AN ABSTRACT OF THE THESIS OF

Michael W. Collier for the degree of Master of Science in Water Resources Engineering presented on August 22, 2008.
Title: Demonstration of Fiber Optic Distributed Temperature Sensing to Differentiate Cold Water Refuge between Ground Water Inflows and Hyporheic Exchange.

Abstract approved:

Richard H. Cuenca

Recent developments in Distributed Temperature Sensing (DTS) have allowed new insight into the surface-to-ground water interaction. The continuous temperature measurement by the DTS allows for cool water inflows to be located during warm summer months. These cool water inflows can then be differentiated between ground water and hyporheic exchange. The cool water inflows are important to many species that inhabit the rivers of the Western United States. As temperatures increase due to climate change the importance of cool water inflows will grow.

This study used fiber optic cable and the DTS system to measure the temperature in 2km of the Walla Walla River, near Milton-Freewater, Oregon. The temperature data was split into nighttime and daytime averages. The correlation between these two data sets was calculated to reveal when the daytime and nighttime data followed the same cooling pattern (evidence of ground water inflow) or when the nighttime temperature increased, but the daytime temperature decreased (evidence of hyporheic exchange). Nine areas of apparent ground water inflow and nine areas of expected hyporheic exchange were identified. The average quantity of inflow at each ground water site was calculated as 0.04 m^3/s. The computed average hyporheic exchange depth along the 2000 m channel was 0.32 m. The located cold water inflows were compared to salmon and trout location from a US Fish and Wildlife Survey. This comparison showed that the cool mid-day inflows (either ground water or hyporheic exchange locations) made up 1/3 of the study reach length and had

approximately 60% of the cold water fish. Half of the cool water inflow sites did not have fish present during the survey which suggests that while influent cool water is a major factor for fish congregation, it is not the sole factor.

Demonstration of Fiber Optic Distributed Temperature Sensing to Differentiate Cold Water Refuge between Ground Water Inflows and Hyporheic Exchange

by
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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented August 22, 2008
Commencement June 2009

Master of Science thesis of Michael W. Collier presented on August 22, 2008.

APPROVED:

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Michael W. Collier, Author

ACKNOWLEDGEMENTS

The author expresses sincere appreciation to my faculty advisor, Richard Cuenca, he has been an encourager and friend throughout the graduate years. Also, to my minor advisor and project leader John Selker, he allowed me to work with him on this project and has helped me think through many of the complexities that this project has brought. John has also been a friend and his enthusiasm and energy for research is at a level few may ever understand. I appreciate the entire Hydraulic Science Team, Yutaka, Ari, Josh, Travis, Kent, and Suva, making the rainy Oregon winters bearable with office banter and for helping me with my thesis and research. A special thanks to Yutaka, you are the heart and soul of the HST. Thanks to all of you who read through my thesis, it was a great help. Thanks to Julie, Nick, and Martijn for help with MatLab. Thanks to Chadi and Chris for miscellaneous help throughout the project. I also wanted to acknowledge my parents for teaching me to enjoy education and trust in the Lord. To my family, friends, and fiancé for staying with me through some of the stressful times of research and thesis writing, many of whom also helped in the process. Rachelle, I love you and am grateful for the comfort and grace you have shown me. Lastly, I thank God for blessing me and carrying me through so much during my graduate school years.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

1.0 Introduction

Fresh water is important to many aspects of aquatic and terrestrial life: food, shelter, oxygen, protection, temperature management, and hydration. Problems arise from the limited supply of fresh water available for an ever-increasing number of uses. Managing this limited resource is vital given the growing demand from industry, agriculture, municipalities, and recreation. Also, managers must consider natural ecosystems under stress from these anthropogenic uses (e.g., grazing and mining). The effects of these anthropogenic uses on the natural ecosystems are amplified by the increasing pace of climate change (e.g., Panagoulia and Dimou, 1996; Lettenmaier et al., 1999; Arnell and Liu, 2001; Snyder et al., 2002; Bower et al., 2004; Sophocleous, 2004; Barnett et al., 2005; Hatch, et al., 2006). There have been declining levels of water availability in many streams and aquifers, especially in the summer months, throughout the western United States (Winter et al., 1998; Sophocleous, 2000; Bachman et al., 2005; Hatch et al., 2006). With regards to natural ecosystems, the interaction between ground water and surface water is especially important for riparian systems to stabilize temperatures because they promote areas of increased biological activity. To appropriately manage the riparian systems it is vital to understand and quantify these interaction zones. Therefore, increasing our knowledge about the complexities and dynamics found in the fresh water supply, specifically between surface and ground water sources, is critical for improving our management strategies.

Ground water is water that has passed through the earth's subsurface and arrived at the water table as recharge and surface water is water on the earth's surface generally in the form of ponds, lakes, rivers, and streams (Dingman, 2002). While these have traditionally been managed as separate entities they are in reality one common source. An important aspect in surface-to-ground water interaction is that a change in the quantity of surface water will relate to a change in the water's source. In riparian systems, this relates to precipitation which percolates through the soil within the watershed and becomes ground water. The ground water can be identified and quantified if it flows into a river. Quantification of ground water flows will provide further understanding of spatial and temporal patterns of the interactions between surface and ground water. (Constantz, 1998; Kalbus et al., 2006b).

One limiting issue in understanding the dynamic nature of streams in the past was locating ground water inflows. Hydrologists have shown that stream temperatures can be used to better understand the hydrologic dynamics within a riverine system (Atwell et al., 1971; Ingebritsen et al, 1992; Constantz et al., 1994; Hondzo and Stefan, 1994; Johnson and Jones, 2000; Conant, 2004; Selker et al., 2006a; Selker et al., 2006b). Inflows can be located through temperature measurements that are continuous in time and in distance, however past technology could not give sufficiently high resolution readings over space and time to achieve this. Over the past decade, Distributed Temperature Sensing (DTS) has been developed and applied in a new way, identifying ground water inflows. The DTS system uses fiber optic technology to measure temperatures along the entire fiber. The temperature measurement is made by passing a laser's light through the fiber optic; the light from the laser passes through the glass and is scattered back to a sensor that counts returning photons. These photons return at the initial wavelength and, due to Raman scattering, wavelengths just above and just below this value. The measurement distance along the fiber optic cable is determined from the time of arrival of the back scattered light at the receiver. The intensity of the shorter returning wavelength is highly dependent on the temperature, and is called anti-Stokes. To improve accuracy, measurements are averaged spatially and temporally to increase the number of photons counted. The most common applications of DTS were for pipeline monitoring, oil well monitoring, power cable and fire detection systems (Grattan and Meggitt, 2000).

The possibility of applying DTS technology in the natural sciences has created much interest from hydrologists, ecological scientists, and geologists. This technology has been used in previous experiments (Selker et al., 2006b; and Westhoff et al., 2007) in headwater streams to identify ground water inflow locations. Although Selker et al. (2006b) and Westhoff et al. (2007) used DTS to measure stream temperature to quantify lateral inflow; this was not the first time temperature had been used for this purpose. Temperature is a proven way to quantify gains and losses to streams, either through measurement of stream temperature or the bed material (Stallman, 1965; Lapham, 1989; Silliman et al., 1995; Constantz, 1998; Constantz et al., 2003; Becker et al., 2004; Niswonger et al., 2005). Past temperature methods were based on point measurements. A DTS system has the ability to have temporal resolution from seconds to months. Also, these same temperature measurements can be taken at thousands of locations along the fiber optic cable. These measurements can be done either discretely or on an averaged basis. The new quantity of temperature data available through the DTS technology makes it easier to locate multiple cool water inflows to a river.

The objective of this research is to improve upon locating discrete cool water inflows to the Walla Walla River near Milton Freewater, Oregon through the use of a DTS system. These cooling inflows can then be separated between ground water inflows and hyporheic exchange sites (locations where surface water enters the streambed and re-emerges down gradient). The ground water inflows can be quantified from the temperature measurements and surface water flows. Also, the depth of hyporheic exchange can be quantified by calculating the volumetric heat capacity of the hyporheic exchange from an energy budget. This research also examines the possible relationship between these cool water inflows and the locations trout and salmon may reside in during summertime peak temperatures. The fish locations will be taken from a Fish and Wildlife survey that was completed at the study reach while the instrumentation was in place (between July 30th and August 24th, 2007).

2.0 Literature Review

Ground water to surface water interaction has been an area under critical review. This section of the thesis will give an overview of the cooling processes found in surface waters, how temperature can be used as a tool to analyze these processes, some of the ecological impacts of temperature, and how the DTS system can be used to improve upon the current hydrologic principals for ground water to surface water interaction.

Only recently have water managers and the legal system begun to look upon ground water and surface water as a single interconnected source and managed them as such (Harvey and Fuller, 1998; Winter et al., 1998). For the most part they have been managed as two distinct sources. With increasing water demands however, incorporating the interplay between these water supplies in our calculations has been essential for land managers (Stonestrom and Constantz, 2003). Not only is ground water a necessary component for aquatic ecosystems, it has become important politically. Water rights disputes between ground water and surface water users are increasingly common. Despite the legal distinction, they are, in fact, drawing from a common pool of water. Methods to account for surface water diversions, ground water pumping, and return flows are therefore necessary (Harvey and Fuller, 1998).

The contribution of ground water to surface water has been well established. Field work and data analysis have shown that ground water can make up a large percentage of the surface water budget (Winter, 1978, 1981, 1983, 1986). One of the most difficult tasks for computing the water budget for surface waters is the field identification of ground water upwelling sites (Lee and Hynes, 1977; Lee, 1985). Silliman and Booth (1993) made a significant methodological contribution to quantifying ground water inflows through temperature measurements of the streambed and the surface water. In the past, for hydrologists to locate ground water to surface water interface and quantify ground water discharge to surface water, extensive arrays of boreholes and piezometers were used (Winter, 1986; Kenoyer and Anderson, 1989). Past monitoring was completed through a multitude of methods. Hydrologists would install heat flow meters (Kerfoot, 1987; Ballard, 1996) and complete hydraulic testing with minipiezometers (Lee and Cherry, 1978) and seepage meters (Lee and Cherry, 1978; Lee and Hynes, 1977; Carr and Winter, 1980; Shaw and Prepas, 1990; Shaw et al., 1990; Avery, 1994; Landon et al., 2001; Paulsen et al., 2001). To further understand the ground water component, hydrologists model vertical streambed temperature profiles (Lapham, 1989; Silliman et al., 1995; Constantz and Thomas, 1996; Constantz, 1998; Bartolino and Niswonger, 1999; Fryar et al., 2000) and perform tracer tests (Lee et al., 1980; Harvey and Bencala, 1993; Meigs and Bahr, 1995). These monitoring systems are intensive and expensive to employ, may alter the natural flow in the stream, and are unable to detect small-scale spatial exchanges through the streambed (Conant, 2004).

A more recent development in locating ground water inflows to surface water has been through remote sensing. For example, remote sensing using FLIR (Forward Looking InfraRed) is used to find discrete locations of inflows and has been well established through the work of Nelson et al. (1991), and Atwell et al. (1971). FLIR has high spatial resolution and can be sampled by airplane. FLIR images indicate the temperatures of the land and water surface, showing locations where ground water seepage near the stream banks occurs. One drawback of FLIR is that the image encompasses only a snapshot in time. Distinctions between ground water and surface water temperatures are controlled by weather in diurnal variations, meaning during certain times of year some sources may be missed. Furthermore, FLIR does not penetrate the water column; cold water is denser and sinks, so groundwater upwelling locations may not be visible. Finally, FLIR does not give insight into the ground water exchange dynamics that time series data would (Silliman and Booth, 1993).

Temperature can be measured through other methods besides FLIR imaging to find ground water fluxes into the surface water systems (Stonestrom and Constantz, 2003). Building on early work by Bredehoeft and Papadopolous (1965) and Stallman (1965), temperature profiles have been successfully used in basins to estimate ground water recharge and discharge rates (Cartwright, 1970; Taniguchi, 1993; Taniguchi, 1994; Ferguson et al., 2003; Anderson, 2005). Estimates of ground water discharge are most reliable when the difference between surface water and ground water temperatures are at a maximum. At this point, there is the largest difference in temperature and any variance between the true temperature and the measured temperature will less significantly affect the computed flux. At sites of focused ground water inflows, there are abrupt changes in longitudinal temperature measurements. These ground water inflow sites are more stable than the surface water, which is not directly influenced by the ground water inflows because ground water dampens the extremes found in the surface water alone (Stonestrom and Constantz, 2003; Conant, 2004; Lowry et al., 2007). The temperature differences between the surface and ground water inflows may be observed by a shift in the surface water temperature when compared to the trend in the longitudinal profile of the surface water temperatures for a particular reach (Selker et al., 2006b).

2.1 Temperature and the Energy Budget

To use temperature to find ground water inflows and to differentiate this flow from hyporhiec exchange, it is necessary to understand the processes that give rise to a river's temperature. Stream temperature is influenced by many processes; solar radiation, air temperature, wind speed, shade, relative humidity, percent shade, aspect, ground temperature, precipitation, surface water inflows, and hyporheic exchanges. Other sources of energy for stream temperature include conduction of temperature to the stream substrate (Crittenden, 1978; Hondzo and Stefan, 1994; Evans et al., 1995; Johnson and Jones, 2000), evaporation and sensible heat exchange with the atmosphere (Sinokrat and Stefan, 1993; Webb and Zhang, 1997; Johnson and Jones, 2000), and energy contributed by advection from ground water (Ingebritsen et al., 1992; Sinokrat and Stefan, 1993; Webb and Zhang, 1997; Constantz, 1998; Johnson and Jones, 2000).

The three major processes that contribute to peak river heat reduction are shade, ground water inflows, and hyporheic exchange. Solar radiation on the water surface is the major input of thermal energy to most streams (Beschta et al., 1987; Sinokrat and Stefan, 1993; Webb and Zhang, 1997; Johnson and Jones, 2000).

Shading is known for blocking solar radiation, thus reducing the stream's heat during the day when the solar radiation would be expected to effectively warm the surface water (Davies and Nelson 1994; Hostetler 1991, Li et al., 1994, Naiman et al., 1992; Poole and Berman, 2001). Ground water inputs provide continuous summer cooling by adding water to the stream at distinct locations at the annual average air temperature (here only summer time is considered as this is when the cable was deployed) (Westhoff et al., 2007). Hyporheic exchange averages in time the river temperature, cooling mid-day peak temperature, and increasing nighttime low temperature. This temperature modification occurs due to the increased time water is held at the location of hyporheic exchange (Lee, 1985; Nelson, 1991; Silliman and Booth, 1992; Stonestrom and Constantz, 2003). These three processes of river heat reduction will be further considered in up coming sections of this thesis.

Through analysis of the temperature data we hoped to quantify ground water inflows and hyporheic exchange in the river, both of which could provide cold water refugia for fish. These refugia are expected to be found through the longitudinal temperature profiles acquired by the DTS. If the fiber optic cable goes through an unmixed zone of cool water, it is expected the cable will have a cooler signature until the cool water inflow thoroughly mixes with the surface water. The temperature offset may not differ between a ground water input and hyporheic exchange, both cooling the river during the heat of the day, at a single snap shot in time. The large difference between ground water and hyporheic exchange flows will be witnessed during the night, as ground water carries the average yearly air temperature and the hyporheic exchange will carry a lagged temperature signature from the river earlier in the day. It is anticipated that the return flow from the hyporheic exchange will show an increase in temperature during the night and a decrease during the day.

Hyporheic exchange is stream water that enters riparian sediment and re-emerges further downstream, it is a process that creates surface water refugia but at a much smaller temporal and spatial scale than ground water exchange (Naiman and Bilby, 1998). Hyporheic exchange is pressure driven (Thibodeaux and Boyle, 1987; Savant et al., 1987; Stanford and Ward, 1988; Triska et al., 1989; Williams, 1989;

Hendricks and White, 1991; White, 1993; Hutchinson and Webster, 1998; Wondzell and Swanson, 1999; Stonestrom and Constantz, 2003; Conant, B., Jr, 2004) and is caused by pool-to-riffle sequences, slope changes, and obstacles found in the stream bed, such as a log jam. Hyporheic exchange is an active area in current hydrologic research and is poorly understood due to the dynamic space and time nature and difficulty of measurement. (Larkin and Sharp, 1992; and Harvey and Bencala, 1993) The increased attention to hyporheic exchange has shown that it is present in most rivers (Boulton et al., 1998; Naiman et al., 1998; Winter et al., 1998). Water in the hyporheic exchange locations can range from 100% river water to a mixture dominated by ground water (Hinkle et al., 2001). The work here will concentrate on the thermal affects that this zone may have on surface water bodies and the possible quantification of such affects.

Hyporheic exchange time lag is determined by two components; the tortuous path the water is required to take and the heat capacity of the combined water and bed material. Hyporheic water will have the average temperature for the time duration it was flowing through the porous media of the substrate and will be dampened due to the heat capacity of the gravel and water it has flowed through (see Figure 2.1 for examples of hyporheic exchange). For example, if the surface water enters the substrate and later re-enters the river, it will carry the temperature the average surface water had for the same time duration the water was in the subsurface. The re-entering water would also have a decrease in temperature due to the lack of solar radiation input for the duration it flowed through the bed material and would have an additional drop in temperature due to the volumetric heat capacity in the hyporheic exchange zone versus that of the water alone.

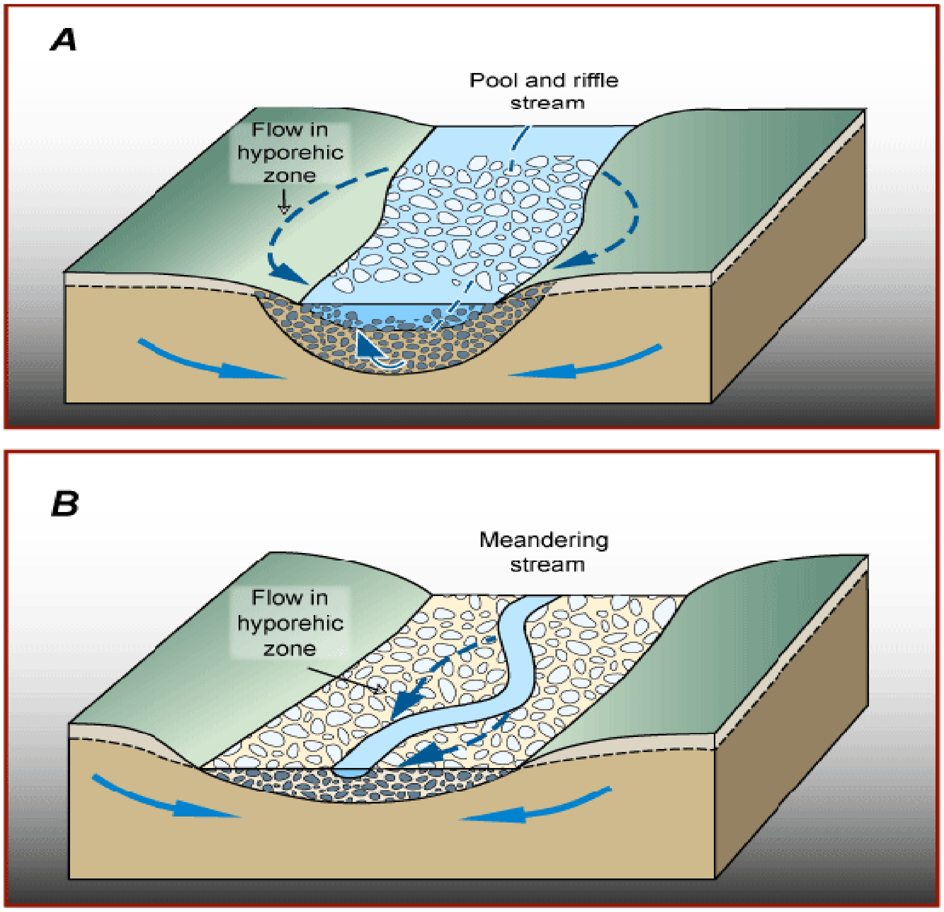

Figure 2.1 Surface water-ground water interaction in hyporheic exchange. With (a) a pool and riffle sequence and (b) with stream meanders (Winter et al., 1998).

When considering a cooled section of stream due to hyporheic exchange it is important to define the hyporheic exchange by residence time. Residence time must be used to distinguish between a ground water inflow and something more closely related to hyporheic exchange if considering DTS temperature data. For this research the residence time has been approximated to be 6 hours in order to simplify calculations for differentiating the daily lag in the temperature measurement through the hyporheic exchange site. To distinguish between the ground water flow and the hyporheic flow from continuous temperature data, you need only average together multiple weeks of data. If the cold water source is in fact ground water, then once averaged, the temperature signature should remain. This is because ground water maintains the yearly average air temperature, which would be distinctly lower than the average mid-summer stream temperature. At a location of ground water inflow the surface water should be cooler for nighttime, daytime, and for the average water temperature, during warm summer months. Hyporheic exchange, on the other hand, would cool the peak daytime river temperatures, but heat these same locations during the low nighttime river temperatures of summer. Rather than providing net cooling, hyporheic exchange simply moderates daily temperature extremes.

2.2 Tracers

The previous section discussed that the subsurface is important for stabilizing surface water temperature and recharging surface waters. One way to gain insight into the interactions between surface and subsurface water systems is through the use of tracers. This approach can be particularly useful for understanding flow patterns and the timing of subsurface waters (Flury, and Wai, 2003). Tracers have been proven useful for illuminating transport and transformation within subsurface flow systems. Use of tracers can improve knowledge of subsurface flows, giving new insight to the hydrological cycle; identifying subsurface flow connections, velocities, and dispersion are all common uses of tracers (Flury and Wai, 2003).

Tracers are chemicals, biological masses, isotopes, or anything else that can be detected at different points along the hydrologic cycle. Tracers used in hydrologic systems come in two main categories, added and natural tracers. Added tracers are artificially incorporated in known quantities at some point in the hydrologic cycle and then are detected at another point along the cycle. Usually there are very low to no background concentrations of these tracers so everything detected will come from the added source. Natural tracers include chemicals, temperature, or isotopes that are found in the natural setting and can be detected at different amounts throughout the hydrologic cycle (Bencala et al., 1987).

Much research has been completed using added chemical tracers to find ground water patterns and flows to surface waters. These studies did not quantify ground water inflows based on the tracer information. Chemical tracers for ground water applications work well if the concentration of the chemical in the ground water is uniform and significantly different than the surface water (Cook et al., 2003). If the concentration difference from ground water to surface water is not detectible, or if measuring the chemical tracer is costly, another method should be considered.

Temperature may be used as a tracer (Kobayashi, 1985; Shanley and Peters, 1988; Kobayashi et al., 1999). One study compared heat (as a natural tracer) to bromide (as an added tracer) (Constantz et al., 2003). Employing the heat and solute ground water transport model VS2DH (Healy and Ronan, 1996), showed that both bromide and natural temperature differences in the stream could be used to find ground water and surface water exchange sites. Cox et al. (2007) compared temperature with selected commonly measured water quality parameters and also found that temperature could be used as an in-stream tracer to evaluate spatial and temporal patterns of surface water and ground water exchange. Temperature as a natural tracer has an added benefit of differentiating between temporal variations in ground water inflows.

Temperature used as a hydrologic tracer has several advantages. The signal arrives naturally and will continue to arrive as long as the ground water and surface water are connected. Measurement of temperature is robust and relatively inexpensive. It also has the additional advantage of not contaminating the local environment with introduced chemicals (Stonestrom and Constantz, 2003; Kalbus et al., 2006a). One disadvantage is that the interactions cannot be seen through temperature measurements if the surface water and ground water are near the same temperature. The importance of using natural tracers, such as temperature, over added tracers to find cool water inflows rivers can now be further understood.

2.3 Distributed Temperature Sensing

Using temperature as a tracer is made robust with the application of the DTS technology. The DTS system sends light down the fiber optic cable and as the light interacts with the glass in the fiber optic cable a portion is scattered, with some returning toward the source. A portion of this scattered light is at the original laser energy and another portion of the light is adsorbed and reemitted at wavelengths just above (“Stokes”) and just below (“anti-Stokes”) the original wavelength due to Raman scattering (Wait and Newson, 1995; Selker et al., 2006a). The back-scattered light has important properties that reflect the temperature of the glass at the scattering location. Specifically, anti-Stokes intensity is related exponentially to the temperature of the fiber, while the Stokes is much less temperature dependent. Thus, the temperature is linearly related to the log of the ratio of the Stokes and anti-Stokes intensities (Selker et al., 2006b). The distance for each recorded temperature measurement is based on the speed of light and the time it took for the light signal to return to the receiver. By the Central Limit Theorem the precision of the temperature measurements will increase with the square root of the integration interval, so for a very precise temperature reading, a longer integration time is required in order to have more photons counted by the receiver. Also, a more powerful laser can give more photons to count, again increasing the precision. (Selker, et al., 2006b)

To deploy a DTS system it is necessary to calibrate the system to the cable planned for use prior to field installment (via the Agilent Configuration Wizard) and it may be necessary to calibrate the temperature measurements post-collection (with at least two known temperatures along the cable). To calibrate the DTS to the specific cable the temperature offset, gain (a parameter to take into account the slope), and attenuation ratio of the fiber are needed. To find the offset, gain, and attenuation ratio two known temperatures are necessary along the cable. This can be done with either two temperature baths or running the DTS in the double-ended configuration. The ongoing auto-calibration present in a double-ended measurement further simplifies the calibration process and improves measurement accuracy by continuously correcting the attenuation ratio (Tufillaro et al., 2007). The offset and gain of the calibration should not change for the cable after the initial calibration, but the attenuation ratio may need re-calibrating if the DTS is not run in the double-ended configuration. The attenuation ratio can change for the cable if it makes many bends, or if the layout of the cable is changed. Calibration is very important for an accurate temperature reading. However, if interested in precise temperature changes and do not care about the temperature itself the manufacturer's calibration of the DTS system is reliable. The calibration of the DTS from Agilent is typically precise on the order of 0.01°C.

There are several different types of DTS systems available. The DTS systems range in cost, power consumption, resolution, and durability. The Optimum DTS for a particular use depends on how the project characteristics correspond to these variables. This research project required a unit that had low energy consumption for remote use, durability for field deployment, and low cost. Resolution was of concern, but it was thought that all units would be adequate to meet the goals. In retrospect, more variables needed to be considered beyond the instrument itself, such as the loss of the fiber optic cable. Agilent's DTS (N4386A), which came to the market in May 2006, was selected. This system was designed for remote environmental applications. This DTS operates on less than 40 W at 12 V within an operating temperature range of 10 to 60°C (other systems operate from 85-150W at a max temperature of 40°C). Also, the Agilent DTS can report temperature every meter along the cable, but if more precise readings are desired the Agilent DTS can integrate over a longer distances of cable (Selker, et al., 2006a). The precision of the instrument doubles if the distance of integration is changed from 1 meter intervals to 1.5 meter intervals. The system consists of a computer with software installed for data retrieval and saving. The software creates ASCII files with temperatures, loss, the distances along the attached fiber optics cable, and the number of measurement points along the cable.

Before the DTS technology was available for environmental applications, temperature was taken through point measurements. One concern of point measurement methods is that the longitudinal resolution is low and there is a risk that some inflows may be missed (Kalbus et al., 2006b). The DTS system overcomes this by providing continuous temporal and longitudinal temperature measurements. The DTS will measure a temperature shift for incoming water at a different temperature than the stream temperature trend prior to the localized inflow (Selker et al., 2006b). This measurement may not be able to find the smallest inflows into large rivers, but it can show many of the significant flows that would occur over a reach and fall outside the standard deviation in the surface water temperature. When the temperature of an inflow is within the standard deviation of the DTS measurement of the river's temperature, the inflow will not be statistically different and not be able to differentiate from the noise found within the DTS measurements.

One concern with the use of fiber optic cable for temperature measurements was the time response upon a change in temperature. It has been shown that fiber optic cable has a fast temperature response through jacketing made of PVC and steel cable, found to be less than a 10 second response time from unpublished studies for a Brusteel fiber optic cable from Brugg.

If care is taken in calibration and high quality fiber optic cable is purchased, temperature resolution of 0.01°C and spatial resolution down to 0.5 m with temporal resolution down to 3 seconds along standard fiber optic communication cables with lengths of up to 30,000 m are all possible (depending on the DTS machine used, manufacturers and models vary) (Selker et al., 2006a; Moffett et al., 2007). There are tradeoffs between theses specifications; shorter integration distances and times will have higher uncertainty in the temperature measurements.

This technology has opened new possibilities for environmental sensing. The fiber is deployable in many different configurations, due to the flexibility of the cable allowing measurement in many new areas (measurement of an air shed or the snow through a net configuration, down a sinuous stream, or the creation of a high resolution pole through wrapping the fiber around a PVC pipe). Measurements that seemed impractical before seem manageable, such as taking thousands of measurements at points longitudinally down a river and collecting data from the network continuously for months. Using the DTS method for this research will give the needed measurements to separate the cool water inflows between ground water and hyporheic exchange.

2.4 Ground water to surface water interaction

One approach to quantify surface-to-ground water interactions is to monitor temperature variations in surface waters due to ground inflows (Lee, 1985; Nelson, 1991; Silliman and Booth, 1993). The use of temperature as a natural tracer has become increasingly common because it can be measured with relative ease in a channel to obtain high resolution temporal and spatial information. (Hatch, et. al., 2006; Constantz and Thomas, 1996; Selker et al, 2006b; Westhoff et al., 2007). Riverine systems are very dynamic and the use of time series temperature data can increase understanding of the changing sources of flow.

Temperature was used to identify the interaction between the surface water and ground water system by Rorabaugh (1956). He used temperature measurements to estimate the stream loses below the Ohio River, OH. Heat has been used as a tracer of surface water and ground water exchanges and to quantify these exchanges (Silliman and Booth, 1993; Silliman et al., 1995). Much of this previous research concentrated on areas of stream loss (Constantz et al., 2002). Analysis of temperature profiles has shown point measurement of ground water flow beneath streams. The temperature differences found on a diurnal and seasonal basis are partially a function of the different temperatures between the stream and near stream sediment (Rorabough, 1963; Stephens and Heermann, 1988; Constantz et al., 1994; Constantz and Zellweger, 1995; Constantz and Thomas, 1996). Through continuous surface water temperature measurements, areas of gain to a stream from ground water can be found (Selker et al., 2006b; Westhoff et al., 2007).

Fiber optic cable (Brusense, Brugg, Switzerland) was installed in the Maisbich, a ground water fed, first order stream in Luxembourg with a DTS (Sentinel DTS-LR, Sensornet, London, England) system. Surface water flux along the study reach was determined through DTS and flow measurements. The changes in temperature at points of ground water input allowed for accurate estimates of point-wise ground water inflows based on an energy balance coupled with a mass balance (Selker et al., 2006b).

As seen by Selker et al., (2006b) a loss in a stream can be assumed when either upstream flows are larger than downstream flows, or when the upstream and downstream flow readings are the same and ground water inflows are witnessed. It is difficult to find where these losses occur through longitudinal surface water temperature measurements. Through a distributed temperature sensing (DTS) system, the gains can be found through the longitudinal surface water temperature measurements and if discharge is not significantly different between upstream and downstream measurements we can conclude that there are some losing sections within this stream, as well as areas gaining. A loss, be it gradual or abrupt, only results in a gradual change of the temperature profile due to changes in warming and cooling patterns; it will reduce the volume and flow of the river which will give more solar radiation per volume of water in the same channel shape. Such losses might be quantified through a complete mass and energy balance for the stream; however, energy budgets of this precision are difficult in natural streams. To have the most distinct temperature difference, in order to estimate ground water inflows from surface flow measurements, data should be retrieved for times of low flow so that any increase in flow can be attributed to ground water inflow and not directly from precipitation (Kalbus et al., 2006b). In-stream flows measured at two points along a stream reach, accounting for stream diversions and tributary inflows first, can be used to determine if a stream is gaining or losing. If downstream flow is greater than upstream flow, the stream gains; if downstream flow is less than the upstream flow, the stream loses water to the aquifer (Riggs, 1972; Stonestrom and Constantz, 2003).

Exchange direction can be determined through stream bed sediment temperature measurements. In a gaining reach, the sediments will take on the ground water temperature, and therefore the sediments will have a stable temperature. On the other hand, losing reaches will take on the surface water temperature, which generally follow the diurnal daily temperature cycle (Winter et al., 1998; Stonestrom and Constantz, 2003; Kalbus et al., 2006a). For the purpose of this thesis, surface water temperature alone will be used to locate gaining portions of the study reach, based on a method that was established by Selker et al. (2006a), Selker et al. (2006b), and Westhoff et al. (2007). It is much more difficult to use only surface water temperatures to find the losing portions of a river, and stream temperature reduction is much more dependent on gaining cool water than on losing warmer water.

Since ground water temperature is generally stable throughout the year, the temperature difference can be interpolated between the ground water and the surface water to differentiate the ground water inflows from the surface water. During the warmest and coldest times of the year there will be the most dramatic temperature difference between the surface and ground water supplies (Stonestrom and Constantz, 2003; Conant, 2004), allowing for easier differentiation.

Through the use of the DTS system cool water inflows to the river can be located during summer months for the entire length of the study reach. An important byproduct of locating the temperature drops in the surface water is determining the cool water inflows. Fluxes usually are calculated for the ground water-to-surface water interface through an application of Darcy's law (Darcy, 1856) which states that water flux is a function of hydraulic gradient and hydraulic conductivity. A second method is based on a water budget; ground water contribution is computed in this method as the difference between the inflow and outflow. For the mixing zones or areas of hyporheic exchange either of the methods can be used (Kalbus et al., 2006b).

2.5 Ecological considerations

The temperature data gathered to estimate ground water and hyporheic exchange can be valuable to ecologists to identify ecosystem dynamics within a river. Temperature-dependent water quality and geochemical processes can be calculated based on the locations found through temperature measurements (Selker et al., 2006b). Also, identification of habitat and migration patterns based on temporal and thermal conditions (Torgersen et al., 1999; Selker et al., 2006b) can be employed to determine the extent of expected distribution of selected species.

Maintaining a specific temperature range in surface waters is vital for many different aquatic habitats. The cooling of summer time surface water occurs from subsurface water emerging to the surface. These locations are important because cold-water fish species have begun to decline in population due to physiological effects from warming waters. The river waters have warmed due to many anthropogenic causes. These anthropogenic causes include de-vegetation, re-chanalization, broader streams from lack of root systems and impacts of grazers, and disconnection of flood plains (Resh et al., 1988; Hornung and Reynolds, 1995). Warming to many surface waters has also been attributed to climate change (Rahel et al., 1996).

Due to the increase in temperature and the decrease in available water, the amount and location of surface and ground water exchange are increasingly important to identify for ecosystem considerations of temperature sensitive fish species. For example, anadromous salmon and many trout require specific temperature ranges to successfully develop, migrate, and spawn (Power, 1980; Baltz et al., 1987; Curry and Noakes, 1995; Curry et al., 1995; Halupka, 2000; Stonestrom and Constantz, 2003). To protect these cold-water species ways must be found to continue to keep our surface waters cool; locating cooling sources is a wise first step (Silliman and Booth, 1993). Stream temperature is also a critical parameter to other ecosystems within the stream. Temperature controls rates of metabolism, the number of aquatic insects, growth, decomposition, and solubility of gases, as well as many other processes and biotic interactions (Beitinger and Fitzpatrick, 1979; Beschta et al., 1987; Harvey et al., 1998; Johnson and Jones, 2000). Hyporheic exchange increases stream temperature regulation and nutrient cycling (Hendricks and White, 1991; Wood and Petts, 1999; Hatch et al., 2006), both of which are important for aquatic habitat (Power et al., 1999; Hayashi and Rosenberry, 2002; Alexander and Caissie, 2003; Hatch et al., 2006).

The Intergovernmental Panel on Climate Change (IPCC) in 2001 employed several Global Climate Models and expects a 1 to 7 °C increase in mean global temperature within the next 100 years. This may have a devastating impact on cold water fish (Ficke et al., 2007). Many rivers and streams in Oregon have been determined to be in violation of the Clean Water Act due to high temperatures by the Environmental Protection Agency (EPA) (DEQ, 2005). Trout and salmon populations in many of these systems are of concern because of the elevated temperatures and have experienced die off during warm summer periods. High water temperature has a significant influence on salmonid behavior and growth (Li et al., 1994). Several species of cold-water fish locate thermal refugia several degrees cooler than ambient water temperatures (Torgersen et al., 1999; Ebersole et al., 2003) during summer. Fish are known to move into cooler ground water springs for refuge from excessively warm stream temperatures (Power et al., 1999). Ground water discharge increases biological abundance, diversity, and biogeochemical cycling (McClain et al., 2003; Hunt, 2006; Lowry, 2007). Fish find these cool ground water sources not just for refuge but also because the flow between surface water and ground water creates habitat for species that are part of the food chain for these fish (Harvey et al., 1998).

When water temperatures are outside of a fish's survival range during the cold of winter or the heat of summer, ground water becomes a crucial component of river habitat. Ground water provides areas of warmer water inflow in the winter, and in the summer, ground water is important for maintaining discharge and moderating surface water temperatures. Learning more about these ground water distribution pathways is critical to developing plans to protect these species (Power et al., 1999).

Habitat suitable for rainbow trout (*Oncorhynchus mykiss)* is temperature dependent, with the lethal limit taken to be 25 °C (Hokanson et al., 1977; Jobling, 1981; Bjornn and Reiser, 1991; Matthews and Berg, 1997). There is a rich supply of literature on the importance of cool water refugia for salmonids during summer periods of high water temperatures (e.g., Gibson, 1966; Keller and Hofstra, 1983; Berman and Quinn, 1991; Matthews et al., 1994; Nielsen and Kiorboe, 1994). In a study by Matthews and Berg (1997), areas of stream temperatures which remained cool due to ground water seeps during summer months consistently had more trout than did areas with higher water temperatures. The Oregon Department of Environmental Quality (DEQ) has temperature TMDLs (total maximum daily loads) for the Walla Walla River in Oregon (this study site) set to below 18 °C for salmonid and trout rearing from spring to early fall. Also, during spawning for these two species (January 1st to June 15th, 2007) 13 °C water is necessary. For Bull trout spawning, the temperature should be $\leq$ 12 °C. (DEQ, 2005)

Salmon and trout begin to experience serious effects at temperatures below their chronic lethal limits. Temperatures selected by these fish correlate with their optimal temperatures for growth, around 17 °C (Myrick and Cech, 2001). Increases in stream temperature below lethal levels have been linked to increased fish mortality of cold water fish (Brett, 1952; Beschta et al., 1988; McCullough, D., 1999), increased occurrence of disease (Becker and Fugihara, 1978), and increases in competition between species (Reeves et al., 1987; Johnson and Jones, 2000). The trout and salmon species are the focus for this thesis because they are the species found within the Walla Walla River that most depend on cool temperatures for their life cycle. Thus, locating and understanding the cool water inflows is vital to further protect these two species. This research was carried out in the northwestern United States where salmon and trout are important to commercial fishing, recreation, and are good indicator species for the current condition of aquatic ecosystems (Cairns, 1974).

3.0 Materials, Methods, and Theory

3.1 Instrumentation

The primary instrument used in this project was the Agilent N4386A Distributed Temperature Sensor.

Table 3.1 Key specifications for the Agilent N4386A (Tufillaro et al., 2007)

Key specifications for Agilent N4386A DTS		Environment	
Distance Range	8 km	Operating Temperature Range	-10 to 60 C
Spatial Resolution (minimum)	1 m	Storage Temperature	-40 to 80 C
Temperature Resolution	0.01 K	Supply Voltage	10 to 30 V DC
Temperature Repeatability	0.1 K	Power	15 W at room temperature, 40 W maximum

Within the DTS housing a Fujitsu Stylistic ST5000 tablet PC was placed in order to run the DTS Configurator version 3.0 and for data saving. Two 1000m lengths of Kaiphone's Mini armored fiber optic cable. The cable was duplex, multi-mode, graded index, 50/125, armored (stainless steal wrapped), black jacketed in PE, and had aramid strength members. End connectors used to connect the cable to the DTS were APC e2000s. Where the two 1000m cables were connected and where the last cable doubled back, female/female e2000 adapters were used. The cable was tied into place along the river using 1/2 inch rebar stakes driven 1/3 of a meter into the streambed approximately every 75 meters. The fiber optic cable was held onto the rebar with zip ties. Aerial cable hangers were also used to secure the cable at three locations where the cable was purposefully out of the water.

Flow measurements were taken using cross-sectional data of the channel and by using a flow meter according to the "Standard Operating Procedure for Stream flow Measurement" (EPA, 2004) (completed by the Walla Walla Basin Watershed Council). Immediately prior to taking the cable out of the river two ice baths were placed along it for system calibration. One ice bath was placed near the DTS and one at the midway where the two cables were connected. Approximately 20 meters of cable were placed into each bath. A digital data logger thermometer (VWR model 61220-601) with a resolution of 0.001 °C and an accuracy of ± 0.05 °C was used to take temperature measurements along the cable and in the ice baths to field check the DTS temperature measurements. Digital photos of the site were taken at locations identified by a Garmin Geko 301 GPS. Meteorological data was downloaded from the LeFore ETo station (identification #TOACI1) south of the research location to check for DTS system errors (sudden jumps in temperature data). Data interpretation was done through the use of Microsoft Excel 2003 and MatLab R2007a.

A snorkel fish survey conducted by the Fish and Wildlife Service parallel to the DTS installation was completed on 8/16/2007 by Courtney Newlon, Marshall Barrows, and Ryan Koch of the USFWS, Columbia River Fisheries Program Office, Vancouver, WA. The survey started at the downstream end of cable and ended at Mauer Lane.

3.2 Site

Milton Freewater, Oregon, USA is within the Walla Walla Watershed, which spans Oregon and Washington (see Figure 3.1a and 3.1b). The southern end of the site was at Mauer lane just north of the city of Milton Freewater. Measurements continued north 2 km along the river's thalweg ending prior to a well-known swimming hole, to reduce the likelihood of tampering and vandalism, approximately 500m south of the Washington State border. (Figure 3.2). The DTS was placed at the end of Mauer Lane (Figure 3.2). This location was chosen based on expected ground water emergences as advised by project collaborator Bob Bower from the Walla Walla Basin Watershed Council and the availability of line power.

The Walla Walla River is habitat to threatened and endangered species such as the Columbia River Salmon, Steelhead Trout, and Bull Trout. The upper geology of the study area consists of a shallow gravel aquifer (approximately 20 to 30m) on top of a deep fractured basalt rock aquifer. The Walla Walla watershed is a 1,758 square mile area with a majority found in the southeast corner of Washington (figure 3.1a). The headwaters originate in the Blue Mountains of Oregon at the eastern boundary of the watershed. The climate is characterized by hot, arid summers and cold, wet winters. Summer temperatures in the basin soar frequently exceed 38° C (100° F) and fall below freezing in the winter. This watershed receives between 12 and 16 inches of annual precipitation (PRISM, 2002), most of which is contained in the annual snow pack (Baldwin and Stohr, 2007). The near-stream vegetation found at this site consists of grasses, blackberry vines, willows, alders and other riparian species (Volkman, 2003). The majority of the water drafted from this river is used for agriculture, some of which eventually returns to the river. Most of the properties surrounding the study reach were either riparian lands or agricultural fields.

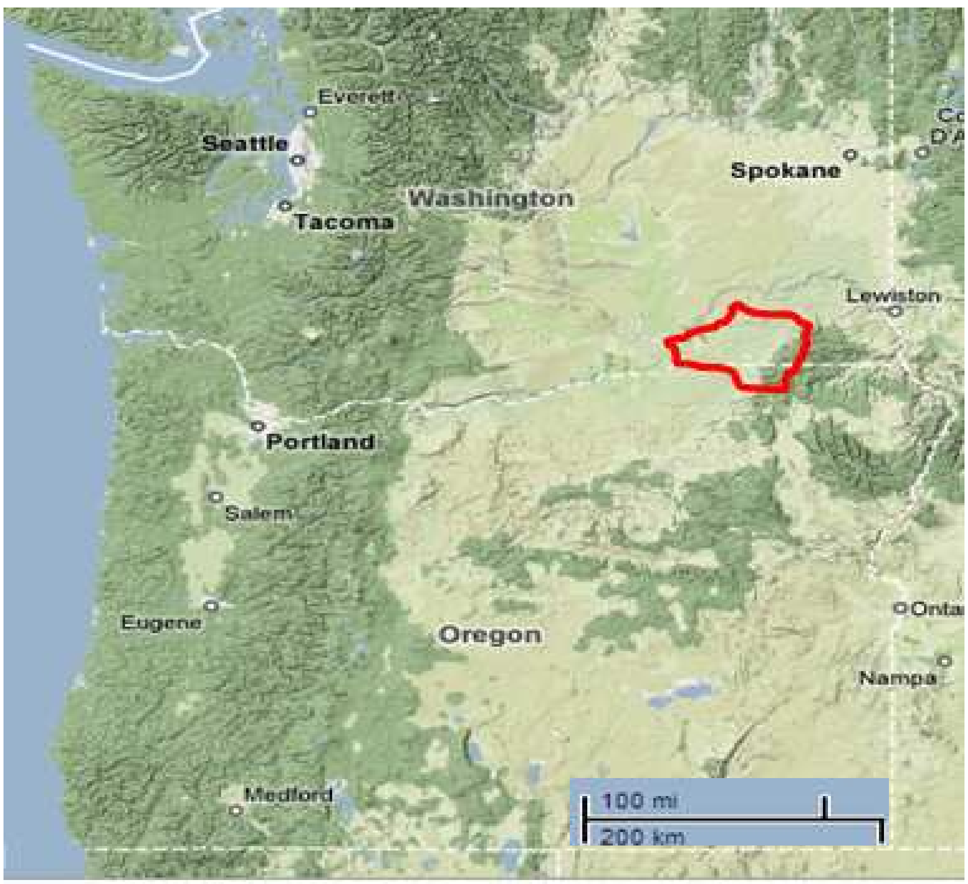

Figure 3.1a Map of the general research location, circle encompasses the Walla Walla Watershed which crosses the Oregon/Washington Border. (Google, 2008)

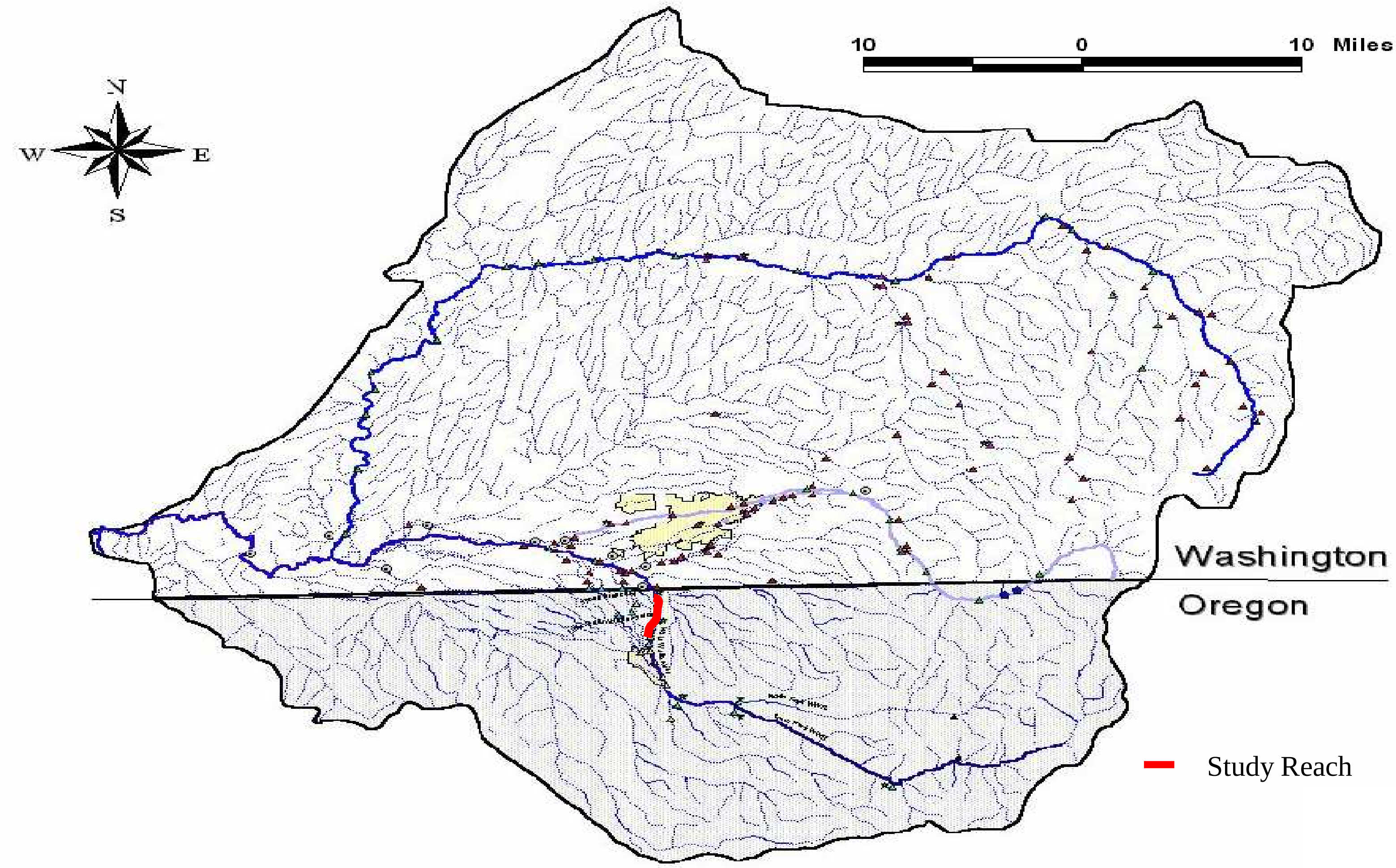

Figure 3.1b Map of study reach location on the Walla Walla River within the Walla Walla Watershed (www.wallawallawatershed.org)

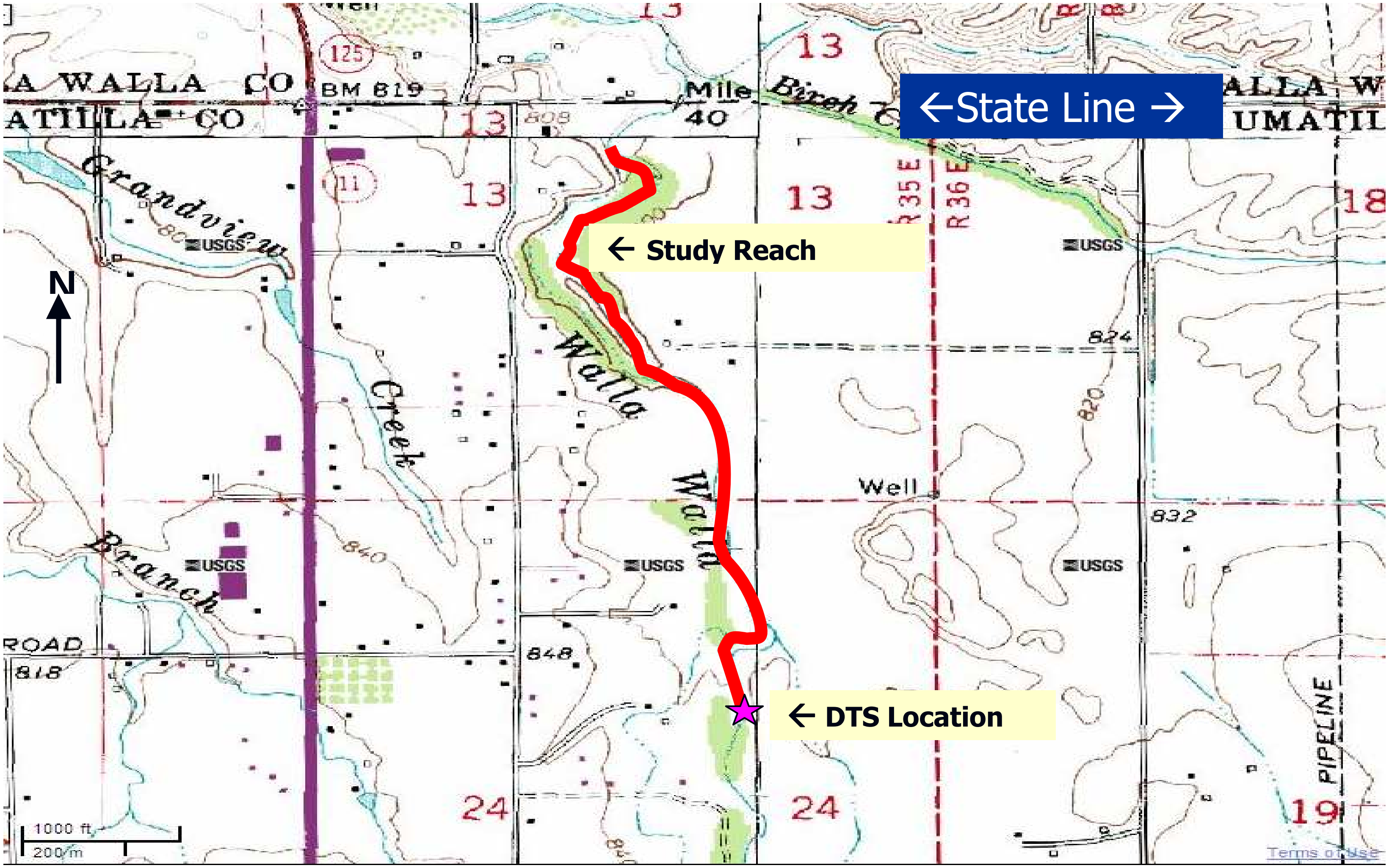

Figure 3.2 Detailed Milton-Freewater quadrangle, Oregon – Umatilla Co., 7.5 minute series, topographic map of study reach on Walla Walla River (contour interval 20ft. National Geodetic Vertical Datum of 1929). (USGS)

3.3 Objectives and Methods

The objectives of this research is to further understand ground water and hyporheic exchange flows as revealed by accurate temperature readings from the DTS for longitudinal temperatures of the Walla Walla River. These inflows were separated between ground water and hyporheic exchange. Then the inflows were compared to fish distribution along the study reach. For this particular project it was most important to get accurate temperature differences in space and time to identify and quantify cool water inflows. This was completed by taking measurements of the river every hour for a three-week duration (July 30th to August 24th, 2007).

The methodology for the research in this thesis can be split into two groups; those methods from before data collection and those after data collection. Prior to data collection consisted of cable selection and cable placement in the thalweg of the river. After the data collection included the initial data cleaning by calibrating the system, smoothing the diurnal temperature, and temperature measurement noise reduction. The analysis of the data was completed by comparing the average daytime and nighttime temperatures through a correlation coefficient. Once completed ground water inflow was quantified and an estimated depth of hyporheic exchange was calculated.

The data was calibrated and processed to locate possible errors in the data; some of the time steps from the DTS were flawed. After the initial data processing the data set was used to find and differentiate areas of cooling within the stream. Finally, the cooled river sections were compared with the US Fish and Wildlife Service (USFWS) snorkel fish survey to see if patterns emerged between fish location during summer daytime temperature and cool water inflows.

3.3.1 Initial data processing

The temperature data was collected through double-ended measurements, which was possible because the fiber optic cable looped back to the Agilent DTS. Double-ended measurements were a new capability for the Agilent DTS as of July 2007. This function passes light one direction through the fiber optic cable then passes light the opposite direction through the cable, allowing for automatic correct for the attenuation ratio (loss of optical energy that may create a false temperature change) and the gain (slope). Double-ended measurements should be used when attenuation ratio and gain may be inaccurate due to poor calibration or multiple sharp bends in the fiber optic cable.

DTS data from fiber optic cables generally require post-collection calibration to be corrected for temperature gain and offset in the measurement. In the case of double-ended measurements, only offset must be found. The data was collected on two cables, resulting in two unique offsets, one for each cable. First estimates for these offsets can be obtained prior to data collection by using the Calibration Wizard found in the Agilent DTS Configurator software package, but generally, these values must be adjusted after returning from the field to precisely address effects of connectors and other non-calibrated elements.

For this study, data acquisition was completed through the DTS Configurator software version 3.0 available for the Agilent DTS system. The data was then imported to MATLAB, a powerful numerical computer program that allows for easy manipulation of matrices. The DTS temperature measurements were double-checked with a hand measurement of the ice bath with the hand-held precision temperature probe (Figure 3.4). An ice or water bath that slowly changes temperature and a second temperature measuring device are important to validate the DTS temperature measurements. Redundant temperature data may be needed if calibration of the fiber optic cable was not properly completed prior to data acquisition from the DTS system. For this research the offset correction made use of a 0°C known temperature provided by two ice baths with 20m of submerged cable in each (Figure 3.3). The temperature measurements from the ice bath were averaged together for the 20 meter length and for one hour in time. The averaged ice bath temperature was then compared with the ice bath temperature taken with the hand-held temperature probe. The upstream ice bath was found to be -0.006° C and the downstream bath to be 0.012° C. The difference between these two temperatures was found and used for the temperature offset of the entire cable.

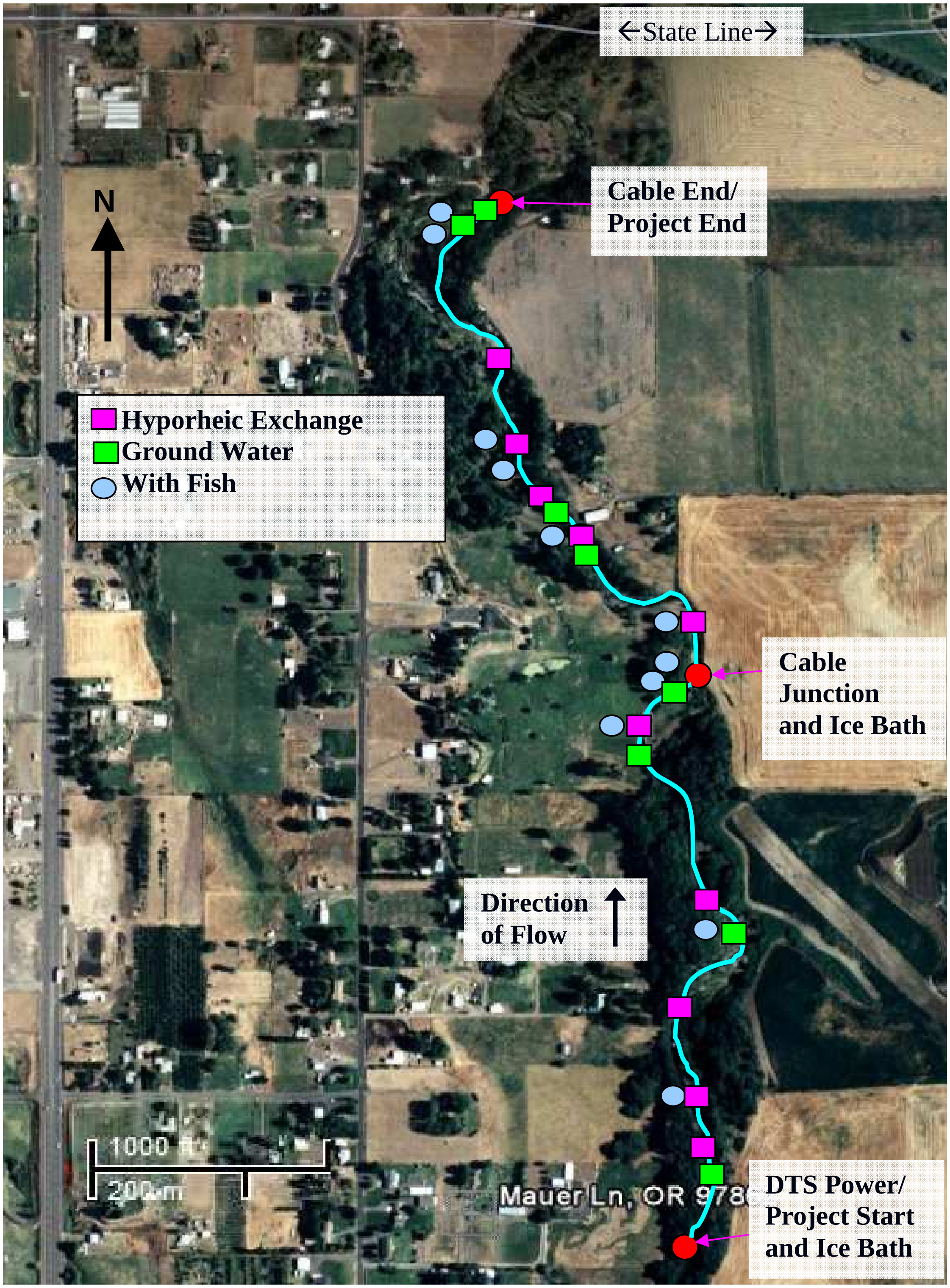

Figure 3.3 Image of study site including the cable junction, start and end of project, ground water and hyporheic exchange sites, and refugia sites with fish present. (Image from Google Earth, 26 June 2008)

The longitudinal temperature profiles were then plotted and viewed in a movie setting through MATLAB as multiple traces viewed through time. This movie making process (not presented in this thesis) is used to view stream dynamics through time, possibly locating temperature patterns for additional evaluation or possible erroneous data.

For this study a true or absolute temperature reading (accuracy) is not as important for final data interpretation as the ability to quantify spatial and temporal changes in temperature (precision). Since the DTS was run in double-ended mode the software adjusts for an incorrect slope of the trace automatically, giving precise measurements of temperature change. If a single temperature measurement is taken at a specific location on the fiber optic cable, then this location is heated and an additional temperature measurement is taken, the difference between the two temperatures is an attribute of the DTS itself and cannot be adjusted through calibration. The DTS has a high precision when looking at the temperature difference between two temperatures as long as the slope, and to a lesser amount, the gain of the trace is correct.

3.3.2 Energy Budget Calculations

For this thesis we used the water budget (based on the conservation of mass) in conjunction with the conservation of energy to quantify the ground water inflows to the surface water. First presented are simple quantifiable methods to see possible effects of different cooling components. The different components that are considered in this research are: how shade may block the solar radiation from increasing stream temperatures, the effect ground water will have on cooling a stream, and the effect the hyporheic exchange will have on cooling a stream.

Shade is a surface process that effects stream temperature. Shading blocks short-wave solar radiation from adding energy to the stream. This blocked solar radiation would have otherwise increased stream temperature. This form of cooling is actually better stated as heat blockage than an actual cooling influence. Shade does

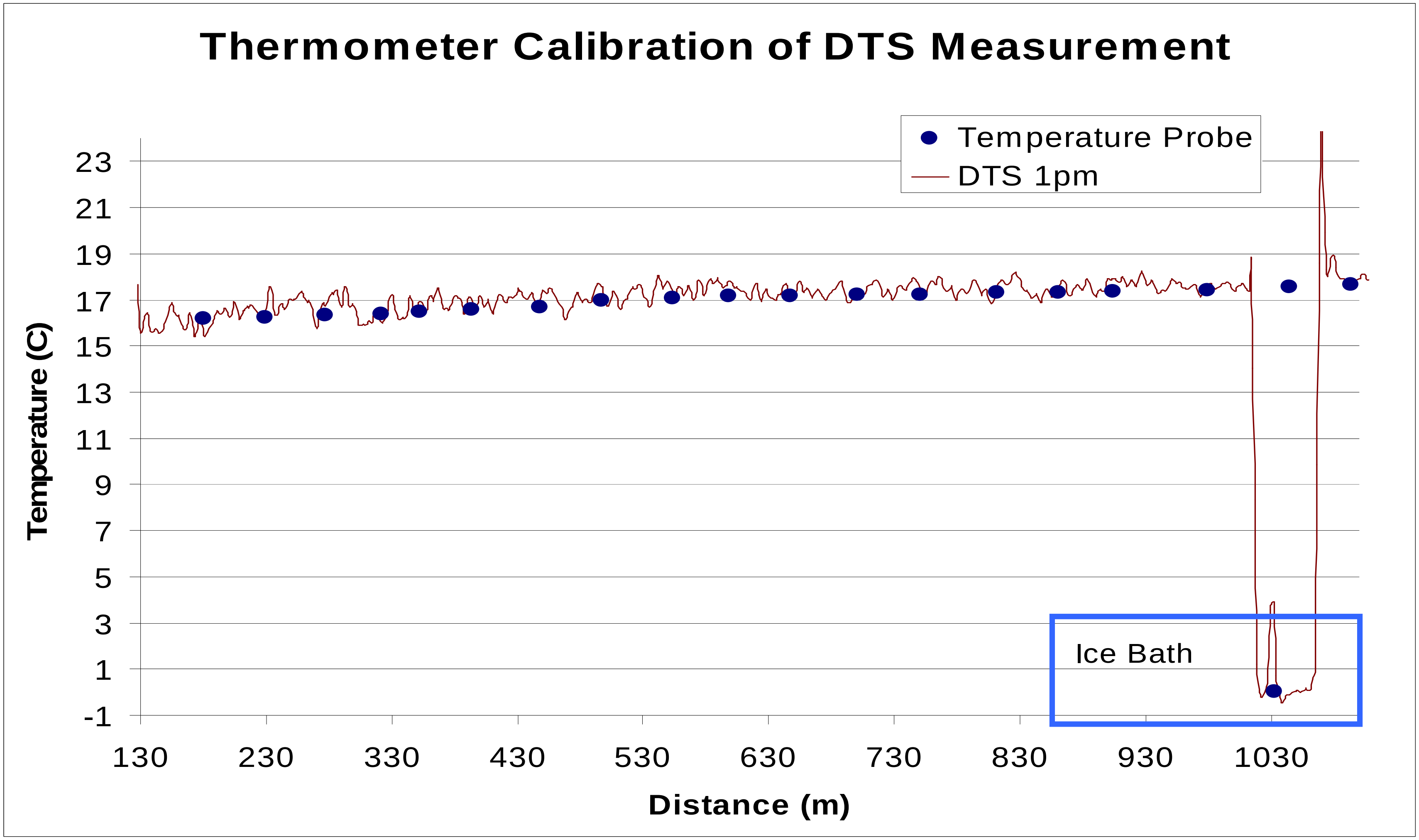

Figure 3.4 High precision temperature probe measurements compared to DTS measurements for 1000m of the study reach at 1pm.

not universally reduce the temperature, but rather diminishes the rate of energy input during the daytime.

For this study it is important to quantify the effects of solar radiation upon the water surface. Once the calculations are completed shading effects on a localized scale can be determined (at our study reach in particular). To find the change in temperature expected for a 50 meter shaded section of the river, it is necessary to know the travel time of the water for the 50 meters, the solar energy expected for the particular setting (location, time of year, and time of day), and the channel width for the 50 meter shaded section of river. The total energy absorbed based on the density, volume, and heat capacity of water for the 50 meter section can then be found and the expected temperature change determined. Shading will be included in the calculations, but will not be located through DTS measurements.

Cold water refugia have been defined as portions of surface water where the water temperature is colder than the daily maximum temperature of the adjacent well-mixed flow of water. These refugia provide local cold water within the surface waters of warm streams, affording potential thermal refuge for cold water fishes during periods of heat stress for energy conservation (Berman and Quinn, 1991; DEQ, 2006; Ebersole et. al., 2003). Examples of common areas of cold water refugia are: water entering from subsurface flow, input from springs, hill slope seeps, and tributaries which have not mixed with surface stream flow. Both ground water upwelling and hyporheic exchange can provide cold water refugia. These locations are often found near islands, pools, and rock out-croppings along stream banks (Berman and Quinn, 1991).

This study concentrates on detection of cool water inflows using a DTS system. The goal is to calculate the effect each ground water inflow and hyporheic exchange will have on the temperature in the study reach on the Walla Walla River. This is completed through energy budget calculations based on the computed flows expected at a ground water site and the calculated volumetric heat capacity at a site of hyporheic exchange.

The correlation coefficient was used to locate cool water inflows and to distinguish them between ground water and hyporheic exchange water. The absolute value of the correlation coefficient of 1.0 is a perfect correlation and anything greater than 0.8 is well correlated. If a 0.7 correlation coefficient was chosen, sites other than refugia would be included; these sites may include deep pools of water and sites of high noise in the data. If a 0.9 correlation was used we would not include many of the refugia sites because they are naturally variable and only sites where the cable is out of the water or connector sites will be found. This correlation coefficient was completed for running 15 meter sections of the temperature dataset that had been averaged for three meter lengths. Fifteen meter sections were used for the correlation coefficient because this length recorded distinguishable ground water inflow and hyporheic exchange sites at above a 0.8 correlation without including areas that were due to noise in the temperature measurements or possibly due to deep pools. The inflows that are cooler both at night and daytime, giving a positive correlation coefficient result in a ground water inflow. The second type of cool water inflows are when the inflow is colder in the day but warmer at night, giving a negative correlation coefficient and resulting in a location of hyporheic exchange. The correlation coefficient shows the locations of temperature change that are distinguishable outside of the measurement noise. These locations can be compared with locations we have visually determined to be ground water or hyporheic exchange in order to see if the correlation coefficient can be used to easily find and differentiate the locations of cold water refugia from the DTS temperature profile.

A ground water inflow can be located by using time series longitudinal surface water temperature traces. The average temperature profile for cool summer nighttime data (3am to 7am) was processed and compared with the average temperature profile of the peak summer daytime data (6pm to 10pm). These traces were compared with the total average temperature trace of the river for the study duration (Figures 3.5, 3.6 and 3.7, respectively). When the comparison was completed, locations where sudden steps or slopes downward in the DTS data, that were at the same location throughout the daily temperature cycle, were considered to be ground water inflow sites.

Locating areas of continuous temperature shift is important when removing other factors that may contribute to cooled locations of surface water during daily peak temperatures. It can be argued that these cooled areas are due to riparian shading, wind, hyporheic exchange, or evapotranspiration. However, when nighttime temperature change is similar to daytime and overall average temperature trends, we are able to remove the temperature signature that may be from environmental factors that give a false cooling signal.

A heat balance equation to calculate ground water discharge from measurements of stream temperatures and surface water flow was developed by Kobayashi et al. (1999) and was used by Becker et al. (2004) and Kalbus et al. (2006). In their research a stream was divided into reaches where temperature measurements were taken and a balanced equation was set up. The local stream temperature is a function of the ground water discharge rate, the difference in stream water and ground water temperature, stream flow, and additional heat gains and losses through the stream surface. This approach will also calculate the ground water inflow based on the flow and temperatures of the surface water and the ground water. The difference between their method and the one chosen for this study is that the Kobayashi method has also incorporated the surface heat flux into its estimations. However, these are considered to be constant over the stream, and can be neglected for this data analysis.

Flow contributions along a reach can be separated into surface and subsurface flow using temperature, through application of mass and heat conservation. For this study a slightly modified versions of the Kobayashi mass and energy balance equations for flows and temperatures were used (Selker et al., 2006b; Westhoff et al., 2007; Tufillaro et al., 2007).

Mass balance, $Q_d = Q_u + Q_l$

Energy balance, $T_d Q_d = T_u Q_u + T_l Q_l$

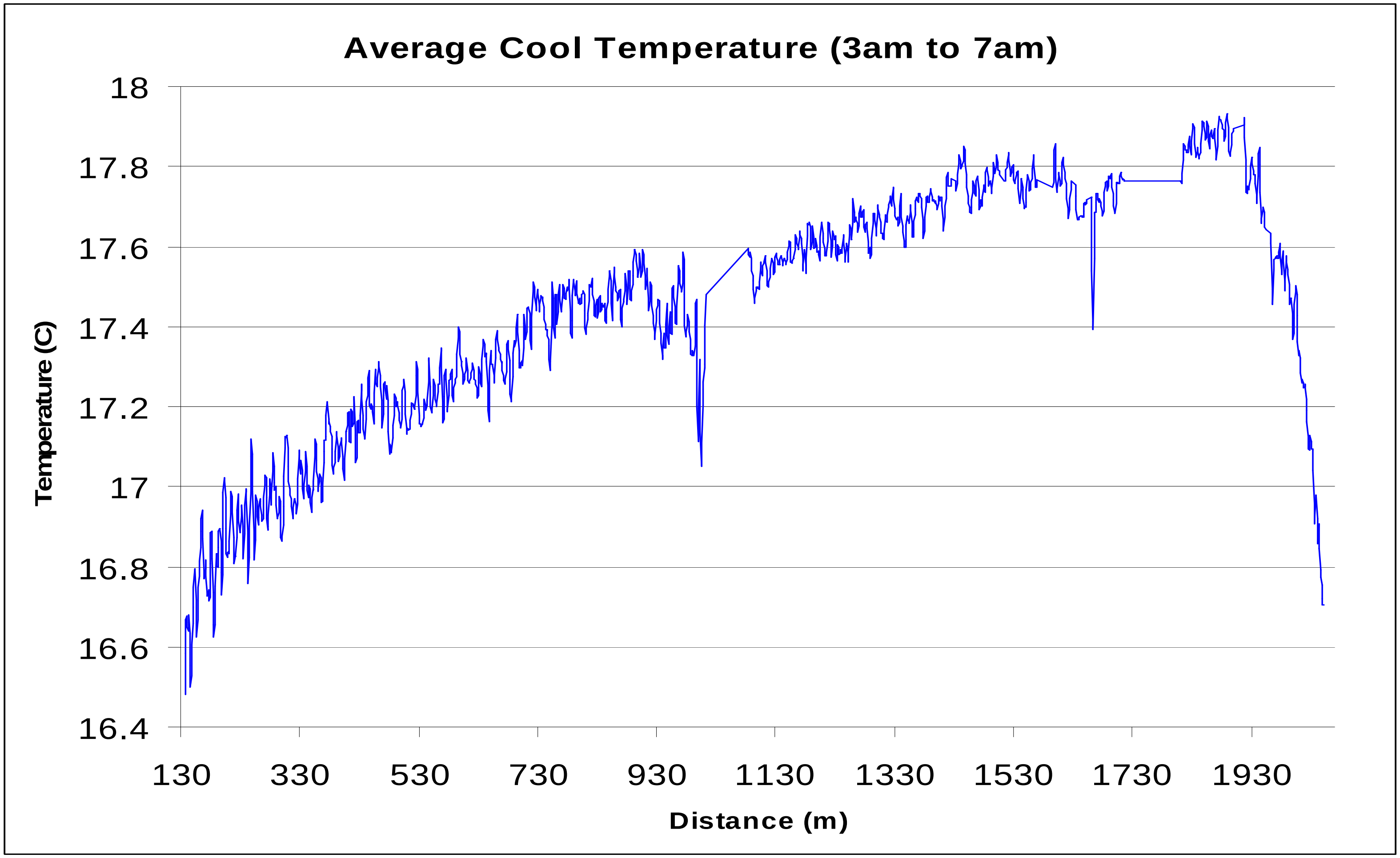

Figure 3.5 Average cool night-time daily summer time temperature profile for the study reach in the Walla Walla River, Oregon for July 30th to August 20th, 2007 with air temperature removed.

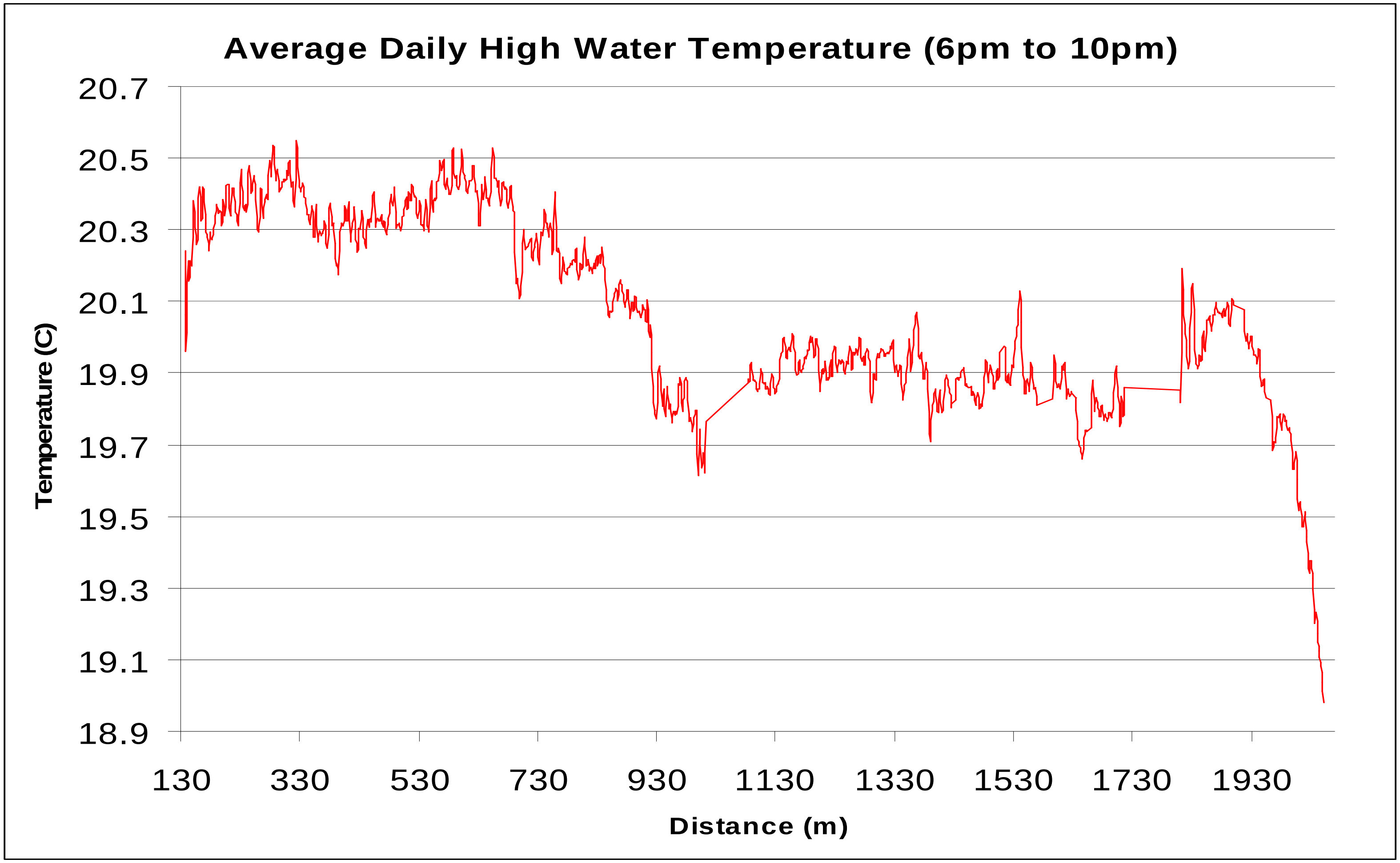

Figure 3.6 Average peak daily summer time temperature profile for the study reach in the Walla Walla River, Oregon from July 30th to August 20th, 2007 with air temperature removed.

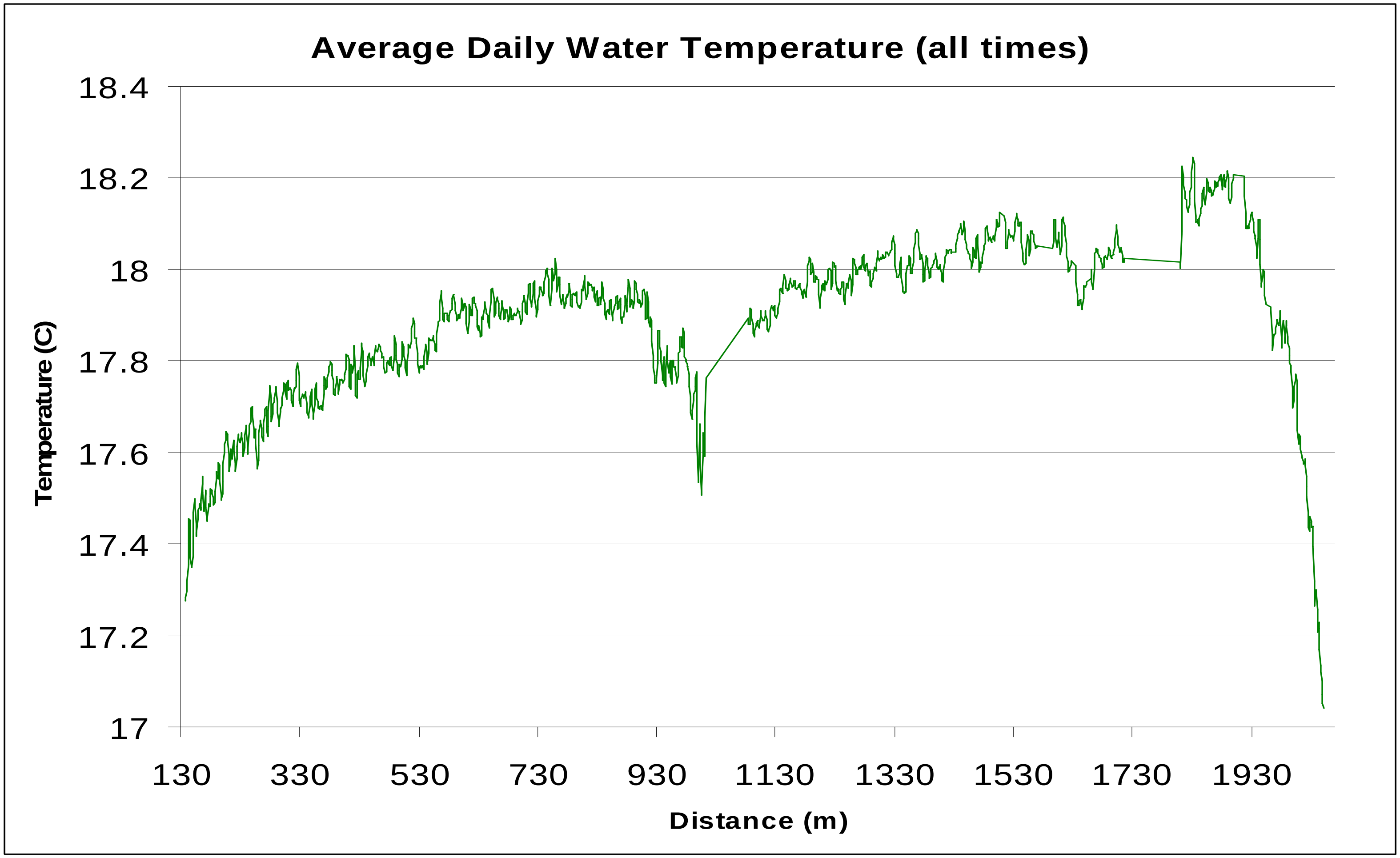

Figure 3.7 Average daily summer time temperature profile for the study reach in the Walla Walla River, Oregon from July 30th to August 20th, 2007 with air temperatures removed.

Where Q is discharge (m^3/s), T ($°C$) is the water temperature and the subscripts d is downstream flow, u upstream flow and l is lateral inflow. The ratio between $\frac{Q_l}{Q_d}$ can be derived by solving the mass and energy balance equations above:

$$\frac{Q_l}{Q_d} = \frac{T_d - T_u}{T_l - T_u}$$

The determination of $\frac{Q_l}{Q_d}$ from temperature measurements can be done only if the lateral inflow significantly alters the stream water temperature. Thus, the more precisely temperature can be measured, the more accurately inflows can be quantified.

An assumption that is implicit in these equations is that over the time interval between the night and day temperature profiles T_l and $\frac{Q_l}{Q_d}$ are constant. The approach assumes there is full mixing soon after the ground water enters the stream, and that the temperature over the cross section of the stream is constant. These equations also assume that the flow is constant over time and only varies due to ground water sources (Westhoff et al., 2007). Other assumptions are: there is no bed conduction loss; there is negligible solar, long wave, and evaporative heat exchange; and that there is negligible direct gain or loss through evaporation and precipitation.

We can move from quantifying each ground water input (for a depiction of the ground water system see Figure 3.8) to how ground water inflows will change surface water DTS measurements. The expected reaction of the summertime surface water temperature due to gains from a ground water inflow is illustrated in Figure 3.9. At a location of ground water inflow we expect that during summer the temperature trace will show reduction in temperature both day and night. This is the case as long as summertime surface water temperatures are above the average yearly air temperature, which is the temperature of incoming ground water from shallow sources.

Ground water inflows can be found through the use of a correlation coefficient computed for spatial changes in daytime to nighttime temperatures. That is to say that at locations of ground water emergence we expect evidence of cooling with downstream flow for both day and nighttime DTS data. The temperature change is determined from 10m before the ground water inflow location to 10m after the ground water inflow location. To use the correlation coefficient to locate the ground water inflows the surface water temperature of the average low nighttime and average peak daytime are used. The temperature data showing the ground water locations can be plotted to ensure that the locations are not only a positive correlation, but are in fact areas of cooling. Based on visual inspection, a false positive from the correlation coefficient can be seen in the data at areas of continuous warming or at a fiber optic cable junction site, both will be discussed later. Each of the ground water inflows that were found can be quantified using the coupled conservation of mass and energy equation from Selker et al., (2006b).

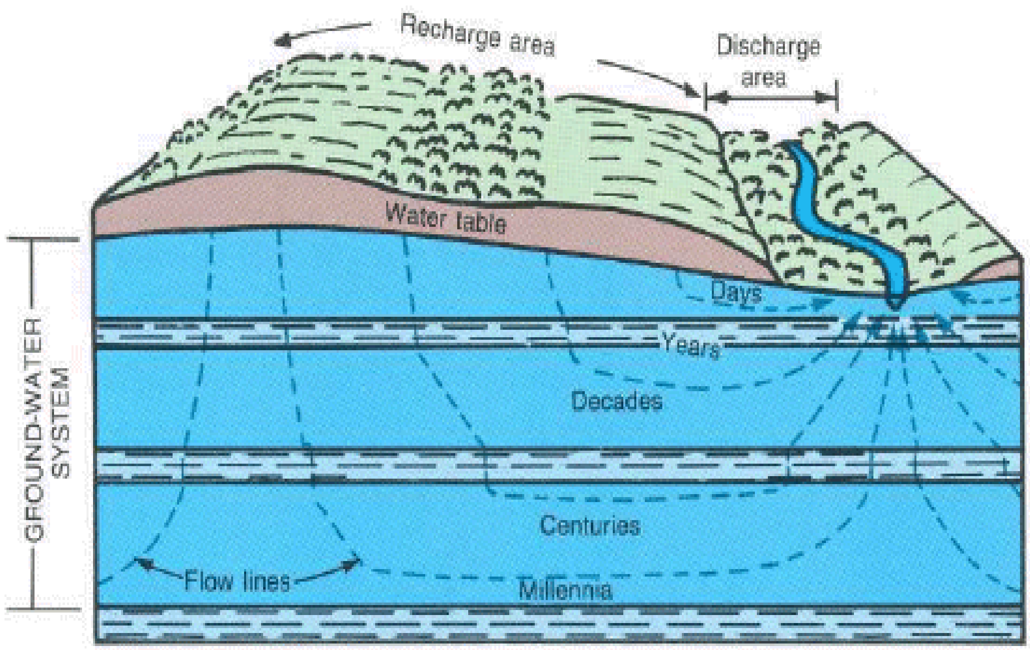

Figure 3.8 Depiction of ground water system (Waller, 1988).

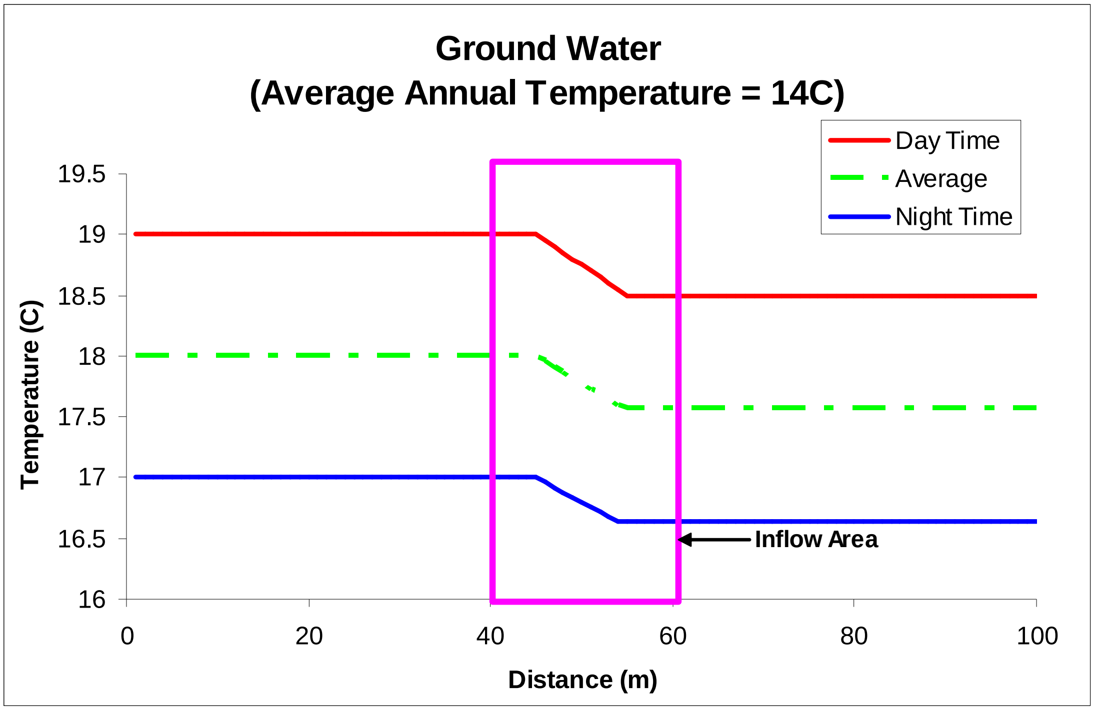

Figure 3.9 Example of what is expected from a trace from a ground water inflow site during summertime temperatures.

Hyporheic exchange sites are found through the correlation coefficient however, a negative correlation also occurs in areas where the cable is out of the water and recording air temperatures. Thus, identification of hyporheic exchange needs to be validated. Areas with cable exposed to the air will have a greater temperature difference than the surface water between the night and day temperatures allowing visual inspection of the traces to easily differentiate between the sites that are hyporheic exchange and the sites that are air exposed cable.

Most hyporheic exchange occurs in pool to riffle sequences, with water entering the sediment after the pool and coming out of the sediment after the riffle. During the warm times of day this creates a slight drop in the temperature at the hyporheic exchange site, and during the cooler time of night it gives an increase in temperature at the same site (Figure 3.10). This change is due to the time it took the water to pass through the sediment. For the purpose of this thesis exchanges longer than 1day duration are not considered in our determination of hyporheic exchange.

Hyporheic flow longer than a one day residence time can occur; examples of these longer duration hyporheic exchanges include when a secondary channel, braided channel, or meander bend is present in the surface waterway (Vervier and Naiman, 1992; Harvey and Bencala, 1993; Wondzell et al., 1996; Wondzell and Swanson, 1999). These longer duration exchanges cannot be found through the three week duration data that we have available. In essence, these locations of hyporheic exchange make the temperature of the surface water more stable, bringing the surface water back to the daily average temperature. These river temperature characteristics along with the porosity of the streambed will be used to calculate the depth and width

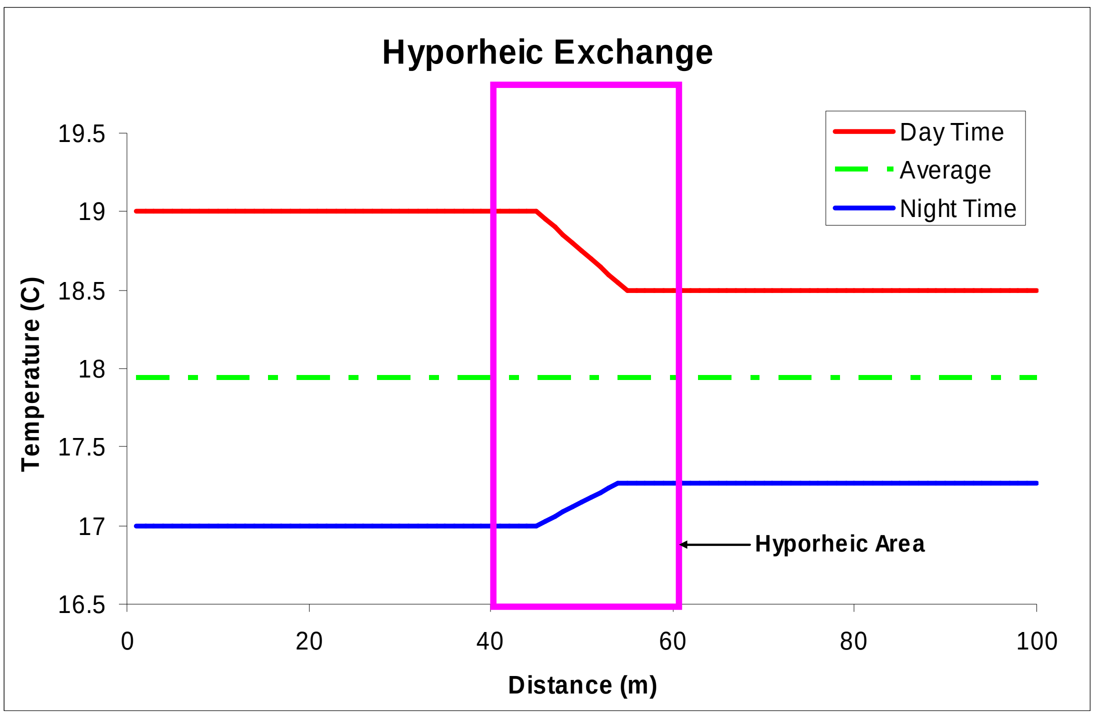

Figure 3.10 Depiction of expected temperature change from hyporheic exchange during summer.

of hyporheic exchange flows. These same parameters will define the water's travel time through the hyporheic exchange zone (Wondzell and Swanson, 1999).

Let us look at the collective cooling from hyporheic exchange between the surface water and the bed material over a section of river. For these calculations the hyporheic volume will be considered a continuous mixing zone throughout the entire length of the river. To estimate this overall hyporheic exchange we can consider the difference in temperature from the average daily temperatures to the average peak daily temperature for the upstream portion of the reach and compare it to this same measurement for the downstream portion of the stream. The upstream and downstream portions of the reach are considered to be the first and last 50 meters of in-stream fiber optic cable, respectively; bounding an 1800m section of the river. This will serve as the upper and lower boundary for an energy balance.

The energy balance is used to find the mass of material required to match the actual in-stream temperature change we see in the data. The amount of energy coming into the reach minus the energy leaving the reach must equal the energy stored within the reach (see Figure 3.11). The energy balance will be used to find the amount of energy that must go into the hyporheic exchange and volume of surface water. The stored energy can be put in terms of thermal heat capacity for the hyporheic exchange and surface water to determine the depth of the hyporheic exchange. To determine the depth of hyporheic exchange that is evenly distributed over the entire river bottom from the stored energy term we will use the surface area of the hyporheic exchange.

To calculate the depth of hyporheic exchange the solar radiation is equally distributed across the river reach, the quantity of ground water inflow are of equal magnitude at each inflow site, and the ground water inflows are restricted to the discrete locations found through the DTS temperature readings. The ground water inflows are included in the calculation for hyporheic exchange depth because we are basing the hyporheic exchange depth on the heat capacity of the hyporheic exchange site and to find the heat capacity we will need to include the ground water energy for the conservation of energy equation that is used. An important feature of this river reach is that the flow from the upstream to the downstream portion of the reach does not change. This is justified by the flow measurements along the reach completed by Bob Bower from the Walla Walla Basin Watershed Council that shows upstream to downstream measurements to be within the 10% error interval of the measurement method (personal communication, Bob Bower, October 2007). Since the flow measurements are within the 10% error interval, there is no statistical difference between the upstream and downstream flows. Lastly, solar radiation, ground water inflow, and hyporheic exchange are assumed to be the major processes contributing to river cooling and are therefore the major components in the energy balance and are the main processes taken into account for this thesis. The long wave radiation, evaporation, and air exchange (convection) will be lumped into one term. The value for this term was estimated using a calibrated energy balance via the software Heat Source v. 7.0 (ODEQ, 2005), energy balance software that was calibrated and updated for the Walla Walla River in the summer of 2005.

We can now look at the method developed to find the expected volumetric heat capacity for the hyporheic exchange. Prior to calculation a conceptual model may help to understand the major contributions and makeup of the channel energy budget in question (see Figure 3.11 and 3.12). Using this conceptual model we can find the thermal mass of the hyporheic exchange by using a conservation of energy balance equation. For the conservation equation we need to account for all the major inputs and outputs of energy, depicted in Figure 3.11. The input energies to this system are the inflowing surface water energy, the solar energy, the ground water energy. The out flow of energies include the losses of surface water to ground water, the lumped term for the convection, evaporation, and long wave radiation energies, and the water energy leaving the study reach. The energies will be calculated as a flux in joules per second.

The objective here is to determine the thermal mass of hyporheic exchange. This was completed by computing the energy fluxes into and out of the control volume to find the rate of change of stored energy within the control volume. Since the control volume contains a known volume of surface water the thermal mass of hyporheic exchange can be separated and computed.

The energy balance for this study is based on the control volume in Figure 3.13. This control volume comes from the instantaneous energies for the study reach assuming all flows of water are steady. The control volume consists of the incoming energy of the water [1], the incoming solar radiation energy [2], the ground water energy into the reach [3], the ground water energy out of the reach [4], the lumped energy term (from the energy for evaporation, convection, and long wave radiation) [5], the outgoing energy of the water [6], and the stored energy (going into hyporheic exchange and the surface water). Conduction is an additional energy in the system. The control volume contains both the river water and the conduction of river water to bed material (the hyporheic exchange site). Therefore, the conduction term is incorporated into the stored energy in the control volume.

The energy balance is based on the conservation of energy and can be written as the rate of change of stored energy is equal to the difference between the total incoming energy (E_{ti}) and the total out going energy (E_{to}).

Rate of change of stored energy within the control volume = E_c [J/s] = $E_{ti} - E_{to}$

For the purpose of this study it can be stated as:

Rate of change of stored energy = (incoming water energy + solar radiation energy + ground water energy in) – (ground water energy out + lumped energy + outgoing water energy)

Where the energy stored remains in the materials within the control volume, including the surface water and the hyporheic exchange zone.

The energy fluxes are denoted:

water energy in = E_i [J/s]

solar radiation energy = E_s [J/s]

ground water energy in = E_{gi} [J/s]

ground water energy out = E_{go} [J/s]

lumped energy term = E_l [J/s]

water energy out = E_o [J/s]

In this notation the energy balance can be written as:

$$E_c = (E_i + E_s + E_{gi}) - (E_{go} + E_l + E_o)$$

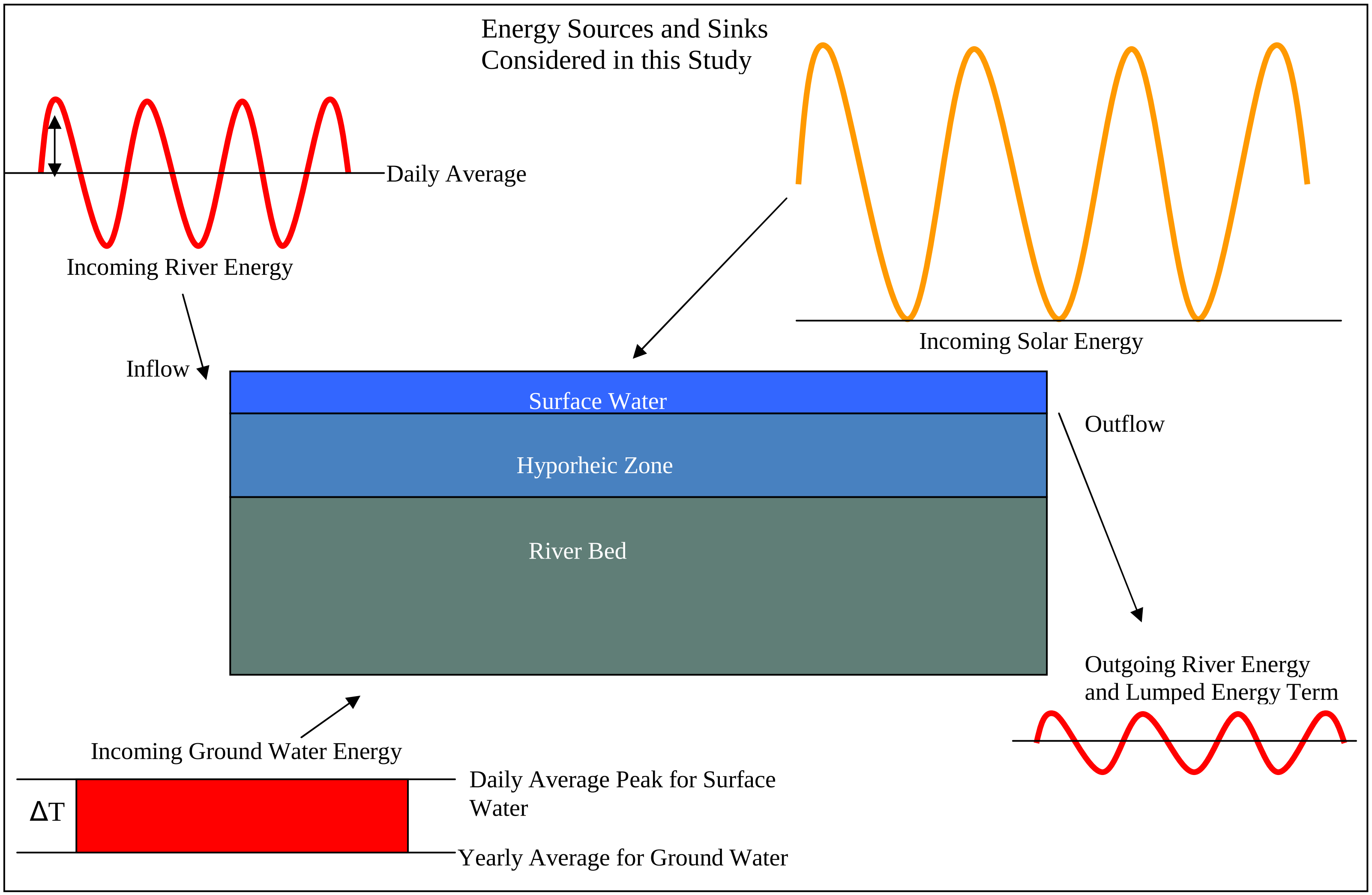

Figure 3.11 Depiction of the energy sources and sinks for the study reach in Milton Freewater, OR

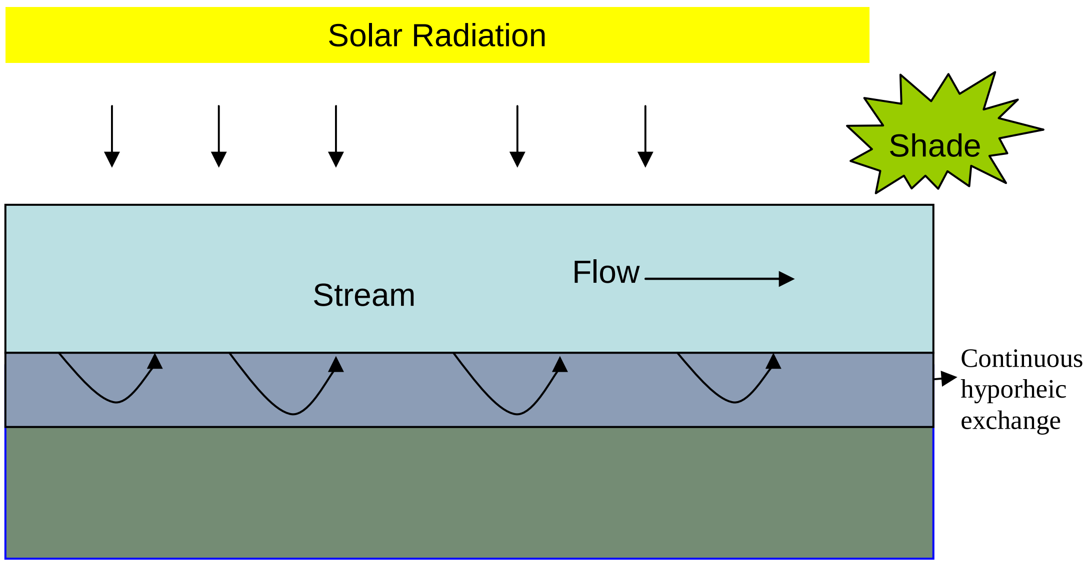

Figure 3.12 Conceptual model of the continuous hyporheic exchange.

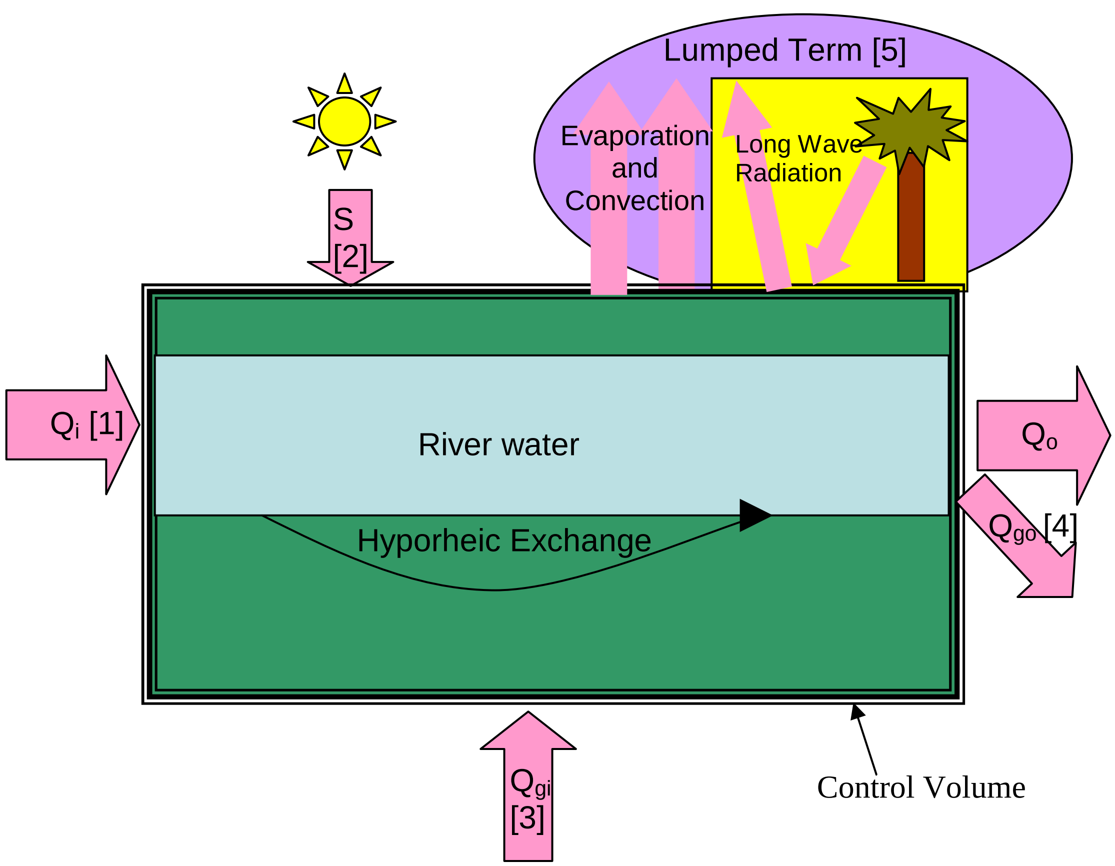

Figure 3.13 Depiction of energy inflows and outflows to the control volume.

The makeup of each energy flux within the energy balance can now be determined. The energy fluxes will be computed to solve for the difference between the inflowing and outgoing energy giving the rate of change of stored energy within the control volume (see Figure 3.14 for concept of dampened temperature at outflow due to hyporheic exchange). First the inflowing energy flux is computed. The incoming water energy [1] is computed at the point entry to the control volume by finding the incoming temperature (T_u [°C]). All temperatures are referenced to 0°C to insure correct energy flux calculations. To compute the energy flux the temperature is multiplied by the volumetric thermal heat capacity of water ($C_{vw} = 4.18 \times 10^6$ J/°C m^3, for water at 20°C) and the flow into the study reach (Q_s [m^3/s]) to determine the inflow energy.

$E_i = C_{vw}(T_u)(Q_s)$

Solar radiation follows a diurnal pattern and is therefore a function of time. The energy input from solar radiation (S) [2] was acquired from weather station data in the Walla Walla River Basin near the study reach. The net solar energy flux is computed as the solar radiation as a function of time multiplied by the fraction of the river's surface area (R [m^2]) that is exposed to the solar radiation. Because the solar radiation does not directly impact the shaded portion of the river, the surface area will be multiplied by the fraction of area that is exposed to the solar radiation. In this case 10% of the river was shaded so the surface area was multiplied by a shade factor (F) of 0.9.

$E_s = S(R)(F)$

The energy of the ground water inflow [3] can be determined by finding the temperature of the ground water inflow (T_{gi} = 14°C). The energy flux is computed by multiplying by the volumetric thermal heat capacity of water and the total ground water flow in the reach (Q_{gi} = 0.36 m^3/s).

$E_{gi} = C_{vw}(T_{gi})(Q_{gi})$

The energy for the ground water outflow [4] is determined similarly, taking its temperature to be equal to that of the surface water of the control volume, T_{cv} [°C]. The flow data for the study reach shows no significant change in water from the inflow to the outflow; since we have determined that there is cold water flowing into the reach their must be an equal amount of water flowing out of the reach. For this particular case the ground water outflow we take to be equal to the ground water inflow (Q_{go} = 0.36 m^3/s).

$E_{go} = C_{vw}(T_{cv})(Q_{go})$

The lumped energy term (L [J/s m^2]) representing evaporation, convection and long wave radiation [5] was obtained from Heat Source v. 7.0 (ODEQ, 2005), an energy model that has been calibrated for this river reach. This term for our study reach was determined by using the Heat Source information from August 2002, giving an estimate for this study (summer of 2007). As seen in Figures 3.15 and 3.16 the climatic data for August in these two years is similar, therefore 2002 data can be used as an approximation for 2007. The energy taken from Heat Source is then multiplied by the surface area of the river reach.

$E_l = L(R)$

The energy flux out of the river reach [6] is determined in the same manner as the energy into the reach. The volumetric heat capacity of water and the flow of the reach are multiplied by the downstream temperature (T_d [°C]).

$E_o = C_{vw}(T_d)(Q_s)$

The conceptual model (Figure 3.12) above also pertains to the energy balance necessary to find the functional volume of the hyporheic exchange. The hyporheic exchange depicted in the model along with the surface area of the hyporheic exchange can be used together to find the functioning depth of this zone. Some assumptions made for this calculation are that the hyporheic exchange is continuous along the study reach and is directly below the surface water, not coming in on the sides of the channel. The second assumption stated above is viable when there is such a large width of surface water to depth of water ratio. These assumptions help to keep this calculation as a stripped down simple formula to help quantify the hyporheic exchange. The same idea of the continuous hyporheic exchange can be used to find the depth for discrete zones of hyporheic exchange; the depth will be much greater in discrete locations of hyporheic exchange because the same amount of cooling must

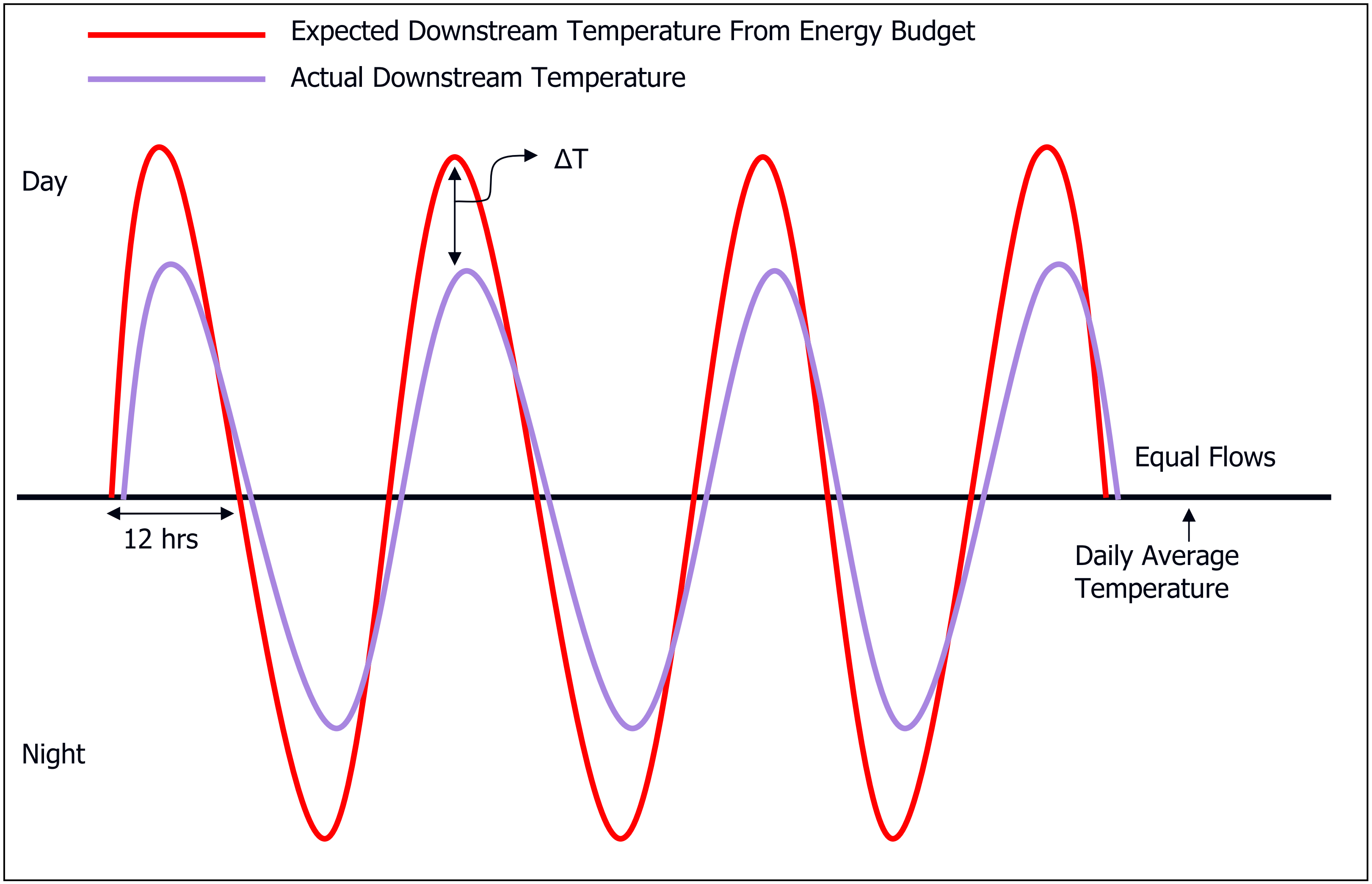

Figure 3.14 Expected temperature from the energy budget compared to the actual temperature with hyporheic exchange.

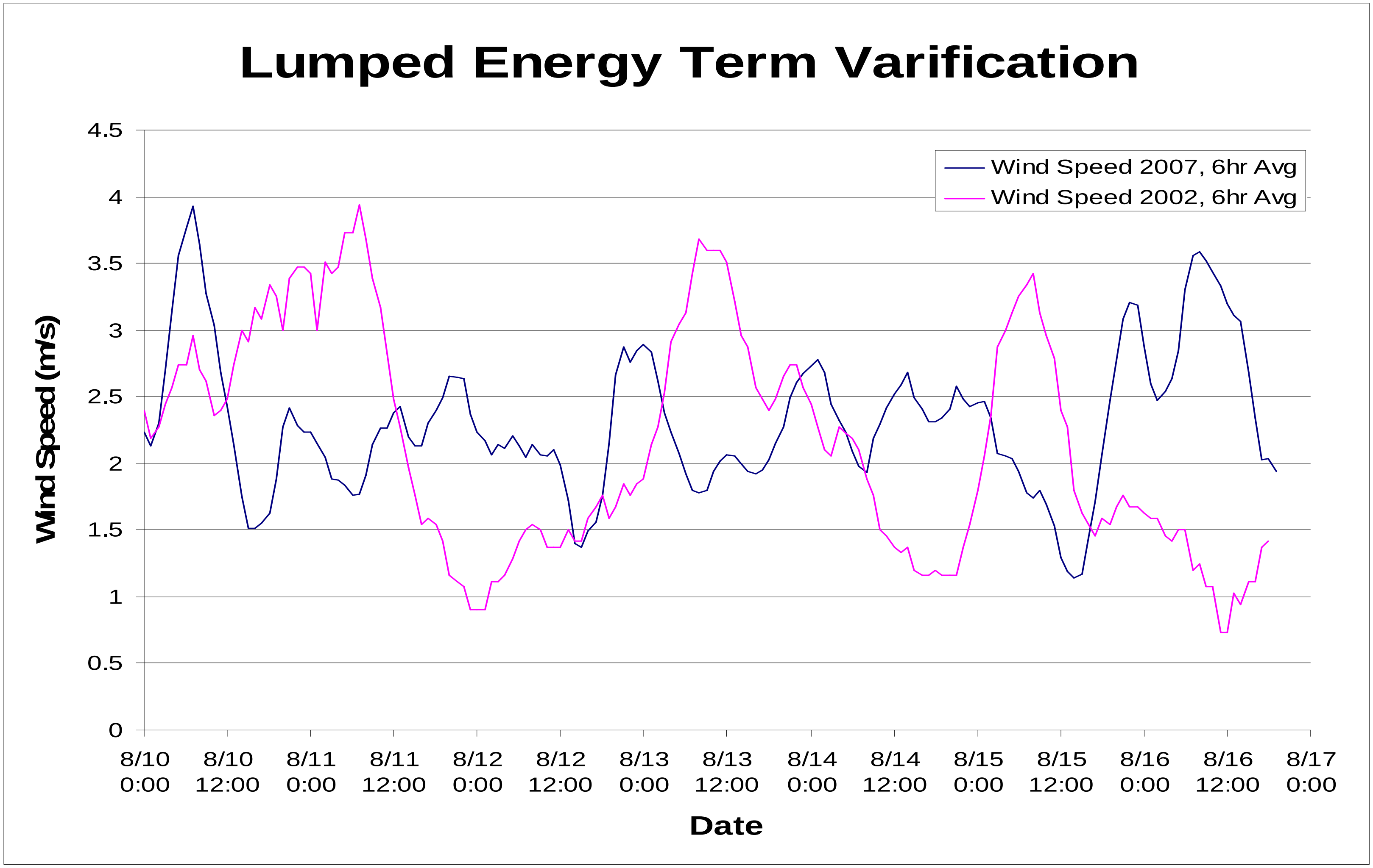

Figure 3.15 Wind speed comparison between 2002 to 2007 for the Walla Walla River near Milton-Freewater, Oregon.

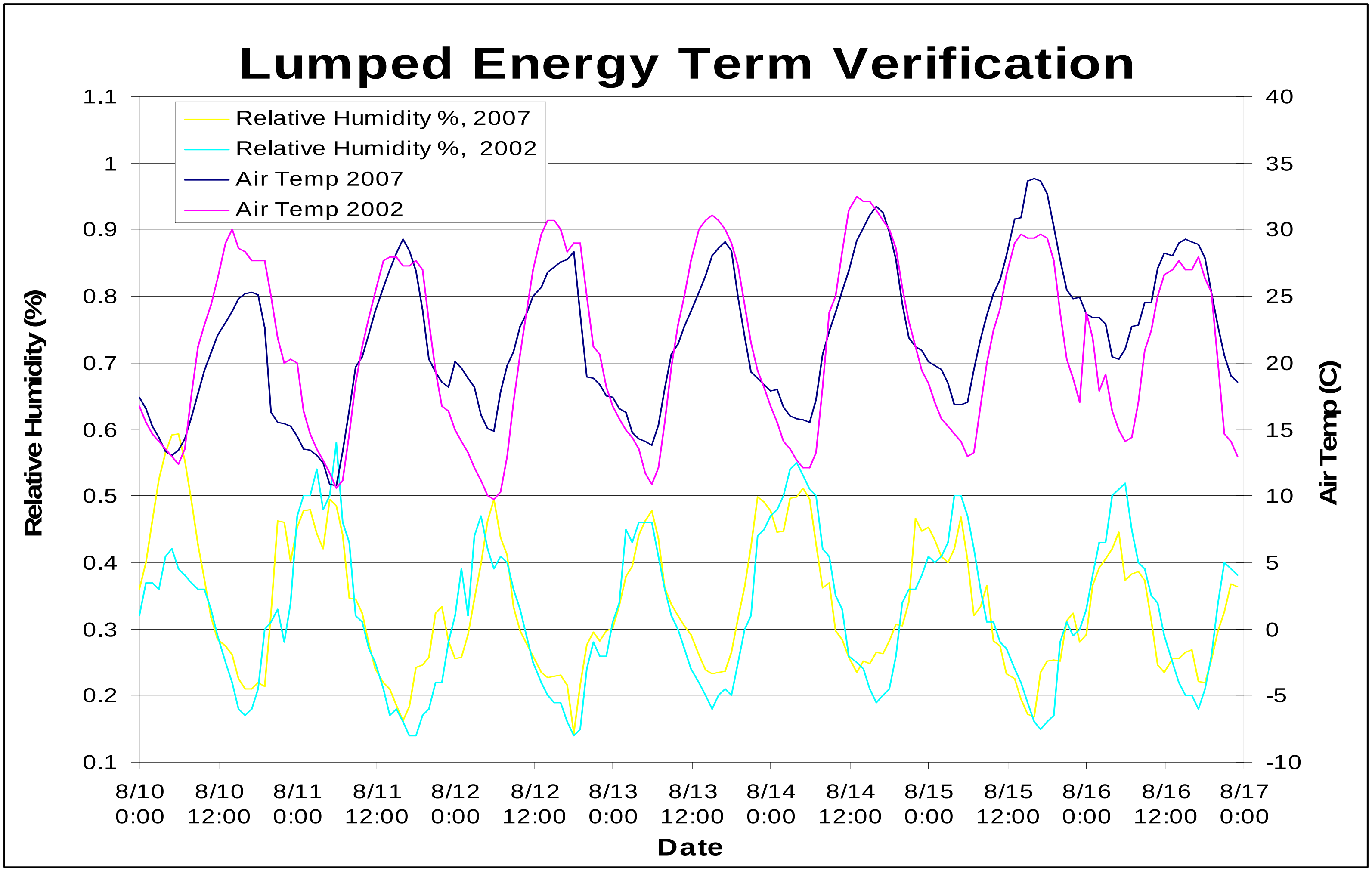

Figure 3.16 Comparison of air temperature and relative humidity between 2002 and 2007 for the Walla Walla River near Milton-Freewater, Oregon

take place in a shorter distance. Both continuous and discrete hyporheic exchange are important to consider, but the DTS instrument is capable to pin point the discrete locations based on the peak hot and cold daily temperature profiles.

Depth of the hyporheic exchange can be found through consideration of the control volume (Figure 3.13). Since we have the calculation for the rate of change of stored energy for the control volume (hyporheic exchange plus surface water) and we know the volumetric heat capacity for water and the bed material, the volume of water above the hyporheic exchange site, and the porosity of the bed material to be 0.3 (Constantz et al., 1996; Edwards, 1998), we are able to calculate the volume of the hyporheic exchange site. Since the porosity of the bed material is 0.3 we know that the bed material takes up 0.7 of the volume in the hyporheic exchange site, this will be used to help calculate the volume of the hyporheic exchange site.

The energy stored within the control volume (E_c [J/s]) resides in both surface water and the water sediment mix of the hyporheic exchange. The depth of hyporheic exchange calculation is based on the energy stored in the control volume that is not stored in the surface water.

The energy balance will be based on the volumetric heat capacities of the different material within the control volume and the stored energy within the control volume. The stored energy within the control volume will be integrated over time in order to find the cumulative energy the thermal mass of the hyporheic exchange must account for. From Figure 3.17 we can see a model of what the control volume contains. Using this model (containing a known volume of surface water), the volumetric heat capacity of the sediment, and the temperature change of the control volume over a specific time period we can derive an equation to determine the depth of the hyporheic exchange.

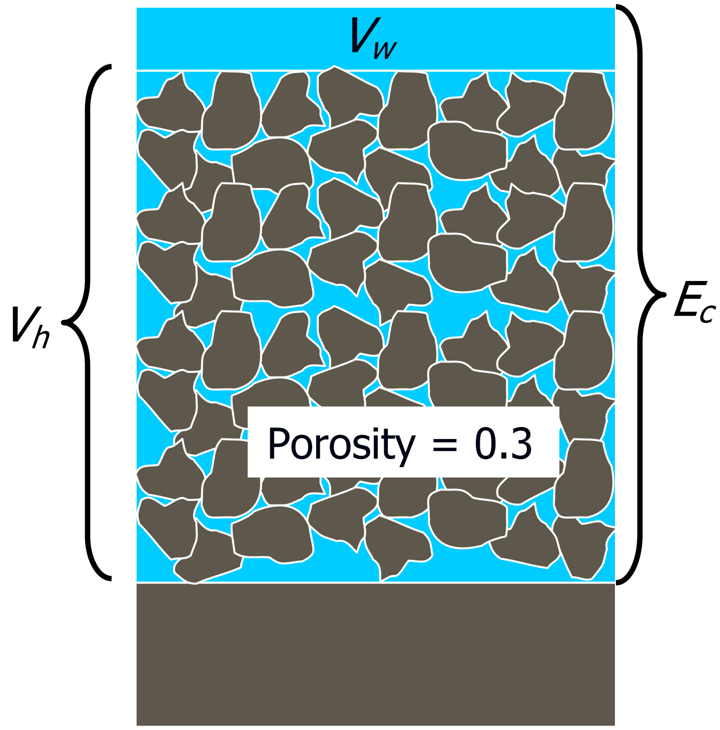

Figure 3.17 Conceptual model of continuous hyporheic exchange.

The terms used for this derivation are denoted:

E_c= Rate of change of stored energy within the control volume (J/s)

V_{cv} = Total volume of control volume (m^3)

V_h = Total volume of hyporheic (m^3)

V_w = Total volume of water above hyporheic exchange zone (m^3)

T = Temperature of the control volume for time duration (°C)

t = Time duration the calculation was completed (s)

C_{cv} = Thermal volumetric heat capacity of control volume (J/°C m^3)

C_{vw} = Thermal volumetric heat capacity of water (J/°C m^3)

C_{vs} = Thermal volumetric heat capacity of sediment (J/°C m^3)

SA = Surface area of hyporheic zone (m^2)

D_h = Depth of hyporheic zone (m)

We begin with the previously calculated energy stored within the control volume and find:

$$E_c = \left(\frac{dT}{dt}\right) C_{cv} V_{cv}$$

This can be integrated as:

$$\int dT = \frac{E_c}{C_{cv} V_{cv}} \int dt$$

Giving:

$$\Delta T = \frac{E_c}{C_{cv} V_{cv}} \Delta t$$

Now we can expand the control volume terms to incorporate the materials involved.

$$C_{cv} V_{cv} = C_{vw}\left(V_w + 0.3V_h\right) + C_{vs}\, 0.7V_h$$

This can be substituded in for the control volume terms:

$$\Delta T = \frac{E_c}{C_{vw}\left(V_w + 0.3V_h\right) + C_{vs}\, 0.7V_h} \Delta t$$

The volume of hyporheic exchange can be computed as:

$$V_h = \frac{\dfrac{\Delta t E_c}{\Delta T} - C_{vw} V_w}{0.3C_{vw} + 0.7C_{vs}}$$

Once the volume of the hyporheic exchange has been calculated the depth of the exchange can be found by simply dividing the calculated volume by the surface area the hyporheic exchange occurs over (for our case we have made the assumption that the hyporheic exchange occurs over the entire length and width of the channel).

$$D_h = \frac{V_h}{SA}$$

3.3.3 Fish Survey

During this study, the USFWS conducted a survey on the fish found in this reach of the Walla Walla River. The survey determined the number of fish and species found throughout the study reach during warm daytime temperatures. The surveyors recorded the cable distances when they came to a school of fish during their snorkel survey which started at the downstream section of the study reach and went up the river to the end of the study reach. This fish survey will be used to determine if the fish populations are locating the cold water inflows during warm daytime periods.

4.0 Results

4.1 Calibration and Jitter Removal of DTS Data

The temperature offset for post calibration of the DTS data was determined to be approximately 5° C by checking ice bath temperatures using a high resolution VWR temperature probe, which has a temperature resolution of 0.001° C. This was determined through calculating the difference between the VWR temperature measurement and the temperature measurement given by the DTS for the ice bath. The upstream ice bath was found to be -0.006° C and the downstream bath to be 0.012° C. The two fiber optic cables used for this study meet at the ice bath at the 1030 meter mark. This junction is noticeable in the temperature measurements because at this point the temperature profile shows a spike in the record due to the barrel connector. In Figure 4.1 it is easy to see that the ice slurry baths are not read as zero by the DTS system, giving the necessity for the offset correction. The entire temperature profile was adjusted for this offset to get temperatures that will be close to the true stream temperature.

The offset was found to be a reduction of the DTS measurements by 5.02° Celsius. Figure 4.2 shows the basic trace acquired from DTS viewed through MatLab that has been adjusted for the offset. This trace gives the temperature averaged for one hour every meter along the 2000 meter study reach.

When the temperature data was viewed in the MatLab movie format, a jitter (typically between 0.5 to 1.0° C) was seen, where the data was displaced either up or down (movie not presented in this thesis). This “jitter” was first seen in an ice temperature bath. The temperature should not quickly change within the bath, but some jumps were noticed. Through discussions with the DTS manufacturer it was learned that this defect reflected a firmware defect which is prominent when the instrument is used in double-ended mode with high loss fiber optic cable (our case). The jitter seen was not due to true temperature changes from the river and therefore it was necessary to remove before further data interpretation took place. This jitter was corrected for by first plotting temperature versus the time for the DTS measurements (Figure 4.3). The plotted river temperature should follow a smooth pattern due to the influence of air temperature, solar radiation, and the high thermal heat capacity of water. This was not the case with the jitter present so the data set needed to be smoothed out post collection. To accomplish the smoothing, a 5hr running average of the hourly temperatures was taken to get an adjusted temperature measurement (see Figure 4.4). For the running average a section from 1077 to 1425 meters along the river was used because it showed quality water temperature with no spikes due to air temperature. The differences between the averaged temperature and the true temperature were found and added to the entire dataset for the duration of the study. This gave a new adjusted temperature dataset to be used for all calculations.

4.2 Cold Water Refugia

The temperature data was viewed at several different time intervals throughout the day to see how nighttime temperature changes may differ from the ones during the daytime (see Figures 3.5 and 3.6). The temperature data were averaged throughout space and time to find locations where there was a continuous drop in the surface water temperature; possibly indicating areas of cool water inflow (see Figure 4.5). The three meter average nighttime (3am to 7am) temperature was plotted along with the three meter average hot daytime (6pm to 10pm) temperature in Figure 4.5 to see if the dynamics expected between hyporheic interaction zones and ground water inflows would become noticeable in this dataset.

The flow survey done by the Walla Walla Basin Watershed Council (WWBWC) at the time of the DTS and fish study found average stream flow of 0.9 m^3/s (Table 4.1) for the entire river reach with an error of 10 % for the cross-sectional flow measurement method used (Bob Bower, per communication, 2007). The flow data was necessary to help quantify the ground water inflow to our study reach. The ground water temperature is also necessary for the combined conservation of mass and conservation of energy equation used to quantify ground water inflow.

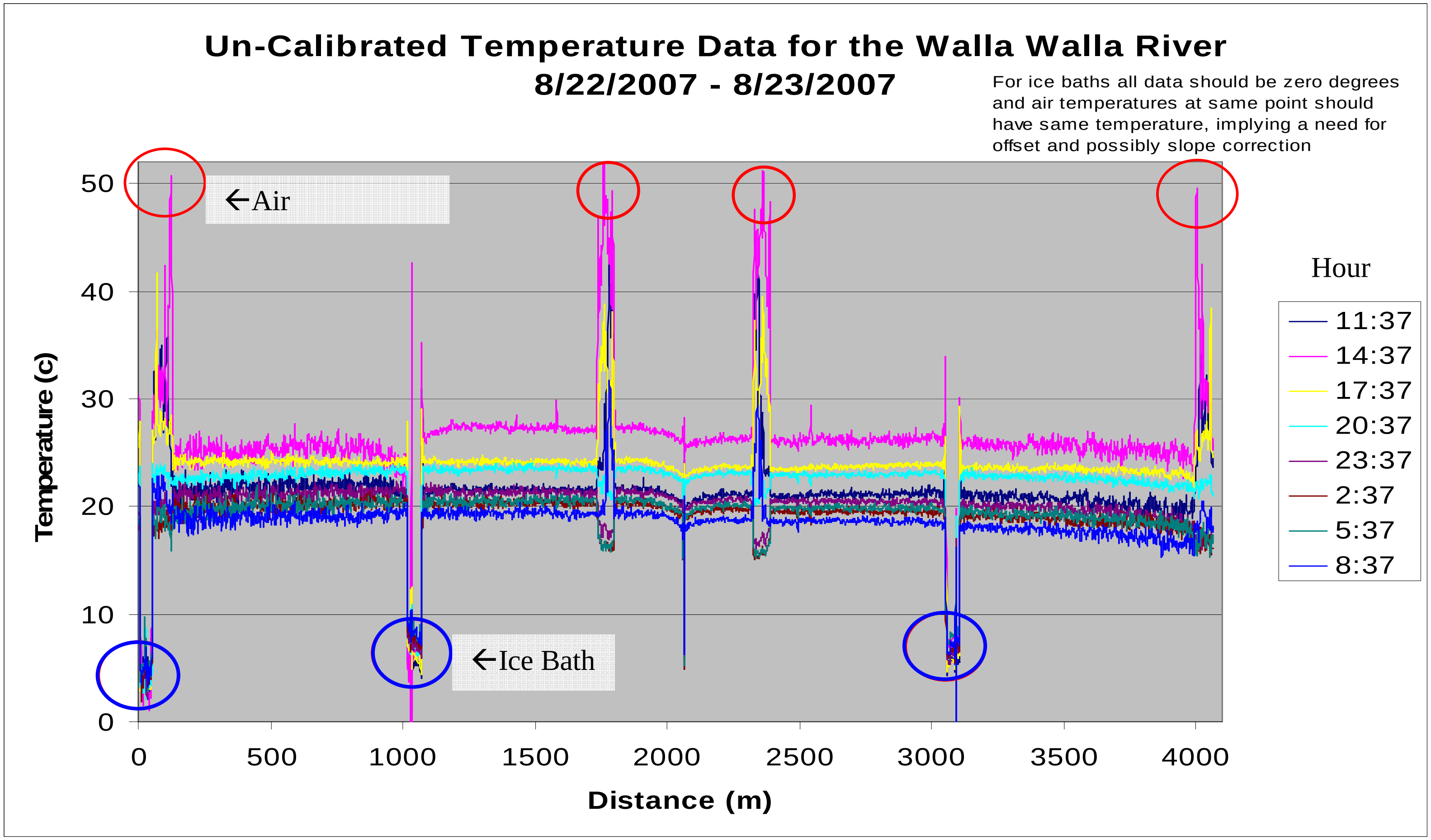

Figure 4.1 The un-calibrated graph shows eight hours of temperature profile for the reach. The duplex cable used shows a mirrored image after 2060 meters. Blue circles indicate ice baths and red circles locations of known air exposed sections of cable.

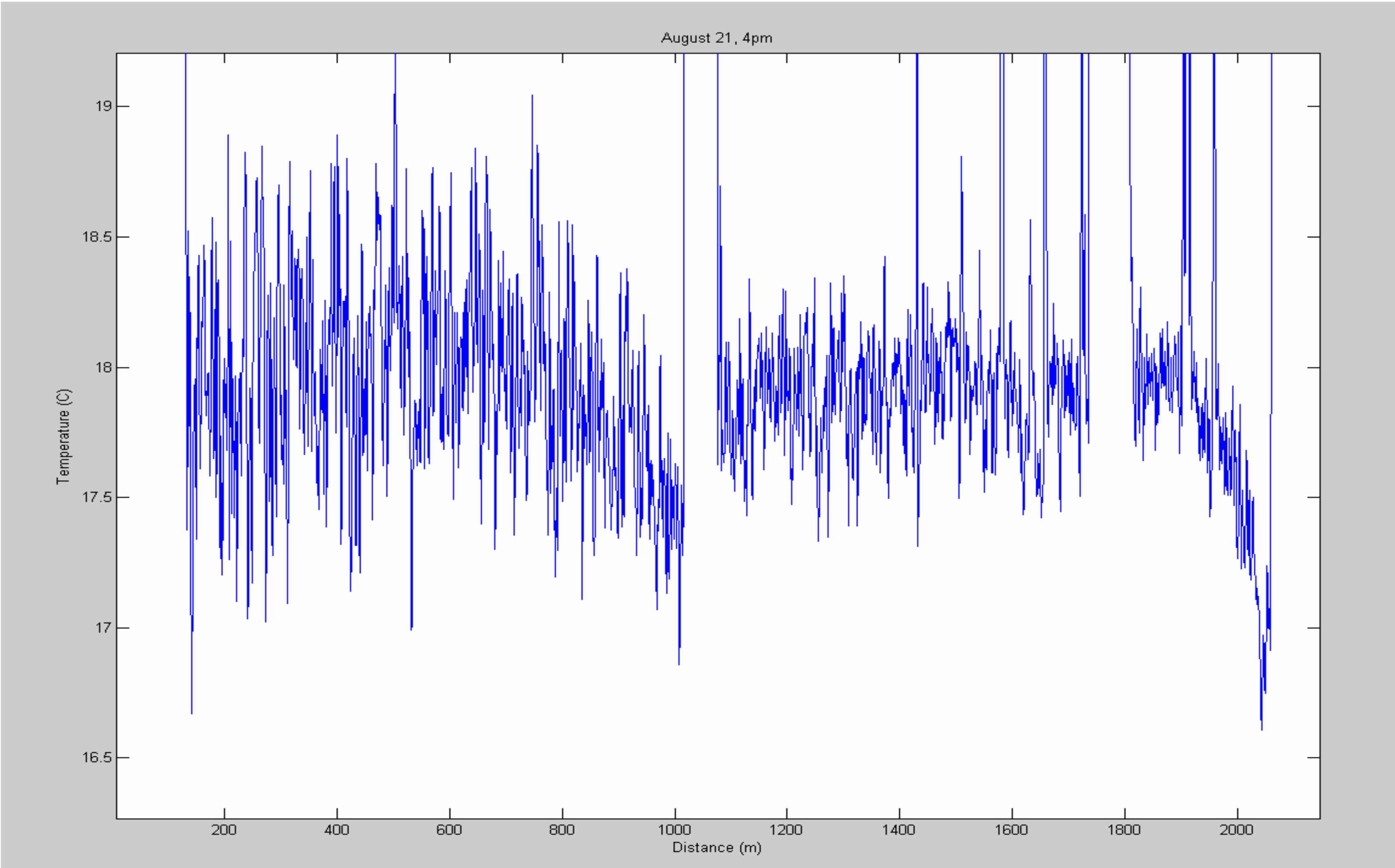

Figure 4.2 Single temperature profile of raw data for study site on Walla Walla River, 21 August 2007 at 4pm only adjusted for temperature offset.

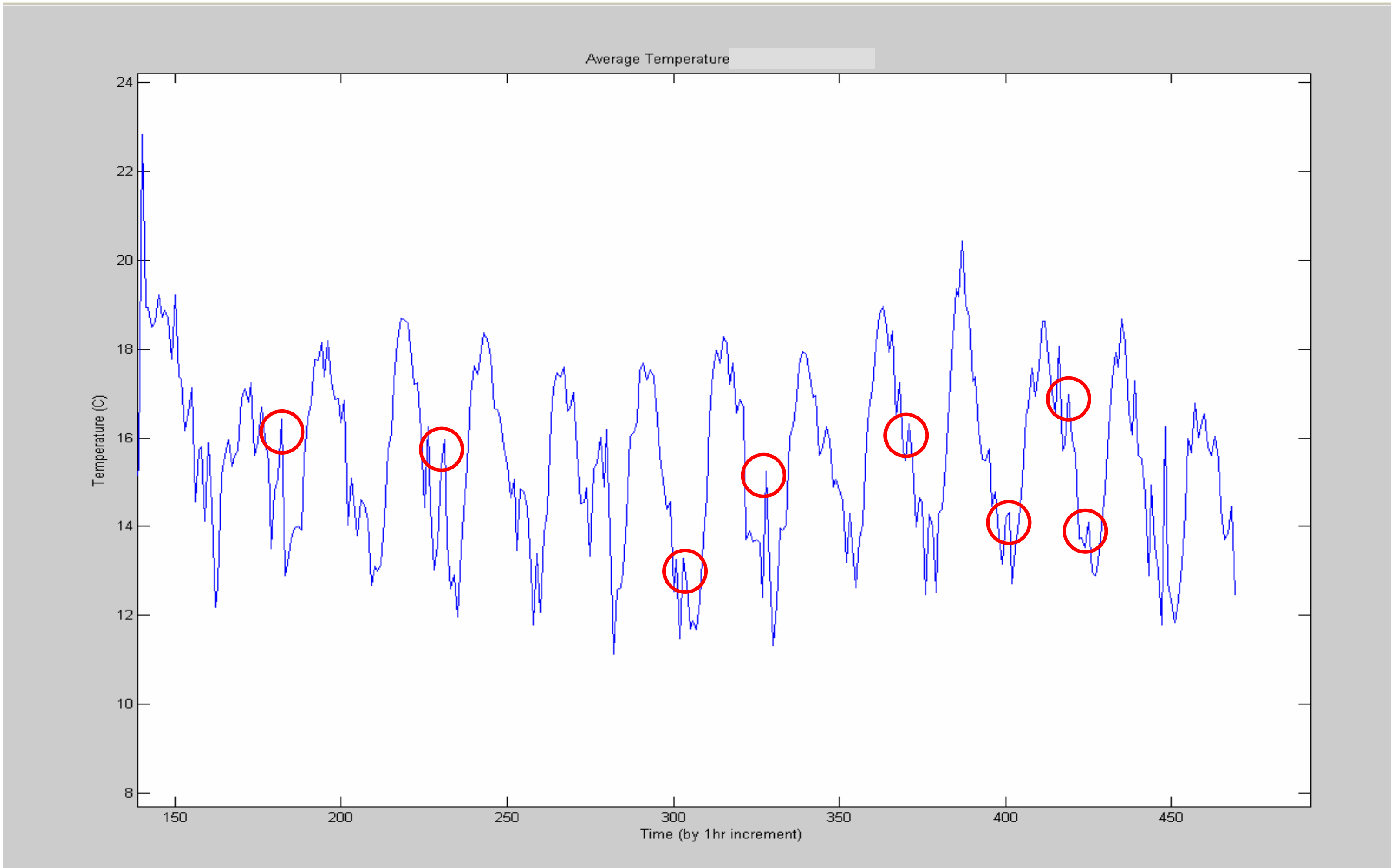

Figure 4.3 Daily temperature variations with jitter present for July 30th to August 20th, 2007 for meter markings on cable of 1077 to 1425m; typical examples of jitter circled.

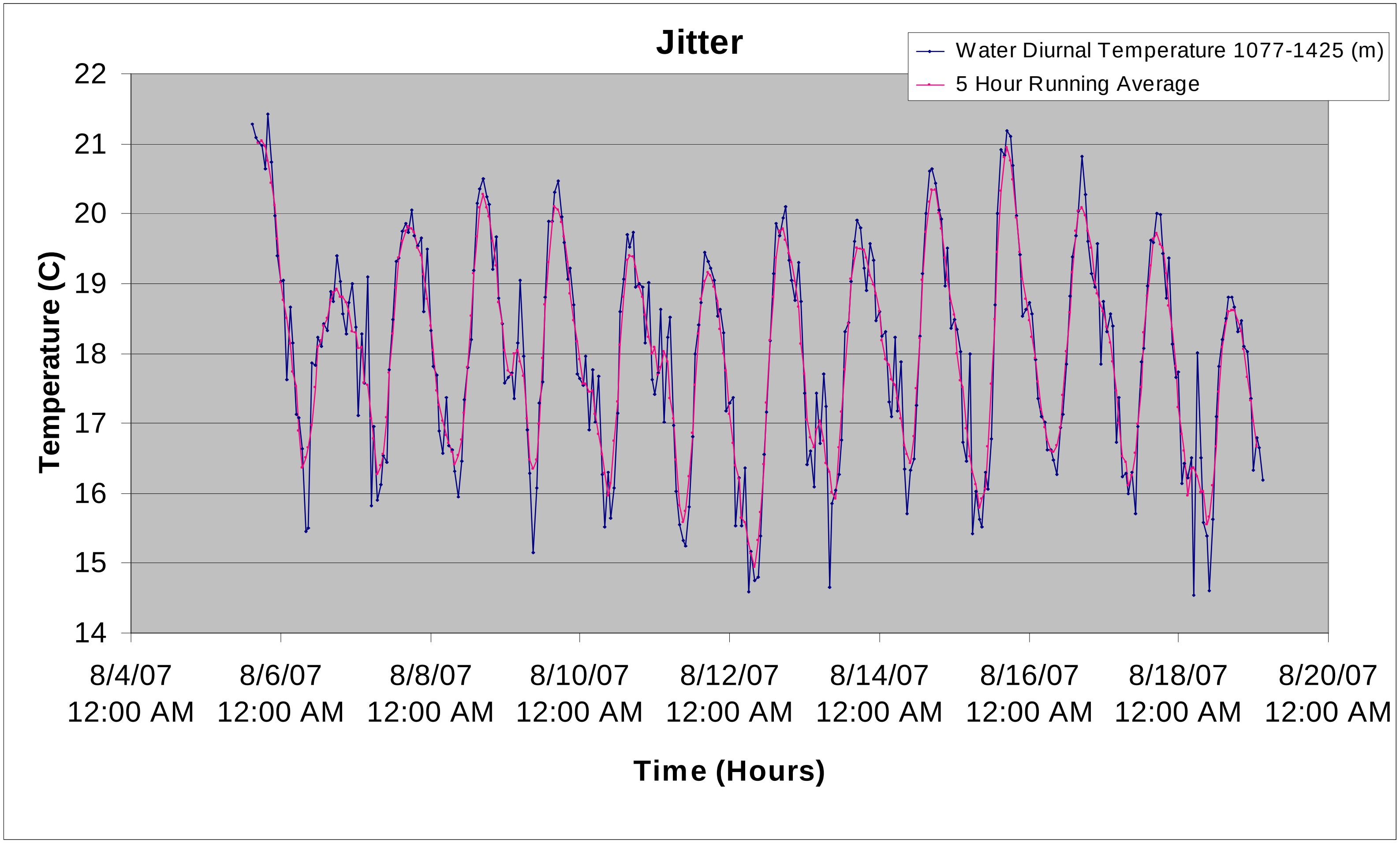

Figure 4.4 Daily temperatures from DTS with running average for to smooth Jitter from August 4th to August 20th from the 1077 to the 1425 meter mark.

Table 4.1 Surface water flow measurements and calculated ground water inflows. Shaded ground water inflow neglected in averages due to connector effect.

Ground Water		Surface Water	Temperature (C)			Ground Water	
Start (m)	Stop (m)	Flows (cfs)	Tg	Ti	To	Flow (cfs)	Flow (m^3)
315	355	32.8	14	17.96	17.87	0.76	0.02
460	500	34.2	14	18.04	17.96	0.69	0.02
630	705	32.5	14	18.12	18.00	0.98	0.03
918	940	32.6	14	18.04	17.84	1.70	0.05
978	1008	32.1	14	17.92	17.72	1.73	0.05
1610	1643	32.9	14	18.20	18.00	1.64	0.05
1900	2048	30.4			Average	1.25	0.04
	Average	32.9					

The data from ground water wells in the same aquifer indicate the average ground water temperature for July of 2006 (most recent data) to be 14° C. The ground water inflow sites were determined through the correlation coefficient from cool nighttime to the warm daytime temperature of the surface water (Figure 4.5). Any place that the two dropped in unison was designated as ground water and the distance that the drop lasted was recorded (see Figure 4.6 for specific sites). At each identified ground water inflow the temperatures from 10m before the drop to 10m after the temperature drop were recorded and the ground water inflows were quantified using (Table 4.1).

The traces for peak daytime temperature and for cool nighttime temperature (Figures 3.5 and 3.6) can be examined for hyporheic exchange as well. The overall average will not show any temperature shift or will show very little temperature structure for the location of hyporheic exchange. However, when comparing the peak daily to the cool nightly temperatures the location of hyporheic exchange should be noticeable. Remembering that these locations can be seen as temperature drops during the peak daily surface water temperatures, but should rise in temperature at the same location during the low nightly temperatures (see Figure 4.7 for possible hyporheic exchange sites). The temperature shift between night and daytime temperatures at these hyporheic exchange sites are a negative correlation coefficient (Figure 4.5).

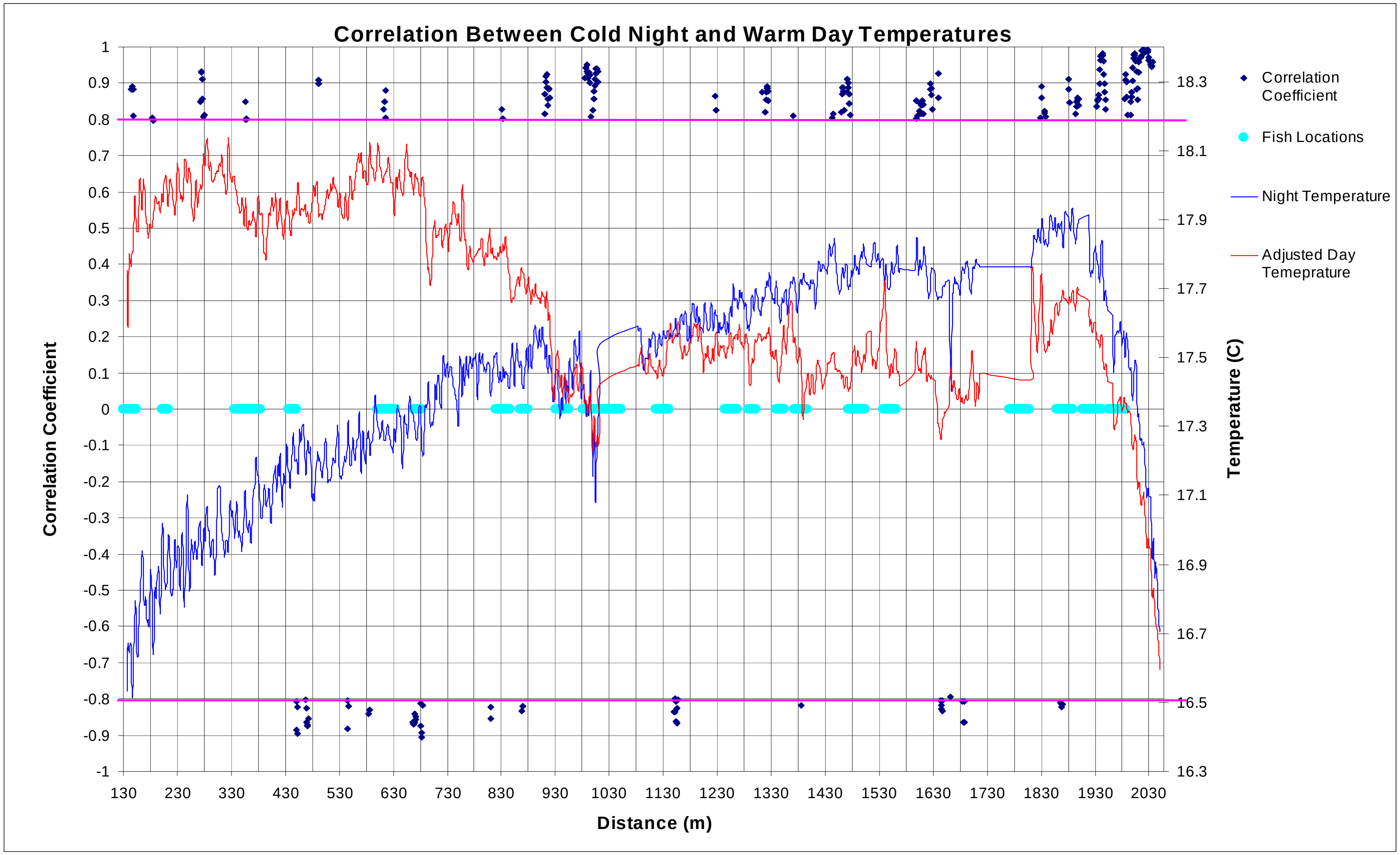

Figure 4.5 Average day summertime temperature reduced by 2.2 °C compared with a correlation coefficient to nighttime temperature for July 30th to August 20th, 2007 along the study reach in the Walla Walla River, Oregon. Light blue line represents locations fish were found from the USFWS survey.

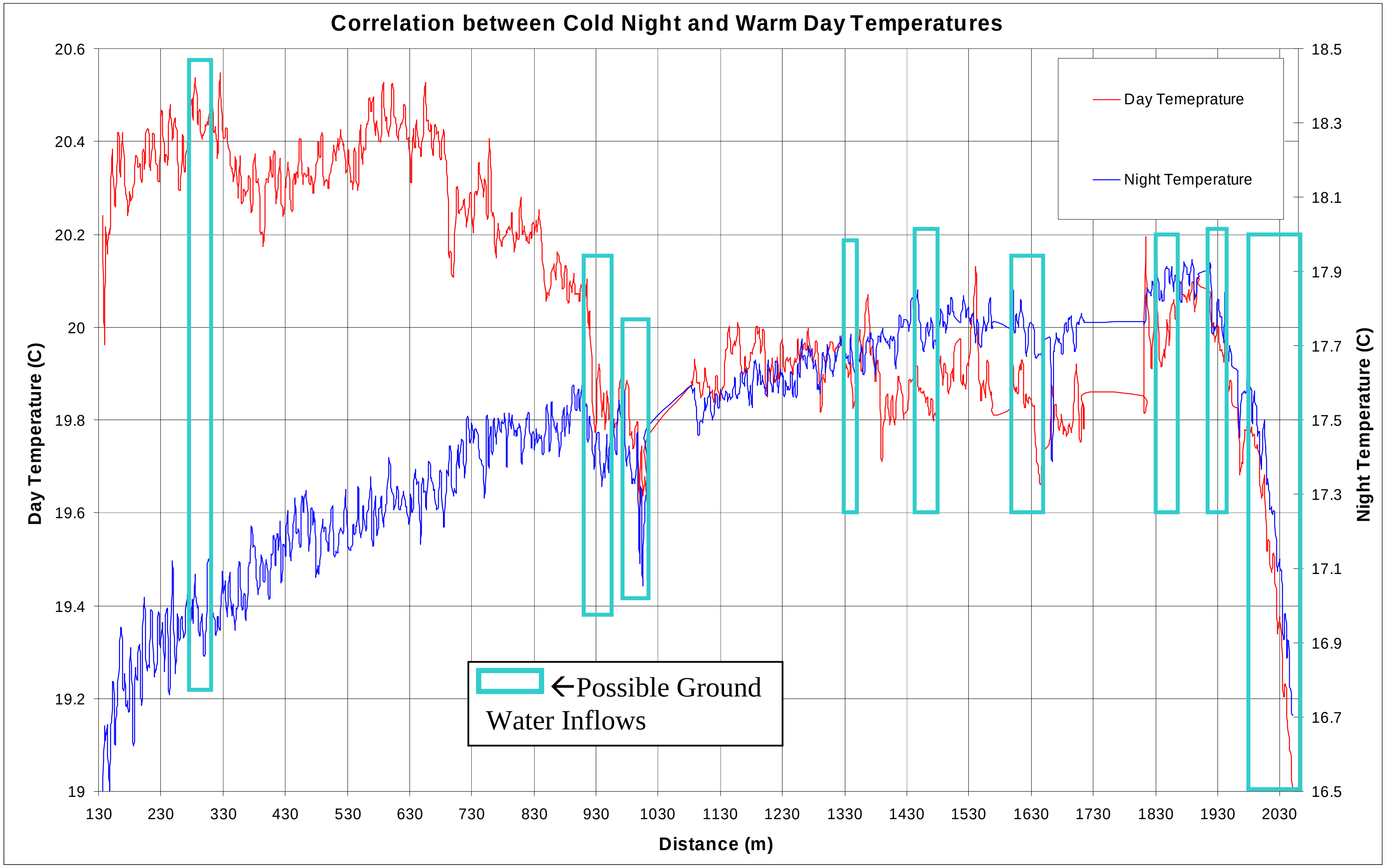

Figure 4.6 Possible locations of ground water inflows for the Walla Walla River study site based on temperature data from 30 July to 20 August 2007.

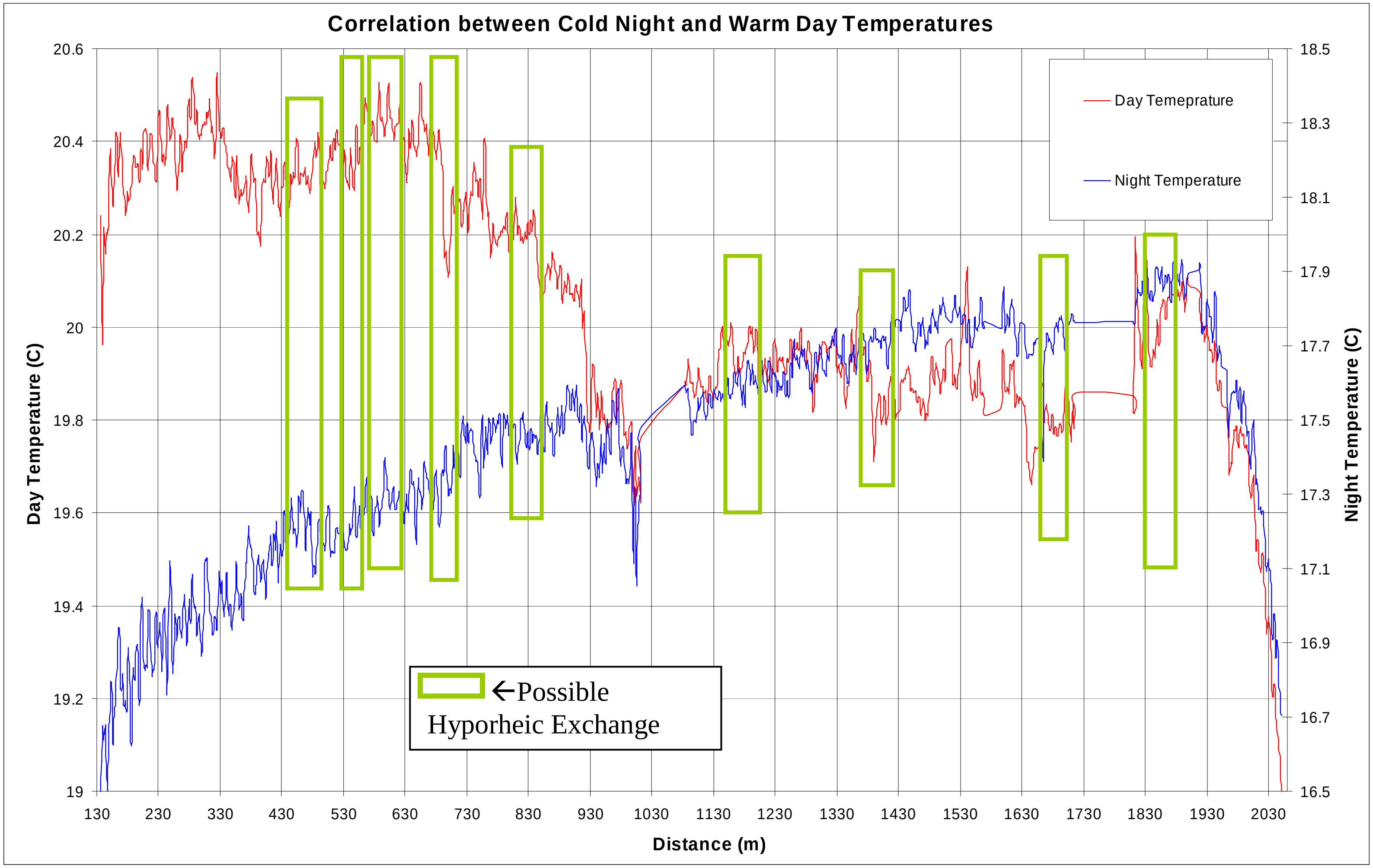

Figure 4.7 Possible locations of hyporheic exchange for the Walla Walla River study site based on temperature data from 30 July to 20 August 2007

4.3 Calculations

4.3.1 Solar Radiation

For this section the influence of solar radiation is considered. This calculation will be used to understand the expected magnitude of the solar radiation from sunrise to mid-day and the amount shade will reduce the surface water temperature. To complete this calculation we will use the solar radiation, a shade factor (the shade changes diurnally on the channel, we have used the shade expected during the mid-day peak solar radiation), and the channel's surface area. The total solar radiation will be determined based on the surface area of the water that is affected by the solar radiation. Using the Lefore Eto meteorological station data for the study duration we found the average hourly values of solar radiation from sunrise to sunset. The length for the site specific channel values was taken from the DTS measurements and the width was determined from a field visit (the width is not precise and therefore can be considered an assumed width). The calculation for the effect of shading at peak solar radiation can be completed as follows:

Peak solar radiation: 1000 W/m^2 or 1000 J/ (m^2s) (NASA, 2008)

Example shaded channel distance: 50 m

Average channel width: 10 m

Average water depth: 0.1 m

Heat capacity of water: 1 cal/ (gram °C) or 4.18 J/ (gram °C)

Water flow (Q): 32 cfs or 0.9 m^3/s

Velocity = Q / cross-sectional area

= 0.9 m^3/s / (0.1m*10m) = 0.9m/s

Time of water travel = distance / velocity

= 50m/0.9 m/s = 55 s

Water mass = density * volume

= 1g/cm^3 (1000cm*10cm*5000cm) = $5.0*10^7$g

Total Solar radiation = Travel time * solar energy * surface area

= 55.12s * 1000 J/ (m^2s) * 500 m^2 = $2.76*10^7$ J

Energy per water mass

= $2.76*10^7$ J / ($5.0*10^7$g) = 0.55 J/g

Change in water temperature from 50m of shade

= 0.55 J/g / (4.18 J/ (g °C)) = 0.13 °C

4.3.2 Ground Water

To quantify the expected down stream temperature in the river due to ground water inflow, it is necessary to use the flow and temperature of the upstream water and average it with the flow and temperature of each ground water inflow site. The following is a simple calculation to quantify the effect a ground water inflow has on the surface water temperature in our study reach in the Walla Walla River, Oregon. Surface water flow, 32 cfs or 0.9 m^3/s; average ground water inflow quantified (table 4.1), 1.4 cfs or 0.04 m^3/s; surface water average peak summer daytime temperature to be 20.44 $°C$ found from averaging the daytime temperature from the temperature measurements in Figure 4.6; and ground water temperature, 14 $°C$.

After mixing (weighted average) the expected down stream temperature is

= (0.9 m^3/s * 20.44 $°C$ + 0.04 m^3/s *14 $°C$)/ (0.04 m^3/s +0.9 m^3/s) = 20.18 $°C$

This calculation suggests that there is an average decrease of 0.26 $°C$ to the surface water per ground water site. All sites do not have the same flow, but here we have used the average flow expected for the typical ground water site along the study reach (see Table 4.2 for flow data). This value is useful when determining how much each ground water site throughout the study reach may decrease the river's overall temperature. Also, the calculated temperature decrease from ground water is important to find the expected energy stored in hyporheic exchange, which is discussed later in this thesis.

As discussed earlier, the ground water inflow sites (Figure 4.6) have a strong positive correlation coefficient because in summer months the ground water inflows are continuously at a cooler temperature than the surface water flow. Both nighttime and daytime temperatures at these sites will be cooler than the surface water

Table 4.2 Ground water inflows calculated; the inflow from 1980 to 2045m was neglected in average due to the possible end effects that could be giving a false decrease in temperature reading at this site. Standard deviations of surface water temperature of the 10m section before and 10m section after the ground water inflow are given.

Ground Water Start (m)	Ground Water Stop (m)	Surface Water Flows (m^3/s)	Temperature (C) Tg	Temperature (C) Cold Nighttime Ti	Temperature (C) Cold Nighttime To	Standard Deviation	Ground Water Flow (m^3/s)	Temperature (C) Warm Daytime Ti	Temperature (C) Warm Daytime To	Standard Deviation	Ground Water Flow (m^3/s)
240	260	0.93	14	16.98	16.94	0.06	0.01	20.45	20.30	0.02	0.02
600	630	0.97	14	17.38	17.23	0.04	0.05	20.47	20.33	0.03	0.02
918	940	0.92	14	17.57	17.38	0.11	0.05	20.08	19.78	0.07	0.05
970	1000	0.91	14	17.55	17.15	0.03	0.12	19.88	19.65	0.01	0.04
1330	1345	0.92	14	17.73	17.61	0.02	0.03	19.98	19.84	0.03	0.02
1445	1455	0.92	14	17.84	17.69	0.08	0.04	19.91	19.82	0.04	0.01
1825	1835	0.91	14	17.89	17.82	0.02	0.02	20.13	19.92	0.05	0.03
1925	1950	0.93	14	17.81	17.57	0.08	0.06	20.00	19.70	0.06	0.05
1980	2045	0.86	14	17.55	16.70		0.27	19.77	18.97		0.14
						Average	0.05			Average	0.03
							Average Inflow		0.04		

temperatures found upstream to these sites; one example is Figure 4.8. In Figure 4.8 the highlighted section of the graph shows that both the nighttime temperature and the daytime temperature both have a cooling trend in this location which, according to our definitions, is a ground water inflow.

Using the nighttime temperature change at meters 915 – 930, using the ground water inflow calculation we find:

$$Q_1 = 0.9\,\text{m}^3/\text{s} * \left(\frac{17.38\,°\text{C} - 17.57\,°\text{C}}{14.0\,°\text{C} - 17.57\,°\text{C}} \right) = 0.05\text{m}^3/\text{s}$$

And for a daytime temperature change at the same location we find:

$$Q_1 = 0.9\,\text{m}^3/\text{s} * \left(\frac{19.78\,°\text{C} - 20.08\,°\text{C}}{14.0\,°\text{C} - 20.08\,°\text{C}} \right) = 0.05\text{m}^3/\text{s}$$

this represents about 5 % of the total stream flow per ground water site.

4.3.3 Hyporheic Exchange

For this discussion hyporheic exchange will be characterized as an area where surface water drops below the bed material into the subsurface where it is not directly affected by solar radiation for duration of up to one day. The water then re-emerges to combine with the surface water. The temperature in the hyporheic exchange is based on the diurnal temperature cycle and therefore was important to set the passage of water through the hyporheic exchange to six hours. If the duration of water passage through the gravel was less than six hours it is expected that downstream temperatures would not cool off to the same degree that were found in the measurements. The water would not carry the temperature signature from a cooler time of day, but rather a signature from a time of day slightly prior to the recorded time. Likewise, if the time of travel were much longer than the six hours, a longer lag in the temperature would be expected and it will begin to re-enter the stream with a signature close to the average daily or average weekly temperature. If hyporheic exchange is defined by a longer duration it will be difficult to locate through DTS measurements. Water emerging with residence time greater than one day will be designate as a ground water for the purpose of this study.

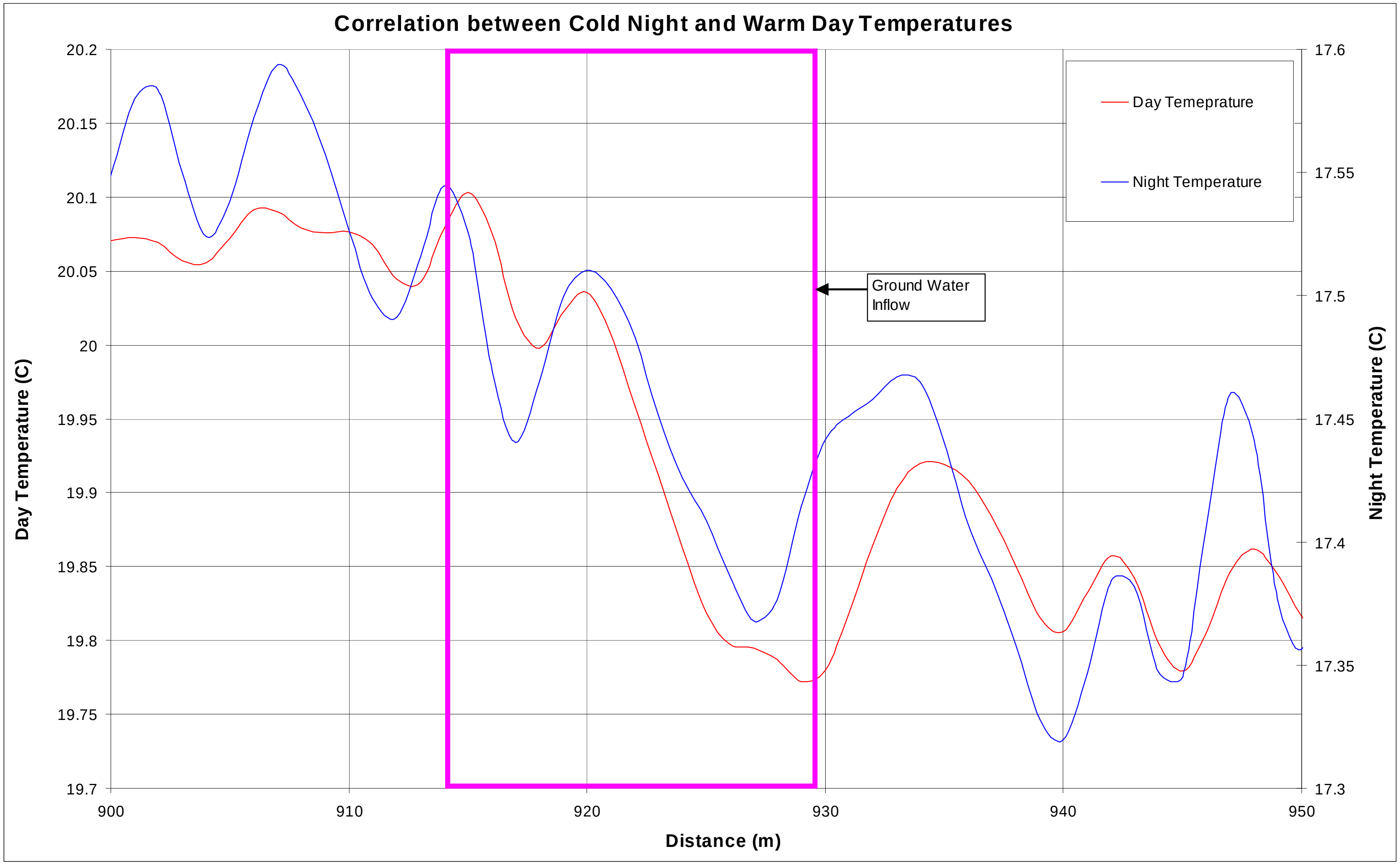

Figure 4.8 Example of a ground water inflow based on the locations found through the correlation coefficient from 915 to 930 meters.

For the hyporheic exchange we are interested in finding the depth of the hyporheic exchange that is necessary for the temperatures we have recorded along the fiber optic cable. For the data interpretation, a 6-hour travel time for water through the gravel will be used to further simplify the calculations. Through the energy balance incoming and outgoing calculated energies are used to find the necessary rate of change of stored energy in our control volume to show where any excess energy must have gone. The energy balance can be used to find the rate of change of stored energy in the control volume with the assumption that the hyporheic exchange is continuous over the entire study reach (1.7 km). In order to further understand the calculation it has been broken up into energy budget components and calculated for each hour from sunrise to peak solar radiation (the example calculations will be for 1pm, peak solar radiation for the Walla Walla River in August, 2007).

Incoming energy, $E_i = C_{vw}(T_u)(Q_s)$

$4.18 \times 10^6 \text{ J}/(°Cm^3) * 20.64\ °C * 0.9 \text{ m}^3/\text{s} = 7.8 \times 10^7 \text{ J/s}$

Solar radiation energy, $E_s = S(R)(F)$

$1011 \text{ J/sm}^2 * 20000 \text{ m}^2 * 0.9 = 1.6 \times 10^7 \text{ J/s}$

Ground water energy in, $E_{gi} = C_{vw}(T_{gi})(Q_{gi})$

$4.18 \times 10^6 \text{ J}/(°Cm^3) * 14\,°C * 0.32 \text{ m}^3/\text{s} = 1.9 \times 10^7 \text{ J/s}$

Ground water energy out, $E_{go} = C_{vw}(T_{cv})(Q_{go})$

$4.18 \times 10^6 \text{ J}/(°Cm^3) * 20.45\,°C * 0.32 \text{ m}^3/\text{s} = 2.0 \times 10^7 \text{ J/s}$

Lumped energy term, $E_l = L(R)$

$88.2 \text{ J/sm}^2 * 20000\text{m}^2 = 1.5 \times 10^6 \text{ J/s}$

Outgoing energy, $E_o = C_{vw}(T_d)(Q_s)$

$4.18 \times 10^6 \text{ J}/(°Cm^3) * 20.35\,°C * 0.9 \text{ m}^3/\text{s} = 7.7 \times 10^7 \text{ J/s}$

The rate of change of stored energy would be the incoming energies minus the outgoing energies, $E_c = (E_i + E_s + E_{gi}) - (E_{go} + E_l + E_o) = 6.5 \times 10^6 \text{ J/s}$

This was done for all hours from sunrise to the peak mid-day solar radiation (Table 4.3) and the sum was computed. The depth of the hyporheic exchange can now be found from the cumulative amount of energy that went into storage. This depth can be computed with the known volumetric heat capacity of both water and sediment in the control volume, the porosity of the bed material, and the known volume of surface water.

Table 4.3 Calculated hourly energy fluxes.

Hour	Ei (J/s)	Es (J/s)	Egi (J/s)	Ego (J/s)	El (J/s)	Eo (J/s)	Ec (J/s)
5am	5.4E+07	2.2E+05	1.9E+07	2.0E+07	2.8E+06	5.8E+07	-8.2E+06
6am	5.7E+07	2.1E+06	1.9E+07	2.1E+07	2.8E+06	6.0E+07	-5.7E+06
7am	6.1E+07	4.5E+06	1.9E+07	2.2E+07	2.6E+06	6.3E+07	-3.5E+06
8am	6.5E+07	7.5E+06	1.9E+07	2.3E+07	2.4E+06	6.5E+07	-1.4E+05
9am	7.0E+07	9.7E+06	1.9E+07	2.5E+07	2.0E+06	7.0E+07	1.6E+06
10am	7.3E+07	1.2E+07	1.9E+07	2.6E+07	1.6E+06	7.3E+07	3.1E+06
11am	7.6E+07	1.3E+07	1.9E+07	2.7E+07	1.5E+06	7.5E+07	4.3E+06
12pm	7.7E+07	1.5E+07	1.9E+07	2.7E+07	1.4E+06	7.6E+07	6.1E+06
1pm	7.8E+07	1.6E+07	1.9E+07	2.7E+07	1.5E+06	7.7E+07	6.5E+06
						Sum	4.0E+06

The apparent heat capacity of the hyporheic exchange should equal the heat capacity of the overlaying water (C_{vw}) plus the heat capacity of the sediment (C_{vs}) (2.64×10^6 J/($°C$ m^3)) (Kulongoski and Izbicki, 2008) and the water in the hyporheic exchange combined. Using these values we may calculate the apparent hyporheic exchange depth. The heat capacities used are volumetric so the volumes of water (V_w) and hyporheic exchange (V_h) must be incorporated. These volumes are necessary to calculate the depth of hyporheic exchange. The volume for the hyporheic exchange is based on porosity for the alluvium; the stream bed material for the study has an assumed porosity of 0.3. Once the volume for the hyporheic exchange is found, the depth can be derived by dividing the volume by the surface area (SA) for the reach; 17,080 m^2. For a continuous hyporheic exchange in this study reach we can calculate the volume as:

$$V_h = \frac{\dfrac{32400s * 4.0 * 10^6 \ J/s}{5.3°C} - 4.18 * 10^6 \ J/m^3°C}{0.3 * 4.18 * 10^6 \ J/m^3°C + 0.7 * 2.64 * 10^6 \ J/m^3°C} = 5530m^3$$

V_h/SA = Depth

5530m^3 / 17080 m^2 = 0.32 m

0.3 m *100 cm/m = 30 cm

Having assumed that there is 10 cm surface water present above these locations of hyporheic exchange (based on field visits) the same methodology as used for the continuous hyporheic exchange above is acceptable for discrete locations of hyporheic exchange with one exception; the surface area of allowable exchange has been limited. The volume of the discrete hyporheic exchange will still be the same:

$$V_h = \frac{\dfrac{32400s * 4.0 * 10^6 J/s}{5.3°C} - 4.18 * 10^6 J/m^3 °C}{0.3 * 4.18 * 10^6 J/m^3 °C + 0.7 * 2.64 * 10^6 J/m^3 °C} = 5530 m^3$$

However the surface area of interaction has changed:

5530 m^3 / 3100 m^2 = giving 1.8 m of depth per site.

Individual locations, determined through the negative correlation coefficient between night and daytime surface water temperature measurements, of hyporheic exchange can be seen in Figure 4.9.

4.4 Fish locations

The last objective of this research was to compare the USFWS fish survey with the locations of cool water refugia that had been determined through the correlation coefficient. The USFWS survey was overlain on the hyporheic and ground water sites found through the stream analysis. This was done to see if the cold water fish species are congregating in cool water inflows during the warmest times of the day. Through this comparison the number of cold water fish found at these sites is compared to the total amount of cold water fish found over the entire reach (see Figure 3.3 for satellite imagery of the stream reach). Table 4.4 shows the fish location data collected by the USFWS during their fish survey completed for the study reach. Through the cool water location data and the fish survey data, a greater understanding of where fish may be located to avoid warm river temperatures in the Walla Walla River may be realized. The percentage of fish congregating at cold water refugia sites and whether they are cold water species is seen in Table 4.5 and is discussed later in this thesis. Ultimately, this may provide valuable information for the protection of these species.

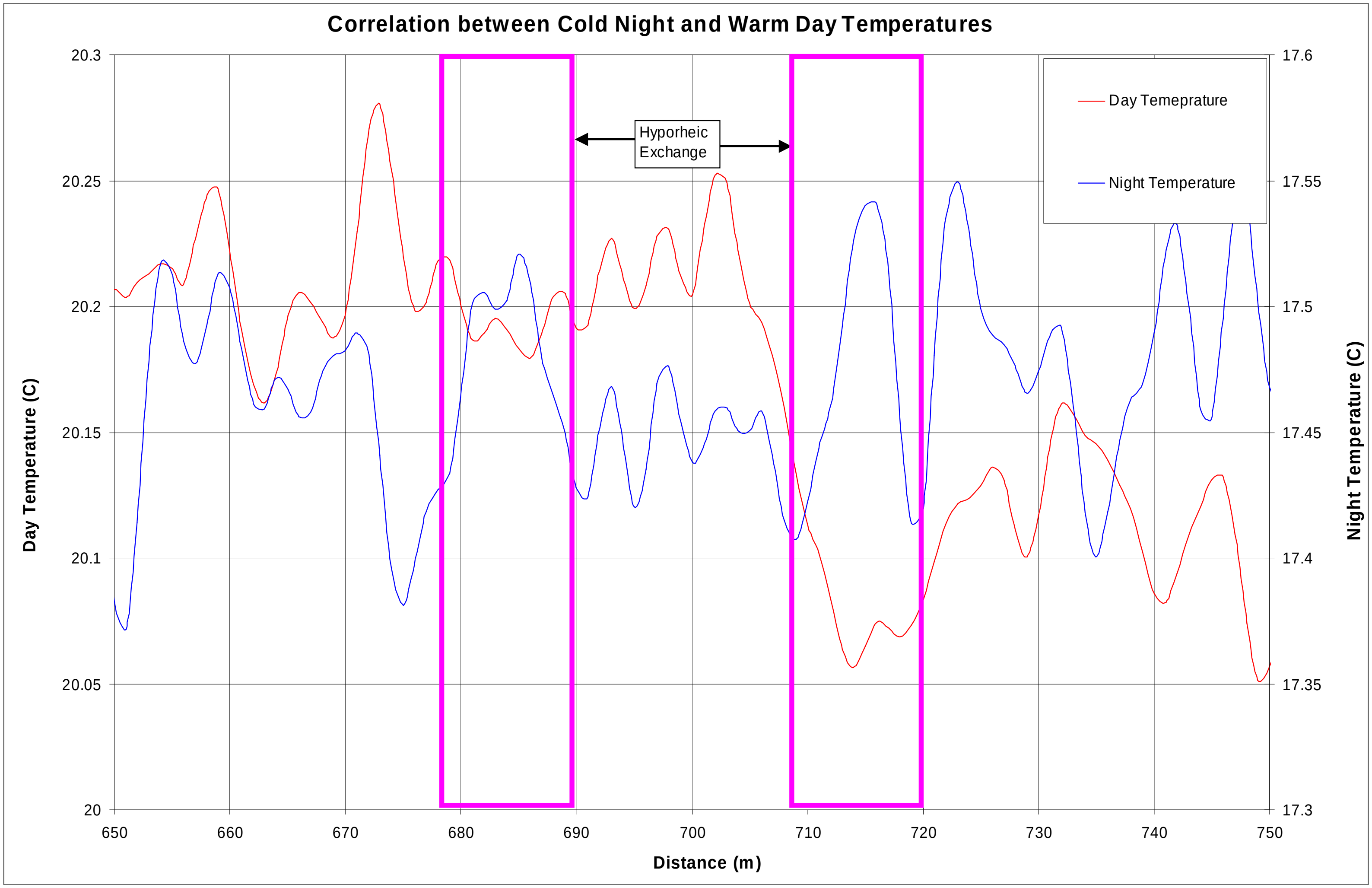

Figure 4.9 Two examples of hyporheic exchange based on the locations found through the correlation coefficient.

Table 4.4

Snorkel surveys completed on 8/16/2007. This survey was completed by Courtney Newlon, Marshall Barrows, and Ryan Koch of the USFWS, Columbia River Fisheries Program Office, Vancouver, WA.

Snorkeling started at the downstream end of cable and ended at Maurer Lane.

Cable start (meters)	Cable end (meters)	Hat. CHK juv	Nat. CHK juv	O. mykiss juv	Redside Sh.	Dace	sucker	N. pikeminnow	Adult Chinook
13	45	0	24	12	200	200	60	100	0
58	85	0	17	10	50	150	10	25	0
68	94	3	6	7	80	150	20	15	0
111	141	2	25	21	100	150	20	20	3
192	228	3	8	20	50	250	100	25	0
438	462	2	75	30	200	300	10	30	0
496	527	0	15	4	25	500	25	5	0
604	627	0	160	22	200	400	35	25	0
645	660	0	20	0	250	200	100	10	0
698	712	0	144	25	100	200	40	15	0
733	756	0	26	3	50	300	25	15	0
860	883	1	194	55	300	500	100	50	0
948	1018	0	15	35	50	100	0	5	0
1045	1068	2	40	18	50	100	10	10	0
1120	1135	0	19	8	50	20	5	2	0
1154	1180	1	40	25	150	300	40	30	0

Table 4.2 (continued)

1318	1332	1	16	15	20	150	5	2	0
1366	1398	4	128	60	100	400	60	30	0
1550	1564	0	41	27	20	250	0	3	0
1616	1664	0	105	63	200	550	75	100	0
1787	1798	0	23	5	18	55	0	3	0
1845	1886	1	75	38	100	200	50	25	0
		Hat. CHK juv	Nat. CHK juv	O. mykiss juv	Redside Sh.	Dace	sucker	N. pikeminnow	Adult Chinook
	Totals	20	1216	503	2363	5425	790	545	3

Table 4.5 Fish locations from USFWS survey in connection with sites of refugia

Shading for locations with ground water inflow or hyporheic exchange				
Cable start (meters)	Cable end (meters)	Distance (meters)	All fish	Chinook Salmon and Rainbow Trout
1987	1955	32	596	36
1942	1915	27	262	27
1932	1906	26	281	16
1889	1859	30	341	51
1808	1772	36	456	31
1562	1538	24	647	107
1504	1473	31	574	19
1396	1373	23	842	182
1355	1340	15	580	20
1302	1288	14	524	169
1267	1244	23	419	29
1140	1117	23	1200	250
1052	982	70	205	50
955	932	23	230	60
880	865	15	104	27
846	820	26	586	66
682	668	14	209	32
634	602	32	782	192
450	436	14	341	68
384	336	48	1093	168
213	202	11	104	28
155	114	41	489	114
% stream length in refugia with fish present		17.8		

	All Fish	Cold water species
Total Individuals residing in refugia	5810	1015
% of Individuals residing in refugia	53	59

5.0 Discussion

When the data analysis was first underway some issues arose that had to be managed for; this included the high noise in this data set and the jitter from the DTS. The temperature profiles for this study had high noise; the standard deviation in the data is 0.52 °C. This high noise is probably due to the high loss cable used (discussed further in the concluding remarks of this thesis) and the short distance that was used to integrate the temperature over (one meter). For the jitter found in this data set a smoothing average was employed to have the data follow the smooth daily temperature variations that are occurring in the natural setting. Still some small bumps in the data remain. These bumps, seen in Figure 4.3, may represent true temperature variations that occur in this river. The river is completely regulated during the time of year the cable was deployed. The temperature changes may be due to water being drafted or diverted for agriculture up stream of the study reach (per communication with WWBWC, 25 June 2008).

5.1 Solar Radiation Blocked

Solar radiation is the largest contributor to river heat and is therefore important to understand. It is equally important to understand what happens to the river temperature when the solar radiation is blocked. Shading blocks solar radiation, in essence, cooling a stream reach by reducing the heat load (Hostetler, 1991; Naiman et al., 1992; Davies and Nelson, 1994; Li et al., 1994; Poole and Berman, 2001). The magnitude of reduced heating from shading can be seen through simple calculations that account for the heat capacity of water, the solar radiation input, the surface area of the river, and the flow for the river. The objective is to see if these calculations will show that the heat blocked from a shaded stretch of a river reach will be noticed in the DTS temperature profile of the study reach.

Let us consider the difference a 50-meter patch of shading would have on a 2000-meter section of river. The addition of a 50-meter patch of shade would result in a 0.13 °C reduction in the peak downstream temperature, as seen in the results section.

This calculation was completed using the peak summertime solar radiation of 1000 Watt/m^2, as discussed earlier. This gives the basic understanding of what may be expected for a small section of shade in a 2000-meter segment of river in a location similar to the Walla Walla River where this study was completed. Due to the high noise in our measurements and the gradual nature of surface water cooling from shade we are unlikely to detect the discrete temperature changes from shade, in our study reach. A single patch of shade will have a temperature change that would fall within the standard deviation of a single trace.

Now consider our study site in the Walla Walla River specifically. A majority of the river had limited vegetative cover during the peak solar radiation. There was approximately triple the amount of shade from the above example, 150-meters of shade over the entire 2000-meter stretch that was surveyed. This suggests a maximum of 0.47 ° C mid-day reduction of temperature once the water flows from the top to the bottom of the 2000-meter study reach. Since this temperature change in the natural setting is gradual for the river reach (shading is in distinct locations covering the entire river at some locations, and is in patchy spots for other locations) sudden drops in the DTS temperature trace due to the shaded sections are not expected. Cumulatively these shaded sections have an effect on the reach, giving a net change of temperature for the entire study reach of 0.47 ° C. This shows how re-vegetating a river may decrease the river's temperature significantly if completed over a long stretch of the river. Shading a river can have a large cumulative affect on decreasing the river's overall daily temperature. This is especially true for those rivers that need a 1 or 2 °C drop in the peak temperature for their TMDLs. By shading an additional 300 meters of the study reach we would expect approximately a 1 °C drop in the temperature of the outflow of the reach during peak temperatures.

This same calculation can be used to find solar heating for the entire 2000 meter reach un-shaded. When calculated for peak daily solar radiation, an increase in temperature by about 40 times this amount or 5.3 ° C was found. If the 2000 meter study reach was not shaded the water temperature would increase 5.3 ° C from beginning to end of the study reach. Through this we can see that when a river reach has its vegetative cover completely removed, we may expect some devastating affects on cool water dependent fish species. The shade does not create any sudden changes in structure in the temperature profile that would give rise to thermal refuge for surface water species; however it does keep the river from maximized temperatures.

For the study reach the heat blocked by shade is scattered and is therefore difficult to quantify and locate through the DTS measurements. Much of this study reach has full sun exposure and is not well shaded. This study will take into account the effect shade will have on blocking solar radiation, but will not try and find an example of shading using the DTS measurements. There may be a reduction in temperature for the entire river due to shade, but for the study reach it is difficult to locate specific changes from the DTS temperature data due to stream shade.

5.2 Refugia

The hyporheic exchange and ground water inflow sites (Figures 4.6 and 4.7) were found by using DTS temperature data. The sections of the river that were identified through the correlation coefficient as either hyporheic exchange or ground water inflow were then visually checked to see if the locations agreed with our understanding of what a ground water inflow or hyporheic exchange location would look like from temperature profiles of the river. We have created a method to continuously locate areas along any particular river reach that give the most amount of cooling. These locations can be differentiated and maintained in order to help ensure that cooling at the hyporheic exchange and ground water sites during peak temperatures continues.

One concern with temperature measurements from the DTS system is the magnitude of the temperature change that the DTS measures from the cool water input to the river. The DTS is giving a reading every meter, but the water flowing from the hyporheic exchange may not fully mix for several meters, so a false reading for the amount of cooling occurring to the surface water from hyporheic exchange or ground water input may be seen. If the surface water is not completely mixed with the cool water inflow a larger drop in temperature for each cool water inflow site would be used in the calculations, giving calculated cool water inflows that are larger than reality.

5.2.1 Ground Water Inflow

The ground water inflow sites were chosen based on the positive correlation coefficient between the night and daytime temperatures. This was then visually inspected to make sure that the temperature pattern expected for ground water is found from the data determined to be ground water through the correlation coefficient. Areas that are not accepted as ground water inflow sites are discussed later. For an example of ground water inflow see Figure 4.8, the correlation coefficient for the site is 0.95. The expectation for a strong positive correlation for a ground water location is a sudden drop in temperature for both night and day time temperatures. Surface water temperatures will not show a sudden decrease in temperature continuously for the three week average day and three week average nighttime temperatures unless a cooling source enters the river. For the data from the Walla Walla River, locations that have the characteristics seen in example Figure 4.8 are considered ground water sources. Through the DTS method we have successfully located cool ground water inflows to the study reach. This information will be useful for the Walla Walla Basin Watershed Council to help protect cold water fish in the region.

The ground water inflows were based on the surface water flows found in the river at one hour of the day. This river fluctuates in surface water flow during the summer months due to withdrawals upstream. The fluctuating surface water flows will give a fluctuating computed ground water inflow; this was not accounted for in this thesis. The surface water flows from the single hour flow survey were used to show the utility of the hyporheic exchange calculation not for accurate daily ground water flow measurements.

5.2.2 Hyporheic Exchange

The apparent global hyporheic exchange and evidence for local hyporheic exchange were also considered in this research. The difference in energy inflows and outflows to the study reach will show the amount of energy the hyporheic exchange must have stored. For the hyporheic exchange calculation to find the incoming water temperature the first 50 meters of DTS surface water temperature data were used. For the outgoing water temperature the last 50 meters of DTS water temperature data were used. By subtracting the average daily temperature from the peak daily temperature for the upstream section, we find a $1.73\,°C$ average daily and when the same is done for the downstream section we get a $0.88\,°C$ average daily increase. Making this calculation we see that the upstream temperature change is greater than the downstream temperature change. So a question that was brought up is what happened to this excess temperature? We think that this can be explained through the hyporheic exchange sites in the river.

The stored energy in the control volume gives the necessary thermal mass for the hyporheic exchange in order for the downstream temperature of the study reach to have a temperature lower than what would be found through the energy budget if no hyporheic exchange was considered. Because there is no assumed depth we can use the heat capacity of the hyporheic exchange and surface area of the river to determine the necessary depth of the hyporheic exchange.

From what has been calculated for the thermal mass of the hyporheic exchange the necessary depth for this zone can now be found. This depth is the distance that surface water had to continuously infiltrate into the streambed for the entire reach length in order to create the energy exchange needed for the downstream temperature found in the DTS temperature profile.

The effective depth that the surface water flowed into the hyporheic is approximately 30 cm. This is on the same order as the 2.5-15cm range that Harvey et al. (1998) found for similar stream bed porosity as this study (0.3). This indicates that approximately 50 percent of the total water is continually in hyporheic exchange, or that an additional 9.6 cm of water can be found in the sediment below the 10 cm of surface water that is flowing along the stream reach.

It is important to consider locations of hyporheic exchange that may be located through the DTS temperature measurements; these are the discrete hyporheic exchange sites. The same calculations as used for continuous hyporheic measurement were for the effective depth of the hyporheic exchange at each of the discrete hyporheic exchange locations. Each site is assumed to have had 10 cm of surface water above them so a majority of the water flows through the porous media of the stream bed. The nine locations where the discrete hyporheic exchange takes place will be used; this is based on a -0.8 correlation coefficient or less.

By changing the calculation from a continuous hyporheic exchange to discrete locations of exchange, while maintaining all other aspects of the study channel equal, each hyporheic site would have approximately 1.8 meters depth of exchange. This depth for a single hyporheic exchange site is comparable with some of the findings by Fellows et al. (2001) where one of the streams in their study had a hyporheic exchange depth of 2.04 meters. This means that below the 10 cm of water on the surface there is an additional 50 cm of water within the sediment, or that 80 percent of the total amount of water is flowing through hyporheic exchange at these locations. This does not seem impractical from what was seen in the field. These calculations show that this new method of locating and describing hyporheic exchange continuously along a river reach looks to be comparable to past research. This method has advantages over past methods in that it will continuously locate the hyporheic exchange and show the temperature dynamics found at the research site. An additional aspect of the method is the use of simple calculations to find the depth of hyporheic exchange sites.

Once the negative correlation has been validated the hyporheic exchange site can be used to quantify the expected depth of sediment that is needed for the amount of cooling that had taken place. For the representative site chosen in Figure 4.9 from distance 705 to 720m the correlation coefficient from Figure 4.5 is found to be -0.83. From Figure 4.9 we can see that at night the river temperature increases approximately 0.1 °C at this location and during the day time the river temperature decreases approximately 0.2 °C at the same location. The calculation was completed for this site that shows the hyporheic depth of exchange for to be approximately 1.8 m in order to reduce the temperature of the water by the amount viewed in the DTS data.

In reality both global and localized hyporheic interaction processes take place, but the analysis completed thus far will be enough to help identify these locations in the DTS data from the research site. One additional point must be made; some of the calculations done here were based on assumptions for the data, or data from a different year, or from low quality data. If higher quality data that represented the exact times considered were used the calculated hyporheic exchange depth would become much more accurate.

The river characteristics that are used for the calculations for the global hyporheic exchange were not very accurate and could easily be off by 25%. So let us consider a situation where the river characteristics make the river cooler, which should give a hyporheic exchange that is not as deep. We will say that the river is 7.5 m wide instead of 10 m, the flow is 1.1 m^3/s instead of 0.9 m^3/s, the 35% of the channel is shaded instead of 10%, and all other factors will remain the same. This would give a negative 4.5 m depth of hyporheic exchange. This means that for these new river characteristics and the temperature change of the control volume we would actually need the hyporheic exchange to increase the temperature of the river. Another possibility is that the river characteristics make a warmer situation than we have shown. Now the river is 12.5 m wide instead of 10 m, the flow is 0.7 m^3/s instead of 0.9 m^3/s, the 0% of the channel is shaded instead of 10%, and all other factors will remain the same. For these river characteristics and the same temperature change for the control volume the global hyporheic exchange would need to be 2.7 m in depth. We can see how accurate measurements of the river's characteristics are important to give accurate measurements of hyporheic exchange depth.

We can also consider how hyporheic exchange changes the river temperature. For the original hyporheic exchange calculation we find the control volume's outflow temperature from sunrise to daily peak solar radiation to have changed by 5 °C. If there is no hyporheic exchange (such as a bedrock reach) we would see this change to be 7 °C and if the hyporheic exchange was doubled we would find the temperature change of the river from sunrise to the daily peak solar radiation to be 3 °C. During peak solar radiation the temperature of the river dropped by 0.1 °C from the bedrock scenario to the hyporheic exchange found in our calculations then dropped another 0.1°C when the hyporheic exchange was doubled.

5.3 Fish Response to Cold Water Inflows

Cross-analysis of the fish survey with the DTS data shows that 60% of the cold water fish (salmonids and trout) were found in the cold water inflow locations that make up 18% of the river, showing that the areas identified by the DTS to be either ground water or hyporheic exchange had over three times the density of cold water fish population than the overall stream. In addition, when cold water fish and warm water fish are combined, 53% of the fish are found in 18% of the river at these cold water inflows (see Table 4.5). This shows that most of the cold water fish will reside at these cold water inflows during warm summer months. A cold water inflow does not seem to be the only attribute that determines fish presence. An additional 13% of the river reach consisted of cold water inflows but did not have fish present. This suggests that cold water inflows are not the sole driver for cold water fish movement, but are one of the defining attributes.

5.4 Difficulties

This research was new and exploratory which led to many difficulties along the way. In this section we will disclose some of the problems that were faced so projects in the future will not follow the same path.

One such difficulty came up when visually validating the cool water inflows determined through the correlation coefficient. Occasionally the cool water inflows were not found at the locations where they were expected from the correlation coefficient analysis. An example of this was when the cable was out of the water as seen in Figure 5.1 from 1570 to 1583 meters. This can happen when the cable is moved around by the water during high flows (if the cable is not well anchored to the river bed) or when people or animals drag the cable out of the water. The cable is also taken out of the water when there is a connector or if the cable is placed into an ice or water bath. At these locations you may find air temperatures show up in the data.

These locations are easy to identify; they will have a strong negative correlation similar to the hyporheic exchange sites, but the temperature will follow the diurnal cycle (warm in the day and cold at night), unlike the expectations for a cool water refugia. This is because the DTS will be measuring the air temperature which has greater peaks than the surface water temperature. For this study the air temperatures, were removed prior to data interpretation.

Unexpected warm water additions to the river added an additional problem with data analysis. This discrepancy was found in the data when using the correlation coefficient to locate cool water inputs. It could be seen as a continuous warm water inflow, such as an agricultural return flow (see Figure 5.1 from a distance of 1627 to 1634 meters for an example). The correlation coefficient for this site is strongly positive (0.95) which would lead us to believe it is a ground water inflow. Visual inspection reveals the opposite of what is expected for a ground water inflow. Instead of the expected ground water temperature change (a drop in temperature both day and night) an increase in temperature both day and night is found, possibly giving the signature that would be expected from an agriculture return flow or some other warm water supply continuously entering the river at this location.

When barrel connectors (a female / female connector, see Figure 5.2 at the 1030 meter distance) are present, there is an increase in the amount of light that escapes; giving more loss. In this circumstance both the night and day time temperature will either remain at an extremely high or low temperature (Figure 5.3). This is for a short distance and has much higher amplitude than the temperature variations that are expected. This large loss at the site of the barrel connecter will give more noise in the signal for the remainder of the measurements. Another problem is that the connectors themselves have shown temperature dependency, this was seen in a project completed at Lake Tahoe (accepted for publication at Water Resource Research, 2008). In addition, it is important to have the connectors be sealed from water. For this reason in this project the connectors remained out of the water which gives us an increased amount of air temperature data. The sections of river where this occurs can be removed from the data set so that it they will not impact any data analysis. However, due to the double-ended nature of the temperature measurements, the locations have already increased the noise of the temperature measurements. This barrel connector affect shows that fusing cables together may be a better option than trying to use the barrel connector.

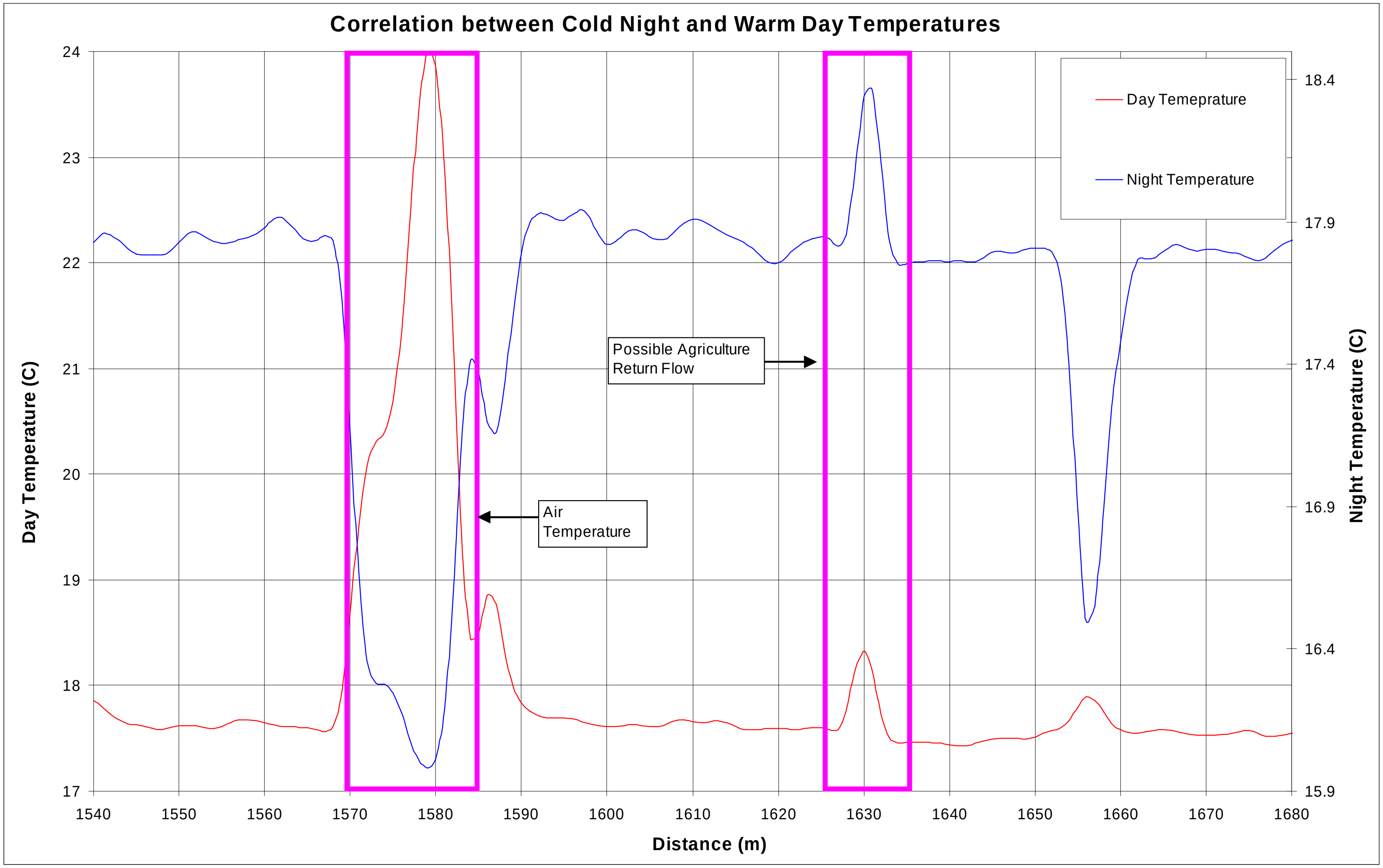

Figure 5.1 Result of air temperature (giving a false hyporheic exchange reading from the correlation coefficient) and agricultural return flow (giving a false ground water inflow reading from the correlation coefficient) in the temperature data.

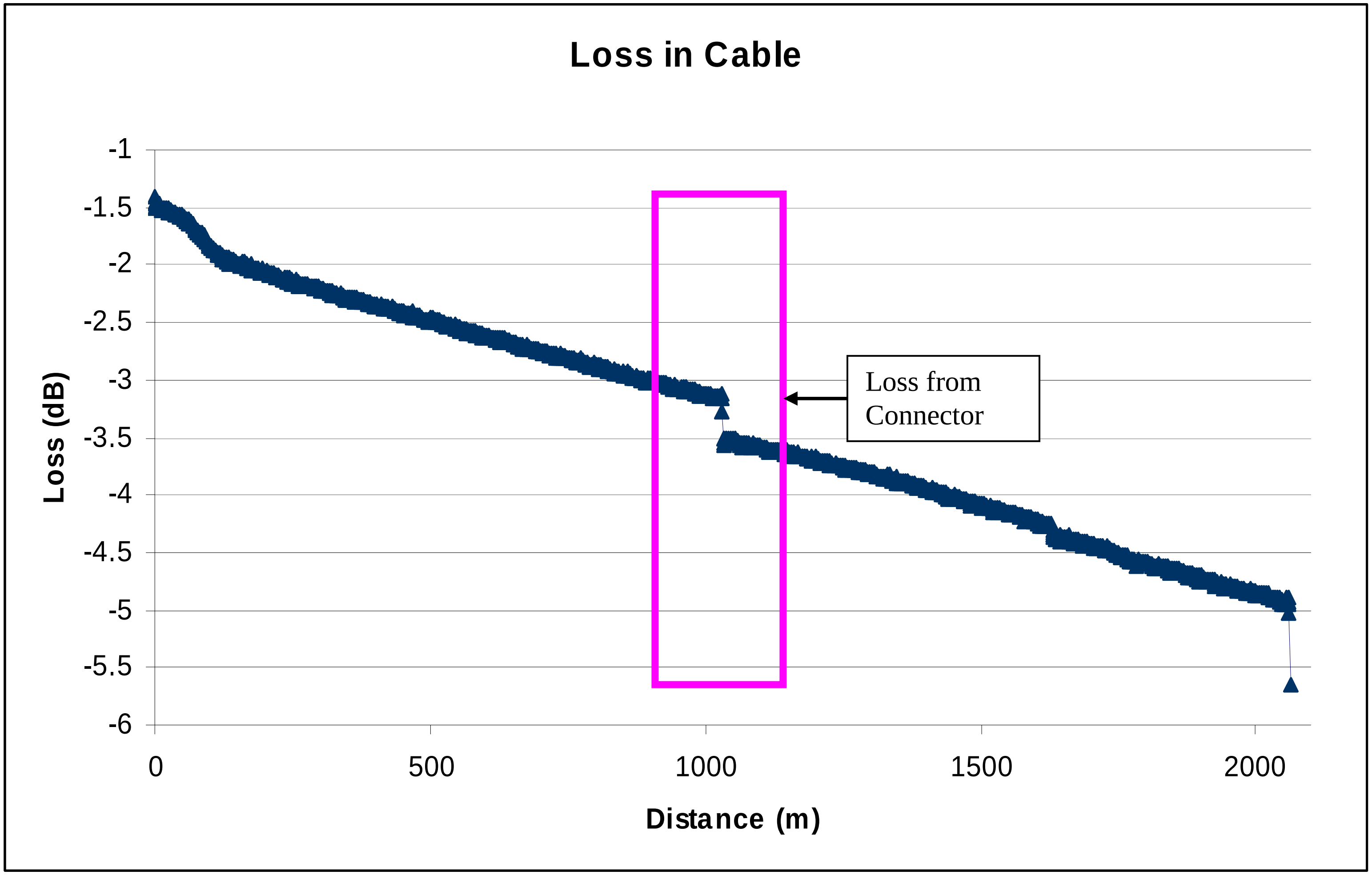

Figure 5.2 High loss cable (acceptable loss is 1dB/ km) and an approximate 0.5 dB loss encountered at a barrel connector at 1030 and 0.75 dB loss at the barrel connector at 2060 meters.

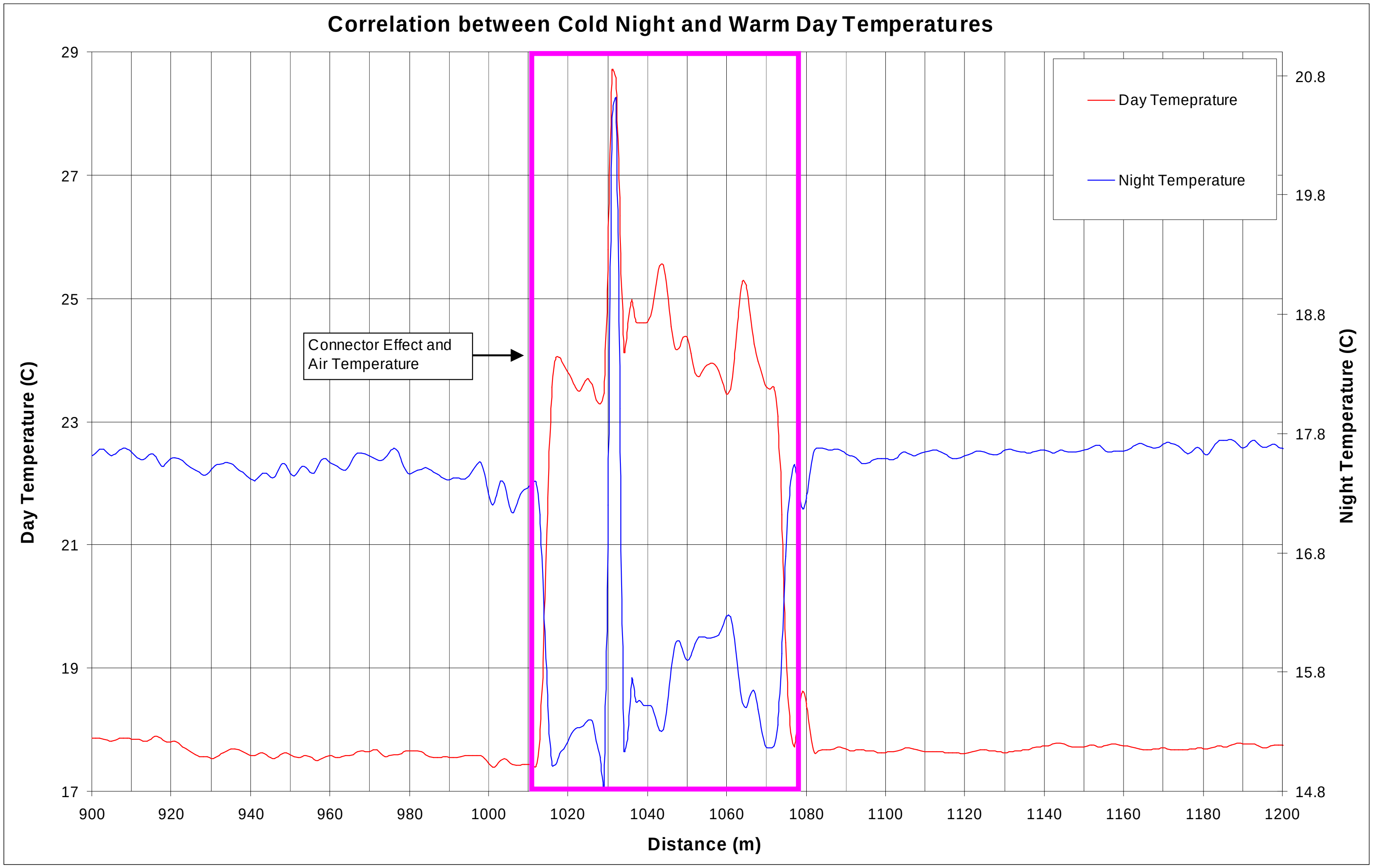

Figure 5.3 Air temperature and barrel connector site from the temperature profile, the barrel connector is the large spike during both the night and day at 1030 m.

6.0 Concluding Remarks and Suggestions for Future Studies

Through continuous temperature analysis we have begun to locate cool water inflows to surface water. Once these areas of interaction are found they can be identified as either ground water or hyporheic exchange (depending on the designated timescales used) and quantified. Using the temperature measurements and stream data we can begin to determine the approximate depth that we would expect for the hyporheic exchange. The research has also used simple calculations to estimate expected temperature changes for a river from increasing shade, known ground water inputs, and from any hyporheic exchange that may be occurring or new hyporheic exchange zones planned in future projects. This temperature data is also being used in correlation with fish surveys to locate areas of habitat; fish rely on during peak day time temperatures and see if the fish locations relate to sites of cool water refugia found through DTS temperature analysis.

Cooling of surface waters during peak temperatures is important for the future of surface water ecosystems. With increasing temperatures worldwide do to climate change, it is important to find new ways to examine, define, and measure cool water inflows. We have presented the basics behind warming a river due to solar radiation. We briefly described the affects of shading on a river reach, quantified the amount of energy that is blocked by shading, and translated this to effective temperature reduction of the river. Then cold water inflows that cool peak temperatures, possibly sources of cold water refugia (ground water inflows and hyporheic exchange sites), were found. These sources of cool water were used to calculate the cooling expected on the study reach in the Walla Walla River. Then the data was used to quantify ground water inflows and the depth of the hyporheic exchange throughout the study reach. The data from the DTS was used to locate the cool water inflows for peak day time temperatures during the summer months. By comparing the nighttime to peak daytime temperatures through the correlation coefficient the hyporheic exchange sites were separated from the ground water inflows. This gave the WWBWC locations that can be protected for cold water inflows into the river to try to meet the TMDLs (Total

Maximum Daily Load) for temperature. Finally, the cold water sites were matched with a US Fish and Wildlife Service survey to see if the cold water fish were congregating at these cold water sites during the warm daytime temperatures. We found that 60% of the cold water fish were gathering in 18% of the river where cool water inflows were present. It is also important to note that 56% of the cold water inflows had the cold water fish present. The cold water inflows (ground water and hyporheic exchange) make up approximately one-third of the river's total length. We have given a method to locate cool water inflows and determine where approximately 60% of the cold water fish are located during summer daytime temperatures. We now know that 60% of the fish are in 18% of the river and that through the DTS measurements we can narrow the search for these cold water fish to 32% of the river.

This project has given new insight into river dynamics through the use of distributed temperature measurement. This data can be valuable to land managers in determining locations that deserve special protection in order to maintain cool water flows to the river and has shown how different cold water fish species rely on the cold water inflows for habitat during the warm summer months. We gave a simple overview on how cooling of surface waters may be represented in a natural setting and how this may look quantitatively.

A few problems did arise during the data acquisition and interpretation that should be briefly reviewed. DTS technology has been used in the environmental sciences for only a few decades and is still relatively new. The technology is coming along quickly, but there are a few problems that were seen during our field deployment. One of these issues is calibration of the system. Calibrating the DTS to your specific cable is very important, but can be difficult, especially when multiple cables are used. Each section of cable must be calibrated using two different known temperatures for each calibrated cable in order to get a correct calibration for both gain and offset. Recently, Agilent created a double-ended measurement which corrects for attenuation constantly along the cable which is a great improvement for the technology; however this has increased the overall noise of the temperature measurements. Since noise has a significant effect on fine-scaled measurements, a high quality cable is important. One of the cables used in this study had a large amount of loss (on the order of 8dB once connectors were added) which got attributed to both ends of the cable due to the double-ended measurement setup. A cable should have less than 1dB/km loss to maintain minimal noise in the measurement when using the double ended setting. Also, it is important to minimize the number of connectors used as they have a much greater loss than a fusion splice. The fusion splices are another issue; they are a necessary evil. The fusion splice is a learned skill and some of the field deployable units are finicky and demand a very clean environment. It is important to be well prepared before attempting fusions in the field.

Additional problems became evident during data interpretation. The cable doubles back at the 2061 meter mark, at this point there is a large drop in temperature. This drop may be where the ground water table is at the river's elevation, but it could also be due to a large loss and possibly some other effects from the connector at this location. This data had a slight "jitter" in the daily temperatures. The jitter was an artifact of the Agilent DTS; it was noticed because the water temperature did not follow the daily air temperature and daily solar radiation pattern. The daily air temperature and daily solar radiation data sets were plotted and viewed on an hourly basis and no jumps were seen. When the DTS data was viewed on an hourly basis for the entire stream we could see jumps in the data occurring, since water changes temperature slowly due to solar radiation and air temperature these jumps were determined to be instrument noise and have since been brought to the attention of Agilent.

DTS measurements are an excellent way to record temperature data for an entire stream reach continuously over time. This technology can be used in the future for the Walla Walla Basin Watershed Council, or by others, to show cold water inflows into a river. An additional season of data would greatly help clarify some of the findings presented in this thesis. It would allow us to determine if the ground water inflows are still occurring in the same locations and how the hyporheic exchange sites might change year to year. We could also investigate whether the fish are still in the same cold water refugia as observed in the summer of 2007. We might be able to determine if the large cool water zone at the end of the 2061 meters of cable was indeed a ground water upwelling. This could be found by increasing the reach length approximately 100 meters on the downstream end of the reach. If this location continued to show a large cooling we would know that there is a large interaction with the ground water occurring. If it had disappeared or had moved down to the new cable end, we would know that there is either a problem with the cable layout or the DTS itself.

Due to the high amount of light loss in the cable, the low spatial resolution of 1m, and capturing the data only ¼ of the time desired the temperature measurements from the project have high noise. We expect to find 1dB loss for 1km of cable distance, so for this project we would expect 4db loss for the 4km of cable we were getting data from. However, for this project we had a total loss of 12dB, which is a 93.7% loss of light and is 33.7% less light than what was expected. Since noise goes with the light$^{0.5}$ a quality cable would give 2.5 times less noise, changing spatial resolution from 1m to 1.5m would give 1.4 times less noise, and capturing data every 15 minutes instead of every hour would give 2 times less noise; giving a possible total noise reduction of 7 times; therefore improving the calculated ground water inflow and hyporheic exchange depth quantities.

This research attempts to further introduce the DTS technology as an important new technology for environmental analysis. The DTS can be a useful tool in many areas of ecological engineering. Newer DTS instruments may not have as many of the problems that were noticed in this instrument; jitter in data, lack of temperature validation until the end of the project, the use of high loss fiber optic cable, increased care in the deployment and retrieval of the cable (at least with a 5 man crew if relying on man power), and loss of data due to the instrument not taking as much data as expected due to the nature of the double-ended measurement setting. Recently, a competing company has made steps toward a new DTS option that will automatically calibrate the cable to the DTS system. This development would be great progress in making the DTS a tool for land managers of all disciplines; as calibration is one of the more problematic features of the current technology.

There was a large learning curve in the use of DTS as a tool for ecosystem science during this project. Future work can rely on this account to get through instrument set-up, deployment, and interpretation without some of the same issues arising. Additional studies using the DTS system should have a better data set to work with if the problem items listed above are taken into account. This should improve the temperature measurements greatly, reducing the noise to levels that will allow easier determination of the temperature changes in the sites of refugia.

This report will be sent to Bob Bower and the WWBWC to further their threatened and endangered fish projects in the basin. It will be added to the general research that has occurred in the basin in conjunction with Oregon State University over the past decade. It will also be used for practical management that may come from increased knowledge of the locations of the cool water locations found throughout the study reach.

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AN ABSTRACT OF THE THESIS OF

Michael W. Collier for the degree of Master of Science in Water Resources Engineering presented on August 22, 2008.
Title: Demonstration of Fiber Optic Distributed Temperature Sensing to Differentiate Cold Water Refuge between Ground Water Inflows and Hyporheic Exchange.

Abstract approved:

Richard H. Cuenca

Recent developments in Distributed Temperature Sensing (DTS) have allowed new insight into the surface-to-ground water interaction. The continuous temperature measurement by the DTS allows for cool water inflows to be located during warm summer months. These cool water inflows can then be differentiated between ground water and hyporheic exchange. The cool water inflows are important to many species that inhabit the rivers of the Western United States. As temperatures increase due to climate change the importance of cool water inflows will grow.

This study used fiber optic cable and the DTS system to measure the temperature in 2km of the Walla Walla River, near Milton-Freewater, Oregon. The temperature data was split into nighttime and daytime averages. The correlation between these two data sets was calculated to reveal when the daytime and nighttime data followed the same cooling pattern (evidence of ground water inflow) or when the nighttime temperature increased, but the daytime temperature decreased (evidence of hyporheic exchange). Nine areas of apparent ground water inflow and nine areas of expected hyporheic exchange were identified. The average quantity of inflow at each ground water site was calculated as 0.04 m^3/s. The computed average hyporheic exchange depth along the 2000 m channel was 0.32 m. The located cold water inflows were compared to salmon and trout location from a US Fish and Wildlife Survey. This comparison showed that the cool mid-day inflows (either ground water or hyporheic exchange locations) made up 1/3 of the study reach length and had

approximately 60% of the cold water fish. Half of the cool water inflow sites did not have fish present during the survey which suggests that while influent cool water is a major factor for fish congregation, it is not the sole factor.

Demonstration of Fiber Optic Distributed Temperature Sensing to Differentiate Cold Water Refuge between Ground Water Inflows and Hyporheic Exchange

by
Michael W. Collier

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented August 22, 2008
Commencement June 2009

Master of Science thesis of Michael W. Collier presented on August 22, 2008.

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Michael W. Collier, Author

ACKNOWLEDGEMENTS

The author expresses sincere appreciation to my faculty advisor, Richard Cuenca, he has been an encourager and friend throughout the graduate years. Also, to my minor advisor and project leader John Selker, he allowed me to work with him on this project and has helped me think through many of the complexities that this project has brought. John has also been a friend and his enthusiasm and energy for research is at a level few may ever understand. I appreciate the entire Hydraulic Science Team, Yutaka, Ari, Josh, Travis, Kent, and Suva, making the rainy Oregon winters bearable with office banter and for helping me with my thesis and research. A special thanks to Yutaka, you are the heart and soul of the HST. Thanks to all of you who read through my thesis, it was a great help. Thanks to Julie, Nick, and Martijn for help with MatLab. Thanks to Chadi and Chris for miscellaneous help throughout the project. I also wanted to acknowledge my parents for teaching me to enjoy education and trust in the Lord. To my family, friends, and fiancé for staying with me through some of the stressful times of research and thesis writing, many of whom also helped in the process. Rachelle, I love you and am grateful for the comfort and grace you have shown me. Lastly, I thank God for blessing me and carrying me through so much during my graduate school years.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

1.0 Introduction

Fresh water is important to many aspects of aquatic and terrestrial life: food, shelter, oxygen, protection, temperature management, and hydration. Problems arise from the limited supply of fresh water available for an ever-increasing number of uses. Managing this limited resource is vital given the growing demand from industry, agriculture, municipalities, and recreation. Also, managers must consider natural ecosystems under stress from these anthropogenic uses (e.g., grazing and mining). The effects of these anthropogenic uses on the natural ecosystems are amplified by the increasing pace of climate change (e.g., Panagoulia and Dimou, 1996; Lettenmaier et al., 1999; Arnell and Liu, 2001; Snyder et al., 2002; Bower et al., 2004; Sophocleous, 2004; Barnett et al., 2005; Hatch, et al., 2006). There have been declining levels of water availability in many streams and aquifers, especially in the summer months, throughout the western United States (Winter et al., 1998; Sophocleous, 2000; Bachman et al., 2005; Hatch et al., 2006). With regards to natural ecosystems, the interaction between ground water and surface water is especially important for riparian systems to stabilize temperatures because they promote areas of increased biological activity. To appropriately manage the riparian systems it is vital to understand and quantify these interaction zones. Therefore, increasing our knowledge about the complexities and dynamics found in the fresh water supply, specifically between surface and ground water sources, is critical for improving our management strategies.

Ground water is water that has passed through the earth's subsurface and arrived at the water table as recharge and surface water is water on the earth's surface generally in the form of ponds, lakes, rivers, and streams (Dingman, 2002). While these have traditionally been managed as separate entities they are in reality one common source. An important aspect in surface-to-ground water interaction is that a change in the quantity of surface water will relate to a change in the water's source. In riparian systems, this relates to precipitation which percolates through the soil within the watershed and becomes ground water. The ground water can be identified and quantified if it flows into a river. Quantification of ground water flows will provide further understanding of spatial and temporal patterns of the interactions between surface and ground water. (Constantz, 1998; Kalbus et al., 2006b).

One limiting issue in understanding the dynamic nature of streams in the past was locating ground water inflows. Hydrologists have shown that stream temperatures can be used to better understand the hydrologic dynamics within a riverine system (Atwell et al., 1971; Ingebritsen et al, 1992; Constantz et al., 1994; Hondzo and Stefan, 1994; Johnson and Jones, 2000; Conant, 2004; Selker et al., 2006a; Selker et al., 2006b). Inflows can be located through temperature measurements that are continuous in time and in distance, however past technology could not give sufficiently high resolution readings over space and time to achieve this. Over the past decade, Distributed Temperature Sensing (DTS) has been developed and applied in a new way, identifying ground water inflows. The DTS system uses fiber optic technology to measure temperatures along the entire fiber. The temperature measurement is made by passing a laser's light through the fiber optic; the light from the laser passes through the glass and is scattered back to a sensor that counts returning photons. These photons return at the initial wavelength and, due to Raman scattering, wavelengths just above and just below this value. The measurement distance along the fiber optic cable is determined from the time of arrival of the back scattered light at the receiver. The intensity of the shorter returning wavelength is highly dependent on the temperature, and is called anti-Stokes. To improve accuracy, measurements are averaged spatially and temporally to increase the number of photons counted. The most common applications of DTS were for pipeline monitoring, oil well monitoring, power cable and fire detection systems (Grattan and Meggitt, 2000).

The possibility of applying DTS technology in the natural sciences has created much interest from hydrologists, ecological scientists, and geologists. This technology has been used in previous experiments (Selker et al., 2006b; and Westhoff et al., 2007) in headwater streams to identify ground water inflow locations. Although Selker et al. (2006b) and Westhoff et al. (2007) used DTS to measure stream temperature to quantify lateral inflow; this was not the first time temperature had been used for this purpose. Temperature is a proven way to quantify gains and losses to streams, either through measurement of stream temperature or the bed material (Stallman, 1965; Lapham, 1989; Silliman et al., 1995; Constantz, 1998; Constantz et al., 2003; Becker et al., 2004; Niswonger et al., 2005). Past temperature methods were based on point measurements. A DTS system has the ability to have temporal resolution from seconds to months. Also, these same temperature measurements can be taken at thousands of locations along the fiber optic cable. These measurements can be done either discretely or on an averaged basis. The new quantity of temperature data available through the DTS technology makes it easier to locate multiple cool water inflows to a river.

The objective of this research is to improve upon locating discrete cool water inflows to the Walla Walla River near Milton Freewater, Oregon through the use of a DTS system. These cooling inflows can then be separated between ground water inflows and hyporheic exchange sites (locations where surface water enters the streambed and re-emerges down gradient). The ground water inflows can be quantified from the temperature measurements and surface water flows. Also, the depth of hyporheic exchange can be quantified by calculating the volumetric heat capacity of the hyporheic exchange from an energy budget. This research also examines the possible relationship between these cool water inflows and the locations trout and salmon may reside in during summertime peak temperatures. The fish locations will be taken from a Fish and Wildlife survey that was completed at the study reach while the instrumentation was in place (between July 30th and August 24th, 2007).

2.0 Literature Review

Ground water to surface water interaction has been an area under critical review. This section of the thesis will give an overview of the cooling processes found in surface waters, how temperature can be used as a tool to analyze these processes, some of the ecological impacts of temperature, and how the DTS system can be used to improve upon the current hydrologic principals for ground water to surface water interaction.

Only recently have water managers and the legal system begun to look upon ground water and surface water as a single interconnected source and managed them as such (Harvey and Fuller, 1998; Winter et al., 1998). For the most part they have been managed as two distinct sources. With increasing water demands however, incorporating the interplay between these water supplies in our calculations has been essential for land managers (Stonestrom and Constantz, 2003). Not only is ground water a necessary component for aquatic ecosystems, it has become important politically. Water rights disputes between ground water and surface water users are increasingly common. Despite the legal distinction, they are, in fact, drawing from a common pool of water. Methods to account for surface water diversions, ground water pumping, and return flows are therefore necessary (Harvey and Fuller, 1998).

The contribution of ground water to surface water has been well established. Field work and data analysis have shown that ground water can make up a large percentage of the surface water budget (Winter, 1978, 1981, 1983, 1986). One of the most difficult tasks for computing the water budget for surface waters is the field identification of ground water upwelling sites (Lee and Hynes, 1977; Lee, 1985). Silliman and Booth (1993) made a significant methodological contribution to quantifying ground water inflows through temperature measurements of the streambed and the surface water. In the past, for hydrologists to locate ground water to surface water interface and quantify ground water discharge to surface water, extensive arrays of boreholes and piezometers were used (Winter, 1986; Kenoyer and Anderson, 1989). Past monitoring was completed through a multitude of methods. Hydrologists would install heat flow meters (Kerfoot, 1987; Ballard, 1996) and complete hydraulic testing with minipiezometers (Lee and Cherry, 1978) and seepage meters (Lee and Cherry, 1978; Lee and Hynes, 1977; Carr and Winter, 1980; Shaw and Prepas, 1990; Shaw et al., 1990; Avery, 1994; Landon et al., 2001; Paulsen et al., 2001). To further understand the ground water component, hydrologists model vertical streambed temperature profiles (Lapham, 1989; Silliman et al., 1995; Constantz and Thomas, 1996; Constantz, 1998; Bartolino and Niswonger, 1999; Fryar et al., 2000) and perform tracer tests (Lee et al., 1980; Harvey and Bencala, 1993; Meigs and Bahr, 1995). These monitoring systems are intensive and expensive to employ, may alter the natural flow in the stream, and are unable to detect small-scale spatial exchanges through the streambed (Conant, 2004).

A more recent development in locating ground water inflows to surface water has been through remote sensing. For example, remote sensing using FLIR (Forward Looking InfraRed) is used to find discrete locations of inflows and has been well established through the work of Nelson et al. (1991), and Atwell et al. (1971). FLIR has high spatial resolution and can be sampled by airplane. FLIR images indicate the temperatures of the land and water surface, showing locations where ground water seepage near the stream banks occurs. One drawback of FLIR is that the image encompasses only a snapshot in time. Distinctions between ground water and surface water temperatures are controlled by weather in diurnal variations, meaning during certain times of year some sources may be missed. Furthermore, FLIR does not penetrate the water column; cold water is denser and sinks, so groundwater upwelling locations may not be visible. Finally, FLIR does not give insight into the ground water exchange dynamics that time series data would (Silliman and Booth, 1993).

Temperature can be measured through other methods besides FLIR imaging to find ground water fluxes into the surface water systems (Stonestrom and Constantz, 2003). Building on early work by Bredehoeft and Papadopolous (1965) and Stallman (1965), temperature profiles have been successfully used in basins to estimate ground water recharge and discharge rates (Cartwright, 1970; Taniguchi, 1993; Taniguchi, 1994; Ferguson et al., 2003; Anderson, 2005). Estimates of ground water discharge are most reliable when the difference between surface water and ground water temperatures are at a maximum. At this point, there is the largest difference in temperature and any variance between the true temperature and the measured temperature will less significantly affect the computed flux. At sites of focused ground water inflows, there are abrupt changes in longitudinal temperature measurements. These ground water inflow sites are more stable than the surface water, which is not directly influenced by the ground water inflows because ground water dampens the extremes found in the surface water alone (Stonestrom and Constantz, 2003; Conant, 2004; Lowry et al., 2007). The temperature differences between the surface and ground water inflows may be observed by a shift in the surface water temperature when compared to the trend in the longitudinal profile of the surface water temperatures for a particular reach (Selker et al., 2006b).

2.1 Temperature and the Energy Budget

To use temperature to find ground water inflows and to differentiate this flow from hyporhiec exchange, it is necessary to understand the processes that give rise to a river’s temperature. Stream temperature is influenced by many processes; solar radiation, air temperature, wind speed, shade, relative humidity, percent shade, aspect, ground temperature, precipitation, surface water inflows, and hyporheic exchanges. Other sources of energy for stream temperature include conduction of temperature to the stream substrate (Crittenden, 1978; Hondzo and Stefan, 1994; Evans et al., 1995; Johnson and Jones, 2000), evaporation and sensible heat exchange with the atmosphere (Sinokrat and Stefan, 1993; Webb and Zhang, 1997; Johnson and Jones, 2000), and energy contributed by advection from ground water (Ingebritsen et al., 1992; Sinokrat and Stefan, 1993; Webb and Zhang, 1997; Constantz, 1998; Johnson and Jones, 2000).

The three major processes that contribute to peak river heat reduction are shade, ground water inflows, and hyporheic exchange. Solar radiation on the water surface is the major input of thermal energy to most streams (Beschta et al., 1987; Sinokrat and Stefan, 1993; Webb and Zhang, 1997; Johnson and Jones, 2000).

Shading is known for blocking solar radiation, thus reducing the stream's heat during the day when the solar radiation would be expected to effectively warm the surface water (Davies and Nelson 1994; Hostetler 1991, Li et al., 1994, Naiman et al., 1992; Poole and Berman, 2001). Ground water inputs provide continuous summer cooling by adding water to the stream at distinct locations at the annual average air temperature (here only summer time is considered as this is when the cable was deployed) (Westhoff et al., 2007). Hyporheic exchange averages in time the river temperature, cooling mid-day peak temperature, and increasing nighttime low temperature. This temperature modification occurs due to the increased time water is held at the location of hyporheic exchange (Lee, 1985; Nelson, 1991; Silliman and Booth, 1992; Stonestrom and Constantz, 2003). These three processes of river heat reduction will be further considered in up coming sections of this thesis.

Through analysis of the temperature data we hoped to quantify ground water inflows and hyporheic exchange in the river, both of which could provide cold water refugia for fish. These refugia are expected to be found through the longitudinal temperature profiles acquired by the DTS. If the fiber optic cable goes through an unmixed zone of cool water, it is expected the cable will have a cooler signature until the cool water inflow thoroughly mixes with the surface water. The temperature offset may not differ between a ground water input and hyporheic exchange, both cooling the river during the heat of the day, at a single snap shot in time. The large difference between ground water and hyporheic exchange flows will be witnessed during the night, as ground water carries the average yearly air temperature and the hyporheic exchange will carry a lagged temperature signature from the river earlier in the day. It is anticipated that the return flow from the hyporheic exchange will show an increase in temperature during the night and a decrease during the day.

Hyporheic exchange is stream water that enters riparian sediment and re-emerges further downstream, it is a process that creates surface water refugia but at a much smaller temporal and spatial scale than ground water exchange (Naiman and Bilby, 1998). Hyporheic exchange is pressure driven (Thibodeaux and Boyle, 1987; Savant et al., 1987; Stanford and Ward, 1988; Triska et al., 1989; Williams, 1989;

Hendricks and White, 1991; White, 1993; Hutchinson and Webster, 1998; Wondzell and Swanson, 1999; Stonestrom and Constantz, 2003; Conant, B., Jr, 2004) and is caused by pool-to-riffle sequences, slope changes, and obstacles found in the stream bed, such as a log jam. Hyporheic exchange is an active area in current hydrologic research and is poorly understood due to the dynamic space and time nature and difficulty of measurement. (Larkin and Sharp, 1992; and Harvey and Bencala, 1993) The increased attention to hyporheic exchange has shown that it is present in most rivers (Boulton et al., 1998; Naiman et al., 1998; Winter et al., 1998). Water in the hyporheic exchange locations can range from 100% river water to a mixture dominated by ground water (Hinkle et al., 2001). The work here will concentrate on the thermal affects that this zone may have on surface water bodies and the possible quantification of such affects.

Hyporheic exchange time lag is determined by two components; the tortuous path the water is required to take and the heat capacity of the combined water and bed material. Hyporheic water will have the average temperature for the time duration it was flowing through the porous media of the substrate and will be dampened due to the heat capacity of the gravel and water it has flowed through (see Figure 2.1 for examples of hyporheic exchange). For example, if the surface water enters the substrate and later re-enters the river, it will carry the temperature the average surface water had for the same time duration the water was in the subsurface. The re-entering water would also have a decrease in temperature due to the lack of solar radiation input for the duration it flowed through the bed material and would have an additional drop in temperature due to the volumetric heat capacity in the hyporheic exchange zone versus that of the water alone.

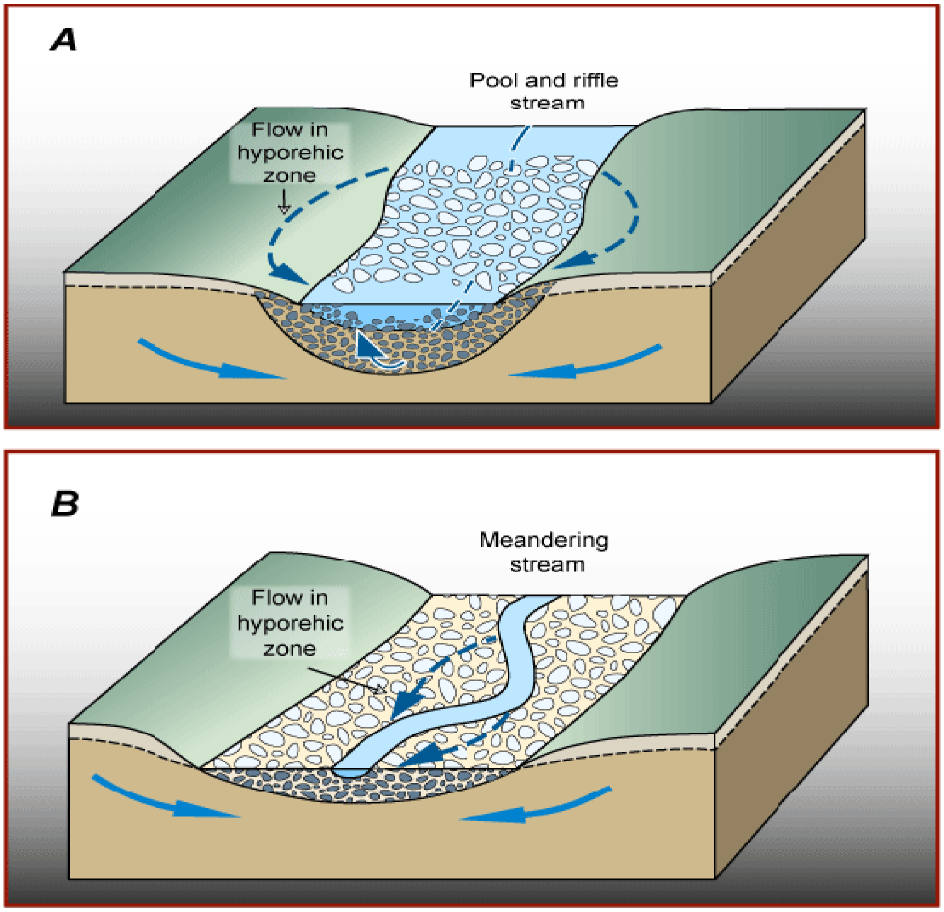

Figure 2.1 Surface water-ground water interaction in hyporheic exchange. With (a) a pool and riffle sequence and (b) with stream meanders (Winter et al., 1998).

When considering a cooled section of stream due to hyporheic exchange it is important to define the hyporheic exchange by residence time. Residence time must be used to distinguish between a ground water inflow and something more closely related to hyporheic exchange if considering DTS temperature data. For this research the residence time has been approximated to be 6 hours in order to simplify calculations for differentiating the daily lag in the temperature measurement through the hyporheic exchange site. To distinguish between the ground water flow and the hyporheic flow from continuous temperature data, you need only average together multiple weeks of data. If the cold water source is in fact ground water, then once averaged, the temperature signature should remain. This is because ground water maintains the yearly average air temperature, which would be distinctly lower than the average mid-summer stream temperature. At a location of ground water inflow the surface water should be cooler for nighttime, daytime, and for the average water temperature, during warm summer months. Hyporheic exchange, on the other hand, would cool the peak daytime river temperatures, but heat these same locations during the low nighttime river temperatures of summer. Rather than providing net cooling, hyporheic exchange simply moderates daily temperature extremes.

2.2 Tracers

The previous section discussed that the subsurface is important for stabilizing surface water temperature and recharging surface waters. One way to gain insight into the interactions between surface and subsurface water systems is through the use of tracers. This approach can be particularly useful for understanding flow patterns and the timing of subsurface waters (Flury, and Wai, 2003). Tracers have been proven useful for illuminating transport and transformation within subsurface flow systems. Use of tracers can improve knowledge of subsurface flows, giving new insight to the hydrological cycle; identifying subsurface flow connections, velocities, and dispersion are all common uses of tracers (Flury and Wai, 2003).

Tracers are chemicals, biological masses, isotopes, or anything else that can be detected at different points along the hydrologic cycle. Tracers used in hydrologic systems come in two main categories, added and natural tracers. Added tracers are artificially incorporated in known quantities at some point in the hydrologic cycle and then are detected at another point along the cycle. Usually there are very low to no background concentrations of these tracers so everything detected will come from the added source. Natural tracers include chemicals, temperature, or isotopes that are found in the natural setting and can be detected at different amounts throughout the hydrologic cycle (Bencala et al., 1987).

Much research has been completed using added chemical tracers to find ground water patterns and flows to surface waters. These studies did not quantify ground water inflows based on the tracer information. Chemical tracers for ground water applications work well if the concentration of the chemical in the ground water is uniform and significantly different than the surface water (Cook et al., 2003). If the concentration difference from ground water to surface water is not detectible, or if measuring the chemical tracer is costly, another method should be considered.

Temperature may be used as a tracer (Kobayashi, 1985; Shanley and Peters, 1988; Kobayashi et al., 1999). One study compared heat (as a natural tracer) to bromide (as an added tracer) (Constantz et al., 2003). Employing the heat and solute ground water transport model VS2DH (Healy and Ronan, 1996), showed that both bromide and natural temperature differences in the stream could be used to find ground water and surface water exchange sites. Cox et al. (2007) compared temperature with selected commonly measured water quality parameters and also found that temperature could be used as an in-stream tracer to evaluate spatial and temporal patterns of surface water and ground water exchange. Temperature as a natural tracer has an added benefit of differentiating between temporal variations in ground water inflows.

Temperature used as a hydrologic tracer has several advantages. The signal arrives naturally and will continue to arrive as long as the ground water and surface water are connected. Measurement of temperature is robust and relatively inexpensive. It also has the additional advantage of not contaminating the local environment with introduced chemicals (Stonestrom and Constantz, 2003; Kalbus et al., 2006a). One disadvantage is that the interactions cannot be seen through temperature measurements if the surface water and ground water are near the same temperature. The importance of using natural tracers, such as temperature, over added tracers to find cool water inflows rivers can now be further understood.

2.3 Distributed Temperature Sensing

Using temperature as a tracer is made robust with the application of the DTS technology. The DTS system sends light down the fiber optic cable and as the light interacts with the glass in the fiber optic cable a portion is scattered, with some returning toward the source. A portion of this scattered light is at the original laser energy and another portion of the light is adsorbed and reemitted at wavelengths just above (“Stokes”) and just below (“anti-Stokes”) the original wavelength due to Raman scattering (Wait and Newson, 1995; Selker et al., 2006a). The back-scattered light has important properties that reflect the temperature of the glass at the scattering location. Specifically, anti-Stokes intensity is related exponentially to the temperature of the fiber, while the Stokes is much less temperature dependent. Thus, the temperature is linearly related to the log of the ratio of the Stokes and anti-Stokes intensities (Selker et al., 2006b). The distance for each recorded temperature measurement is based on the speed of light and the time it took for the light signal to return to the receiver. By the Central Limit Theorem the precision of the temperature measurements will increase with the square root of the integration interval, so for a very precise temperature reading, a longer integration time is required in order to have more photons counted by the receiver. Also, a more powerful laser can give more photons to count, again increasing the precision. (Selker, et al., 2006b)

To deploy a DTS system it is necessary to calibrate the system to the cable planned for use prior to field installment (via the Agilent Configuration Wizard) and it may be necessary to calibrate the temperature measurements post-collection (with at least two known temperatures along the cable). To calibrate the DTS to the specific cable the temperature offset, gain (a parameter to take into account the slope), and attenuation ratio of the fiber are needed. To find the offset, gain, and attenuation ratio two known temperatures are necessary along the cable. This can be done with either two temperature baths or running the DTS in the double-ended configuration. The ongoing auto-calibration present in a double-ended measurement further simplifies the calibration process and improves measurement accuracy by continuously correcting the attenuation ratio (Tufillaro et al., 2007). The offset and gain of the calibration should not change for the cable after the initial calibration, but the attenuation ratio may need re-calibrating if the DTS is not run in the double-ended configuration. The attenuation ratio can change for the cable if it makes many bends, or if the layout of the cable is changed. Calibration is very important for an accurate temperature reading. However, if interested in precise temperature changes and do not care about the temperature itself the manufacturer's calibration of the DTS system is reliable. The calibration of the DTS from Agilent is typically precise on the order of 0.01°C.

There are several different types of DTS systems available. The DTS systems range in cost, power consumption, resolution, and durability. The Optimum DTS for a particular use depends on how the project characteristics correspond to these variables. This research project required a unit that had low energy consumption for remote use, durability for field deployment, and low cost. Resolution was of concern, but it was thought that all units would be adequate to meet the goals. In retrospect, more variables needed to be considered beyond the instrument itself, such as the loss of the fiber optic cable. Agilent's DTS (N4386A), which came to the market in May 2006, was selected. This system was designed for remote environmental applications. This DTS operates on less than 40 W at 12 V within an operating temperature range of 10 to 60°C (other systems operate from 85-150W at a max temperature of 40°C). Also, the Agilent DTS can report temperature every meter along the cable, but if more precise readings are desired the Agilent DTS can integrate over a longer distances of cable (Selker, et al., 2006a). The precision of the instrument doubles if the distance of integration is changed from 1 meter intervals to 1.5 meter intervals. The system consists of a computer with software installed for data retrieval and saving. The software creates ASCII files with temperatures, loss, the distances along the attached fiber optics cable, and the number of measurement points along the cable.

Before the DTS technology was available for environmental applications, temperature was taken through point measurements. One concern of point measurement methods is that the longitudinal resolution is low and there is a risk that some inflows may be missed (Kalbus et al., 2006b). The DTS system overcomes this by providing continuous temporal and longitudinal temperature measurements. The DTS will measure a temperature shift for incoming water at a different temperature than the stream temperature trend prior to the localized inflow (Selker et al., 2006b). This measurement may not be able to find the smallest inflows into large rivers, but it can show many of the significant flows that would occur over a reach and fall outside the standard deviation in the surface water temperature. When the temperature of an inflow is within the standard deviation of the DTS measurement of the river's temperature, the inflow will not be statistically different and not be able to differentiate from the noise found within the DTS measurements.

One concern with the use of fiber optic cable for temperature measurements was the time response upon a change in temperature. It has been shown that fiber optic cable has a fast temperature response through jacketing made of PVC and steel cable, found to be less than a 10 second response time from unpublished studies for a Brusteel fiber optic cable from Brugg.

If care is taken in calibration and high quality fiber optic cable is purchased, temperature resolution of 0.01°C and spatial resolution down to 0.5 m with temporal resolution down to 3 seconds along standard fiber optic communication cables with lengths of up to 30,000 m are all possible (depending on the DTS machine used, manufacturers and models vary) (Selker et al., 2006a; Moffett et al., 2007). There are tradeoffs between theses specifications; shorter integration distances and times will have higher uncertainty in the temperature measurements.

This technology has opened new possibilities for environmental sensing. The fiber is deployable in many different configurations, due to the flexibility of the cable allowing measurement in many new areas (measurement of an air shed or the snow through a net configuration, down a sinuous stream, or the creation of a high resolution pole through wrapping the fiber around a PVC pipe). Measurements that seemed impractical before seem manageable, such as taking thousands of measurements at points longitudinally down a river and collecting data from the network continuously for months. Using the DTS method for this research will give the needed measurements to separate the cool water inflows between ground water and hyporheic exchange.

2.4 Ground water to surface water interaction

One approach to quantify surface-to-ground water interactions is to monitor temperature variations in surface waters due to ground inflows (Lee, 1985; Nelson, 1991; Silliman and Booth, 1993). The use of temperature as a natural tracer has become increasingly common because it can be measured with relative ease in a channel to obtain high resolution temporal and spatial information. (Hatch, et. al., 2006; Constantz and Thomas, 1996; Selker et al, 2006b; Westhoff et al., 2007). Riverine systems are very dynamic and the use of time series temperature data can increase understanding of the changing sources of flow.

Temperature was used to identify the interaction between the surface water and ground water system by Rorabaugh (1956). He used temperature measurements to estimate the stream loses below the Ohio River, OH. Heat has been used as a tracer of surface water and ground water exchanges and to quantify these exchanges (Silliman and Booth, 1993; Silliman et al., 1995). Much of this previous research concentrated on areas of stream loss (Constantz et al., 2002). Analysis of temperature profiles has shown point measurement of ground water flow beneath streams. The temperature differences found on a diurnal and seasonal basis are partially a function of the different temperatures between the stream and near stream sediment (Rorabough, 1963; Stephens and Heermann, 1988; Constantz et al., 1994; Constantz and Zellweger, 1995; Constantz and Thomas, 1996). Through continuous surface water temperature measurements, areas of gain to a stream from ground water can be found (Selker et al., 2006b; Westhoff et al., 2007).

Fiber optic cable (Brusense, Brugg, Switzerland) was installed in the Maisbich, a ground water fed, first order stream in Luxembourg with a DTS (Sentinel DTS-LR, Sensornet, London, England) system. Surface water flux along the study reach was determined through DTS and flow measurements. The changes in temperature at points of ground water input allowed for accurate estimates of point-wise ground water inflows based on an energy balance coupled with a mass balance (Selker et al., 2006b).

As seen by Selker et al., (2006b) a loss in a stream can be assumed when either upstream flows are larger than downstream flows, or when the upstream and downstream flow readings are the same and ground water inflows are witnessed. It is difficult to find where these losses occur through longitudinal surface water temperature measurements. Through a distributed temperature sensing (DTS) system, the gains can be found through the longitudinal surface water temperature measurements and if discharge is not significantly different between upstream and downstream measurements we can conclude that there are some losing sections within this stream, as well as areas gaining. A loss, be it gradual or abrupt, only results in a gradual change of the temperature profile due to changes in warming and cooling patterns; it will reduce the volume and flow of the river which will give more solar radiation per volume of water in the same channel shape. Such losses might be quantified through a complete mass and energy balance for the stream; however, energy budgets of this precision are difficult in natural streams. To have the most distinct temperature difference, in order to estimate ground water inflows from surface flow measurements, data should be retrieved for times of low flow so that any increase in flow can be attributed to ground water inflow and not directly from precipitation (Kalbus et al., 2006b). In-stream flows measured at two points along a stream reach, accounting for stream diversions and tributary inflows first, can be used to determine if a stream is gaining or losing. If downstream flow is greater than upstream flow, the stream gains; if downstream flow is less than the upstream flow, the stream loses water to the aquifer (Riggs, 1972; Stonestrom and Constantz, 2003).

Exchange direction can be determined through stream bed sediment temperature measurements. In a gaining reach, the sediments will take on the ground water temperature, and therefore the sediments will have a stable temperature. On the other hand, losing reaches will take on the surface water temperature, which generally follow the diurnal daily temperature cycle (Winter et al., 1998; Stonestrom and Constantz, 2003; Kalbus et al., 2006a). For the purpose of this thesis, surface water temperature alone will be used to locate gaining portions of the study reach, based on a method that was established by Selker et al. (2006a), Selker et al. (2006b), and Westhoff et al. (2007). It is much more difficult to use only surface water temperatures to find the losing portions of a river, and stream temperature reduction is much more dependent on gaining cool water than on losing warmer water.

Since ground water temperature is generally stable throughout the year, the temperature difference can be interpolated between the ground water and the surface water to differentiate the ground water inflows from the surface water. During the warmest and coldest times of the year there will be the most dramatic temperature difference between the surface and ground water supplies (Stonestrom and Constantz, 2003; Conant, 2004), allowing for easier differentiation.

Through the use of the DTS system cool water inflows to the river can be located during summer months for the entire length of the study reach. An important byproduct of locating the temperature drops in the surface water is determining the cool water inflows. Fluxes usually are calculated for the ground water-to-surface water interface through an application of Darcy's law (Darcy, 1856) which states that water flux is a function of hydraulic gradient and hydraulic conductivity. A second method is based on a water budget; ground water contribution is computed in this method as the difference between the inflow and outflow. For the mixing zones or areas of hyporheic exchange either of the methods can be used (Kalbus et al., 2006b).

2.5 Ecological considerations

The temperature data gathered to estimate ground water and hyporheic exchange can be valuable to ecologists to identify ecosystem dynamics within a river. Temperature-dependent water quality and geochemical processes can be calculated based on the locations found through temperature measurements (Selker et al., 2006b). Also, identification of habitat and migration patterns based on temporal and thermal conditions (Torgersen et al., 1999; Selker et al., 2006b) can be employed to determine the extent of expected distribution of selected species.

Maintaining a specific temperature range in surface waters is vital for many different aquatic habitats. The cooling of summer time surface water occurs from subsurface water emerging to the surface. These locations are important because cold-water fish species have begun to decline in population due to physiological effects from warming waters. The river waters have warmed due to many anthropogenic causes. These anthropogenic causes include de-vegetation, re-chanalization, broader streams from lack of root systems and impacts of grazers, and disconnection of flood plains (Resh et al., 1988; Hornung and Reynolds, 1995). Warming to many surface waters has also been attributed to climate change (Rahel et al., 1996).

Due to the increase in temperature and the decrease in available water, the amount and location of surface and ground water exchange are increasingly important to identify for ecosystem considerations of temperature sensitive fish species. For example, anadromous salmon and many trout require specific temperature ranges to successfully develop, migrate, and spawn (Power, 1980; Baltz et al., 1987; Curry and Noakes, 1995; Curry et al., 1995; Halupka, 2000; Stonestrom and Constantz, 2003). To protect these cold-water species ways must be found to continue to keep our surface waters cool; locating cooling sources is a wise first step (Silliman and Booth, 1993). Stream temperature is also a critical parameter to other ecosystems within the stream. Temperature controls rates of metabolism, the number of aquatic insects, growth, decomposition, and solubility of gases, as well as many other processes and biotic interactions (Beitinger and Fitzpatrick, 1979; Beschta et al., 1987; Harvey et al., 1998; Johnson and Jones, 2000). Hyporheic exchange increases stream temperature regulation and nutrient cycling (Hendricks and White, 1991; Wood and Petts, 1999; Hatch et al., 2006), both of which are important for aquatic habitat (Power et al., 1999; Hayashi and Rosenberry, 2002; Alexander and Caissie, 2003; Hatch et al., 2006).

The Intergovernmental Panel on Climate Change (IPCC) in 2001 employed several Global Climate Models and expects a 1 to 7 °C increase in mean global temperature within the next 100 years. This may have a devastating impact on cold water fish (Ficke et al., 2007). Many rivers and streams in Oregon have been determined to be in violation of the Clean Water Act due to high temperatures by the Environmental Protection Agency (EPA) (DEQ, 2005). Trout and salmon populations in many of these systems are of concern because of the elevated temperatures and have experienced die off during warm summer periods. High water temperature has a significant influence on salmonid behavior and growth (Li et al., 1994). Several species of cold-water fish locate thermal refugia several degrees cooler than ambient water temperatures (Torgersen et al., 1999; Ebersole et al., 2003) during summer. Fish are known to move into cooler ground water springs for refuge from excessively warm stream temperatures (Power et al., 1999). Ground water discharge increases biological abundance, diversity, and biogeochemical cycling (McClain et al., 2003; Hunt, 2006; Lowry, 2007). Fish find these cool ground water sources not just for refuge but also because the flow between surface water and ground water creates habitat for species that are part of the food chain for these fish (Harvey et al., 1998).

When water temperatures are outside of a fish's survival range during the cold of winter or the heat of summer, ground water becomes a crucial component of river habitat. Ground water provides areas of warmer water inflow in the winter, and in the summer, ground water is important for maintaining discharge and moderating surface water temperatures. Learning more about these ground water distribution pathways is critical to developing plans to protect these species (Power et al., 1999).

Habitat suitable for rainbow trout (*Oncorhynchus mykiss)* is temperature dependent, with the lethal limit taken to be 25 °C (Hokanson et al., 1977; Jobling, 1981; Bjornn and Reiser, 1991; Matthews and Berg, 1997). There is a rich supply of literature on the importance of cool water refugia for salmonids during summer periods of high water temperatures (e.g., Gibson, 1966; Keller and Hofstra, 1983; Berman and Quinn, 1991; Matthews et al., 1994; Nielsen and Kiorboe, 1994). In a study by Matthews and Berg (1997), areas of stream temperatures which remained cool due to ground water seeps during summer months consistently had more trout than did areas with higher water temperatures. The Oregon Department of Environmental Quality (DEQ) has temperature TMDLs (total maximum daily loads) for the Walla Walla River in Oregon (this study site) set to below 18 °C for salmonid and trout rearing from spring to early fall. Also, during spawning for these two species (January 1st to June 15th, 2007) 13 °C water is necessary. For Bull trout spawning, the temperature should be $\leq$ 12 °C. (DEQ, 2005)

Salmon and trout begin to experience serious effects at temperatures below their chronic lethal limits. Temperatures selected by these fish correlate with their optimal temperatures for growth, around 17 °C (Myrick and Cech, 2001). Increases in stream temperature below lethal levels have been linked to increased fish mortality of cold water fish (Brett, 1952; Beschta et al., 1988; McCullough, D., 1999), increased occurrence of disease (Becker and Fugihara, 1978), and increases in competition between species (Reeves et al., 1987; Johnson and Jones, 2000). The trout and salmon species are the focus for this thesis because they are the species found within the Walla Walla River that most depend on cool temperatures for their life cycle. Thus, locating and understanding the cool water inflows is vital to further protect these two species. This research was carried out in the northwestern United States where salmon and trout are important to commercial fishing, recreation, and are good indicator species for the current condition of aquatic ecosystems (Cairns, 1974).

3.0 Materials, Methods, and Theory

3.1 Instrumentation

The primary instrument used in this project was the Agilent N4386A Distributed Temperature Sensor.

Table 3.1 Key specifications for the Agilent N4386A (Tufillaro et al., 2007)

Key specifications for Agilent N4386A DTS		Environment	
Distance Range	8 km	Operating Temperature Range	-10 to 60 C
Spatial Resolution (minimum)	1 m	Storage Temperature	-40 to 80 C
Temperature Resolution	0.01 K	Supply Voltage	10 to 30 V DC
Temperature Repeatability	0.1 K	Power	15 W at room temperature, 40 W maximum

Within the DTS housing a Fujitsu Stylistic ST5000 tablet PC was placed in order to run the DTS Configurator version 3.0 and for data saving. Two 1000m lengths of Kaiphone's Mini armored fiber optic cable. The cable was duplex, multi-mode, graded index, 50/125, armored (stainless steal wrapped), black jacketed in PE, and had aramid strength members. End connectors used to connect the cable to the DTS were APC e2000s. Where the two 1000m cables were connected and where the last cable doubled back, female/female e2000 adapters were used. The cable was tied into place along the river using 1/2 inch rebar stakes driven 1/3 of a meter into the streambed approximately every 75 meters. The fiber optic cable was held onto the rebar with zip ties. Aerial cable hangers were also used to secure the cable at three locations where the cable was purposefully out of the water.

Flow measurements were taken using cross-sectional data of the channel and by using a flow meter according to the "Standard Operating Procedure for Stream flow Measurement" (EPA, 2004) (completed by the Walla Walla Basin Watershed Council). Immediately prior to taking the cable out of the river two ice baths were placed along it for system calibration. One ice bath was placed near the DTS and one at the midway where the two cables were connected. Approximately 20 meters of cable were placed into each bath. A digital data logger thermometer (VWR model 61220-601) with a resolution of 0.001 °C and an accuracy of ± 0.05 °C was used to take temperature measurements along the cable and in the ice baths to field check the DTS temperature measurements. Digital photos of the site were taken at locations identified by a Garmin Geko 301 GPS. Meteorological data was downloaded from the LeFore ETo station (identification #TOACI1) south of the research location to check for DTS system errors (sudden jumps in temperature data). Data interpretation was done through the use of Microsoft Excel 2003 and MatLab R2007a.

A snorkel fish survey conducted by the Fish and Wildlife Service parallel to the DTS installation was completed on 8/16/2007 by Courtney Newlon, Marshall Barrows, and Ryan Koch of the USFWS, Columbia River Fisheries Program Office, Vancouver, WA. The survey started at the downstream end of cable and ended at Mauer Lane.

3.2 Site

Milton Freewater, Oregon, USA is within the Walla Walla Watershed, which spans Oregon and Washington (see Figure 3.1a and 3.1b). The southern end of the site was at Mauer lane just north of the city of Milton Freewater. Measurements continued north 2 km along the river's thalweg ending prior to a well-known swimming hole, to reduce the likelihood of tampering and vandalism, approximately 500m south of the Washington State border. (Figure 3.2). The DTS was placed at the end of Mauer Lane (Figure 3.2). This location was chosen based on expected ground water emergences as advised by project collaborator Bob Bower from the Walla Walla Basin Watershed Council and the availability of line power.

The Walla Walla River is habitat to threatened and endangered species such as the Columbia River Salmon, Steelhead Trout, and Bull Trout. The upper geology of the study area consists of a shallow gravel aquifer (approximately 20 to 30m) on top of a deep fractured basalt rock aquifer. The Walla Walla watershed is a 1,758 square mile area with a majority found in the southeast corner of Washington (figure 3.1a). The headwaters originate in the Blue Mountains of Oregon at the eastern boundary of the watershed. The climate is characterized by hot, arid summers and cold, wet winters. Summer temperatures in the basin soar frequently exceed 38° C (100° F) and fall below freezing in the winter. This watershed receives between 12 and 16 inches of annual precipitation (PRISM, 2002), most of which is contained in the annual snow pack (Baldwin and Stohr, 2007). The near-stream vegetation found at this site consists of grasses, blackberry vines, willows, alders and other riparian species (Volkman, 2003). The majority of the water drafted from this river is used for agriculture, some of which eventually returns to the river. Most of the properties surrounding the study reach were either riparian lands or agricultural fields.

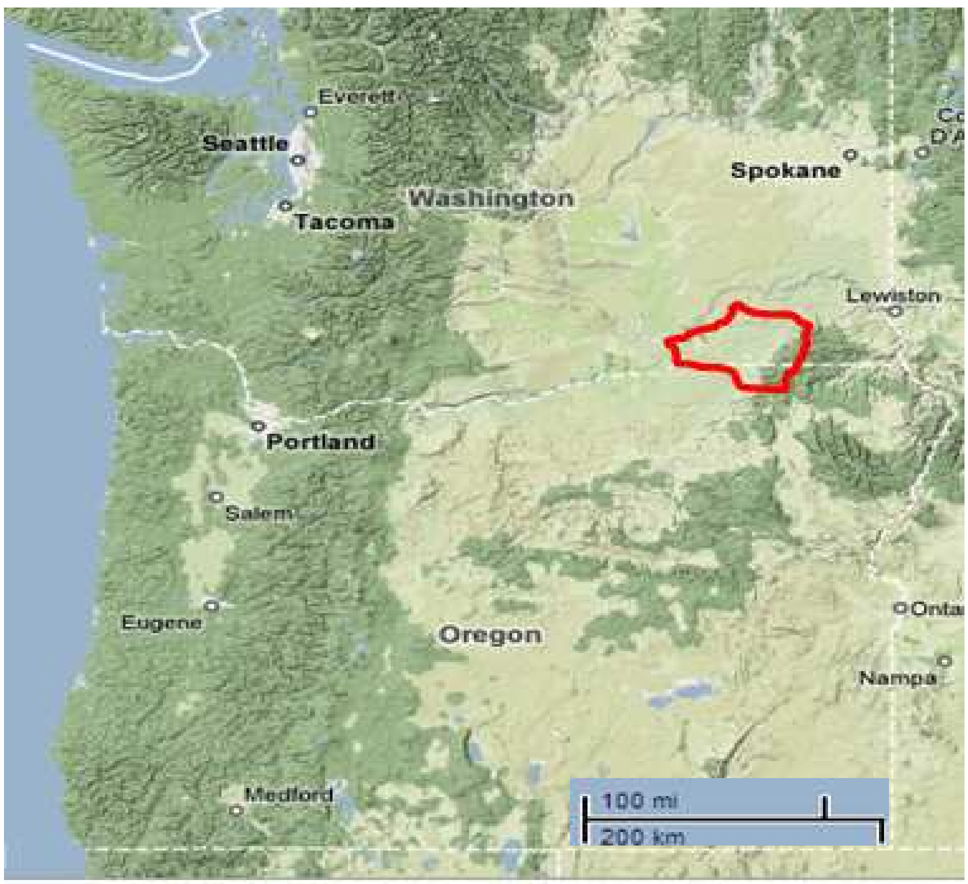

Figure 3.1a Map of the general research location, circle encompasses the Walla Walla Watershed which crosses the Oregon/Washington Border. (Google, 2008)

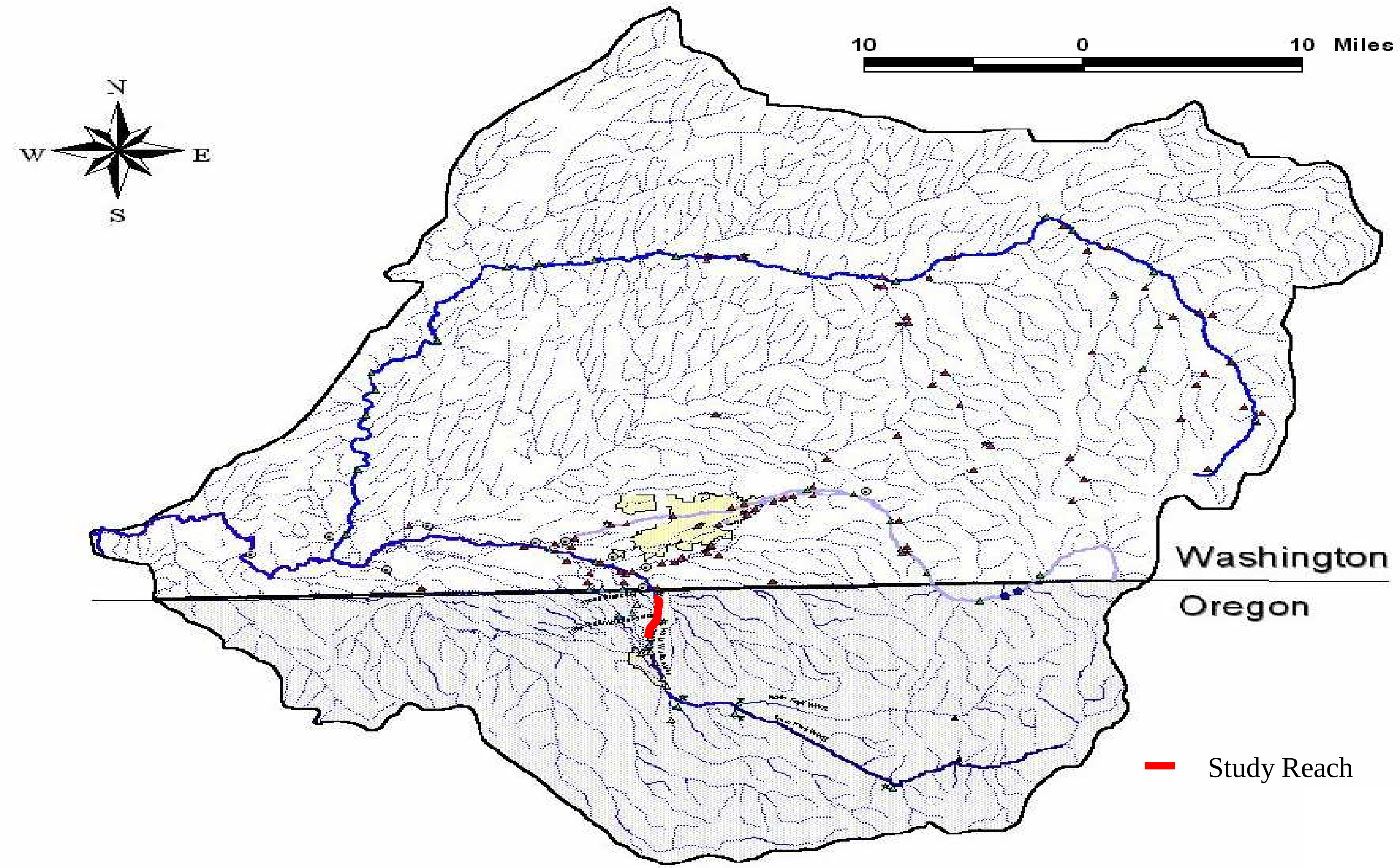

Figure 3.1b Map of study reach location on the Walla Walla River within the Walla Walla Watershed (www.wallawallawatershed.org)

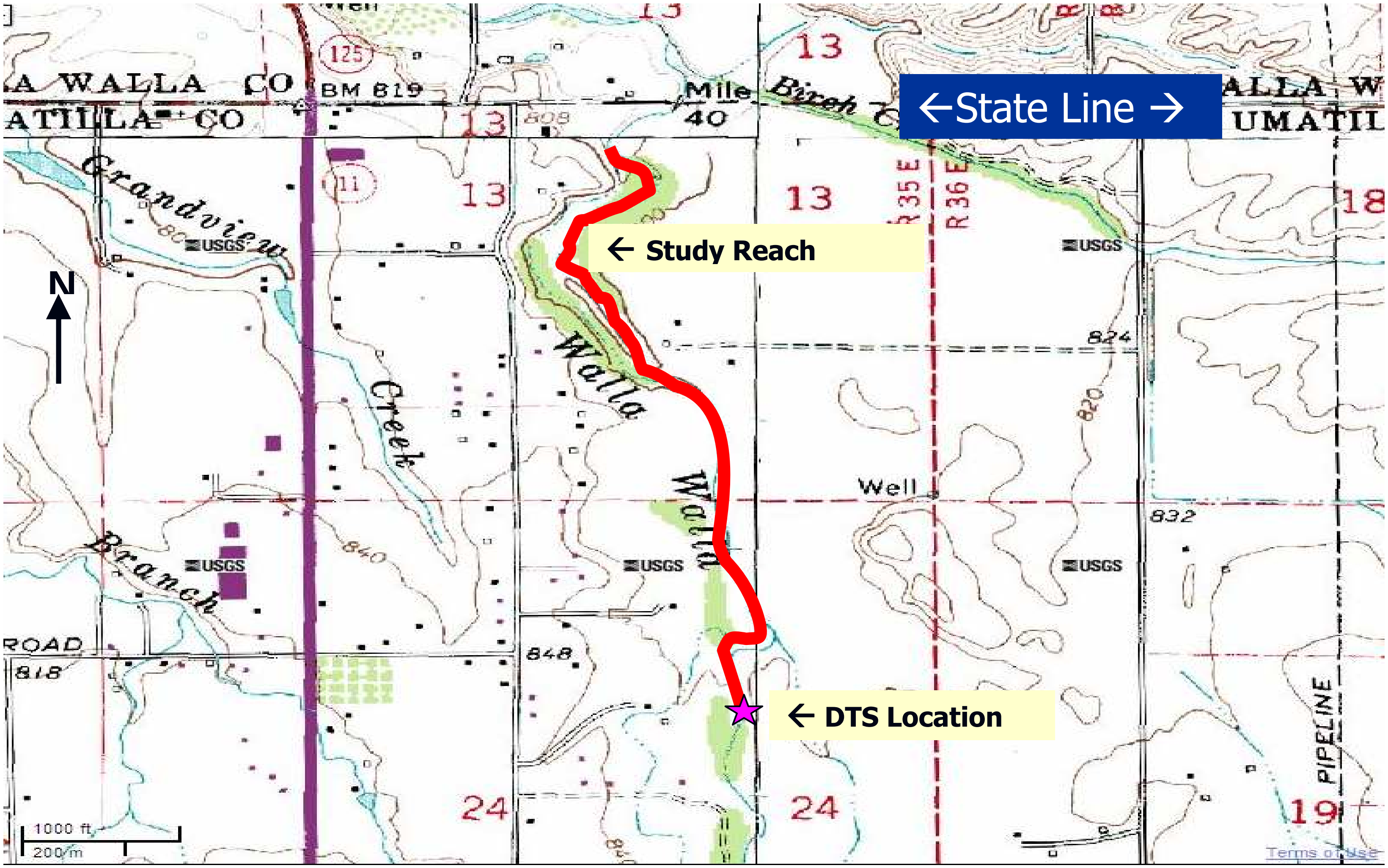

Figure 3.2 Detailed Milton-Freewater quadrangle, Oregon – Umatilla Co., 7.5 minute series, topographic map of study reach on Walla Walla River (contour interval 20ft. National Geodetic Vertical Datum of 1929). (USGS)

3.3 Objectives and Methods

The objectives of this research is to further understand ground water and hyporheic exchange flows as revealed by accurate temperature readings from the DTS for longitudinal temperatures of the Walla Walla River. These inflows were separated between ground water and hyporheic exchange. Then the inflows were compared to fish distribution along the study reach. For this particular project it was most important to get accurate temperature differences in space and time to identify and quantify cool water inflows. This was completed by taking measurements of the river every hour for a three-week duration (July 30th to August 24th, 2007).

The methodology for the research in this thesis can be split into two groups; those methods from before data collection and those after data collection. Prior to data collection consisted of cable selection and cable placement in the thalweg of the river. After the data collection included the initial data cleaning by calibrating the system, smoothing the diurnal temperature, and temperature measurement noise reduction. The analysis of the data was completed by comparing the average daytime and nighttime temperatures through a correlation coefficient. Once completed ground water inflow was quantified and an estimated depth of hyporheic exchange was calculated.

The data was calibrated and processed to locate possible errors in the data; some of the time steps from the DTS were flawed. After the initial data processing the data set was used to find and differentiate areas of cooling within the stream. Finally, the cooled river sections were compared with the US Fish and Wildlife Service (USFWS) snorkel fish survey to see if patterns emerged between fish location during summer daytime temperature and cool water inflows.

3.3.1 Initial data processing

The temperature data was collected through double-ended measurements, which was possible because the fiber optic cable looped back to the Agilent DTS. Double-ended measurements were a new capability for the Agilent DTS as of July 2007. This function passes light one direction through the fiber optic cable then passes light the opposite direction through the cable, allowing for automatic correct for the attenuation ratio (loss of optical energy that may create a false temperature change) and the gain (slope). Double-ended measurements should be used when attenuation ratio and gain may be inaccurate due to poor calibration or multiple sharp bends in the fiber optic cable.

DTS data from fiber optic cables generally require post-collection calibration to be corrected for temperature gain and offset in the measurement. In the case of double-ended measurements, only offset must be found. The data was collected on two cables, resulting in two unique offsets, one for each cable. First estimates for these offsets can be obtained prior to data collection by using the Calibration Wizard found in the Agilent DTS Configurator software package, but generally, these values must be adjusted after returning from the field to precisely address effects of connectors and other non-calibrated elements.

For this study, data acquisition was completed through the DTS Configurator software version 3.0 available for the Agilent DTS system. The data was then imported to MATLAB, a powerful numerical computer program that allows for easy manipulation of matrices. The DTS temperature measurements were double-checked with a hand measurement of the ice bath with the hand-held precision temperature probe (Figure 3.4). An ice or water bath that slowly changes temperature and a second temperature measuring device are important to validate the DTS temperature measurements. Redundant temperature data may be needed if calibration of the fiber optic cable was not properly completed prior to data acquisition from the DTS system. For this research the offset correction made use of a 0°C known temperature provided by two ice baths with 20m of submerged cable in each (Figure 3.3). The temperature measurements from the ice bath were averaged together for the 20 meter length and for one hour in time. The averaged ice bath temperature was then compared with the ice bath temperature taken with the hand-held temperature probe. The upstream ice bath was found to be -0.006° C and the downstream bath to be 0.012° C. The difference between these two temperatures was found and used for the temperature offset of the entire cable.

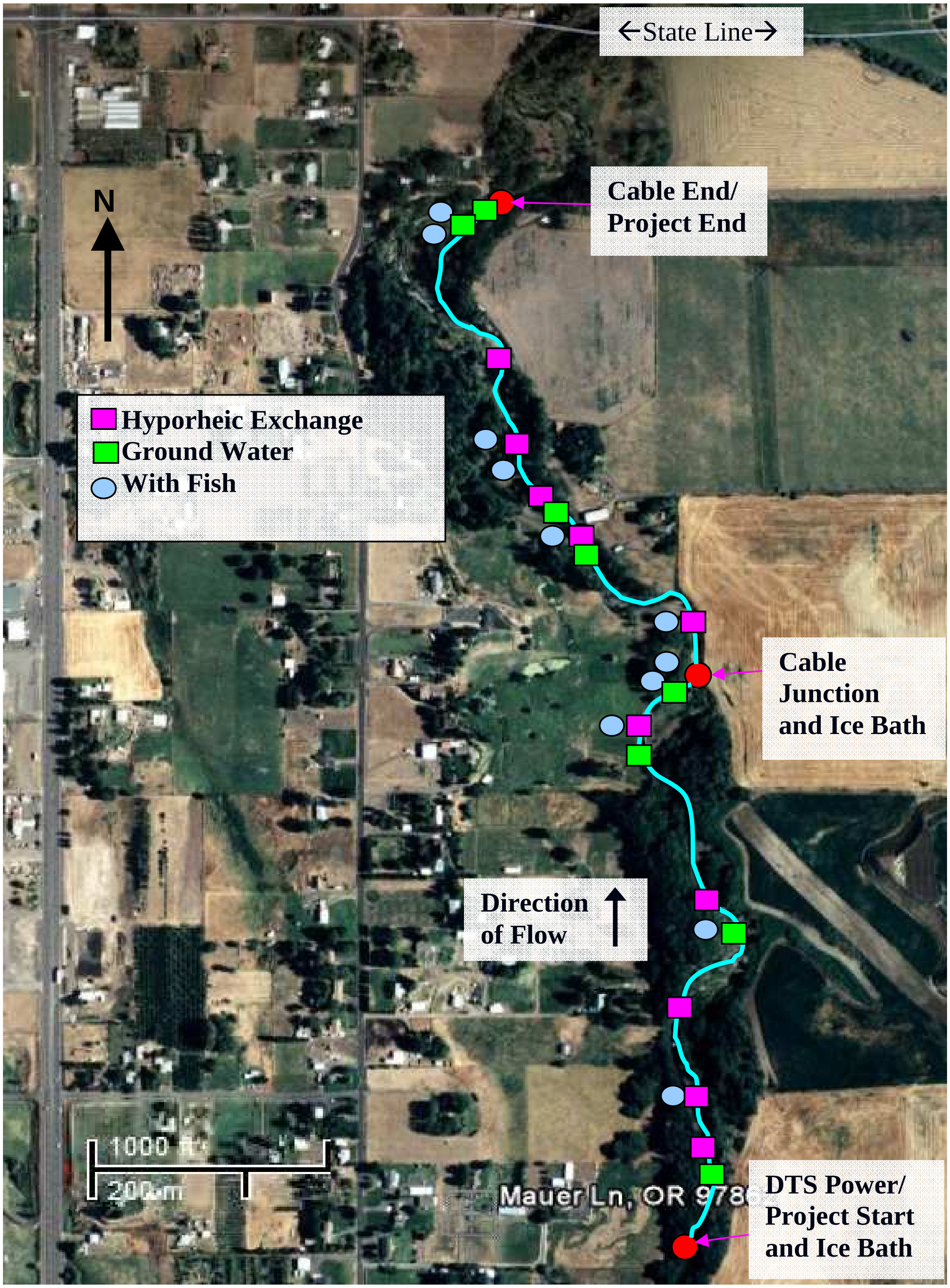

Figure 3.3 Image of study site including the cable junction, start and end of project, ground water and hyporheic exchange sites, and refugia sites with fish present. (Image from Google Earth, 26 June 2008)

The longitudinal temperature profiles were then plotted and viewed in a movie setting through MATLAB as multiple traces viewed through time. This movie making process (not presented in this thesis) is used to view stream dynamics through time, possibly locating temperature patterns for additional evaluation or possible erroneous data.

For this study a true or absolute temperature reading (accuracy) is not as important for final data interpretation as the ability to quantify spatial and temporal changes in temperature (precision). Since the DTS was run in double-ended mode the software adjusts for an incorrect slope of the trace automatically, giving precise measurements of temperature change. If a single temperature measurement is taken at a specific location on the fiber optic cable, then this location is heated and an additional temperature measurement is taken, the difference between the two temperatures is an attribute of the DTS itself and cannot be adjusted through calibration. The DTS has a high precision when looking at the temperature difference between two temperatures as long as the slope, and to a lesser amount, the gain of the trace is correct.

3.3.2 Energy Budget Calculations

For this thesis we used the water budget (based on the conservation of mass) in conjunction with the conservation of energy to quantify the ground water inflows to the surface water. First presented are simple quantifiable methods to see possible effects of different cooling components. The different components that are considered in this research are: how shade may block the solar radiation from increasing stream temperatures, the effect ground water will have on cooling a stream, and the effect the hyporheic exchange will have on cooling a stream.

Shade is a surface process that effects stream temperature. Shading blocks short-wave solar radiation from adding energy to the stream. This blocked solar radiation would have otherwise increased stream temperature. This form of cooling is actually better stated as heat blockage than an actual cooling influence. Shade does

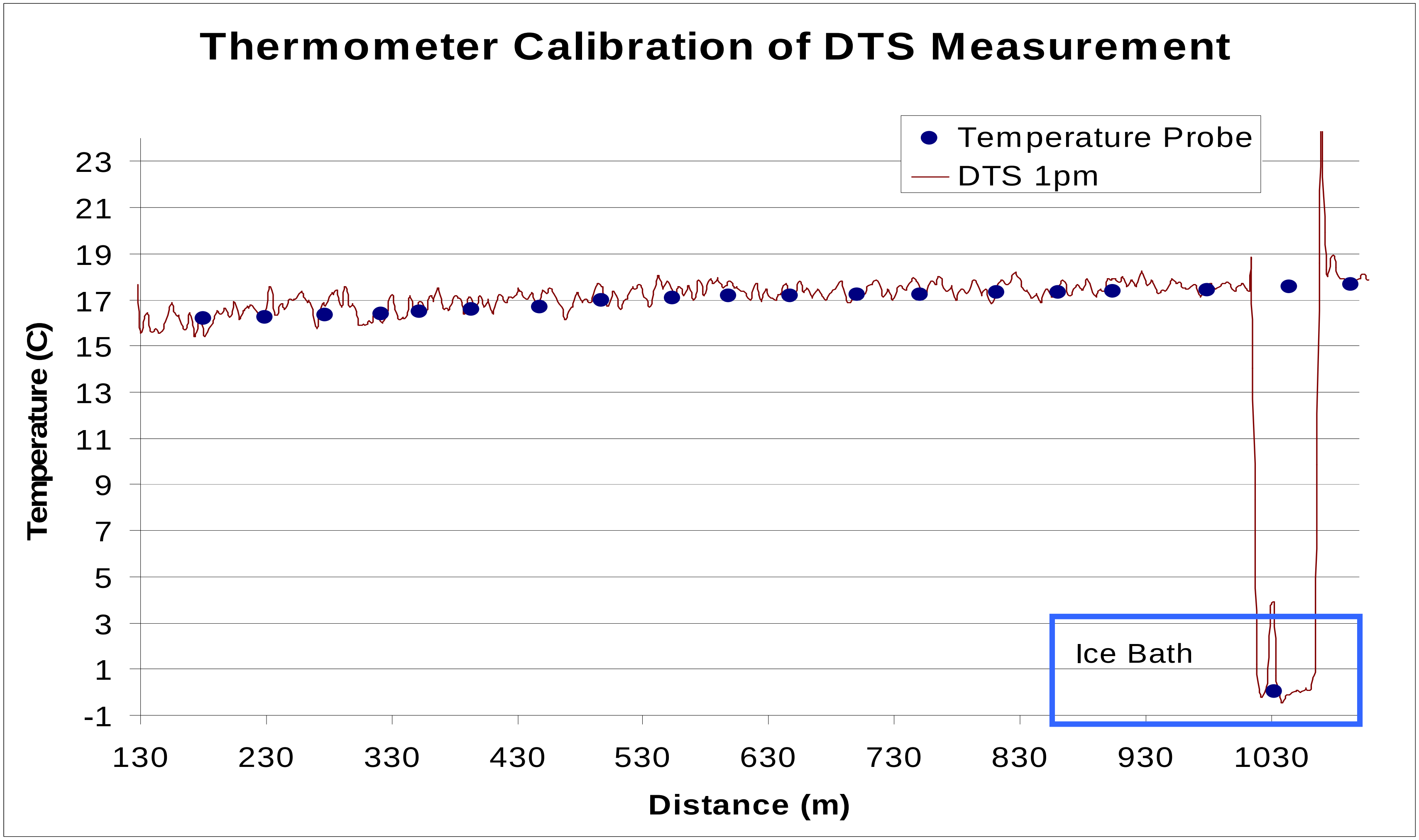

Figure 3.4 High precision temperature probe measurements compared to DTS measurements for 1000m of the study reach at 1pm.

not universally reduce the temperature, but rather diminishes the rate of energy input during the daytime.

For this study it is important to quantify the effects of solar radiation upon the water surface. Once the calculations are completed shading effects on a localized scale can be determined (at our study reach in particular). To find the change in temperature expected for a 50 meter shaded section of the river, it is necessary to know the travel time of the water for the 50 meters, the solar energy expected for the particular setting (location, time of year, and time of day), and the channel width for the 50 meter shaded section of river. The total energy absorbed based on the density, volume, and heat capacity of water for the 50 meter section can then be found and the expected temperature change determined. Shading will be included in the calculations, but will not be located through DTS measurements.

Cold water refugia have been defined as portions of surface water where the water temperature is colder than the daily maximum temperature of the adjacent well-mixed flow of water. These refugia provide local cold water within the surface waters of warm streams, affording potential thermal refuge for cold water fishes during periods of heat stress for energy conservation (Berman and Quinn, 1991; DEQ, 2006; Ebersole et. al., 2003). Examples of common areas of cold water refugia are: water entering from subsurface flow, input from springs, hill slope seeps, and tributaries which have not mixed with surface stream flow. Both ground water upwelling and hyporheic exchange can provide cold water refugia. These locations are often found near islands, pools, and rock out-croppings along stream banks (Berman and Quinn, 1991).

This study concentrates on detection of cool water inflows using a DTS system. The goal is to calculate the effect each ground water inflow and hyporheic exchange will have on the temperature in the study reach on the Walla Walla River. This is completed through energy budget calculations based on the computed flows expected at a ground water site and the calculated volumetric heat capacity at a site of hyporheic exchange.

The correlation coefficient was used to locate cool water inflows and to distinguish them between ground water and hyporheic exchange water. The absolute value of the correlation coefficient of 1.0 is a perfect correlation and anything greater than 0.8 is well correlated. If a 0.7 correlation coefficient was chosen, sites other than refugia would be included; these sites may include deep pools of water and sites of high noise in the data. If a 0.9 correlation was used we would not include many of the refugia sites because they are naturally variable and only sites where the cable is out of the water or connector sites will be found. This correlation coefficient was completed for running 15 meter sections of the temperature dataset that had been averaged for three meter lengths. Fifteen meter sections were used for the correlation coefficient because this length recorded distinguishable ground water inflow and hyporheic exchange sites at above a 0.8 correlation without including areas that were due to noise in the temperature measurements or possibly due to deep pools. The inflows that are cooler both at night and daytime, giving a positive correlation coefficient result in a ground water inflow. The second type of cool water inflows are when the inflow is colder in the day but warmer at night, giving a negative correlation coefficient and resulting in a location of hyporheic exchange. The correlation coefficient shows the locations of temperature change that are distinguishable outside of the measurement noise. These locations can be compared with locations we have visually determined to be ground water or hyporheic exchange in order to see if the correlation coefficient can be used to easily find and differentiate the locations of cold water refugia from the DTS temperature profile.

A ground water inflow can be located by using time series longitudinal surface water temperature traces. The average temperature profile for cool summer nighttime data (3am to 7am) was processed and compared with the average temperature profile of the peak summer daytime data (6pm to 10pm). These traces were compared with the total average temperature trace of the river for the study duration (Figures 3.5, 3.6 and 3.7, respectively). When the comparison was completed, locations where sudden steps or slopes downward in the DTS data, that were at the same location throughout the daily temperature cycle, were considered to be ground water inflow sites.

Locating areas of continuous temperature shift is important when removing other factors that may contribute to cooled locations of surface water during daily peak temperatures. It can be argued that these cooled areas are due to riparian shading, wind, hyporheic exchange, or evapotranspiration. However, when nighttime temperature change is similar to daytime and overall average temperature trends, we are able to remove the temperature signature that may be from environmental factors that give a false cooling signal.

A heat balance equation to calculate ground water discharge from measurements of stream temperatures and surface water flow was developed by Kobayashi et al. (1999) and was used by Becker et al. (2004) and Kalbus et al. (2006). In their research a stream was divided into reaches where temperature measurements were taken and a balanced equation was set up. The local stream temperature is a function of the ground water discharge rate, the difference in stream water and ground water temperature, stream flow, and additional heat gains and losses through the stream surface. This approach will also calculate the ground water inflow based on the flow and temperatures of the surface water and the ground water. The difference between their method and the one chosen for this study is that the Kobayashi method has also incorporated the surface heat flux into its estimations. However, these are considered to be constant over the stream, and can be neglected for this data analysis.

Flow contributions along a reach can be separated into surface and subsurface flow using temperature, through application of mass and heat conservation. For this study a slightly modified versions of the Kobayashi mass and energy balance equations for flows and temperatures were used (Selker et al., 2006b; Westhoff et al., 2007; Tufillaro et al., 2007).

Mass balance, $Q_d = Q_u + Q_l$

Energy balance, $T_d Q_d = T_u Q_u + T_l Q_l$

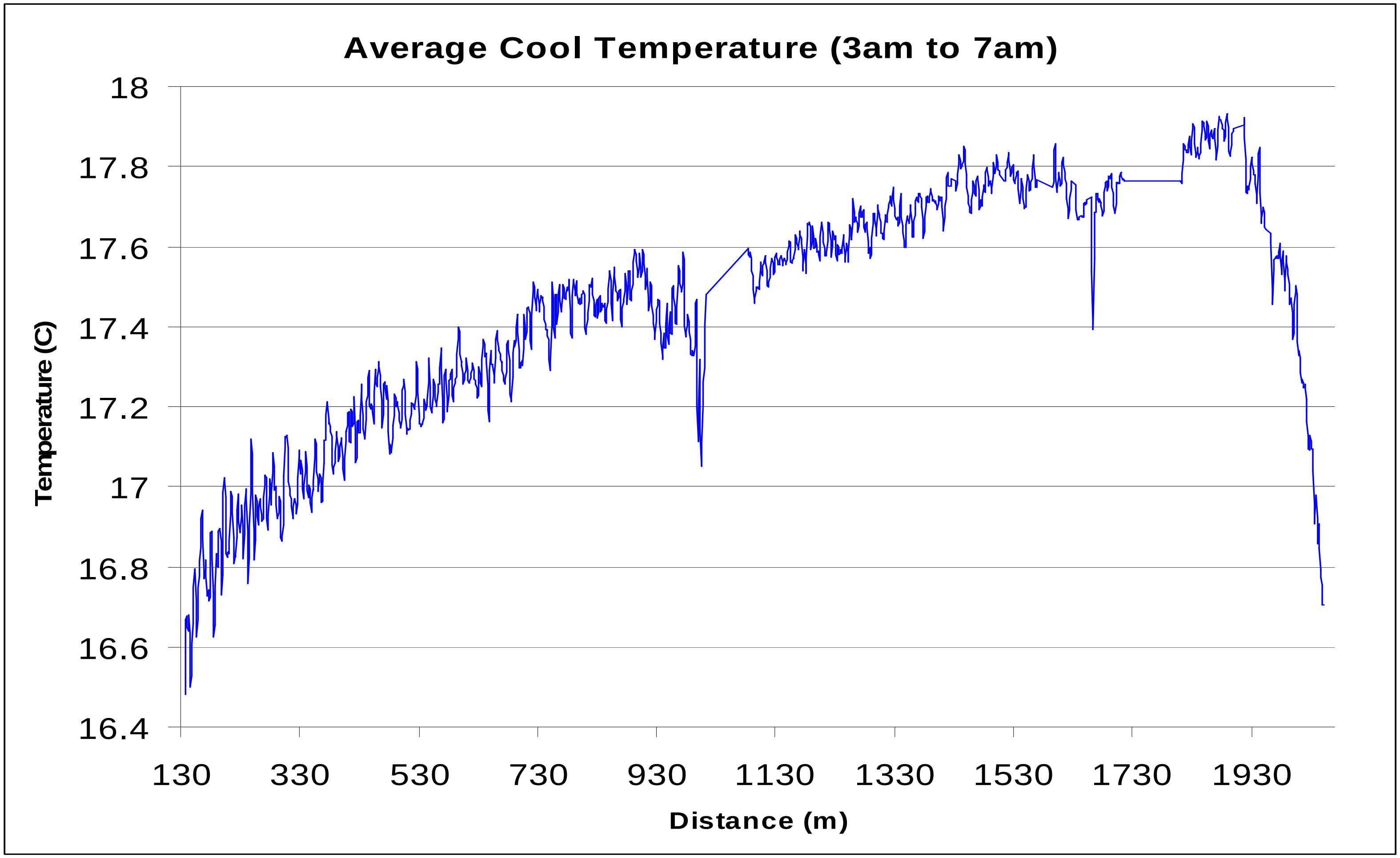

Figure 3.5 Average cool night-time daily summer time temperature profile for the study reach in the Walla Walla River, Oregon for July 30th to August 20th, 2007 with air temperature removed.

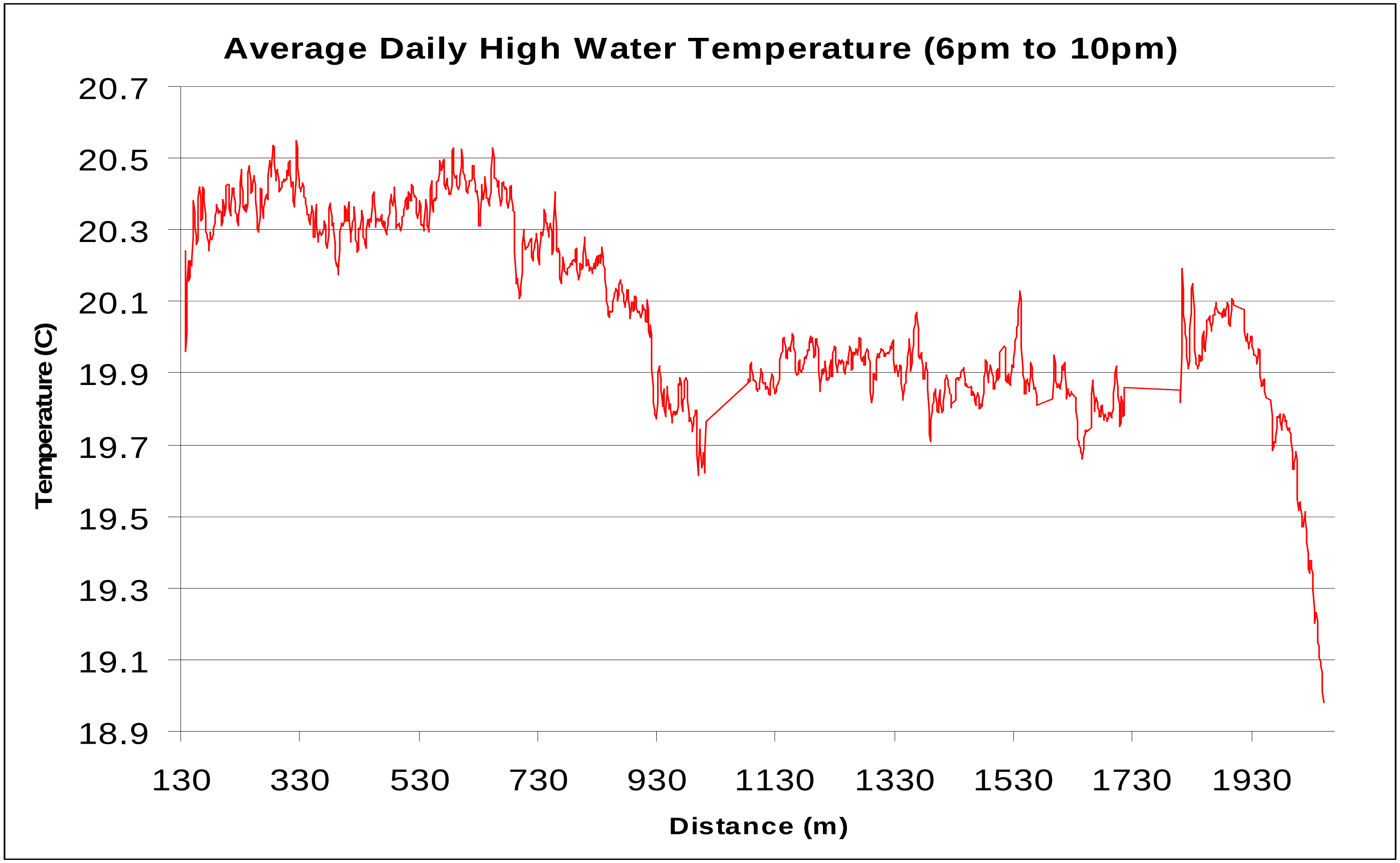

Figure 3.6 Average peak daily summer time temperature profile for the study reach in the Walla Walla River, Oregon from July 30th to August 20th, 2007 with air temperature removed.

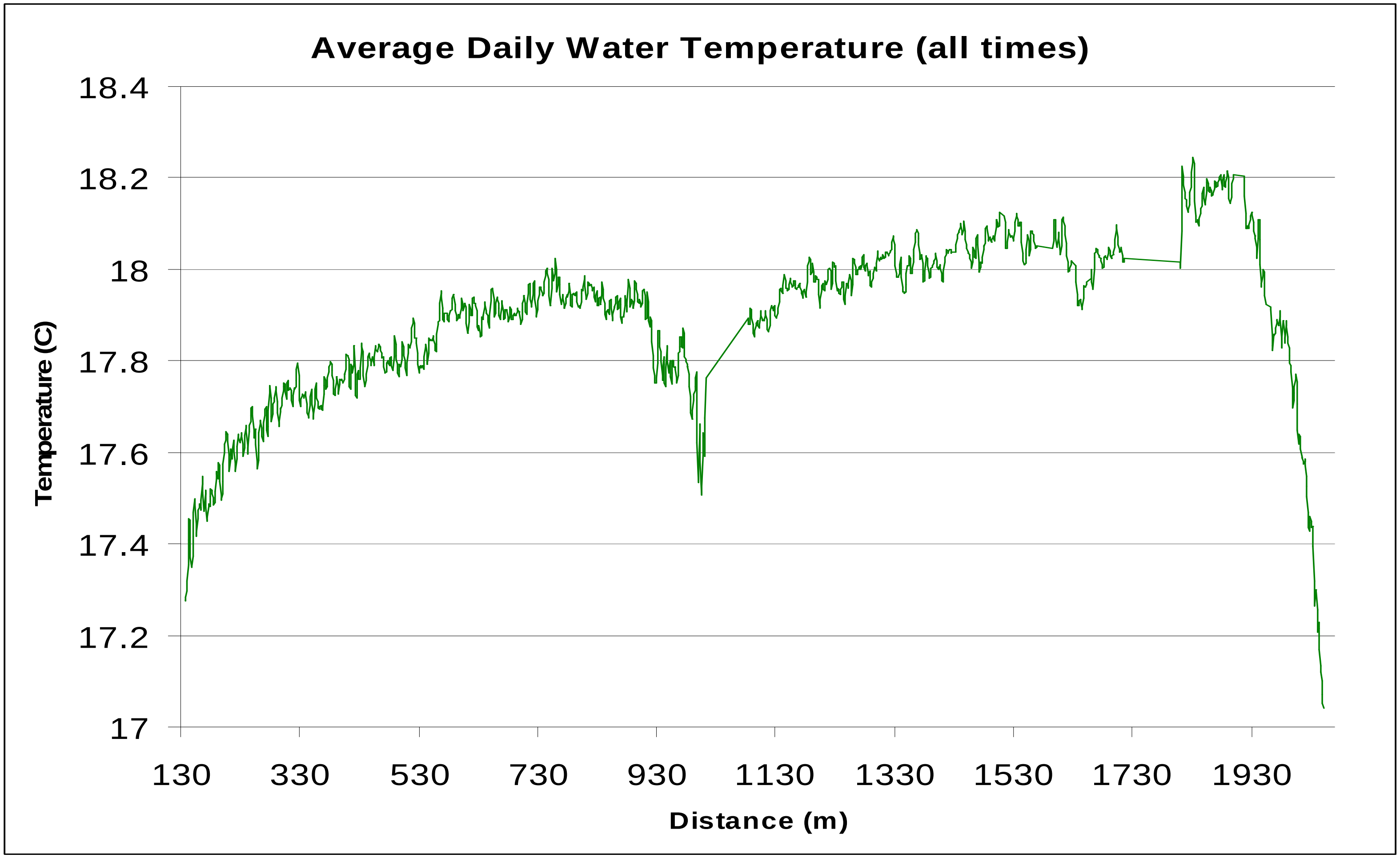

Figure 3.7 Average daily summer time temperature profile for the study reach in the Walla Walla River, Oregon from July 30th to August 20th, 2007 with air temperatures removed.

Where Q is discharge (m^3/s), T ($°C$) is the water temperature and the subscripts d is downstream flow, u upstream flow and l is lateral inflow. The ratio between $\frac{Q_l}{Q_d}$ can be derived by solving the mass and energy balance equations above:

$$\frac{Q_l}{Q_d} = \frac{T_d - T_u}{T_l - T_u}$$

The determination of $\frac{Q_l}{Q_d}$ from temperature measurements can be done only if the lateral inflow significantly alters the stream water temperature. Thus, the more precisely temperature can be measured, the more accurately inflows can be quantified.

An assumption that is implicit in these equations is that over the time interval between the night and day temperature profiles T_l and $\frac{Q_l}{Q_d}$ are constant. The approach assumes there is full mixing soon after the ground water enters the stream, and that the temperature over the cross section of the stream is constant. These equations also assume that the flow is constant over time and only varies due to ground water sources (Westhoff et al., 2007). Other assumptions are: there is no bed conduction loss; there is negligible solar, long wave, and evaporative heat exchange; and that there is negligible direct gain or loss through evaporation and precipitation.

We can move from quantifying each ground water input (for a depiction of the ground water system see Figure 3.8) to how ground water inflows will change surface water DTS measurements. The expected reaction of the summertime surface water temperature due to gains from a ground water inflow is illustrated in Figure 3.9. At a location of ground water inflow we expect that during summer the temperature trace will show reduction in temperature both day and night. This is the case as long as summertime surface water temperatures are above the average yearly air temperature, which is the temperature of incoming ground water from shallow sources.

Ground water inflows can be found through the use of a correlation coefficient computed for spatial changes in daytime to nighttime temperatures. That is to say that at locations of ground water emergence we expect evidence of cooling with downstream flow for both day and nighttime DTS data. The temperature change is determined from 10m before the ground water inflow location to 10m after the ground water inflow location. To use the correlation coefficient to locate the ground water inflows the surface water temperature of the average low nighttime and average peak daytime are used. The temperature data showing the ground water locations can be plotted to ensure that the locations are not only a positive correlation, but are in fact areas of cooling. Based on visual inspection, a false positive from the correlation coefficient can be seen in the data at areas of continuous warming or at a fiber optic cable junction site, both will be discussed later. Each of the ground water inflows that were found can be quantified using the coupled conservation of mass and energy equation from Selker et al., (2006b).

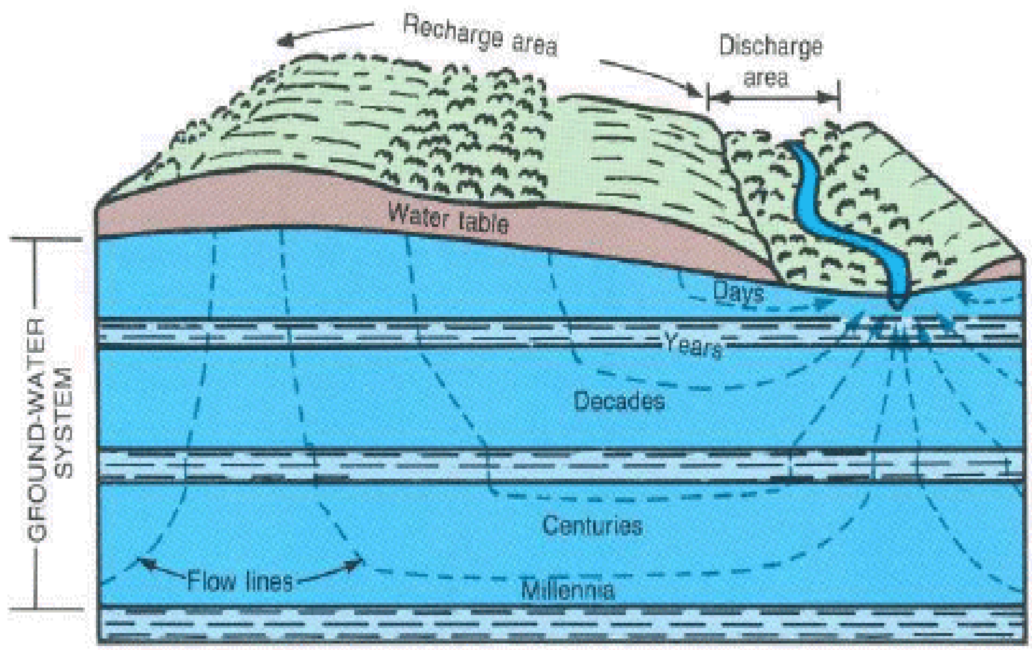

Figure 3.8 Depiction of ground water system (Waller, 1988).

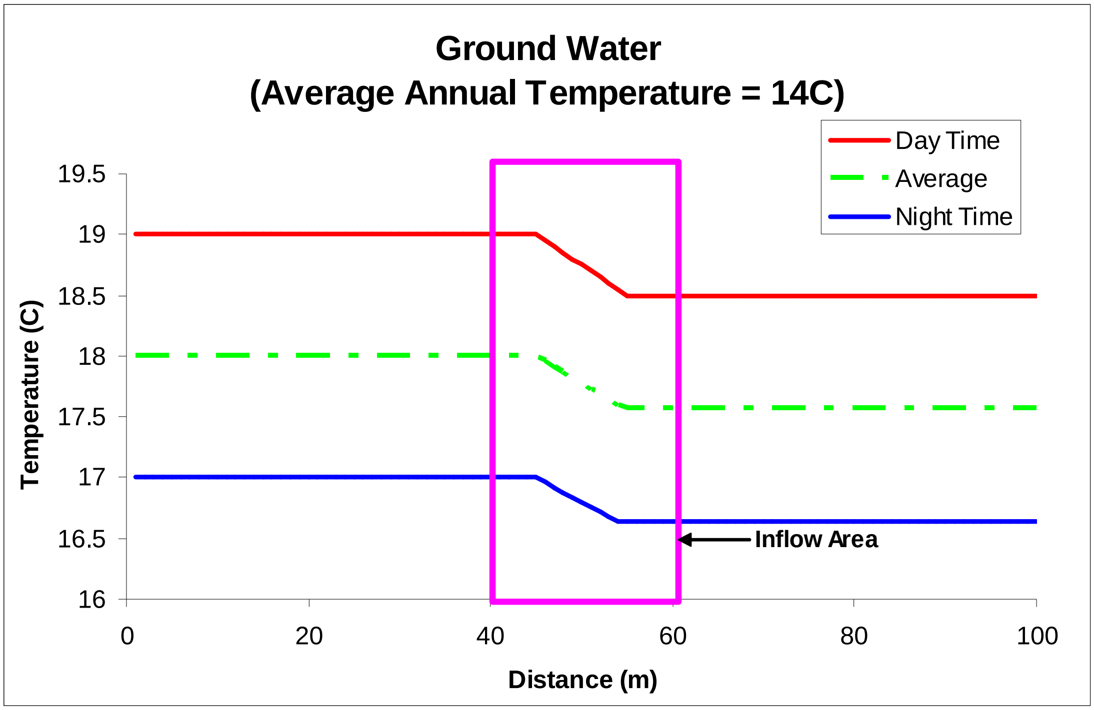

Figure 3.9 Example of what is expected from a trace from a ground water inflow site during summertime temperatures.

Hyporheic exchange sites are found through the correlation coefficient however, a negative correlation also occurs in areas where the cable is out of the water and recording air temperatures. Thus, identification of hyporheic exchange needs to be validated. Areas with cable exposed to the air will have a greater temperature difference than the surface water between the night and day temperatures allowing visual inspection of the traces to easily differentiate between the sites that are hyporheic exchange and the sites that are air exposed cable.

Most hyporheic exchange occurs in pool to riffle sequences, with water entering the sediment after the pool and coming out of the sediment after the riffle. During the warm times of day this creates a slight drop in the temperature at the hyporheic exchange site, and during the cooler time of night it gives an increase in temperature at the same site (Figure 3.10). This change is due to the time it took the water to pass through the sediment. For the purpose of this thesis exchanges longer than 1day duration are not considered in our determination of hyporheic exchange.

Hyporheic flow longer than a one day residence time can occur; examples of these longer duration hyporheic exchanges include when a secondary channel, braided channel, or meander bend is present in the surface waterway (Vervier and Naiman, 1992; Harvey and Bencala, 1993; Wondzell et al., 1996; Wondzell and Swanson, 1999). These longer duration exchanges cannot be found through the three week duration data that we have available. In essence, these locations of hyporheic exchange make the temperature of the surface water more stable, bringing the surface water back to the daily average temperature. These river temperature characteristics along with the porosity of the streambed will be used to calculate the depth and width

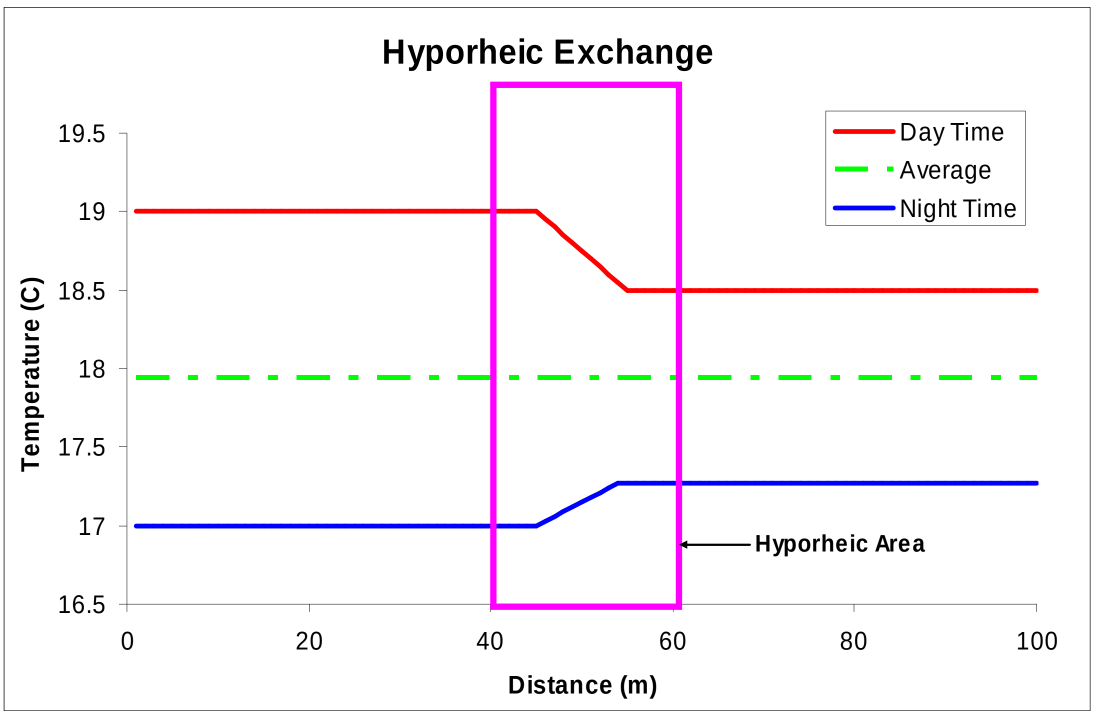

Figure 3.10 Depiction of expected temperature change from hyporheic exchange during summer.

of hyporheic exchange flows. These same parameters will define the water's travel time through the hyporheic exchange zone (Wondzell and Swanson, 1999).

Let us look at the collective cooling from hyporheic exchange between the surface water and the bed material over a section of river. For these calculations the hyporheic volume will be considered a continuous mixing zone throughout the entire length of the river. To estimate this overall hyporheic exchange we can consider the difference in temperature from the average daily temperatures to the average peak daily temperature for the upstream portion of the reach and compare it to this same measurement for the downstream portion of the stream. The upstream and downstream portions of the reach are considered to be the first and last 50 meters of in-stream fiber optic cable, respectively; bounding an 1800m section of the river. This will serve as the upper and lower boundary for an energy balance.

The energy balance is used to find the mass of material required to match the actual in-stream temperature change we see in the data. The amount of energy coming into the reach minus the energy leaving the reach must equal the energy stored within the reach (see Figure 3.11). The energy balance will be used to find the amount of energy that must go into the hyporheic exchange and volume of surface water. The stored energy can be put in terms of thermal heat capacity for the hyporheic exchange and surface water to determine the depth of the hyporheic exchange. To determine the depth of hyporheic exchange that is evenly distributed over the entire river bottom from the stored energy term we will use the surface area of the hyporheic exchange.

To calculate the depth of hyporheic exchange the solar radiation is equally distributed across the river reach, the quantity of ground water inflow are of equal magnitude at each inflow site, and the ground water inflows are restricted to the discrete locations found through the DTS temperature readings. The ground water inflows are included in the calculation for hyporheic exchange depth because we are basing the hyporheic exchange depth on the heat capacity of the hyporheic exchange site and to find the heat capacity we will need to include the ground water energy for the conservation of energy equation that is used. An important feature of this river reach is that the flow from the upstream to the downstream portion of the reach does not change. This is justified by the flow measurements along the reach completed by Bob Bower from the Walla Walla Basin Watershed Council that shows upstream to downstream measurements to be within the 10% error interval of the measurement method (personal communication, Bob Bower, October 2007). Since the flow measurements are within the 10% error interval, there is no statistical difference between the upstream and downstream flows. Lastly, solar radiation, ground water inflow, and hyporheic exchange are assumed to be the major processes contributing to river cooling and are therefore the major components in the energy balance and are the main processes taken into account for this thesis. The long wave radiation, evaporation, and air exchange (convection) will be lumped into one term. The value for this term was estimated using a calibrated energy balance via the software Heat Source v. 7.0 (ODEQ, 2005), energy balance software that was calibrated and updated for the Walla Walla River in the summer of 2005.

We can now look at the method developed to find the expected volumetric heat capacity for the hyporheic exchange. Prior to calculation a conceptual model may help to understand the major contributions and makeup of the channel energy budget in question (see Figure 3.11 and 3.12). Using this conceptual model we can find the thermal mass of the hyporheic exchange by using a conservation of energy balance equation. For the conservation equation we need to account for all the major inputs and outputs of energy, depicted in Figure 3.11. The input energies to this system are the inflowing surface water energy, the solar energy, the ground water energy. The out flow of energies include the losses of surface water to ground water, the lumped term for the convection, evaporation, and long wave radiation energies, and the water energy leaving the study reach. The energies will be calculated as a flux in joules per second.

The objective here is to determine the thermal mass of hyporheic exchange. This was completed by computing the energy fluxes into and out of the control volume to find the rate of change of stored energy within the control volume. Since the control volume contains a known volume of surface water the thermal mass of hyporheic exchange can be separated and computed.

The energy balance for this study is based on the control volume in Figure 3.13. This control volume comes from the instantaneous energies for the study reach assuming all flows of water are steady. The control volume consists of the incoming energy of the water [1], the incoming solar radiation energy [2], the ground water energy into the reach [3], the ground water energy out of the reach [4], the lumped energy term (from the energy for evaporation, convection, and long wave radiation) [5], the outgoing energy of the water [6], and the stored energy (going into hyporheic exchange and the surface water). Conduction is an additional energy in the system. The control volume contains both the river water and the conduction of river water to bed material (the hyporheic exchange site). Therefore, the conduction term is incorporated into the stored energy in the control volume.

The energy balance is based on the conservation of energy and can be written as the rate of change of stored energy is equal to the difference between the total incoming energy (E_{ti}) and the total out going energy (E_{to}).

Rate of change of stored energy within the control volume = E_c [J/s] = $E_{ti} – E_{to}$

For the purpose of this study it can be stated as:

Rate of change of stored energy = (incoming water energy + solar radiation energy + ground water energy in) – (ground water energy out + lumped energy + outgoing water energy)

Where the energy stored remains in the materials within the control volume, including the surface water and the hyporheic exchange zone.

The energy fluxes are denoted:

water energy in = E_i [J/s]

solar radiation energy = E_s [J/s]

ground water energy in = E_{gi} [J/s]

ground water energy out = E_{go} [J/s]

lumped energy term = E_l [J/s]

water energy out = E_o [J/s]

In this notation the energy balance can be written as:

$$E_c = (E_i + E_s + E_{gi}) – (E_{go} + E_l + E_o)$$

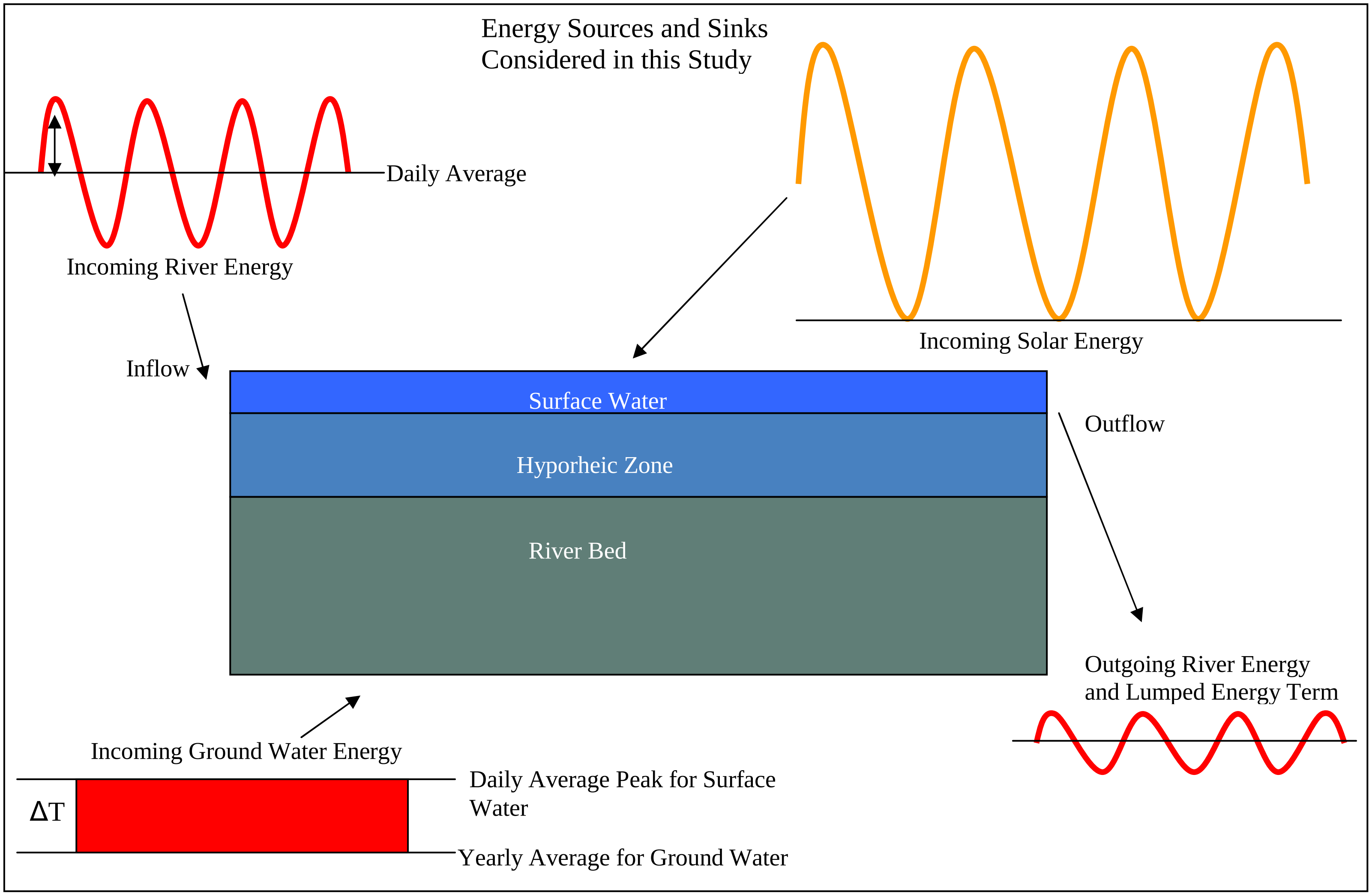

Figure 3.11 Depiction of the energy sources and sinks for the study reach in Milton Freewater, OR

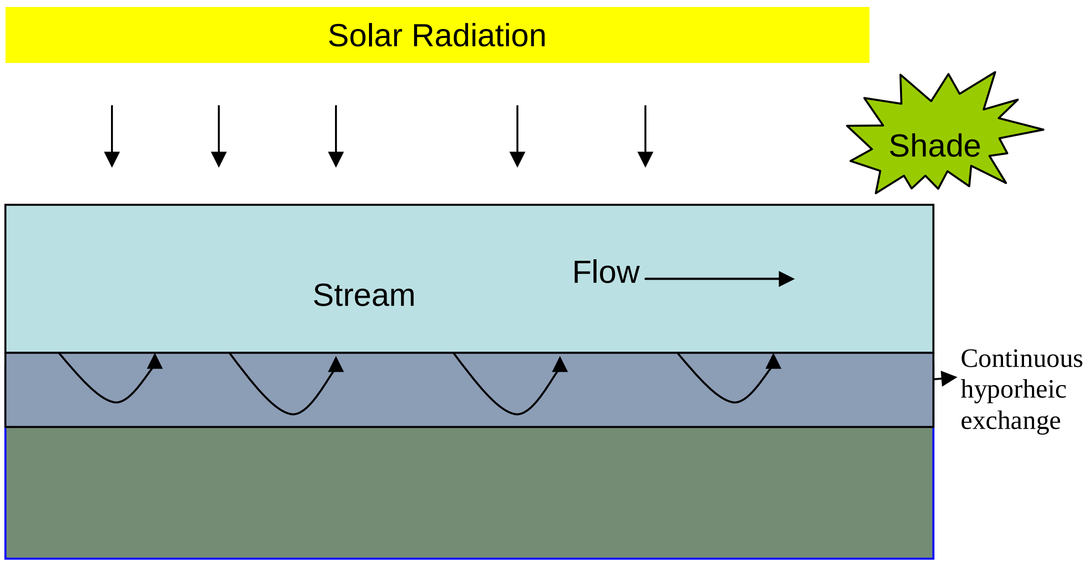

Figure 3.12 Conceptual model of the continuous hyporheic exchange.

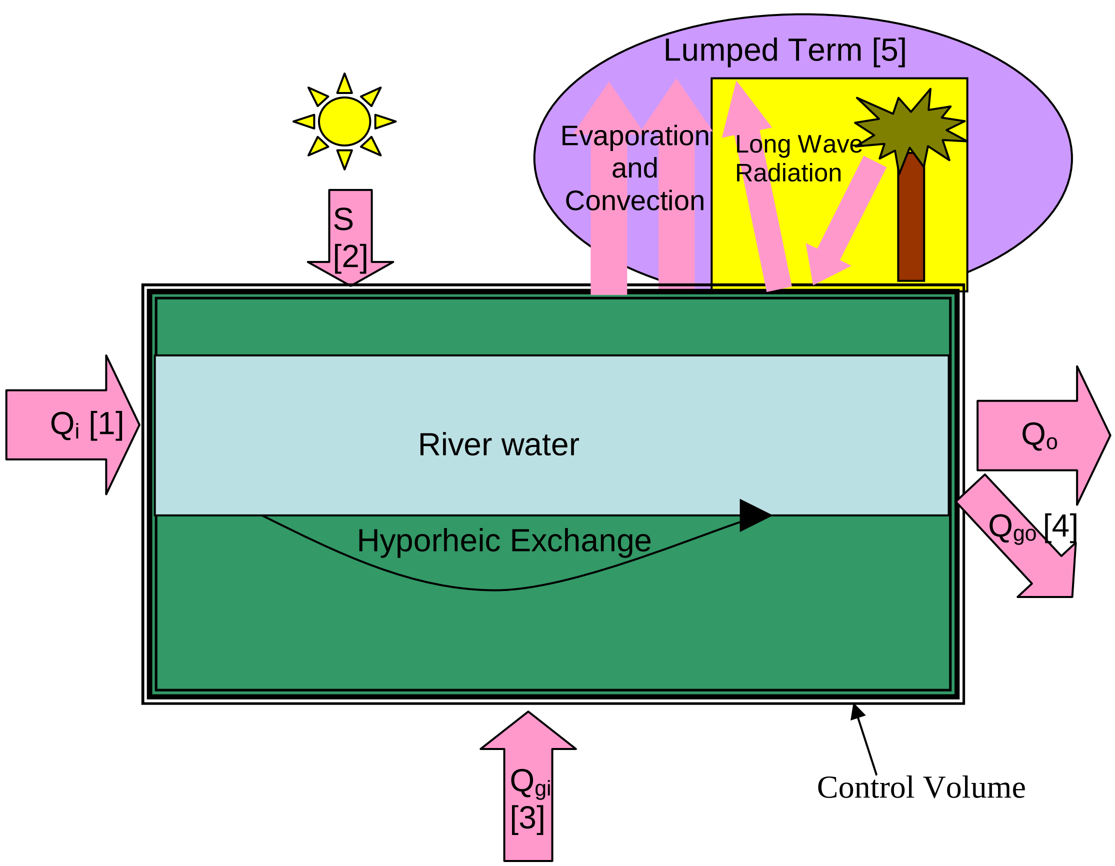

Figure 3.13 Depiction of energy inflows and outflows to the control volume.

The makeup of each energy flux within the energy balance can now be determined. The energy fluxes will be computed to solve for the difference between the inflowing and outgoing energy giving the rate of change of stored energy within the control volume (see Figure 3.14 for concept of dampened temperature at outflow due to hyporheic exchange). First the inflowing energy flux is computed. The incoming water energy [1] is computed at the point entry to the control volume by finding the incoming temperature (T_u [°C]). All temperatures are referenced to 0°C to insure correct energy flux calculations. To compute the energy flux the temperature is multiplied by the volumetric thermal heat capacity of water ($C_{vw} = 4.18 \times 10^6$ J/°C m^3, for water at 20°C) and the flow into the study reach (Q_s [m^3/s]) to determine the inflow energy.

$E_i = C_{vw}(T_u)(Q_s)$

Solar radiation follows a diurnal pattern and is therefore a function of time. The energy input from solar radiation (S) [2] was acquired from weather station data in the Walla Walla River Basin near the study reach. The net solar energy flux is computed as the solar radiation as a function of time multiplied by the fraction of the river's surface area (R [m^2]) that is exposed to the solar radiation. Because the solar radiation does not directly impact the shaded portion of the river, the surface area will be multiplied by the fraction of area that is exposed to the solar radiation. In this case 10% of the river was shaded so the surface area was multiplied by a shade factor (F) of 0.9.

$E_s = S(R)(F)$

The energy of the ground water inflow [3] can be determined by finding the temperature of the ground water inflow (T_{gi} = 14°C). The energy flux is computed by multiplying by the volumetric thermal heat capacity of water and the total ground water flow in the reach (Q_{gi} = 0.36 m^3/s).

$E_{gi} = C_{vw}(T_{gi})(Q_{gi})$

The energy for the ground water outflow [4] is determined similarly, taking its temperature to be equal to that of the surface water of the control volume, T_{cv} [°C]. The flow data for the study reach shows no significant change in water from the inflow to the outflow; since we have determined that there is cold water flowing into the reach their must be an equal amount of water flowing out of the reach. For this particular case the ground water outflow we take to be equal to the ground water inflow (Q_{go} = 0.36 m^3/s).

$E_{go} = C_{vw}(T_{cv})(Q_{go})$

The lumped energy term (L [J/s m^2]) representing evaporation, convection and long wave radiation [5] was obtained from Heat Source v. 7.0 (ODEQ, 2005), an energy model that has been calibrated for this river reach. This term for our study reach was determined by using the Heat Source information from August 2002, giving an estimate for this study (summer of 2007). As seen in Figures 3.15 and 3.16 the climatic data for August in these two years is similar, therefore 2002 data can be used as an approximation for 2007. The energy taken from Heat Source is then multiplied by the surface area of the river reach.

$E_l = L(R)$

The energy flux out of the river reach [6] is determined in the same manner as the energy into the reach. The volumetric heat capacity of water and the flow of the reach are multiplied by the downstream temperature (T_d [°C]).

$E_o = C_{vw}(T_d)(Q_s)$

The conceptual model (Figure 3.12) above also pertains to the energy balance necessary to find the functional volume of the hyporheic exchange. The hyporheic exchange depicted in the model along with the surface area of the hyporheic exchange can be used together to find the functioning depth of this zone. Some assumptions made for this calculation are that the hyporheic exchange is continuous along the study reach and is directly below the surface water, not coming in on the sides of the channel. The second assumption stated above is viable when there is such a large width of surface water to depth of water ratio. These assumptions help to keep this calculation as a stripped down simple formula to help quantify the hyporheic exchange. The same idea of the continuous hyporheic exchange can be used to find the depth for discrete zones of hyporheic exchange; the depth will be much greater in discrete locations of hyporheic exchange because the same amount of cooling must

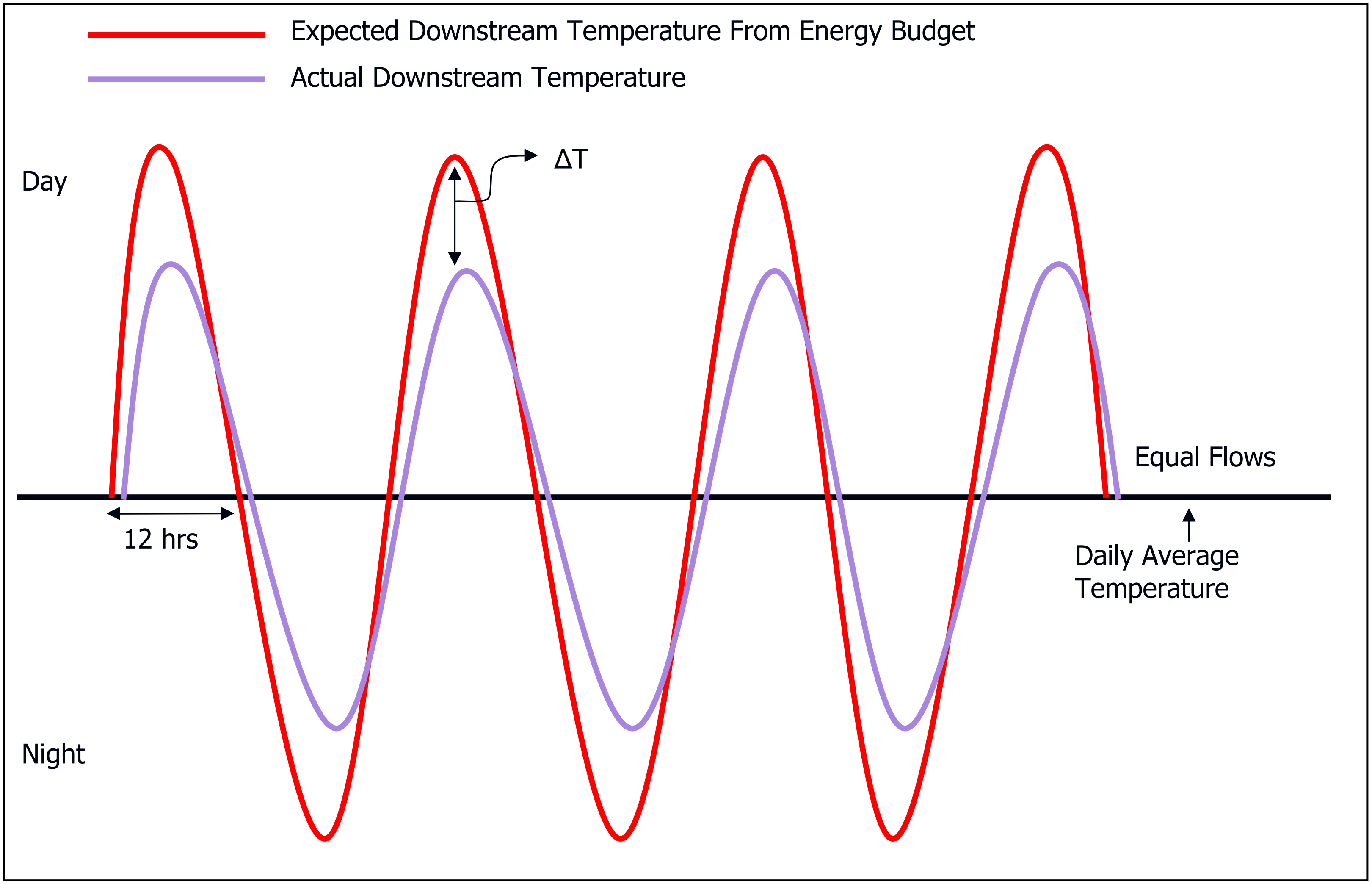

Figure 3.14 Expected temperature from the energy budget compared to the actual temperature with hyporheic exchange.

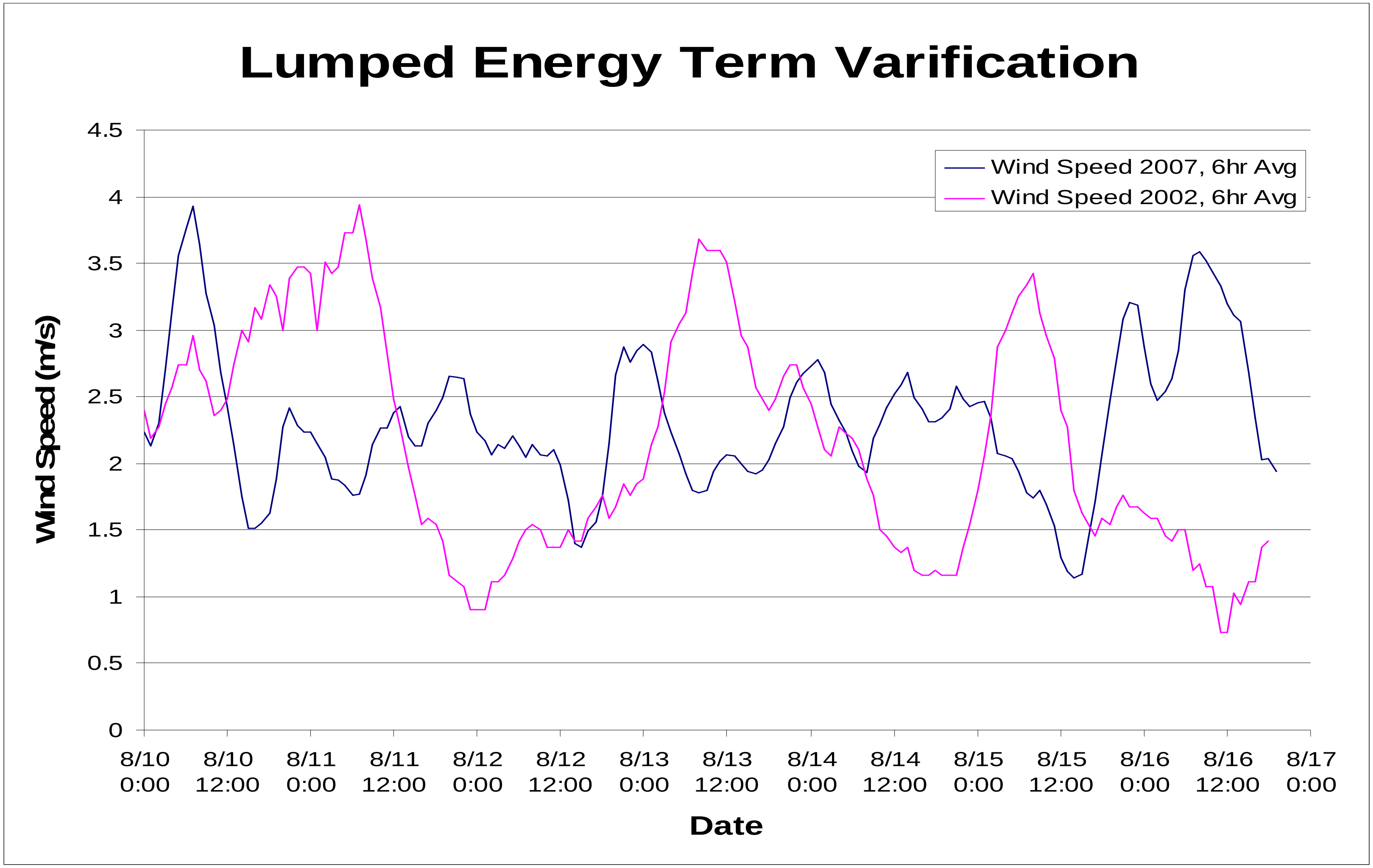

Figure 3.15 Wind speed comparison between 2002 to 2007 for the Walla Walla River near Milton-Freewater, Oregon.

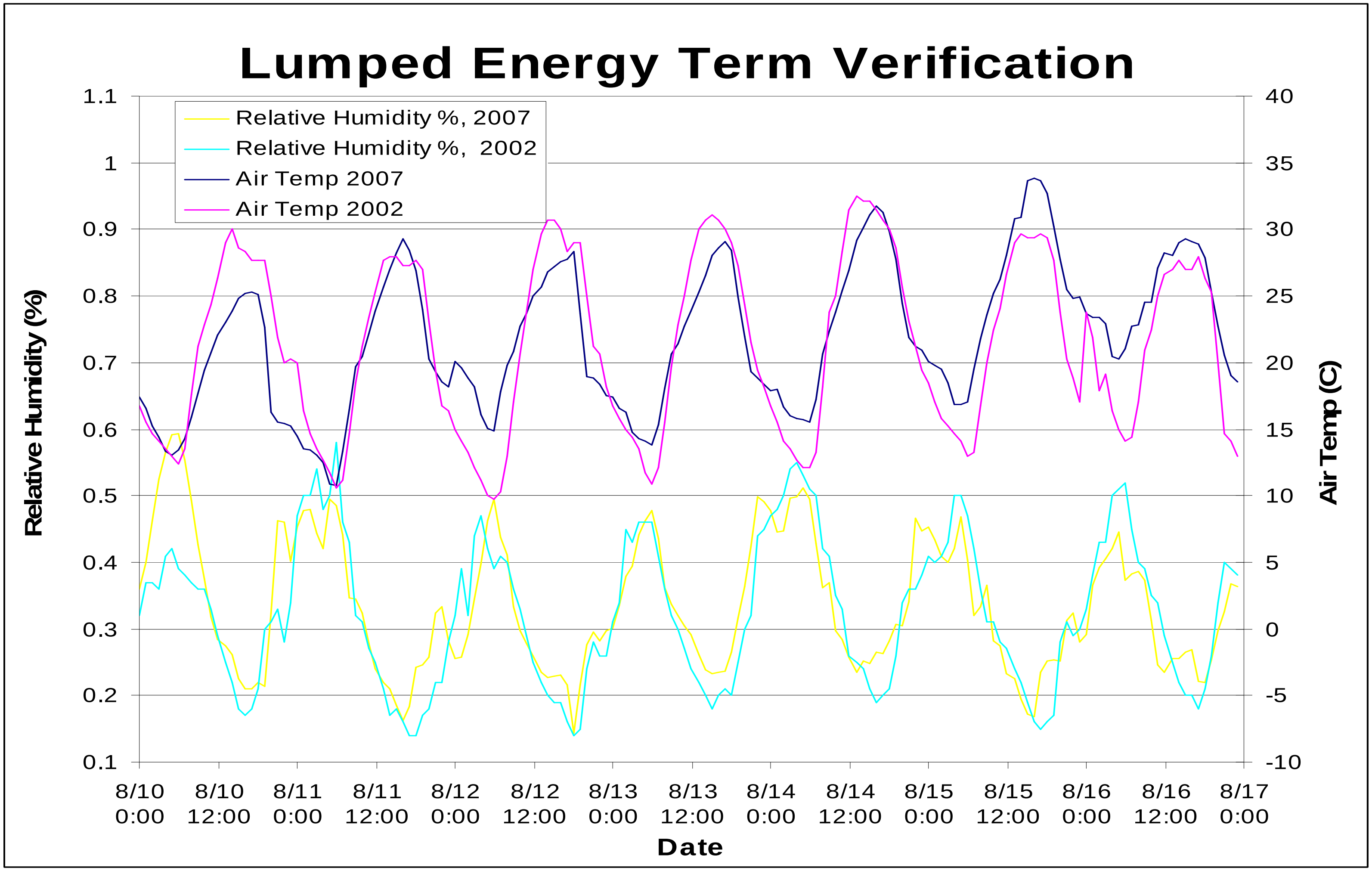

Figure 3.16 Comparison of air temperature and relative humidity between 2002 and 2007 for the Walla Walla River near Milton-Freewater, Oregon

take place in a shorter distance. Both continuous and discrete hyporheic exchange are important to consider, but the DTS instrument is capable to pin point the discrete locations based on the peak hot and cold daily temperature profiles.

Depth of the hyporheic exchange can be found through consideration of the control volume (Figure 3.13). Since we have the calculation for the rate of change of stored energy for the control volume (hyporheic exchange plus surface water) and we know the volumetric heat capacity for water and the bed material, the volume of water above the hyporheic exchange site, and the porosity of the bed material to be 0.3 (Constantz et al., 1996; Edwards, 1998), we are able to calculate the volume of the hyporheic exchange site. Since the porosity of the bed material is 0.3 we know that the bed material takes up 0.7 of the volume in the hyporheic exchange site, this will be used to help calculate the volume of the hyporheic exchange site.

The energy stored within the control volume (E_c [J/s]) resides in both surface water and the water sediment mix of the hyporheic exchange. The depth of hyporheic exchange calculation is based on the energy stored in the control volume that is not stored in the surface water.

The energy balance will be based on the volumetric heat capacities of the different material within the control volume and the stored energy within the control volume. The stored energy within the control volume will be integrated over time in order to find the cumulative energy the thermal mass of the hyporheic exchange must account for. From Figure 3.17 we can see a model of what the control volume contains. Using this model (containing a known volume of surface water), the volumetric heat capacity of the sediment, and the temperature change of the control volume over a specific time period we can derive an equation to determine the depth of the hyporheic exchange.

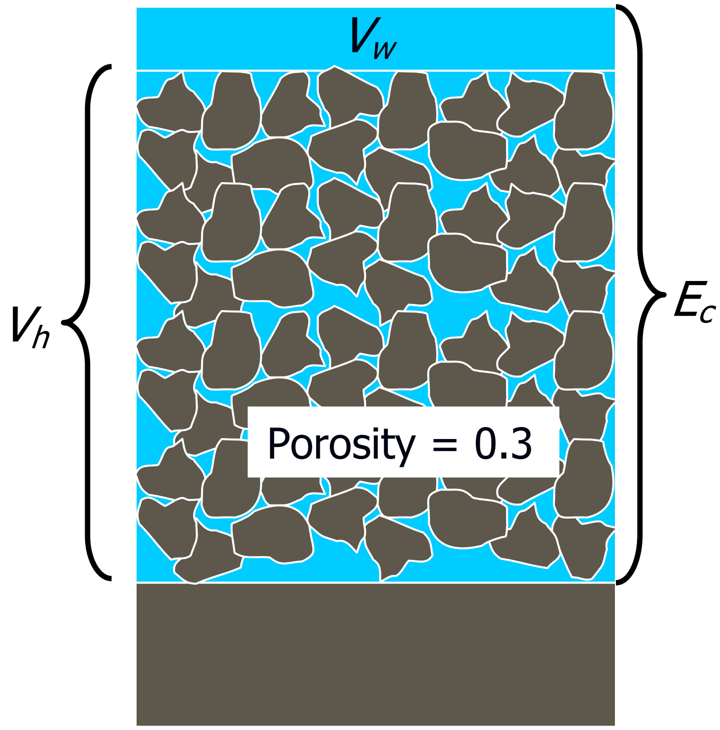

Figure 3.17 Conceptual model of continuous hyporheic exchange.

The terms used for this derivation are denoted:

E_c= Rate of change of stored energy within the control volume (J/s)

V_{cv} = Total volume of control volume (m^3)

V_h = Total volume of hyporheic (m^3)

V_w = Total volume of water above hyporheic exchange zone (m^3)

T = Temperature of the control volume for time duration (°C)

t = Time duration the calculation was completed (s)

C_{cv} = Thermal volumetric heat capacity of control volume (J/°C m^3)

C_{vw} = Thermal volumetric heat capacity of water (J/°C m^3)

C_{vs} = Thermal volumetric heat capacity of sediment (J/°C m^3)

SA = Surface area of hyporheic zone (m^2)

D_h = Depth of hyporheic zone (m)

We begin with the previously calculated energy stored within the control volume and find:

$$E_c = \left(\frac{dT}{dt}\right) C_{cv} V_{cv}$$

This can be integrated as:

$$\int dT = \frac{E_c}{C_{cv} V_{cv}} \int dt$$

Giving:

$$\Delta T = \frac{E_c}{C_{cv} V_{cv}} \Delta t$$

Now we can expand the control volume terms to incorporate the materials involved.

$$C_{cv} V_{cv} = C_{vw}\left(V_w + 0.3V_h\right) + C_{vs} 0.7V_h$$

This can be substituded in for the control volume terms:

$$\Delta T = \frac{E_c}{C_{vw}\left(V_w + 0.3V_h\right) + C_{vs} 0.7V_h} \Delta t$$

The volume of hyporheic exchange can be computed as:

$$V_h = \frac{\frac{\Delta t E_c}{\Delta T} - C_{vw} V_w}{0.3C_{vw} + 0.7C_{vs}}$$

Once the volume of the hyporheic exchange has been calculated the depth of the exchange can be found by simply dividing the calculated volume by the surface area the hyporheic exchange occurs over (for our case we have made the assumption that the hyporheic exchange occurs over the entire length and width of the channel).

$$D_h = \frac{V_h}{SA}$$

3.3.3 Fish Survey

During this study, the USFWS conducted a survey on the fish found in this reach of the Walla Walla River. The survey determined the number of fish and species found throughout the study reach during warm daytime temperatures. The surveyors recorded the cable distances when they came to a school of fish during their snorkel survey which started at the downstream section of the study reach and went up the river to the end of the study reach. This fish survey will be used to determine if the fish populations are locating the cold water inflows during warm daytime periods.

4.0 Results

4.1 Calibration and Jitter Removal of DTS Data

The temperature offset for post calibration of the DTS data was determined to be approximately 5° C by checking ice bath temperatures using a high resolution VWR temperature probe, which has a temperature resolution of 0.001° C. This was determined through calculating the difference between the VWR temperature measurement and the temperature measurement given by the DTS for the ice bath. The upstream ice bath was found to be -0.006° C and the downstream bath to be 0.012° C. The two fiber optic cables used for this study meet at the ice bath at the 1030 meter mark. This junction is noticeable in the temperature measurements because at this point the temperature profile shows a spike in the record due to the barrel connector. In Figure 4.1 it is easy to see that the ice slurry baths are not read as zero by the DTS system, giving the necessity for the offset correction. The entire temperature profile was adjusted for this offset to get temperatures that will be close to the true stream temperature.

The offset was found to be a reduction of the DTS measurements by 5.02° Celsius. Figure 4.2 shows the basic trace acquired from DTS viewed through MatLab that has been adjusted for the offset. This trace gives the temperature averaged for one hour every meter along the 2000 meter study reach.

When the temperature data was viewed in the MatLab movie format, a jitter (typically between 0.5 to 1.0° C) was seen, where the data was displaced either up or down (movie not presented in this thesis). This "jitter" was first seen in an ice temperature bath. The temperature should not quickly change within the bath, but some jumps were noticed. Through discussions with the DTS manufacturer it was learned that this defect reflected a firmware defect which is prominent when the instrument is used in double-ended mode with high loss fiber optic cable (our case). The jitter seen was not due to true temperature changes from the river and therefore it was necessary to remove before further data interpretation took place. This jitter was corrected for by first plotting temperature versus the time for the DTS measurements (Figure 4.3). The plotted river temperature should follow a smooth pattern due to the influence of air temperature, solar radiation, and the high thermal heat capacity of water. This was not the case with the jitter present so the data set needed to be smoothed out post collection. To accomplish the smoothing, a 5hr running average of the hourly temperatures was taken to get an adjusted temperature measurement (see Figure 4.4). For the running average a section from 1077 to 1425 meters along the river was used because it showed quality water temperature with no spikes due to air temperature. The differences between the averaged temperature and the true temperature were found and added to the entire dataset for the duration of the study. This gave a new adjusted temperature dataset to be used for all calculations.

4.2 Cold Water Refugia

The temperature data was viewed at several different time intervals throughout the day to see how nighttime temperature changes may differ from the ones during the daytime (see Figures 3.5 and 3.6). The temperature data were averaged throughout space and time to find locations where there was a continuous drop in the surface water temperature; possibly indicating areas of cool water inflow (see Figure 4.5). The three meter average nighttime (3am to 7am) temperature was plotted along with the three meter average hot daytime (6pm to 10pm) temperature in Figure 4.5 to see if the dynamics expected between hyporheic interaction zones and ground water inflows would become noticeable in this dataset.

The flow survey done by the Walla Walla Basin Watershed Council (WWBWC) at the time of the DTS and fish study found average stream flow of 0.9 m^3/s (Table 4.1) for the entire river reach with an error of 10 % for the cross-sectional flow measurement method used (Bob Bower, per communication, 2007). The flow data was necessary to help quantify the ground water inflow to our study reach. The ground water temperature is also necessary for the combined conservation of mass and conservation of energy equation used to quantify ground water inflow.

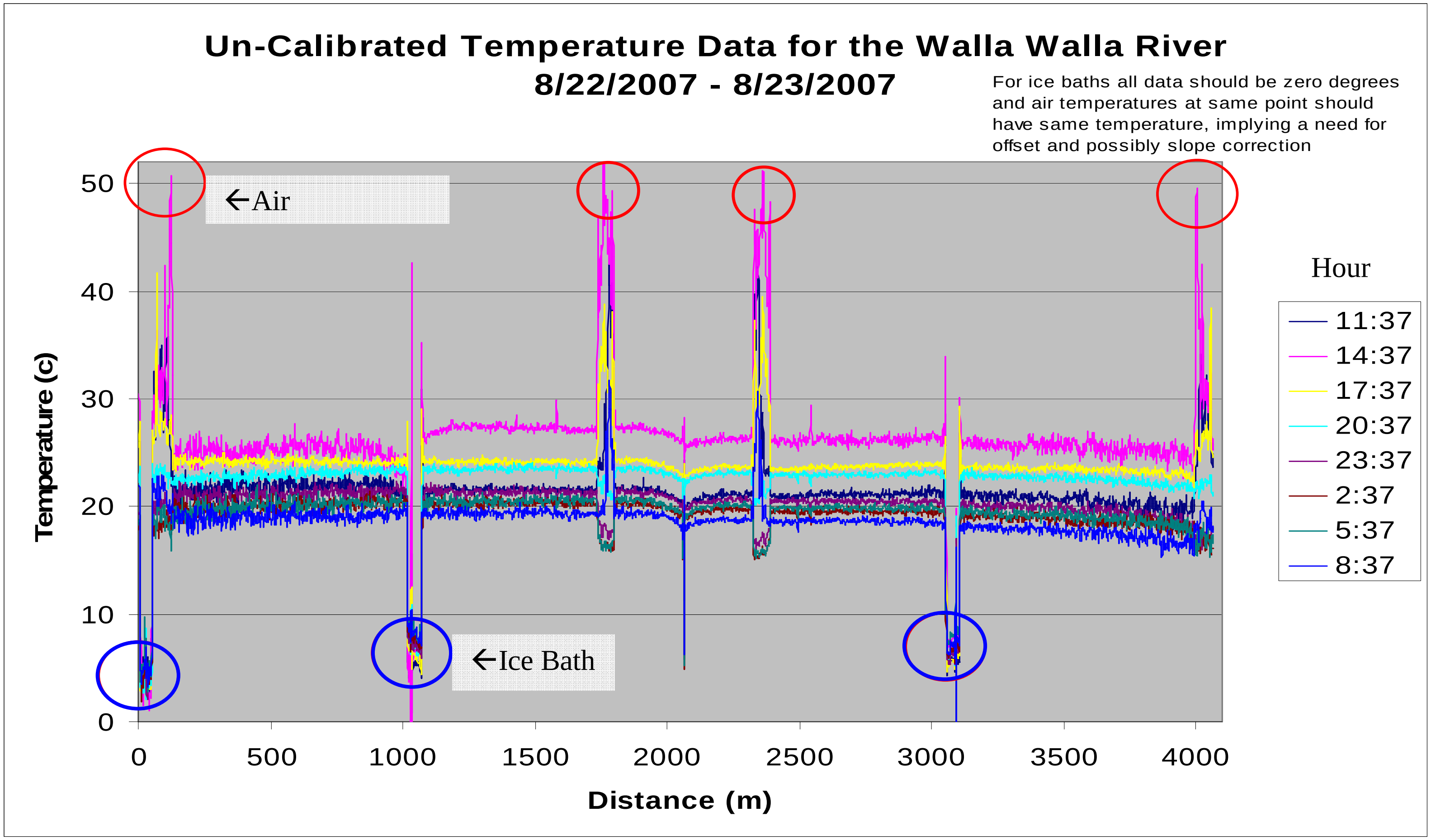

Figure 4.1 The un-calibrated graph shows eight hours of temperature profile for the reach. The duplex cable used shows a mirrored image after 2060 meters. Blue circles indicate ice baths and red circles locations of known air exposed sections of cable.

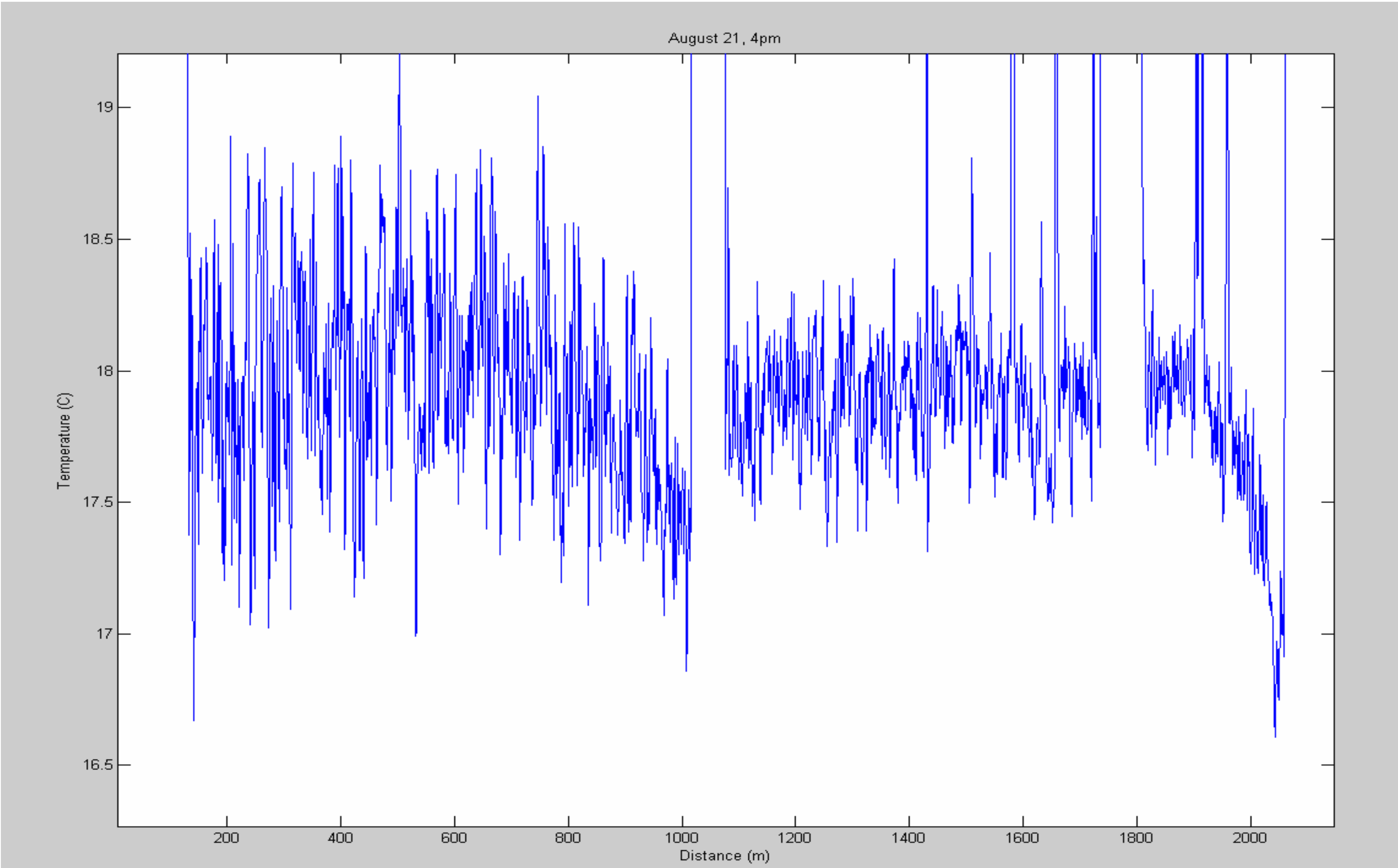

Figure 4.2 Single temperature profile of raw data for study site on Walla Walla River, 21 August 2007 at 4pm only adjusted for temperature offset.

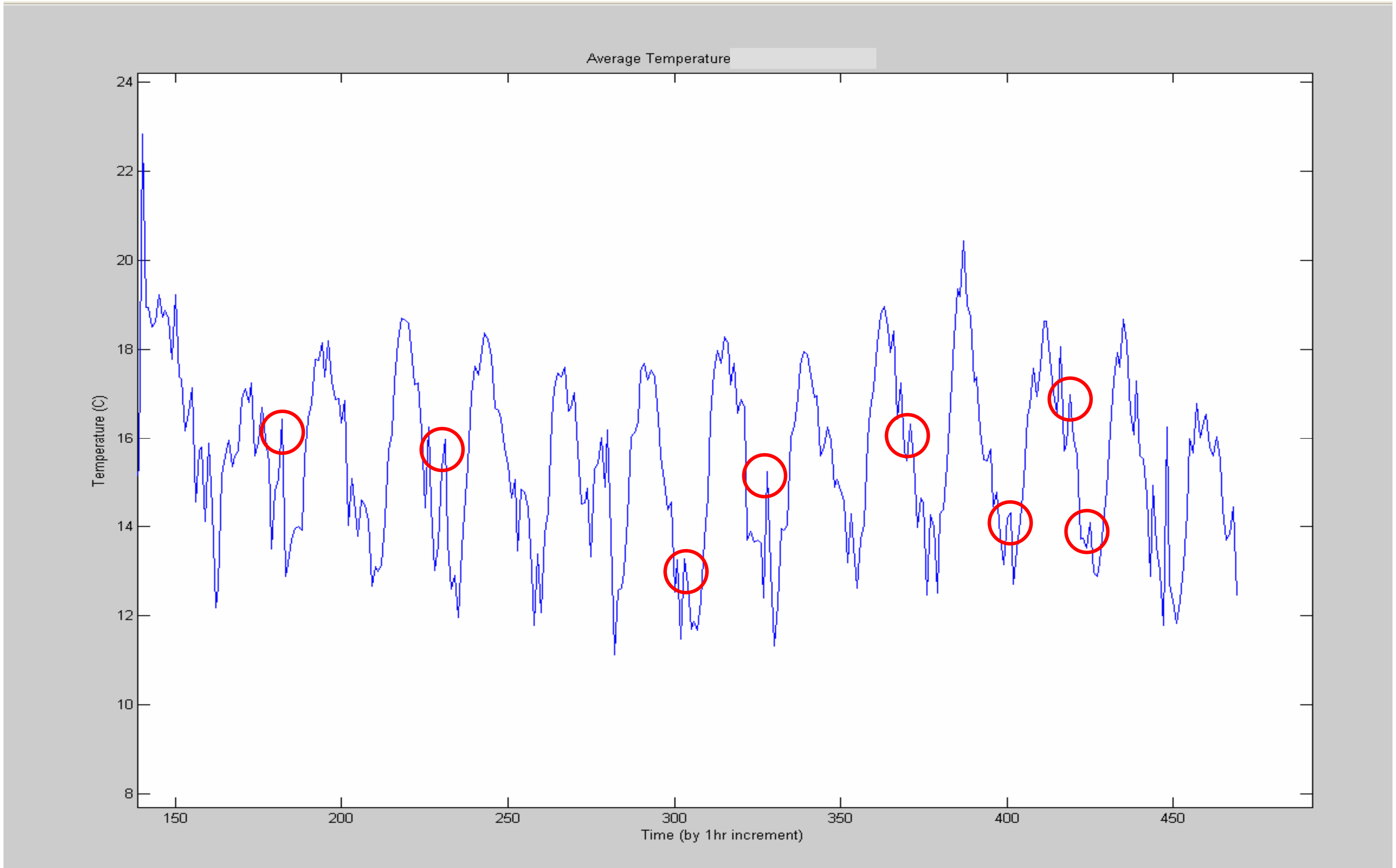

Figure 4.3 Daily temperature variations with jitter present for July 30th to August 20th, 2007 for meter markings on cable of 1077 to 1425m; typical examples of jitter circled.

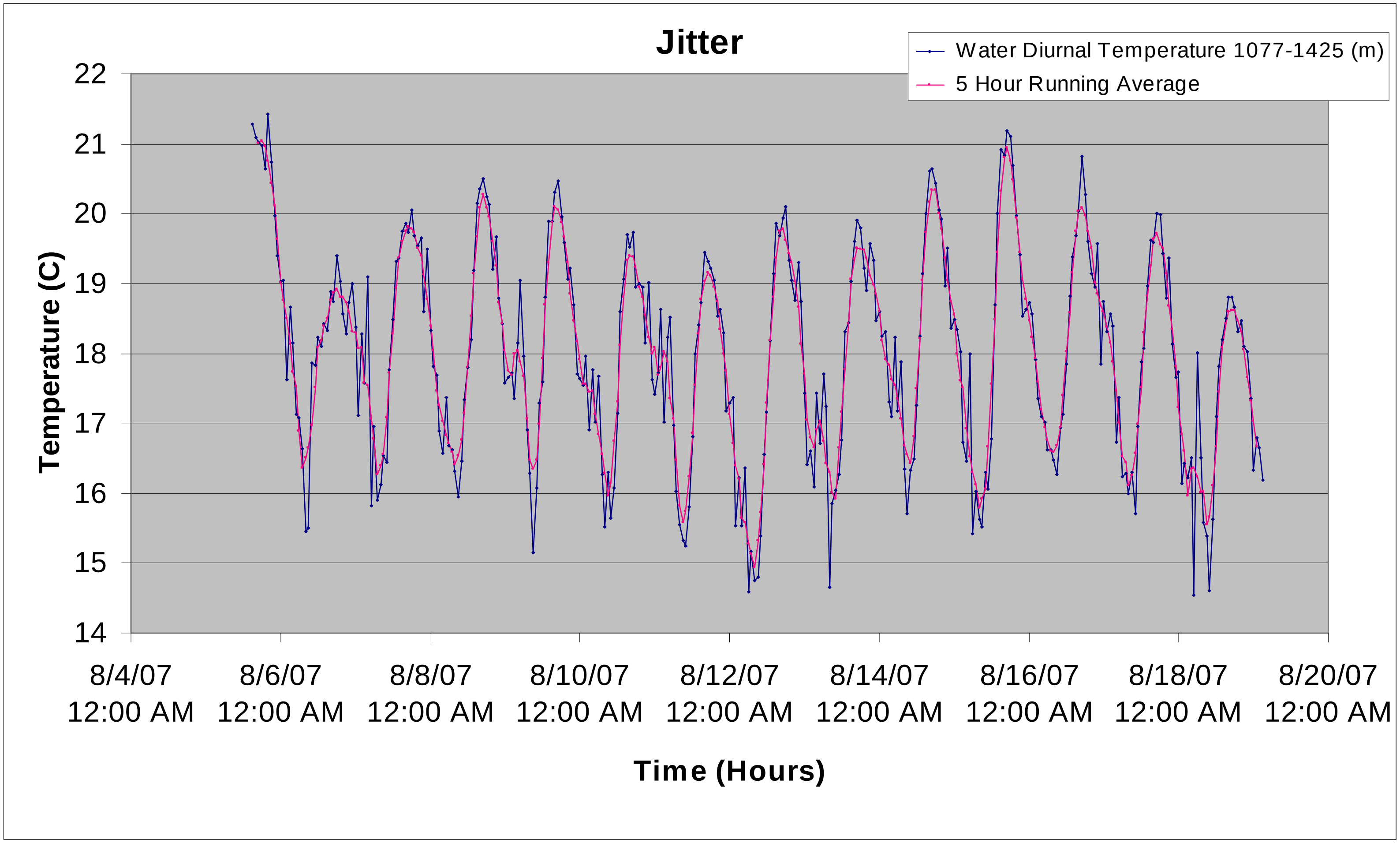

Figure 4.4 Daily temperatures from DTS with running average for to smooth Jitter from August 4th to August 20th from the 1077 to the 1425 meter mark.

Table 4.1 Surface water flow measurements and calculated ground water inflows. Shaded ground water inflow neglected in averages due to connector effect.

Ground Water		Surface Water	Temperature (C)			Ground Water	
Start (m)	Stop (m)	Flows (cfs)	Tg	Ti	To	Flow (cfs)	Flow (m^3)
315	355	32.8	14	17.96	17.87	0.76	0.02
460	500	34.2	14	18.04	17.96	0.69	0.02
630	705	32.5	14	18.12	18.00	0.98	0.03
918	940	32.6	14	18.04	17.84	1.70	0.05
978	1008	32.1	14	17.92	17.72	1.73	0.05
1610	1643	32.9	14	18.20	18.00	1.64	0.05
1900	2048	30.4			Average	1.25	0.04
	Average	32.9					

The data from ground water wells in the same aquifer indicate the average ground water temperature for July of 2006 (most recent data) to be 14° C. The ground water inflow sites were determined through the correlation coefficient from cool nighttime to the warm daytime temperature of the surface water (Figure 4.5). Any place that the two dropped in unison was designated as ground water and the distance that the drop lasted was recorded (see Figure 4.6 for specific sites). At each identified ground water inflow the temperatures from 10m before the drop to 10m after the temperature drop were recorded and the ground water inflows were quantified using (Table 4.1).

The traces for peak daytime temperature and for cool nighttime temperature (Figures 3.5 and 3.6) can be examined for hyporheic exchange as well. The overall average will not show any temperature shift or will show very little temperature structure for the location of hyporheic exchange. However, when comparing the peak daily to the cool nightly temperatures the location of hyporheic exchange should be noticeable. Remembering that these locations can be seen as temperature drops during the peak daily surface water temperatures, but should rise in temperature at the same location during the low nightly temperatures (see Figure 4.7 for possible hyporheic exchange sites). The temperature shift between night and daytime temperatures at these hyporheic exchange sites are a negative correlation coefficient (Figure 4.5).

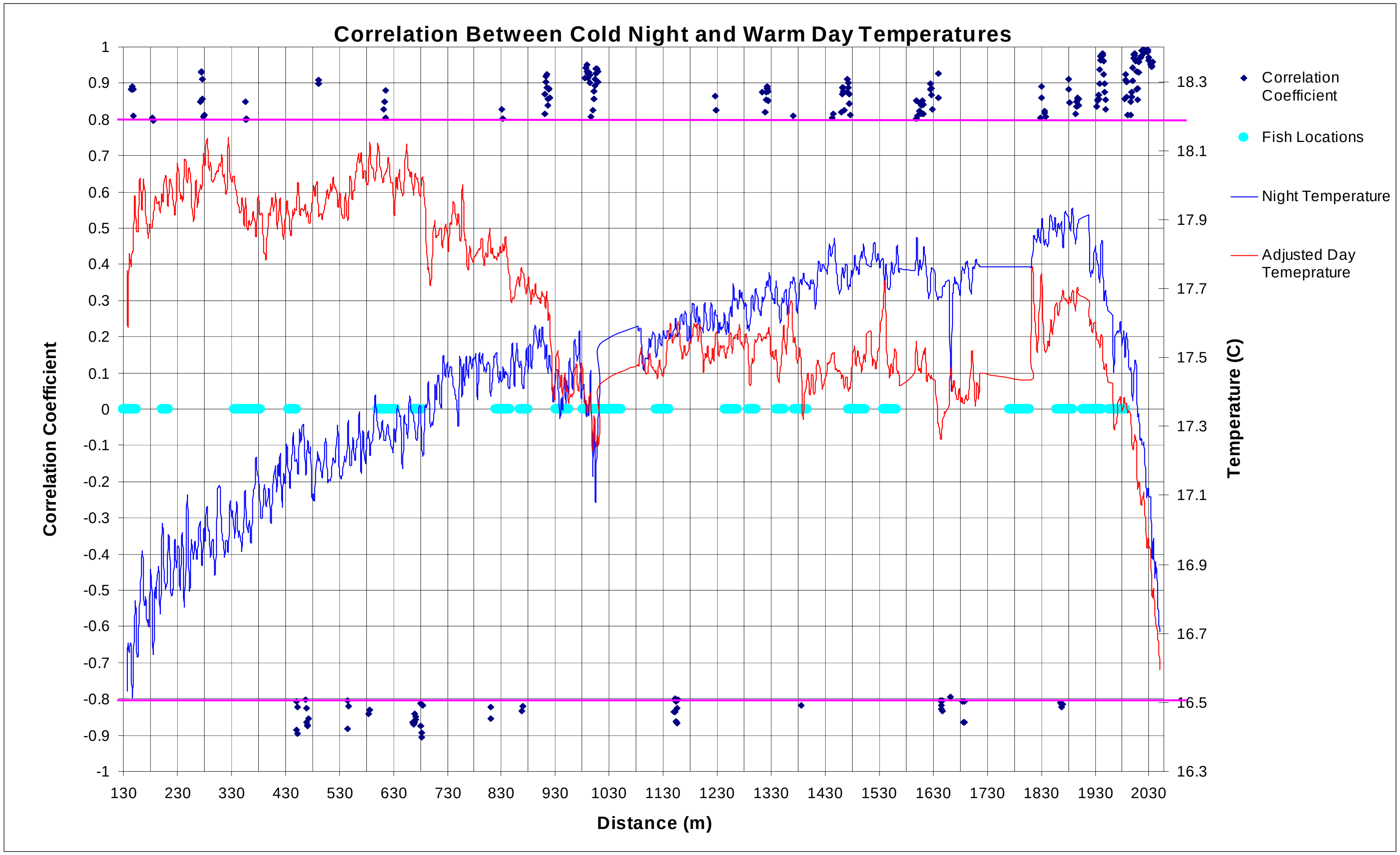

Figure 4.5 Average day summertime temperature reduced by 2.2 °C compared with a correlation coefficient to nighttime temperature for July 30th to August 20th, 2007 along the study reach in the Walla Walla River, Oregon. Light blue line represents locations fish were found from the USFWS survey.

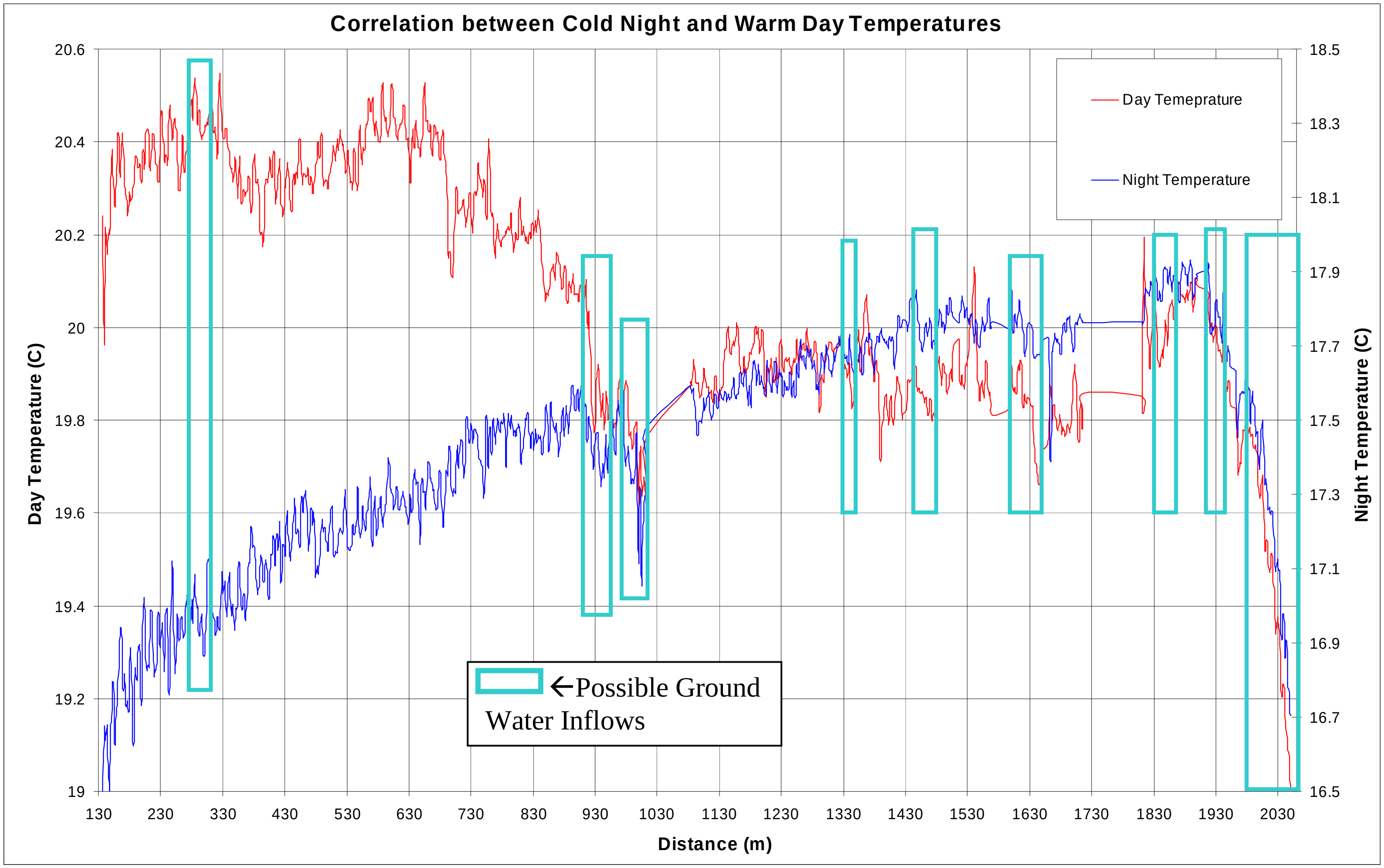

Figure 4.6 Possible locations of ground water inflows for the Walla Walla River study site based on temperature data from 30 July to 20 August 2007.

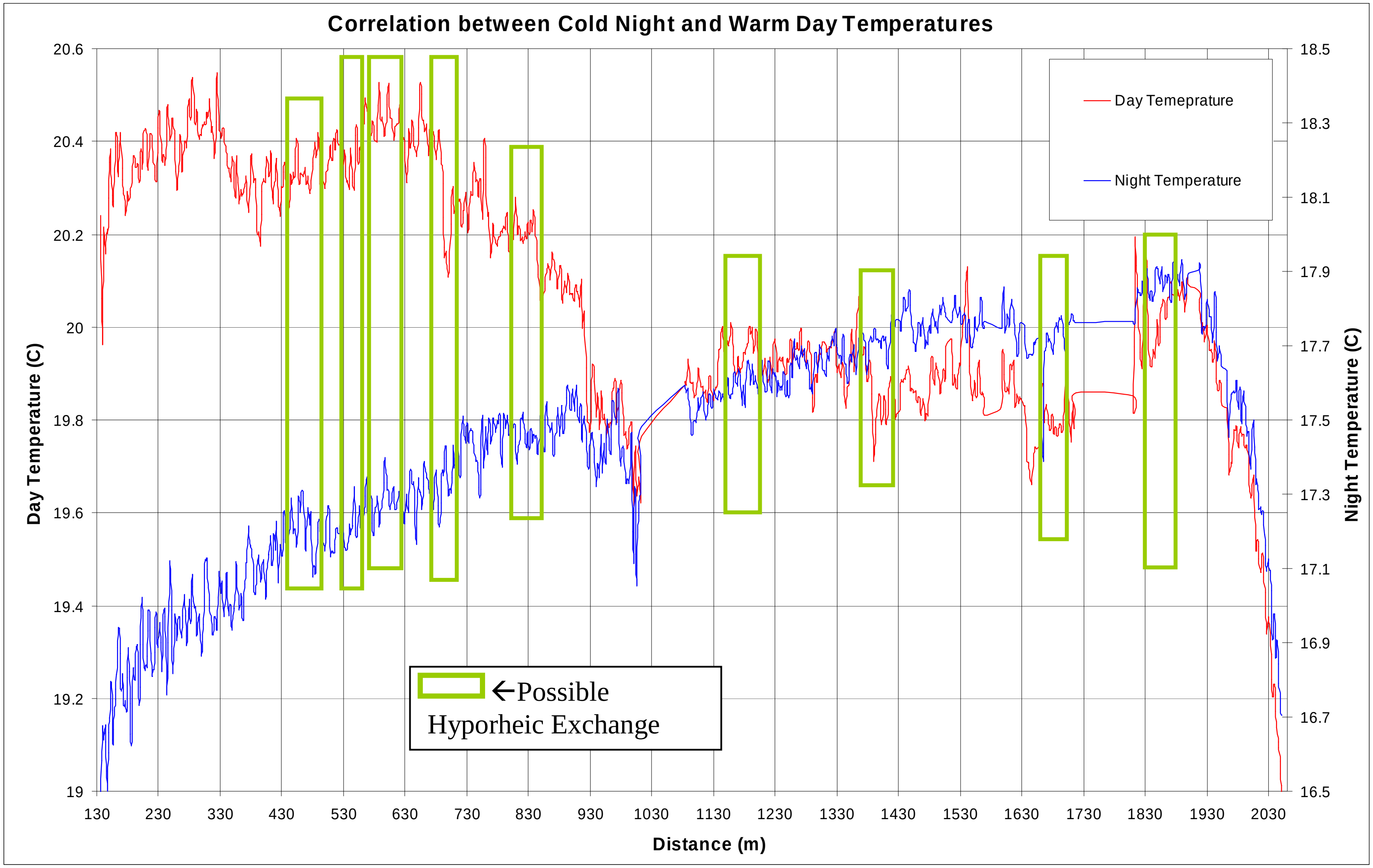

Figure 4.7 Possible locations of hyporheic exchange for the Walla Walla River study site based on temperature data from 30 July to 20 August 2007

4.3 Calculations

4.3.1 Solar Radiation

For this section the influence of solar radiation is considered. This calculation will be used to understand the expected magnitude of the solar radiation from sunrise to mid-day and the amount shade will reduce the surface water temperature. To complete this calculation we will use the solar radiation, a shade factor (the shade changes diurnally on the channel, we have used the shade expected during the mid-day peak solar radiation), and the channel's surface area. The total solar radiation will be determined based on the surface area of the water that is affected by the solar radiation. Using the Lefore Eto meteorological station data for the study duration we found the average hourly values of solar radiation from sunrise to sunset. The length for the site specific channel values was taken from the DTS measurements and the width was determined from a field visit (the width is not precise and therefore can be considered an assumed width). The calculation for the effect of shading at peak solar radiation can be completed as follows:

Peak solar radiation: 1000 W/m^2 or 1000 J/ (m^2s) (NASA, 2008)

Example shaded channel distance: 50 m

Average channel width: 10 m

Average water depth: 0.1 m

Heat capacity of water: 1 cal/ (gram °C) or 4.18 J/ (gram °C)

Water flow (Q): 32 cfs or 0.9 m^3/s

Velocity = Q / cross-sectional area

$= 0.9\ m^3/s\ /\ (0.1m*10m) = 0.9m/s$

Time of water travel = distance / velocity

$= 50m/0.9\ m/s = 55\ s$

Water mass = density * volume

$= 1g/cm^3\ (1000cm*10cm*5000cm) = 5.0*10^7 g$

Total Solar radiation = Travel time * solar energy * surface area

$= 55.12s * 1000\ J/\ (m^2 s) * 500\ m^2 = 2.76*10^7\ J$

Energy per water mass

$= 2.76*10^7$ J / $(5.0*10^7$g) = 0.55 J/g

Change in water temperature from 50m of shade

= 0.55 J/g / (4.18 J/ (g °C)) = 0.13 °C

4.3.2 Ground Water

To quantify the expected down stream temperature in the river due to ground water inflow, it is necessary to use the flow and temperature of the upstream water and average it with the flow and temperature of each ground water inflow site. The following is a simple calculation to quantify the effect a ground water inflow has on the surface water temperature in our study reach in the Walla Walla River, Oregon. Surface water flow, 32 cfs or 0.9 m^3/s; average ground water inflow quantified (table 4.1), 1.4 cfs or 0.04 m^3/s; surface water average peak summer daytime temperature to be 20.44 $°C$ found from averaging the daytime temperature from the temperature measurements in Figure 4.6; and ground water temperature, 14 $°C$.

After mixing (weighted average) the expected down stream temperature is

$= (0.9\ m^3/s * 20.44°C + 0.04\ m^3/s * 14°C)/ (0.04\ m^3/s + 0.9\ m^3/s) = 20.18°C$

This calculation suggests that there is an average decrease of 0.26 $°C$ to the surface water per ground water site. All sites do not have the same flow, but here we have used the average flow expected for the typical ground water site along the study reach (see Table 4.2 for flow data). This value is useful when determining how much each ground water site throughout the study reach may decrease the river's overall temperature. Also, the calculated temperature decrease from ground water is important to find the expected energy stored in hyporheic exchange, which is discussed later in this thesis.

As discussed earlier, the ground water inflow sites (Figure 4.6) have a strong positive correlation coefficient because in summer months the ground water inflows are continuously at a cooler temperature than the surface water flow. Both nighttime and daytime temperatures at these sites will be cooler than the surface water

Table 4.2 Ground water inflows calculated; the inflow from 1980 to 2045m was neglected in average due to the possible end effects that could be giving a false decrease in temperature reading at this site. Standard deviations of surface water temperature of the 10m section before and 10m section after the ground water inflow are given.

			Temperature (C)					Temperature (C)			
Ground Water		Surface Water		Cold Nighttime		Standard Deviation	Ground Water	Warm Daytime		Standard Deviation	Ground Water
Start (m)	Stop (m)	Flows (m^3/s)	Tg	Ti	To		Flow (m^3/s)	Ti	To		Flow (m^3/s)
240	260	0.93	14	16.98	16.94	0.06	0.01	20.45	20.30	0.02	0.02
600	630	0.97	14	17.38	17.23	0.04	0.05	20.47	20.33	0.03	0.02
918	940	0.92	14	17.57	17.38	0.11	0.05	20.08	19.78	0.07	0.05
970	1000	0.91	14	17.55	17.15	0.03	0.12	19.88	19.65	0.01	0.04
1330	1345	0.92	14	17.73	17.61	0.02	0.03	19.98	19.84	0.03	0.02
1445	1455	0.92	14	17.84	17.69	0.08	0.04	19.91	19.82	0.04	0.01
1825	1835	0.91	14	17.89	17.82	0.02	0.02	20.13	19.92	0.05	0.03
1925	1950	0.93	14	17.81	17.57	0.08	0.06	20.00	19.70	0.06	0.05
1980	2045	0.86	14	17.55	16.70		0.27	19.77	18.97		0.14
						Average	0.05			Average	0.03
							Average Inflow		0.04		

temperatures found upstream to these sites; one example is Figure 4.8. In Figure 4.8 the highlighted section of the graph shows that both the nighttime temperature and the daytime temperature both have a cooling trend in this location which, according to our definitions, is a ground water inflow.

Using the nighttime temperature change at meters 915 – 930, using the ground water inflow calculation we find:

$$Q_l = 0.9\ \mathrm{m^3/s} * \left(\frac{17.38\,°\mathrm{C} - 17.57\,°\mathrm{C}}{14.0\,°\mathrm{C} - 17.57\,°\mathrm{C}} \right) = 0.05\mathrm{m^3/s}$$

And for a daytime temperature change at the same location we find:

$$Q_l = 0.9\ \mathrm{m^3/s} * \left(\frac{19.78\,°\mathrm{C} - 20.08\,°\mathrm{C}}{14.0\,°\mathrm{C} - 20.08\,°\mathrm{C}} \right) = 0.05\mathrm{m^3/s}$$

this represents about 5 % of the total stream flow per ground water site.

4.3.3 Hyporheic Exchange

For this discussion hyporheic exchange will be characterized as an area where surface water drops below the bed material into the subsurface where it is not directly affected by solar radiation for duration of up to one day. The water then re-emerges to combine with the surface water. The temperature in the hyporheic exchange is based on the diurnal temperature cycle and therefore was important to set the passage of water through the hyporheic exchange to six hours. If the duration of water passage through the gravel was less than six hours it is expected that downstream temperatures would not cool off to the same degree that were found in the measurements. The water would not carry the temperature signature from a cooler time of day, but rather a signature from a time of day slightly prior to the recorded time. Likewise, if the time of travel were much longer than the six hours, a longer lag in the temperature would be expected and it will begin to re-enter the stream with a signature close to the average daily or average weekly temperature. If hyporheic exchange is defined by a longer duration it will be difficult to locate through DTS measurements. Water emerging with residence time greater than one day will be designate as a ground water for the purpose of this study.

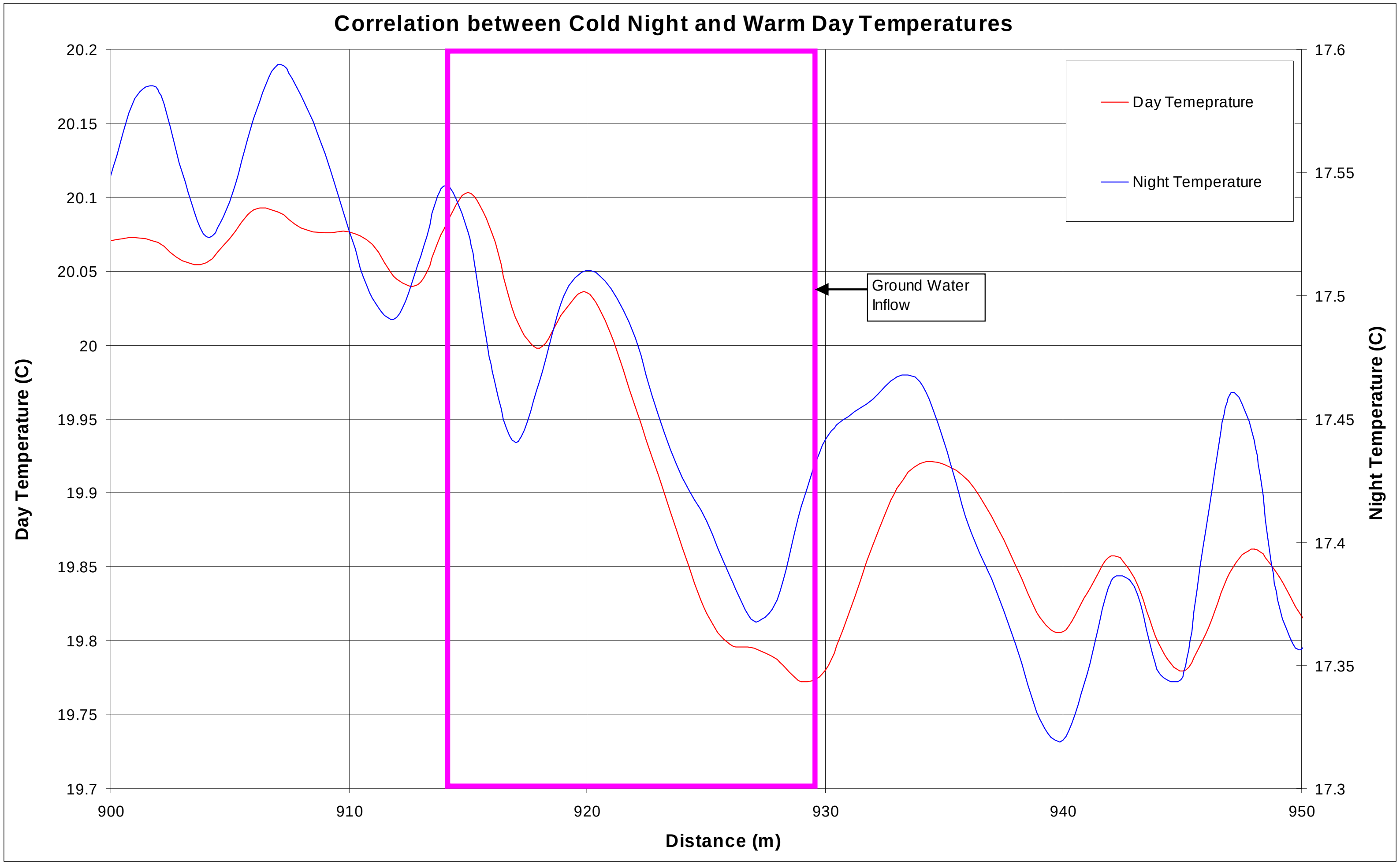

Figure 4.8 Example of a ground water inflow based on the locations found through the correlation coefficient from 915 to 930 meters.

For the hyporheic exchange we are interested in finding the depth of the hyporheic exchange that is necessary for the temperatures we have recorded along the fiber optic cable. For the data interpretation, a 6-hour travel time for water through the gravel will be used to further simplify the calculations. Through the energy balance incoming and outgoing calculated energies are used to find the necessary rate of change of stored energy in our control volume to show where any excess energy must have gone. The energy balance can be used to find the rate of change of stored energy in the control volume with the assumption that the hyporheic exchange is continuous over the entire study reach (1.7 km). In order to further understand the calculation it has been broken up into energy budget components and calculated for each hour from sunrise to peak solar radiation (the example calculations will be for 1pm, peak solar radiation for the Walla Walla River in August, 2007).

Incoming energy, $E_i = C_{vw}(T_u)(Q_s)$

$4.18 \times 10^6\ J/(°Cm^3) * 20.64\ °C * 0.9\ m^3/s = 7.8 \times 10^7\ J/s$

Solar radiation energy, $E_s = S(R)(F)$

$1011\ J/sm^2 * 20000\ m^2 * 0.9 = 1.6 \times 10^7\ J/s$

Ground water energy in, $E_{gi} = C_{vw}(T_{gi})(Q_{gi})$

$4.18 \times 10^6\ J/(°Cm^3) * 14\,°C * 0.32\ m^3/s = 1.9 \times 10^7\ J/s$

Ground water energy out, $E_{go} = C_{vw}(T_{cv})(Q_{go})$

$4.18 \times 10^6\ J/(°Cm^3) * 20.45\,°C * 0.32\ m^3/s = 2.0 \times 10^7\ J/s$

Lumped energy term, $E_l = L(R)$

$88.2\ J/sm^2 * 20000m^2 = 1.5 \times 10^6\ J/s$

Outgoing energy, $E_o = C_{vw}(T_d)(Q_s)$

$4.18 \times 10^6\ J/(°Cm^3) * 20.35\,°C * 0.9\ m^3/s = 7.7 \times 10^7\ J/s$

The rate of change of stored energy would be the incoming energies minus the outgoing energies, $E_c = (E_i + E_s + E_{gi}) – (E_{go} + E_l + E_o) = 6.5 \times 10^6\ J/s$

This was done for all hours from sunrise to the peak mid-day solar radiation (Table 4.3) and the sum was computed. The depth of the hyporheic exchange can now be found from the cumulative amount of energy that went into storage. This depth can be computed with the known volumetric heat capacity of both water and sediment in the control volume, the porosity of the bed material, and the known volume of surface water.

Table 4.3 Calculated hourly energy fluxes.

Hour	Ei (J/s)	Es (J/s)	Egi (J/s)	Ego (J/s)	El (J/s)	Eo (J/s)	Ec (J/s)
5am	5.4E+07	2.2E+05	1.9E+07	2.0E+07	2.8E+06	5.8E+07	-8.2E+06
6am	5.7E+07	2.1E+06	1.9E+07	2.1E+07	2.8E+06	6.0E+07	-5.7E+06
7am	6.1E+07	4.5E+06	1.9E+07	2.2E+07	2.6E+06	6.3E+07	-3.5E+06
8am	6.5E+07	7.5E+06	1.9E+07	2.3E+07	2.4E+06	6.5E+07	-1.4E+05
9am	7.0E+07	9.7E+06	1.9E+07	2.5E+07	2.0E+06	7.0E+07	1.6E+06
10am	7.3E+07	1.2E+07	1.9E+07	2.6E+07	1.6E+06	7.3E+07	3.1E+06
11am	7.6E+07	1.3E+07	1.9E+07	2.7E+07	1.5E+06	7.5E+07	4.3E+06
12pm	7.7E+07	1.5E+07	1.9E+07	2.7E+07	1.4E+06	7.6E+07	6.1E+06
1pm	7.8E+07	1.6E+07	1.9E+07	2.7E+07	1.5E+06	7.7E+07	6.5E+06
						Sum	4.0E+06

The apparent heat capacity of the hyporheic exchange should equal the heat capacity of the overlaying water (C_{vw}) plus the heat capacity of the sediment (C_{vs}) (2.64 x 10^6 J/($°C$ m^3)) (Kulongoski and Izbicki, 2008) and the water in the hyporheic exchange combined. Using these values we may calculate the apparent hyporheic exchange depth. The heat capacities used are volumetric so the volumes of water (V_w) and hyporheic exchange (V_h) must be incorporated. These volumes are necessary to calculate the depth of hyporheic exchange. The volume for the hyporheic exchange is based on porosity for the alluvium; the stream bed material for the study has an assumed porosity of 0.3. Once the volume for the hyporheic exchange is found, the depth can be derived by dividing the volume by the surface area (SA) for the reach; 17,080 m^2. For a continuous hyporheic exchange in this study reach we can calculate the volume as:

$$V_h = \frac{\dfrac{32400s * 4.0 * 10^6\, J/s}{5.3°C} - 4.18 * 10^6\, J/m^3 °C}{0.3 * 4.18 * 10^6\, J/m^3 °C + 0.7 * 2.64 * 10^6\, J/m^3 °C} = 5530 m^3$$

V_h/SA = Depth

5530m^3 / 17080 m^2 = 0.32 m

0.3 m *100 cm/m = 30 cm

Having assumed that there is 10 cm surface water present above these locations of hyporheic exchange (based on field visits) the same methodology as used for the continuous hyporheic exchange above is acceptable for discrete locations of hyporheic exchange with one exception; the surface area of allowable exchange has been limited. The volume of the discrete hyporheic exchange will still be the same:

$$V_h = \frac{\dfrac{32400s * 4.0 * 10^6\,J/s}{5.3°C} - 4.18 * 10^6\,J/m^3°C}{0.3 * 4.18 * 10^6\,J/m^3°C + 0.7 * 2.64 * 10^6\,J/m^3°C} = 5530m^3$$

However the surface area of interaction has changed:

5530 m^3 / 3100 m^2 = giving 1.8 m of depth per site.

Individual locations, determined through the negative correlation coefficient between night and daytime surface water temperature measurements, of hyporheic exchange can be seen in Figure 4.9.

4.4 Fish locations

The last objective of this research was to compare the USFWS fish survey with the locations of cool water refugia that had been determined through the correlation coefficient. The USFWS survey was overlain on the hyporheic and ground water sites found through the stream analysis. This was done to see if the cold water fish species are congregating in cool water inflows during the warmest times of the day. Through this comparison the number of cold water fish found at these sites is compared to the total amount of cold water fish found over the entire reach (see Figure 3.3 for satellite imagery of the stream reach). Table 4.4 shows the fish location data collected by the USFWS during their fish survey completed for the study reach. Through the cool water location data and the fish survey data, a greater understanding of where fish may be located to avoid warm river temperatures in the Walla Walla River may be realized. The percentage of fish congregating at cold water refugia sites and whether they are cold water species is seen in Table 4.5 and is discussed later in this thesis. Ultimately, this may provide valuable information for the protection of these species.

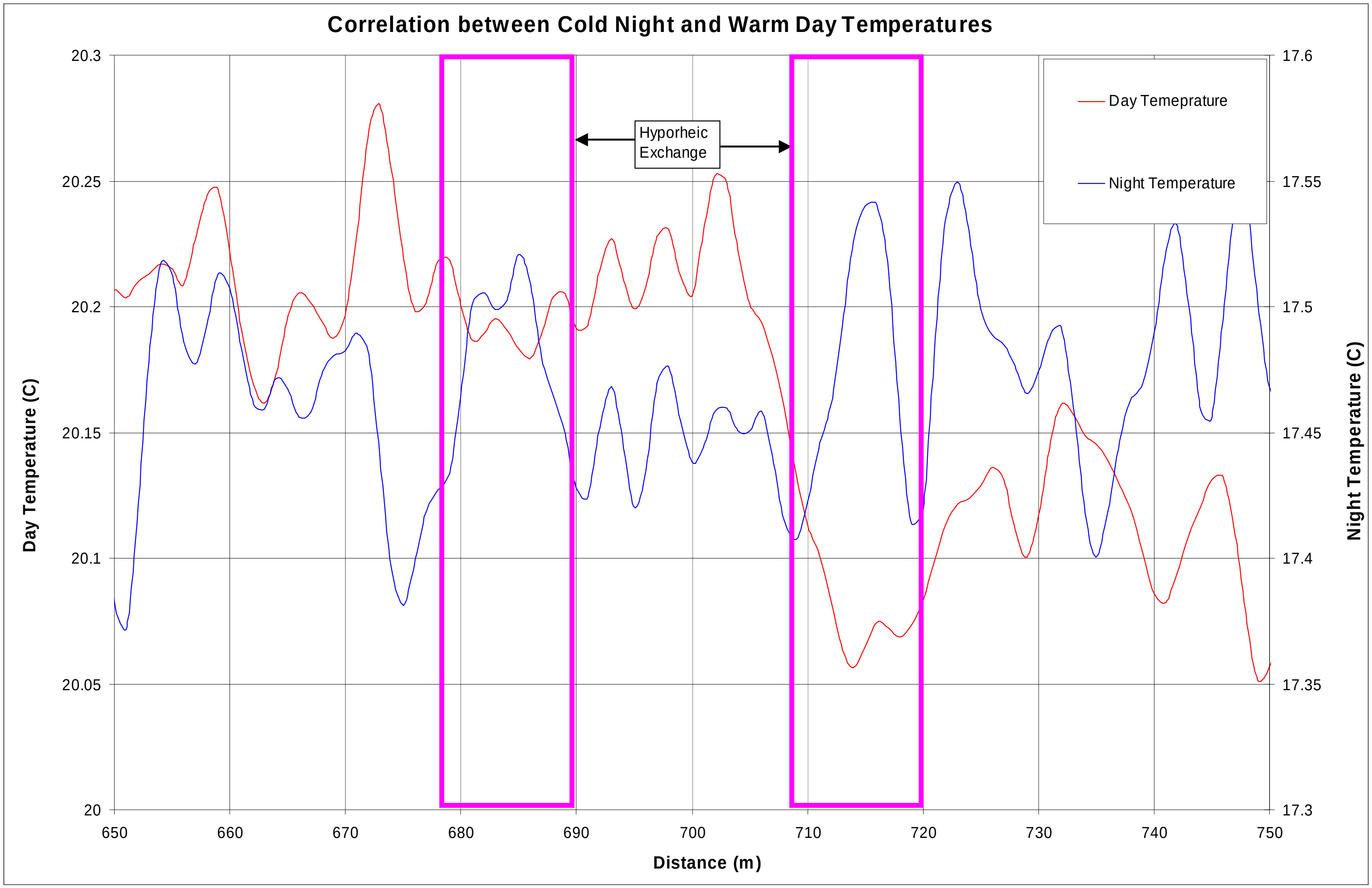

Figure 4.9 Two examples of hyporheic exchange based on the locations found through the correlation coefficient.

Table 4.4

Snorkel surveys completed on 8/16/2007. This survey was completed by Courtney Newlon, Marshall Barrows, and Ryan Koch of the USFWS, Columbia River Fisheries Program Office, Vancouver, WA.

Snorkeling started at the downstream end of cable and ended at Maurer Lane.

Cable start (meters)	Cable end (meters)	Hat. CHK juv	Nat. CHK juv	O. mykiss juv	Redside Sh.	Dace	sucker	N. pikeminnow	Adult Chinook
13	45	0	24	12	200	200	60	100	0
58	85	0	17	10	50	150	10	25	0
68	94	3	6	7	80	150	20	15	0
111	141	2	25	21	100	150	20	20	3
192	228	3	8	20	50	250	100	25	0
438	462	2	75	30	200	300	10	30	0
496	527	0	15	4	25	500	25	5	0
604	627	0	160	22	200	400	35	25	0
645	660	0	20	0	250	200	100	10	0
698	712	0	144	25	100	200	40	15	0
733	756	0	26	3	50	300	25	15	0
860	883	1	194	55	300	500	100	50	0
948	1018	0	15	35	50	100	0	5	0
1045	1068	2	40	18	50	100	10	10	0
1120	1135	0	19	8	50	20	5	2	0
1154	1180	1	40	25	150	300	40	30	0

Table 4.2 (continued)

1318	1332	1	16	15	20	150	5	2	0
1366	1398	4	128	60	100	400	60	30	0
1550	1564	0	41	27	20	250	0	3	0
1616	1664	0	105	63	200	550	75	100	0
1787	1798	0	23	5	18	55	0	3	0
1845	1886	1	75	38	100	200	50	25	0
		Hat. CHK juv	Nat. CHK juv	O. mykiss juv	Redside Sh.	Dace	sucker	N. pikeminnow	Adult Chinook
	Totals	20	1216	503	2363	5425	790	545	3

Table 4.5 Fish locations from USFWS survey in connection with sites of refugia

Shading for locations with ground water inflow or hyporheic exchange

Cable start (meters)	Cable end (meters)	Distance (meters)	All fish	Chinook Salmon and Rainbow Trout
1987	1955	32	596	36
1942	1915	27	262	27
1932	1906	26	281	16
1889	1859	30	341	51
1808	1772	36	456	31
1562	1538	24	647	107
1504	1473	31	574	19
1396	1373	23	842	182
1355	1340	15	580	20
1302	1288	14	524	169
1267	1244	23	419	29
1140	1117	23	1200	250
1052	982	70	205	50
955	932	23	230	60
880	865	15	104	27
846	820	26	586	66
682	668	14	209	32
634	602	32	782	192
450	436	14	341	68
384	336	48	1093	168
213	202	11	104	28
155	114	41	489	114
% stream length in refugia with fish present		17.8		

	All Fish	Cold water species
Total Individuals residing in refugia	5810	1015
% of Individuals residing in refugia	53	59

5.0 Discussion

When the data analysis was first underway some issues arose that had to be managed for; this included the high noise in this data set and the jitter from the DTS. The temperature profiles for this study had high noise; the standard deviation in the data is 0.52 °C. This high noise is probably due to the high loss cable used (discussed further in the concluding remarks of this thesis) and the short distance that was used to integrate the temperature over (one meter). For the jitter found in this data set a smoothing average was employed to have the data follow the smooth daily temperature variations that are occurring in the natural setting. Still some small bumps in the data remain. These bumps, seen in Figure 4.3, may represent true temperature variations that occur in this river. The river is completely regulated during the time of year the cable was deployed. The temperature changes may be due to water being drafted or diverted for agriculture up stream of the study reach (per communication with WWBWC, 25 June 2008).

5.1 Solar Radiation Blocked

Solar radiation is the largest contributor to river heat and is therefore important to understand. It is equally important to understand what happens to the river temperature when the solar radiation is blocked. Shading blocks solar radiation, in essence, cooling a stream reach by reducing the heat load (Hostetler, 1991; Naiman et al., 1992; Davies and Nelson, 1994; Li et al., 1994; Poole and Berman, 2001). The magnitude of reduced heating from shading can be seen through simple calculations that account for the heat capacity of water, the solar radiation input, the surface area of the river, and the flow for the river. The objective is to see if these calculations will show that the heat blocked from a shaded stretch of a river reach will be noticed in the DTS temperature profile of the study reach.

Let us consider the difference a 50-meter patch of shading would have on a 2000-meter section of river. The addition of a 50-meter patch of shade would result in a 0.13 °C reduction in the peak downstream temperature, as seen in the results section.

This calculation was completed using the peak summertime solar radiation of 1000 Watt/m^2, as discussed earlier. This gives the basic understanding of what may be expected for a small section of shade in a 2000-meter segment of river in a location similar to the Walla Walla River where this study was completed. Due to the high noise in our measurements and the gradual nature of surface water cooling from shade we are unlikely to detect the discrete temperature changes from shade, in our study reach. A single patch of shade will have a temperature change that would fall within the standard deviation of a single trace.

Now consider our study site in the Walla Walla River specifically. A majority of the river had limited vegetative cover during the peak solar radiation. There was approximately triple the amount of shade from the above example, 150-meters of shade over the entire 2000-meter stretch that was surveyed. This suggests a maximum of 0.47 ° C mid-day reduction of temperature once the water flows from the top to the bottom of the 2000-meter study reach. Since this temperature change in the natural setting is gradual for the river reach (shading is in distinct locations covering the entire river at some locations, and is in patchy spots for other locations) sudden drops in the DTS temperature trace due to the shaded sections are not expected. Cumulatively these shaded sections have an effect on the reach, giving a net change of temperature for the entire study reach of 0.47 ° C. This shows how re-vegetating a river may decrease the river's temperature significantly if completed over a long stretch of the river. Shading a river can have a large cumulative affect on decreasing the river's overall daily temperature. This is especially true for those rivers that need a 1 or 2 °C drop in the peak temperature for their TMDLs. By shading an additional 300 meters of the study reach we would expect approximately a 1 °C drop in the temperature of the outflow of the reach during peak temperatures.

This same calculation can be used to find solar heating for the entire 2000 meter reach un-shaded. When calculated for peak daily solar radiation, an increase in temperature by about 40 times this amount or 5.3 ° C was found. If the 2000 meter study reach was not shaded the water temperature would increase 5.3 ° C from beginning to end of the study reach. Through this we can see that when a river reach has its vegetative cover completely removed, we may expect some devastating affects on cool water dependent fish species. The shade does not create any sudden changes in structure in the temperature profile that would give rise to thermal refuge for surface water species; however it does keep the river from maximized temperatures.

For the study reach the heat blocked by shade is scattered and is therefore difficult to quantify and locate through the DTS measurements. Much of this study reach has full sun exposure and is not well shaded. This study will take into account the effect shade will have on blocking solar radiation, but will not try and find an example of shading using the DTS measurements. There may be a reduction in temperature for the entire river due to shade, but for the study reach it is difficult to locate specific changes from the DTS temperature data due to stream shade.

5.2 Refugia

The hyporheic exchange and ground water inflow sites (Figures 4.6 and 4.7) were found by using DTS temperature data. The sections of the river that were identified through the correlation coefficient as either hyporheic exchange or ground water inflow were then visually checked to see if the locations agreed with our understanding of what a ground water inflow or hyporheic exchange location would look like from temperature profiles of the river. We have created a method to continuously locate areas along any particular river reach that give the most amount of cooling. These locations can be differentiated and maintained in order to help ensure that cooling at the hyporheic exchange and ground water sites during peak temperatures continues.

One concern with temperature measurements from the DTS system is the magnitude of the temperature change that the DTS measures from the cool water input to the river. The DTS is giving a reading every meter, but the water flowing from the hyporheic exchange may not fully mix for several meters, so a false reading for the amount of cooling occurring to the surface water from hyporheic exchange or ground water input may be seen. If the surface water is not completely mixed with the cool water inflow a larger drop in temperature for each cool water inflow site would be used in the calculations, giving calculated cool water inflows that are larger than reality.

5.2.1 Ground Water Inflow

The ground water inflow sites were chosen based on the positive correlation coefficient between the night and daytime temperatures. This was then visually inspected to make sure that the temperature pattern expected for ground water is found from the data determined to be ground water through the correlation coefficient. Areas that are not accepted as ground water inflow sites are discussed later. For an example of ground water inflow see Figure 4.8, the correlation coefficient for the site is 0.95. The expectation for a strong positive correlation for a ground water location is a sudden drop in temperature for both night and day time temperatures. Surface water temperatures will not show a sudden decrease in temperature continuously for the three week average day and three week average nighttime temperatures unless a cooling source enters the river. For the data from the Walla Walla River, locations that have the characteristics seen in example Figure 4.8 are considered ground water sources. Through the DTS method we have successfully located cool ground water inflows to the study reach. This information will be useful for the Walla Walla Basin Watershed Council to help protect cold water fish in the region.

The ground water inflows were based on the surface water flows found in the river at one hour of the day. This river fluctuates in surface water flow during the summer months due to withdrawals upstream. The fluctuating surface water flows will give a fluctuating computed ground water inflow; this was not accounted for in this thesis. The surface water flows from the single hour flow survey were used to show the utility of the hyporheic exchange calculation not for accurate daily ground water flow measurements.

5.2.2 Hyporheic Exchange

The apparent global hyporheic exchange and evidence for local hyporheic exchange were also considered in this research. The difference in energy inflows and outflows to the study reach will show the amount of energy the hyporheic exchange must have stored. For the hyporheic exchange calculation to find the incoming water temperature the first 50 meters of DTS surface water temperature data were used. For the outgoing water temperature the last 50 meters of DTS water temperature data were used. By subtracting the average daily temperature from the peak daily temperature for the upstream section, we find a $1.73\,°C$ average daily and when the same is done for the downstream section we get a $0.88\,°C$ average daily increase. Making this calculation we see that the upstream temperature change is greater than the downstream temperature change. So a question that was brought up is what happened to this excess temperature? We think that this can be explained through the hyporheic exchange sites in the river.

The stored energy in the control volume gives the necessary thermal mass for the hyporheic exchange in order for the downstream temperature of the study reach to have a temperature lower than what would be found through the energy budget if no hyporheic exchange was considered. Because there is no assumed depth we can use the heat capacity of the hyporheic exchange and surface area of the river to determine the necessary depth of the hyporheic exchange.

From what has been calculated for the thermal mass of the hyporheic exchange the necessary depth for this zone can now be found. This depth is the distance that surface water had to continuously infiltrate into the streambed for the entire reach length in order to create the energy exchange needed for the downstream temperature found in the DTS temperature profile.

The effective depth that the surface water flowed into the hyporheic is approximately 30 cm. This is on the same order as the 2.5-15cm range that Harvey et al. (1998) found for similar stream bed porosity as this study (0.3). This indicates that approximately 50 percent of the total water is continually in hyporheic exchange, or that an additional 9.6 cm of water can be found in the sediment below the 10 cm of surface water that is flowing along the stream reach.

It is important to consider locations of hyporheic exchange that may be located through the DTS temperature measurements; these are the discrete hyporheic exchange sites. The same calculations as used for continuous hyporheic measurement were for the effective depth of the hyporheic exchange at each of the discrete hyporheic exchange locations. Each site is assumed to have had 10 cm of surface water above them so a majority of the water flows through the porous media of the stream bed. The nine locations where the discrete hyporheic exchange takes place will be used; this is based on a -0.8 correlation coefficient or less.

By changing the calculation from a continuous hyporheic exchange to discrete locations of exchange, while maintaining all other aspects of the study channel equal, each hyporheic site would have approximately 1.8 meters depth of exchange. This depth for a single hyporheic exchange site is comparable with some of the findings by Fellows et al. (2001) where one of the streams in their study had a hyporheic exchange depth of 2.04 meters. This means that below the 10 cm of water on the surface there is an additional 50 cm of water within the sediment, or that 80 percent of the total amount of water is flowing through hyporheic exchange at these locations. This does not seem impractical from what was seen in the field. These calculations show that this new method of locating and describing hyporheic exchange continuously along a river reach looks to be comparable to past research. This method has advantages over past methods in that it will continuously locate the hyporheic exchange and show the temperature dynamics found at the research site. An additional aspect of the method is the use of simple calculations to find the depth of hyporheic exchange sites.

Once the negative correlation has been validated the hyporheic exchange site can be used to quantify the expected depth of sediment that is needed for the amount of cooling that had taken place. For the representative site chosen in Figure 4.9 from distance 705 to 720m the correlation coefficient from Figure 4.5 is found to be -0.83. From Figure 4.9 we can see that at night the river temperature increases approximately 0.1 °C at this location and during the day time the river temperature decreases approximately 0.2 °C at the same location. The calculation was completed for this site that shows the hyporheic depth of exchange for to be approximately 1.8 m in order to reduce the temperature of the water by the amount viewed in the DTS data.

In reality both global and localized hyporheic interaction processes take place, but the analysis completed thus far will be enough to help identify these locations in the DTS data from the research site. One additional point must be made; some of the calculations done here were based on assumptions for the data, or data from a different year, or from low quality data. If higher quality data that represented the exact times considered were used the calculated hyporheic exchange depth would become much more accurate.

The river characteristics that are used for the calculations for the global hyporheic exchange were not very accurate and could easily be off by 25%. So let us consider a situation where the river characteristics make the river cooler, which should give a hyporheic exchange that is not as deep. We will say that the river is 7.5 m wide instead of 10 m, the flow is 1.1 m^3/s instead of 0.9 m^3/s, the 35% of the channel is shaded instead of 10%, and all other factors will remain the same. This would give a negative 4.5 m depth of hyporheic exchange. This means that for these new river characteristics and the temperature change of the control volume we would actually need the hyporheic exchange to increase the temperature of the river. Another possibility is that the river characteristics make a warmer situation than we have shown. Now the river is 12.5 m wide instead of 10 m, the flow is 0.7 m^3/s instead of 0.9 m^3/s, the 0% of the channel is shaded instead of 10%, and all other factors will remain the same. For these river characteristics and the same temperature change for the control volume the global hyporheic exchange would need to be 2.7 m in depth. We can see how accurate measurements of the river's characteristics are important to give accurate measurements of hyporheic exchange depth.

We can also consider how hyporheic exchange changes the river temperature. For the original hyporheic exchange calculation we find the control volume's outflow temperature from sunrise to daily peak solar radiation to have changed by 5 °C. If there is no hyporheic exchange (such as a bedrock reach) we would see this change to be 7 °C and if the hyporheic exchange was doubled we would find the temperature change of the river from sunrise to the daily peak solar radiation to be 3 °C. During peak solar radiation the temperature of the river dropped by 0.1 °C from the bedrock scenario to the hyporheic exchange found in our calculations then dropped another 0.1°C when the hyporheic exchange was doubled.

5.3 Fish Response to Cold Water Inflows

Cross-analysis of the fish survey with the DTS data shows that 60% of the cold water fish (salmonids and trout) were found in the cold water inflow locations that make up 18% of the river, showing that the areas identified by the DTS to be either ground water or hyporheic exchange had over three times the density of cold water fish population than the overall stream. In addition, when cold water fish and warm water fish are combined, 53% of the fish are found in 18% of the river at these cold water inflows (see Table 4.5). This shows that most of the cold water fish will reside at these cold water inflows during warm summer months. A cold water inflow does not seem to be the only attribute that determines fish presence. An additional 13% of the river reach consisted of cold water inflows but did not have fish present. This suggests that cold water inflows are not the sole driver for cold water fish movement, but are one of the defining attributes.

5.4 Difficulties

This research was new and exploratory which led to many difficulties along the way. In this section we will disclose some of the problems that were faced so projects in the future will not follow the same path.

One such difficulty came up when visually validating the cool water inflows determined through the correlation coefficient. Occasionally the cool water inflows were not found at the locations where they were expected from the correlation coefficient analysis. An example of this was when the cable was out of the water as seen in Figure 5.1 from 1570 to 1583 meters. This can happen when the cable is moved around by the water during high flows (if the cable is not well anchored to the river bed) or when people or animals drag the cable out of the water. The cable is also taken out of the water when there is a connector or if the cable is placed into an ice or water bath. At these locations you may find air temperatures show up in the data.

These locations are easy to identify; they will have a strong negative correlation similar to the hyporheic exchange sites, but the temperature will follow the diurnal cycle (warm in the day and cold at night), unlike the expectations for a cool water refugia. This is because the DTS will be measuring the air temperature which has greater peaks than the surface water temperature. For this study the air temperatures, were removed prior to data interpretation.

Unexpected warm water additions to the river added an additional problem with data analysis. This discrepancy was found in the data when using the correlation coefficient to locate cool water inputs. It could be seen as a continuous warm water inflow, such as an agricultural return flow (see Figure 5.1 from a distance of 1627 to 1634 meters for an example). The correlation coefficient for this site is strongly positive (0.95) which would lead us to believe it is a ground water inflow. Visual inspection reveals the opposite of what is expected for a ground water inflow. Instead of the expected ground water temperature change (a drop in temperature both day and night) an increase in temperature both day and night is found, possibly giving the signature that would be expected from an agriculture return flow or some other warm water supply continuously entering the river at this location.

When barrel connectors (a female / female connector, see Figure 5.2 at the 1030 meter distance) are present, there is an increase in the amount of light that escapes; giving more loss. In this circumstance both the night and day time temperature will either remain at an extremely high or low temperature (Figure 5.3). This is for a short distance and has much higher amplitude than the temperature variations that are expected. This large loss at the site of the barrel connecter will give more noise in the signal for the remainder of the measurements. Another problem is that the connectors themselves have shown temperature dependency, this was seen in a project completed at Lake Tahoe (accepted for publication at Water Resource Research, 2008). In addition, it is important to have the connectors be sealed from water. For this reason in this project the connectors remained out of the water which gives us an increased amount of air temperature data. The sections of river where this occurs can be removed from the data set so that it they will not impact any data analysis. However, due to the double-ended nature of the temperature measurements, the locations have already increased the noise of the temperature measurements. This barrel connector affect shows that fusing cables together may be a better option than trying to use the barrel connector.

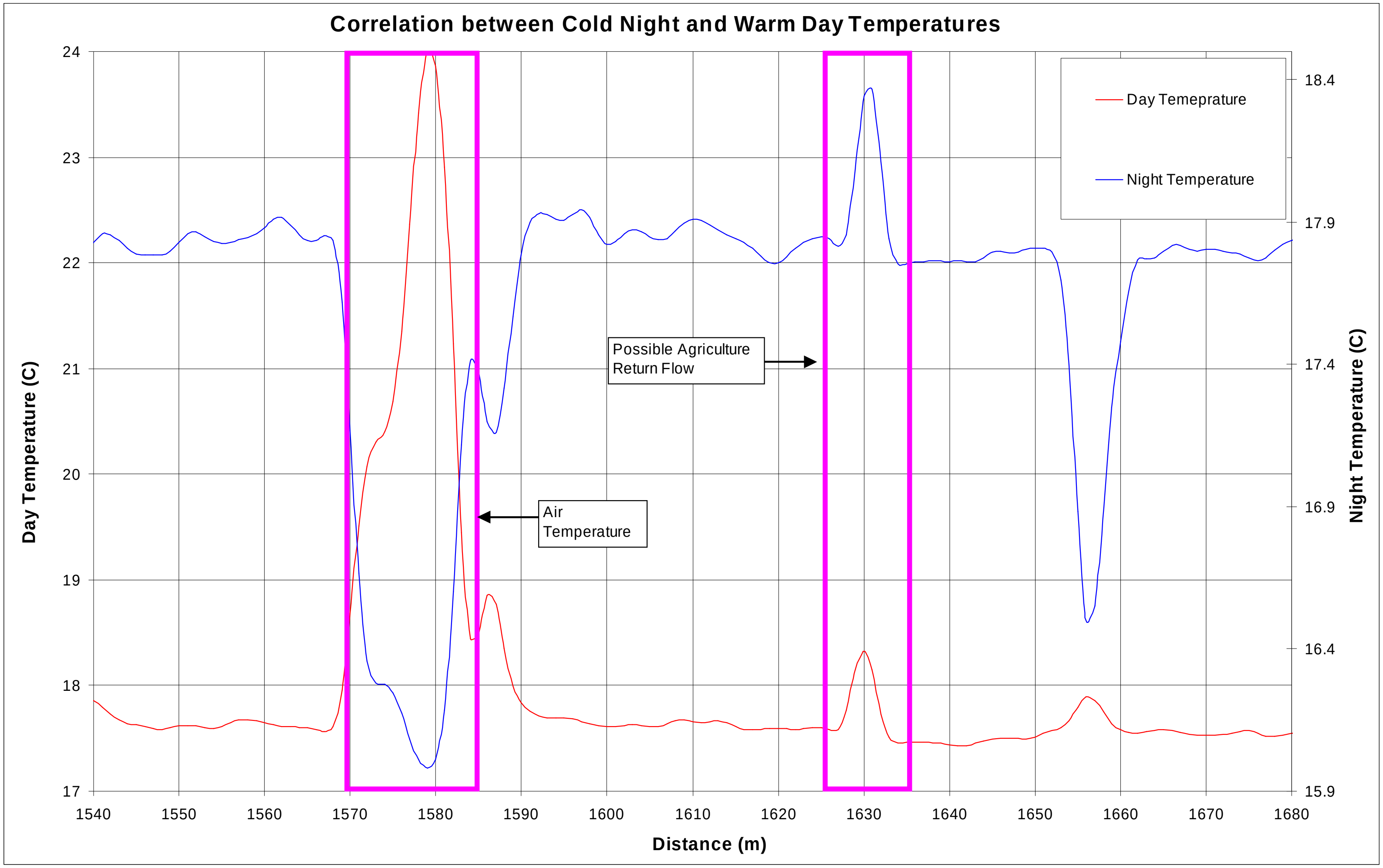

Figure 5.1 Result of air temperature (giving a false hyporheic exchange reading from the correlation coefficient) and agricultural return flow (giving a false ground water inflow reading from the correlation coefficient) in the temperature data.

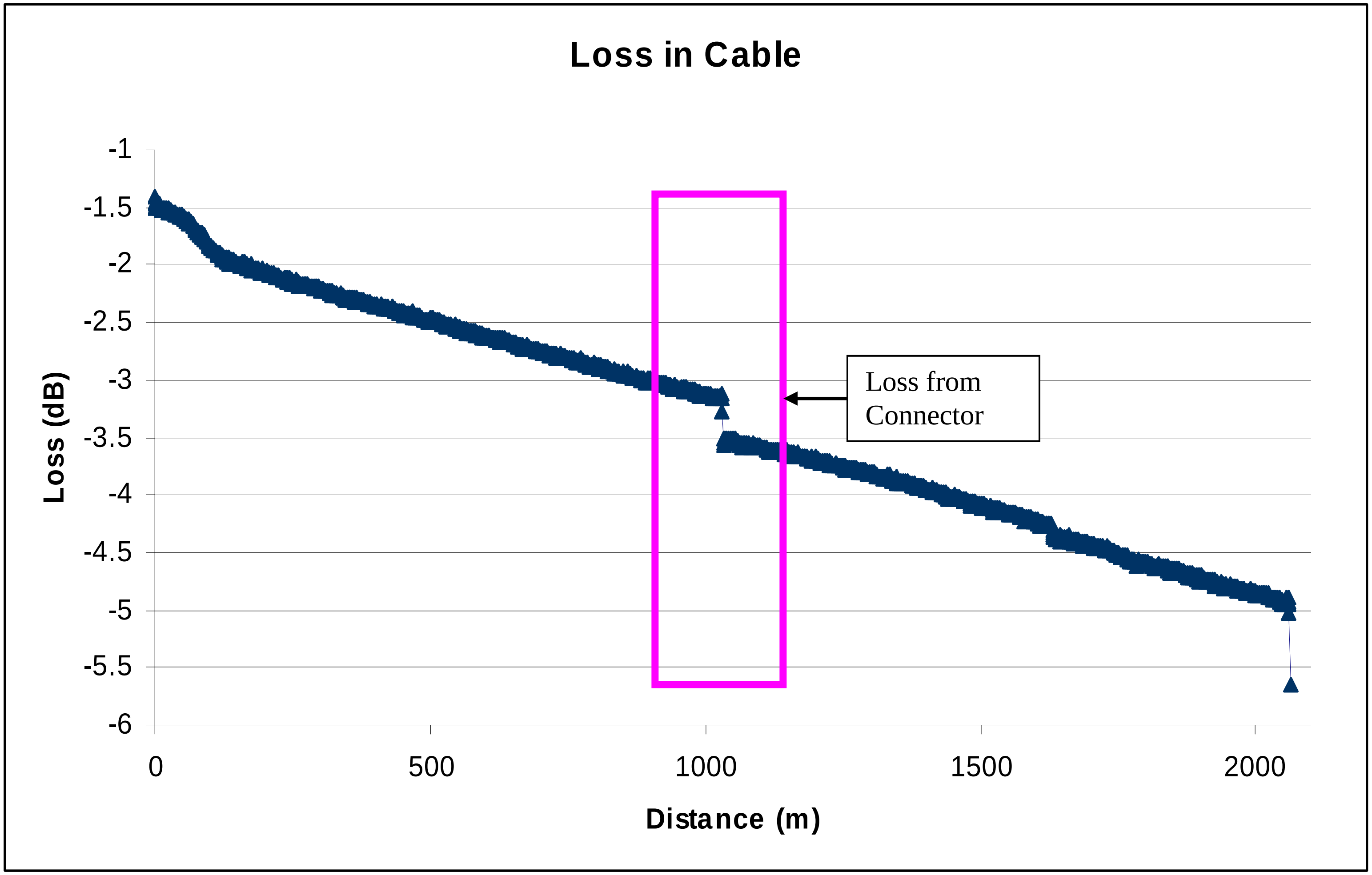

Figure 5.2 High loss cable (acceptable loss is 1dB/ km) and an approximate 0.5 dB loss encountered at a barrel connector at 1030 and 0.75 dB loss at the barrel connector at 2060 meters.

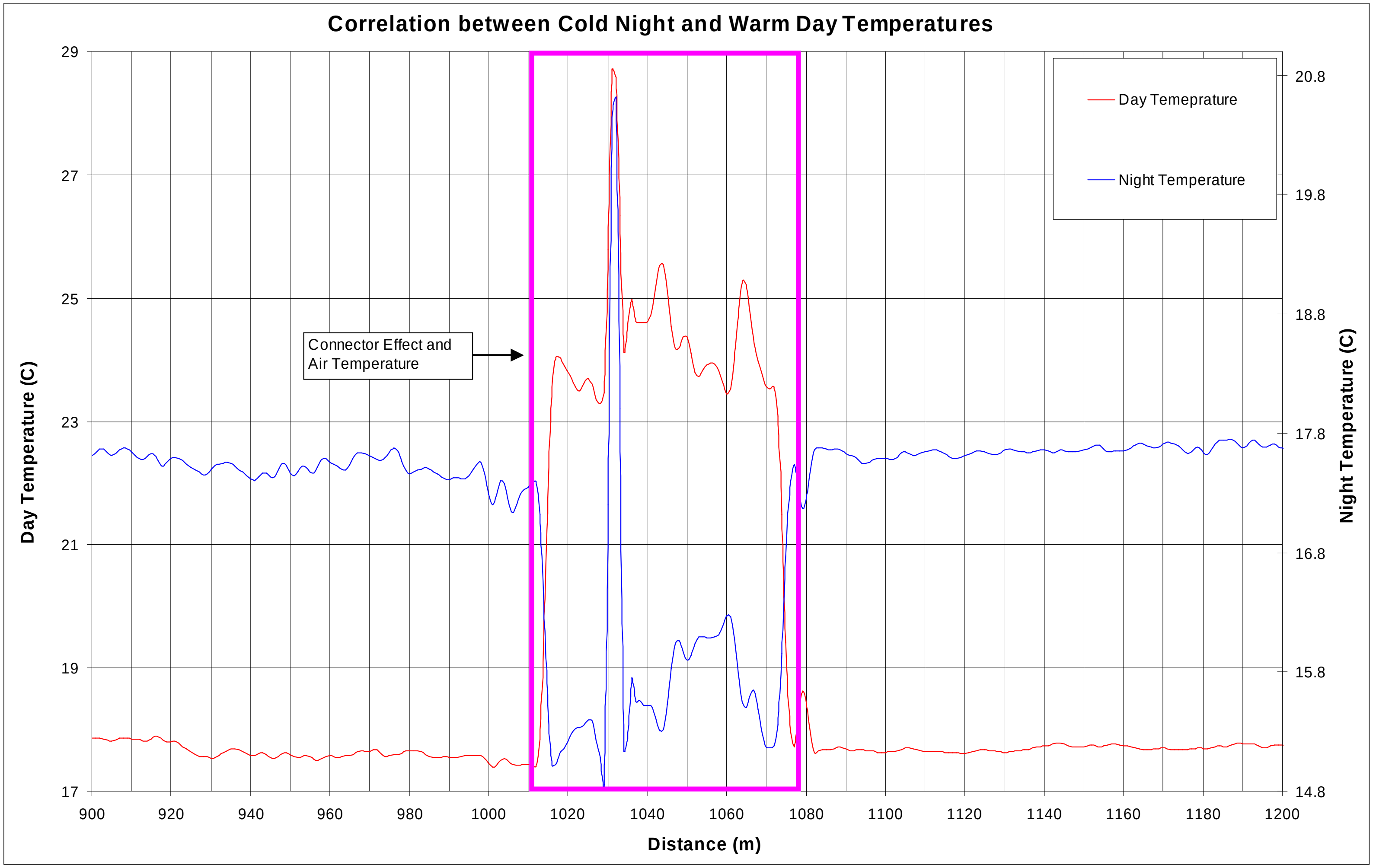

Figure 5.3 Air temperature and barrel connector site from the temperature profile, the barrel connector is the large spike during both the night and day at 1030 m.

6.0 Concluding Remarks and Suggestions for Future Studies

Through continuous temperature analysis we have begun to locate cool water inflows to surface water. Once these areas of interaction are found they can be identified as either ground water or hyporheic exchange (depending on the designated timescales used) and quantified. Using the temperature measurements and stream data we can begin to determine the approximate depth that we would expect for the hyporheic exchange. The research has also used simple calculations to estimate expected temperature changes for a river from increasing shade, known ground water inputs, and from any hyporheic exchange that may be occurring or new hyporheic exchange zones planned in future projects. This temperature data is also being used in correlation with fish surveys to locate areas of habitat; fish rely on during peak day time temperatures and see if the fish locations relate to sites of cool water refugia found through DTS temperature analysis.

Cooling of surface waters during peak temperatures is important for the future of surface water ecosystems. With increasing temperatures worldwide do to climate change, it is important to find new ways to examine, define, and measure cool water inflows. We have presented the basics behind warming a river due to solar radiation. We briefly described the affects of shading on a river reach, quantified the amount of energy that is blocked by shading, and translated this to effective temperature reduction of the river. Then cold water inflows that cool peak temperatures, possibly sources of cold water refugia (ground water inflows and hyporheic exchange sites), were found. These sources of cool water were used to calculate the cooling expected on the study reach in the Walla Walla River. Then the data was used to quantify ground water inflows and the depth of the hyporheic exchange throughout the study reach. The data from the DTS was used to locate the cool water inflows for peak day time temperatures during the summer months. By comparing the nighttime to peak daytime temperatures through the correlation coefficient the hyporheic exchange sites were separated from the ground water inflows. This gave the WWBWC locations that can be protected for cold water inflows into the river to try to meet the TMDLs (Total

Maximum Daily Load) for temperature. Finally, the cold water sites were matched with a US Fish and Wildlife Service survey to see if the cold water fish were congregating at these cold water sites during the warm daytime temperatures. We found that 60% of the cold water fish were gathering in 18% of the river where cool water inflows were present. It is also important to note that 56% of the cold water inflows had the cold water fish present. The cold water inflows (ground water and hyporheic exchange) make up approximately one-third of the river's total length. We have given a method to locate cool water inflows and determine where approximately 60% of the cold water fish are located during summer daytime temperatures. We now know that 60% of the fish are in 18% of the river and that through the DTS measurements we can narrow the search for these cold water fish to 32% of the river.

This project has given new insight into river dynamics through the use of distributed temperature measurement. This data can be valuable to land managers in determining locations that deserve special protection in order to maintain cool water flows to the river and has shown how different cold water fish species rely on the cold water inflows for habitat during the warm summer months. We gave a simple overview on how cooling of surface waters may be represented in a natural setting and how this may look quantitatively.

A few problems did arise during the data acquisition and interpretation that should be briefly reviewed. DTS technology has been used in the environmental sciences for only a few decades and is still relatively new. The technology is coming along quickly, but there are a few problems that were seen during our field deployment. One of these issues is calibration of the system. Calibrating the DTS to your specific cable is very important, but can be difficult, especially when multiple cables are used. Each section of cable must be calibrated using two different known temperatures for each calibrated cable in order to get a correct calibration for both gain and offset. Recently, Agilent created a double-ended measurement which corrects for attenuation constantly along the cable which is a great improvement for the technology; however this has increased the overall noise of the temperature measurements. Since noise has a significant effect on fine-scaled measurements, a high quality cable is important. One of the cables used in this study had a large amount of loss (on the order of 8dB once connectors were added) which got attributed to both ends of the cable due to the double-ended measurement setup. A cable should have less than 1dB/km loss to maintain minimal noise in the measurement when using the double ended setting. Also, it is important to minimize the number of connectors used as they have a much greater loss than a fusion splice. The fusion splices are another issue; they are a necessary evil. The fusion splice is a learned skill and some of the field deployable units are finicky and demand a very clean environment. It is important to be well prepared before attempting fusions in the field.

Additional problems became evident during data interpretation. The cable doubles back at the 2061 meter mark, at this point there is a large drop in temperature. This drop may be where the ground water table is at the river's elevation, but it could also be due to a large loss and possibly some other effects from the connector at this location. This data had a slight "jitter" in the daily temperatures. The jitter was an artifact of the Agilent DTS; it was noticed because the water temperature did not follow the daily air temperature and daily solar radiation pattern. The daily air temperature and daily solar radiation data sets were plotted and viewed on an hourly basis and no jumps were seen. When the DTS data was viewed on an hourly basis for the entire stream we could see jumps in the data occurring, since water changes temperature slowly due to solar radiation and air temperature these jumps were determined to be instrument noise and have since been brought to the attention of Agilent.

DTS measurements are an excellent way to record temperature data for an entire stream reach continuously over time. This technology can be used in the future for the Walla Walla Basin Watershed Council, or by others, to show cold water inflows into a river. An additional season of data would greatly help clarify some of the findings presented in this thesis. It would allow us to determine if the ground water inflows are still occurring in the same locations and how the hyporheic exchange sites might change year to year. We could also investigate whether the fish are still in the same cold water refugia as observed in the summer of 2007. We might be able to determine if the large cool water zone at the end of the 2061 meters of cable was indeed a ground water upwelling. This could be found by increasing the reach length approximately 100 meters on the downstream end of the reach. If this location continued to show a large cooling we would know that there is a large interaction with the ground water occurring. If it had disappeared or had moved down to the new cable end, we would know that there is either a problem with the cable layout or the DTS itself.

Due to the high amount of light loss in the cable, the low spatial resolution of 1m, and capturing the data only ¼ of the time desired the temperature measurements from the project have high noise. We expect to find 1dB loss for 1km of cable distance, so for this project we would expect 4db loss for the 4km of cable we were getting data from. However, for this project we had a total loss of 12dB, which is a 93.7% loss of light and is 33.7% less light than what was expected. Since noise goes with the light$^{0.5}$ a quality cable would give 2.5 times less noise, changing spatial resolution from 1m to 1.5m would give 1.4 times less noise, and capturing data every 15 minutes instead of every hour would give 2 times less noise; giving a possible total noise reduction of 7 times; therefore improving the calculated ground water inflow and hyporheic exchange depth quantities.

This research attempts to further introduce the DTS technology as an important new technology for environmental analysis. The DTS can be a useful tool in many areas of ecological engineering. Newer DTS instruments may not have as many of the problems that were noticed in this instrument; jitter in data, lack of temperature validation until the end of the project, the use of high loss fiber optic cable, increased care in the deployment and retrieval of the cable (at least with a 5 man crew if relying on man power), and loss of data due to the instrument not taking as much data as expected due to the nature of the double-ended measurement setting. Recently, a competing company has made steps toward a new DTS option that will automatically calibrate the cable to the DTS system. This development would be great progress in making the DTS a tool for land managers of all disciplines; as calibration is one of the more problematic features of the current technology.

There was a large learning curve in the use of DTS as a tool for ecosystem science during this project. Future work can rely on this account to get through instrument set-up, deployment, and interpretation without some of the same issues arising. Additional studies using the DTS system should have a better data set to work with if the problem items listed above are taken into account. This should improve the temperature measurements greatly, reducing the noise to levels that will allow easier determination of the temperature changes in the sites of refugia.

This report will be sent to Bob Bower and the WWBWC to further their threatened and endangered fish projects in the basin. It will be added to the general research that has occurred in the basin in conjunction with Oregon State University over the past decade. It will also be used for practical management that may come from increased knowledge of the locations of the cool water locations found throughout the study reach.

7.0 References

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