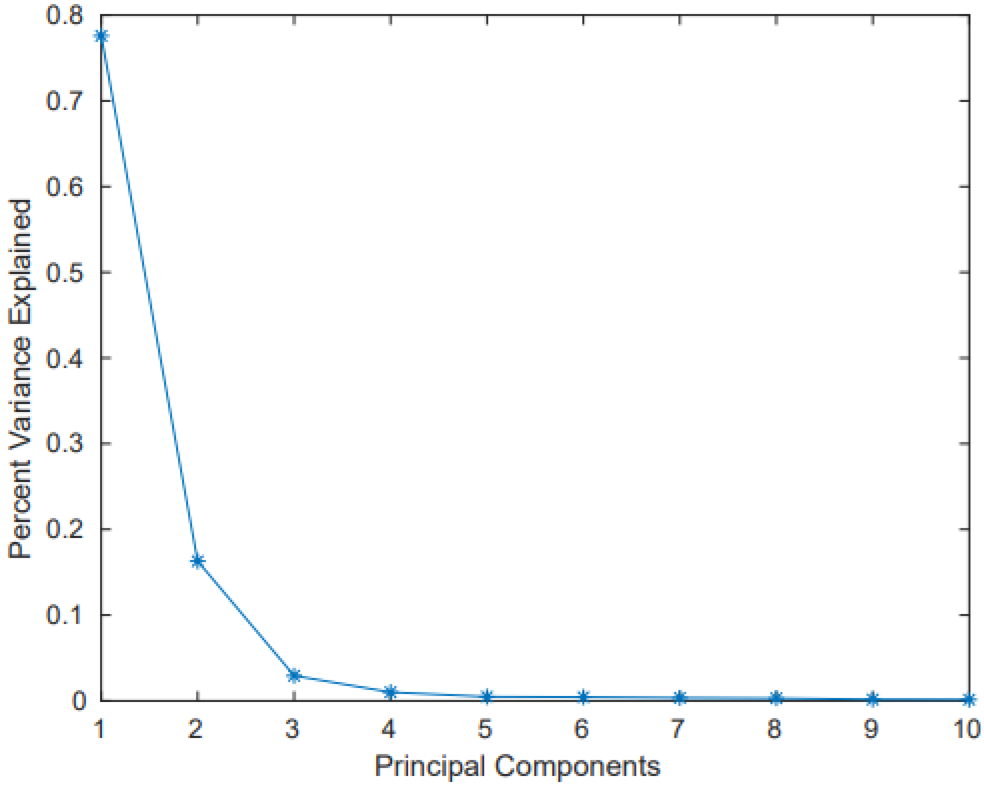

Figure 4.4 Principle component analysis for mean daily temperatures at 27 sites from July 19 to September 7, 2019.

Nodes 1-4 have a warming trend over the first two days of the monitoring period (Figure 4.5). The response curve for Node 1 is cooler across the monitoring period compared to Nodes 2-4, and Node 1 had a cold water response from days 8-16. Nodes 2-4 had elevated water temperatures during the early cool response period of Node 1 (Figure 4.5). Nodes 2, 3, and 4 (Figure 4.5) have overall similar patterns in their respective water temperature curves, however the temperature range varies by up to several degrees Celsius between these three nodes. Node 1 shows a different pattern in its signature water temperature curve, with an overall lower temperature throughout the monitoring period (Figure 4.5). The results of the SOM analysis indicated that fourteen of the sites matched SOM Node 1 (W1-2019 to W7-2019, W10-2019, W13-2019 to W15-2019, W18-2019, W19-2019, and W28-2019), four of the sites matched SOM Node 2 (W8-2019, W23-2019, W26-2019, and W27-2019), one site matched SOM Node 3 (W20-2019), and eight sites matched SOM Node 4 (W9-2019, W11-2019, W12-2019, W16-2019, W21-2019, W22-2019, W24-2019, and W25-2019).

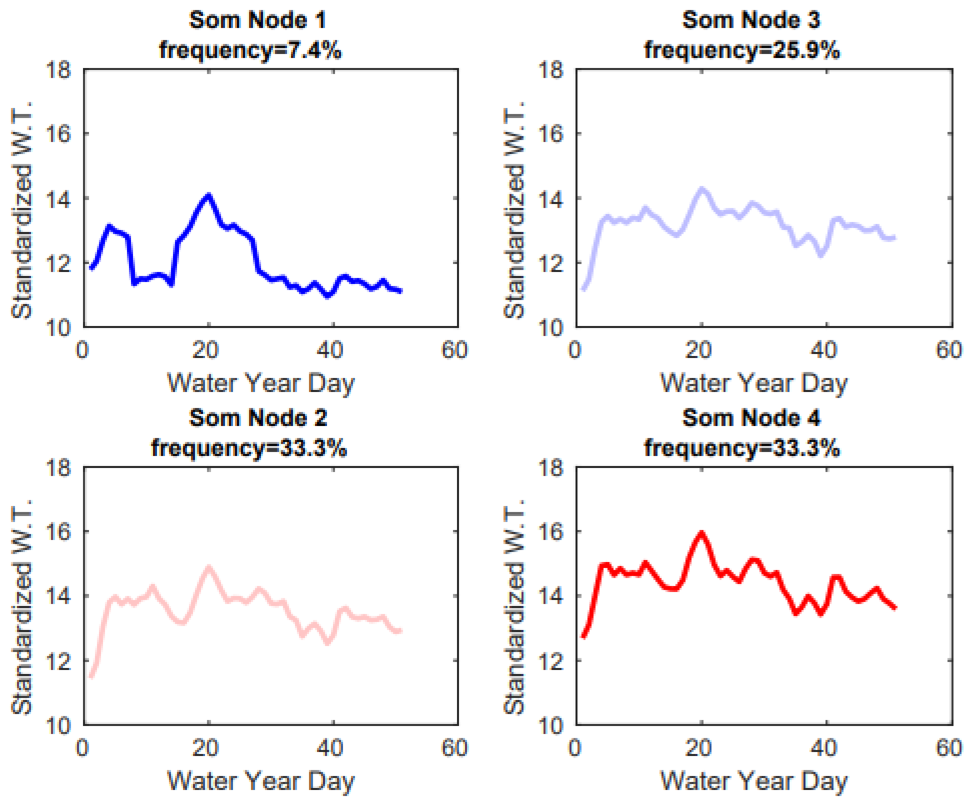

Figure 4.5 SOM nodes showing the four signature water curves for the mean daily temperatures of the 27 sites from July 19 to September 7, 2019.

4.1.2. Comparison between 2019 Water and Air Temperature Loggers

Table 4.2 shows the statistical parameters from the linear regression models.

Table 4.2 Statistical parameters from linear regression model for all loggers.

Site	Paired Air Logger	Intercept (°C)	SE of intercept	Slope	SE of slope	Adjusted p-value	Adjusted r^2 value	Interpretation of Null Hypothesis
W1-2019	A1-2019	6.8	3.2	0.66	0.18	0.029	0.52	Reject
W2-2019	A1-2019	9.5	1.5	0.51	0.084	0.0029	0.75	Reject
W3-2019	A1-2019	6.8	3.2	0.66	0.18	0.029	0.52	Reject
W4-2019	A2-2019	4.0	4.9	0.80	0.28	0.084	0.38	Fail to reject
W5-2019	A2-2019	-1.2	2.3	1.1	0.13	0.00048	0.85	Reject
W6-2019	A1-2019	3.2	4.5	0.83	0.25	0.050	0.46	Fail to reject
W7-2019	A1-2019	8.8	3.9	0.55	0.21	0.13	0.32	Fail to reject
W8-2019	A1-2019	7.7	4.2	0.62	0.23	0.12	0.34	Fail to reject
W9-2019	A1-2019	8.6	2.5	0.64	0.14	0.016	0.62	Reject
W10-2019	A1-2019	6.0	3.2	0.67	0.18	0.029	0.52	Reject
W11-2019	A1-2019	9.2	2.7	0.61	0.15	0.024	0.57	Reject

Site	Paired Air Logger	Intercept (°C)	SE of intercept	Slope	SE of slope	Adjusted p-value	Adjusted r^2 value	Interpretation of Null Hypothesis
W12-2019	A2-2019	10.3	3.1	0.57	0.18	0.053	0.44	Fail to reject
W13-2019	A1-2019	10.3	4.4	0.47	0.24	0.36	0.2	Fail to reject
W14-2019	A1-2019	11.1	3.2	0.43	0.18	0.16	0.31	Fail to reject
W15-2019	A2-2019	2.3	3.2	0.90	0.18	0.016	0.74	Reject
W16-2019	A1-2019	4.1	2.0	0.86	0.11	0.0017	0.85	Reject
W17-2019*	A1-2019	11.1	1.8	0.50	0.10	0.53	0.92	Fail to reject
W18-2019	A2-2019	9.1	1.3	0.40	0.075	0.016	0.78	Reject
W19-2019	A2-2019	1.9	5.1	0.92	0.28	0.094	0.58	Fail to reject
W20-2019	A2-2019	1.8	16.9	0.89	0.94	1.0	-0.01	Fail to reject
W21-2019	A2-2019	5.6	3.0	0.80	0.17	0.029	0.75	Reject
W22-2019	A1-2019	4.4	2.5	0.85	0.13	0.016	0.85	Reject
W23-2019	A2-2019	-0.62	6.0	1.1	0.33	0.084	0.61	Fail to reject
W24-2019	A2-2019	5.9	3.1	0.81	0.81	0.029	0.75	Reject
W25-2019	A2-2019	9.9	4.1	0.65	0.23	0.15	0.50	Fail to reject
W26-2019	A2-2019	4.4	3.0	0.83	0.16	0.031	0.80	Reject
W27-2019	A1-2019	5.0	3.3	0.78	0.18	0.050	0.75	Fail to reject
W28-2019	A2-2019	9.0	5.1	0.51	0.28	0.54	0.27	Fail to reject

Table 4.2 shows that there was not a statistically significant relationship between air and water temperature at 14 of the 28 sites (W4-2019, W6-2019, W7-2019, W8-2019, W12-2019, W13-2019, W14-2019, W17-2019, W19-2019, W20-2019, W23-2019, W25-2019, W27-2019, and W28-2019). The adjusted p-values show that there is a statistically significant relationship between air and water temperature at the remaining 14 sites. The slopes and intercepts derived from the linear regression were plotted in Figure 4.6.

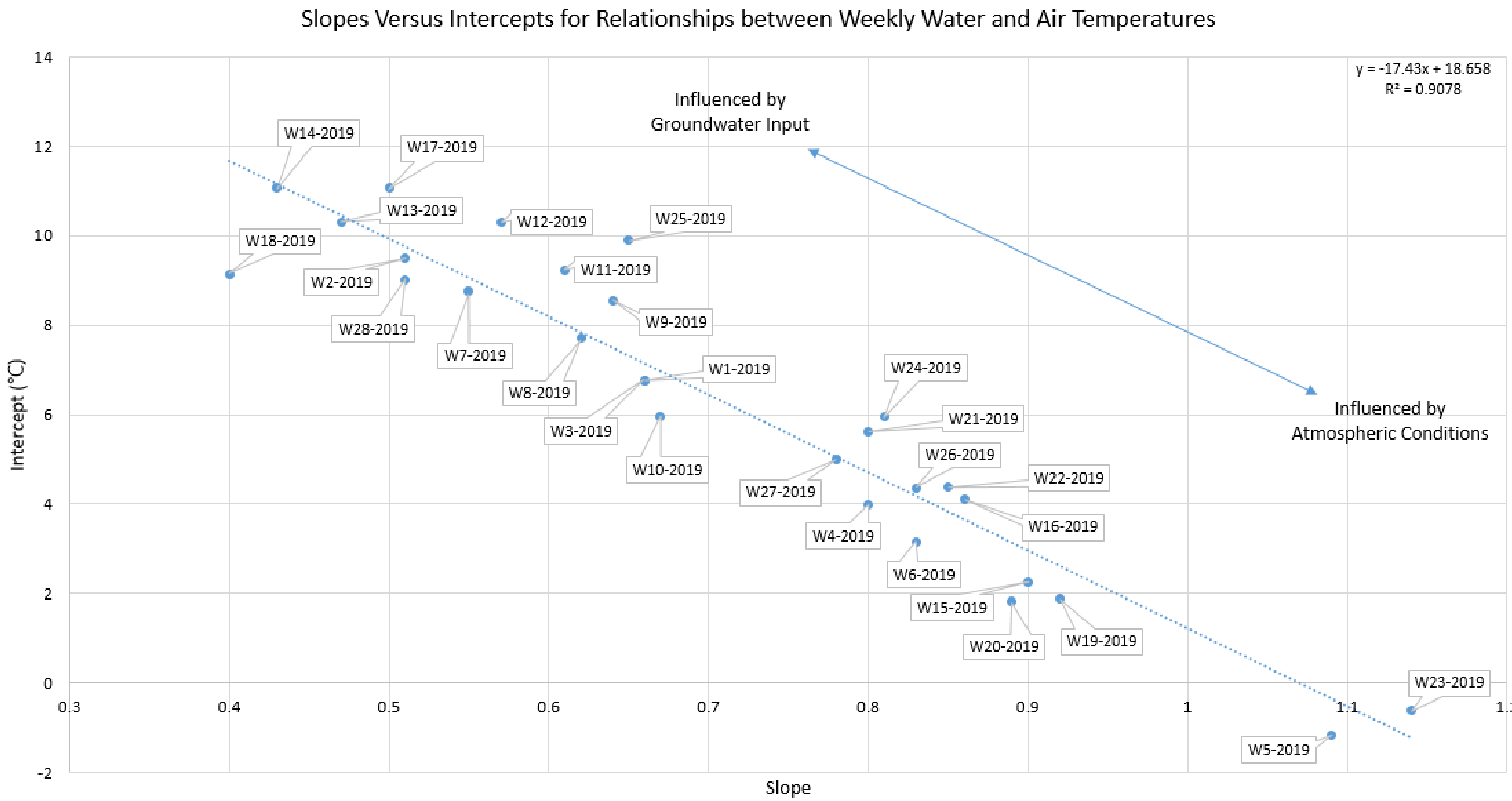

Figure 4.6 Comparison of slopes versus intercepts for the relationship between weekly water and air temperatures for each logger.

Time series graphs comparing water and air temperature logger pairs for a site that did not appear to have groundwater influence (W1-2019) and a site that did appear to have groundwater influence (W20-2019) are presented in Figures 4.7 and 4.8 (including precipitation volumes), respectively.

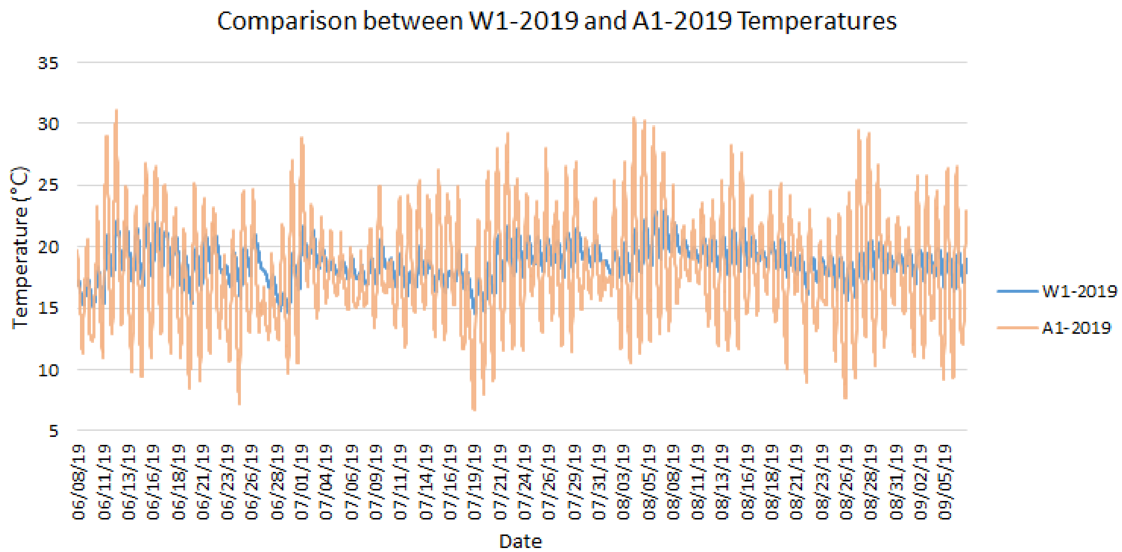

Figure 4.7 W1-2019 and A1-2019 temperatures from June 8 to September 7, 2019.

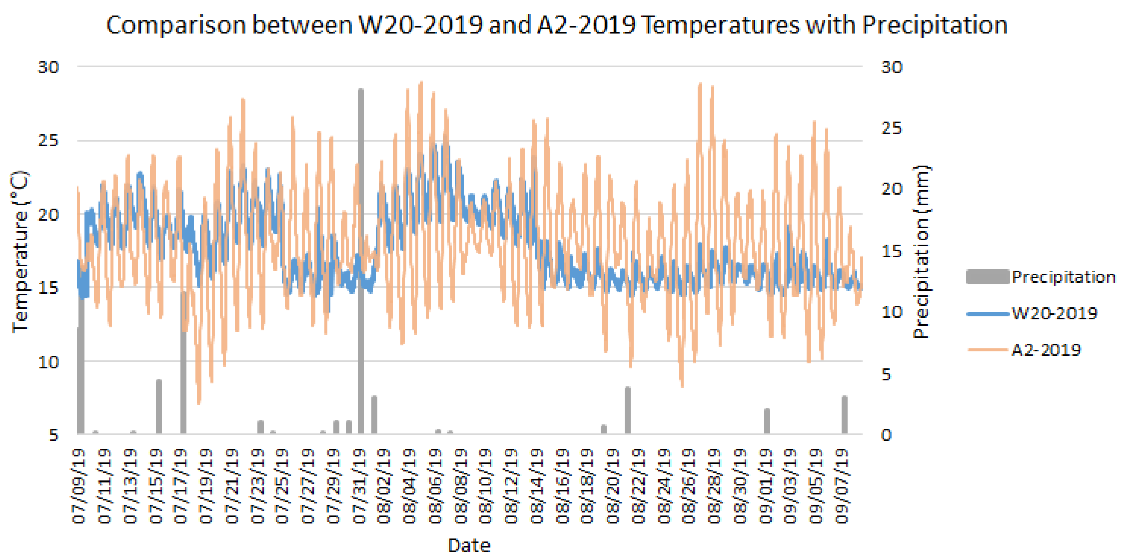

Figure 4.8 W20-2019 and A2-2019 temperatures and precipitation volumes from July 9 to September 9, 2019.

Time series graphs for W1-2019 and W20-2019 with the slopes of trendlines are shown in Figure 4.9 and Figure 4.10 respectively.

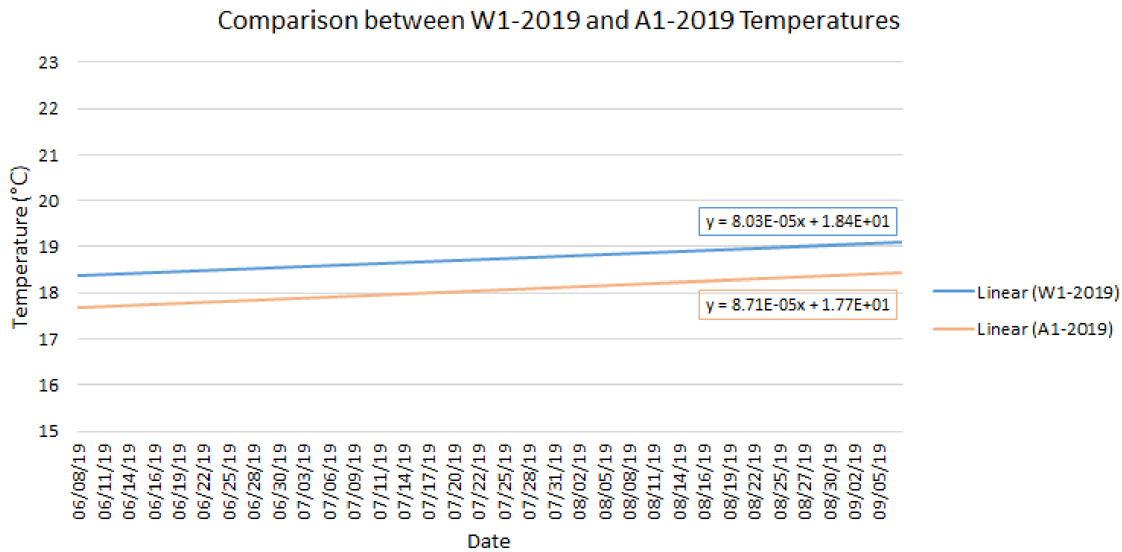

Figure 4.9 The trendlines (showing the slopes) for W1-2019 and A1-2019 from June 8 to September 7, 2019.

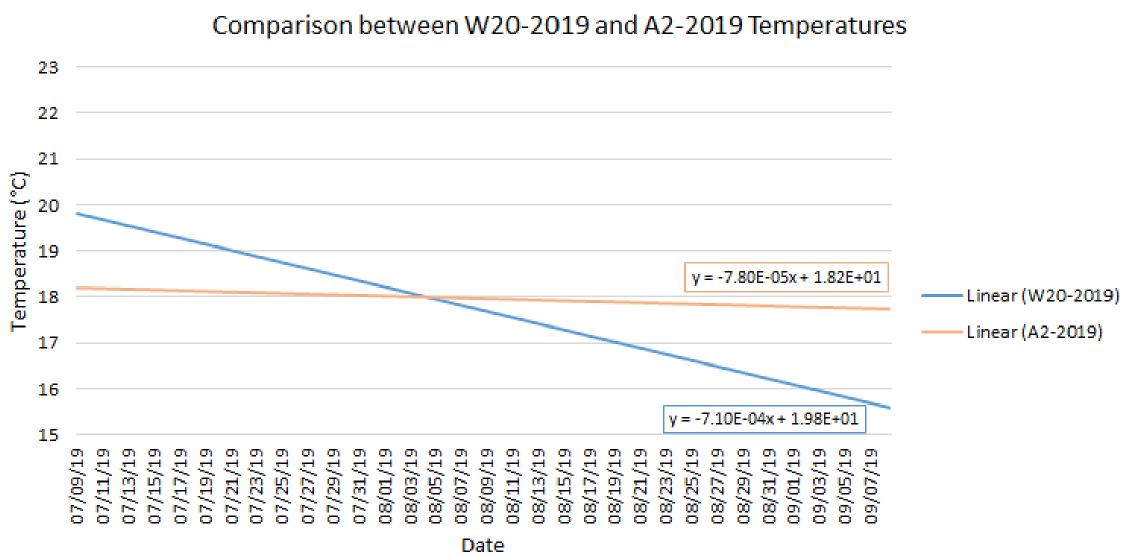

Figure 4.10 The trendlines (showing the slopes) for W20-2019 and A2-2019 from July 9 to September 9, 2019.

The time series graphs for the remaining loggers are presented in Appendix E. An explanation of the results for the various forms of analysis for each site are presented in Appendix F.

4.1.3. Comparison between 2019 and Historical Temperatures

The historical average of daily mean temperatures at the “Lower Tsolum” site ranged from 11.4°C to 19.5°C between 1998 and 2002, compared to the 2019 temperature of 19.9°C at W17-2019 (Table 4.3). Also shown in Table 4.3, the historical average of daily mean temperatures at the “Yew Tree” site were 18.6°C and 14.3°C in 1998 and 1999, respectively, compared to the 2019 temperature of 18.2°C at W28-2019. Figures 4.11 and 4.12 show the mean daily temperatures at W17-2019 and W28-2019 compared to the historical data for the same time period at “Lower Tsolum” and “Yew Tree”, respectively.

Table 4.3 Comparison of historical average of daily mean temperatures and 2019 average of daily mean temperatures for W17-2019 and W28-2019.

Year	Average of daily mean temperatures (°C)	
	W17-2019*	W28-2019**
1998	19.5	18.6
1999	11.4	14.3
2000	18.5	---
2001	18.8	---
2002	17.4	---
2019	19.9	18.2

* Average of daily mean temperatures from June 25 to July 16

** Average of daily mean temperatures from July 19 to September 7

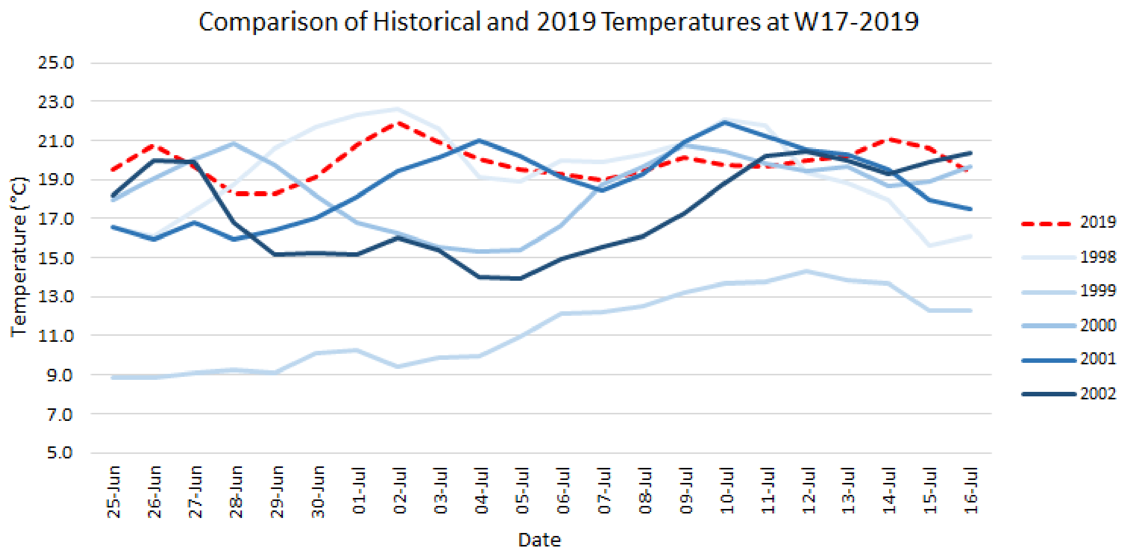

Figure 4.11 Historical mean daily temperatures and 2019 mean daily temperatures at W17-2019 from June 25 to July 16.

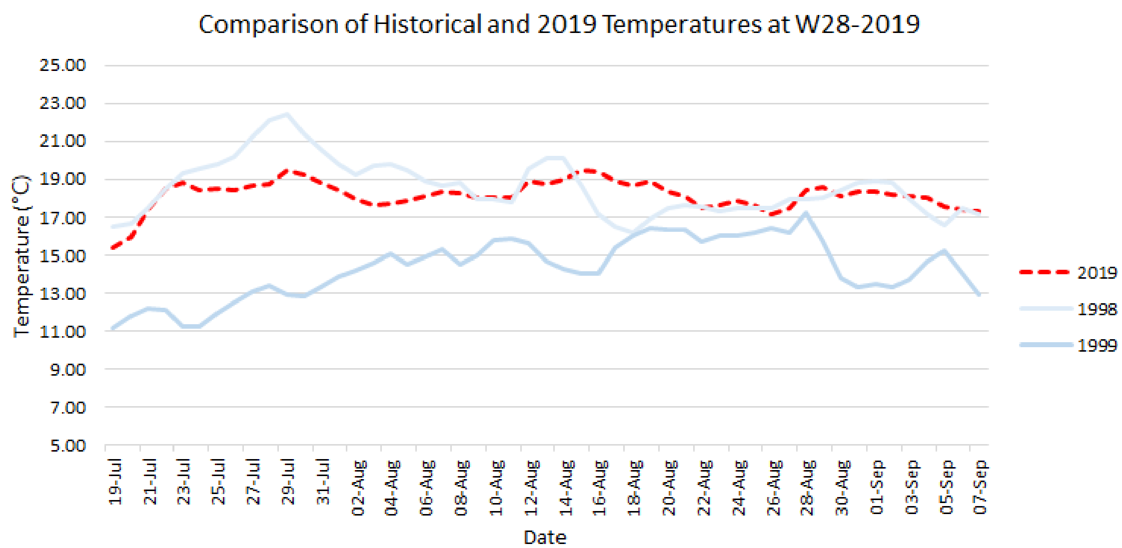

Figure 4.12 Historical mean daily temperatures and 2019 mean daily temperatures at W28-2019 from July 19 to September 7.

4.1.4. Cowichan River Watershed Temperature Results

The mean of the hourly water temperatures at W29-2019 and W30-2019 from August 7 to September 7, 2019 were 15.3°C and 20.4°C, respectively. The mean of the hourly air temperatures at the North Cowichan weather station for the same time period was 18.5°C. Figure 4.13 shows the time series graph of the temperatures at W29-2019, W30-2019, and the North Cowichan weather station throughout the study period. Figure 4.14 shows the trendlines of these temperatures over the same time period and their slopes.

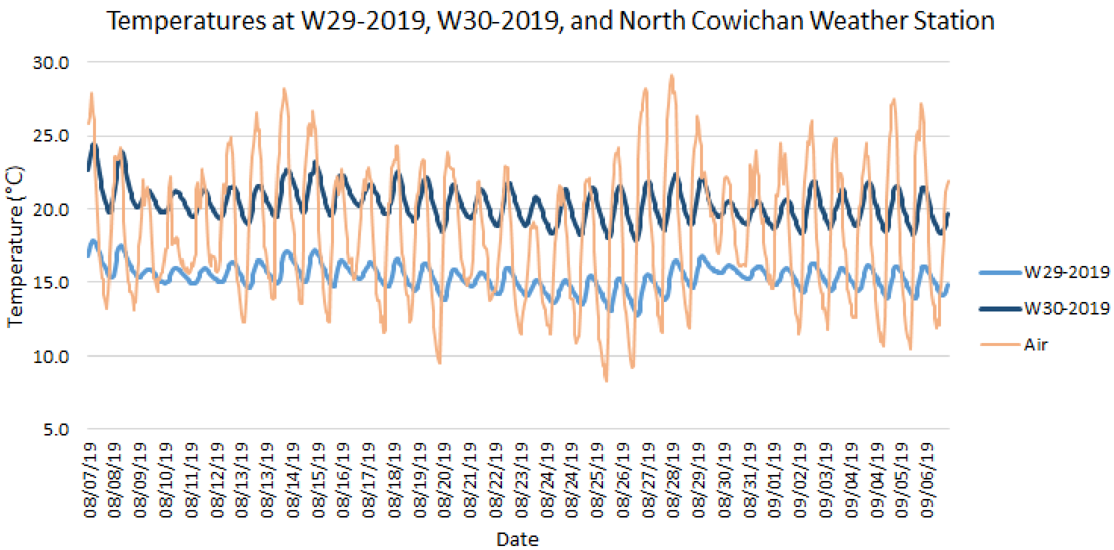

Figure 4.13 Temperatures at W29-2019, W30-2019, and the North Cowichan weather station from August 7 to September 7, 2019.

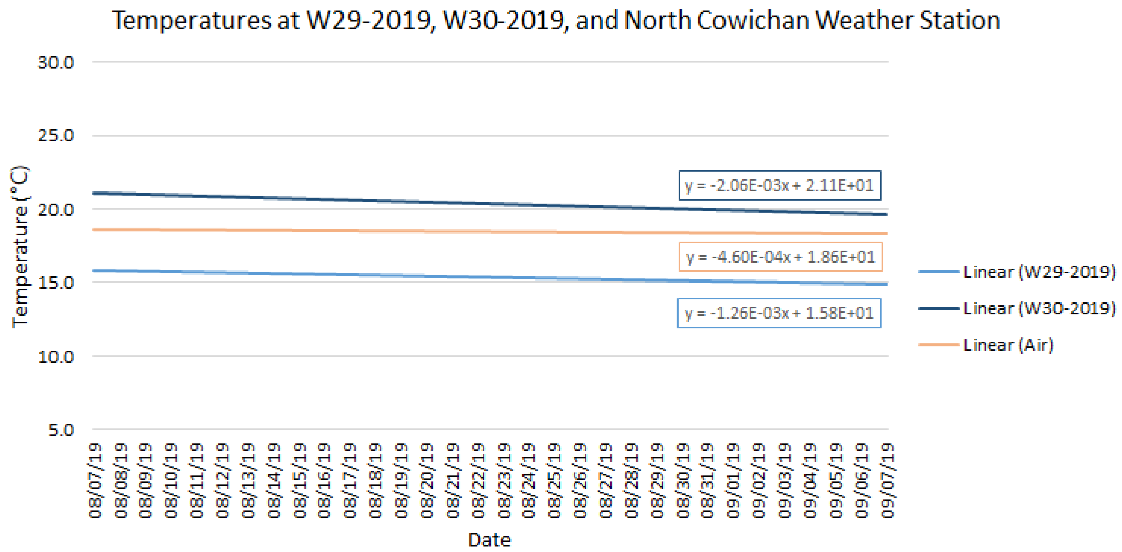

Figure 4.14 The trendlines (showing the slopes) of temperatures at W29-2019, W30-2019, and the North Cowichan weather station from August 7 to September 7, 2019.

4.2. Stream Discharge Results

The stream discharge results throughout the three sampling periods showed that discharge was low during the late June and early July sampling period (ranging from 0.002 m^3/s – 0.45 m^3/s), increased during the late July/early August sampling period (ranging from 0.008 m^3/s – 1.41 m^3/s), and decreased during the late August sampling period to levels similar to the late June/early July sampling period (ranging from 0.002 m^3/s – 0.22 m^3/s) (Table 4.4 and Figure 4.15). The discharge downstream of the tributaries was higher than within the tributaries for all sampling periods. There did not appear to be a consistent trend in discharge levels moving downstream. Stream discharge was measured infrequently due to logistical constraints. Additionally, there were precipitation events during and between the measurements at different sites within the same sampling period (i.e. monthly). As such, the stream discharge data in Table 4.4 is not a reliable indicator of discharge throughout the summer months.

Table 4.4 Total discharge at each sampling station throughout the sampling periods.

Sampling Station	Sampling Date	Total Discharge (m^3/s)
In Headquarters Creek	28-Jun-19	0.11
	02-Aug-19	0.23
	26-Aug-19	0.26
Downstream of Headquarters Creek	26-Jun-19	0.22
	02-Aug-19	1.41
	26-Aug-19	0.33
In Dove Creek	02-Jul-19	0.018
	30-Jul-19	0.021
	28-Aug-19	0.018
Downstream of Dove Creek	02-Jul-19	0.45
	30-Jul-19	0.37
	28-Aug-19	0.33
In Portuguese Creek	02-Jul-19	0.002
	06-Aug-19	0.008
	27-Aug-19	0.002
Downstream of Portuguese Creek	03-Jul-19	0.39
	05-Aug-19	0.91
	27-Aug-19	0.32

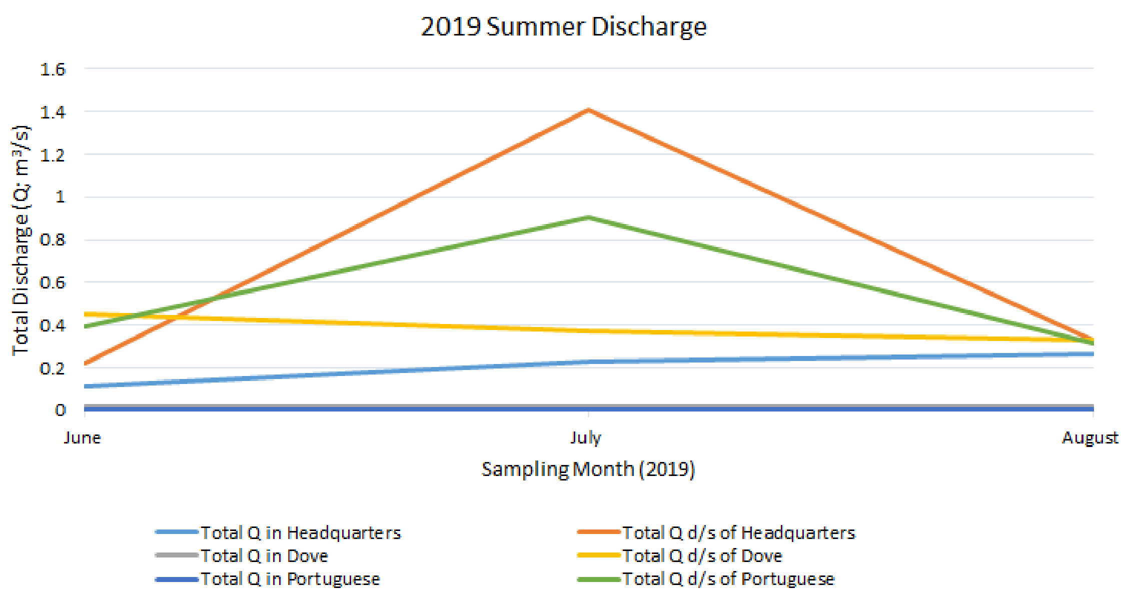

Figure 4.15 Total discharge for all sampling stations throughout the study period.

The primary water level and discharge data from June 6 to September 15, 2018 and 2019 from the WSC Tsolum River near Courtenay 08HB011 Station are shown in Figures 4.16 and 4.17, respectively (Government of Canada 2014). Annual discharge data from 2017, 2018, and 2019 for the Tsolum River near Courtenay 08HB011 Station are presented in Appendix G (Government of Canada 2014).

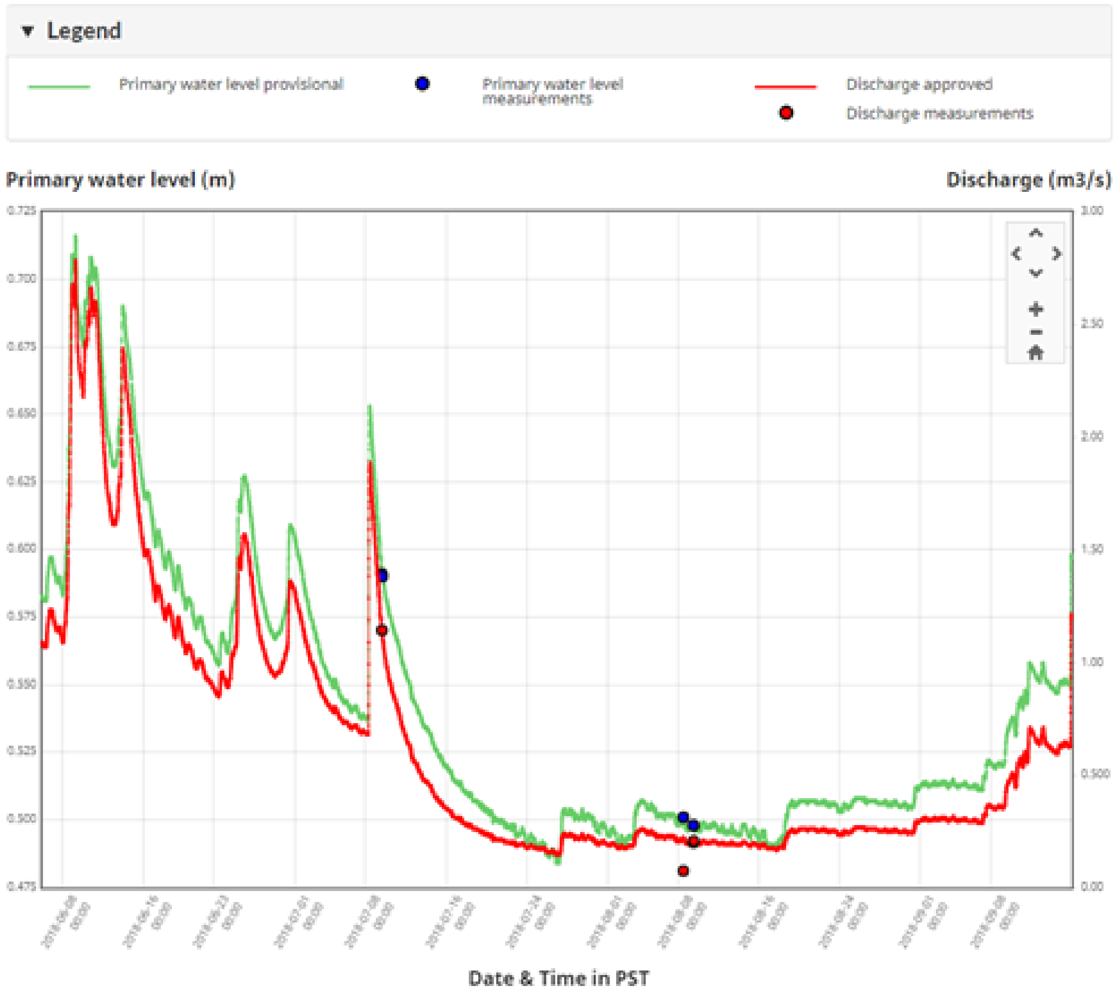

Figure 4.16 Primary water level and discharge at Tsolum River near Courtenay 08HB011 Station from June 6 to September 15, 2018 (Government of Canada 2014).

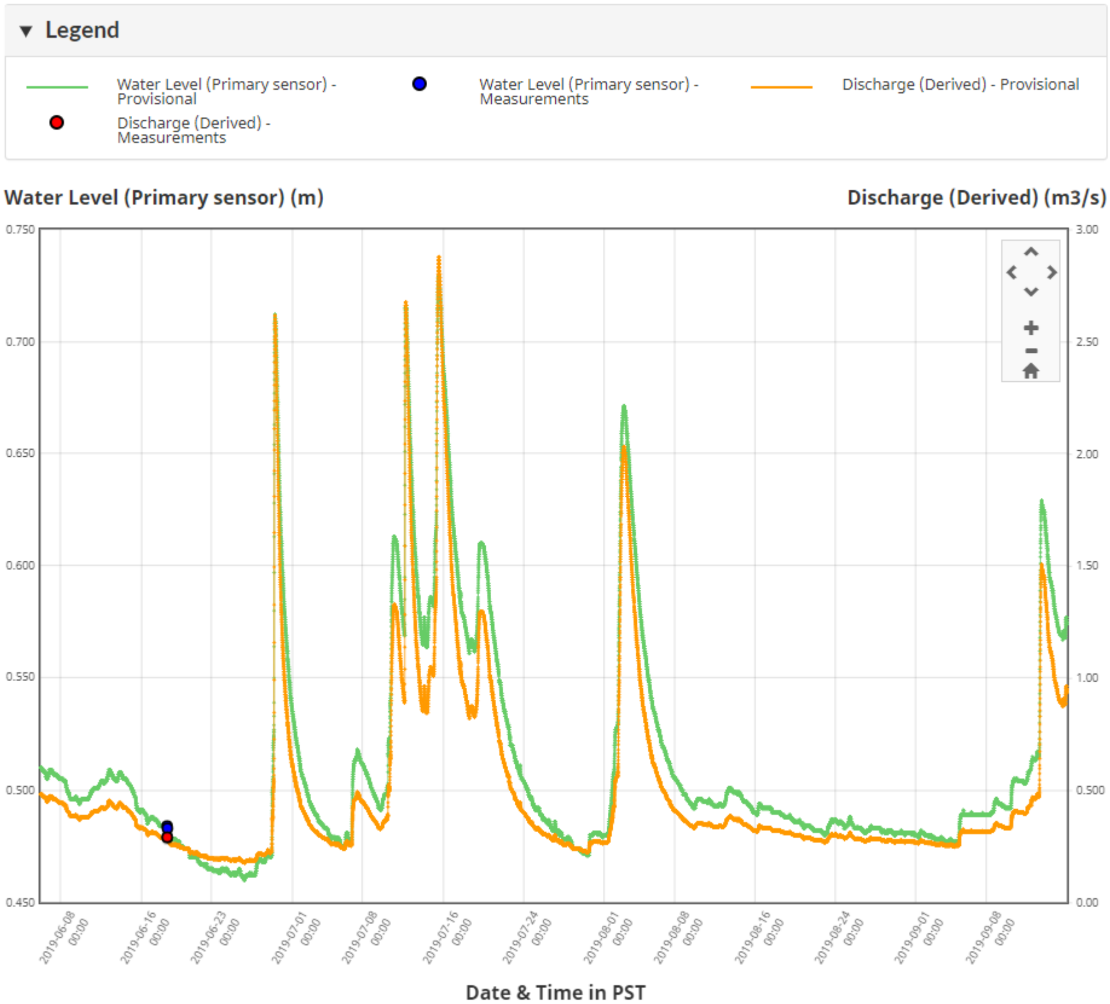

Figure 4.17 **Primary water level and discharge at Tsolum River near Courtenay 08HB011 Station from June 6 to September 15, 2019 (Government of Canada 2014).**

4.3. Riparian Vegetation Assessment Results

The percent riparian cover calculated at each logger in the Tsolum River watershed is shown in Table 4.5. The percent riparian cover was less than 50% at 16 sites and greater than 50% at 14 sites. The air temperature logger that each water temperature logger was compared to according to percent riparian cover is also shown in Table 4.5.

Table 4.5 Percent riparian cover measured at each logger in August 2019.

Site	% Riparian Cover	Comparative Air Temperature Logger
A1-2019	6.5	---
A2-2019	99.8	---
W1-2019	17.9	A1
W2-2019	29.6	A1
W3-2019	8.6	A1
W4-2019	52.3	A2
W5-2019	80.1	A2
W6-2019	32.0	A1
W7-2019	28.6	A1
W8-2019	32.5	A1
W9-2019	8.6	A1
W10-2019	36.4	A1
W11-2019	8.3	A1
W12-2019	73.3	A2
W13-2019	21.3	A1
W14-2019	11.7	A1
W15-2019	95.7	A2
W16-2019	17.2	A1
W17-2019	23.1	A1
W18-2019	77.0	A2
W19-2019	79.8	A2
W20-2019	54.3	A2
W21-2019	90.7	A2
W22-2019	23.1*	A1
W23-2019	78.3**	A2
W24-2019	73.3	A2
W25-2019	97.2	A2
W26-2019	73.6	A2
W27-2019	34.6	A1
W28-2019	82.9	A2

* Centre measurement used here since too deep at logger - closest to centre
** Right bank measurement used here since too deep at logger - closest to right bank

The results from the riparian assessment that was conducted in 2014 by D.R. Clough Consulting are presented in Table 4.6. The average percent riparian cover measured during the 2019 study along the transect where each logger was located is also presented in Table 4.6. All of the reaches where loggers were located had poor to fair riparian cover except for the reference site (W18-2019) which had good riparian cover (Table 4.6).

Table 4.6 Percent riparian cover and rating of cover from 2014 FHAP riparian assessment and percent riparian cover for logger transects from 2019 study.

Site	Reach	% Riparian Cover*	Result/Rating of Riparian Cover*	Average % Riparian Cover from Densiometer**
W1-2019	T6	62	Fair; 3	35.2
W2-2019	D1	68	---	29.9
W3-2019	T5	58.5	Fair; 3	12.8
W4-2019	T7	55.5	Fair; 3	69.8
W5-2019	HQ1	68.5	---	78.5
W6-2019	T6	62	Fair; 3	75.1
W7-2019	T5	58.5	Fair; 3	24.0
W8-2019	T5	58.5	Fair; 3	32.2
W9-2019	T2	49.5	Fair; 3	27.2
W10-2019	P1	39	---	79.4
W11-2019	T3	34	Poor; 5	21.9
W12-2019	T1	48	Fair; 3	60.2
W13-2019	T5	58.5	Fair; 3	20.3
W14-2019	T5	58.5	Fair; 3	30.1
W15-2019	T6	62	Fair; 3	76.4
W16-2019	T5	58.5	Fair; 3	22.1
W17-2019	T1	48	Fair; 3	34.5
W18-2019	T12	90.5	Good; 1	85.2
W19-2019	T6	62	Fair; 3	81.5
W20-2019	T3	34	Poor; 5	39.2
W21-2019	T3	34	Poor; 5	59.4
W22-2019	T3	34	Poor; 5	42.8
W23-2019	T3	34	Poor; 5	45.4
W24-2019	T1	48	Fair; 3	53.7
W25-2019***	HQ3	---	---	97.7
W26-2019	T5	58.5	Fair; 3	45.6
W27-2019	T5	58.5	Fair; 3	29.6
W28-2019	T7	55.5	Fair; 3	81.6

* Results from FHAP by D.R. Clough Consulting (2014).
** Results from densiometer measurements from 2019 temperature study (average of left bank, centre, and right bank at each transect).
*** HQ3 was not surveyed during FHAP, therefore there are no riparian assessment results for that reach.

4.4. Methodology Testing Results

4.4.1. Specific Conductance Results

The specific conductance measured at each of the monitoring sites in August 2019 ranged from 36 µS/cm to 106 µS/cm (Figure 4.18).

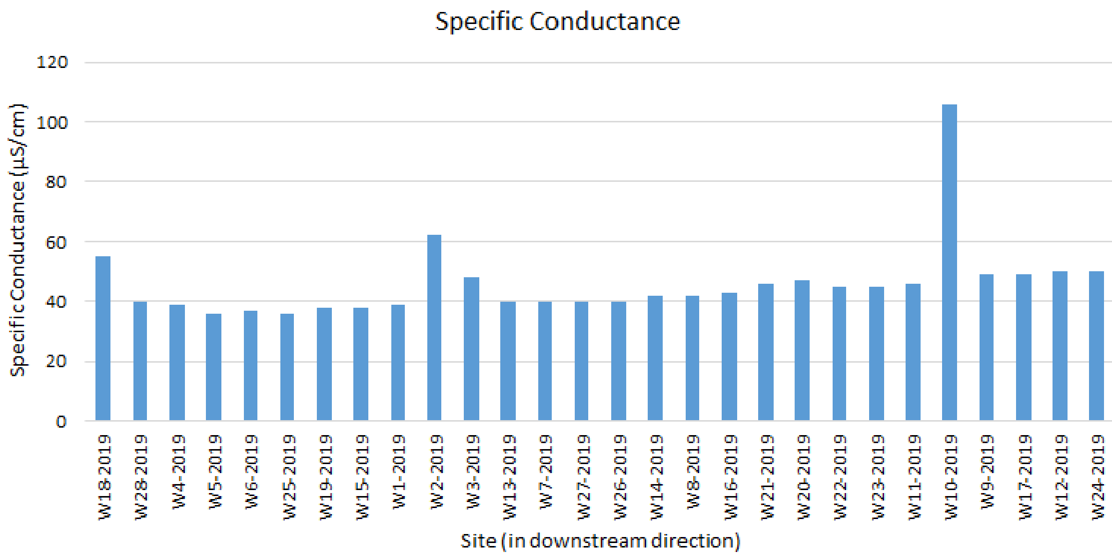

Figure 4.18 Specific conductance measurements from August 2019 at each site.

4.4.2. Longitudinal Temperature Measurement Results

The temperatures of both the surface and streambed loggers were similar until approximately 13:05:30, where Streambed-2019 dropped off steeply, becoming approximately 2°C cooler (Figure 4.19). Streambed-2019 stayed cooler than Surface-2019 until approximately 13:21:10 where the temperatures of the two loggers nearly converged, followed by an increase in the temperature of Surface-2019 and a decrease in the temperature of Streambed-2019 immediately afterwards (Figure 4.19). The temperature of Surface-2019 decreased steadily as the loggers were dragged downstream, starting at 12:45:58 and ending at 13:27:27 (Figure 4.19). The temperature of Surface-2019 ranged from 20.4°C to 22.3°C, a difference of 1.9°C over the length of the logger drag. The temperature of Streambed-2019 ranged from 19.3°C to 22.5°C, with a larger difference of 3.2°C throughout the logger drag, showing greater variability in temperatures.

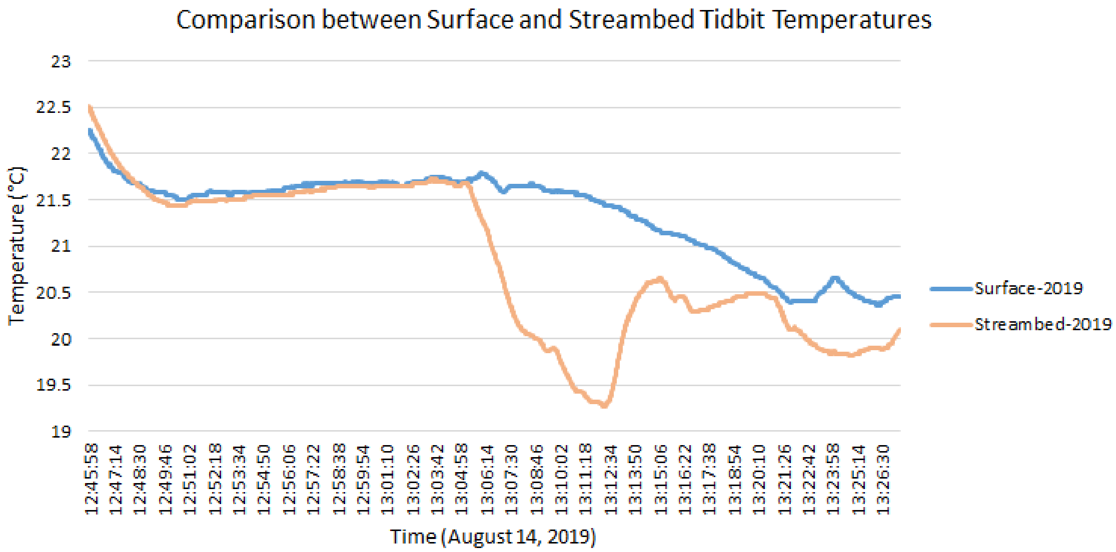

Figure 4.19 Comparison between temperatures of Surface-2019 and Streambed-2019 loggers during testing of the longitudinal logger drag on August 14, 2019.

4.4.3. Forward-Looking Infrared Radar Drone Survey Results

The FLIR drone only identified hotspots within the river, which were areas where temperatures exceeded 40°C. It was not possible to stitch the images into a single orthomosaic for each surveyed section due to the low resolution of the thermal images. Additionally, the single line of photos over the thalweg at each section resulted in insufficient geometry which did not allow for the creation of the orthomosaic.

4.5. Wolf Lake Physiochemical Sampling Results

Temperatures decreased with depth at both N-2019 and S-2019 (Figures 4.20 and 4.21, respectively). The temperature was 6.4°C at the deepest point and 23.1°C at the surface at N-2019 as shown in Table H-1 in Appendix H. Also shown in Table H-1, the temperature was 14.4°C at the deepest point and 22.8°C at the surface at S-2019. Conversely, DO concentrations increased with depth as temperatures decreased at both N-2019 and S-2019 (Figures 4.20 and 4.21, respectively). The DO concentrations were 10.6 mg/L at the deepest point and 8.4 mg/L at the surface at N-2019 (Table H-1). The DO concentrations were 10.0 mg/L at the deepest point and 7.7 mg/L at the surface at S-2019 (Table H-1).

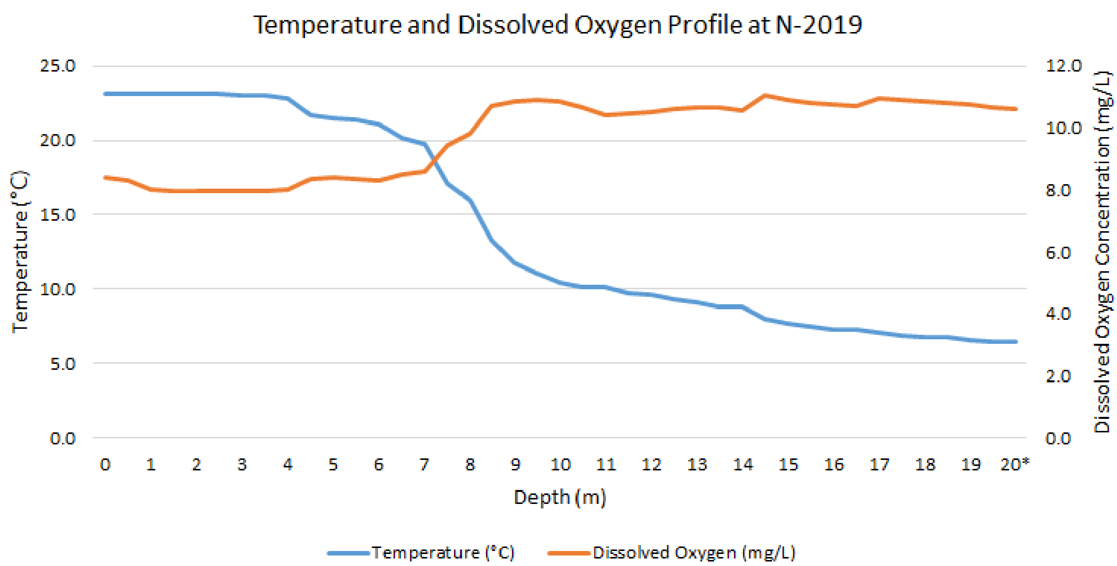

Figure 4.20 **Profile of temperature and dissolved oxygen concentrations from the surface to a depth of 20 m at N-2019 in Wolf Lake on August 9, 2019.**

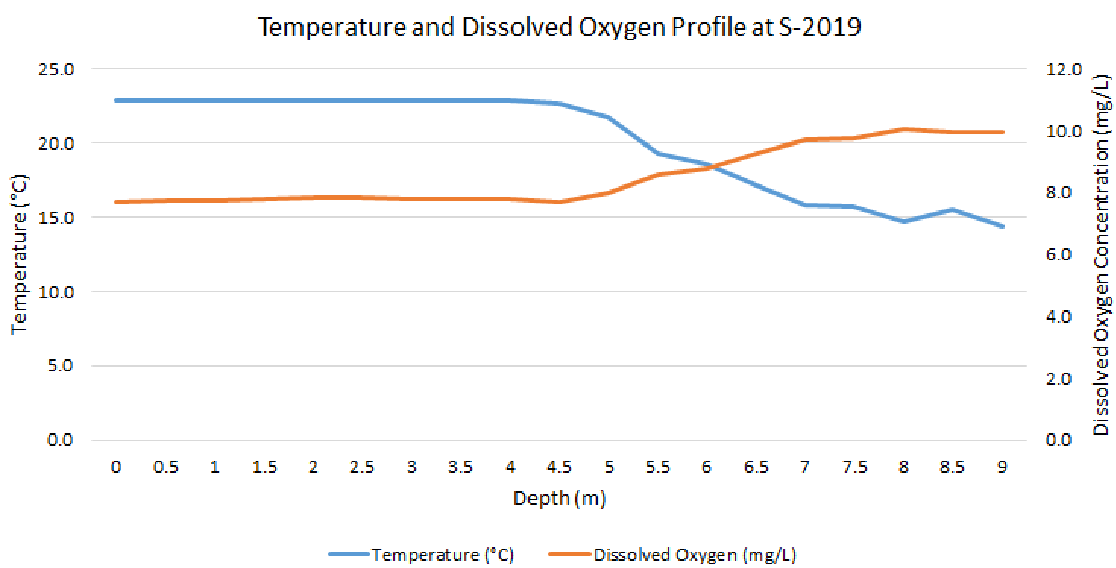

Figure 4.21 **Profile of temperature and dissolved oxygen concentrations from the surface to a depth of 9 m at S-2019 in Wolf Lake on August 9, 2019.**

Chapter 5. Discussion

5.1. Temperature

5.1.1. Tsolum River Temperature Study

Figures 4.1 to 4.3 show that water temperature in the Tsolum River increases steadily in a downstream direction, as is typical for streams (Caissie 2006). There are a few exceptions to this trend, including W20-2019 and W10-2019, which were cooler, despite being lower in the watershed. The mean monthly temperatures for each logger show that temperatures increased from July to August and decreased in September (Table 4.1).

W25-2019 had the highest monthly and daily averages, and W10-2019, W18-2019, and W20-2019 had the coolest monthly and daily averages (Figures 4.1 to 4.3). W10-2019 was located in close proximity to W9-2019 and W11-2019, and it was approximately 2°C cooler than the loggers during July, August, and September. Similarly, W20-2019 was 2-3°C cooler during the summer months than W21-2019 to W23-2019, which are located nearby. W10-2019 and W20-2019 were located in the downstream reaches near the air temperature loggers, however they were cooler than the remaining temperature loggers nearby. This suggests that there may be other factors driving the stream temperature at W10-2019 and W20-2019 besides air temperature. Figure 4.3 shows that the temperatures at W20-2019 were cool throughout the majority of the study period, except after large rain events. This suggests that rain may be mixing with the stream water, masking the cool groundwater signal, as has been shown in other studies (Kaandorp et al. 2019).

W25-2019 was located in the by-pass channel at the outlet of Wolf Lake, into which surface water was spilling. The high temperatures are likely due to the warm surface water from Wolf Lake, as explained in Section 5.5. Besides W25-2019, the warmest locations in the Tsolum River watershed were W9-2019, W11-2019, W12-2019 and W21-2019 to W24-2019 (Figures 4.1 to 4.3), which were all located in the lower 4.5 km of the river (Figure 3.1 and Figure C-5 in Appendix C). These are the reaches where pastures for dairy production and residential properties are located and where the majority of water extraction occurs (D.R. Clough Consulting 2014; Metherall 2019).

The average monthly summer stream temperatures surpassed the optimal juvenile coho rearing threshold of 17ºC (Table 1.1) at all sites, with the exception of W18-2019 (reference site) in July, August, and September and W20-2019 (potential groundwater site) in September (Table 4.1). The average monthly stream temperatures from July to September at all other loggers ranged from 17.7ºC to 21.9ºC (Table 4.1). This is concerning since coho fry were observed in the Tsolum River during these summer months. The optimal juvenile rearing threshold for coho is higher than for chinook and chum, which are 14.8ºC and 15ºC, respectively (Table 1.1). As such, the monthly average stream temperatures at all sites were higher than the optimal rearing threshold for both chinook and chum. The lethal juvenile rearing thresholds are 20ºC, 21ºC, and 23ºC for sockeye, chum, and coho, respectively (Table 1.1). The monthly average temperatures exceeded the lethal threshold for sockeye in July and August at W9-2019, W11-2019, W12-2019, W21-2019, W22-2019, and W25-2019 (Table 4.1). All of these sites were located in the lower 4.5 km of the river (Figure 3.1 and Figure C-5 in Appendix C), with the exception of W25-2019 which was located at the outflow of Wolf Lake (Figure C-2 in Appendix C). The monthly average stream temperatures at W25-2019 also exceeded the lethal threshold for chum in August and September (Table 4.1). The monthly average stream temperatures did not exceed the lethal threshold for coho at any of the sites.

The SOMs show that the sites that are most similar to Node 1 (W1-2019 to W7-2019, W10-2019, W13-2019 to W15-2019, W18-2019, W19-2019, and W28-2019) are cooler than the sites that are most closely associated with Nodes 2 to 4. With the exception of W10-2019, all of these sites are in the upstream areas of the study area (approximately 15.1 river km to 31.8 river km upstream of the estuary), which could be the reason for the cooler temperatures (Figures 4.1 to 4.3). W10-2019 is located in Portuguese Creek, which has previous accounts of groundwater influence (Metherall 2019), therefore groundwater could be contributing to the cooler temperatures in this location. Node 4 shows warmer temperatures than Nodes 1 to 3. All of the sites except W25-2019 that are most characteristic of Node 4 (W9-2019, W11-2019, W12-2019, W16-2019, W21-2019, W22-2019, W24-2019, and W25-2019) are located in the downstream sections of the study area (approximately 3.4 river km to 10.5 river km upstream of the estuary). W25-2019 is at the outlet of Wolf Lake, which had the highest average temperatures compared to all of the monitoring sites (Figures 4.1 to 4.3).

Although is it possible that the four signature water temperature curves indicate sites where there is groundwater influence, the differences in temperature patterns seem to be correlated with the location of the sites within the watershed. The coolest sites (Node 1) are primarily in the upper section of the study area, the sites most similar to Nodes 2 and 3 are in the mid-sections of the study area and the warmest sites (Node 4) are primarily in the lower section of the study area. As such, the SOM results have not been included in the analyses used to determine potential groundwater influence (Table 5.1).

Based on the linear regression results (p-value interpretations, intercepts, and slopes) as well as the time series graphs, it does not appear that there is groundwater input at W1-2019, W3-2019, W5-2019, W15-2019, W16-2019, W21-2019, W22-2019, W24-2019, or W26-2019. There are no contradictory results for these nine sites, with air temperature likely driving the stream temperature in these locations. Conversely, the linear regression results and the time series graphs show that there may be groundwater input at W7-2019, W8-2019, W12-2019, W13-2019, W17-2019, and W28-2019. There are no contradictory results for these six sites, therefore air temperature does not appear to be the primary factor driving stream temperatures at these locations.

Other than at W13-2019, groundwater inputs were not observed during the 2019 study, therefore it cannot be conclusively stated that groundwater is the primary driver of stream temperature at the aforementioned six sites. Seepage along the right bank beside W13-2019 was observed, and its temperature was measured using a handheld thermometer. The temperature of the water seeping out of the bank was 11ºC, which is within the range of the expected groundwater temperature in the Comox Valley. Therefore, based on the cooler seepage and the results of the linear regression and time series graphs, it appears likely that there is groundwater input near W13-2019. W7-2019 was installed approximately 75 m downstream and also showed signs of groundwater input based on the linear regression and time series results.

There are contradictory results for W2-2019, W4-2019, W6-2019 W9-2019, W11-2019, W14-2019, W18-2010, W19-2019, W20-2019, W23-2019, W25-2019, and W27-2019. Table 5.1 shows whether each form of analysis indicated groundwater input, as well as which sites should be monitored in the future. A detailed explanation of the results of each analysis method for each site are presented in Appendix F.

Table 5.1 Indication of groundwater at each site from each analysis.

Site	Indicates potential for groundwater influence (Y/N/Unclear)			Recommend further studies (Y/N)
	p-value Interpretation from Linear Regression	Slope and Intercept from Linear Regression	Slope of Trendlines from Time Series Graphs	
W1-2019	N	N	N	N
W2-2019	N	Y	Y	Y
W3-2019	N	Unclear	N	N
W4-2019	Y	Unclear	N	N
W5-2019	N	N	N	N
W6-2019	Y	N	N	N
W7-2019	Y	Y	Y	Y
W8-2019	Y	Y	Y	Y
W9-2019	N	Y	Y	Y
W10-2019	N	Unclear	Y	Y
W11-2019	N	Y	Y	Y
W12-2019	Y	Y	Y	Y
W13-2019	Y	Y	Y	Y
W14-2019	Y	Y	N	Y
W15-2019	N	N	N	N
W16-2019	N	N	N	N
W17-2019*	Y	Y	Y	Y
W18-2019	N	Y	N	N
W19-2019	Y	N	N	N
W20-2019	Y	N	Y	Y
W21-2019	N	N	N	N
W22-2019	N	N	N	N
W23-2019	Y	N	Y	N
W24-2019	N	N	N	N
W25-2019	Y	Y	N	Y
W26-2019	N	N	N	N
W27-2019	Y	N	N	N
W28-2019	Y	Y	Y	Y

* Only three weeks of data for W17-2019 since logger was lost, therefore further studies need to be conducted to confirm the potential for groundwater input

There are several factors that may be causing the contradictory results at the aforementioned sites. These include proximity to Portuguese Creek, stream depth, and precipitation.

W9-2019 is downstream of Portuguese Creek and W10-2019 is in Portuguese Creek where groundwater inputs have previously been observed (Metherall 2018). They both show signs of groundwater, however the signal is weak and there is a statistically significant relationship between air and groundwater at these sites. This suggests that upstream Portuguese groundwater inputs may be slightly influencing stream temperatures at W9-2019 and W10-2019, however water temperatures are still dependent on air temperatures.

Stream temperatures at W19-2019 increased while air temperatures decreased, and the relationship between the two was not statistically significant. However, due to the warm temperatures it is unlikely that groundwater is influencing W19-2019. This decoupling of stream and air temperatures may be due to the relatively shallow water depth at W19-2019 (0.5 m; Table A-1 in Appendix A). Shallower sections of streams typically increase in temperature more rapidly compared to deeper sections (Kaandorp et al. 2019). Conversely, W23-2019 was located in a deep pool (2.6 m; Table A-1 in Appendix A). The time series graphs for W23-2019 showed the potential for groundwater input, however, it is likely the pool depth that is responsible for this cooling effect, since the slope and intercept from the linear regression indicate that stream temperatures at W23-2019 are primarily influenced by atmospheric conditions. Deeper pools can absorb a greater amount of heat energy than shallow sections, thus heating up more slowly (Kaandorp et al. 2019). Temperatures in the bottom of pools often provide a buffered temperature signal, similar to that of groundwater input (Kaandorp et al. 2019). This is because pool temperatures are less sensitive to changing air temperatures than shallower sections of the stream due to the greater volume of water (Kaandorp et al. 2019).

It is likely that there is an inflow of cooler groundwater at W20-2019, since the average stream temperatures at W20-2019 were cooler throughout the study period compared to other sites, despite being farther downstream. The linear regression results and time series graphs also indicated that groundwater could be influencing stream temperatures at W20-2019. As shown in Figure 4.8, the temperature at W20-2019 remained relatively steady and was cooler than the air temperature for two periods in July and August. Stream temperatures appeared to track air temperatures for the remaining study period. Daily precipitation volumes are also presented in Figure 4.8, showing that stream temperatures tracked air temperatures more closely after large rain events. Water temperatures were warmer than air temperatures at the start of the study period, matching the time period when water temperature tracked air temperature. However, water temperatures became cooler than air temperatures in August, remaining stable as air temperatures fluctuated diurnally. Figure 4.8 shows that precipitation volumes were low during this time period. It has been shown that stream temperatures can increase due to rain events, therefore if there is groundwater input at W20-2019, the signal may have been dampened due to the warming effects of rain after precipitation events (Kaandorp et al. 2019). The standard deviation around the mean daily temperatures was the largest for W20-2019, as shown in Figure 4.2. Typically, lower average daily standard deviations indicate groundwater influence in a stream since groundwater temperatures have less daily variation (Kaandorp et al. 2019). However, due to the effects of precipitation potentially muting the groundwater signal at various times throughout the summer, the water temperature at W20-2019 varied considerably. The cooling effect that groundwater had at W20-2019 was minimized after large rain events.

There are 12 sites that have the potential for groundwater input based on 2019 results (Figure 5.1).

Figure 5.1 **Temperature monitoring locations within the Tsolum River watershed. Red markers indicate sites that likely do not have groundwater input, blue markers indicate sites that have the potential for groundwater input, and green markers indicate air temperature loggers (Esri 2009).**

Limitations

There were many contradictory results, making it challenging to determine whether groundwater was influencing stream temperatures at certain locations. One of the potential reasons for these contradictory results was the limited amount of data. Loggers were installed throughout the summer and were all removed between September 7 and 11, 2019. Therefore, the number of weeks of data for the linear regressions were between 7 and 13. A similar study conducted by Krider et al. in 2013 only performed linear regressions between air and water temperatures at sites that had a minimum of 15 weekly averages. The limited number of weekly averages likely decreased the ability of the linear regressions to determine whether a site was more influenced by atmospheric conditions or by groundwater input.

Additionally, temperature loggers were typically installed in the deepest part of the stream at each location so that they did not dry with decreasing summer water levels. It is possible that they could have missed groundwater input areas in the general vicinity since groundwater/surface water interaction areas are highly variable, based on aquifer heterogeneity, land cover, and slope in various parts of the watershed (Driscoll & DeWalle 2004). Conducting streamflow measurements in locations with suspected groundwater prior to the installation of loggers may help narrow down the locations where groundwater is entering the river.

5.1.2. Comparison to Historical Temperatures

As shown in Table 4.3, the average temperature at W17-2019 from June 25 to July 16 was higher than the average temperatures for the same time period from 1998 to 2002. However, Figure 4.11 shows that the mean daily temperatures at W17-2019 were similar to historical mean daily temperatures, with some days higher and some days lower than temperatures over the same time period from 1998 to 2002.

There were only two previous years of data (1998 and 1999) at W28-2019 to compare to the 2019 data. The average temperature at W28-2019 from July 19 to September 7 is between the average temperatures for the same time period from 1998 and 1999 (Table 4.3). Figure 4.12 shows that 2019 temperatures were higher than 1999 temperatures, for the study period, however 1998 temperatures were often higher than 2019 temperatures.

Comparing W17-2019 and W28-2019 data to historical data suggests that temperatures in the Tsolum River have not increased considerably since the measurements conducted in the late 1990s and early 2000s.

5.1.3. Cowichan River Temperature Study

For the study period of August 7 to September 7, 2019, the average temperature within Bear Creek (W29-2019) was 5.1°C cooler than the average temperature within the Cowichan River mainstem (W30-2019). W29-2019 was only located approximately 85 m downstream of W30-2019, therefore it is not likely that this temperature difference is due to the spatial distance between the two sites. Additionally, the average water temperature at W29-2019 for the study period was 3.2°C cooler than the average air temperature measured at the North Cowichan weather station (Government of Canada 2019b). Conversely, the average water temperature at W30-2019 was 1.9°C warmer than the average air temperature. As shown in Figure 4.14, the slope of W29-2019 (-1.26e-03) is slightly lower than the slope of W30-2019 (-2.06e-03), suggesting that the temperature within Bear Creek fluctuated less over time than in the Cowichan River. Bear Creek is a tributary in the Cowichan River watershed with suspected groundwater input which is contributing to colder temperatures to the Cowichan River (Craig & Kulchyski 2016). The confluence of Bear Creek and the Cowichan River is a potential thermal refugia due to the cooler temperatures (Craig & Kulchyski 2016). This temperature comparison between a known groundwater input area and a second location within the Cowichan River mainstem shows that temperature loggers can be used to identify potential areas of groundwater input. Additionally, comparing these water temperatures to nearby air temperatures did reveal that there is likely groundwater influence at W29-2019.

5.1.4. Climatic Influences

It is typical that air temperatures are warmest during the summer months in the Comox Valley, with average temperatures of 15.5°C, 18.0°C, and 17.9°C in June, July, and August, respectively, according to the 1981 to 2010 Canadian Climate Normals for the Comox A weather station (Government of Canada 2019a). Comparatively, average air temperature usually decreases in this area in September, with an average September temperature of 14.5°C (Government of Canada 2019a). This is common throughout British Columbia, with smaller differences between the temperature of groundwater and stream water in September compared to June, July, and August (Birkham et al. 2014). The diurnal changes in surface water during the warmer summer months highlight the groundwater signal more clearly, which is why it is recommended that temperature studies to locate groundwater be conducted during the warm summer months when groundwater input will be more evident (Birkham et al. 2014). In 2019, the average temperatures during the summer months were 16.8°C, 18.5°C, and 18.9°C in June, July, and August, respectively (Government of Canada 2019c). The average temperature in September 2019 was 15.1°C, therefore the historical and predicted trend of warmest temperatures during June, July, and August, with cooler temperatures beginning in September was observed during this study (Government of Canada 2019c).

The precipitation trends in 2019 were inconsistent with the five previous years (2014 to 2018) according to Environment Canada's historical weather data for the closest weather station, the Courtenay Puntledge station (Government of Canada 2019d). They were also inconsistent with Canadian Climate Normals from 1981 to 2010 at the Comox A station (Government of Canada 2019a). With the exception of the months leading up to the summer of 2014 (October 2013 to May 2014), all of the months leading up to the summers of 2015 to 2018 had more rain than the months leading up to the summer of 2019. The total average volume of rain that fell in the months leading up to the summers of 2014 to 2018 was 1,239.4 mm, compared to 968.6 mm in the months leading up to the summer of 2019 (October 2018 to May 2019; Government of Canada 2019d).

June was also drier in 2019 than the previous five years, with a total of 18.9 mm of rain in June 2019 compared to an average of 66.6 mm of rain in June from 2014 to 2018 (Table 5.2; Government of Canada 2019d). The Canadian Climate Normals for the Comox A weather station from 1981 to 2010 also showed more rain in June compared to the 2019 volume (Government of Canada 2019a; Figure 5.2). The average rain volume from 2014 to 2018 during July, August, and September were 28.4 mm, 31.6 mm, and 59.1 mm, respectively (Table 5.2; Government of Canada 2019d). Comparatively, more rain fell during the summer of 2019, with volumes of 47.5 mm, 35.8 mm, and 61.8 mm for July, August, and September, respectively (Table 5.2; Government of Canada 2019c). Figure 5.2 also shows that there was more rain in July and September (and a similar amount in August) in 2019 compared to historical data from 1981 to 2010 (Government of Canada 2019a).

Table 5.2 Monthly rain volumes from June to September from 2014 to 2019.

Year	Total Monthly Rain (mm)			
	June	July	August	September
2014	44.7	29.1	22.2	25.4
2015	16.9	40.5	76.3	55.9
2016	102.2	16.2	51.5	43.4
2017	48.0	8.8	1.2	37.5
2018	121.4	47.6	6.8	133.1
Average (2014-2018)	66.6	28.4	31.6	59.1
2019	18.9	47.5	35.8	61.8

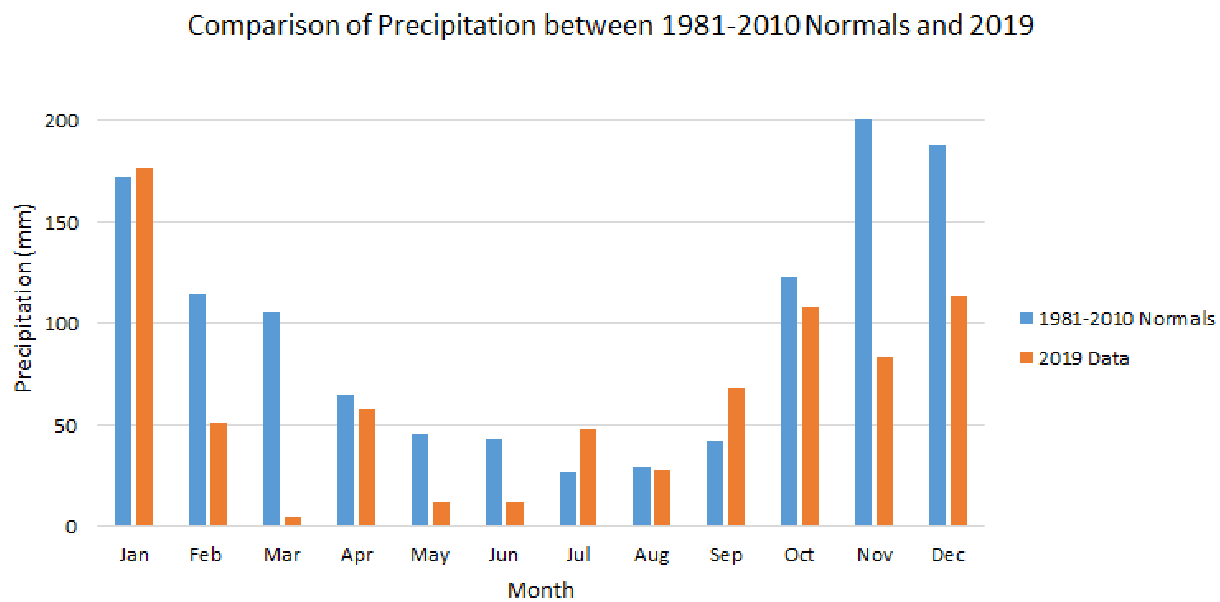

Figure 5.2 Monthly precipitation data from 1981 to 2010 compared to 2019 at the Comox A weather station (data from Government of Canada 2019a).

The precipitation volume is important since it is more difficult to identify areas of groundwater input with higher amounts of rain (Kaandorp et al. 2019). This is because rain dilutes the river, masking the cooler groundwater signature, as was observed at W20-2019 (Figures 4.3 and 4.8; Kaandorp et al. 2019). The elevated levels of rain in July, August, and

September 2019 likely affected stream temperatures, increasing the difficulty in locating groundwater/surface water interactions.

5.2. Stream Discharge

The streamflow measurements taken using the flow meter during the summer of 2019 were unreliable due to frequent precipitation events throughout the monitoring periods. Therefore, the data could not be compared accurately between sites. As such, the WSC hydrometric station data was used to assess discharge and compare it to previous years.

The WSC hydrometric station data shows that the hydrology of the river in the summer of 2019 was very different than the hydrology in the summer of 2018 (Figures 4.17 and 4.16, respectively). The discharge in June 2019 was lower than in June 2018, however there were more precipitation events in July and August in 2019, contributing to higher discharge and a flashier streamflow regime within the Tsolum River. Additionally, the winter and spring 2019 discharge was lower than usual, as shown in the comparison hydrographs between 2017, 2018, and 2019 in Appendix G.

The climatic conditions of 2019 (dry winter and spring and wet summer) contributed to anomalous discharge patterns within the Tsolum River during the summer months. Since discharge influences stream temperature (Poole & Berman 2001), the hydrology of the stream during the 2019 study period likely affected the temperatures recorded, making future predictions of stream temperatures challenging.

5.3. Riparian Vegetation

The riparian vegetation assessment conducted during the FHAP (D.R. Clough Consulting 2014) shows that the majority of reaches where loggers were located had fair to poor crown cover (Table 4.6; D.R. Clough Consulting 2014). The only reach with good crown cover was reach T12, which is located above Highway 19 in the forested crown land (where W18-2019 was located; D.R. Clough Consulting 2014). All of the lower reaches had previously been logged to the bank, therefore the riparian forest is all second-growth (D.R. Clough Consulting 2014). The average percent cover of the transects where the loggers were installed ranged from 12.8% at W3-2019 to 85.2% at W18-2019 (the reference site higher in the watershed; Table

4.6). This does not include W25-2019 which had a percent cover of 97.7%, since it was in a narrow section of Headquarters Creek, near Wolf Lake.

Shading caused by riparian vegetation along the river banks minimizes the amount of solar radiation on a stream's surface and protects the stream from wind so that it is not as sensitive to changes in air temperature (Erickson & Stefan 2000). The relationship between stream and air temperatures is not fully dependent on solar radiation, however it is influenced by solar radiation (Erickson & Stefan 2000). There are multiple factors that affect the degree to which the air/water relationship is influenced by shading, including the width of the stream, the season (e.g. full leaf-out in the summer versus bare deciduous trees in the winter), and the riparian coverage upstream of the monitoring location (Erickson & Stefan). Shading by riparian vegetation produces a similar effect on stream temperature as groundwater inflows do, by creating high intercepts and gentle slopes when performing a linear regression between air and water temperatures (Erickson & Stefan 2000). Therefore, it is possible that for those sites where the regressional analysis does not show a strong correlation between air and water temperatures, shading may be playing a larger part in the decoupling of these variables than is groundwater input. Due to time and logistical constraints of this study, the percent cover from riparian vegetation was only measured along the stream transect where each logger was located, and not upstream. This means that the riparian cover data is insufficient to determine how the water/air temperature relationships are affected by stream shading at each site.

5.4. Methodology Testing to Identify Groundwater

5.4.1. Specific Conductance

The physical, biological, and chemical attributes of groundwater are different than those of surface water, in part due to the degree of interaction with soil and vegetation (Hem 1985; Kalbus et al. 2006). Precipitation typically has low concentrations of dissolved solids due to its lack of contact with soil and vegetation (Hem 1985). Runoff water is in contact with surface soil and vegetation for a short period of time, picking up dissolved solids and increasing their concentrations in the water (Hem 1985). Groundwater has the highest concentration of dissolved solids due to its longer residence time below ground (Hem 1985). These dissolved solids from the soil contain conductive ions, resulting in higher EC since increased concentrations of ions lead to increased EC (Hem 1985; Fondriest Environmental Inc 2014).

A surface water/groundwater interaction study conducted in the nearby Englishman River determined that EC was highest in the spring (approximately 115 µS/cm) when stream water mainly consisted of groundwater inflow (GW Solutions Inc 2012). Electrical conductivity in the Englishman River ranged from 80 µS/cm to 100 µS/cm in the summer and fall when flows were influenced by groundwater (GW Solutions Inc 2012). Conversely, EC measurements in the winter were less than 40 µS/cm since the stream was predominantly composed of rainwater (GW Solutions Inc 2012).

The majority of the water temperature monitoring sites in the Tsolum River had specific conductance values between 36 µS/cm and 55 µS/cm (Figure 4.18), which are closer to the rain-dominated winter conductivity values from the Englishman River study. This suggests that there was not a large inflow of groundwater increasing specific conductance at these locations. Two of the sites had higher specific conductance measurements, with 62 µS/cm at W2-2019 and 106 µS/cm at W10-2019 (Figure 4.18). Both W2-2019 (in Dove Creek) and W10-2019 (in Portuguese Creek) showed the potential for groundwater inflow based on temperature results.

It has been found that specific conductance typically ranges from 2 to 100 µS/cm for stream water and from 50 to 50,000 µS/cm for groundwater (Sanders 1998). Since the majority of the sites had specific conductance values less than or equal to 50 µS/cm, the conductivity at these sites do not indicate groundwater influence. W2-2019 and W18-2019 had specific conductance values of 62 µS/cm and 55 µS/cm, respectively, which are still within the stream water range and at the low end of the groundwater range. This suggests that although there could be groundwater inflow influencing conductivity at these sites, it is likely not a large inflow due to the relatively low values. The specific conductance of W10-2019 (106 µS/cm) is in the groundwater range, indicating that there may be groundwater flow at this location. This is corroborated by the temperature results of this study and prior indications of groundwater springs and seepages in Portuguese Creek (Metherall 2019).

Measuring specific conductance is likely an efficient and cost-effective way of identifying groundwater input in streams, however it did not allow for conclusive identification of groundwater sites for this study due to the limited amount of specific conductance data.

5.4.2. Longitudinal Temperature Measurements

The longitudinal temperature drag showed differences in temperatures as the two loggers moved downstream, as well as between the surface and streambed loggers. The GPS track showed various legs of the logger drag, with the associated times for the start of those legs. The times on the GPS track were correlated with the times recorded by the loggers, allowing for the determination of stream location at various temperatures. For example, as described in Section 4.5.1, at approximately 13:05:30, the temperature of Streambed-2019 became 2°C cooler than the temperature of Surface-2019. The GPS track showed that this divergence of temperatures between the loggers occurred at the start of the deep pool on the right bank, where W22-2019 was deployed. The temperatures of the two loggers converged again at approximately 13:21:10, which was shown by the GPS track to be between the pools where W22-2019 and W23-2019 were located, likely in a shallow riffle. The temperatures immediately diverged again, with Streambed-2019 becoming colder as the two loggers were dragged through the pool where W23-2019 was located.

There is potential for a longitudinal temperature assessment such as this to identify areas of cooler groundwater upwelling, since it did show differences between the surface and streambed temperatures and between various locations within the river. However, it was a challenge to keep the streambed and surface loggers in a direct vertical line with each other. If this methodology were to be replicated, it is recommended that the system holding them together and keeping the surface logger floating be improved. Additionally, the GPS track did not show the time every second, which was the recording interval of the loggers. This created some difficulty in determining the exact location of the loggers for every second that they were recording. The person holding the GPS and creating the track was also standing on the bank and walking beside the swimmer with the loggers. It may be possible for the person swimming with the loggers to wear a GPS watch with software such as Strava downloaded. This could provide real-time GPS information to improve the accuracy with which the temperatures can be correlated to their location in the river.

5.4.3. Forward-Looking Infrared Radar Drone Survey

The drone was set to record a specific range of temperatures, allowing the pallet (otherwise known as the look up table) to be constant between frames (E. Saczuk 2020, British Columbia Institute of Technology, Burnaby, BC, personal communication). The range of temperatures must be set in advance so that the RBG and thermal images can be stitched together (E. Saczuk 2020, British Columbia Institute of Technology, Burnaby, BC, personal communication). During the 2019 survey on the Tsolum River, the thermal images recorded data in gray scale when the temperature was below 40°C, therefore it was only locating hotspots within the river (E. Saczuk 2020, British Columbia Institute of Technology, Burnaby, BC, personal communication). The hotspots gave limited information about the temperature of the river (e.g. it identified warm gravel bars), potentially missing cool areas within the stream (E. Saczuk 2020, British Columbia Institute of Technology, Burnaby, BC, personal communication).

The output images from the drone survey are in JPEG format, which do not allow for the encoding of radiometric temperature data (E. Saczuk 2020, British Columbia Institute of Technology, Burnaby, BC, personal communication). Thus, ground-truthing surveys would also be required to correlate pixel values and surface temperatures to be able to extract accurate temperature data from the JPEG images (E. Saczuk 2020, British Columbia Institute of Technology, Burnaby, BC, personal communication). Additionally, the hybrid thermal and RGB images are relatively low resolution (640x480), resulting in the inability to fully stitch the images together due to the limited information provided to the software (E. Saczuk 2020, British Columbia Institute of Technology, Burnaby, BC, personal communication). Finally, a single strip of photos were captured along the stream thalweg, resulting in insufficient geometry for stitching the photos together (E. Saczuk 2020, British Columbia Institute of Technology, Burnaby, BC, personal communication).

Drone surveys have been shown to be an effective method for mapping spatial and temporal temperature trends in a stream (Faux et al. 2001). A longitudinal temperature profile can be developed for a stream by analyzing surface water temperatures from thermal infrared (TIR) images (Faux et al. 2001). Areas of groundwater inflow can also be observed with TIR imagery (Faux et al. 2001). Temperature data derived from the TIR images should be compared to the daily and seasonal changes in stream temperatures (Faux et al. 2001). Conducting a drone survey in conjunction with the installation of loggers can allow for a comparison between the daily water temperature maximums at the logger sites and the daily temperatures derived from the drone survey to assess the TIR image accuracy (Faux et al. 2001). Since loggers are installed in a localized area, it is possible for them to miss areas of cooler inflow, therefore drone surveys can capture these spatial changes in temperature along a stream better than loggers installed in one location can (Faux et al. 2001). Loggers that continuously monitor stream temperatures are extremely valuable due to the large data sets and the temporal variation that they show, however drone surveys can complement this data by providing stream temperatures between the logger monitoring locations, thereby potentially expanding the area of data collection to the entire surface of the river stretch (Faux et al. 2001). Moreover, a drone survey can indicate areas where there are changes in the thermal profile, indicating areas where loggers can be installed in the future (Faux et al. 2001).

Drone surveys can be conducted in the summer or winter for stream temperature assessments (Faux et al. 2001). Maximum stream temperatures typically occur in the afternoon (between 2:00 to 6:00 pm) in the mid to late summer (between mid-July to early September) in the PNW (Faux et al. 2001). Therefore, the temperature differences between stream and groundwater temperatures will be largest at this time, making it easier to detect groundwater inputs (Faux et al. 2001). Although TIR has the potential to detect cold groundwater inflows in the summer months due to the temperature difference between stream water and groundwater, locating groundwater using TIR imagery in the winter can be more effective (Faux et al. 2001). This is because cold groundwater is denser than warmer stream water, sinking and making it more difficult for drones to identify it (Faux et al. 2001). Conversely, groundwater in the winter is warmer than stream water, making it easier for drones to detect (Faux et al. 2001).

It is clear that FLIR drone surveys can be used to identify cooler areas of groundwater input, however there are several recommendations that would improve the success of these surveys. Firstly, the temperature range on the drone needs to be set to record a wider range of temperatures, identifying both cool and warm spots in the river. Secondly, ground-truthing surveys to correlate stream temperatures with the pixel values from the drone images should be conducted so that the JPEG images can provide temperature data. Thirdly, the drone settings should result in the output of higher resolution images, allowing them to be aligned and stitched together. Finally, the drone should be flown in multiple parallel lines (three to five lines) rather than a single line along the thalweg, resulting in sufficient redundancy between point positions for photo stitching and alignment (E. Saczuk 2020, British Columbia Institute of Technology, Burnaby, BC, personal communication). For proper photo alignment, the forward-lap should be 80% and the side-lap should be 60% (E. Saczuk 2020, British Columbia Institute of Technology, Burnaby, BC, personal communication).

5.5. Recommended Changes to Wolf Lake Augmentation

It has been found that upstream water reservoirs (such as lakes with dams on them) can influence temperature and flow downstream if water is released from the reservoir (Risley et al. 2010). Dimictic lakes stratify in the late spring and summer months as solar radiation warms the surface layers of the lake (called the epilimnion), causing the colder and denser water to stay at the bottom of the lake in the area called the hypolimnion (Risley et al. 2010). It appears that Wolf Lake is thermally stratified during the summer months, since the surface water was warmer than the deeper water during the August 2019 temperature profiling. At N-2019, the temperature at the surface was 23.1°C, compared to 6.4°C at a depth of 20 m (Table H-1 in Appendix H). Similarly, the temperature at the surface of S-2019 was 22.8°C, with a colder temperature of 14.4°C at a depth of 9 m (Table H-1 in Appendix H).

Water was released from Wolf Lake into the by-pass channel that flows into Headquarters Creek from July 29, 2019 until the end of November 2019 (J. Amos 2019, Puntledge River Hatchery, Courtenay, BC, personal communication). As shown in the time series temperature graph for W25-2019 in Appendix E, the stream temperature at W25-2019 increased between July 28 and July 30, 2019, when the augmentation from Wolf Lake began. This suggests that the surface water flowing through the weir into the by-pass channel may be warmer than the natural temperature of the by-pass channel without flow augmentation from the lake. Additionally, Figure 4.1 shows that the average temperature at W25-2019 from July 18 to September 8 is higher than the 26 other loggers within the Tsolum River watershed. The average temperature of W25-2019 during the above-mentioned time period was 21.6°C, with the second highest average temperature being 1.1°C cooler (20.5°C) at W24-2019, located approximately 12.4 km southeast (farther downstream). The surface water temperature at the closest sampling point to the lake outlet (S-2019) was 22.8°C on August 9, 2019. This was warmer than temperatures measured at any other logger in the watershed on August 9, 2019 at the same time, with the exception of W25-2019, which was also 22.8°C. Stream temperatures at the remaining loggers in the watershed ranged from 16.8°C (W18-2019) to 20.7°C (W12-2019 and W24-2019) on the same day at the same time.

Many of the dams/reservoirs in the United States release water from the hypolimnion into rivers downstream, causing downstream temperatures to be cooler in the summer months than they otherwise would be (Risley et al. 2010). These cooling trends would likely not occur if water was being drawn from the epilimnion of the reservoir and being released downstream, as is the case in Wolf Lake (Risley et al. 2010). It has been shown that the thermal effect of releasing water from an upstream reservoir diminishes downstream with distance away from the reservoir (Risley et al. 2010). This is because solar radiation and groundwater inputs have a greater influence on stream temperatures as the distance from the reservoir increases, relative to the cooling effects of the reservoir water release (Risley et al. 2010). However, modeling conducted on hypothetical streams showed that an upstream dam from which hypolimnetic water was released resulted in cooler than natural stream temperatures even in lower reaches of the watershed (Risley et al. 2010). The model compared stream temperatures downstream of the reservoir with and without the dam and the associated release of hypolimnetic water (Risley et al. 2010). Colder water released from the hypolimnion of a lake upstream can have an effect on the temperature of the stream as far as 40 km downstream of the dam (Sinokrot et al. 1995). The distance between the outflow of Wolf Lake and the K'ómoks estuary is approximately 26 river km, therefore there is the potential for hypolimnetic water from Wolf Lake to influence temperatures all the way down to the estuary.

Due to the observed high temperatures in the by-pass channel where the water from Wolf Lake is released, it is possible that flow augmentation is causing an increase in temperature in Headquarters Creek and the Tsolum River downstream. Therefore, it may be beneficial to alter the design of the dam and weir, withdrawing water from the deeper sections of the lake where the water temperatures are at least 17°C colder than surface temperatures (Table H-1 in Appendix H). As mentioned in Section 3.5, it is important to assess whether DO levels are adequate for fish in the hypolimnion prior to the construction of a system to withdraw water from deeper in the lake. This is because low DO concentrations can kill or have significant adverse behavioural and physiological effects on fish (CCME 1999). Dissolved oxygen concentrations are higher in colder water, therefore as temperatures decrease in the hypolimnion, DO levels increase, often with almost 100% saturation (CCME 1999). However, DO levels in the hypolimnion tend to decrease throughout the summer months as oxidation and respiration occurs, especially in eutrophic lakes (CCME 1999). Oxygen cannot be replenished in the deeper parts of the lake throughout the summer while the lake is stratified and DO levels do not increase again until lake turnover in the fall (Addy and Green 1997). Additionally, DO concentrations in lakes depend on climatic, morphologic, nutrient, and watershed conditions, meaning site-specific sampling is required to assess DO levels in a lake (CCME 1999). As such, it is important to measure DO concentrations in the hypolimnion throughout the months when flow augmentation occurs.

The Canadian Council of Ministers of the Environment (CCME) water quality guidelines for the protection of aquatic life in freshwater state that the minimum DO concentrations in warm water are 6 mg/L and 5.5 mg/L for fish in their early life stages and later life stages, respectively (CCME 1999). In cold water these guidelines are 9.5 mg/L and 6.5 mg/L for fish in their early life stages and later life stages, respectively (CCME 1999). At N-2019, the DO concentration was 10.6 mg/L at a depth of 20 m (Table H-1 in Appendix H), which is higher than the most conservative guideline of 9.5 mg/L for early life stages in cold water (CCME 1999). At S-2019, the DO concentration was 10.0 mg/L at a depth of 9 m (Table H-1 in Appendix H), which was also greater than the 9.5 mg/L guideline (Table H-1 in Appendix H). These results suggest that there is potential to draw water from the hypolimnion of the lake without resulting in detrimental anoxic conditions for fish downstream.

This was a preliminary study to assess whether temperatures were lower in the hypolimnion compared to the epilimnion and whether DO levels were above CCME guidelines for the protection of aquatic life. Prior to any adjustment to the current Wolf Lake augmentation program, it is crucial that a detailed study of temperature and DO in multiple areas of the lake be conducted to assess how temperatures and DO levels change annually and seasonally. It is recommended that temperature and DO measurements be conducted on a weekly basis from August to November (when there is the potential for flow augmentation to occur), at 0.5 m intervals from the surface to the lake bottom (Marshall et al. 2002; Spooner 2016). In order for sampling to be consistent, measurements should always be collected at the same time of the day to account for changing photosynthetic rates throughout the day (Addy and Green 1997). The same two sampling locations (N-2019 and S-2019) can be used, with the potential for a third location in the deepest part of the lake near N-2019. A YSI cable longer than 20 m should be used so there is the potential to reach the bottom in the deepest sections of the lake.

5.6. Recommendations for Future Studies and Improvements to Methodology

This temperature study showed that it is possible to determine areas where there may be groundwater upwelling by assessing the strength of the relationship between air and water temperatures. However, this was the first temperature study conducted on the Tsolum River with the aim of determining where groundwater is interacting with surface water, and a second, more refined study should be conducted to narrow down these potential groundwater upwelling areas. Additionally, there were multiple locations within the stream that should be assessed but were not due to logistical, financial, and time constraints of the 2019 field season. Table 5.3 lists recommended sites that should be studied due to their potential for groundwater input.

Table 5.3 Recommended temperature monitoring sites for future studies.

Recommended Site for 2020 Study	Rationale for Future Studies	GPS Coordinates
W2-2019	Potential for groundwater input based on 2019 results	49.74741, -125.08665
W7-2019	Potential for groundwater input based on 2019 results	49.74675, -125.08434
W8-2019	Potential for groundwater input based on 2019 results	49.74681, -125.07584
W9-2019	Potentially influenced by cooler water in Portuguese Creek	49.71804, -125.01185
W10-2019	Potential for groundwater input based on 2019 results	49.71834, -125.01189
W11-2019	Potential for groundwater input based on 2019 results	49.71816, -125.01228
W12-2019	Potential for groundwater input based on 2019 results	49.70398, -124.99712
W13-2019	Potential for groundwater input based on 2019 results	49.74671, -125.08534
W14-2019	Potential for groundwater input based on 2019 results	49.74699, -125.07603
W17-2019	Potential for groundwater input based on 2019 results	49.70357, -125.00555
W20-2019	Potential for groundwater input based on 2019 results	49.71701, -125.01949
W25-2019	Confirm warmer temperature from Wolf Lake augmentation	49.75277, -125.15177
W28-2019	Potential for groundwater input based on 2019 results	49.76793, -125.11906
Upstream of W10-2019*	Potential for groundwater input based on 2019 results	To be determined
In Nelson Pool**	Reports that water may be cooler in this pool in summer	49.73820, -125.05951
In pool in front of 6019 Tsolum River Road**	Reports that water may be cooler in this pool in summer	49.74630, -125.07326

* Consult with local landowners and Phase 1 Tsolum River Agricultural Watershed Plan (Metherall 2019) to determine likely areas of groundwater input in Portuguese Creek.

** Approximate coordinates of pool, however best location for logger installation will need to be determined with surveys.

There are several recommendations for changes to the methodology employed during the 2019 field season. These changes are based on a review of relevant literature as well as lessons learned from the 2019 study. The proposed improvements/changes are described in Sections 5.6.1 to 5.6.5.

5.6.1. Sediment Temperature Measurements

A study conducted by Silliman and Booth (1993) in a creek in northern Indiana used thermistors to measure both sediment and water temperatures. At each of their monitoring locations, one thermistor was buried 7.6 cm to 10.2 cm deep in the streambed sediments and a second thermistor was installed in the water column of the creek, approximately 2.5 cm above the streambed (Silliman & Booth 1993). The sediment and water temperatures were compared at each site, showing areas where sediment temperatures were cooler and more constant than water temperatures (Silliman & Booth 1993). This study showed that it is possible to identify areas of groundwater input into a stream by comparing sediment and stream temperatures over time (Silliman & Booth 1993).

Loggers were not installed in the sediment in the Tsolum River watershed in the 2019 temperature study since they were being downloaded on a regular basis and it would have been time consuming to remove them from the sediment each time. However, installing two loggers in each monitoring location (one in the streambed and one 2 cm above the bottom of the streambed) may accentuate the groundwater signal, making it more obvious where groundwater is entering the Tsolum River. Air temperatures should continue to be measured and compared to each monitoring location. For each monitoring location, a time series graph can be produced with three lines: (1) streambed temperature, (2) water temperature, and (3) air temperature. This may aid in determining where groundwater is interacting with surface water at various locations within the stream.

5.6.2. Stream Discharge Measurements

The stream discharge measurements from the 2019 study were conducted too infrequently and were not close enough to each of the temperature stations. Additionally, streamflow was typically only measured at two of the six sites per day due to the time required to accurately measure discharge. As such, it took multiple days to collect the data at all sites every month. There were unexpected precipitation events between the streamflow measurements each month, making the comparison between the different stations inaccurate. The streamflow results were therefore not useful in determining areas of the stream that were gaining and losing. It has been shown that conducting nested streamflow measurements with temperature assessments can indicate which sections of a stream are gaining or losing, indicating where groundwater is entering a stream (Driscoll & DeWalle 2004).

A study conducted by Kaandorp et al. (2019) located an area that has diffuse groundwater seepage, as evidenced by streamflow increases and iron oxide precipitation visible along the stream banks. However, the FO-DTS method they used was not able to identify the groundwater temperature signal since the input was so diffuse (Kaandorp et al. 2019). Streamflow served as a better indicator of groundwater input than temperature in this location (Kaandorp et al. 2019). No visible areas of groundwater input were observed or felt in the

Tsolum River, suggesting that areas of groundwater input are diffuse. As such, streamflow measurements may be useful in determining areas of upwelling.

5.6.3. Longer Study Period

Groundwater inputs have the opposite effect on stream temperatures in the winter compared to the summer, since groundwater in the winter is typically warmer than stream water (Risley et al. 2019; Kaandorp et al. 2019). Winter stream temperatures often have a higher daily mean and a lower daily standard deviation in areas influenced by groundwater due to its buffering effect (Kaandorp et al. 2019). Identifying groundwater inputs in the Tsolum River would be more likely if temperatures are recorded year-round, capturing both the summer and winter cooling and warming effects of groundwater, respectively. Annual temperature monitoring would also increase the number of weeks to be used in the linear regression model, increasing the likelihood that it will accurately show the relationship between water and air temperature.

5.6.4. Frequent Specific Conductance Measurements

Electrical conductivity in streams changes as water temperature and flow change, both daily and seasonally (Fondriest Environmental Inc 2014). For this reason, it would be useful to measure EC more frequently than once a summer, to capture the variation in EC due to alterations in stream temperature and flow. Ideally, EC and temperature would be measured continuously and at the same time, using a logger that measures both such as the Manta 20+ water probe (Campbell Scientific Canada 2020).

5.6.5. Fish Distribution and Abundance Data

Understanding how fish are using different areas in the stream would be helpful for identifying critical thermal refugia, ensuring restoration budgets are used as efficiently as possible. McGrath and Walsh (2012) conducted winter and summer habitat use surveys of juvenile coho, comparing habitat use at paired groundwater and non-groundwater control sites in the Interior of BC. Once groundwater upwelling areas have been confirmed in the Tsolum River, each groundwater site should be compared with a control site where there is no groundwater inflow to determine whether salmonids are preferentially using groundwater upwelling sites. Snorkel swims and fry trapping using Gee traps should be conducted in the Tsolum River at the paired sites (McGrath and Walsh 2012).

Chapter 6. Regulatory Context

6.1. Water Sustainability Act

In order to legally withdraw surface or groundwater in British Columbia, a water license must be issued to the water user, under the provincial *Water Sustainability Act* (WSA; 2016). However, these licenses are not metered, therefore actual withdrawal amounts are unknown (Metherall 2019). Under Section 30 of the WSA (2016) all license holders must submit a declaration stating that they are using the extracted water efficiently and per their license conditions (both quantity and purpose of use). If water levels in a stream or its tributaries are less than or at risk of becoming less than the critical environmental flow thresholds (CEFTs) for that waterbody, the Minister can declare a significant water shortage (SWS) for that stream under Section 86 of the WSA (2016). Once a SWS has been declared, the CEFTs for fish species living in that waterbody take priority over other water usage, with the exception of essential household use.

Section 88 of the WSA (2016) also states that the Minister can issue a Fish Population Protection Order if flows become so low that fish survival is at risk. The Minister can then regulate water diversions including who can divert water, when it can be diverted, and how much can be diverted. The CEFT has not yet been determined for the Tsolum River, however this will likely be done during Phase 2 of the Tsolum River Agricultural Watershed Plan (Metherall 2019). Once the CEFT has been established, the provincial government can issue a Fish Population Protection Order if levels drop below the CEFT, providing greater protection for fish species within the river.

In August 2019, FLNRORD established water use restrictions on the Koksilah River until September 30, 2019, by issuing a fish population protection order (Government of British Columbia 2019). Restrictions were put in place to protect fish populations since water levels decreased to less than 2% of the river's MAD (180 l/s; Government of British Columbia 2019). Water licenses for industrial extraction of groundwater wells that were hydraulically connected to the river and for irrigation of corn and hay crops were restricted, with all diversion ceased (Government of British Columbia 2019). Licenses for watering livestock and irrigating vegetables and perennial crops were not restricted (Government of British Columbia 2019). These types of water use restrictions could be implemented in the Tsolum River to protect fish populations should discharge drop to critically low levels.

Under Section 128 of the WSA (2016), a stream can be designated as a sensitive stream if a fish population in the stream is deemed at risk due to environmental degradation. Mitigation measures may be required for any authorizations relating to that stream, including water diversions and use. Additional monitoring and reporting may also be a requirement for any authorizations or change approvals in the sensitive stream. There are currently 15 streams in BC that have been designated as sensitive according to the Water Sustainability Regulation (2019). The Tsolum River is not currently on that list, however this could change in the future if fish populations in the river are threatened due to low summer flows and high summer temperatures.

6.2. Environmental Protection and Management Regulation

Section 28 of the Environmental Protection and Management Regulation (2016) under the *Oil and Gas Activities Act* states that a fish-bearing stream can be designated as “temperature sensitive” if it has been determined that the temperature of the stream can be improved for fish by increasing riparian cover. This is a tool that can be used by the provincial government to minimize thermal stress to fish in streams with temperature concerns due to riparian vegetation loss (Forest Practices Board 2018). In order to be eligible to be designated as a sensitive stream, there must be data showing that fish species within the stream are at risk of thermal stress, there are vulnerable fish species, there is temperature sensitivity within the stream, and the thermal stress will be decreased by maintaining and improving riparian vegetation cover (Forest Practices Board 2018).

British Columbia has not currently designated any streams as temperature sensitive (Ministry of Environment N.D.). However, the data from the 2014 FHAP and the 2019 temperature data show that riparian cover is lacking in the lower reaches of the Tsolum River, and there are elevated stream temperatures that exceed the optimal thermal thresholds of juvenile salmonids. As such, the Tsolum River could potentially be listed as a temperature sensitive stream in the future, affording it extra protection.

Chapter 7. Restoration and Climate Adaptation Plan

Groundwater temperatures are predicted to increase due to climate change, especially when groundwater is located in shallow, subsurface layers, as it is throughout much of the Tsolum River watershed (Kuryluk et al. 2014). This means that even once areas of groundwater input in the Tsolum River are identified, they cannot necessarily be relied on to provide thermal buffering in the future since groundwater temperatures may also increase (Kuryluk et al. 2014). Therefore, along with identifying thermal refugia, it is important that other restoration measures are implemented to protect salmonids from further stream warming. Restoration actions that are aimed at decreasing stream temperatures and improving thermal refugia for salmonids will likely be the most effective when considering restoration through a climate change lens (Beechie et al. 2012).

7.1. Thermal Stressors

There are multiple stressors in the Tsolum River watershed that may be contributing to stream warming. These stressors may become exacerbated over time, especially with climate change. It is therefore important to identify these stressors and conduct restoration activities as pre-emptive climate adaptation strategies. These stressors are: (1) surface water and groundwater extraction (2) release of warm surface water from Wolf Lake, (3) poor riparian cover, and (4) extensive gravel bars throughout the channel. Each of these stressors and their proposed treatments are detailed in Sections 7.1.1 to 7.1.4 below.

7.1.1. Water Extraction

Water is becoming a scarcity throughout Canada, with many water bodies becoming overcommitted with regards to anthropogenic water extraction and environmental needs (Bjornlund 2010). It is for this reason that it is increasingly crucial that solutions be implemented to decrease the amount of water that is being extracted from overcommitted water resources, leaving more water in the river for salmonids (Bjornlund 2010). Environmental flow needs for aquatic species should be met before water is extracted for consumptive use (Bjornlund 2010). Decreasing the volume of groundwater extracted from a stream can increase the levels and seepage of groundwater (Kaandorp et al. 2019). This will allow for more groundwater to enter the Tsolum River water and its tributaries, potentially providing and improving thermal refugia for cold water fish species.

As explained in Section 1.2, allowable consumptive water license amounts are 2,437,027 m^3/year, including both surface water and groundwater extraction (Metherall 2019). This is concerning since it has been shown that stream temperatures tend to increase during the dry summer months when flows are decreased by water withdrawals (Risley et al. 2010). When groundwater near a stream is extracted, less groundwater enters the stream in gaining reaches, more surface water enters the groundwater in losing reaches, and gaining reaches can convert to losing reaches (Risley et al. 2010). Stream depth decreases when water is removed from a stream, causing a loss in the stream's thermal mass and a gain in the surface area to volume ratio (Risley et al. 2010). This can lead to more heat transfer between the atmosphere and the stream surface, further warming stream temperatures (Risley et al. 2010). These warming effects can be especially extreme when groundwater is removed from a watershed, since not only is there a loss in cool groundwater buffering the stream's temperature, but there is also increased heat transfer across the air/surface water interface (Risley et al. 2010).

It is clear that water extraction from the Tsolum River is of concern to salmonids, for the effect it has on the discharge and thermal properties of the stream. There is an allowable amount of water that can legally be extracted as per licenses requirements, however this is not metered, leaving a gap in knowledge of actual water withdrawal amounts (Metherall 2019). The Comox Valley Regional District and Ministry of Agriculture developed an Agricultural Water Demand Model (AWDM), which made predictions that by the 2050s, water requirements for existing agricultural practices in the valley could increase by 139% due to the expected hotter and drier climate (Metherall 2019). If more farms are developed in the valley, even more water would be required for irrigation (the AWDA showed that a 40% increase in agricultural production could lead to an increase in water requirements of 563%; Metherall 2019). Only 28% of the Agricultural Land Reserve (ALR) is currently used for farming, therefore water demands could increase if new agricultural lands are developed within the ALR (Metherall 2019). The AWDM estimates that water demands in the Comox Valley could increase by 463% due to both increased farming activities and climate change effects (Metherall 2019). Environmental flow needs have not yet been determined for the Tsolum River, however maintaining flows of 0.5 m^3/s during the low flow summer months was suggested as an acceptable target (Szczot 2018 in Metherall 2019). The WSC Tsolum River near Courtenay 08HB011 Station data from 2019 showed that discharge in the Tsolum River was often less than 0.5 m^3/s throughout the summer months (Government of Canada 2014). The environmental flow needs are already at risk for salmonids and stream temperatures are predicted to continue to rise with climate change (van Vliet et al. 2013).

Proposed Treatment

It would be valuable for all water extractions in the Tsolum River watershed to be metered, allowing for management and enforcement of water resources within the watershed. For BC to establish a successful water use reporting system, the actual amount of surface water and groundwater withdrawals should be tracked rather than estimating withdrawal quantities based on allocated amounts under water licenses (Parfitt 2013). The majority of water licenses in the Tsolum River are for agricultural uses (Metherall 2019), therefore, if these license holders were required to meter and track their withdrawals as per the recommended water use reporting system, actual amounts being extracted from the watershed would be better understood. Requiring metering of water withdrawals may prevent license holders from exceeding their allocated withdrawal amounts, provided enforcement actions are taken when necessary. Additionally, metering water extractions would increase the credibility and reliability of the water licensing process in the province (Bjornlund 2010).

Purchasing water licenses from existing license holders is another way in which water can be left in the stream, increasing flows and thus ameliorating stream temperatures (Beechie et al. 2010). In-stream flows could be increased if conservation groups and non-governmental organizations bought currently assigned water licenses from license holders who would rather be paid for the licenses rather than use the water (Bjornlund 2010). Buying licenses from holders who pump water from groundwater wells would allow the water to be kept in the aquifer since the previous license holder would no longer be able to extract the groundwater (Amos and Burke 2018). This could help to ensure that more water stays in the river and aquifer, improving water levels for environmental flow needs.

Using diverted water efficiently is critical for water conservation (Bjornlund 2010). License holders are entitled to use the full allocation in their licence, therefore they can choose what they want to do with the remaining water if they save water due to efficiency measures (Bjornlund 2010). It would be beneficial for the provincial government to buy back any remaining allocated water not used by a license holder, incentivizing license holders to use water as efficiently as possible (Bjornlund 2010). It has been shown in Australia that farmers are more efficient with their irrigation practices when a price is put on their water licenses and they are able to sell some or all of their allocated water (Bjornlund 2010). Depending on the price of water, it may be more beneficial for a farmer to sell water than to use it for low-value crops (Bjornlund 2010).

Farmers should follow best management practices for efficient water usage to decrease the amount of water being extracted from the river. This includes maintaining and repairing irrigation equipment to ensure pipes are not leaking, using efficient systems such as trickle/drip irrigation systems, understanding the water requirements of crops and only applying the necessary amounts, and irrigating at appropriate times (Tam et al. 2005). It is crucial that irrigation schedules are aligned with the water holding capacity of the soil, the water requirements for the target crops, and climatic factors such as temperature and evapotranspiration rates (Tam et al. 2005).

It has been found that increasing the efficiency of irrigation systems results in extracted water being used more effectively, however this can lead to higher withdrawal amounts (Pfeiffer & Lin 2014). With water being used more effectively, profit maximization changes for the farmer, in turn affecting the yield, crop selection, and amount of land that is irrigated, potentially increasing water withdrawal amounts (Pfeiffer & Lin 2014). Therefore, education is a key component of irrigation efficiency, ensuring that farmers understand that the increase in efficiency should result in more water being left in the river for fish, rather than increased agricultural profits. It is recommended that improved efficiency of irrigation practices should result in a regulatory decrease in the allocated water quantities for each license, taxing of excess water extraction, or government buy-back of excess water quantities for each license (Pfeiffer & Lin 2014; Bjornlund 2010).

Finally, increasing water storage on agricultural lands to capture rainwater could also serve to decrease the amount of water being extracted from the Tsolum River watershed (Metherall 2019). This could include ponds or cisterns on agricultural land which have the potential to store rainwater from the wet winter months to be used during the dry summer months (Metherall 2019). These water storage solutions will cost farmers a significant amount of money since there will be costs associated with the construction of the storage areas as well as lost profit from decreasing the area of land that can be used for agriculture (Metherall 2019). Therefore, it would be beneficial for these costs to be subsidized by the provincial or federal government.

7.1.2. Wolf Lake Flow Augmentation

As explained in Section 5.5, the temperatures at the by-pass channel below the Wolf Lake dam are elevated, likely due to warm surface water being released into the channel from Headquarters Creek.

Proposed Treatment

Further temperature and DO studies need to be conducted in Wolf Lake prior to any changes to the current augmentation system. If it has been determined after extensive sampling that temperatures and DO levels are appropriate, a hypolimnetic withdrawal system can be constructed. Hypolimnetic water extraction rather than surface water extraction has previously been conducted on Chain Lake in the interior of British Columbia (Macdonald et al. 2009). The reason for hypolimnetic extraction in this case was to decrease phosphorous concentrations and minimize anoxic conditions in the hypolimnion (Macdonald et al. 2009). The rationale for hypolimnetic withdrawal in Wolf Lake is different from that in Chain Lake, however the mechanism is the same and the lessons learned can be applied to Wolf Lake.

As with the Chain Lake hypolimnetic withdrawal system, a withdrawal pipe can be installed from the outlet of Wolf Lake in the southeast corner, running along the lake bottom to a deep section of the lake where the hypolimnetic temperatures are the coolest (Macdonald et al. 2009). A coffer dam box can be constructed between the withdrawal pipe on the lake bottom and the pipe at the outlet of the lake, providing a difference in elevation between the lake level and the level of water in the coffer dam box (Figure 7.1; Macdonald et al. 2009). This elevation difference will be the driving force that will move water into the bypass channel (Macdonald et al. 2009). If DO levels in the hypolimnion will cause anoxic conditions for fish downstream, it is possible to install an aeration system (e.g. a fountain and plunge pool) at the outlet of the pipe where the hypolimnetic water enters the bypass channel into Headquarters Creek (Macdonald et al. 2009).

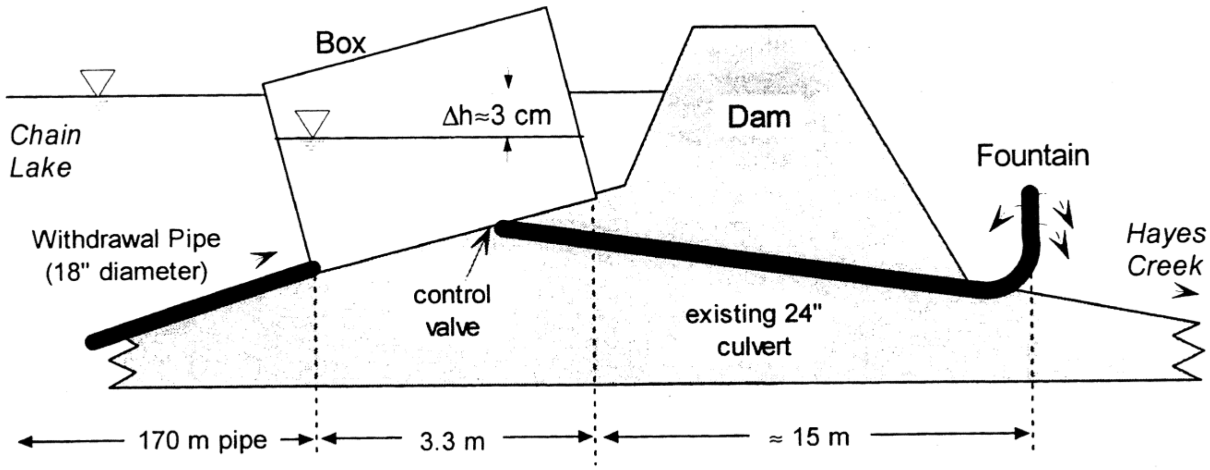

Figure 7.1 **Example of hypolimnetic withdrawal system from Chain Lake (Macdonald et al. 2009).**

The hypolimnetic water withdrawal amount should be equal to the amount that would otherwise be released from the surface dam, preventing any alteration of the lake level (Macdonald et al. 2009). Withdrawal from the hypolimnion may impact the thermal regime within the lake, since cold water will be removed rather than warm surface water (Macdonald et al. 2009). Additionally, removal of cold hypolimnetic water could result in early mixing of the hypolimnion, warming the bottom of the lake which may result in increased oxygen demand and depletion (Macdonald et al. 2009). Therefore, if a hypolimnetic withdrawal system is put in place, temperature and DO sampling should continue in the lake to monitor potential adverse effects to the lake ecosystem. Water sampling in the bypass channel should also occur to monitor nutrient and heavy metal concentrations, which could be present in the hypolimnetic water (Macdonald et al. 2009).

7.1.3. Riparian Cover

It is clear from this study and previous studies that riparian cover is lacking in the lower reaches of the river. The crown cover rating from the FHAP conducted by D.R Clough Consulting (2014) was poor to fair in all of the reaches where the loggers were located, with the exception of W18-2019 which was the reference site (Table 4.6). Additionally, the average percent cover at each transect where the loggers were located ranged from 12.8% to 97.7%, with more than half of the transects having riparian cover below 50% (Table 4.6).

Riparian vegetation affects stream temperatures through various mechanisms including reducing solar radiation, providing microclimate conditions that influence evapotranspiration, and minimizing wind velocities (Johnson 2004). In addition, riparian vegetation stabilizes banks, decreasing stream width and increasing stream depth (Johnson 2004). Decreasing the width to depth ratio in turn decreases stream temperature (Risley et al. 2010).

Proposed Treatment

Based on the FHAP conducted in 2014, percent crown cover was poor and fair in reaches T1 to T7 and T9 (D.R. Clough Consulting 2014). Therefore, it is recommended that riparian planting should occur in these reaches. A complete riparian assessment was not conducted as part of this ARP, therefore the 2014 FHAP should be consulted prior to planting in each reach since the dominant species observed in each reach is listed, as well as recommendations for restoration actions (D.R. Clough Consulting 2014).

Native deciduous trees such as willow (*Salix* spp.), red osier dogwood (*Cornus sericea*), and red alder (*Alnus rubra*) should be planted along the banks since these will stabilize the banks and allow for succession by conifers (D.R. Clough Consulting 2014). Willow and red osier dogwood can be planted by live cuttings harvested locally, increasing their likelihood of success due to their local adaptation (Pearson and Blair 2013). Plantings should be surrounded by fencing to protect them from herbivory from animals such as deer, beavers, and voles (Pearson and Blair 2013). Plantings can be in the form of plugs, potted plants, or live stakes (discussed in Section 7.1.4; Ministry of Agriculture 2012). It is best to plant plugs and potted plants when they are dormant in the early spring or fall, avoiding summer drought conditions (Ministry of Agriculture 2012).

7.1.4. Gravel Bars

There are many large gravel bars throughout the river which have resulted from historical logging in the upper watershed (Metherall 2019). Lower water volumes in the main channel due to subsurface flow beneath the gravel bars are contributing to challenging upstream spawning migrations for salmonids as well as increased stream temperatures (Gooding 2010; Metherall 2019). Additionally, the drone survey conducted on July 29, 2019 showed that the gravel bars were equal to or greater than 40°C, which could be contributing to an increase in stream temperatures.

Proposed Treatment

The TRRS has been planting gravel bars with live willow stakes in the upper reaches annually since 2018. Digging deep trenches to plant the willow stakes in the gravel bars has been relatively successful for stabilizing the gravel bars (Gooding 2010). Gooding (2010) indicated that the priority areas for gravel bar plantings are below Murex Creek within the Tsolum River mainstem, between Helldiver Creek (approximately 2 km upstream of the confluence with the Tsolum River) and Murex Creek confluences, and in the lower sections of Murex Creek above the confluence of the Tsolum River. Additionally, due to the high gravel bar temperatures observed during the drone surveys, live staking should also be conducted on gravel bars in the lower reaches to prevent mobilization and increase shading. Stream temperatures are highest in the lower reaches, therefore increasing shading from live staking on these gravel bars may decrease stream temperatures. Gravel bars mobilize easily in high flows, therefore bedload transport downstream should be minimized and stabilized through planting at these locations (Gooding 2010).

Willow cuttings should be collected in the late fall, winter, or early spring when the plants are dormant (Ministry of Forests 2002). The length of the cuttings should be at least 40 cm and they should have a minimum diameter of 2 cm (Ministry of Agriculture 2012). At least two nodes need to be present on the cutting (Ministry of Forests 2002). The basal cut should be below the first node with the top cut approximately 2 cm above the second node (Ministry of Forests 2002). Prior to live staking it is important to keep the cuttings cool and moist (Ministry of Forests 2002). They can be stored with the basel ends buried in sandy soil or placed in a stream (Ministry of Forests 2002; Ministry of Agriculture 2012). It is important to soak the cuttings for 8 to 10 days in freshwater before planting them (Ministry of Agriculture 2012). A variety of techniques can be used to prepare a hole in which the live stake will be planted, including poking a hole in the sediment using a piece of rebar or digging a hole with an excavator (Ministry of Agriculture 2012; Iowa Department of Natural Resources 2018). The cuttings should be spaced 30 cm from each other, with a minimum of 80% of the cutting planted in the gravel bar (Ministry of Agriculture 2012).

Chapter 8. Conclusion

A total of 28 water temperature loggers and two air temperature loggers were installed within the Tsolum River watershed during summer 2019, continuously measuring stream and air temperatures, respectively. Each water temperature logger was compared to one of the air temperature loggers to determine whether stream temperatures were primarily regulated by air temperature or groundwater temperature at that location. Linear regressions, SOM analyses, and time series graphs were used to determine the potential for groundwater input at each site. The results show that there is the potential for groundwater at twelve of the monitoring locations, namely: W2-2019, W7-2019, W8-2019, W9-2019, W10-2019, W11-2019, W12-2019, W13-2019, W14-2019, W17-2019, W20-2019, and W28-2019.

Additional methods were tested to locate groundwater input, including FLIR drone surveys, longitudinal temperature measurements, and conductivity measurements. The FLIR drone survey only identified locations in the stream that were greater than 40ºC, however different settings and additional survey effort would allow for the drone to identify cooler areas within the stream. As such, there is the potential for FLIR drone surveys to be used to identify areas of groundwater input. The longitudinal temperature measurements did distinguish between the surface and streambed temperatures, showing differences in temperatures throughout the surveyed section. As such, there is the potential for longitudinal temperature surveys to be conducted using two loggers to determine areas of groundwater input, however the method should be refined. Finally, the conductivity measurements were only conducted once, and did not provide conclusive evidence of groundwater input, therefore measurements should be taken simultaneously with temperature to identify groundwater input areas.

Temperature and dissolved oxygen sampling in Wolf Lake indicated that the cooler hypolimnetic water had adequate oxygen levels. Therefore, additional sampling should be conducted to determine whether it is possible to augment summer flows in the Tsolum River using water from the hypolimnion rather than the epilimnion.

Further temperature measurements should be conducted at the twelve locations that have the potential for groundwater input. Recommendations to improve the efficacy of identifying groundwater include a dual logger system at each location, weekly streamflow measurements at each location, a longer study period, and fish sampling.

The recommended restoration treatments to mitigate against increasing stream temperatures include riparian planting in the lower reaches, gravel bar live staking, additional sampling in Wolf Lake, and minimizing water extraction (e.g. metering withdrawals, implementing efficient irrigation practices, buying back water licenses, and constructing winter storage on agricultural lands). Results from the 2019 study showed that stream temperatures were highest in the lower reaches (loggers installed in the lower 4.5 km of the river had the highest stream temperatures). Additionally, the 2014 riparian vegetation assessment showed that the lower reaches had poor to fair riparian vegetation (D.R. Clough Consulting 2014). As such, the lower reaches should be prioritized for riparian planting. Live staking should also be conducted in theses reaches due to the high stream and grave bar temperatures.

Overall, this study showed that it is possible to use loggers to identify areas of cooler groundwater input in a stream. Identifying these areas is critical since they are considered thermal refugia and should be protected and restored to promote resilience for salmonids in the face of climate change.

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Appendix A: Average Stream Depth, Site Description, and Rationale for Site Selection

Table A-1 Average stream depth, site description, and rationale for selection of each site.

Site Name	Average Stream Depth (m)	Site Description and Rationale for Site Selection
W1-2019	0.5	Located slightly upstream of Dove Creek and Tsolum River confluence. Purpose of this tidbit was to assess Tsolum River temperature prior to confluence so there was a “reference” temperature that could be compared to W3-2019.
W2-2019	0.7	In Dove Creek, near confluence with Tsolum River. Purpose of this tidbit was to assess temperature within Dove Creek, to understand whether it could be influencing temperature in Tsolum River.
W3-2019	1.1	Located slightly downstream of Dove Creek and Tsolum River confluence. Purpose of this tidbit was to assess temperature of Tsolum River after Dove Creek has flowed into it, to understand whether Dove Creek could be influencing temperature in Tsolum River.
W4-2019	0.7	Located slightly upstream of Headquarters Creek and Tsolum River confluence. Purpose of this tidbit was to assess temperature of Tsolum River after Headquarters Creek has flowed into it, to understand whether Dove Creek could be influencing temperature in Tsolum River.

Site Name	Average Stream Depth (m)	Site Description and Rationale for Site Selection
W5-2019	0.5	In Headquarters Creek, near confluence with Tsolum River. Purpose of this tidbit was to assess temperature within Headquarters Creek, to understand whether it could be influencing temperature in Tsolum River.
W6-2019	0.8	Located slightly downstream of Headquarters Creek and Tsolum River confluence. Purpose of this tidbit was to assess temperature of Tsolum River after Headquarters Creek has flowed into it, to understand whether Headquarters Creek could be influencing temperature in Tsolum River. Compared to “reference” temperature upstream of tributary (W4-2019).
W7-2019	0.9	Seepage in right bank visible during periods with no rain. Potential for groundwater input therefore tidbit installed in pool in centre of channel near seepage. Temperature measured with handheld thermometer in right bank seepage slightly upstream of W7-2019 was 11°C, which was potentially indicative of groundwater.
W8-2019	0.9	Figure 11 in Phase 1 Tsolum River Agricultural Watershed Plan (Metherall 2019) shows cross section of delineated aquifer boundaries, showing that the Tsolum Aquifer “TS-2” comes very close to intersecting with the Tsolum River in this area. Purpose of this tidbit was to determine whether aquifer intersects with Tsolum River, with the potential for groundwater/surface water interactions.

Site Name	Average Stream Depth (m)	Site Description and Rationale for Site Selection
W9-2019	1.1	Located slightly downstream of Portuguese Creek and Tsolum River confluence. Purpose of this tidbit was to assess temperature of Tsolum River after Portuguese Creek has flowed into it, to understand whether Portuguese Creek could be influencing temperature in Tsolum River.
W10-2019	0.6	In Portuguese Creek, near confluence with Tsolum River. Purpose of this tidbit was to assess temperature within Portuguese Creek, to understand whether it could be influencing temperature in Tsolum River.
W11-2019	1.0	Located slightly upstream of Portuguese Creek and Tsolum River confluence. Purpose of this tidbit was to assess Tsolum River temperature prior to confluence so there was a "reference" temperature that could be compared to W9-2019.
W12-2019	0.8	At outflow of ephemeral stream that enters the Tsolum River slightly south of Glacier Road. No surface flow in ephemeral stream during summer months, however deep pool at output of ephemeral stream, therefore potential for subsurface/groundwater flow. Purpose of this tidbit was to assess whether temperature was cooler at outflow of ephemeral stream.
W13-2019	0.9	Slightly upstream of right bank seepage near W7-2019. Purpose was to compare to W7-2019 to understand whether right bank seepage was influencing temperature of Tsolum River. Temperature measured with handheld thermometer in right bank seepage beside W13-2019 was 11°C, which was potentially indicative of groundwater.

Site Name	Average Stream Depth (m)	Site Description and Rationale for Site Selection
W14-2019	0.5	Slightly upstream of W8-2019, downstream of large boulder near left bank. Mound of silt and clean gravel downstream of large boulder during installation in June 2019, therefore potential for groundwater welling since gravel to the sides and upstream of boulder not clean. Purpose of this tidbit was to determine whether there was cooler groundwater upwelling downstream of boulder.
W15-2019	0.3	At outflow of ephemeral stream entering Tsolum River right bank, upstream of McEachern bridge. No surface flow in ephemeral stream during summer months, however water was flowing through culvert crossing Winn Road, therefore potential for subsurface/groundwater flow. Purpose of this tidbit was to assess whether temperature was cooler at outflow of ephemeral stream.
W16-2019	1.2	Figure 10 in Phase 1 Tsolum River Agricultural Watershed Plan (Metherall 2019) shows cross section of delineated aquifer boundaries, showing that the Tsolum Aquifer “TS-2” comes very close to intersecting with the Tsolum River in this area. Purpose of this tidbit was to determine whether aquifer intersects with Tsolum River, with the potential for groundwater/surface water interactions. Additionally, seepage in right bank was visible during periods with no rain, therefore tidbit was installed in pool near right bank.
W17-2019	0.6	Attached to pillar in old pink counting fence. Purpose of this tidbit was to look at historical temperature trends since a logger was installed here from 1996 to 2003.

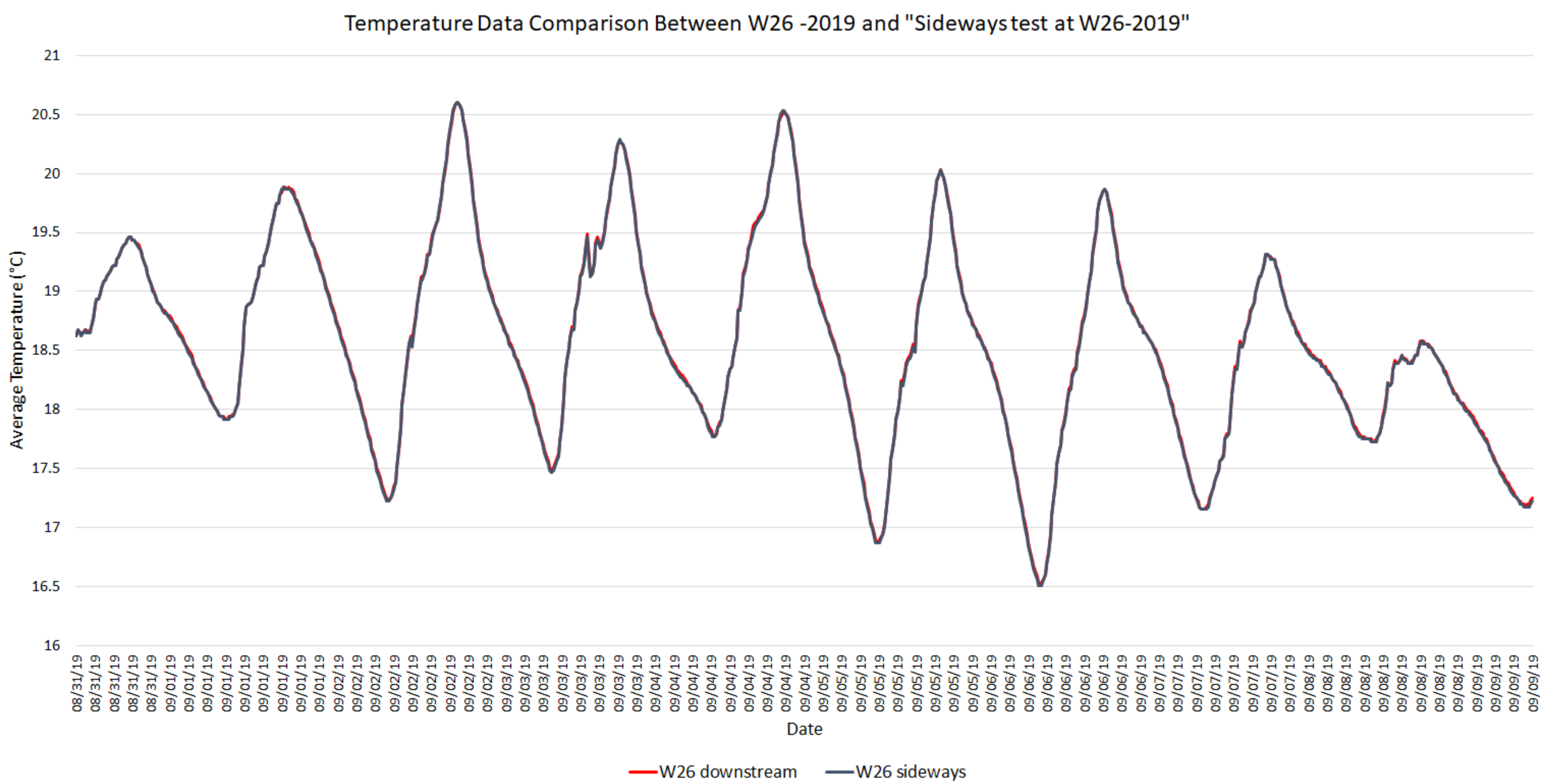
Site Name	Average Stream Depth (m)	Site Description and Rationale for Site Selection
W18-2019	0.6	Upstream of Highway 19, where Duncan Bay Main crosses Tsolum River. Purpose of this tidbit was to serve as a reference site, since there is no water extraction or residential/agricultural development in this area of the Tsolum River.
W19-2019	0.5	Seepage in left bank upstream of W15-2019, therefore tidbit was installed in deeper section near left bank seepage. Purpose of this tidbit was to determine whether seepage is influencing temperature of Tsolum River.
W20-2019	0.6	Matt Vardal from GW Solutions indicated that there could be groundwater/surface water interactions in the area of the Tsolum River near Carwithen Road. Additionally, local landowners from that area mentioned that there are a few locations along the left bank that feel cooler during the summer. W20-2019 was installed in one of these locations along the left bank and it did feel cooler than the centre of the stream at the time of deployment. There were also congregations of coho fry noted in this location throughout the summer.
W21-2019	0.2	Matt Vardal from GW Solutions indicated that there could be groundwater/surface water interactions in the area of the Tsolum River near Carwithen Road. Additionally, local landowners from that area mentioned that there are a few locations along the left bank that feel cooler during the summer. W21-2019 was installed in one of these locations, underneath a log on the left bank.

Site Name	Average Stream Depth (m)	Site Description and Rationale for Site Selection
W22-2019	2.1	Matt Vardal from GW Solutions indicated that there could be groundwater/surface water interactions in the area of the Tsolum River near Carwithen Road. Additionally, local landowners from that area mentioned that there were some swimming holes along the right bank that felt cooler during the summer. They were quite deep relative to the rest of the Tsolum River, therefore there was the potential that groundwater could be entering in these pools. W22-2019 was installed in one of these pools.
W23-2019	2.6	Matt Vardal from GW Solutions indicated that there could be groundwater/surface water interactions in the area of the Tsolum River near Carwithen Road. Additionally, local landowners from that area mentioned that there were some swimming holes along the right bank that felt cooler during the summer. They were quite deep relative to the rest of the Tsolum River, therefore there was the potential that groundwater could be entering in these pools. W23-2019 was installed in one of these pools, downstream of W22-2019.
W24-2019	1.4	At outflow of ephemeral stream that enters the Tsolum River slightly south of Glacier Road. No surface flow in ephemeral stream during summer months, however deep pool at output of ephemeral stream, therefore potential for subsurface/groundwater flow. W24-2019 was installed at the bottom of the pool at the outflow of the ephemeral stream. Purpose of this tidbit was to compare temperatures between the tidbit close to the surface (W12-2019) and the tidbit at the streambed (W24-2019) to determine whether a dual-logger system could capture potential groundwater input.

Site Name	Average Stream Depth (m)	Site Description and Rationale for Site Selection
W25-2019	0.5	Outlet of Wolf Lake in Headquarters Creek. Purpose of this tidbit was to determine the temperature in Headquarters Creek when water from Wolf Lake is augmenting streamflow.
W26-2019	0.7	Figure 20 in Phase 1 Tsolum River Agricultural Watershed Plan (Metherall 2019) shows cross section of delineated aquifer boundaries, showing that the Tsolum Aquifer "TS-2" comes very close to intersecting with the Tsolum River in this area. Purpose of this tidbit was to determine whether aquifer intersects with Tsolum River, with the potential for groundwater/surface water interactions. Seepage along the left bank was also observed upstream of W8-2019 and W14-2019, therefore W26-2019 was installed downstream of the seepage to determine whether it was influencing temperature in the Tsolum River.
W27-2019	0.9	Figure 20 in Phase 1 Tsolum River Agricultural Watershed Plan (Metherall 2019) shows cross section of delineated aquifer boundaries, showing that the Tsolum Aquifer "TS-2" comes very close to intersecting with the Tsolum River in this area. Purpose of this tidbit was to determine whether aquifer intersects with Tsolum River, with the potential for groundwater/surface water interactions. Seepage along the left bank was also observed upstream of W8-2019, W14-2019, and W26-2019, therefore W27-2019 was installed near the left bank seepage to determine whether it was influencing temperature in the Tsolum River.
W28-2019	0.3	Installed across the river from where the historical "Yew Tree" logger was installed. The previous logger had been installed along the right bank where a yew tree stood, however the yew tree was no longer present and the right bank

Site Name	Average Stream Depth (m)	Site Description and Rationale for Site Selection
		did not have sufficient water depth for the logger to stay wetted. The purpose of this tidbit was to look at historical temperature trends since a logger was installed here from 1998 to 2000.
W29-2019	0.21	In tributary entering Cowichan River (Bear Creek). Purpose of this tidbit was to assess temperature in groundwater-fed stream to test tidbit methodology. This stream was observed during a snorkel swim in the Cowichan River during July 2019.
W30-2019	0.62	Upstream of tributary entering Cowichan River to compare temperatures between the mainstem and a groundwater-fed stream.
A1-2019	n/a	Air temperature tidbit installed in gravel bar in Tsolum River near Stephen Road. Riparian vegetation cover of this tidbit was 6.5%, therefore it was compared to water tidbits that had a percent cover below 50%.
A2-2019	n/a	Air temperature tidbit installed under riparian vegetation in left bank of Tsolum River near Stephen Road. Riparian vegetation cover of this tidbit was 99.8%, therefore it was compared to water tidbits that had a percent cover above 50%.

Appendix B: Temperature Comparison between W26-2019 and "Sideways Test at W26-2019"



Appendix C: Temperature Monitoring Locations within the Tsolum River

(Presented in downstream order)

**Figure C-1	Location of W18-2019. The white box shown in the inset box in the top right depicts the location of this site within the study area (Esri 2009).**

Figure C-2 **Location of W25-2019. The white box shown in the inset box in the top right depicts the location of this site within the study area (Esri 2009).**

Figure C-3 Location of W28-2019, W4-2019, W5-2019, W6-2019, W19-2019, and W15-2019. The white box shown in the inset box in the top right depicts the location of these sites within the study area (Esri 2009).

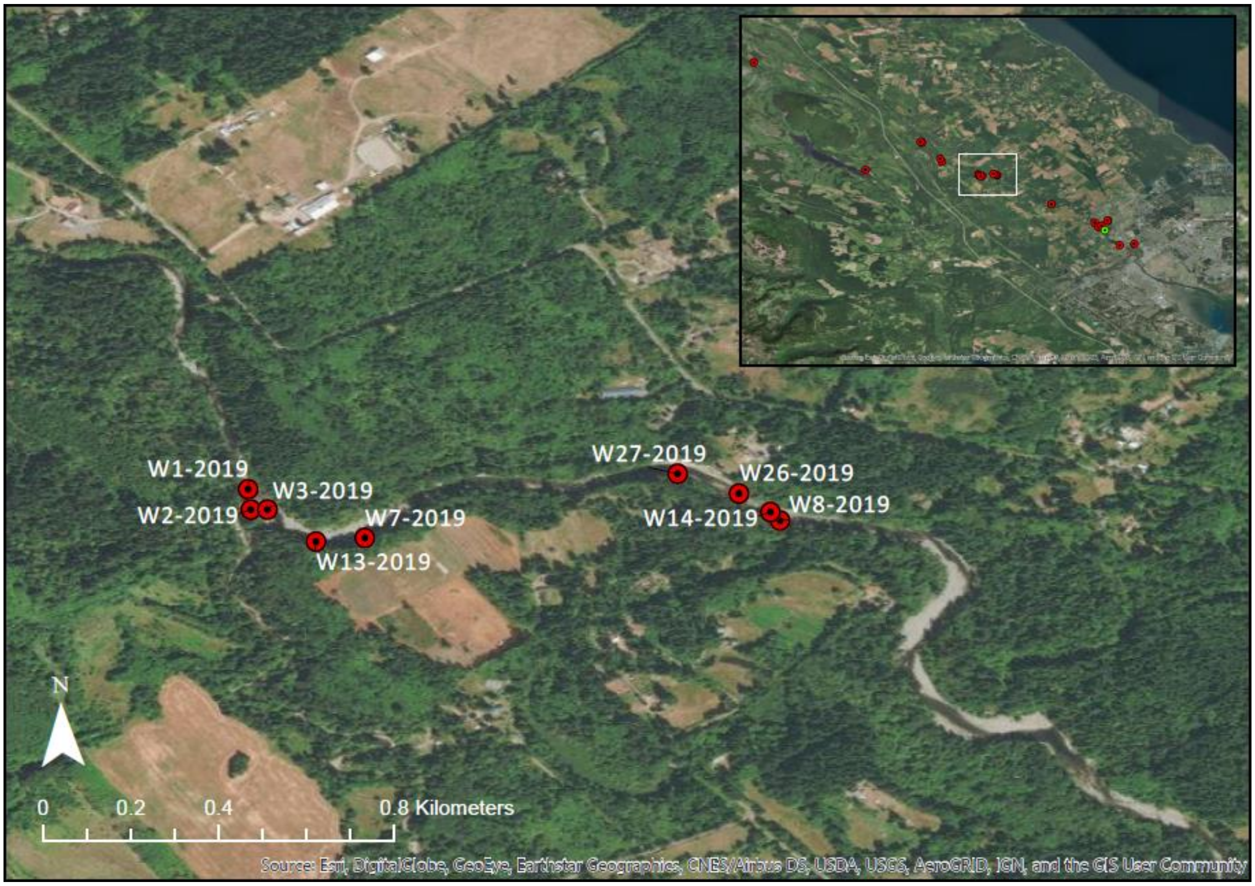


Figure C-4 Location of W1-2019, W2-2019, W3-2019, W13-2019, W7-2019, W27-2019, W26-2019, W14-2019, and W8-2019. The white box shown in the inset box in the top right depicts the location of these sites within the study area (Esri 2009).

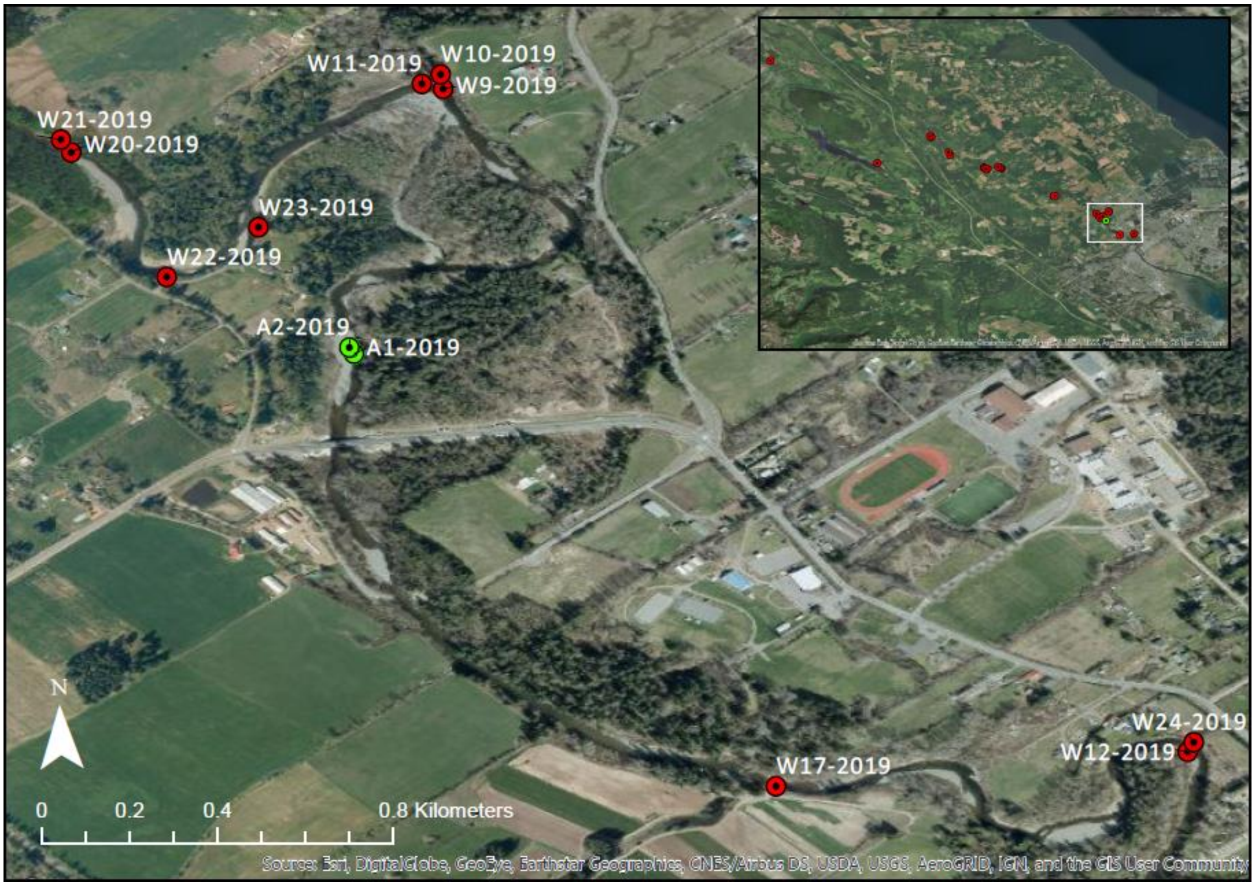


Figure C-5 Location of W21-2019, W20-2019, W22-2019, W23-2019, W11-2019, W10-2019, W9-2019, A2-2019, A1-2019, W17-2019, W24-2019, and W12-2019. The white box shown in the inset box in the top right depicts the location of these sites within the study area (Esri 2009).

Appendix D: Statistical Tests for Normality and Residual Normality/Homoscedasticity

Table D-1 Kolmogorov-Smirnov test for weekly means of air and water temperatures for each water/air temperature logger pair.

Site Name	p-value of Air Temperature Weekly Averages	p-value of Water Temperature Weekly Averages	Interpretation
W1-2019	0.90	0.97	Fail to reject Ho (data is normally distributed)
W2-2019	0.90	0.80	Fail to reject Ho (data is normally distributed)
W3-2019	0.90	0.97	Fail to reject Ho (data is normally distributed)
W4-2019	0.93	0.67	Fail to reject Ho (data is normally distributed)
W5-2019	0.95	1.0	Fail to reject Ho (data is normally distributed)
W6-2019	0.89	0.91	Fail to reject Ho (data is normally distributed)
W7-2019	0.93	1.0	Fail to reject Ho (data is normally distributed)
W8-2019	0.82	0.86	Fail to reject Ho (data is normally distributed)
W9-2019	0.81	0.77	Fail to reject Ho (data is normally distributed)
W10-2019	0.83	0.62	Fail to reject Ho (data is normally distributed)
W11-2019	0.80	0.66	Fail to reject Ho (data is normally distributed)
W12-2019	0.85	0.75	Fail to reject Ho (data is normally distributed)
W13-2019	0.72	0.69	Fail to reject Ho (data is normally distributed)
W14-2019	0.79	0.94	Fail to reject Ho (data is normally distributed)
W15-2019	0.91	1.0	Fail to reject Ho (data is normally distributed)
W16-2019	0.86	0.99	Fail to reject Ho (data is normally distributed)
W17-2019	0.87	0.65	Fail to reject Ho (data is normally distributed)
W18-2019	0.87	0.92	Fail to reject Ho (data is normally distributed)
W19-2019	0.62	0.82	Fail to reject Ho (data is normally distributed)
W20-2019	0.70	0.88	Fail to reject Ho (data is normally distributed)
W21-2019	0.93	0.98	Fail to reject Ho (data is normally distributed)
W22-2019	0.96	0.96	Fail to reject Ho (data is normally distributed)
W23-2019	0.99	0.85	Fail to reject Ho (data is normally distributed)
W24-2019	0.99	0.98	Fail to reject Ho (data is normally distributed)
W25-2019	0.81	0.98	Fail to reject Ho (data is normally distributed)
W26-2019	0.68	0.91	Fail to reject Ho (data is normally distributed)
W27-2019	0.66	0.89	Fail to reject Ho (data is normally distributed)
W28-2019	0.98	1.0	Fail to reject Ho (data is normally distributed)

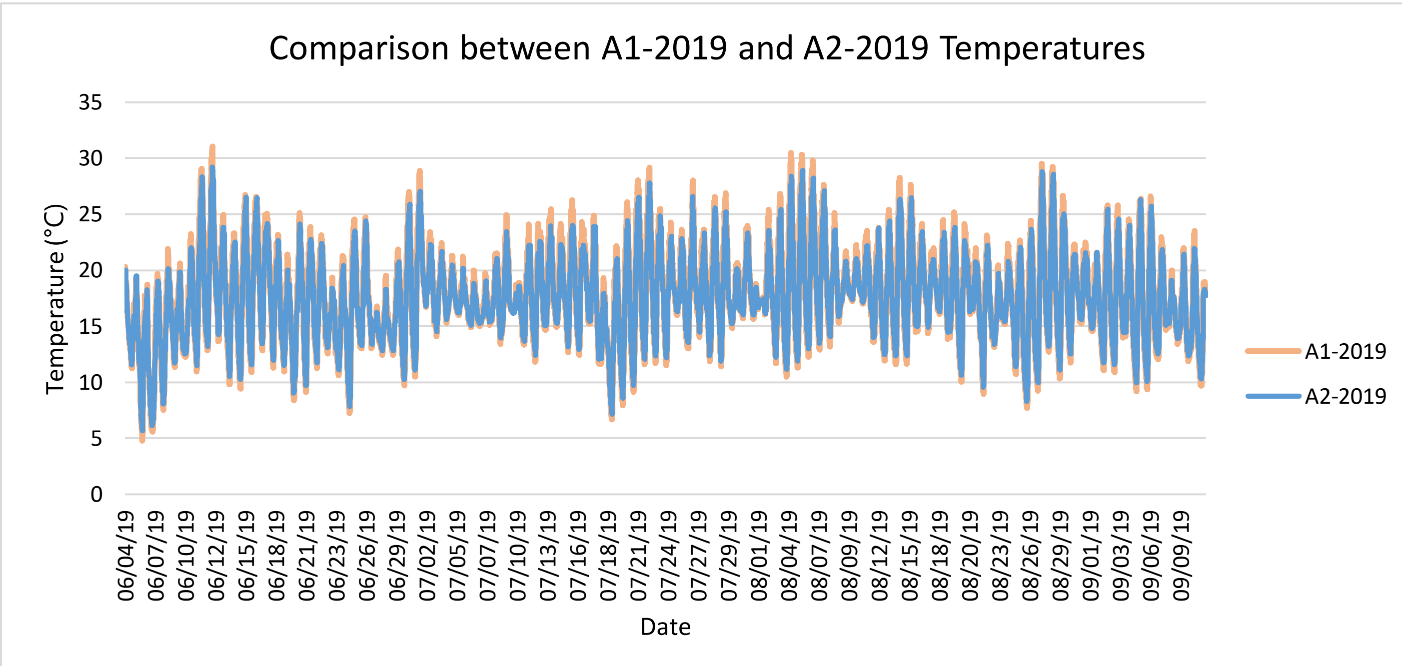
Table D-2 Kolmogorov-Smirnov and Breush-Pagan tests for residuals of weekly means of air and water temperatures for each air/water temperature logger pair.

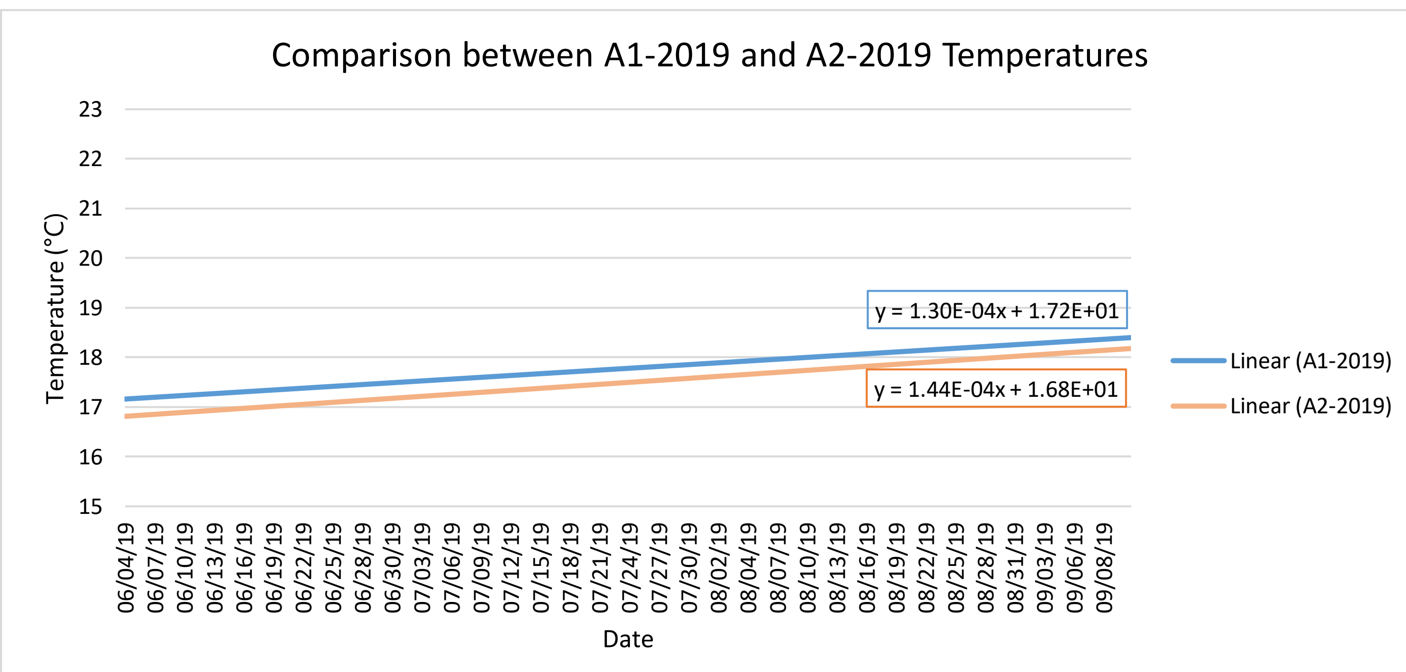
Site Name	p-value for Kolmogrov-Smirnov Test	Interpretation for Kolmogrov-Smirnov Test	p-value for Breush-Pagan Test	Interpretation for Breush-Pagan Test
W1-2019	0.94	Fail to reject Ho (residuals normally distributed)	0.14515	Fail to reject Ho (residuals are homoscedastic)
W2-2019	0.9949	Fail to reject Ho (residuals normally distributed)	0.33119	Fail to reject Ho (residuals are homoscedastic)
W3-2019	0.94	Fail to reject Ho (residuals normally distributed)	0.14515	Fail to reject Ho (residuals are homoscedastic)
W4-2019	0.9431	Fail to reject Ho (residuals normally distributed)	0.74321	Fail to reject Ho (residuals are homoscedastic)
W5-2019	0.9841	Fail to reject Ho (residuals normally distributed)	0.49286	Fail to reject Ho (residuals are homoscedastic)
W6-2019	0.799	Fail to reject Ho (residuals normally distributed)	0.4858	Fail to reject Ho (residuals are homoscedastic)
W7-2019	0.9977	Fail to reject Ho (residuals normally distributed)	0.15804	Fail to reject Ho (residuals are homoscedastic)
W8-2019	0.9718	Fail to reject Ho (residuals normally distributed)	0.30902	Fail to reject Ho (residuals are homoscedastic)
W9-2019	0.8663	Fail to reject Ho (residuals normally distributed)	0.88056	Fail to reject Ho (residuals are homoscedastic)
W10-2019	0.5528	Fail to reject Ho (residuals normally distributed)	0.025	Reject Ho (residuals are not homoscedastic) –value is close to 0.05, therefore not an issue.
W11-2019	0.6292	Fail to reject Ho (residuals normally distributed)	0.14131	Fail to reject Ho (residuals are homoscedastic)
W12-2019	0.7931	Fail to reject Ho (residuals normally distributed)	0.1137	Fail to reject Ho (residuals are homoscedastic)
W13-2019	0.9346	Fail to reject Ho (residuals normally distributed)	0.93097	Fail to reject Ho (residuals are homoscedastic)
W14-2019	0.9391	Fail to reject Ho (residuals normally distributed)	0.76219	Fail to reject Ho (residuals are homoscedastic)
W15-2019	0.9027	Fail to reject Ho (residuals normally distributed)	0.35666	Fail to reject Ho (residuals are homoscedastic)
W16-2019	0.5387	Fail to reject Ho (residuals normally distributed)	0.91294	Fail to reject Ho (residuals are homoscedastic)
W17-2019	0.9593	Fail to reject Ho (residuals normally distributed)	0.48311	Fail to reject Ho (residuals are homoscedastic)
W18-2019	0.8425	Fail to reject Ho (residuals normally distributed)	0.17711	Fail to reject Ho (residuals are homoscedastic)
W19-2019	0.9302	Fail to reject Ho (residuals normally distributed)	0.55025	Fail to reject Ho (residuals are homoscedastic)
W20-2019	0.8469	Fail to reject Ho (residuals normally distributed)	0.96713	Fail to reject Ho (residuals are homoscedastic)
W21-2019	0.9997	Fail to reject Ho (residuals normally distributed)	0.32137	Fail to reject Ho (residuals are homoscedastic)
W22-2019	0.8067	Fail to reject Ho (residuals normally distributed)	0.63917	Fail to reject Ho (residuals are homoscedastic)

Site Name	p-value for Kolmogrov-Smirnov Test	Interpretation for Kolmogrov-Smirnov Test	p-value for Breush-Pagan Test	Interpretation for Breush-Pagan Test
W23-2019	0.8001	Fail to reject Ho (residuals normally distributed)	0.65698	Fail to reject Ho (residuals are homoscedastic)
W24-2019	0.8671	Fail to reject Ho (residuals normally distributed)	0.35256	Fail to reject Ho (residuals are homoscedastic)
W25-2019	0.8613	Fail to reject Ho (residuals normally distributed)	0.35462	Fail to reject Ho (residuals are homoscedastic)
W26-2019	0.9539	Fail to reject Ho (residuals normally distributed)	0.26664	Fail to reject Ho (residuals are homoscedastic)
W27-2019	0.9722	Fail to reject Ho (residuals normally distributed)	0.21861	Fail to reject Ho (residuals are homoscedastic)
W28-2019	0.9868	Fail to reject Ho (residuals normally distributed)	0.22887	Fail to reject Ho (residuals are homoscedastic)

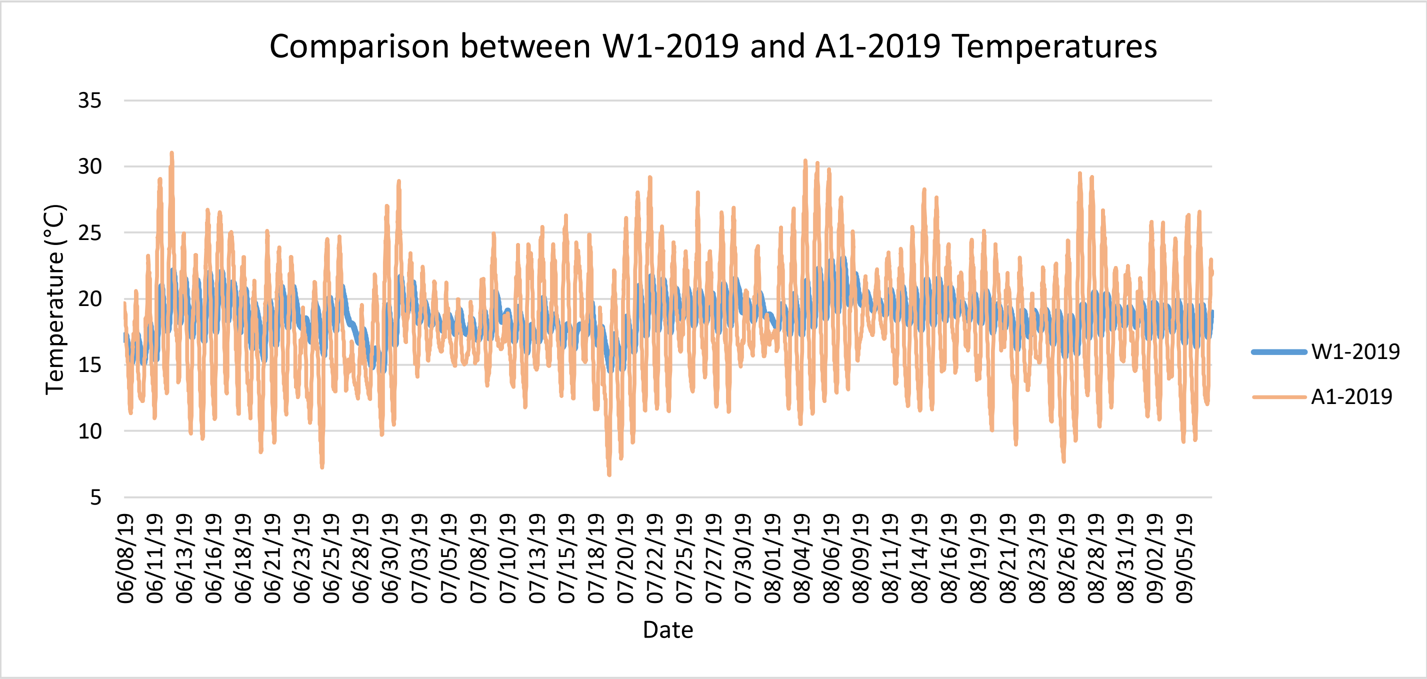
Appendix E: Comparison Graphs between Water and Air Tidbits

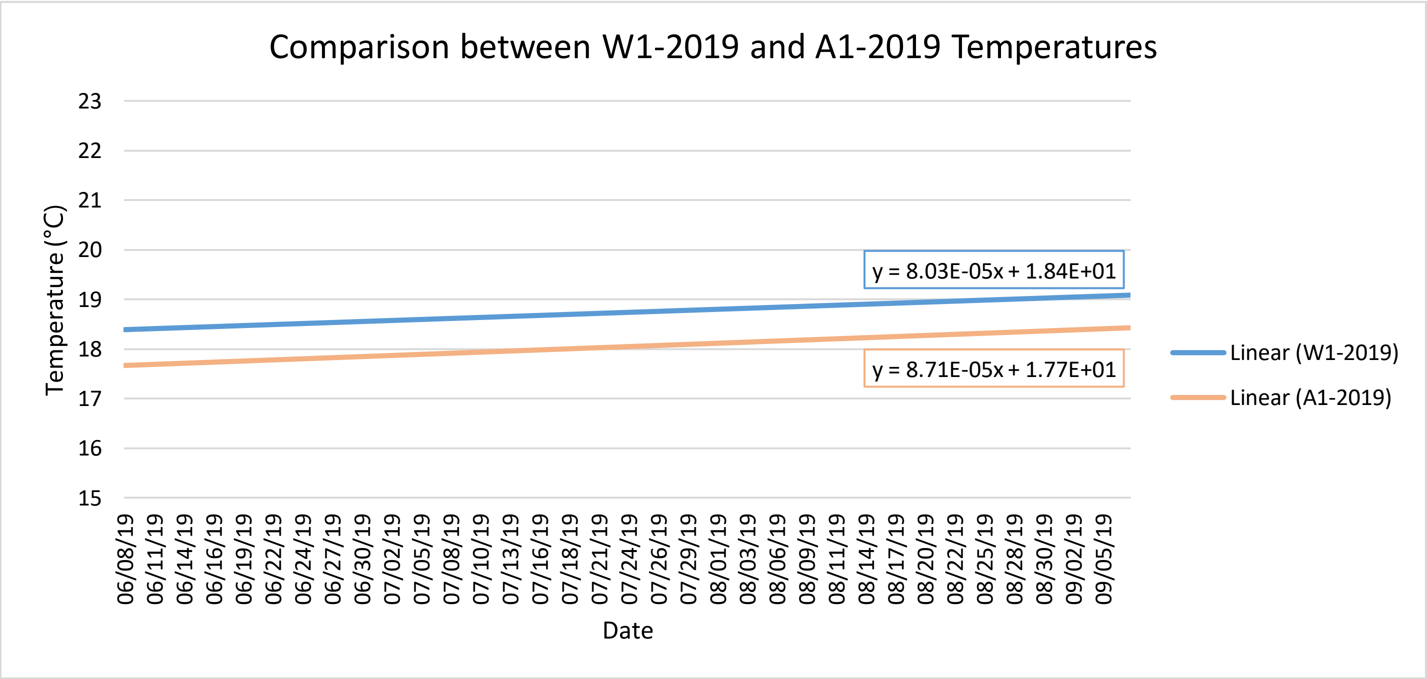
A1-2019 and A2-2019



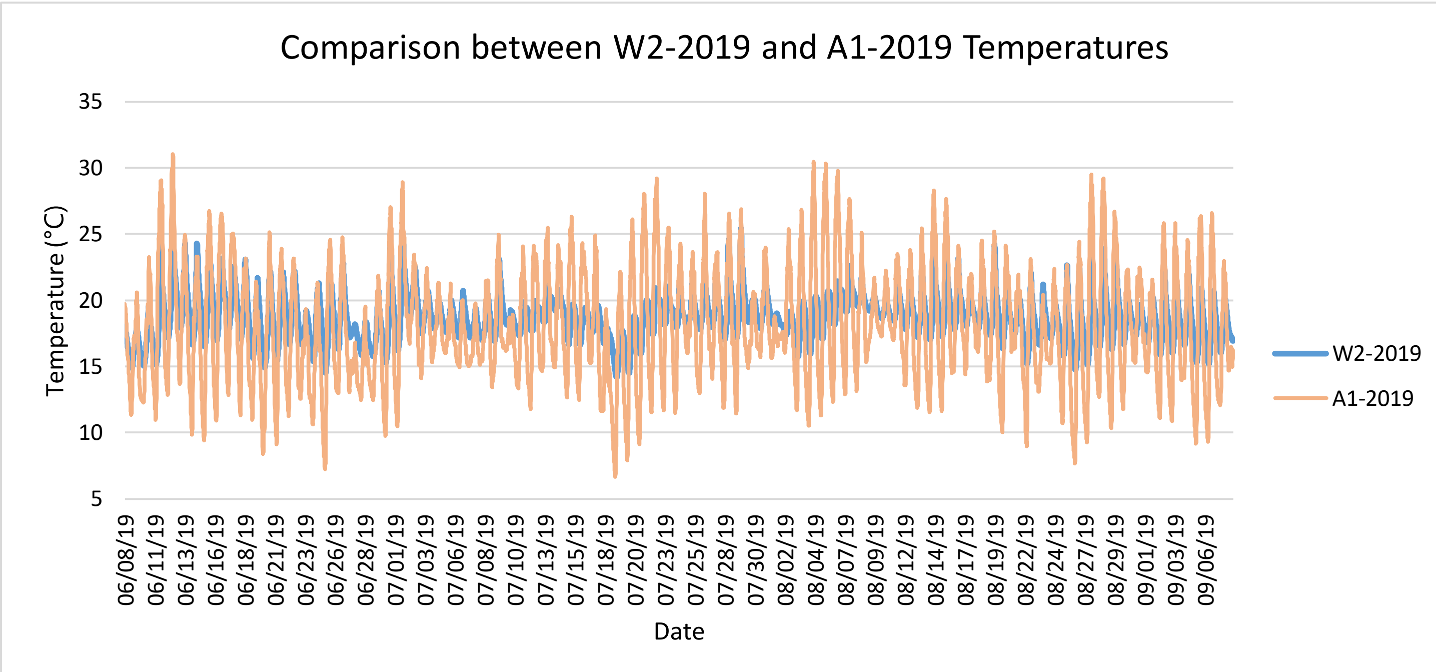


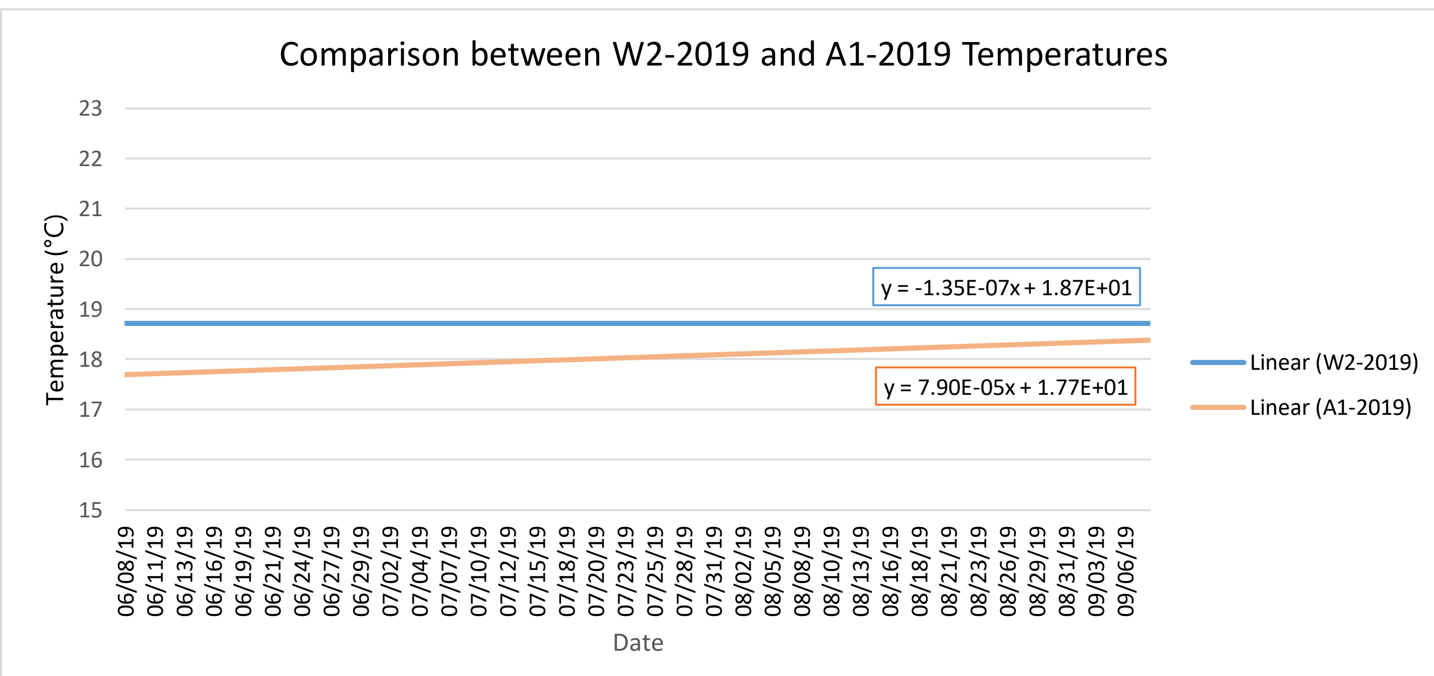
W1-2019 and A1-2019



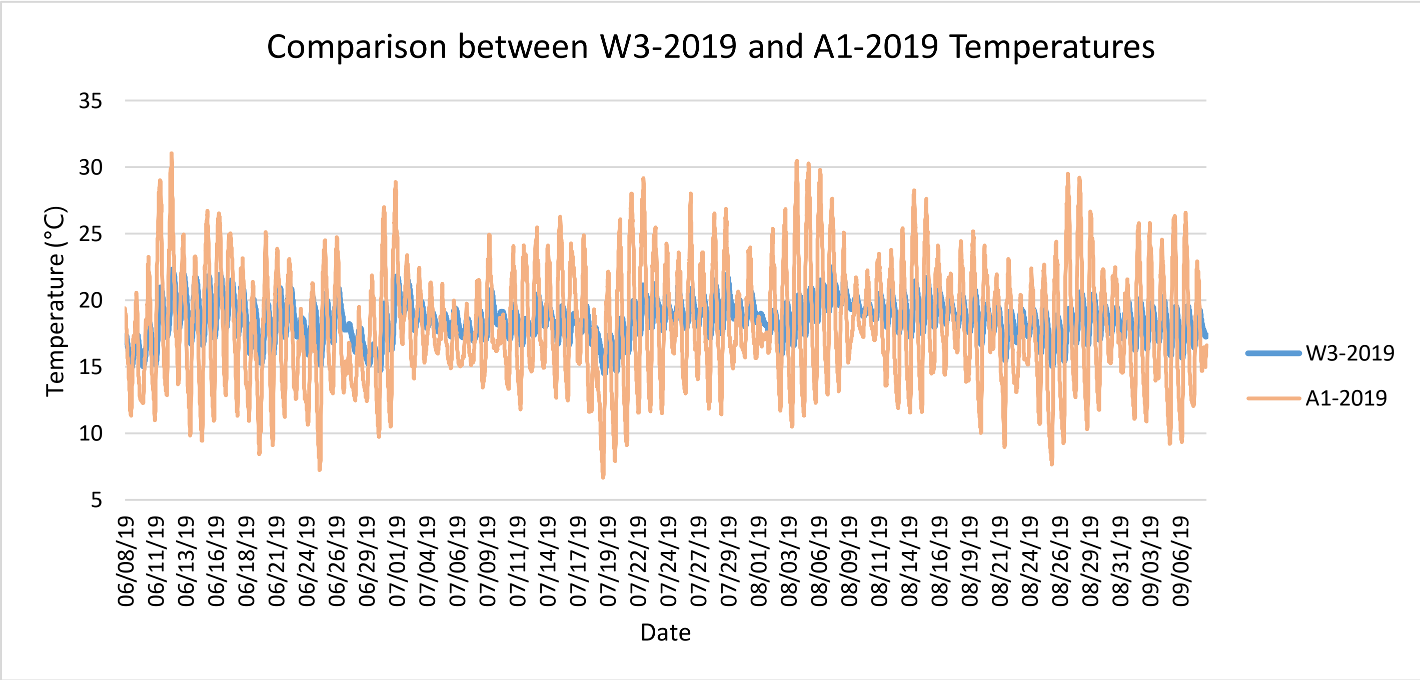


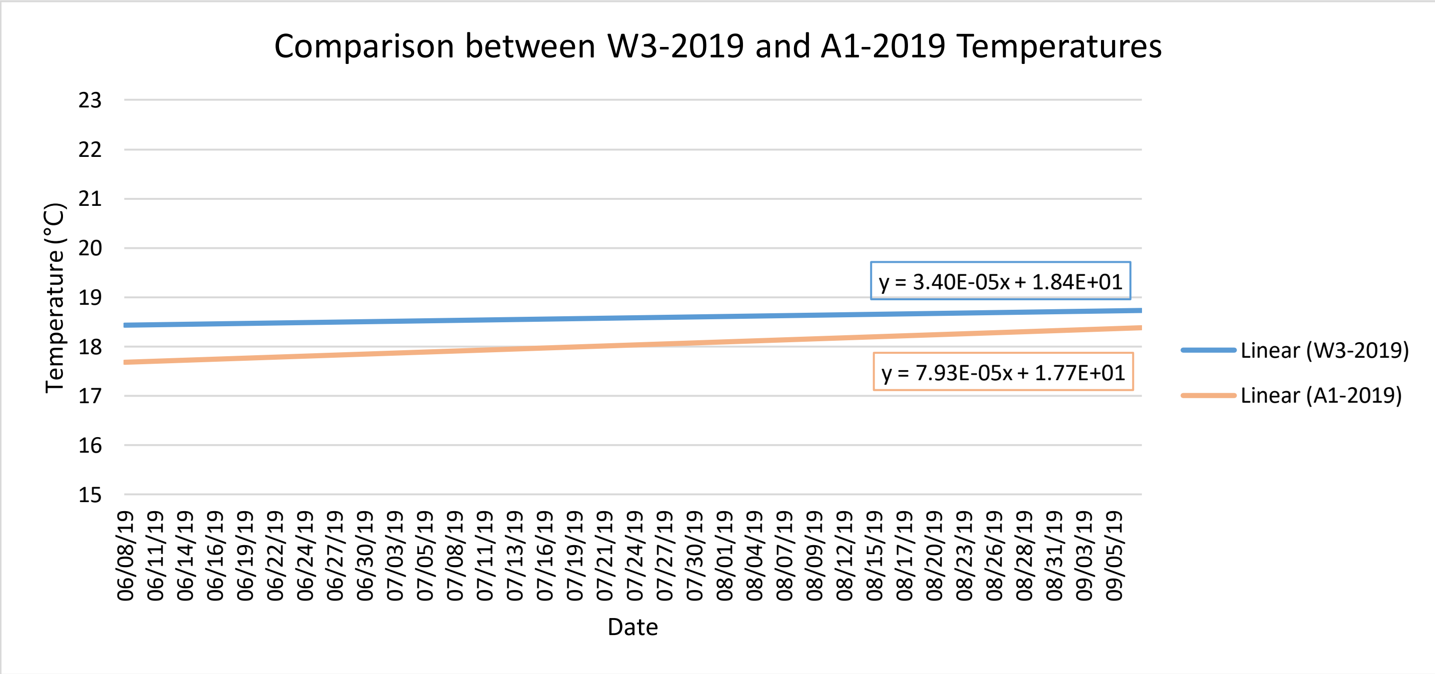
W2-2019 and A1-2019



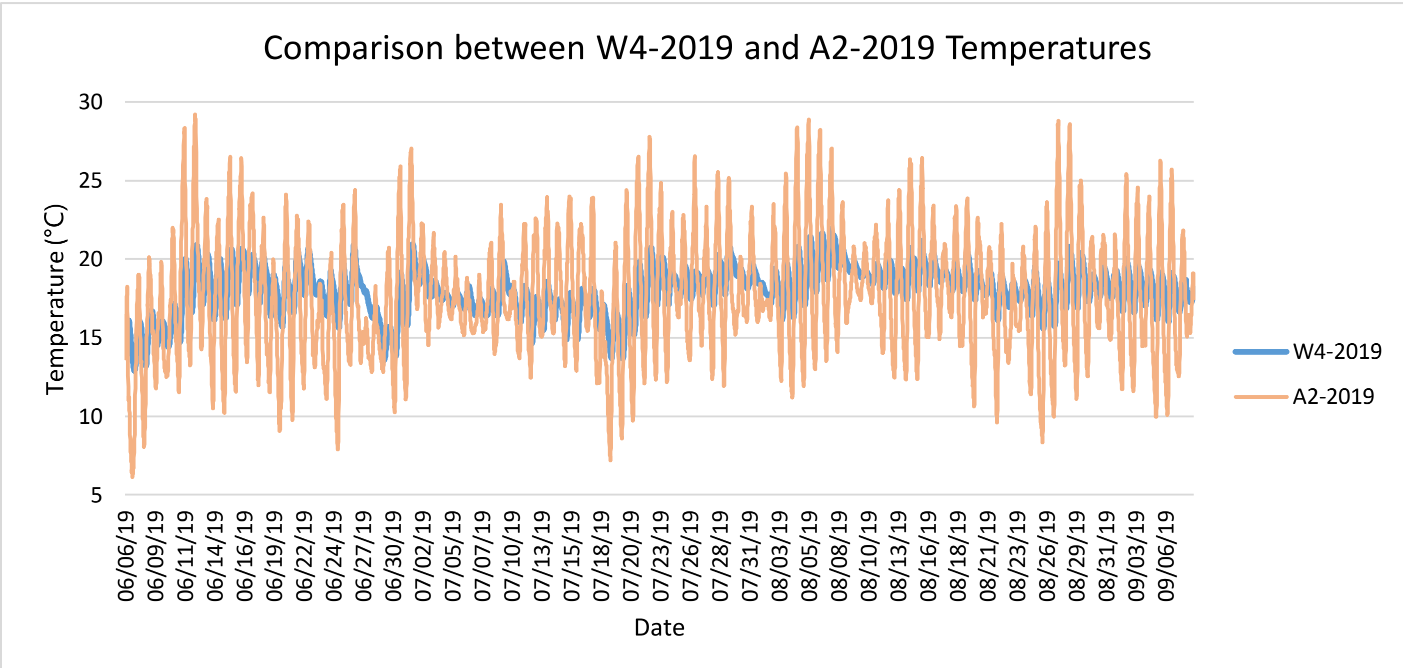


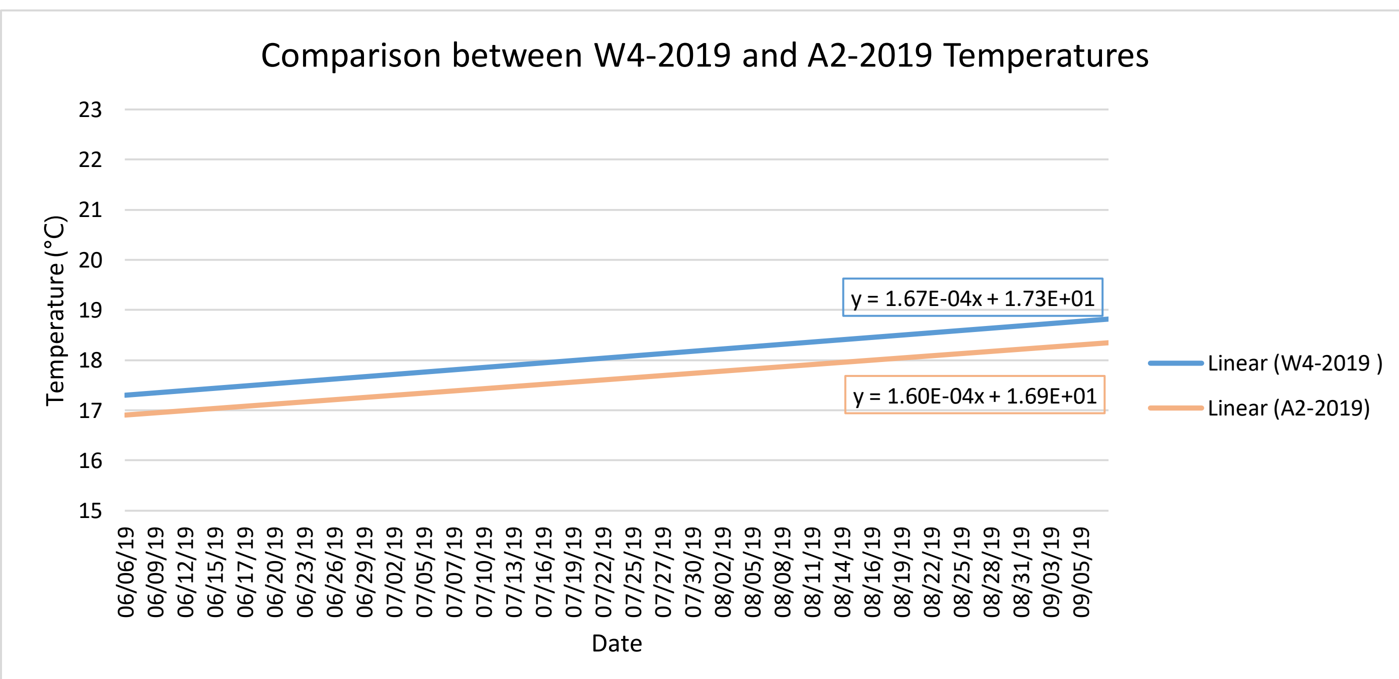
W3-2019 and A1-2019



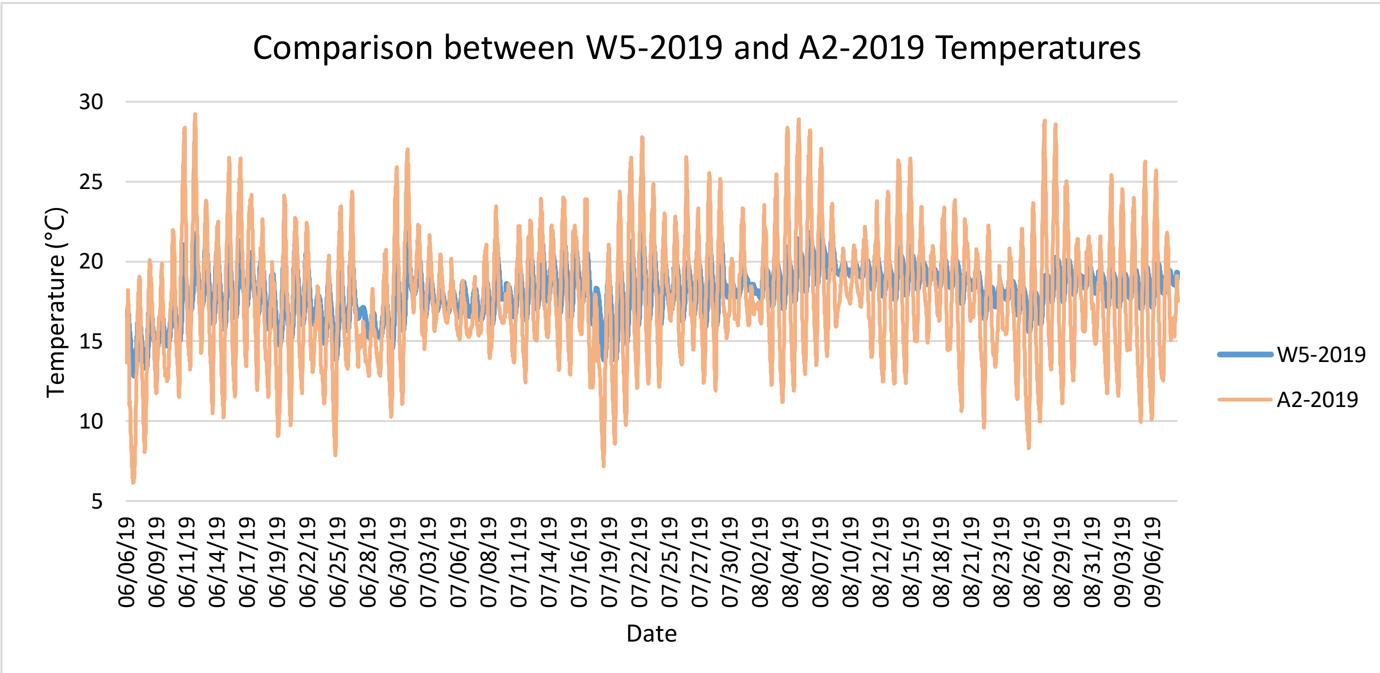


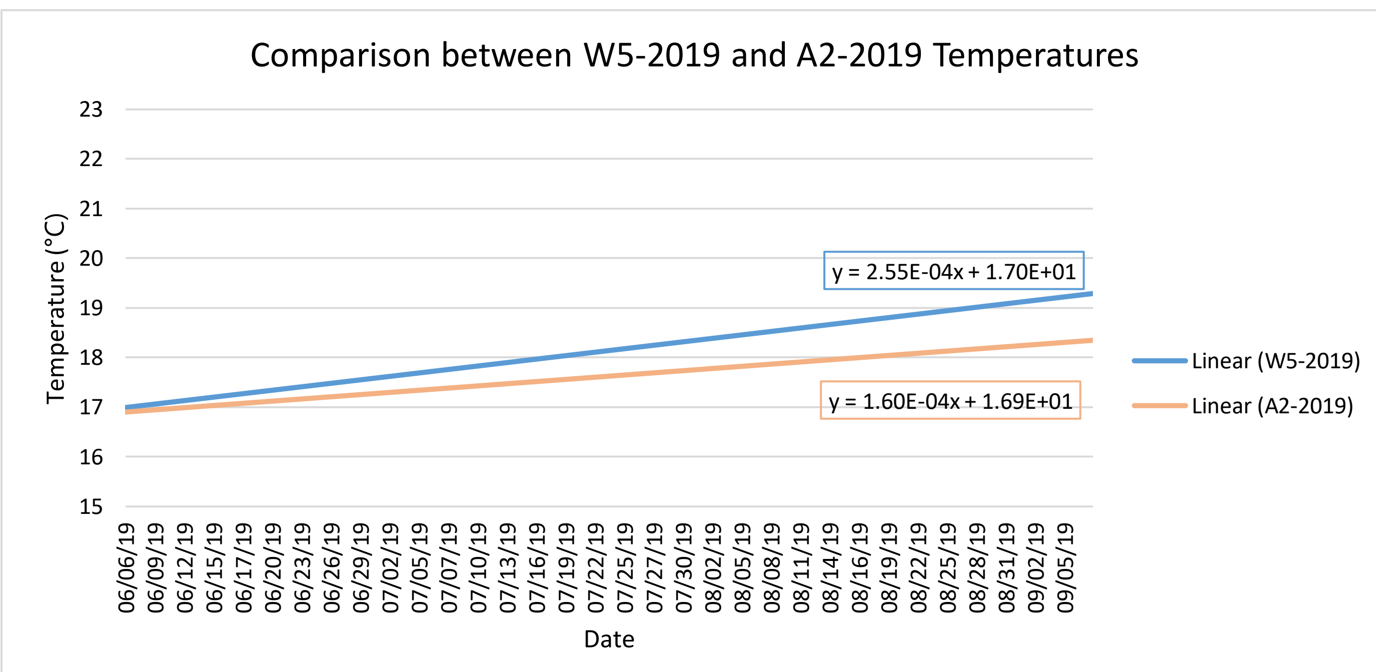
W4-2019 and A2-2019



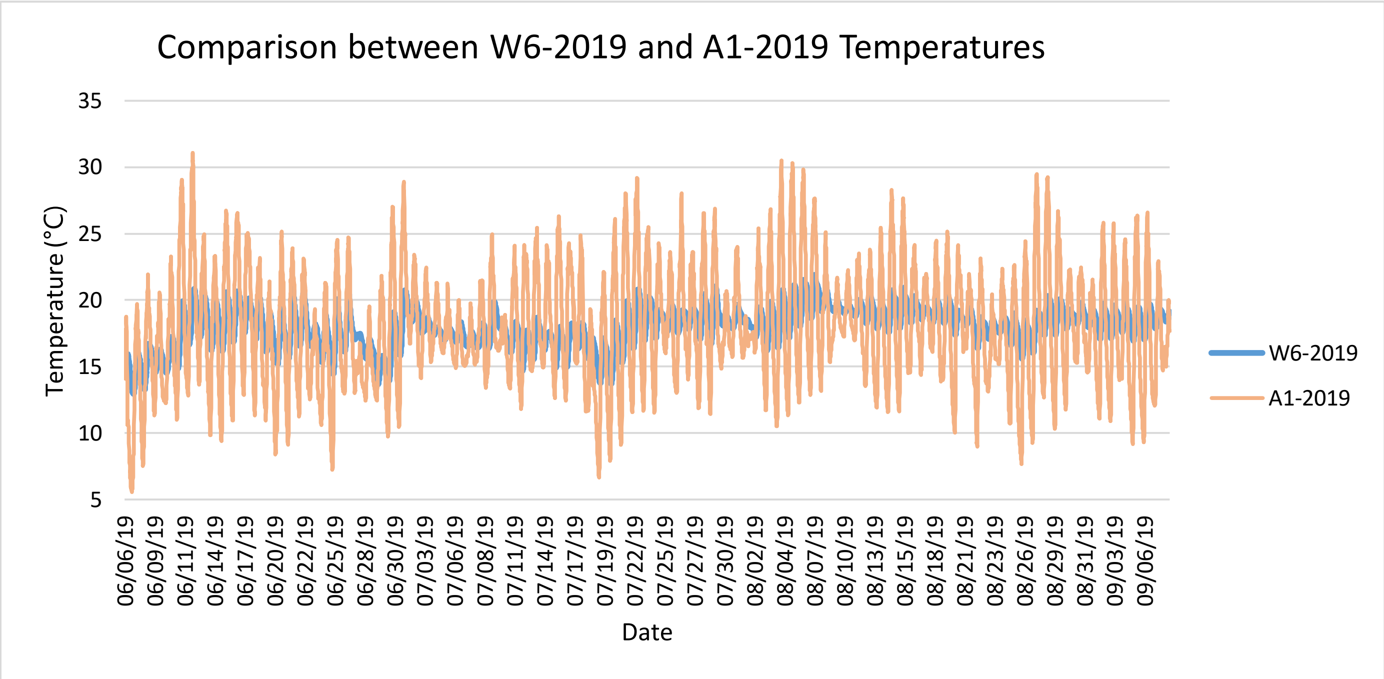


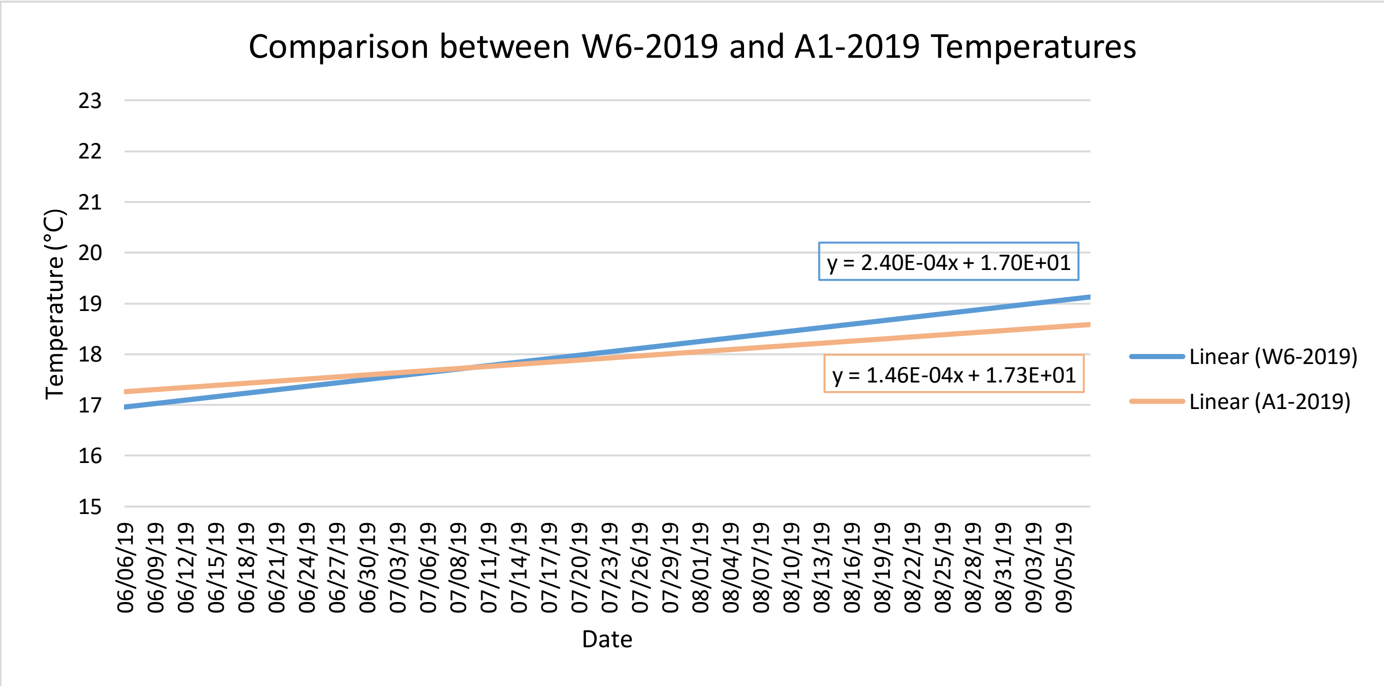
W5-2019 and A2-2019



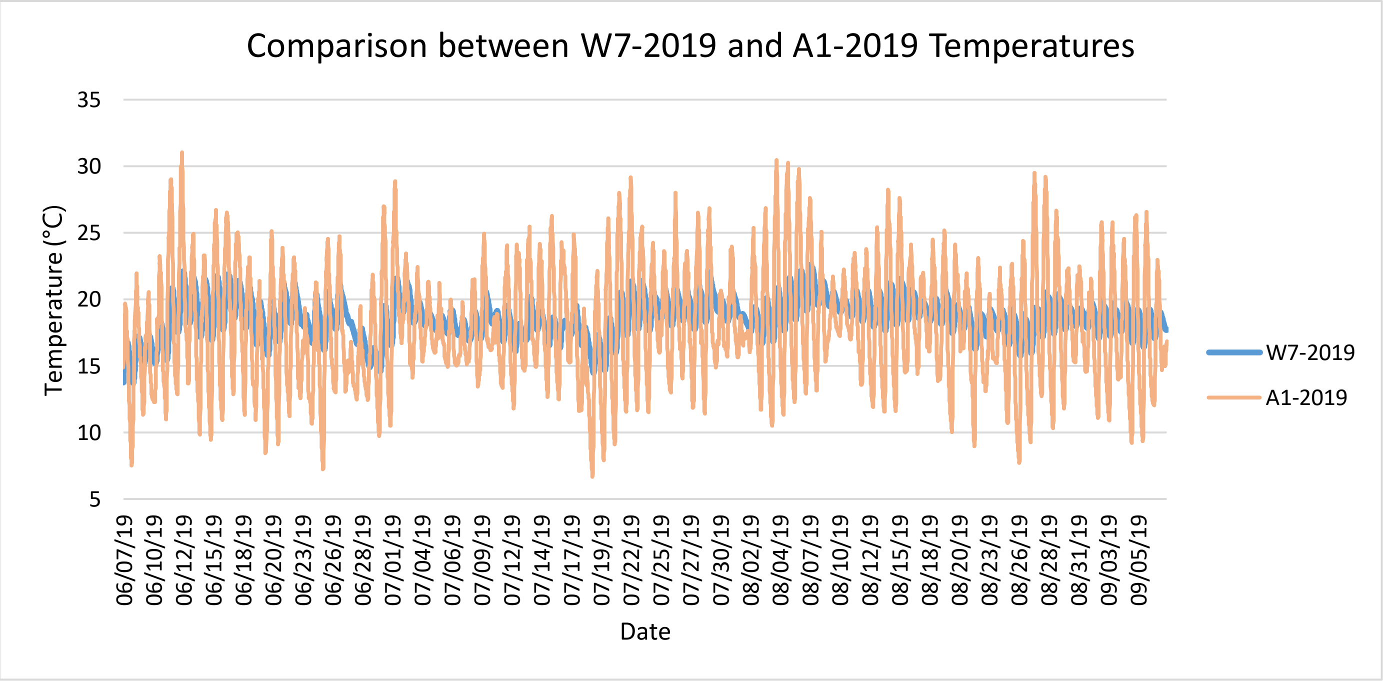


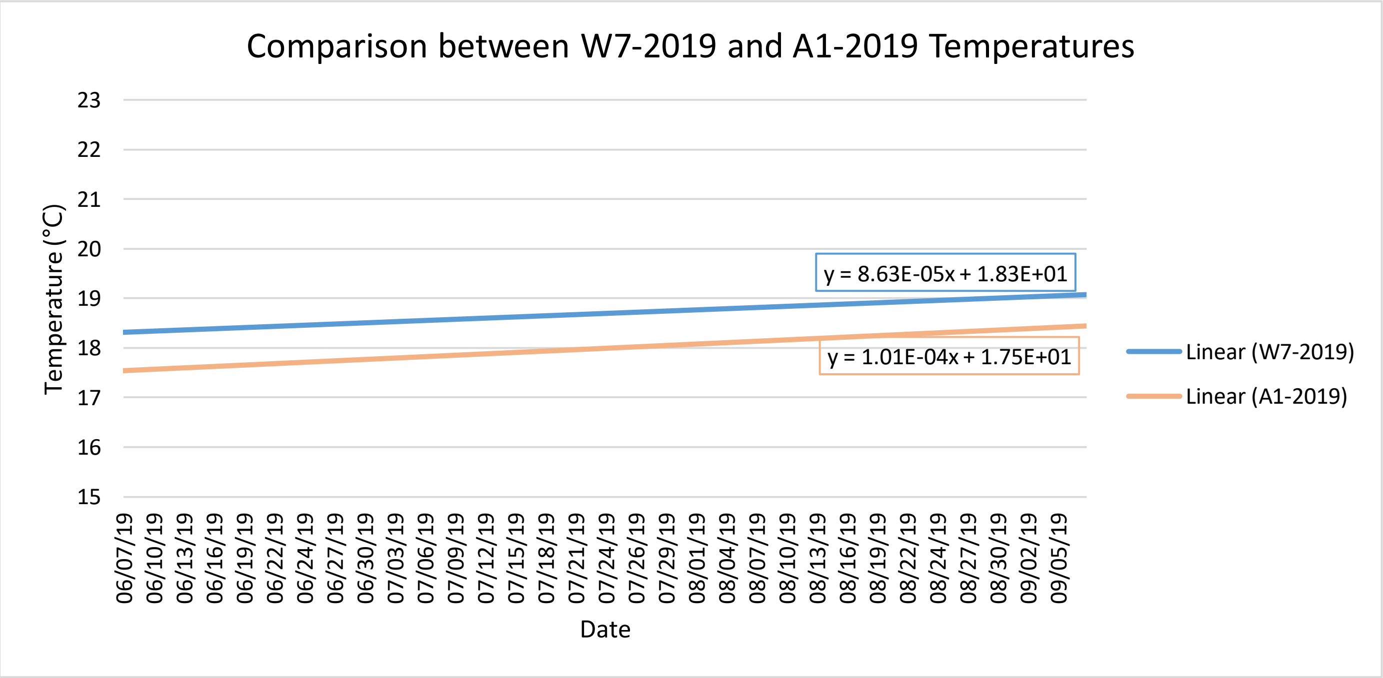
W6-2019 and A1-2019



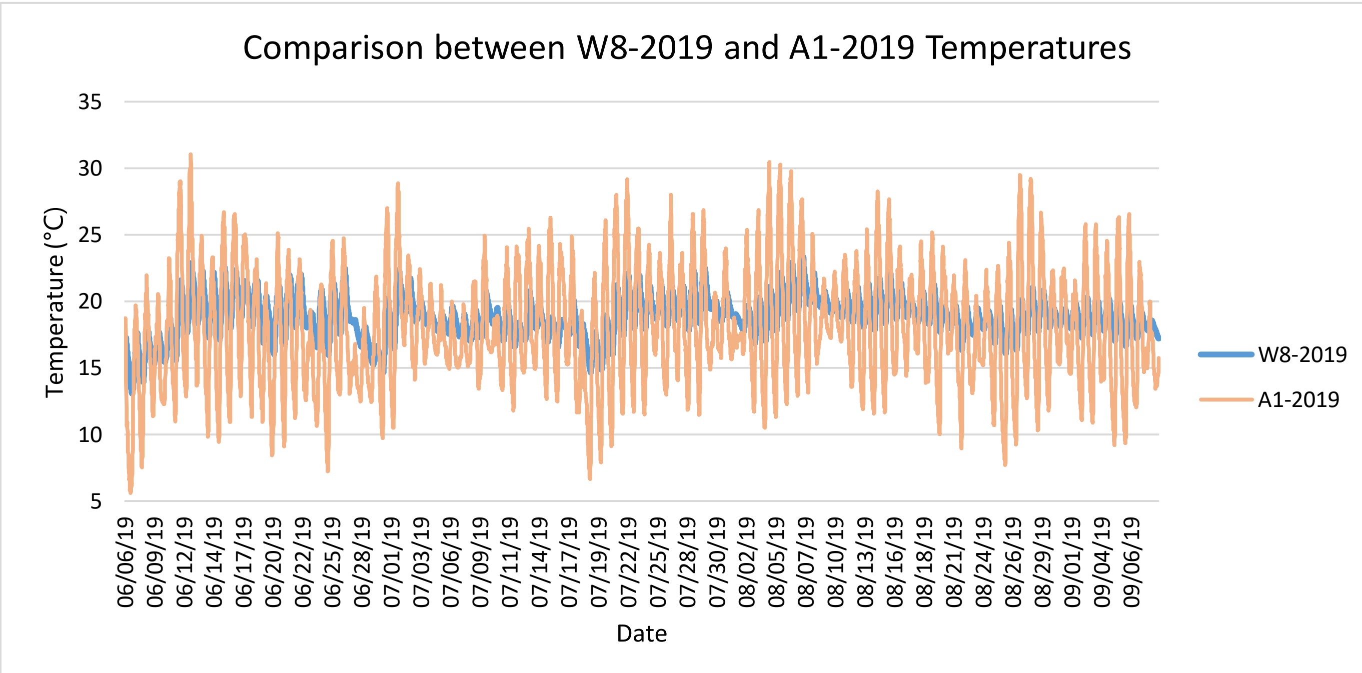


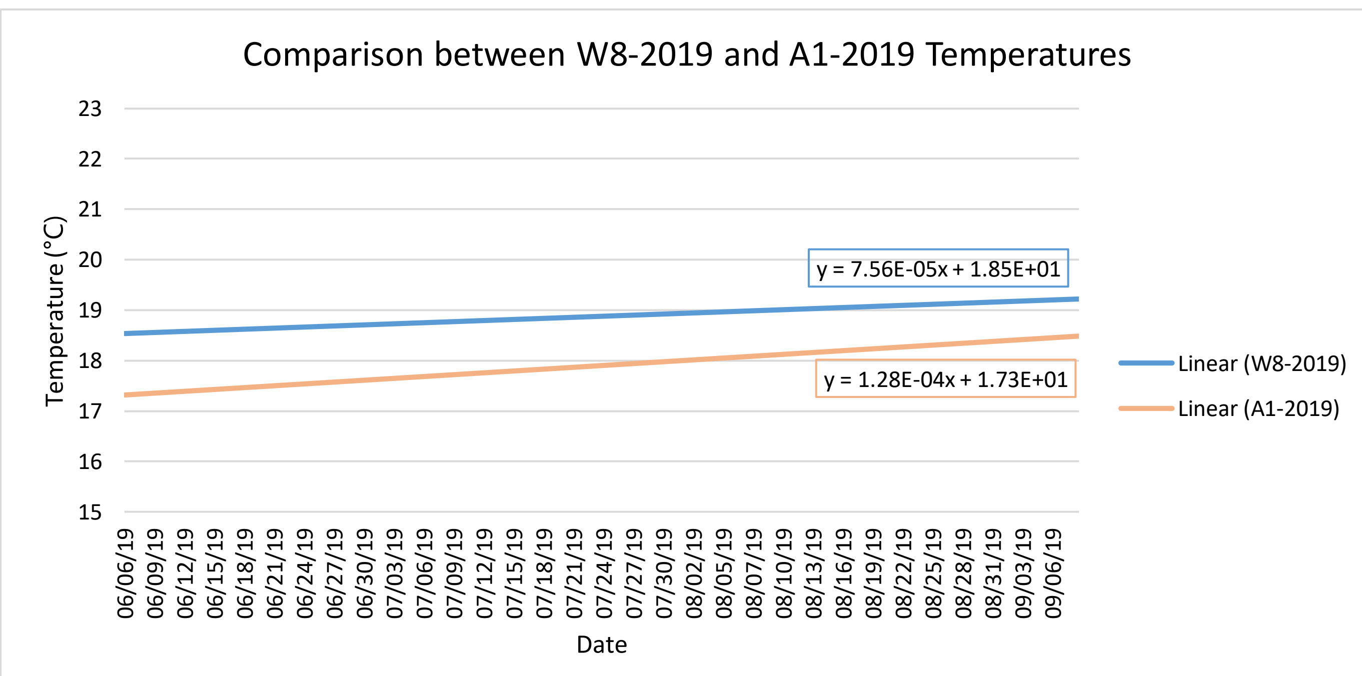
W7-2019 and A1-2019



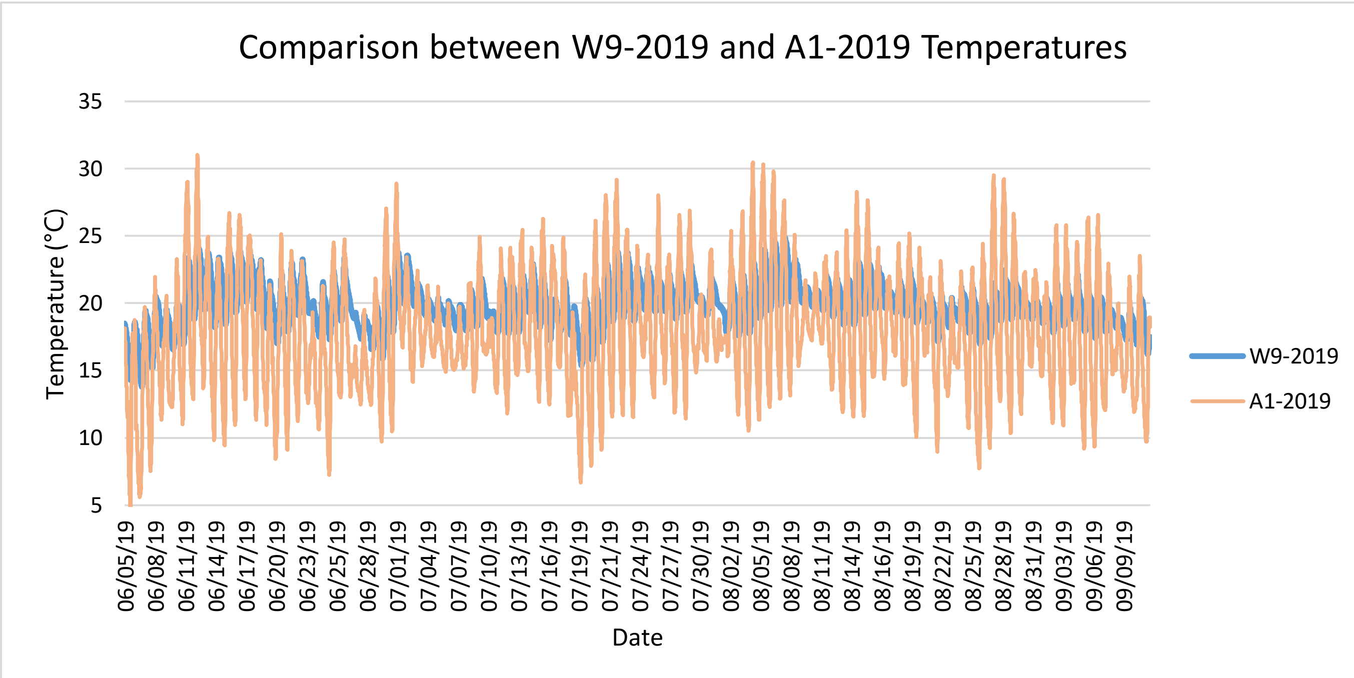


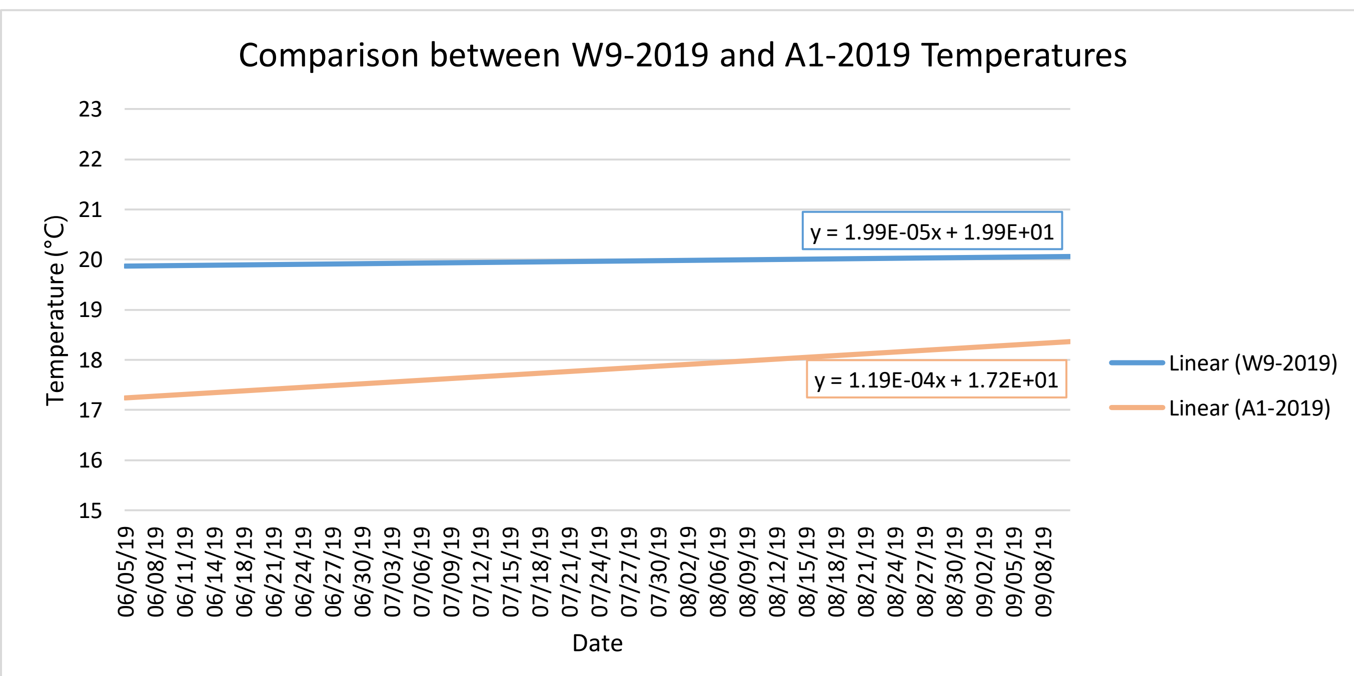
W8-2019 and A1-2019



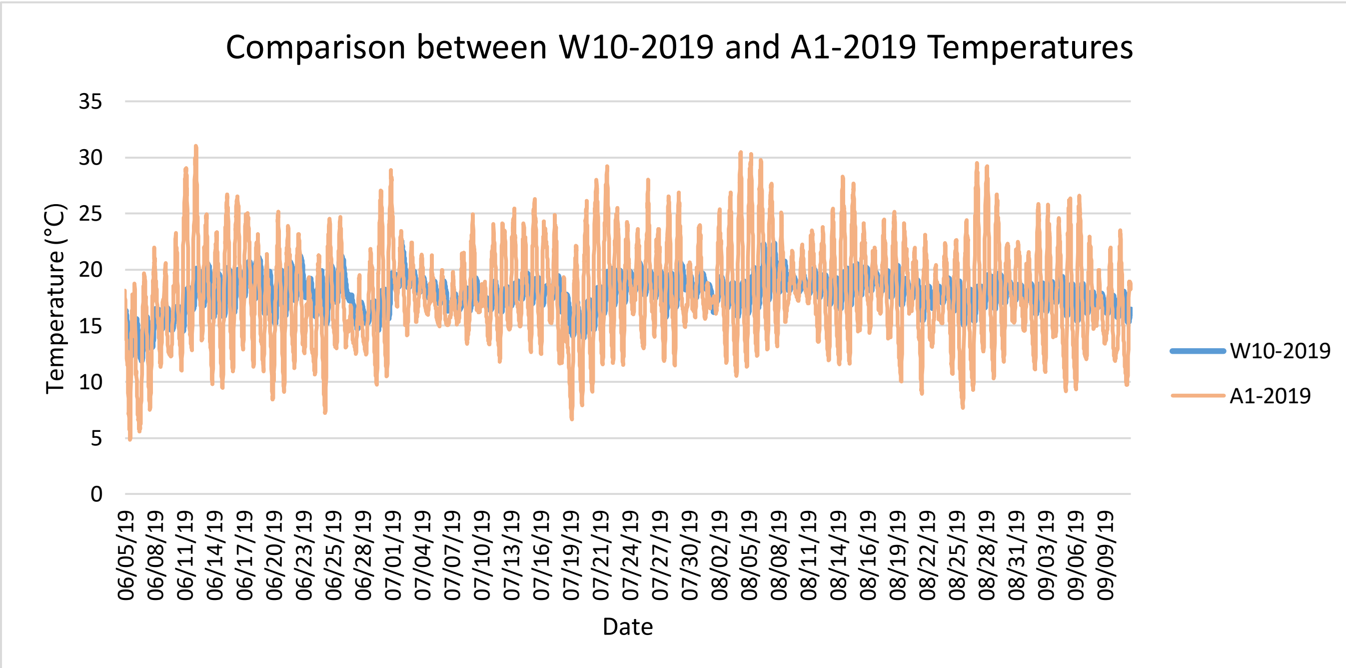


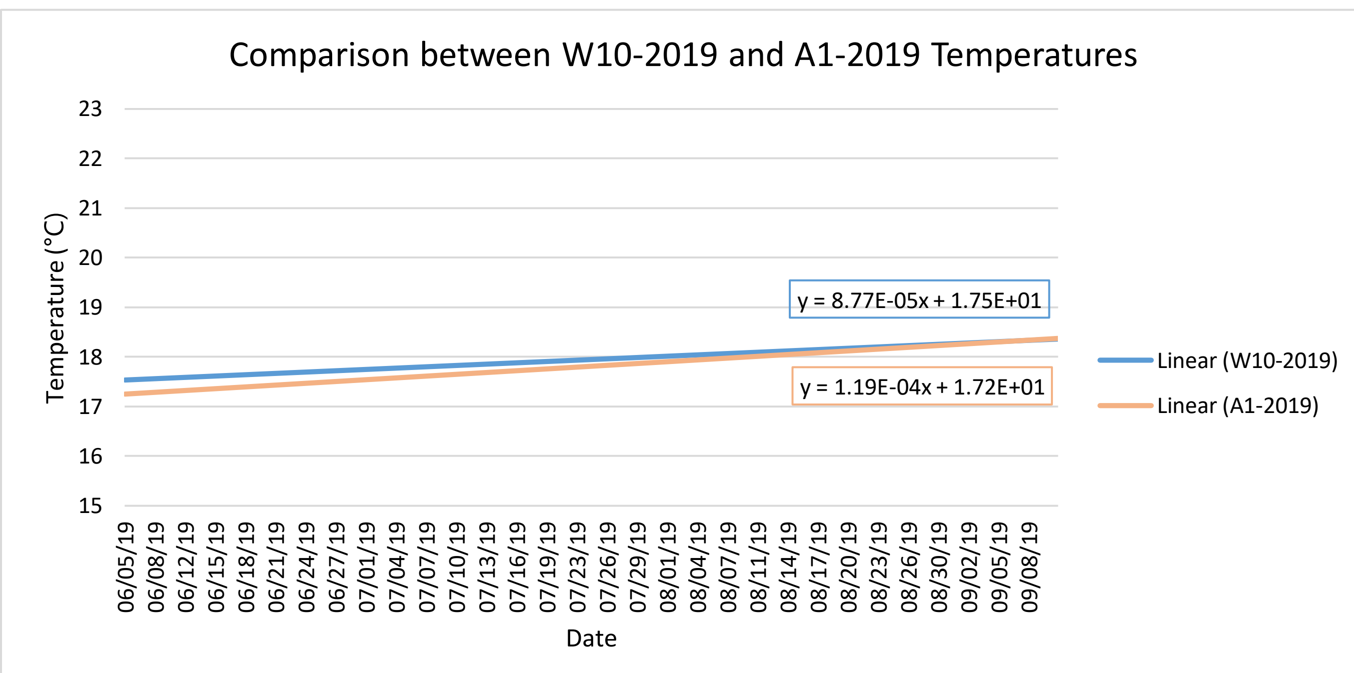
W9-2019 and A1-2019



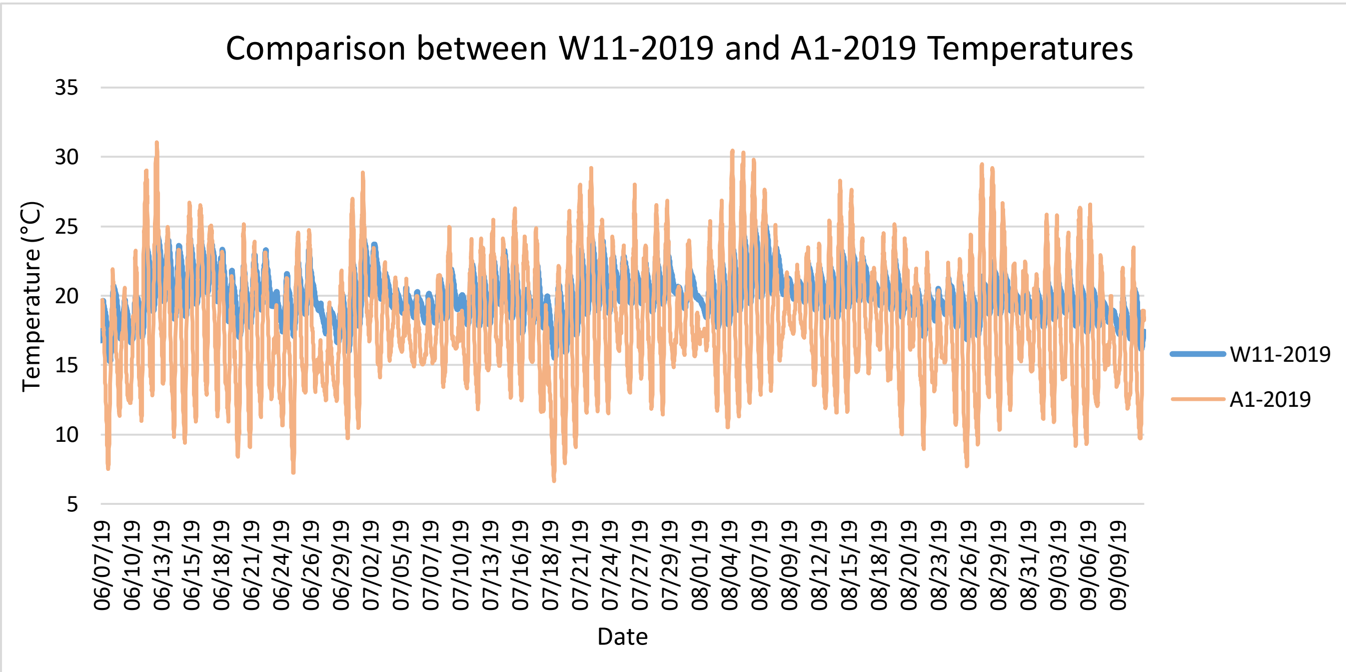


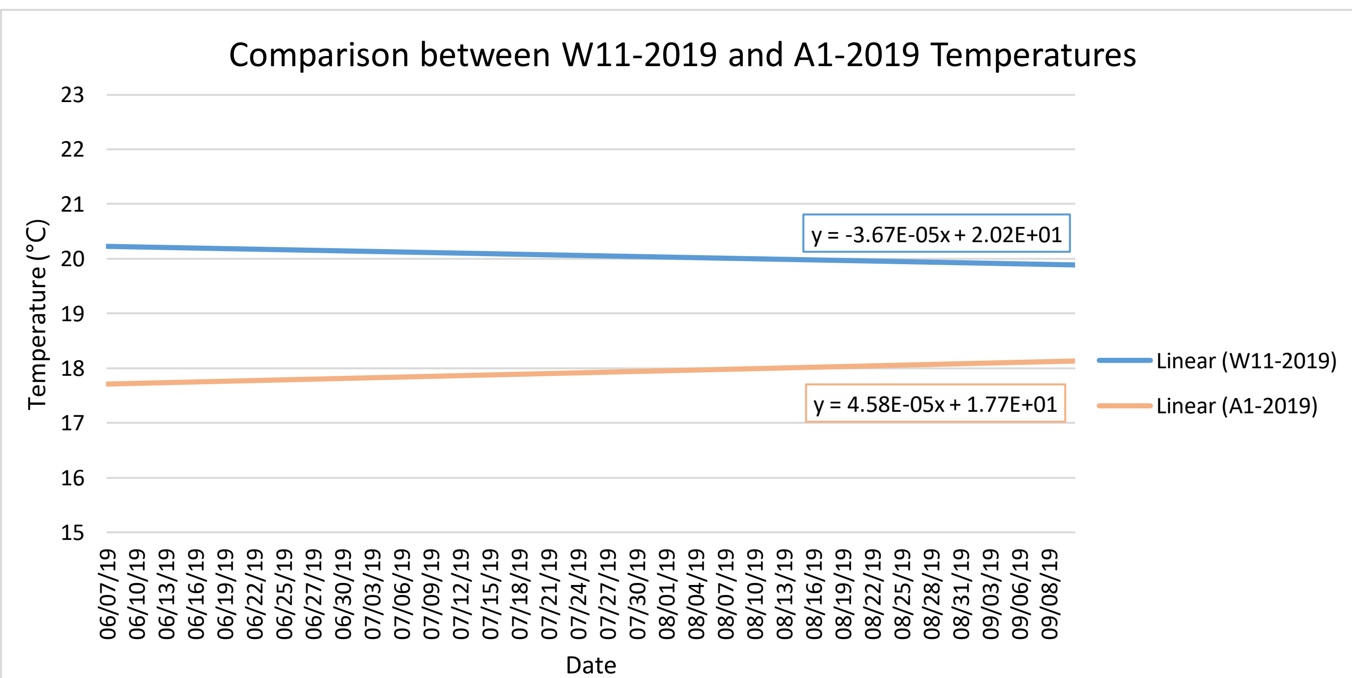
W10-2019 and A1-2019



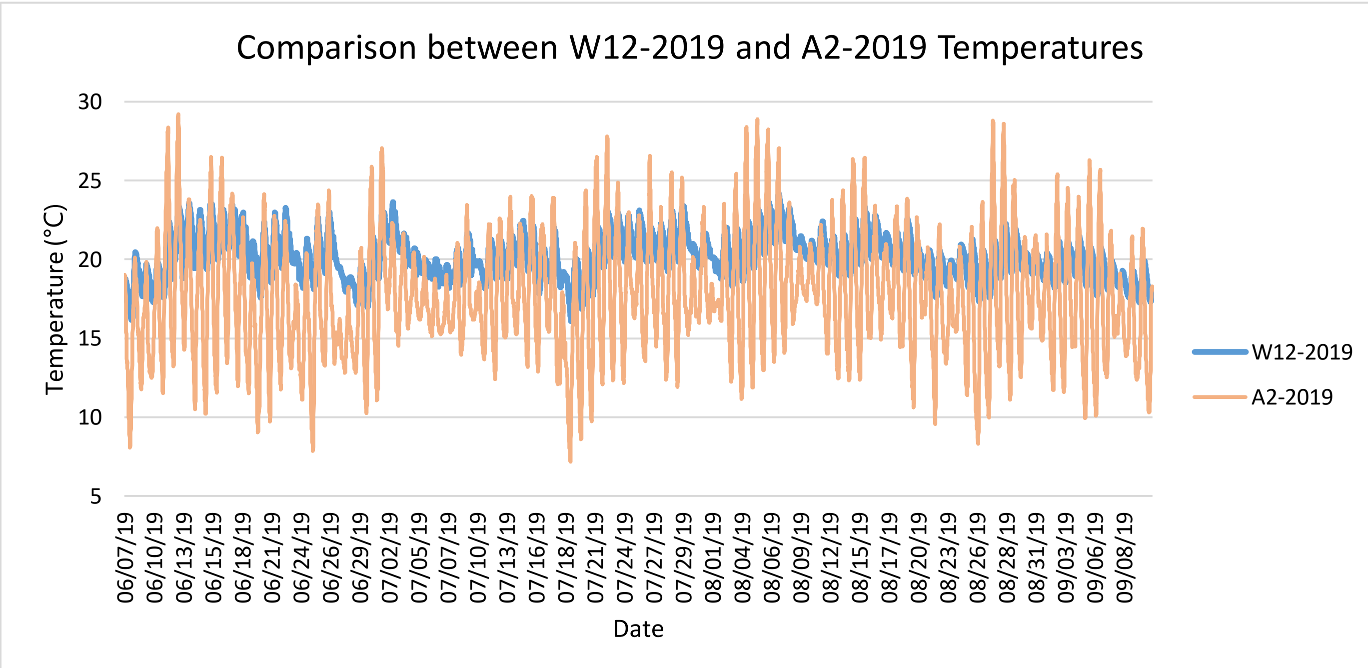


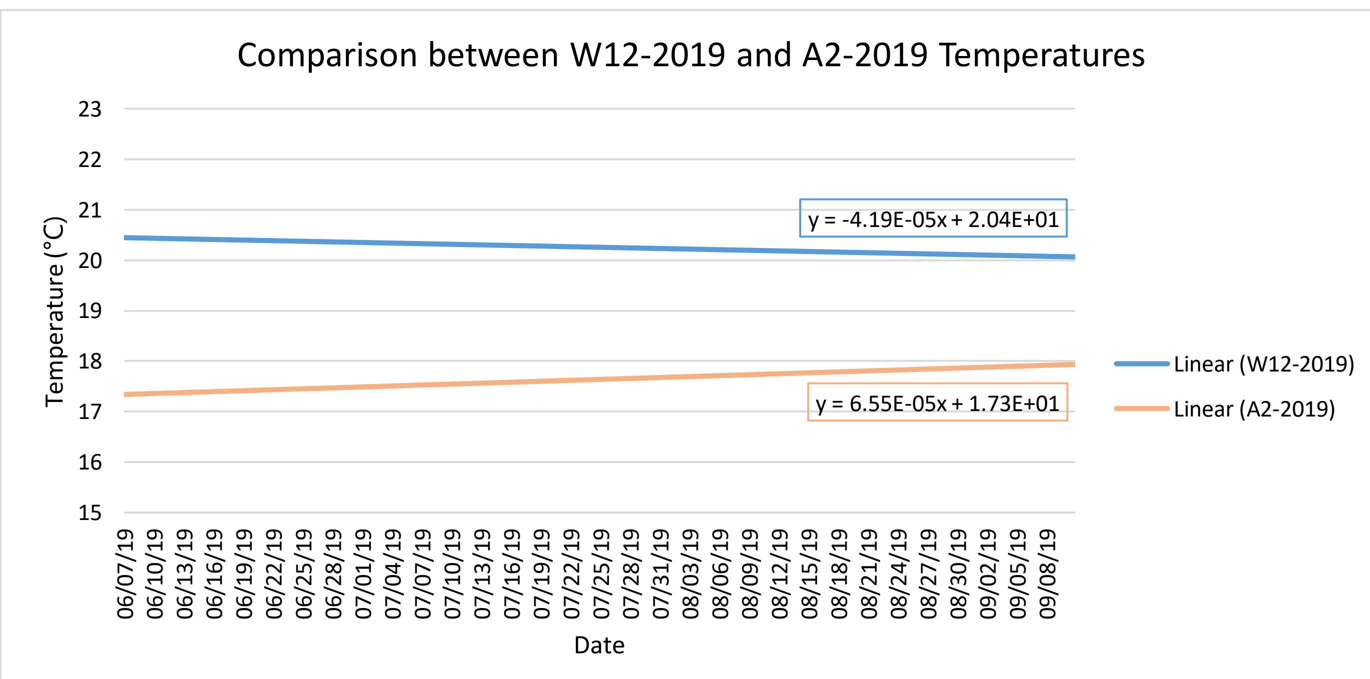
W11-2019 and A1-2019



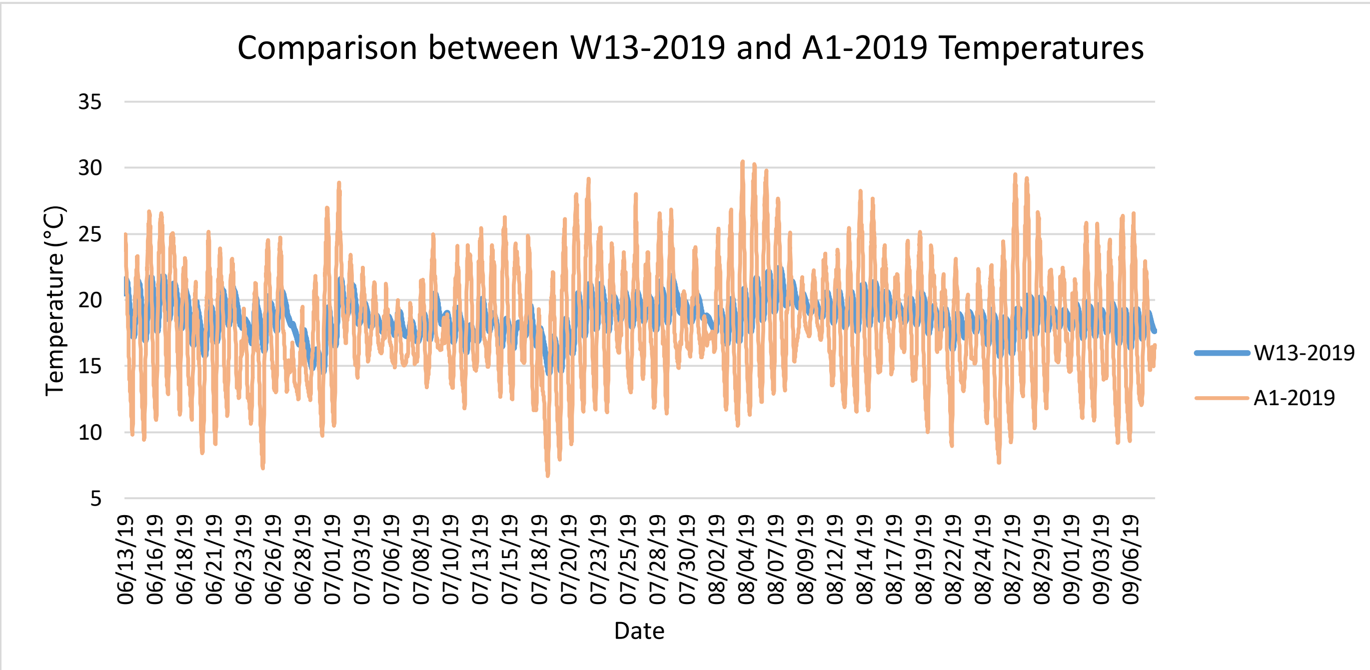


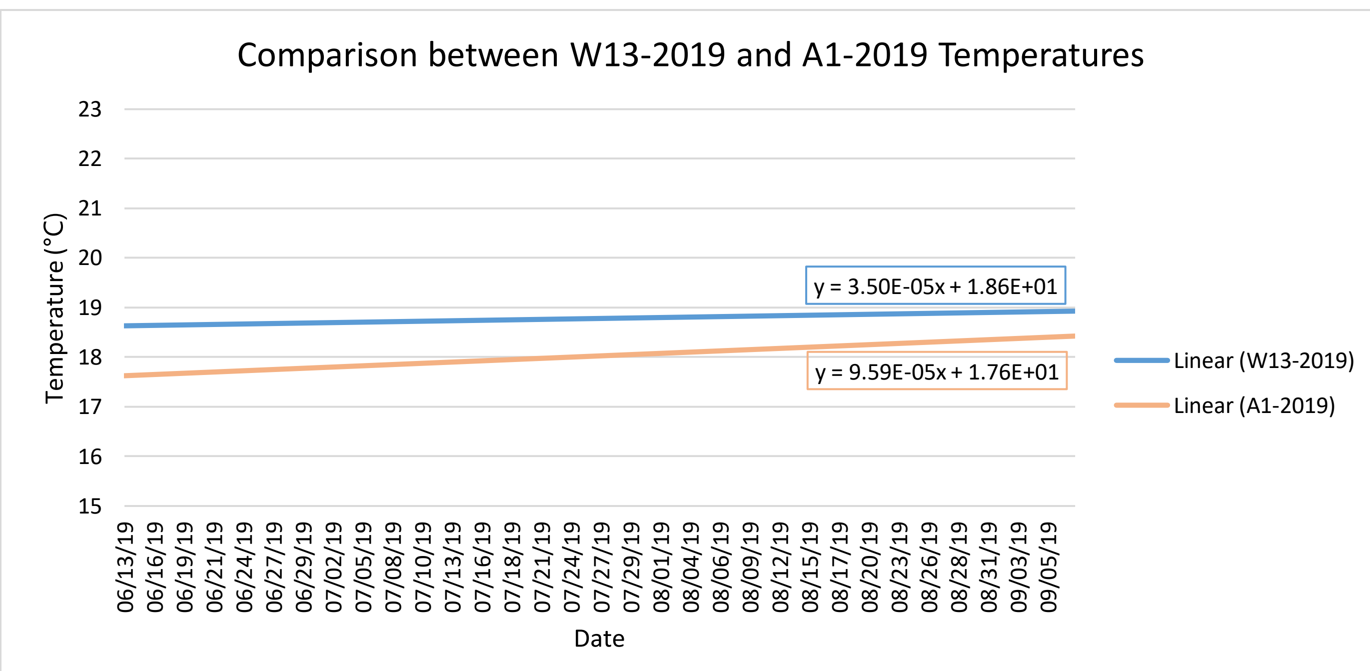
W12-2019 and A1-2019



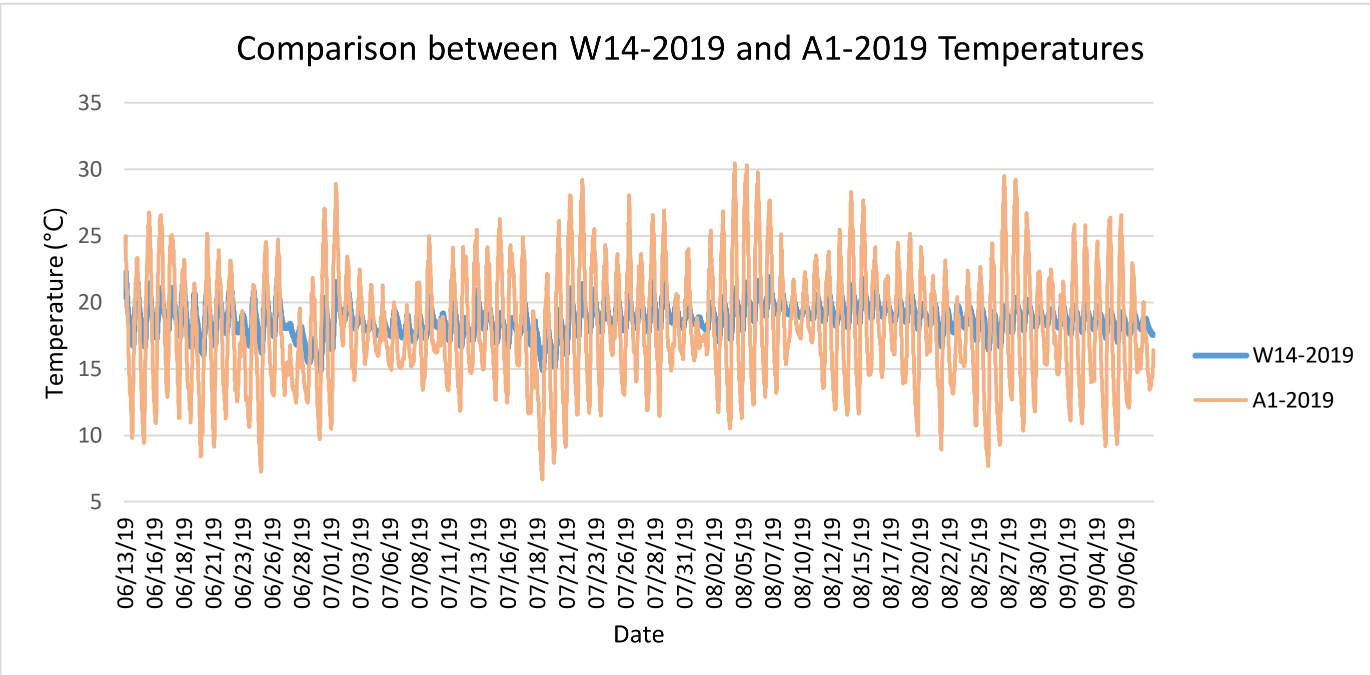


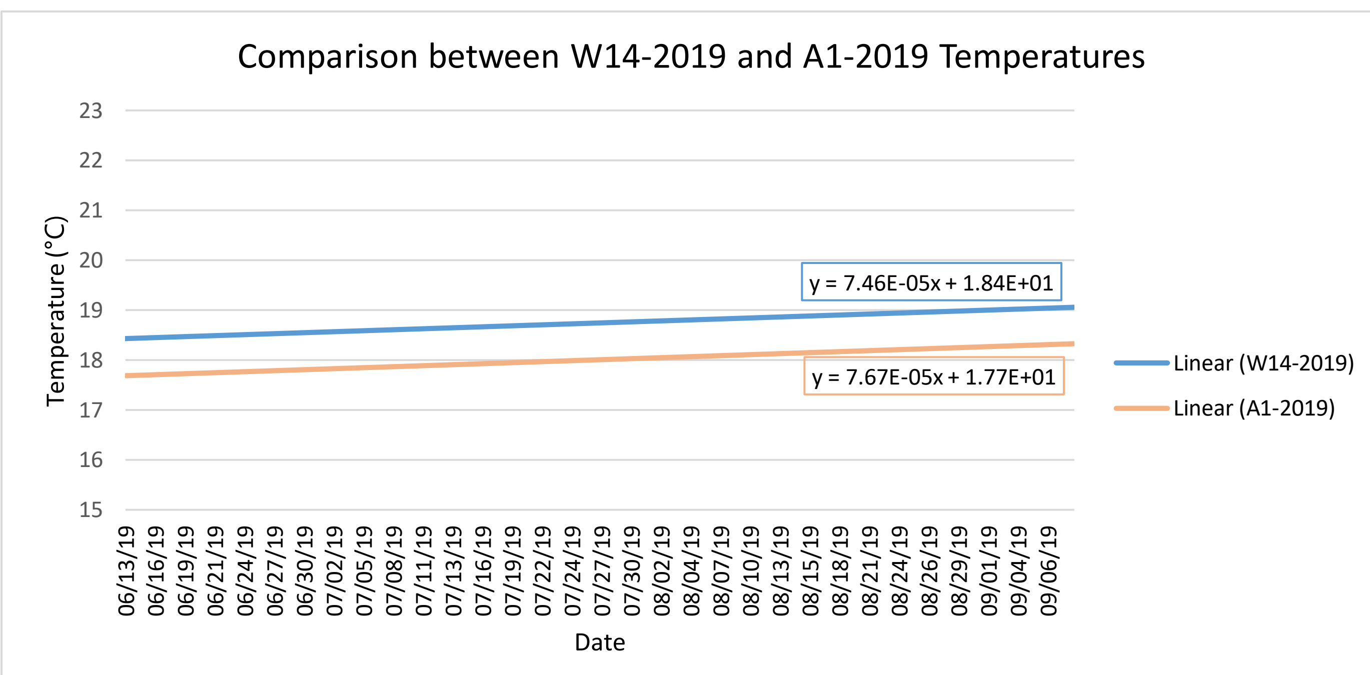
W13-2019 and A1-2019



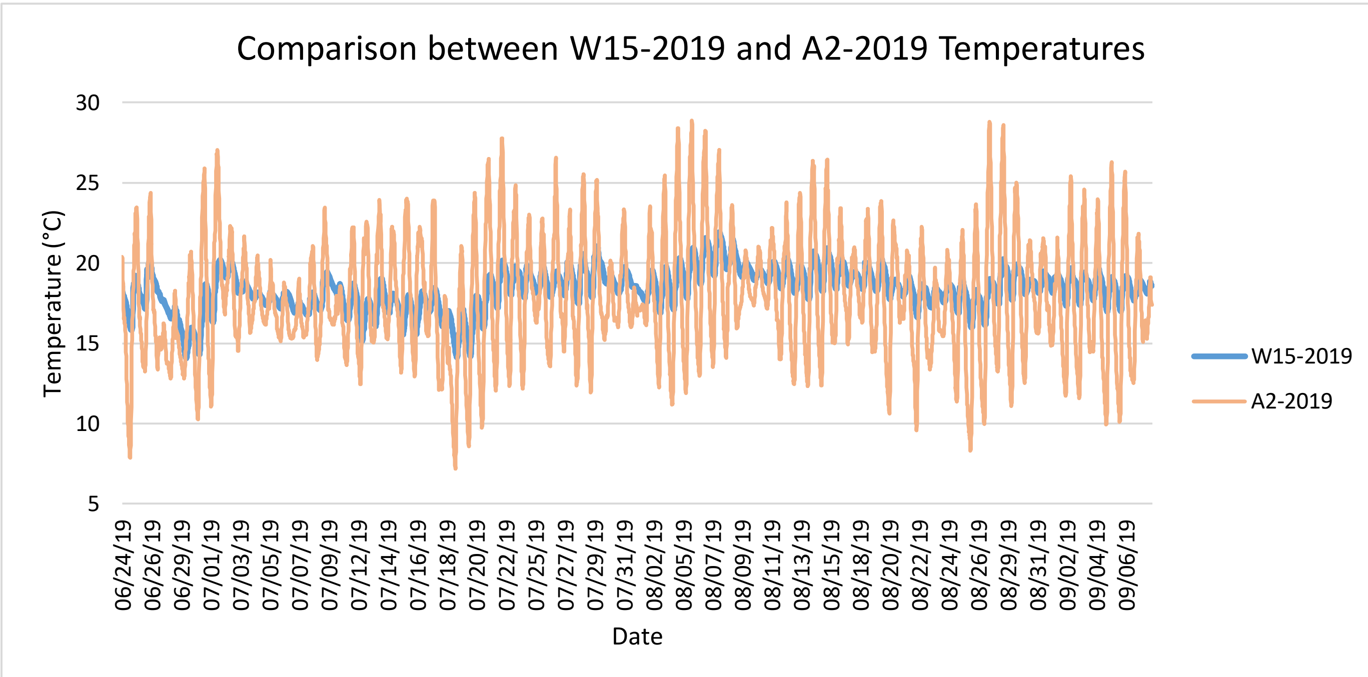


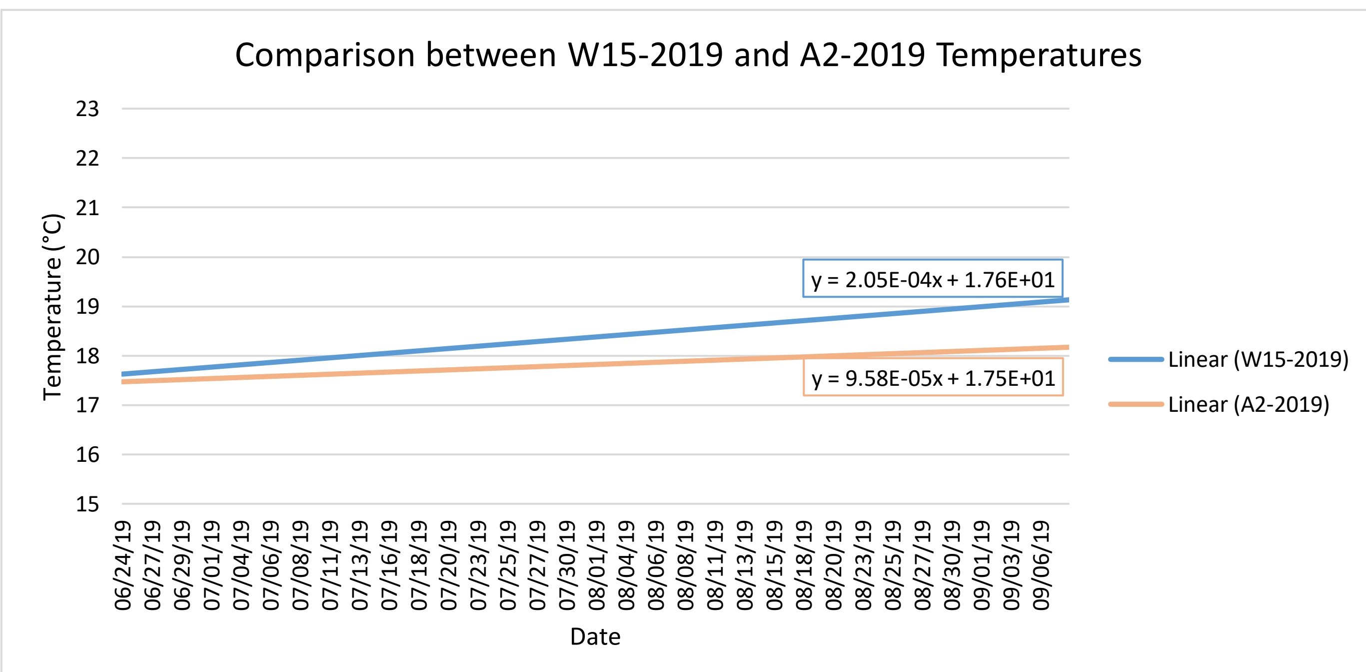
W14-2019 and A1-2019



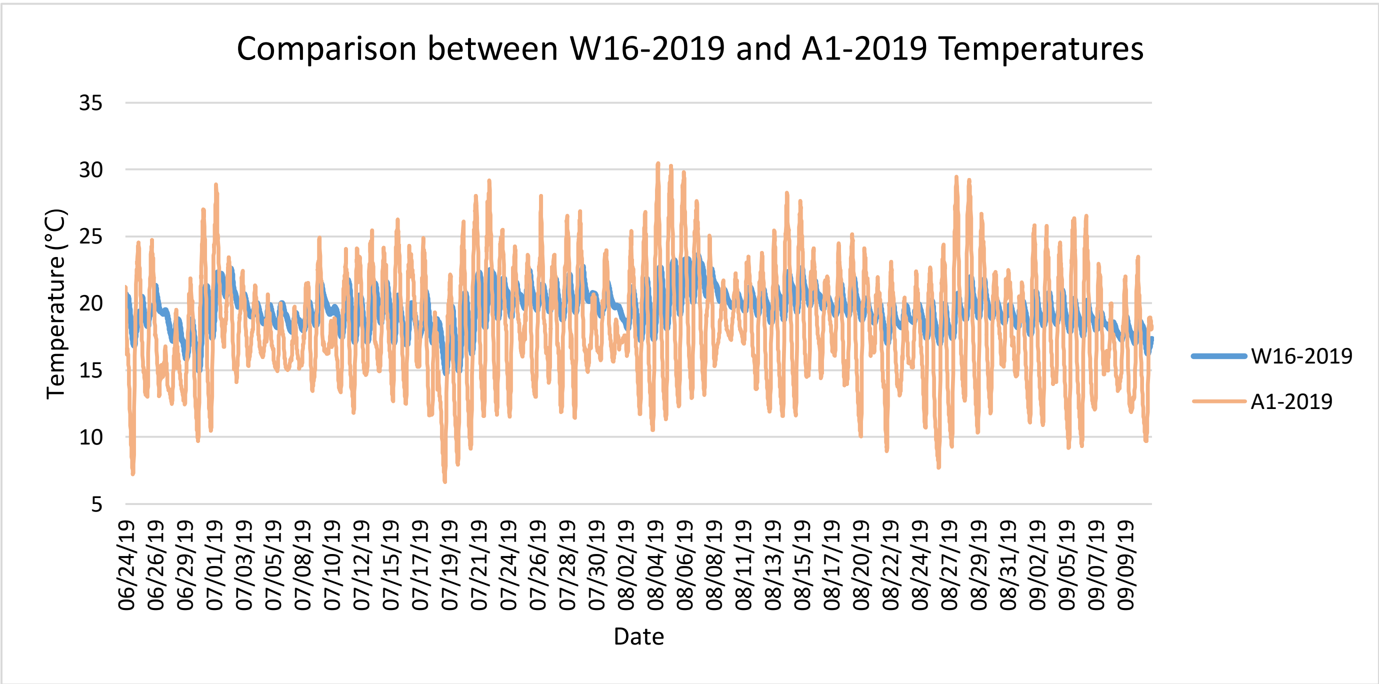


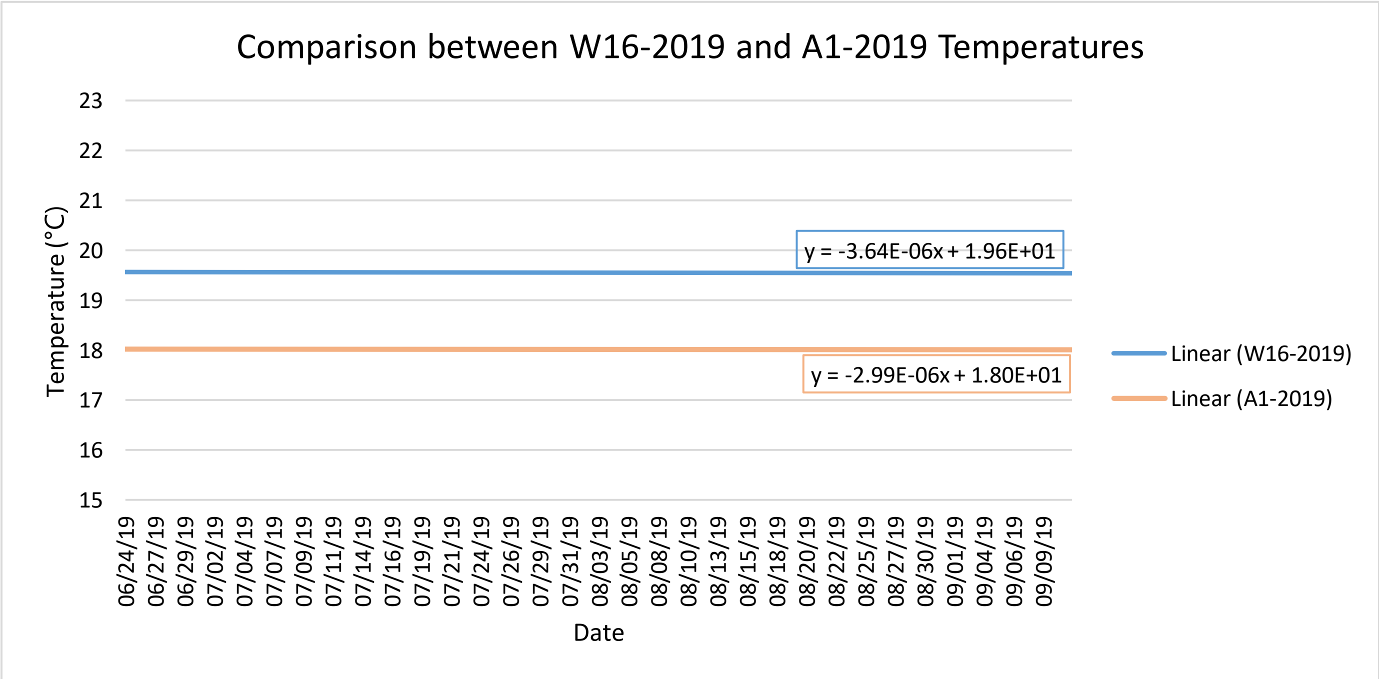
W15-2019 and A2-2019





W16-2019 and A1-2019





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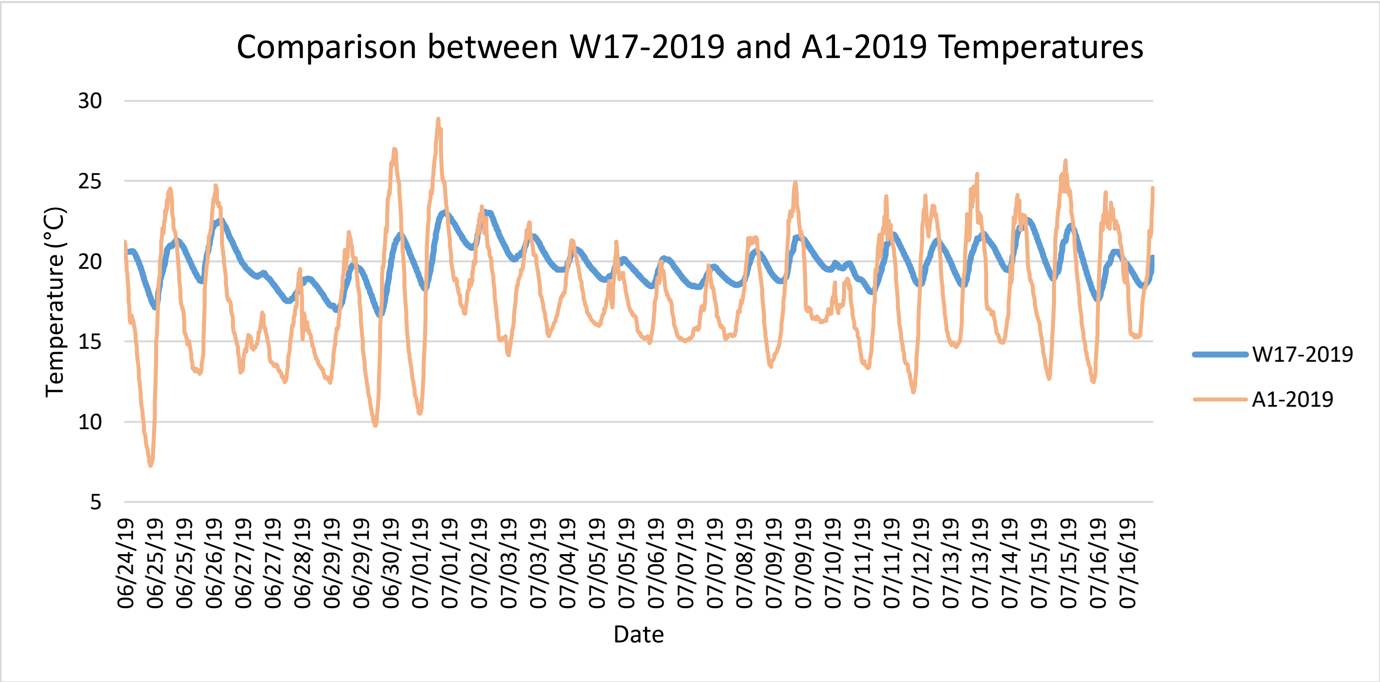
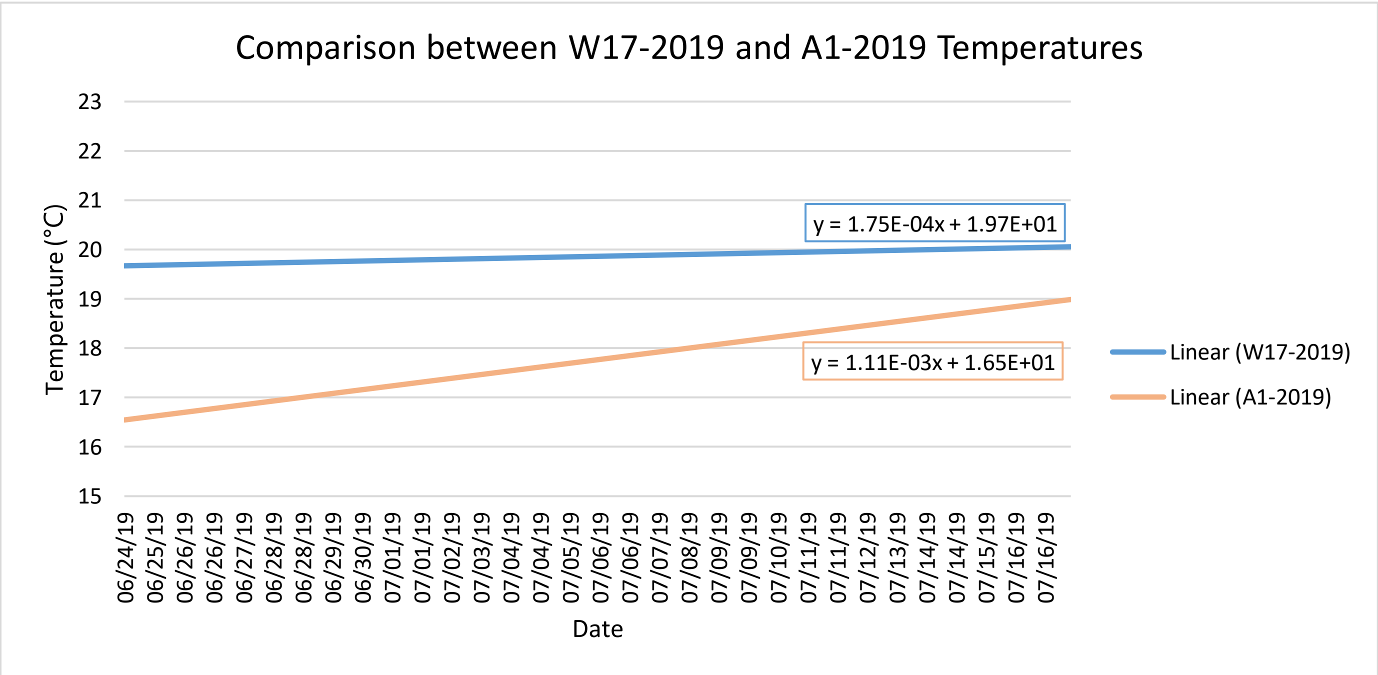
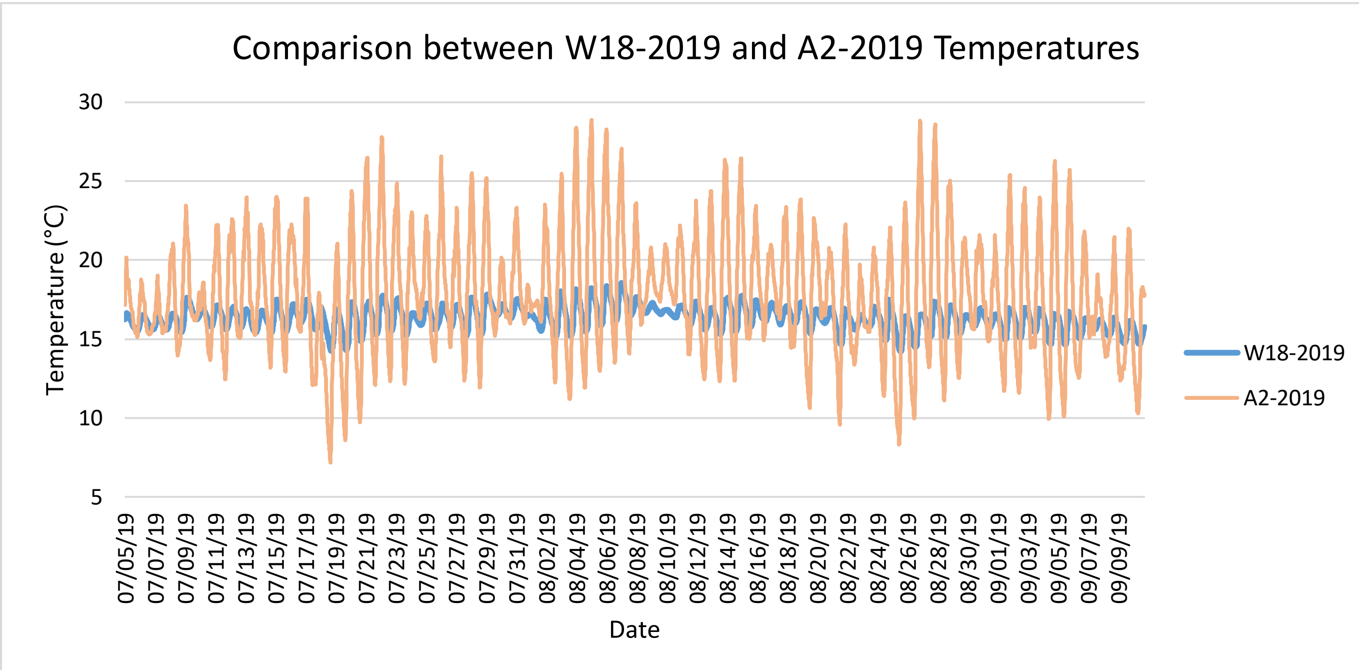
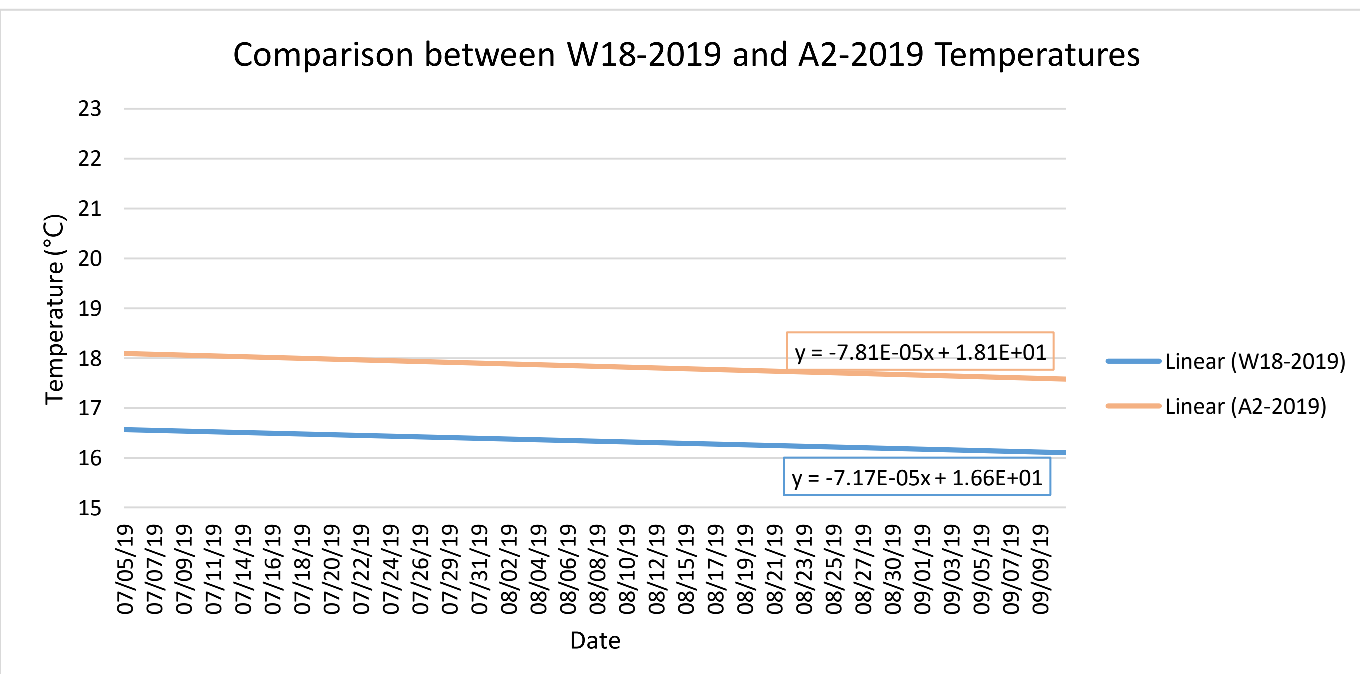


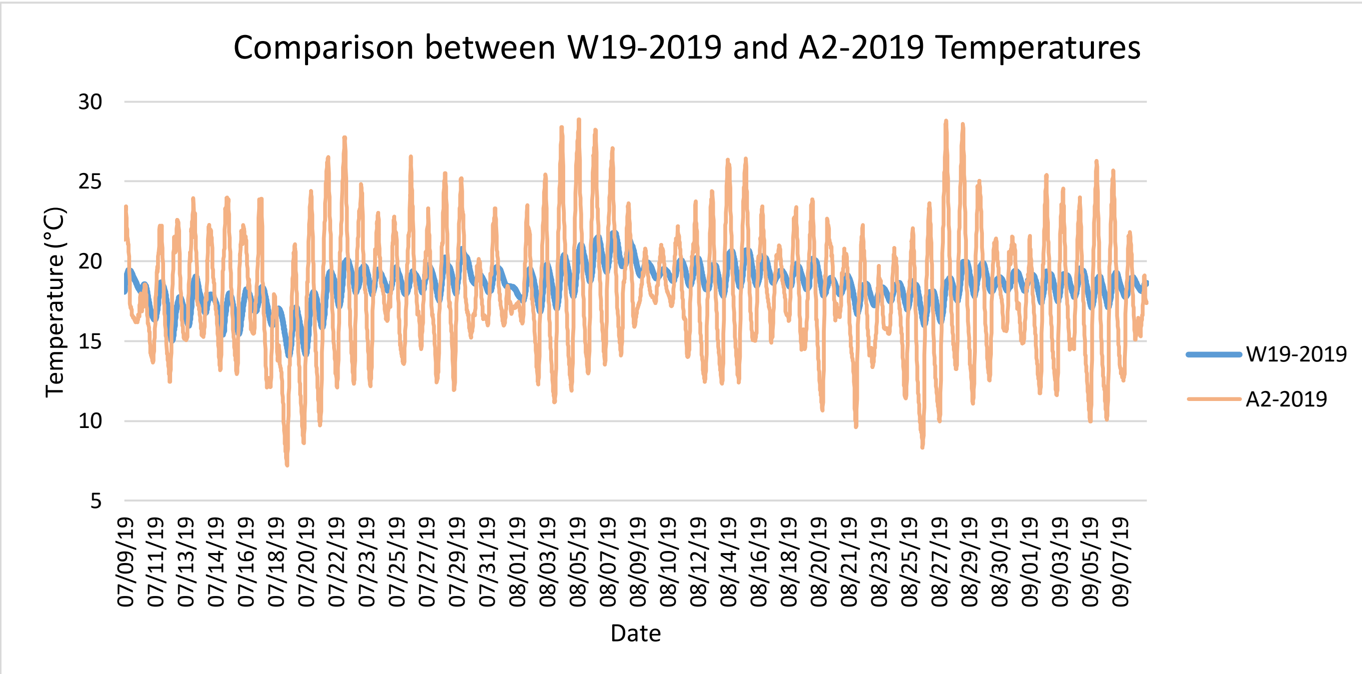


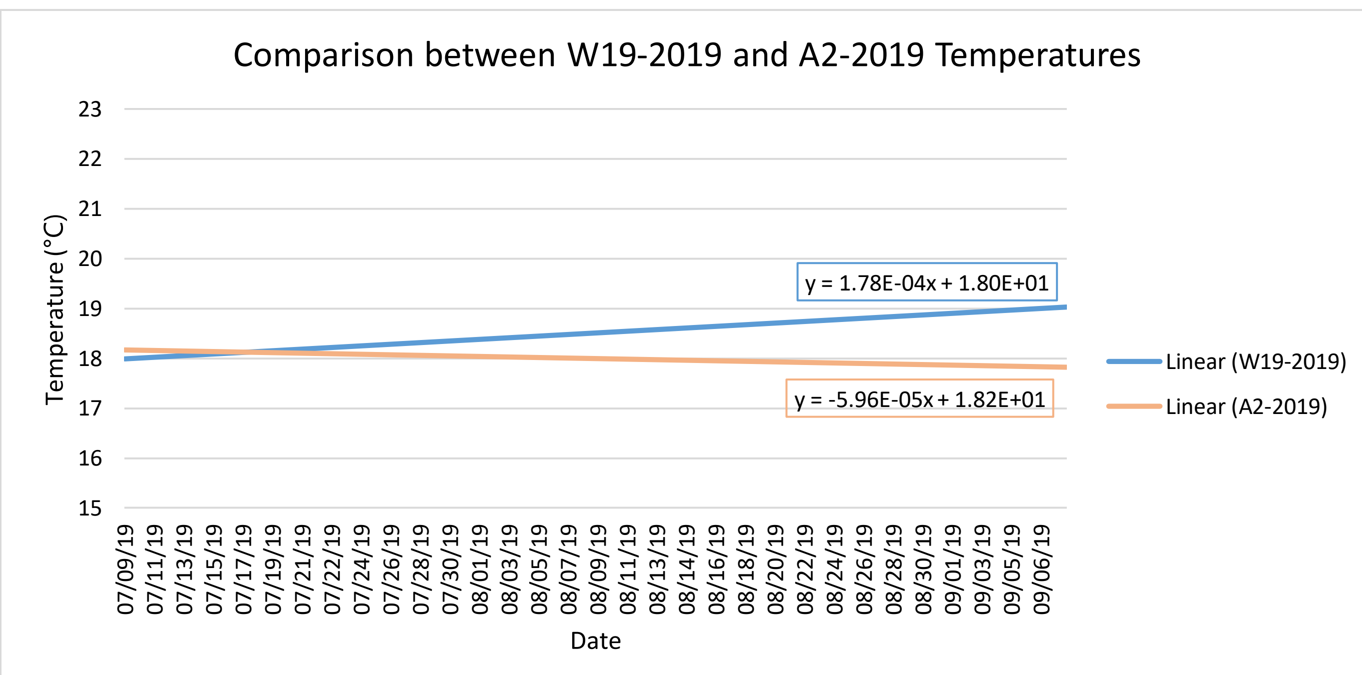
W18-2019 and A2-2019



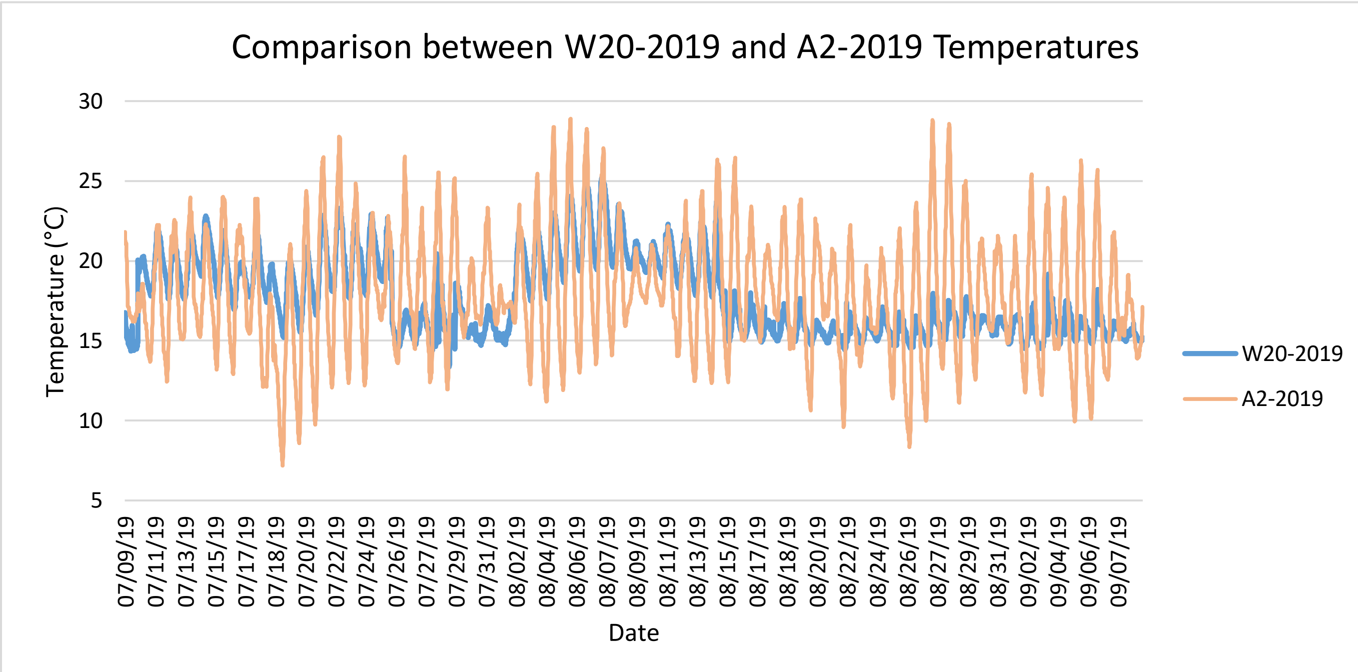


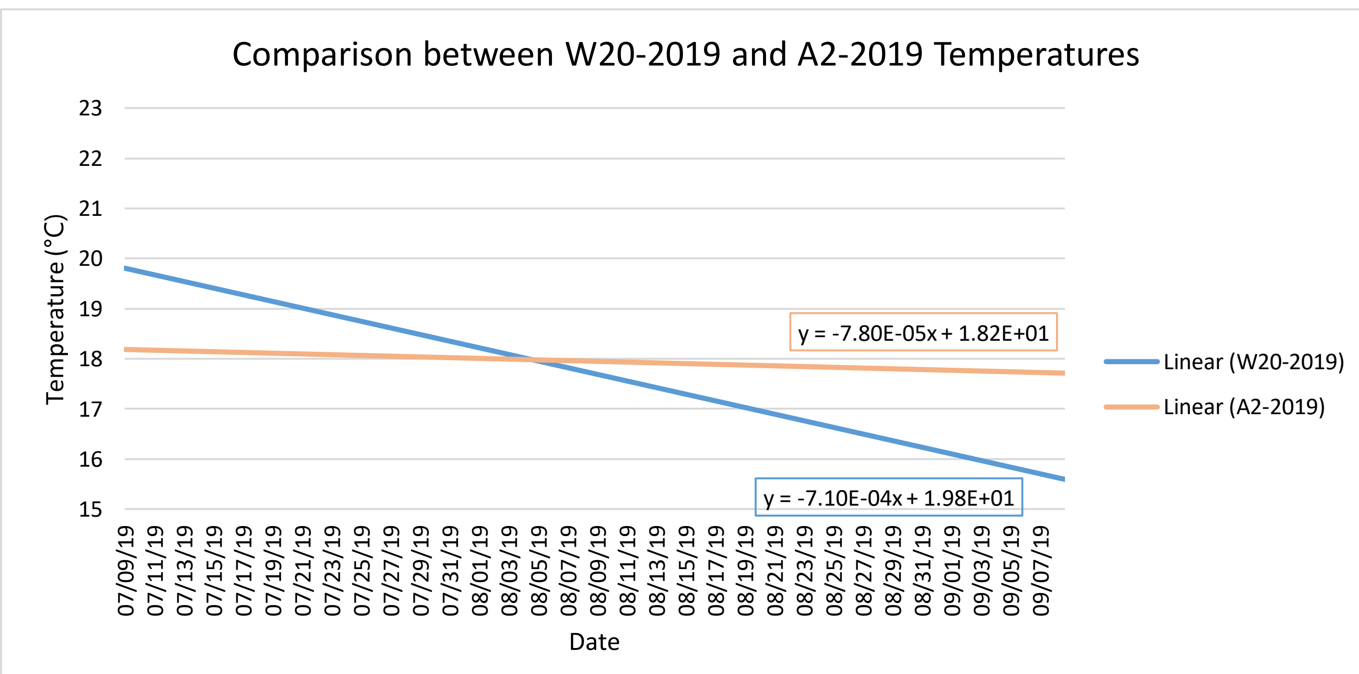
W19-2019 and A2-2019



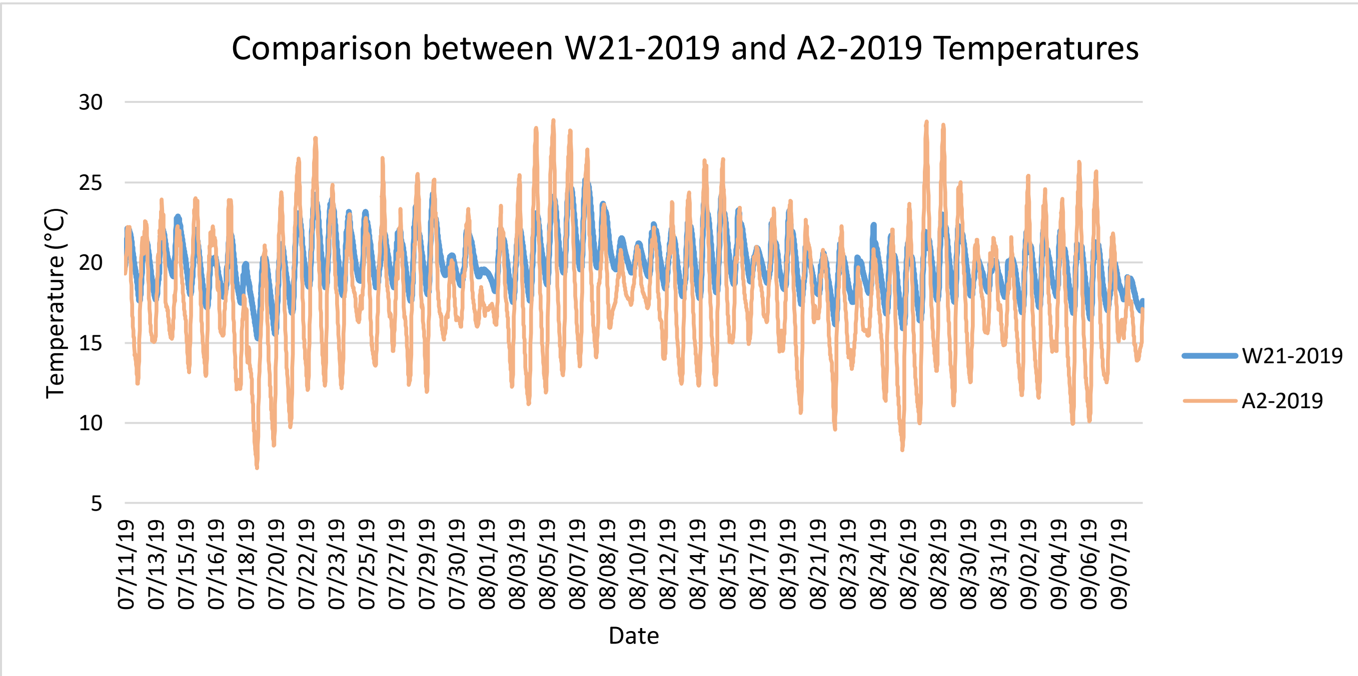


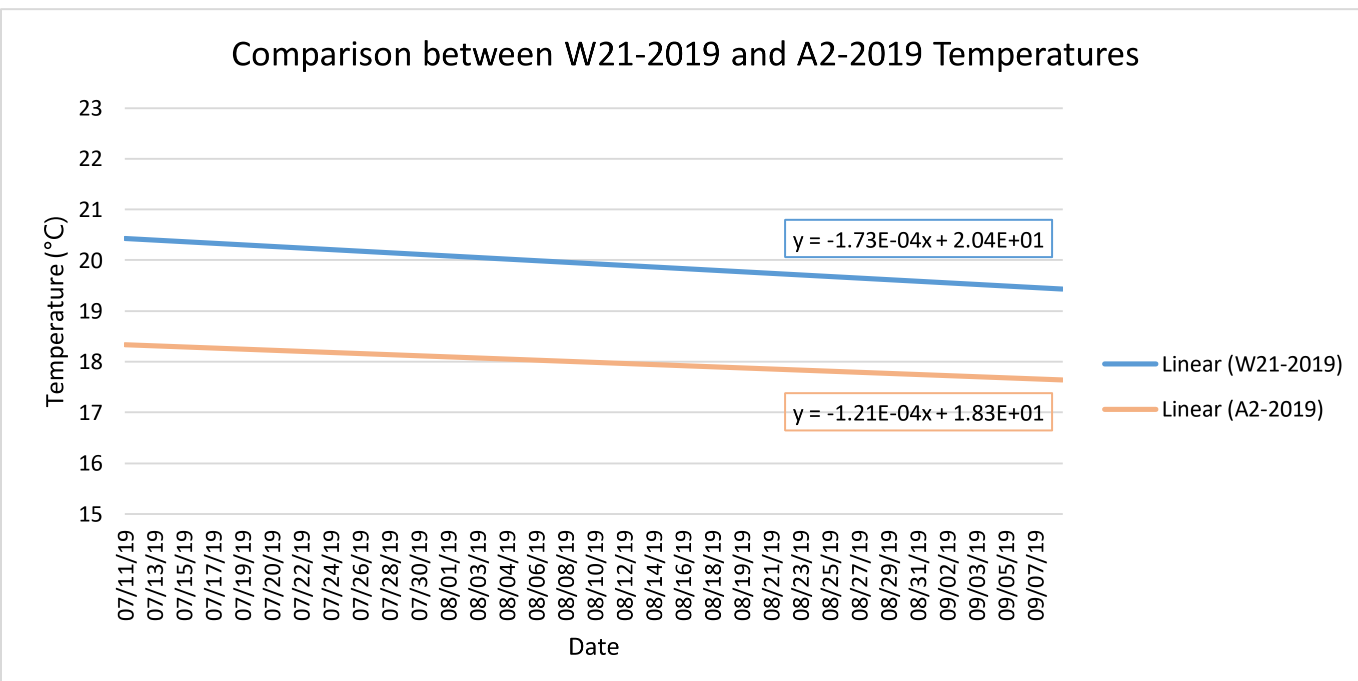
W20-2019 and A2-2019



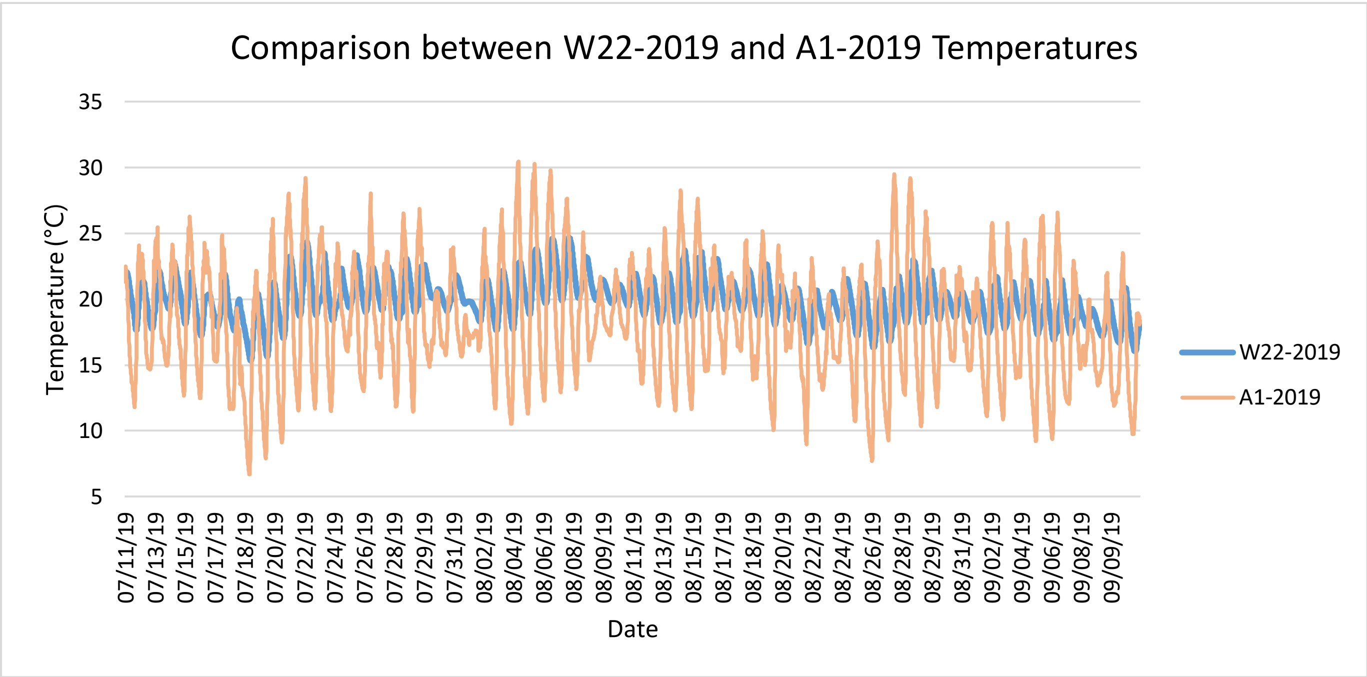


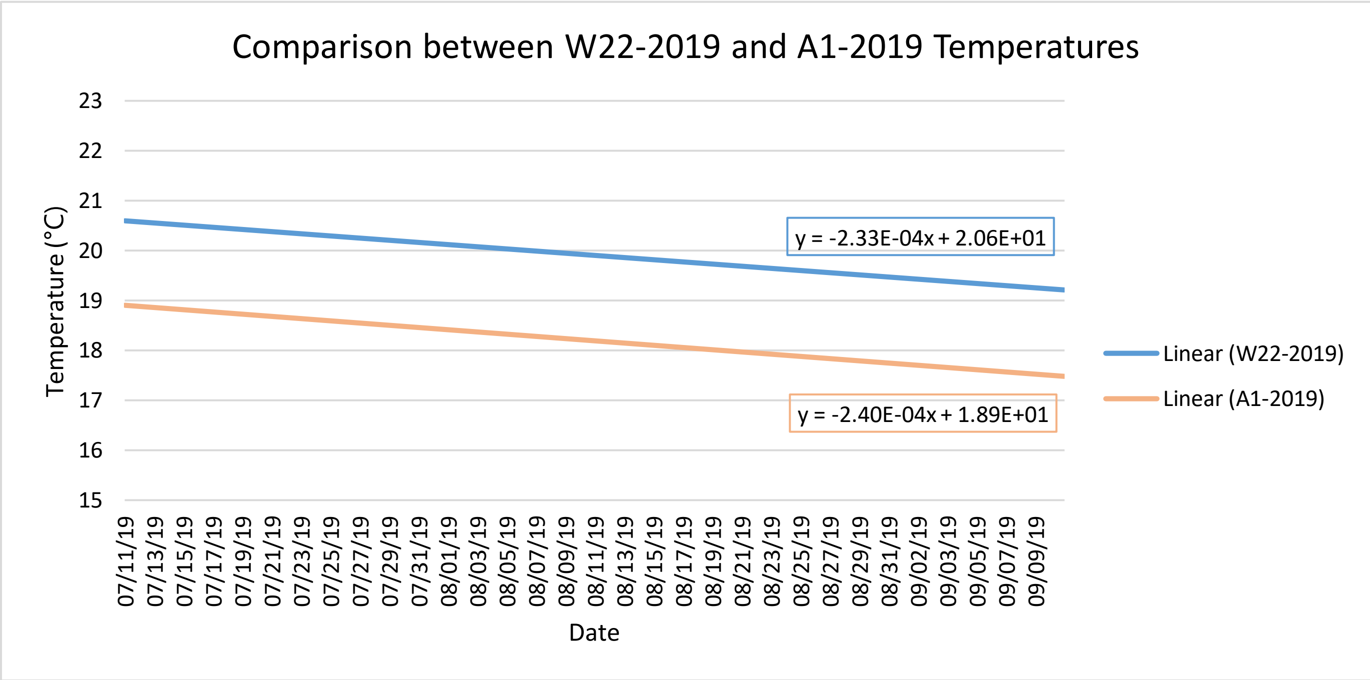
W21-2019 and A2-2019



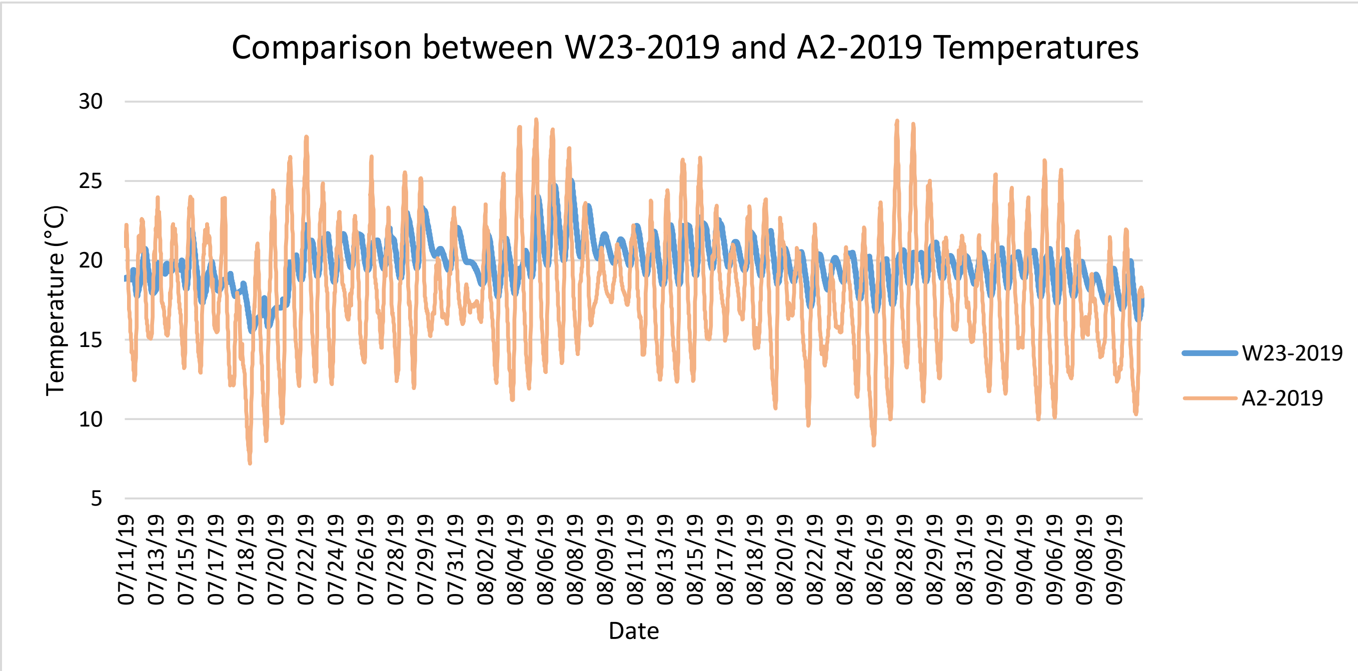


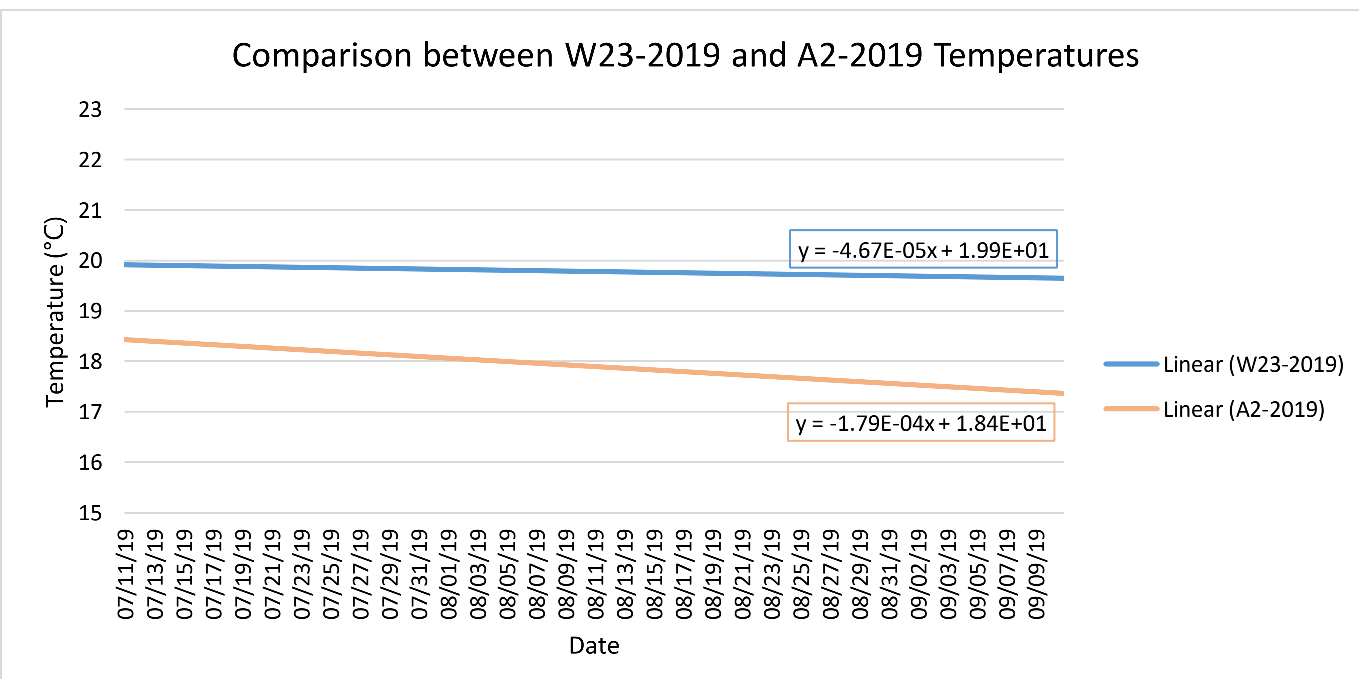
W22-2019 and A1-2019



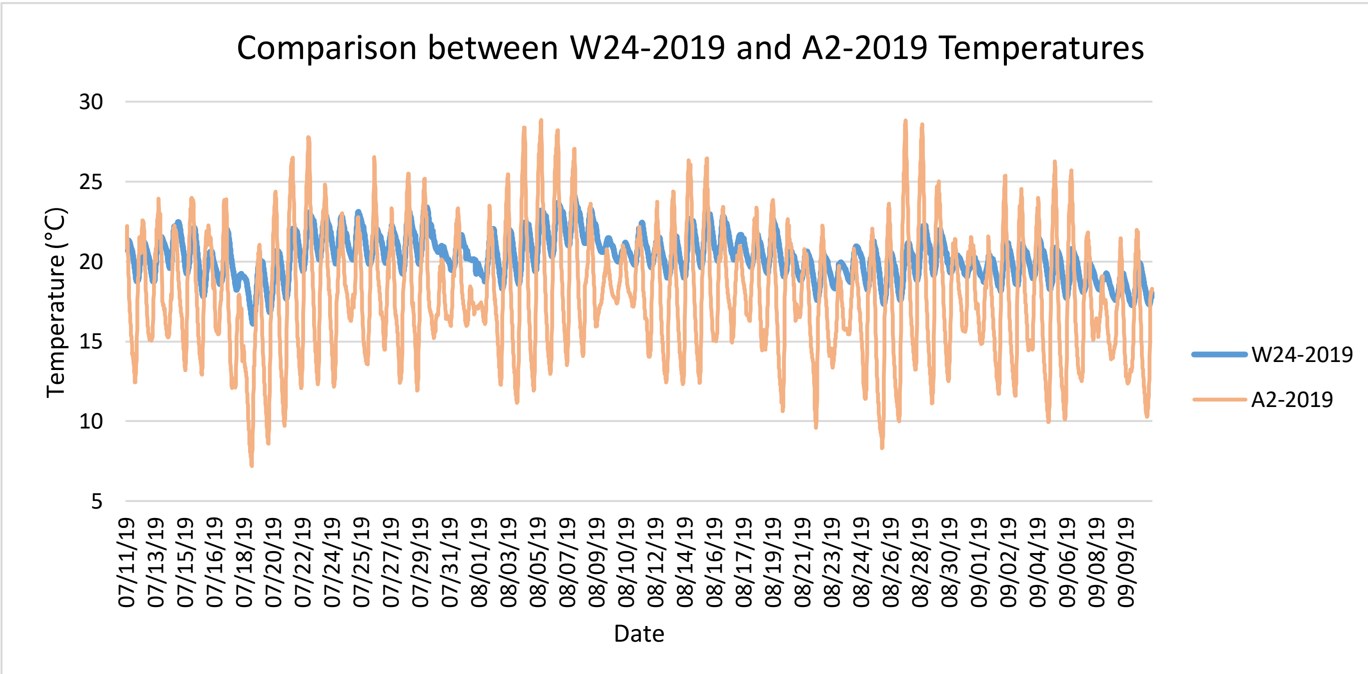


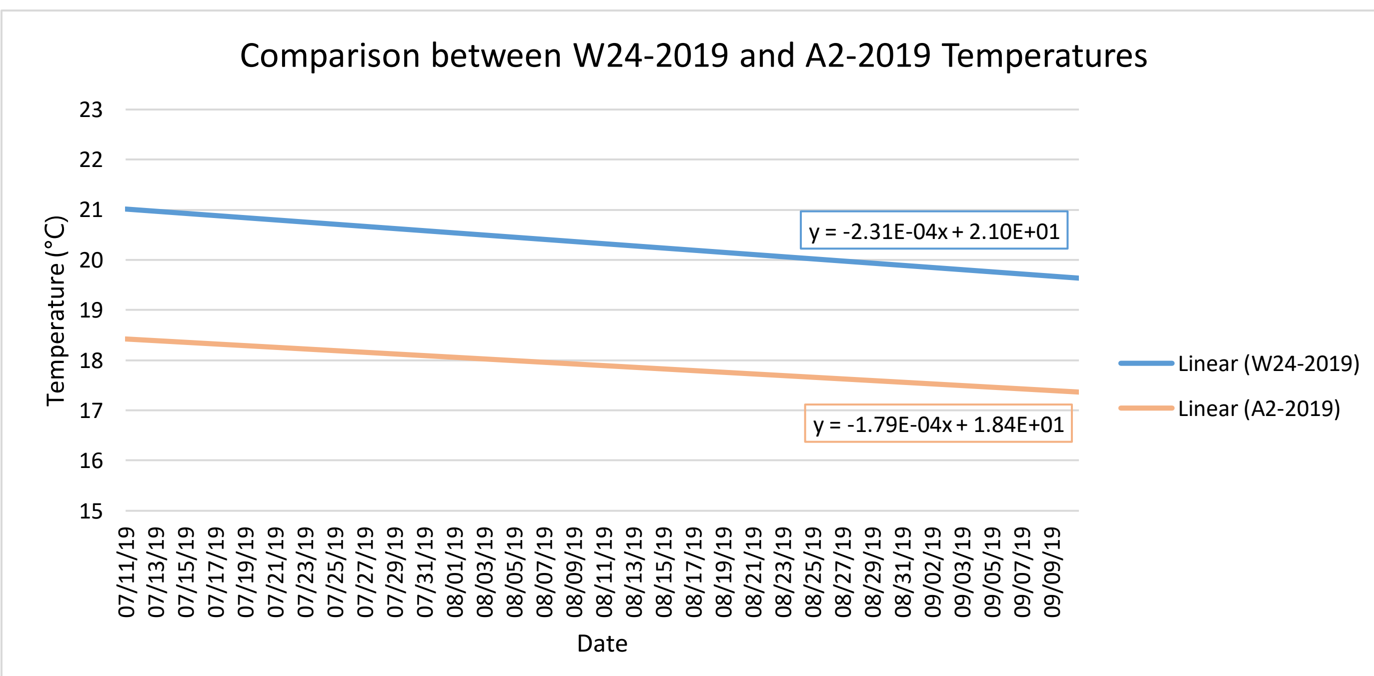
W23-2019 and A2-2019



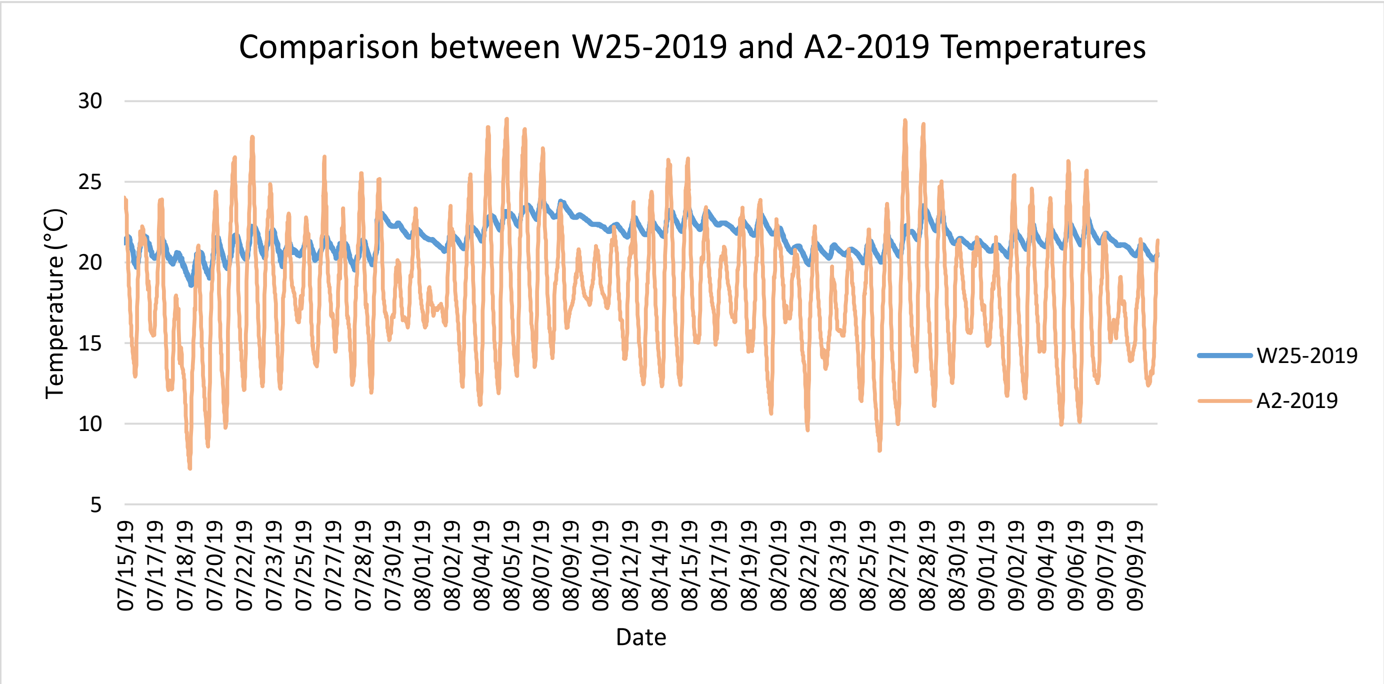


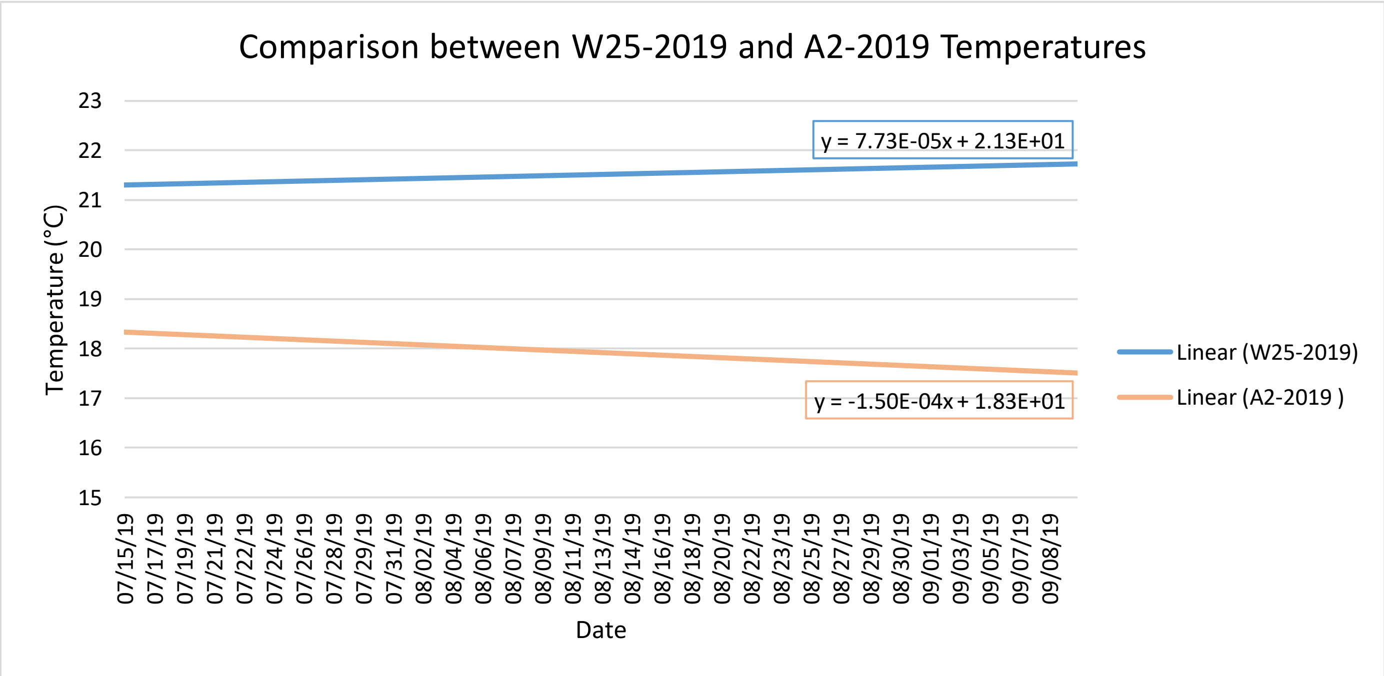
W24-2019 and A2-2019



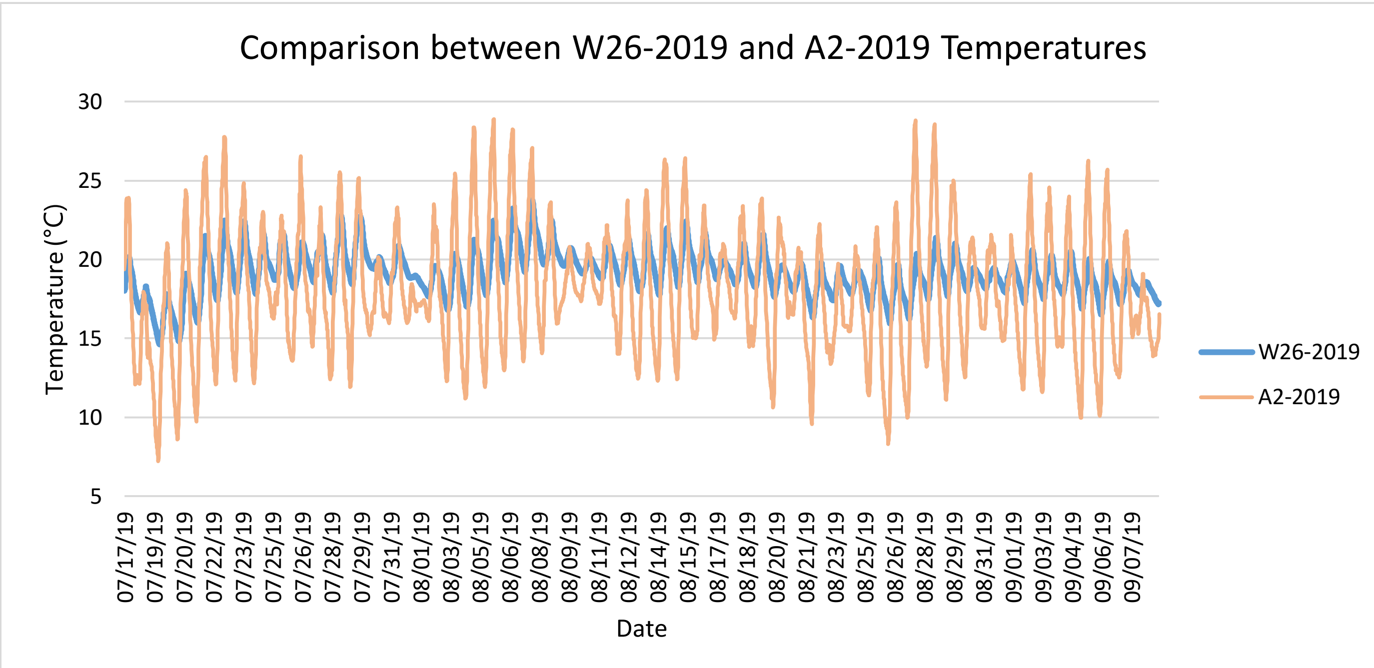


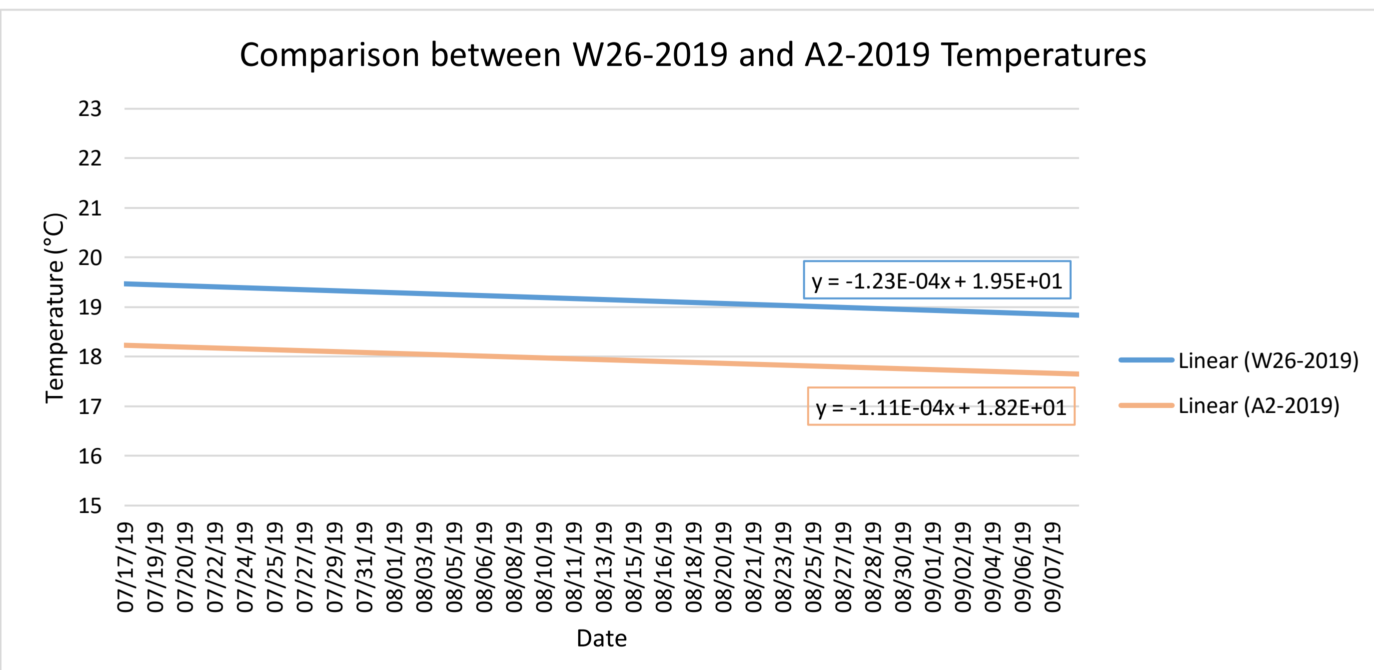
W25-2019 and A2-2019



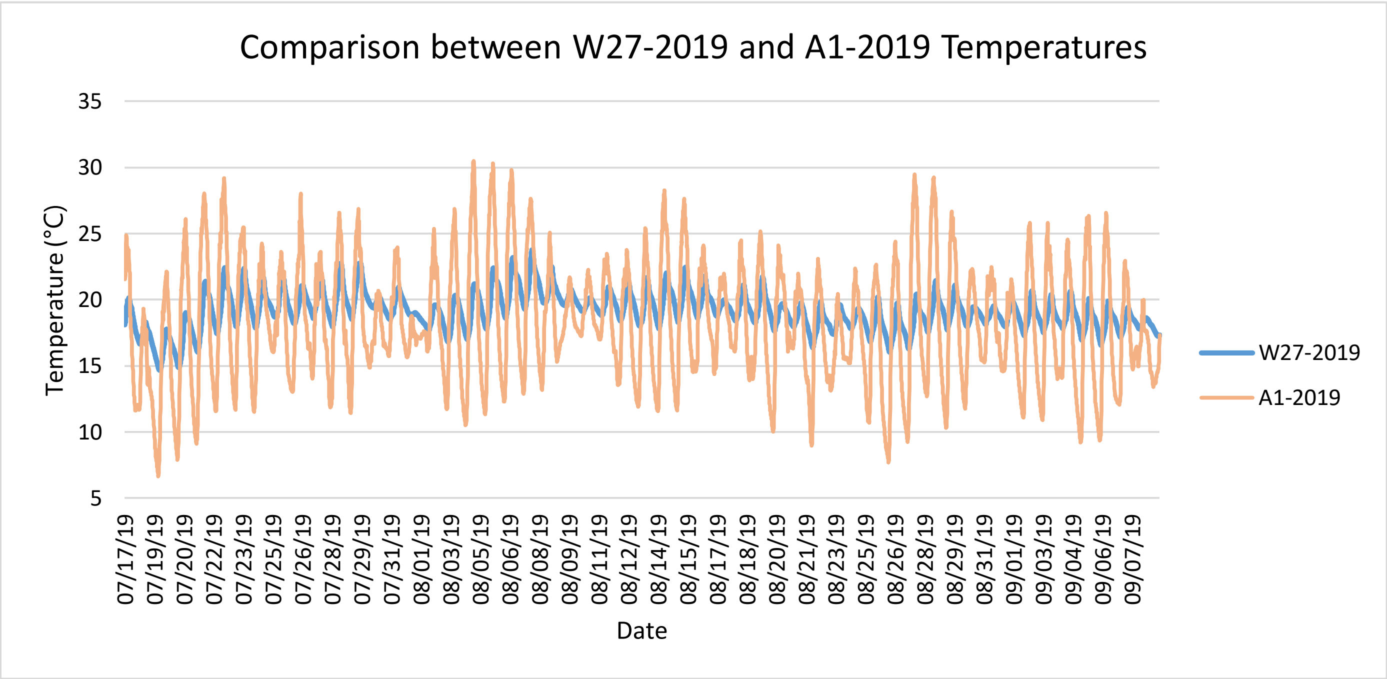


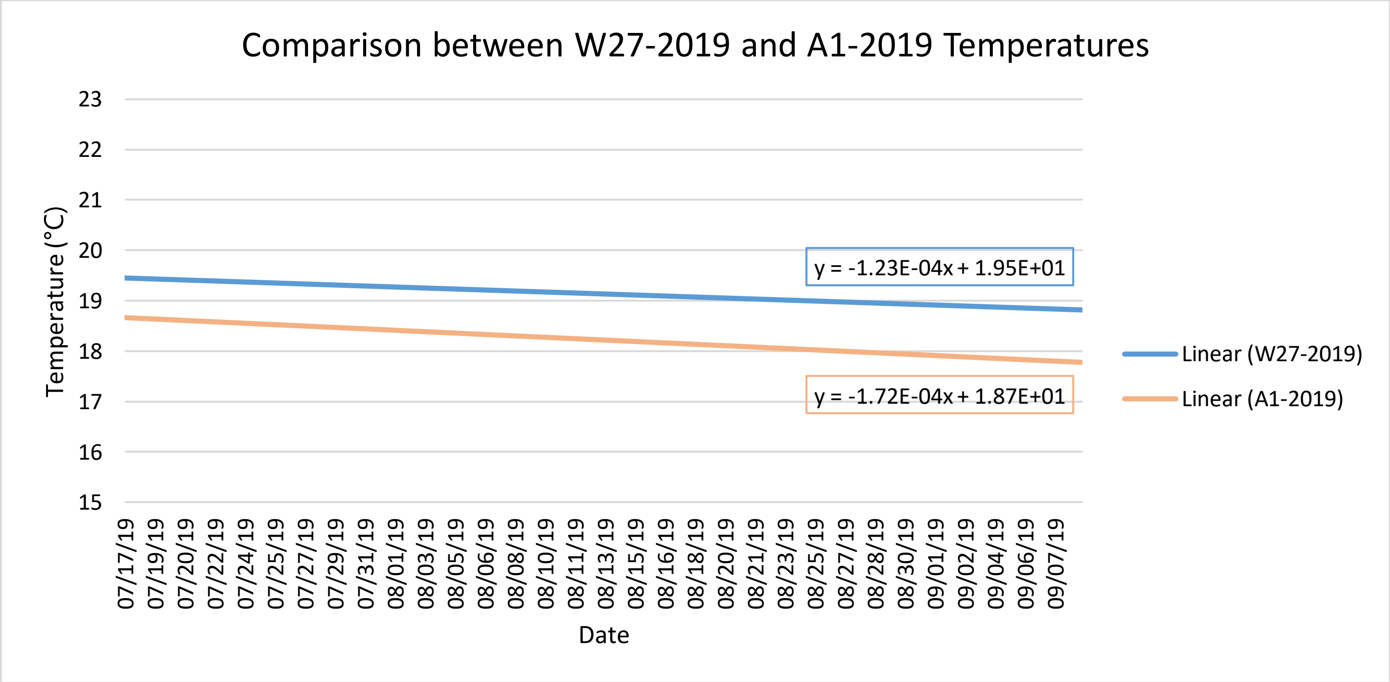
W26-2019 and A2-2019



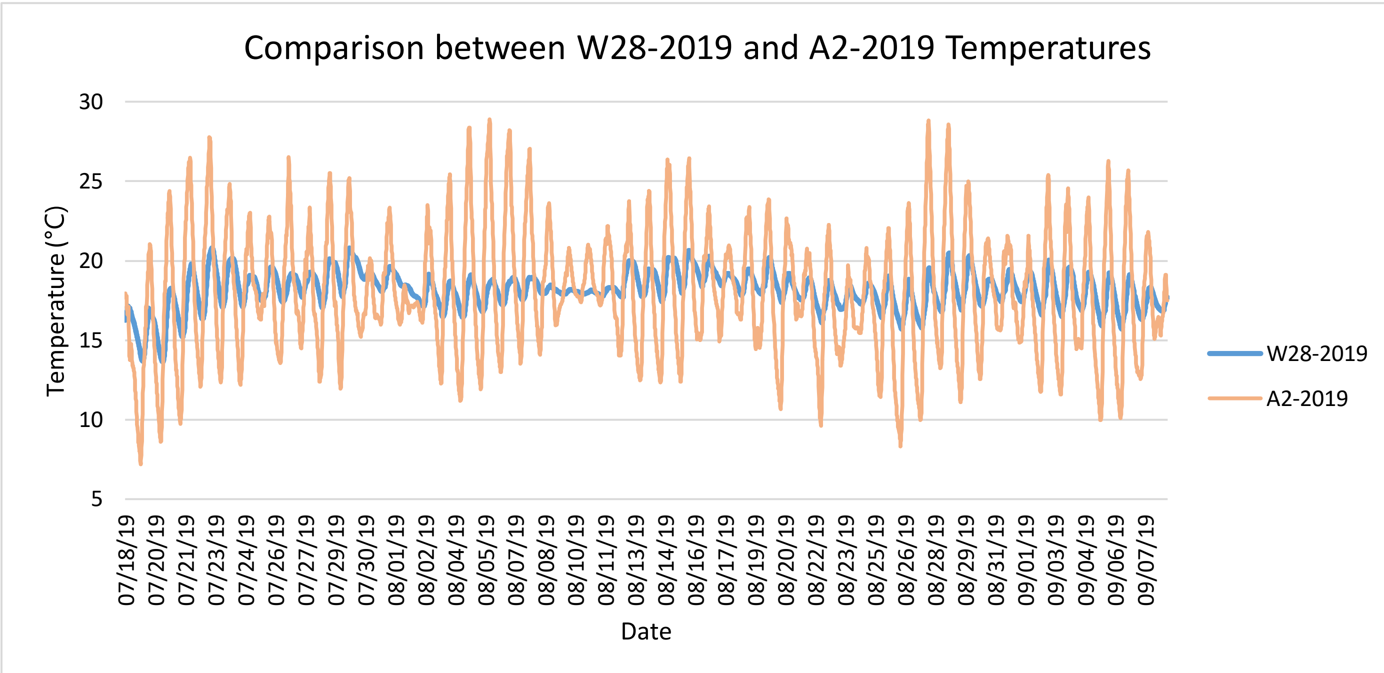


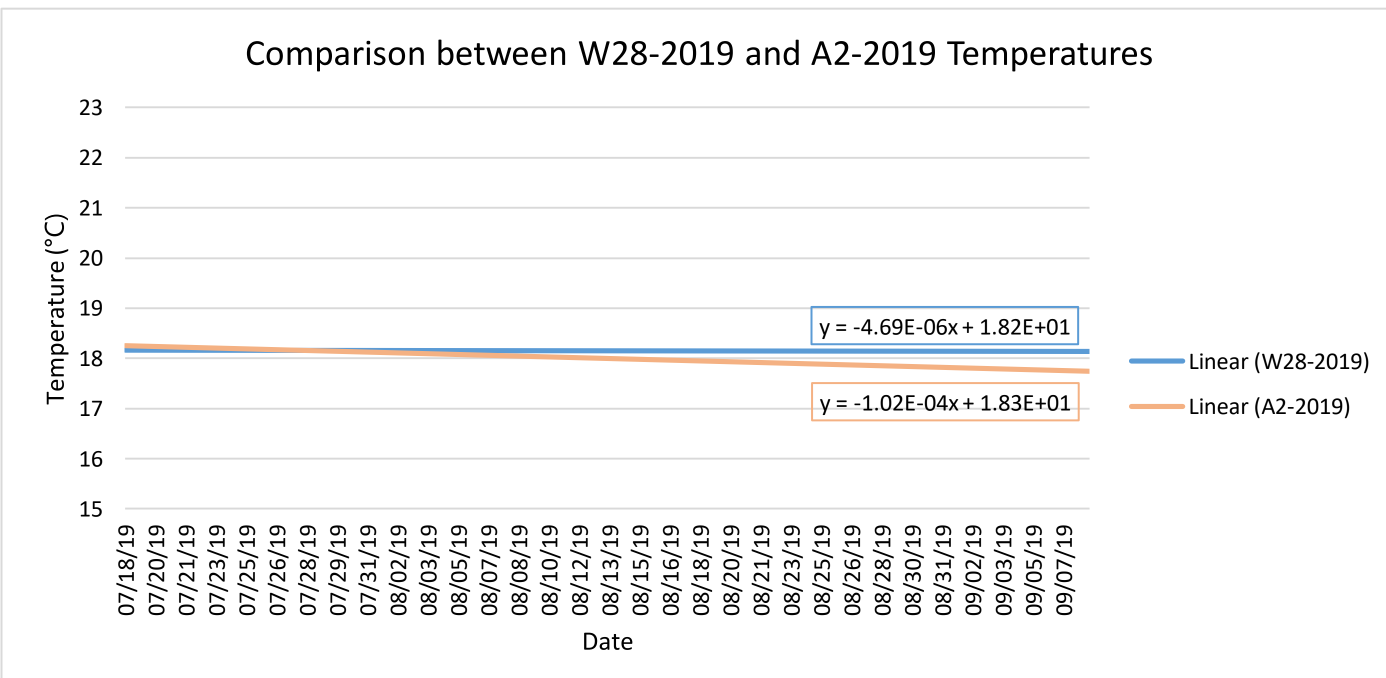
W27-2019 and A1-2019



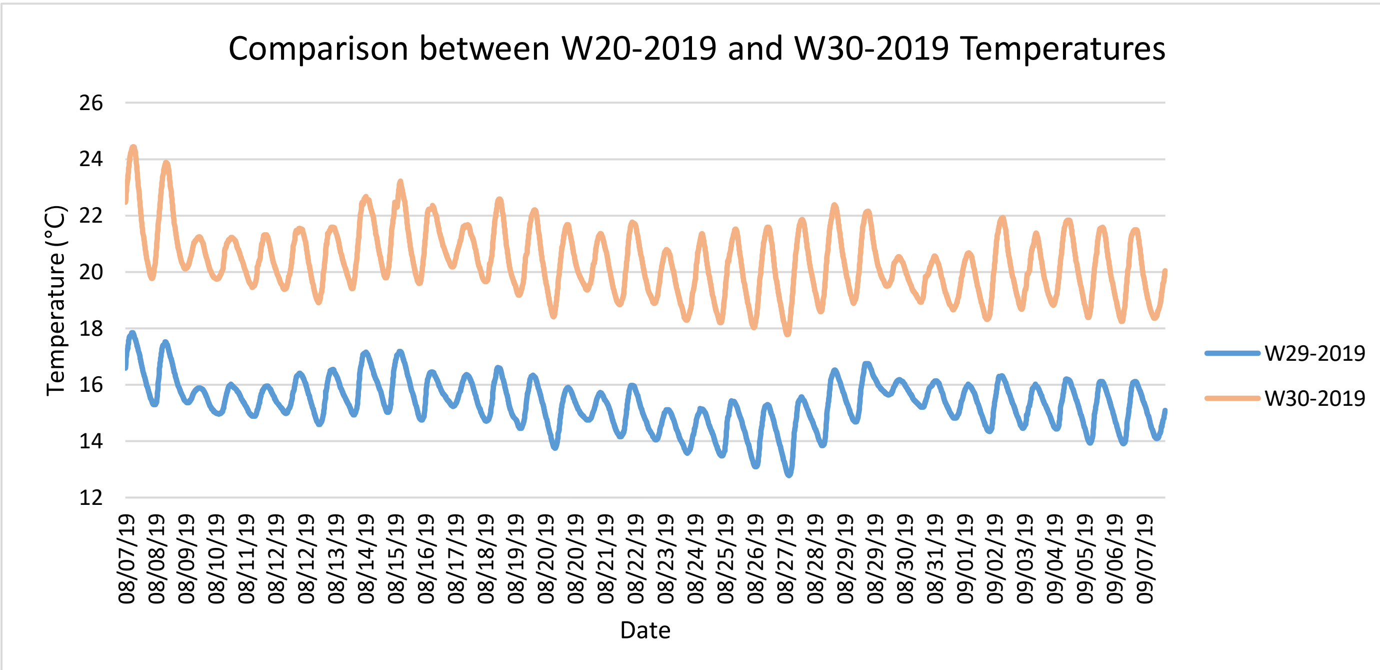


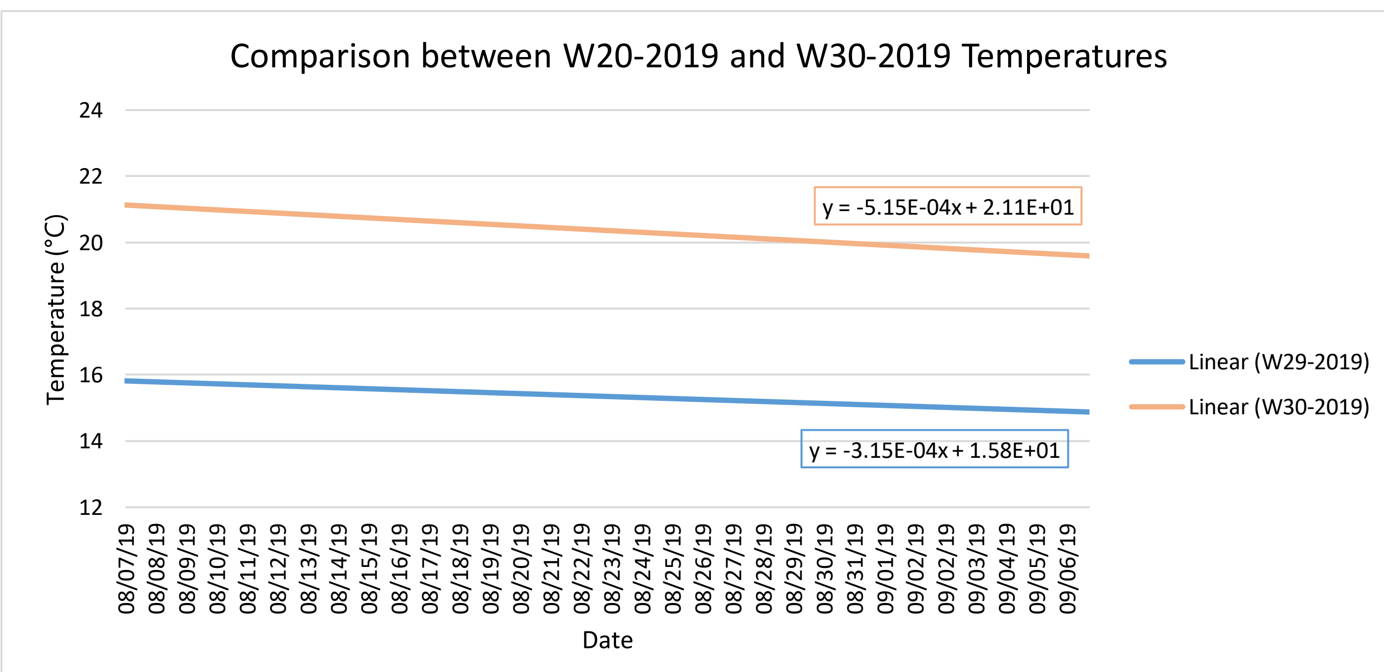
W28-2019 and A2-2019





W29-2019 and W30-2019





Appendix F: Explanation of Results for Each Site

W1-2019

The adjusted p-value for the linear regression between W1-2019 and A1-2019 was 0.03, meaning the null hypothesis (no significant relationship between W1-2019 and A1-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W1-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 6.8°C and a slope of 0.7. Figure 4.6 shows that the intercept and slope for W1-2019 are in the mid-range compared to the other sites, meaning it is unclear whether this location is primarily affected by groundwater or atmospheric factors. The time series graphs (Figures 4.7 and 4.9), show that water temperatures appear to track air temperatures at this site and the slopes of the trendlines for both W1-2019 and A1-2019 are very similar (8.0e-05 and 8.7e-015, respectively). These analyses show that air temperature is likely the primary driver of temperature at W1-2019.

W2-2019

The adjusted p-value for the linear regression between W2-2019 and A1-2019 was 0.003, meaning the null hypothesis (no significant relationship between W2-2019 and A1-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W2-2019. However, as shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 9.5°C and a slope of 0.6. Based on the relatively high intercept and relatively low slope, it appears that the stream temperature at W2-2019 may be influenced by groundwater (Figure 4.6). Additionally, the slope of the trendline from the time series graph of W2-2019 (-1.4e-07) is lower than the slope of the trendline of A1-2019 (7.9 e-05), with water temperatures remaining relatively stable throughout the study period as air temperatures increases, also suggesting potential groundwater influence (Appendix E). Therefore, the linear regression results contradict the comparison of the slopes of the trendlines at W2-2019.

W3-2019

The adjusted p-value for the linear regression between W3-2019 and A1-2019 was 0.03, meaning the null hypothesis (no significant relationship between W3-2019 and A1-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W3-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 6.8°C and a slope of 0.7. Figure 4.6 shows that the intercept and slope for W3-2019 are in the mid-range compared to the other sites, meaning it is unclear whether this location is primarily affected by groundwater or atmospheric factors. Based on the time series graphs (Appendix E), water temperatures appear to track air temperatures at this site and the slopes of the trendlines for both W3-2019 and A1-2019 are similar (3.4e-05 and 7.9e-05, respectively). All of the analyses show that air temperature is likely the primary driver of temperature at W3-2019.

W4-2019

The adjusted p-value for the linear regression between W4-2019 and A2-2019 was 0.08, meaning the null hypothesis (no significant relationship between W4-2019 and A2-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W4-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 4.0°C and a slope of 0.8. Figure 4.6 shows that the intercept and slope for W4-2019 are in the mid-range compared to the other sites, meaning it is unclear whether this location is primarily affected by groundwater or atmospheric factors. Additionally, the time series and slope graphs (Appendix E), show that water temperatures appear to track air temperatures at this site and the slopes of both W4-2019 and A2-2019 are very similar (1.7e-04 and 1.6e-04, respectively). Therefore, the linear regression results suggesting that air temperature is not the primary driver of stream temperature contradicts the comparison of the slopes of the trendlines at W4-2019 and A2-2019.

W5-2019

The adjusted p-value for the linear regression between W5-2019 and A2-2019 was 0.0005, meaning the null hypothesis (no significant relationship between W5-2019 and A2-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W1-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of -1.2°C and a slope of 1.1. Based on the very low intercept and very high slope, W5-2019 does not appear to be influenced by groundwater (Figure 4.6). The time series graph (Appendix E) shows that water temperature increases more rapidly over the study period than air temperature, with trendline slopes of 2.6e-04 and 1.6e-04 for W5-2019 and A2-2019, respectively. W5-2019 was located in a relatively shallow area (average depth of 0.5 m; Table A-1 in Appendix A). This could explain the rapidly increasing water temperatures as shown in the graphs in Appendix D since temperatures in shallower sections of streams tend to increase more rapidly than in deeper sections (Kaandorp et al. 2019). All of the analyses show that air temperature is likely the primary driver of temperature at W1-2019.

W6-2019

The adjusted p-value for the linear regression between W6-2019 and A1-2019 was 0.05, meaning the null hypothesis (no significant relationship between W6-2019 and A1-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W6-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 3.2°C and a slope of 0.8. Based on the relatively low intercept and relatively high slope, W3-2019 does not appear to be influenced by groundwater (Figure 4.6). The time series graph (Appendix E) shows that water temperature increases more rapidly over the study period than air temperature, with slopes of 2.4e-04 and 1.5e-04 for W6-2019 and A1-2019, respectively. The slopes and intercepts from the linear regression and the slope of the trendlines do not indicate that there is groundwater influence at W6-2019, even though the adjusted p-value leads to the failure to reject the null hypothesis. Since the p-value was the same as the significance level and the slope/intercept and time series analysis showed that air is primarily driving the temperature at W6-2019, it is unlikely that groundwater is influencing the stream temperature at W6-2019.

W7-2019

The adjusted p-value for the linear regression between W7-2019 and A1-2019 was 0.1, meaning the null hypothesis (no significant relationship between W7-2019 and A1-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W7-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 8.8°C and a slope of 0.6. Figure 4.6 shows that W7-2019 is likely more influenced by groundwater than by atmospheric conditions, based on where the slope and intercepts lie in comparison to other sites. The time series graph (Appendix E) shows that the slope of the trendline for water temperature is slightly lower than the slope of the trendline for air temperature (8.6e-05 and 1.0 e-4, respectively). This suggests that there may be groundwater influencing the temperature of the stream at W7-2019, as corroborated by the linear regression results.

W8-2019

The adjusted p-value for the linear regression between W8-2019 and A1-2019 was 0.12, meaning the null hypothesis (no significant relationship between W8-2019 and A1-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W8-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 7.7°C and a slope of 0.6. Figure 4.6 shows that W8-2019 is likely more influenced by groundwater than by atmospheric conditions, based on where the slope and intercepts lie in comparison to other sites. The time series graph (Appendix E) shows that the slope of the trendline for water temperature is slightly lower than the slope of the trendline for air temperature (7.6e-05 and 1.3e-4, respectively). This suggests that there may be groundwater influencing the temperature of the stream at W8-2019, as corroborated by the linear regression results.

W9-2019

The adjusted p-value for the linear regression between W9-2019 and A1-2019 was 0.02, meaning the null hypothesis (no significant relationship between W9-2019 and A1-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W9-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 8.6°C and a slope of 0.6. W9-2019 is in a similar location as W8-2019 on Figure 4.6, indicating that it is likely more influenced by groundwater than by atmospheric conditions, based on where the slope and intercepts lie in comparison to other sites. The time series graph (Appendix E) shows that the slope of the trendline for water temperature is lower than the slope of the trendline for air temperature (2.0-05 and 1.2e-4, respectively), meaning water temperature is more stable than air temperature over time which is indicative of potential groundwater input. Therefore, the linear regression results indicating that there is a significant relationship between air and water temperature and therefore likely no groundwater influence contradict the comparison of the slopes of the trendlines at W9-2019. W9-2019 is located approximately 12 m downstream of Portuguese Creek, which likely has groundwater input. As such, W9-2019 may be slightly influenced by groundwater in Portuguese Creek.

W10-2019

The adjusted p-value for the linear regression between W10-2019 and A1-2019 was 0.03, meaning the null hypothesis (no significant relationship between W10-2019 and A1-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W10-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 6.0°C and a slope of 0.7. Figure 4.6 shows that the intercept and slope for W10-2019 are in the mid-range compared to the other sites, meaning it is unclear whether this location is primarily affected by groundwater or atmospheric factors. The time series graph (Appendix E) shows that the slope of the trendline for water temperature is slightly lower than the slope of the trendline for air temperature (8.8e-05 and 1.2 e-4, respectively). This means that water temperature increased more slowly throughout the study period than did air temperature, showing a more stable temperature change. This could be indicative of groundwater influence, however water temperatures at this location still appear to be sensitive to air temperatures, as indicated by the results of the linear regression. W10-2019 was located in Portuguese Creek, which has previously been shown to have a considerable amount of groundwater contribution to it, with many springs and flowing groundwater wells in its vicinity (Metherall 2019). Therefore, it is possible that it is slightly influenced by groundwater upstream in Portuguese Creek.

W11-2019

The adjusted p-value for the linear regression between W11-2019 and A1-2019 was 0.02, meaning the null hypothesis (no significant relationship between W11-2019 and A1-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W1-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 9.2°C and a slope of 0.6. Figure 4.6 shows that W11-2019 is likely more influenced by groundwater than by atmospheric conditions, based on where the slope and intercepts lie in comparison to other sites. Additionally, the time series graph (Appendix E) shows that the slope of the trendline for W11-2019 decreases (-3.7e-05) while the slope of the trendline for A1-2019 increases (4.6e-05). These slopes suggest that there may be groundwater seepage at W11-2019. Therefore, the results of the linear regression indicating that the temperature at W11-2019 is primarily driven by air temperature contradicts the slopes of the trendlines for the time series graphs.

W12-2019

The adjusted p-value for the linear regression between W12-2019 and A2-2019 was 0.05, meaning the null hypothesis (no significant relationship between W12-2019 and A2-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W12-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 10.3°C and a slope of 0.6. Based on the relatively high intercept and relatively low slope, W12-2019 does appear to be influenced by groundwater (Figure 4.6). Additionally, the time series graph (Appendix E) shows that the slope of the trendline for W12-2019 decreases (-4.2e-05) while the slope of the trendline for A1-2019 increases (6.6e-05). These trendline slopes suggest that there may be groundwater seepage at W12-2019, as corroborated by the linear regression results.

W13-2019

The adjusted p-value for the linear regression between W13-2019 and A1-2019 was 0.4, meaning the null hypothesis (no significant relationship between W13-2019 and A1-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W13-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 10.3°C and a slope of 0.5. Based on the relatively high intercept and relatively low slope, W13-2019 does appear to be influenced by groundwater (Figure 4.6). Additionally, the time series graph (Appendix E) shows that the slope of the trendline for W13-2019 is slightly lower than the slope of the trendline for A1-2019 (3.5e-05 and 9.6e-05, respectively). This suggests that there may be groundwater influencing the temperature of the stream at W13-2019, as corroborated by the linear regression results.

W14-2019

The adjusted p-value for the linear regression between W14-2019 and A1-2019 was 0.2, meaning the null hypothesis (no significant relationship between W14-2019 and A1-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W14-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 11.1°C and a slope of 0.4. Based on the high intercept and low slope, W14-2019 does appear to be influenced by groundwater (Figure 4.6). However, the time series graph (Appendix E) shows that the slope of the trendline for W14-2019 is very similar to the slope of the trendline for A1-2019 (7.5e-05 and 7.7e-05, respectively), suggesting that the stream temperatures are still fairly sensitive to changes in air temperatures. Therefore, the linear regression results suggesting that air temperature is not the primary driver of stream temperature contradicts the comparison of the slopes of the trendlines at W14-2019 and A1-2019.

W15-2019

The adjusted p-value for the linear regression between W15-2019 and A2-2019 was 0.02, meaning the null hypothesis (no significant relationship between W15-2019 and A2-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W15-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 2.3°C and a slope of 0.9. Based on the relatively low intercept and relatively high slope, W15-2019 does not appear to be influenced by groundwater (Figure 4.6). The time series graph (Appendix E) shows that water temperature increases more rapidly over the study period than air temperature, with slopes of 2.1e-04 and 9.6e-05 for W15-2019 and A2-2019, respectively. This suggests that it is unlikely that groundwater is influencing the temperature of the stream at W15-2019, as corroborated by the linear regression results.

W16-2019

The adjusted p-value for the linear regression between W16-2019 and A1-2019 was 0.002, meaning the null hypothesis (no significant relationship between W16-2019 and A1-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W16-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 4.1°C and a slope of 0.9. Based on the relatively low intercept and relatively high slope, W16-2019 does not appear to be influenced by groundwater (Figure 4.6). This is corroborated by the time series graphs (Appendix E), showing that water temperatures appear to track air temperatures at this site and the slopes of the trendlines for both W16-2019 and A1-2019 are similar (-3.6e-06 and -3.0e-06, respectively). All of the analyses show that air temperature is likely the primary driver of temperature at W16-2019.

W17-2019

The adjusted p-value for the linear regression between W17-2019 and A1-2019 was 0.5, meaning the null hypothesis (no significant relationship between W17-2019 and A1-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W17-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 11.1°C and a slope of 0.5. Based on the relatively high intercept and relatively low slope, W17-2019 does appear to be influenced by groundwater (Figure 4.6). The time series graph (Appendix E) shows that the slope of the trendline for water temperature is lower than the slope of the trendline for air temperature (1.8e-04 and 1.1e-3, respectively). This means that water temperature increased much more slowly throughout the study period than did air temperature, showing a more stable temperature change. This suggests that there may be groundwater influencing the temperature of the stream at W17-2019, as corroborated by the linear regression results.

W18-2019

The adjusted p-value for the linear regression between W18-2019 and A2-2019 was 0.002, meaning the null hypothesis (no significant relationship between W18-2019 and A2-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W18-2019. However, as shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 9.1°C and a slope of 0.4. Therefore, based on the relatively high intercept and relatively low slope, W18-2019 does appear to be influenced by groundwater (Figure 4.6). The time series graphs (Appendix E), show that water temperatures appear to track air temperatures at this site and the slopes of the trendlines for both W18-2019 and A2-2019 are similar (-7.2e-05 and -7.8e-05, respectively). The time series graphs in Appendix E also show that water temperatures are lower than air temperatures throughout the study period. The rejection of the null hypothesis suggesting that air temperature primarily drives water temperature at W18-2019 is corroborated by the slopes of the trendlines being similar. W18-2019 was located approximately 18.6 km northwest of A2-2019, therefore the comparison between air and water temperatures at this site may not be indicative of potential groundwater inputs. Since the purpose of this site was to be a reference site for the study area, and since it appears unlikely that stream temperatures at W18-2019 are influenced by groundwater, future temperature studies at this site are not recommended.

W19-2019

The adjusted p-value for the linear regression between W19-2019 and A2-2019 was 0.09, meaning the null hypothesis (no significant relationship between W19-2019 and A2-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W19-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 1.9°C and a slope of 0.9. Based on the relatively low intercept and relatively high slope, W19-2019 does not appear to be influenced by groundwater (Figure 4.6). The time series graph (Appendix E) shows that water temperature increases while air temperature decreases throughout the study period, with slopes of 1.8e-04 and -6.0e-05 for W19-2019 and A2-2019, respectively. This suggests that it is unlikely that groundwater is influencing the temperature of the stream at W19-2019. The linear regression results show that air temperature is likely not the primary factor driving the temperature at W19-2019, however it is also unlikely that the stream temperature is influenced by groundwater in this location.

W20-2019

The adjusted p-value for the linear regression between W20-2019 and A2-2019 was 1.0, meaning the null hypothesis (no significant relationship between W20-2019 and A2-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W20-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 1.8°C and a slope of 0.9. Based on the relatively low intercept and relatively high slope, W20-2019 does not appear to be influenced by groundwater (Figure 4.6). The time series graph (Appendix E) shows that water temperature decreases at a much greater rate than does air temperature throughout the study period, with slopes of -7.1e-04 and -7.8e-05 for W20-2019 and A2-2019, respectively. Therefore, the linear regression results suggesting that air temperature is not the primary driver of stream temperature contradicts the analysis of the intercept and slope produced from the linear regression.

W21-2019

The adjusted p-value for the linear regression between W21-2019 and A2-2019 was 0.03, meaning the null hypothesis (no significant relationship between W21-2019 and A2-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W21-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 5.6°C and a slope of 0.8. Figure 4.6 shows that W21-2019 is likely more influenced by atmospheric conditions than by groundwater input, based on where the slope and intercepts lie in comparison to other sites. The time series graphs (Appendix E), show that the slopes of the trendlines for both W21-2019 and A2-2019 are similar, with water temperatures decreasing at a slightly faster rate than air temperatures (-1.7e-04 and -1.2e-04, respectively). This suggests that it is unlikely that groundwater is influencing the temperature of the stream at W21-2019, as corroborated by the linear regression results.

W22-2019

The adjusted p-value for the linear regression between W22-2019 and A1-2019 was 0.02, meaning the null hypothesis (no significant relationship between W22-2019 and A1-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W22-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 4.4°C and a slope of 0.9. Figure 4.6 shows that W22-2019 is likely more influenced by atmospheric conditions than by groundwater input, based on where the slope and intercepts lie in comparison to other sites. The time series graphs (Appendix E), show that the slopes of the trendlines for both W22-2019 and A1-2019 are very similar (-2.3e-04 and -2.4e-04, respectively). This suggests that it is unlikely that groundwater is influencing the temperature of the stream at W22-2019, as corroborated by the linear regression results.

W23-2019

The adjusted p-value for the linear regression between W23-2019 and A2-2019 was 0.08, meaning the null hypothesis (no significant relationship between W23-2019 and A2-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W23-2019. However, as shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of -0.6°C and a slope of 1.1. Based on the low intercept and high slope, W23-2019 appears to be influenced by atmospheric conditions rather than groundwater input, with the highest slope and second lowest intercept compared to the other loggers (Figure 4.6). The time series graph (Appendix E) shows that the slope of the trendline for W23-2019 (-4.7e-0.5) is lower than the slope of the trendline for A2-2019 (-1.8e-04), decreasing at a slower rate over time. This suggests that groundwater may be influencing the stream temperature at W23-2019, buffering water temperature from the decrease in air temperature. The results of the linear regression and slopes of the trendlines indicating that there may be groundwater influence at W23-2019 contradict the analysis of the intercept and slope from the linear regression indicating that the temperature at W23-2019 is unlikely influenced by groundwater inputs.

W24-2019

The adjusted p-value for the linear regression between W24-2019 and A2-2019 was 0.03, meaning the null hypothesis (no significant relationship between W24-2019 and A2-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W24-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of

5.9°C and a slope of 0.8. Figure 4.6 shows that W24-2019 is likely more influenced by atmospheric conditions than by groundwater input, based on where the slope and intercepts lie in comparison to other sites. The time series graphs (Appendix E), show that the slopes of the trendlines for both W24-2019 and A2-2019 are similar (-2.3e-04 and -1.8e-04, respectively). The temperature at W24-2019 decreased at a slightly greater rate than did the temperature at A2-2019 over time. This suggests that it is unlikely that groundwater is influencing the temperature of the stream at W24-2019, as corroborated by the linear regression results.

W25-2019

The adjusted p-value for the linear regression between W25-2019 and A2-2019 was 0.15, meaning the null hypothesis (no significant relationship between W25-2019 and A2-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W25-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 9.9°C and a slope of 0.7. Based on the relatively high intercept and relatively low slope, W25-2019 appears to be more influenced by groundwater input than atmospheric conditions (Figure 4.6). The time series graph (Appendix E) shows that the slope of the trendline for W25-2019 (7.8e-05) increased while the slope of the trendline for A2-2019 (-1.5e-04) decreased over time. This suggests that air is not the primary driver of stream temperature at W25-2019, however groundwater input is also unlikely to be influencing the temperature in this location. Stream temperatures at W25-2019 are likely primarily influenced by the temperature of water being released from Wolf Lake rather than air temperature or groundwater.

W26-2019

The adjusted p-value for the linear regression between W26-2019 and A2-2019 was 0.03, meaning the null hypothesis (no significant relationship between W26-2019 and A2-2019) was rejected. This suggests that air temperature is primarily driving the temperature at W26-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 4.4°C and a slope of 0.8. Based on the relatively low intercept and relatively high slope, W26-2019 appears to be more influenced by atmospheric conditions than groundwater input (Figure 4.6). The time series graphs (Appendix E), show that the slopes of the trendlines for both W26-2019 and A2-2019 are very similar (-1.2e-04 and -1.1e-04, respectively). This suggests that it is unlikely that groundwater is influencing the temperature of the stream at W26-2019, as corroborated by the linear regression results.

W27-2019

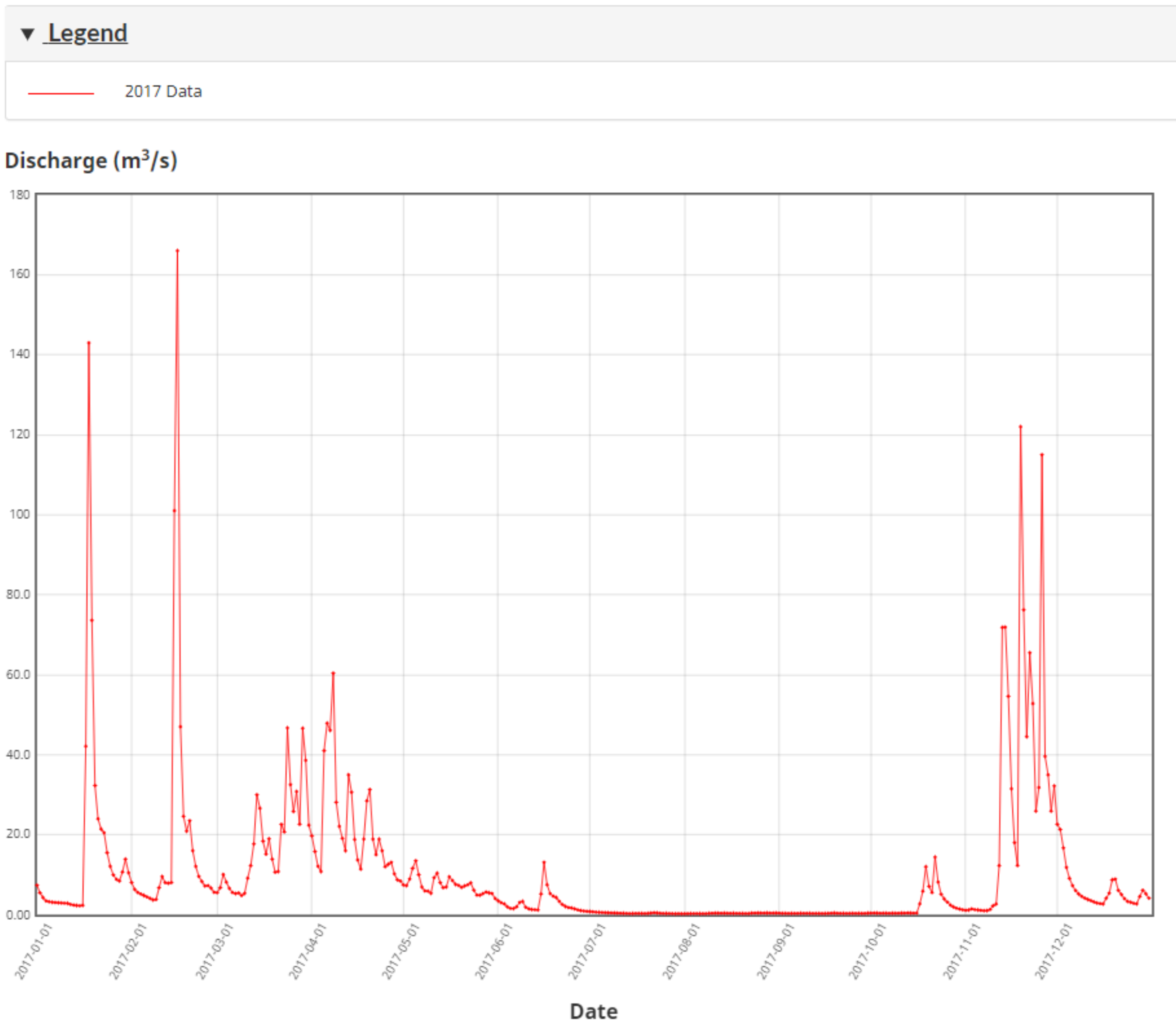
The adjusted p-value for the linear regression between W27-2019 and A2-2019 was 0.05, meaning the null hypothesis (no significant relationship between W27-2019 and A2-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W27-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 5.0°C and a slope of 0.8. Based on the relatively low intercept and relatively high slope, W27-2019 appears to be more influenced by atmospheric conditions than groundwater input (Figure 4.6). The time series graphs (Appendix E), show that the slopes of the trendlines for both W27-2019 and A2-2019 are similar (-1.2e-04 and -1.7e-04, respectively). The slope of the trendline for W27-2019 is slightly lower than the slope of the trendline for A2-2019, decreasing at a slightly slower rate over time. Due to the similarity in trendline slopes and the low intercept and high slope from the linear regression, it is unlikely that groundwater is influencing the temperature of the stream at W27-2019.

W28-2019

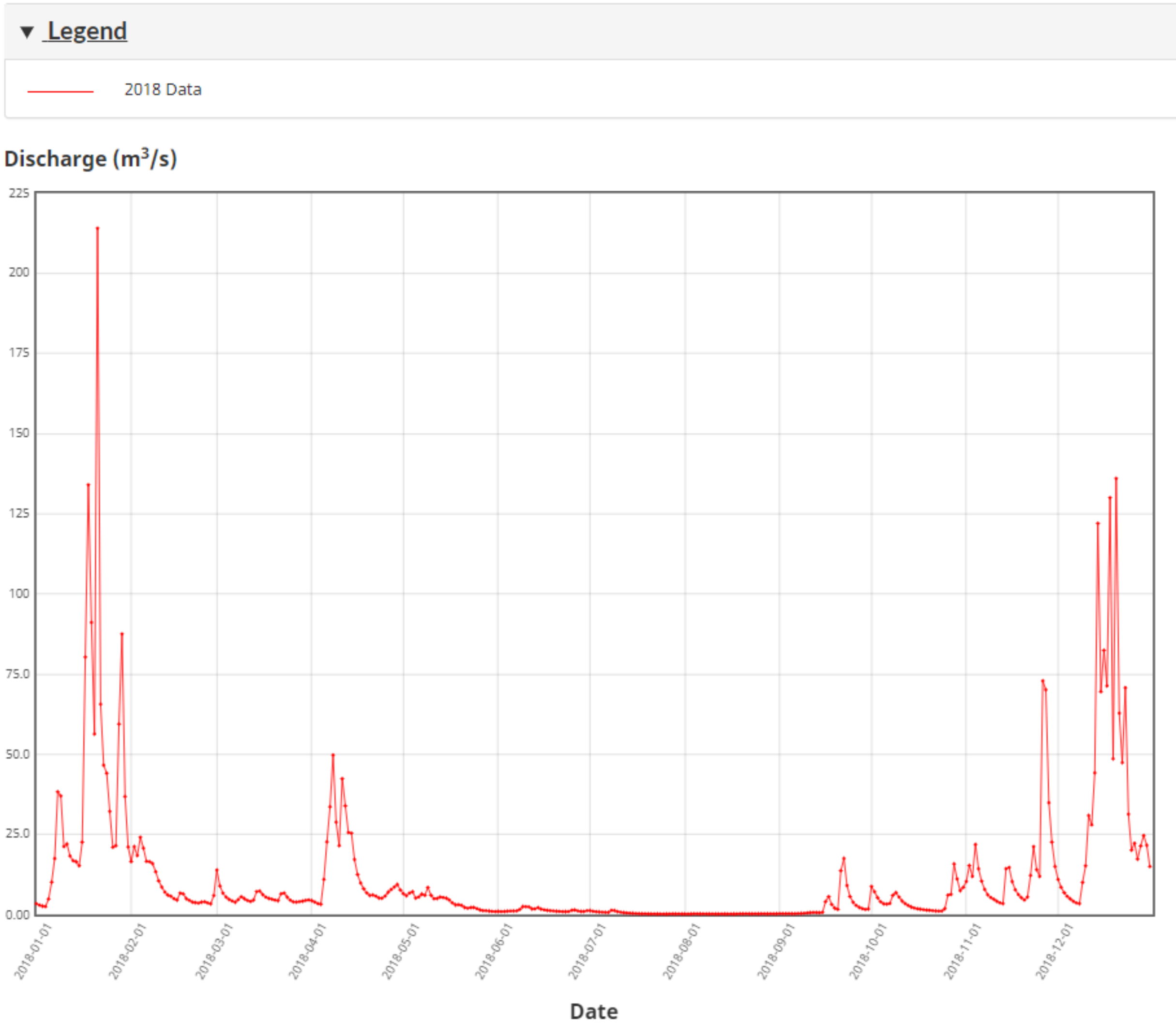
The adjusted p-value for the linear regression between W28-2019 and A2-2019 was 0.54, meaning the null hypothesis (no significant relationship between W28-2019 and A2-2019) was not rejected. This suggests that air temperature is not the primary factor driving the temperature at W28-2019. As shown in Figure 4.6 and Table 4.2, the linear regression produced an intercept of 9.0°C and a slope of 0.5. Based on the relatively high intercept and relatively low slope, W28-2019 appears to be more influenced by groundwater input than by atmospheric conditions (Figure 4.6). The time series graph (Appendix E) shows that the slope of the trendline for W28-2019 (-4.7e-0.6) is lower than the slope of the trendline for A2-2019 (-1.0e-04), decreasing at a slower rate over time. This suggests that groundwater may be influencing the stream temperature at W28-2019, buffering water temperature from the decrease in air temperature, as corroborated by the linear regression results.

Appendix G: Hydrographs for Tsolum River (2017, 2018, 2019; Government of Canada 2014)

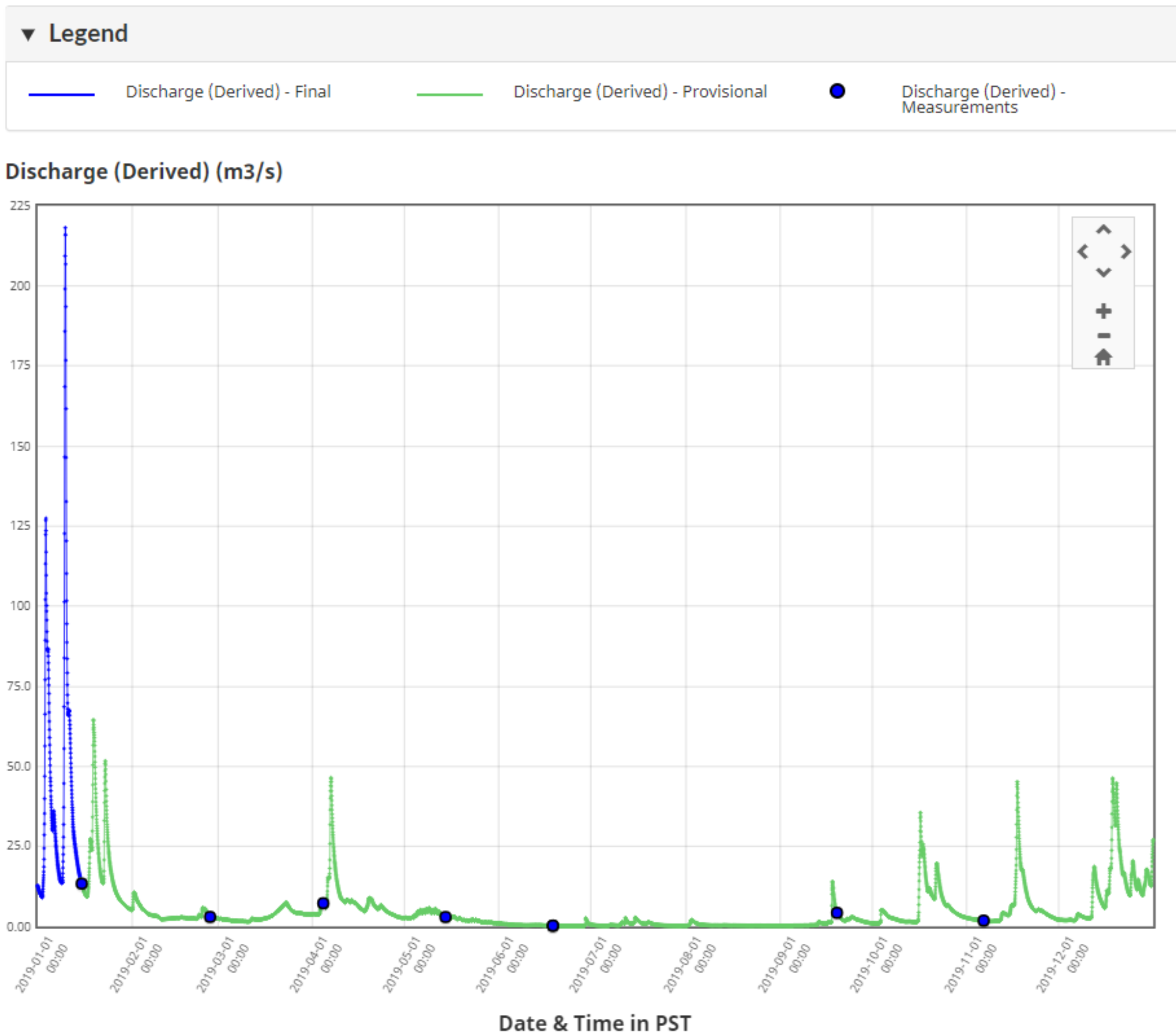
<u>2017 Discharge at Tsolum River near Courtenay 08HB011 Station\</u>



2018 Discharge at Tsolum River near Courtenay 08HB011 Station



2019 Discharge at Tsolum River near Courtenay 08HB011 Station



Appendix H: Wolf Lake Physiochemical Profile Results

Table H-1 Temperature and DO concentrations at 0.5 m depth intervals at N-2019 and S-2019 in Wolf Lake.

Depth (m)*	N-2019		S-2019	
	Temperature (°C)	DO (mg/L)	Temperature (°C)	DO (mg/L)
0.0	23.1	8.4	22.8	7.7
0.5	23.2	8.3	22.9	7.7
1.0	23.2	8.0	22.9	7.8
1.5	23.2	8.0	22.9	7.8
2.0	23.2	8.0	22.9	7.8
2.5	23.1	8.0	22.9	7.8
3.0	23.1	8.0	22.9	7.8
3.5	23.0	7.9	22.9	7.8
4.0	22.8	8.0	22.8	7.8
4.5	21.7	8.4	22.7	7.7
5.0	21.5	8.4	21.7	8.0
5.5	21.4	8.4	19.3	8.6
6.0	21.1	8.3	18.6	8.8
6.5	20.2	8.5	17.2	9.3
7.0	19.7	8.6	15.9	9.7
7.5	17.1	9.4	15.7	9.7
8.0	16.0	9.8	14.7	10.0
8.5	13.3	10.7	15.5	10.0
9.0	11.8	10.8	14.4	10.0
9.5	11.1	10.9	---	---
10.0	10.4	10.8	---	---
10.5	10.1	10.7	---	---
11.0	10.2	10.4	---	---
11.5	9.8	10.5	---	---
12.0	9.6	10.5	---	---
12.5	9.3	10.6	---	---
13.0	9.1	10.6	---	---
13.5	8.9	10.7	---	---
14.0	8.8	10.6	---	---
14.5	8.0	11.1	---	---
15.0	7.7	10.9	---	---
15.5	7.5	10.8	---	---
16.0	7.3	10.7	---	---
16.5	7.2	10.7	---	---
17.0	7.0	11.0	---	---
17.5	6.9	10.9	---	---
18.0	6.8	10.8	---	---
18.5	6.8	10.8	---	---
19.0	6.6	10.7	---	---
19.5	6.5	10.6	---	---
20.0	6.4	10.6	---	---

* Depth of the lake is greater than 20 m at N-2019, however length of YSI cable is 20 m so deepest measurement possible is 20