Restoring the Unseen River: The Viability of Hyporheic Zone Restoration for Improving Groundwater and Surface Water Exchange in an Urban Watershed

by

Chapin Pier

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Chapin Pier

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by

Erin Martin, Ph.D.
Member of the Faculty

Date

ABSTRACT

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Stream restoration is a growing field aimed at mitigating stream degradation caused by human development and urban expansion. Traditionally, stream restoration has focused on surface water and riparian aspects of stream systems. Rarely have restoration projects considered the hyporheic zone (HZ), which exists below the streambed where surface water and groundwater interact. The hyporheic zone provides many benefits, which include, nutrient and energy cycling, temperature regulation, and habitat and refuge benefits. While there is increasing awareness of the hyporheic zone, stream restoration projects rarely incorporate hyporheic zone focused restoration methods.

In the fall of 2014, two restoration projects were completed in the highly urbanized Thornton Creek watershed in Seattle, Washington. The restoration projects were innovative because they incorporated an engineered reconstruction of the hyporheic zone, which was intended to improve HZ exchange. The primary objective of this study is to examine the impacts of restoration on hyporheic zone exchange at the restored sites. During the winter of 2015, intensive streambed temperature surveys were conducted at the restored sites and nearby control (unrestored) sites to track the movement of water through the HZ. The surveys were intended to locate zones of upwelling and downwelling by tracking the movement of heat between the surface water and groundwater zones. Hyporheic zone exchange was anticipated to be greater at the restored sites than the control sites. Furthermore, exchange was expected to be greatest at locations immediately adjacent to in-stream structures, which were installed during restoration.

The results indicated that hyporheic zone exchange was greatest at the control sites when compared to the respective restored sites. However, the results of the surveys were inconclusive due to multiple discrepancies that existed between the sites that couldn't be accounted for in this study. For instance, differences in water residence time may have led to differences in heat transfer at the distinct sites, which may explain the unexpected results of the surveys. Less surprising, the surveys did find that HZ exchange was greatest adjacent to in-stream structures.

This study was intended to be an initial investigation of hyporheic zone exchange post-restoration and does not provide definitive conclusions. However, the results of this study will be correlated with future surveys at the restored sites to better understand both the effectiveness of restoration and also how HZ exchange changes over time. Overall, this study highlights the need for future research to better understand the potential benefits and limitations of stream restoration for improving hyporheic zone function.

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Chapter 1: Introduction

In the summer and fall of 2014, Seattle Public Utilities completed two stream restoration projects on Thornton Creek in Seattle, WA. The restoration projects were completed to address problems that were identified throughout the Thornton Creek Watershed and specifically at the two restoration site locations. The key problems identified were stormwater related flooding, poor water quality, and insufficient in-stream, riparian, and upland habitat for native wildlife species. The restoration projects at the two Thornton Creek sites were designed to address these issues using a variety of methods, including floodplain expansion, riparian revegetation, and installation of physical barriers (i.e. large woody debris, boulders).

An important component of the restoration projects was to restore the hyporheic zone, which is the region beneath the streambed where groundwater and stream water interact. The hyporheic zone provides a variety of beneficial functions such as, nutrient cycling, temperature regulation, pollutant buffering, improvement of biogeochemical processes, and also provides important habitat and refuge for both terrestrial and aquatic life (Hester & Gooseff, 2010; Lawrence et al., 2013). Traditionally, in the field of stream restoration the hyporheic zone has rarely been emphasized in restoration plans. However, with increased research there is growing awareness of the importance of the hyporheic zone for the health of the entire stream ecosystem. Seattle Public Utilities (SPU) decided to try an innovative approach by reconstructing the hyporheic zone at their two restoration sites. SPU achieved this by first excavating the original streambed that contained high levels of fine sediment. The excavated channel was backfilled with gravel and in-stream physical structures such as boulders, large wood, and step-pool features were installed within the streambed.

The primary goal of the hyporheic zone restoration was to improve vertical connectivity between the groundwater and surface water environments. Constructed hyporheic restoration is a novel approach, especially in an urban stream system such as Thornton Creek. In result, there are few other examples of stream restoration projects that have examined the viability of hyporheic zone restoration for improving vertical connectivity in a highly urbanized stream setting.

This study investigates whether or not hyporheic zone restoration is effective in improving vertical connectivity by comparing the two Thornton Creek restoration (treatment) sites with nearby control (unrestored) sites. Streambed and surface water temperature surveys were conducted to track the vertical movement of heat, which is regulated by the flow of water through the hyporheic zone. The temperature surveys were designed to locate the zones of downwelling and upwelling of water and also provide the relative strengths of these processes. The impact of in-stream restoration features (i.e. step-pool structures) on hyporheic zone exchange was also investigated.

Chapter 2: Literature Review

Literature Overview

The purpose of this literature review is to identify relevant and past studies that have examined the observed or potential results of stream restoration on hyporheic exchange. This literature review will first discuss the issues involved with urban streams and the growing field of urban stream restoration. Hyporheic function will then be discussed along with its importance. This will be followed by a description of past and current research on the hyporheic zone. Furthermore, I will discuss the methods used to restore the hyporheic zone and the methods for evaluating hyporheic function. Lastly, I will provide a description of the Thornton Creek watershed and discuss the restoration projects and the post-restoration monitoring at the two project sites. This literature review will highlight the significant gaps in knowledge about hyporheic zone restoration and its impact on vertical connectivity in a highly urbanized watershed.

Urban Streams

Rivers in the United States are experiencing increased degradation with the rise in urbanization throughout the country. Cities are expanding at an accelerated rate as total population grows and rural communities migrate to urban centers. In 1990, 75% of the total population in the United States lived in urban areas, which increased to 81% in 2014. The current projection in the United States for 2050 is 87%, meaning cities will continue to grow considerably over the next several decades (United Nations, 2014). Much of the urban growth has been through the horizontal expansion of suburbs. One consequence of urban population growth is that streams draining urban environments will be at an increased risk from degradation caused by urban development (Shoredits and Clayton, 2013).

Urban watersheds are differentiated from their rural or forested counterparts based on the amount of development in a particular watershed. An urban watershed is broadly defined as an area where human development is significant enough to impact the stream ecosystems (Shoredits and Clayton, 2013). A common metric used for evaluating development, is the percentage of impervious surface cover (ISC). Impervious surface cover of only 10-20% is considered the threshold for significant urban stream degradation. The range of percentages can vary significantly, from 5-20% in sprawled communities to over 75% in highly developed urban regions (Paul and Meyer, 2001). The conversion of permeable surfaces (e.g., forests, grasslands, and fields) to impermeable surfaces (e.g., roads, buildings, sidewalks, and parking lots) is a major issue in urban watersheds. Impervious surfaces reduce the amount of rain and snowmelt that can be absorbed and retained by the land, usually resulting in high levels of surface runoff (Shoredits and Clayton, 2013). In urban areas where ISC is between 75-100%, there is a fivefold increase in surface runoff compared to forested or rural watersheds (Paul and Meyer, 2001). High levels of surface runoff will create flashy, high volume flow conditions in urban streams.

Another unique issue to urban streams is the act of channel armoring, which is completed to reduce flooding on adjacent property and infrastructure. Channel armoring reduces the ability of the stream to meander and move horizontally through the floodplain, which further intensifies stream flows and can lead to streambed erosion and channel incision (Figure 1) (Bernhardt and Palmer, 2007; Lawrence et al., 2013).

Figure 1: Shows a pre-project photograph of the South Fork of Thornton Creek flowing through a culvert underneath 35th Ave. N.E. in Seattle, WA. Photograph provides an excellent example of channel armoring and the absence of floodplain connectivity. Source: Seattle Public Utilities (http://www.seattle.gov/util/EnvironmentConservation/Projects/MeadowbrookThornton/Details/index.htm)

Additionally, riparian vegetation is often removed and replaced with impervious surfaces, which can also increase flow volumes, input of stream contaminants, and lead to unstable sediment regimes (Bernhardt and Palmer, 2007; Lawrence et al., 2013). Increased connectivity with roadways, storm drains, and sewage systems, leads to poor water quality conditions that can be harmful to both wildlife and humans (Shoredits and Clayton, 2013; Violin et al., 2011). Due to the degraded riparian and in-stream habitat, urban stream systems often consist of poor native biodiversity. Macroinvertebrates are particularly sensitive to land use changes and only the most tolerant species are found to live in urban streams (Violin et al., 2011).

Urban Stream Restoration

With increases in urban stream degradation, there is a growing effort nationally to restore and protect these important waterways. The customary goal of stream restoration is to return streams back to pre-impacted conditions (Violin et al., 2011). However, the likelihood of achieving this challenging goal is low. Instead, urban stream managers often focus on restoring streams with the intent of protecting infrastructure, such as drainage and sewer pipes, and nearby buildings. A second goal is to restore and enhance the ecological functions of urban streams (Shoredits and Clayton, 2013; Palmer et al., 2014; Bernhardt and Palmer, 2007).

Urban stream restoration has many unique challenges. The primary challenge is the lack of undeveloped space available for both riparian and in-stream restoration. The acquisition of land is often expensive and requires negotiation with multiple landowners (Violin et al., 2011; Shoredits and Clayton, 2013). Urban stream restoration is often complicated and resource intensive, requiring more dollars spent for each linear meter that is restored than what is required for rural projects (Violin et al., 2011).

Another key issue with urban stream restoration is the lack of pre- and post-project assessment. This is partly due to limitations in resources and in some cases inadequate project design. Also, most restoration projects occur outside of urban centers, which means there are fewer urban stream restoration projects to monitor. Therefore, the majority of pre- and post-project monitoring often occurs in rural watersheds. In result, less scientific evidence is available as to the effectiveness of different restoration approaches when applied to an urban stream system (Shoredits and Clayton, 2013).

Stream restoration strategies vary greatly based on particular stream characteristics, scale of project site, and the intended goals and objectives of restoration. A common restoration strategy is to improve riparian habitat by re-vegetating stream banks and reducing impervious surfaces within the riparian zone. Other restoration strategies focus on improving geomorphological characteristics of the stream channel and substrate. These strategies include bank stabilization using natural structures, such as large wood or boulders, removal of bank armoring installations, culvert 'daylighting' to expose the stream, and removal of in-stream barriers, such as dams (Shoredits and Clayton, 2013).

Another promising restoration strategy includes restoring the hyporheic zone, which is the region beneath the streambed where groundwater and stream water travel back and forth. <u>The following sections will discuss in more detail, the function and importance of the hyporheic zone and the potential benefits of hyporheic zone restoration</u>.

<u>Hyporheic Zone Function and Importance</u>

The hyporheic zone (HZ) is defined as the region below the substrate and into the stream banks where groundwater and surface water interact (Boulton et al., 1998). The extent and function of the hyporheic zone can vary significantly based on a host of variables, including the morphology, hydrology, and ecology of a particular river. In result, the hyporheic zone can range greatly in size and function; from a narrow section of fine sediment with little to no interstitial flow to a fully functional HZ that is over 10 m in depth. The hyporheic zone can also vary greatly in width from several centimeters in confined channels to multiple kilometers in river systems with extensive alluvial floodplains (Lawrence et al., 2013).

Exchange of water through the HZ is primarily influenced by channel features that cause discontinuity in slope (i.e. riffle, step-pools, debris dams, and sediment ripples), permeability of the sediment, and river bend and meanders (Figure 2) (Boulton et al., 2007, 2010; Hester & Gooseff, 2010).

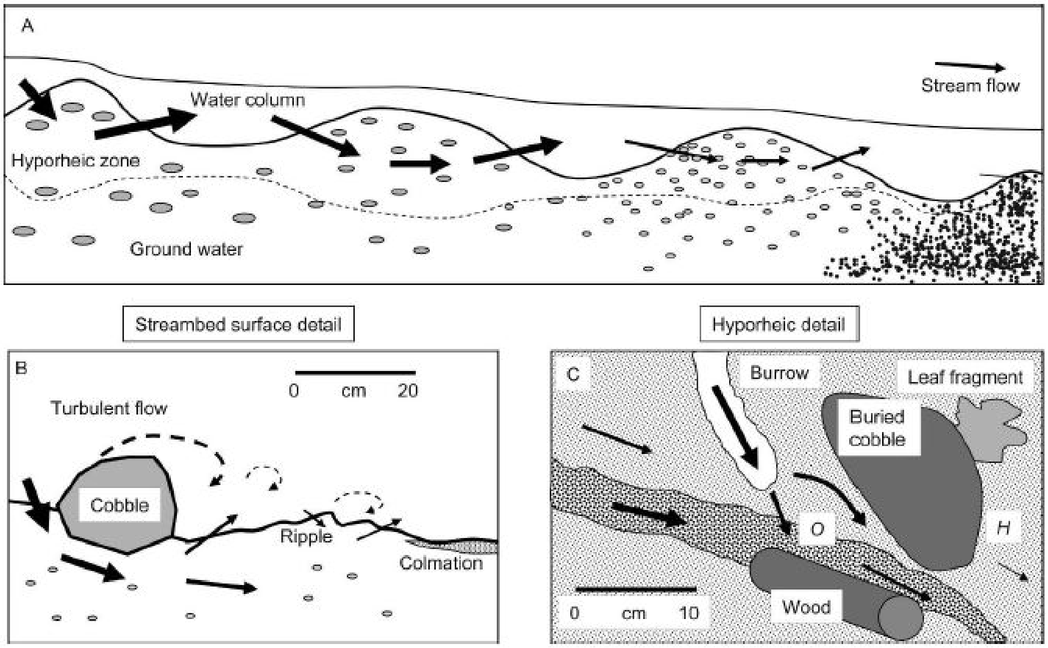

Figure 2: Shows the flow of water through the hyporheic zone at different scales. Streambed topography and size of sediment can influence surface and subsurface flow characteristics. The thickness of the arrows indicates the magnitude of HZ exchange. Graphic (A) shows how HZ exchange is driven by changes in pressure through a riffle-pool sequence. The broken line in graphic (A) represents the groundwater zone. The oval shapes in graphic (A) represent sediment size with a transition (right to left) from coarse sediment to compacted fine sediment. Notice that the magnitude of HZ exchange is greatest in areas of coarse sediment. Graphic (B) illustrates how streambed surface irregularities (i.e. cobble and sediment ripples) cause turbulent HZ flow. Graphic (B) also shows how areas of colmation (fine sediment clogging) can restrict HZ flow. Graphic (C) shows a cross-section of the hyporheic zone, showing how water travels through the subsurface hyporheic zone. The darkened band that cuts through the graphic, indicates a section of coarser sediment. The submerged material such as, cobble, wood, and leaf fragments can also change the direction of flow. The areas with greater flow are usually areas of oxygenated sediment, indicated by the letter O. Areas with lesser flow are usually areas of hypoxic conditions, indicated by the letter H. Source: Boulton et al., (2010)

The discontinuity in slope influences the hydraulic head gradient (variability in pressure) that exists between the surface water down to the groundwater zone. Hydraulic head is defined as a measure of the total energy that forces water to move up and down through the water column, and is measured as water surface elevation using units of length or height. Total head is the sum of water elevation, water pressure head, and water velocity head. Water travels through the hyporheic zone from higher to lower hydraulic head, which represents the hydraulic gradient between two points along the water column (Environment Agency, 2009, Stonestrom & Constantz, 2003). Downwelling is associated with high to low pressure variations, such as found in the transition from a pool to a riffle habitat. Conversely, upwelling is associated with low to high pressure variations, such as found in the transition from a riffle to pool habitat (Environment Agency, 2009; White, 1993).

The influence of particular features depends greatly on the scale of study. At a fine-scale any features that create complexity along the streambed, such as sediment ripples or submerged stones can cause pressure variations, leading to upwelling and downwelling through the hyporheic zone (Boulton et al., 2007; Environment Agency, 2009). At the sediment scale, grain size distribution is a key factor in the function of the hyporheic zone. Grain size determines both bed porosity and hydraulic conductivity, which quantifies how readily water can travel through porous material (Stonestrom & Constantz, 2003). Grain size distribution also significantly influences the biological activity, such as organic matter accumulation and microbial abundance and activity (Brunke & Gonser 1997). Additionally, grain size influences levels of dissolved oxygen and rates of metabolism (Boulton et al., 2007).

The hyporheic zone provides a variety of beneficial ecological functions to river ecosystems, such as carbon, nutrient and energy cycling, river water temperature regulation, and pollutant buffering (Hester & Gooseff, 2010). In addition, the hyporheic zone acts as important habitat, refuge, and a spawning ground for terrestrial and aquatic life, which include fish, benthic and interstitial organisms, macroinvertebrates, and amphibians (Lawrence et al., 2013). The organisms that spend part or all of their lives in the hyporheic zone are referred to as the hyporheos (Hester & Gooseff, 2010; Lawrence et al., 2013). Some of these organisms are endemic, relying exclusively on the hyporheic zone, due to the unique exchange of water and nutrients between the groundwater and surface water ecosystems. Others use the hyporheic zone as a refuge during unfavorable surface water conditions, such as flood or drought events (Lawrence et al., 2013). Salmonids will build redds in the hyporheic zone due to the increased flow of oxygen and nutrients that benefit the development of the eggs and juveniles (Lawrence et al., 2013; Hester & Gooseff, 2011; Hancock, 2002). Furthermore, groundwater temperatures are more consistent than surface water, which is desirable not only to fish, but also other aquatic life, such as benthic macroinvertebrates. Terrestrial insects also utilize the hyporheic zone during the larval stage of their life cycle, which include Ephemeroptera (Mayflies), Plecoptera (Stoneflies), and Trichoptera (Caddisflies) (Hester & Gooseff, 2011).

Hyporheic zones are important locations of nutrient cycling. The exchange of water between the surface water and groundwater zones, transfers dissolved solutes and nutrients that promote large microbial communities in the hyporheic zone (Kasahara and Hill 2006a; Hester and Gooseff, 2010). The microbial community promotes intense biogeochemical cycling of nutrients and also reduce downstream movement of pollutants. The potential for pollutant buffering is particularly important in urban watersheds, which are often highly polluted due to impervious surface runoff. The biogeochemical cycling leads to large amounts of nitrogen (N), phosphorous (P), and carbon (C) being circulated through the hyporheic zone. Furthermore, studies have found that higher rates of denitrification, ammonification, nitrogen mineralization, and nitrification all occur in the hyporheic zone (Hester and Gooseff, 2010; Lawrence et al., 2013).

Historical Research

Traditionally, scientists have treated groundwater and river systems as separate entities (Brunke & Gonser, 1997; Boulton et al., 1998, 2010). This separation is primarily attributed to the differences in accessibility and characteristics between the two systems. Rivers are characterized as dynamic systems, with turbulent hydraulic forces, brief water retention time, variable discharge and water temperature, unidirectional transport of nutrients and materials, and changing channel morphology. In contrast, alluvial groundwater environments are more stable systems, with laminar flow, longer water residence times, constant sediment structure, and exist permanently in the dark (Brunke & Gonser, 1997; Boulton et al., 1998).

Accumulating evidence supports the notion that surface water and groundwater ecosystems are not separate but are rather in constant interaction. The two ecosystems are connected through the back and forth movements of surface and subsurface flow, as well as through energy transfer in the form of organic matter and nutrients. First recognized as a distinct zone in the late 1950s (Boulton et al., 2010), the hyporheic zone represents the transitional section of the hydrological continuum where groundwater and river ecosystems interact. Even though the basic science of groundwater and surface water exchange is better understood, vertical flow dynamics of the hyporheic zone have remained largely understudied when compared to the longitudinal and lateral flow dynamics of river ecosystems (Brunke & Gonser, 1997).

Hyporheic Zone Research

In urban stream systems, ecologists and hydrologists often reference improving stream health as a top priority (Lawrence et al., 2013). However, little mention is given to the health of the hyporheic zone even though scientists have been aware of its importance since the 1950s (Boulton et al., 2010). There is a need for established criteria that is easy to measure, understand, and analyze that can indicate the health of a particular hyporheic zone. For example, Boulton et al., (2010) proposed that hyporheic health be measured using three different criteria: hydrological exchange, rates of biogeochemical activity, and biodiversity of the hyporheos. Yet, due to the lack of research and baseline data on hyporheic zones there is currently no standard for evaluating HZ health (Lawrence et al., 2013; Boulton et al., 2010).

Scientists have adopted a variety of techniques to examine daily fluctuations in the upwelling and downwelling of water through the hyporheic zone. Some of these currently used techniques include seepage meters (Blanchfield & Ridgway, 1996), heat flowmeters, chemical tracer tests, and streambed temperature modeling (Conant, 2004). There is no standard technique used; however, chemical tracer tests, which often use sodium chloride (NaCl) or bromide (Br-) have been one of the primary techniques used to quantify rates of HZ exchange (Boulton et al., 2010). However, scientists have looked for other ways to measure hyporheic flow dynamics without the use of chemical tracers due to the threat of river contamination (Stonestrom & Constantz, 2003).

A method that has gained popularity is the use of heat fluctuations in the streambed to trace groundwater and surface water movements through the hyporheic zone (Stonestrom & Constantz, 2003). Using heat as a tracer has multiple benefits compared to chemical tracers and other methods. First, heat occurs naturally, which means unlike chemical tracers there are no risks of harming the environment. Second, heat is easy to measure and does not require complicated laboratory analysis. (Stonestrom & Constantz, 2013). Third, tracking temperature movement is relatively inexpensive, but also accurate (Hassan et al., 2015).

Whenever there is a difference in temperature between two adjacent points, heat will travel from one point to another through either advective heat flow or conductive heat flow. Advective heat flow travels through the movement of water, whereas conductive heat flow travels through non-moving solids and liquids, such as sediment and other physical objects (Stonestrom & Constantz, 2003). Differences in temperature exist along a vertical flow path from the surface water down to the groundwater zone. Surface water is highly influenced by above ground conditions that can quickly heat or cool water based on factors, such as climate, season, time of day, and amount of riparian cover. Conversely, groundwater temperatures are buffered from above land fluctuations and remain rather constant and close to the cyclical average. The temperature difference between the groundwater and surface water zones is typically greatest during the winter and summer months when surface water reaches maximum and minimum annual temperatures. Furthermore, it is expected that during the summer groundwater is cooler than the above surface water, whereas in the winter it is expected to be warmer. Tracking the movement of heat as it travels from one zone to the other through the streambed is particularly effective in delineating flow paths on a small-scale (Conant, 2004; Stonestrom and Constantz, 2003).

Using heat as a tracer of groundwater movement is not a new technique. In the early 1900s, it was first identified that heat is transferred by the movement of water through sediments. By the 1950s, scientists began to develop ways to use temperature measurements to determine the intensity of flows of groundwater and surface water. However, only recently with improvements in data-acquisition and computational techniques has the use of heat as a hydrological tracer emerged as an economical and efficient method (Stonestrom & Constantz, 2003; Conant, 2004).

Hyporheic Zone Restoration

Human actions can severely damage the structure and function of the hyporheic zone. Damage to the hyporheic zone is often most evident in highly urbanized settings. As previously mentioned, a key issue with urban streams is channel armoring (Environment Agency, 2009). Armoring is harmful because it reduces the dynamic nature of the stream system. Furthermore, armoring leads to increases in streamflow velocity, which will cause streambed erosion, resulting in a deepened and hardened channel with little to no vertical movement of water. Armoring also eliminates the natural pool-riffle sequence, which is a key driver of hyporheic exchange (Hancock, 2002). Channelized and armored streams also lack sinuosity, which reduces hydrologic connectivity with the surrounding floodplain and the parafluvial zone. (Environment Agency, 2009; Hancock, 2002). Riparian vegetation removal is a concern for multiple reasons. First, riparian vegetation provides valuable protection to the stream system from direct solar radiation. Second, riparian vegetation removal limits the amount of large wood and other allochthonous material that will naturally make its way into the stream channel. The lack of wood inputs, leads to a loss of streambed heterogeneity and subsequently HZ exchange. Furthermore, the removal of riparian vegetation also often leads to increased erosion and sediment deposition, which can clog the interstices of the streambed, reducing the vertical movement of water. In the worst cases, a stream can become sediment clogged uniform channels, in which hyporheic zone exchange exists only in the top few centimeters of the streambed (Boulton, 2007; Hancock, 2002).

Stream restoration projects have the ability to restore aspects of hyporheic zone structure and function. However, most stream restoration projects are traditionally focused on restoring surface aspects of the river. Restoration practices are varied, but can include channel modification, riparian revegetation, installation of physical barriers (i.e. large wood debris), restocking of aquatic species, floodplain expansion, and gravel replenishment (Hester and Gooseff, 2010, Lawrence et al., 2013). Rarely is the hyporheic zone considered in restoration plans. Nonetheless, traditional restoration practices can directly impact the hyporheic zone (Hester and Gooseff, 2010). For example, installation of physical barriers, such as large woody debris create channel complexity and increase local streambed gradient, which can lead to significant increases in hydrological exchange (Lawrence et al., 2013; Hester and Gooseff, 2010). In fact, previous studies (Daniluk et al., 2013; Crispell and Endreny, 2009) found that the strongest downwelling occurred at locations immediately upstream of cross-vane restoration structures. These structures created a hydraulic step, resulting in greater hyporheic flux, which is defined as the amount of water that travels through the hyporheic zone.

At present, direct restoration of the hyporheic zone is a relatively novel technique. In fact, this study could not locate any other projects in the country that incorporated hyporheic restoration similar to what was applied on Thornton Creek. Few restoration projects have actually attempted to directly restore the hyporheic zone and improve vertical connectivity in stream systems. Instead, river restoration most often focuses on the surface aspects of streams, concentrating on improving lateral and longitudinal connectivity (Boulton et al., 2010). A study by Daniluk et al. (2013) was able to locate only one comparable study that similarly compared hyporheic flux at restored sites with that of control sites (i.e. degraded or reference reaches). Consequently, the present literature is mostly focused on examining the potential benefits of hyporheic restoration, rather than discussing the actual observed impacts of restoration at completed projects. As hyporheic zone restoration becomes an increasingly used technique, it is important that pre-project and post-project monitoring is thoroughly completed in order to provide tangible evidence as to the effectiveness of the approach. This research project is designed to fulfill this need for post-project assessment, with the goal of improving scientific understanding of urban stream systems and the future potential for hyporheic zone restoration.

Recently, more studies have focused on how restoration impacts hyporheic exchange. Many of studies have examined the influence of constructed restoration structures, such as cross-vanes, step-pools, and weirs. However, none of these studies examined restoration sites that included full restoration of the hyporheic substrate similar to what was completed at Thornton Creek. A thorough search through the available literature found several studies that examined HZ exchange at restored sites. However, very few studies could be found that compared hyporheic exchange at restored sites with control sites, such as equivalent degraded reaches or reference reaches. Also, few studies have examined HZ exchange at the same reach before and after restoration (Zimmer and Lautz, 2015). This study attempts to address the clear gaps in research by comparing hyporheic zone exchange at restored reaches with nearby control (unrestored) reaches.

There are concerns related to hyporheic zone restoration that environmental managers must consider before beginning a project. First, restoration of the HZ involves significant manipulation to the system. These techniques disturb aquatic, benthic and riparian ecosystems. Thus, in the short-term there will be a period of recovery for organisms as populations reestablish communities within the hyporheic zone. Second, river ecosystems are dynamic systems that will put pressure on the constructed features of a restoration site, which could lead to these features failing over time. For example, morphological barriers, such as large wood or boulders may degrade or wash downstream over time. In a natural setting, these barriers will be replaced from another source, such as a falling tree from the adjacent riparian corridor (Hester & Gooseff, 2010). However, in urban settings, rivers are often confined to a limited space and they lack established riparian corridors and floodplains. Therefore, the issue of long-term sustainability becomes a major question. Unfortunately, the questions regarding sustainability are ones that need multiple years of research and analysis and are thus outside the scope of this research project.

Another important question raised by hyporheic zone restoration is whether or not the benefits outweigh the costs? Hyporheic zone restoration involves reconstructing the entire streambed and stream channel, requiring extensive resources. These resources are spent without much certainty what the results of restoration will be. While, this study does not incorporate an economic analysis, it is important to acknowledge the potential costs as well as the benefits of HZ restoration.

Thornton Creek Background

The Thornton Creek watershed is the largest drainage basin in the City of Seattle, draining 7,120 acres (11.1 sq. mile). The watershed is located partially in the City of Shoreline and in the northeast corner of Seattle (Figure 3). There are three main sections of the creek, which include the North Fork, South Fork, and main stem (City of Seattle, 2007, TCWMC, 2000). Furthermore, there are 20 tributaries distributed across the watershed. The three main sections and the tributaries combine to make Thornton Creek the longest stream in Seattle at almost 20 miles in length. The headwaters of the North Fork are located in the southern portion of Shoreline, Washington and drains 7 square miles, 60% of the total watershed. The South Fork originates at the wetlands near Northgate Mall and Interstate 5. The South Fork drains 3.8 square miles, 33 percent of the watershed. The two branches converge near Meadowbrook pond and the main stem continues on another 1.4 miles and then discharges into Lake Washington just south of Matthews Beach Park (City of Seattle, 2007).

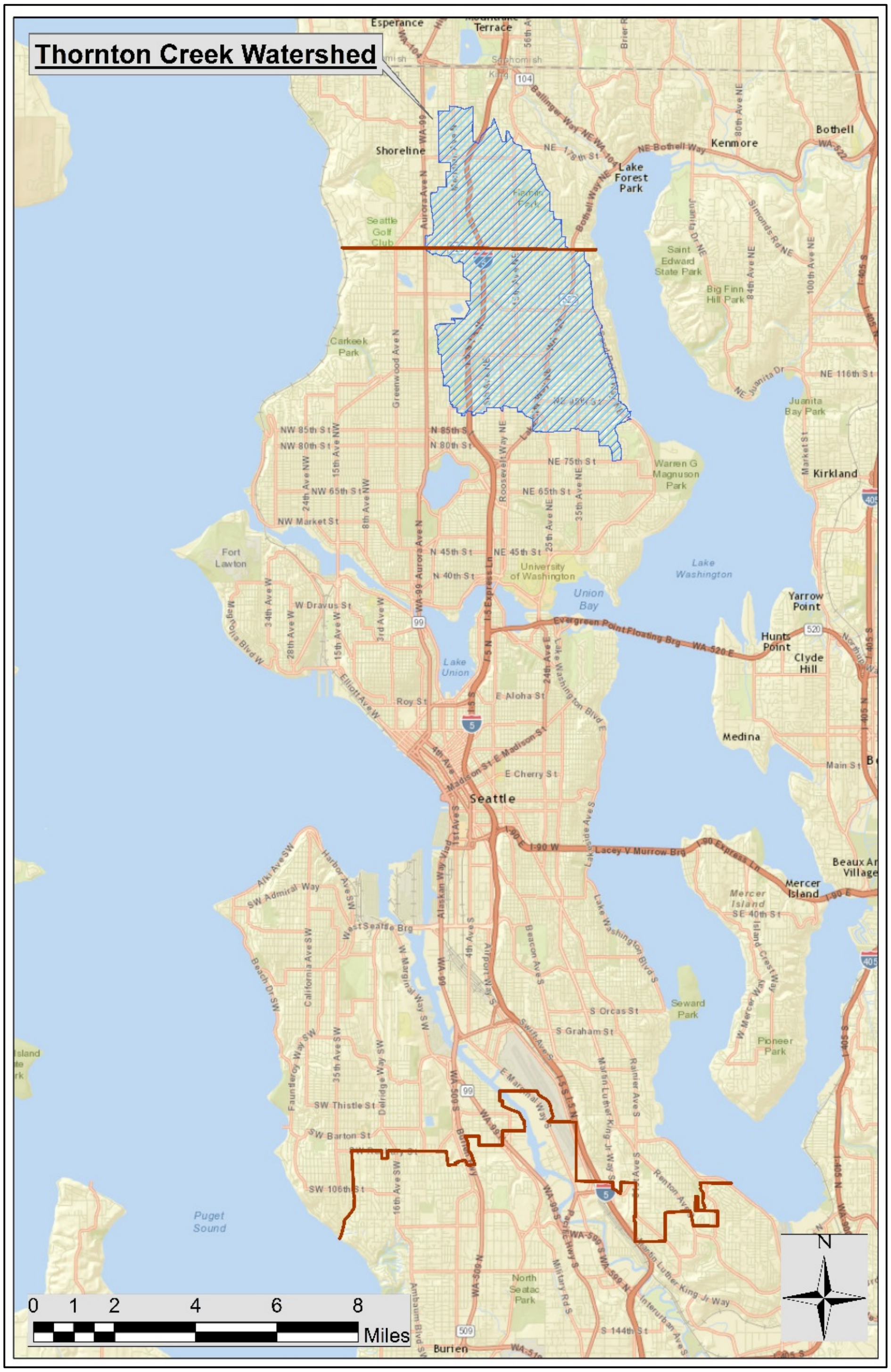

Figure 3: Map showing the location and boundary of the Thornton Creek watershed in relation to the city of Seattle. Dark red lines indicate the North and South boundaries of the city of Seattle.

Land use in the watershed is highly urbanized with 53% as residential, 26% as roads and right-of-way, and 8% as commercial and industrial use. Only 9% of the basin is made up of parks and undeveloped land (City of Seattle, 2007). In result, 59% of the watershed is made up of impervious surfaces. Though much of the watershed is developed, the creek's main channel is unique in that 90% flows above ground (City of Seattle, 2007; TCWMC, 2000).

Extensive development has led to multiple problems that are widespread throughout the watershed. These problems include, but are not limited to, severe flooding and high flashy stream flows, poor water quality, and habitat degradation (TCWMC, 2000). The sediment regime in Thornton Creek is of particular concern due to high rates of bank erosion, causing sand and silt to predominate the stream channel (City of Seattle, 2007). Fine sediment will clog the interstices of the hyporheic zone, reducing flow dynamics (Lawrence et al., 2013). As fine sediment (i.e. sand, silt, and clay) builds up, hydrological exchange in the hyporheic zone is reduced (Nogaro et al., 2010).

Thornton Creek Restoration Projects

In the summer of 2014, Seattle Public Utilities completed two stream restoration projects on Thornton Creek in Seattle, WA. The two project sites are named "Knickerbocker," which is located on the South Fork and "The Confluence," which is located where the north and south channels converge, creating the main stem.

The restoration projects were completed to address problems that were identified throughout the Thornton Creek Watershed and specifically at the two restoration sites. The key problems identified were, storm water related flooding, poor water quality, and insufficient instream, riparian, and upland habitat for native wildlife species (TCWMC, 2000). The restoration projects at the two Thornton Creek sites were designed to address the above issues, using a variety of methods, including floodplain expansion, riparian revegetation, and installation of physical barriers (i.e. large woody debris and boulders).

An important component of the restoration project was to also to restore the hyporheic zone. Seattle Public Utilities decided to try something entirely new by reconstructing the hyporheic zone at the two restoration sites. They achieved this by first excavating the original streambed that contained high amounts of fine sediment. They then added between 1-2 feet of course gravel and cobble. No sand or fine sediment was added during construction, due to the assumption that sediment would come naturally from erosion and sedimentation processes after project completion. The other major component of the restoration was the addition of in-stream physical structures along the streambed, such as boulders, large wood, and step-pool structures (Figure 4). The in-stream structures when combined with the added coarse gravel are expected to improve vertical connectivity between the groundwater and surface water zones.

Figure 4: Photo shows the addition of a step-pool feature at the Knickerbocker treatment site. Also shows the constructed hyporheic substrate that consists of course sediment. Source: Seattle Public Utilities (http://www.seattle.gov/util/EnvironmentConservation/Projects/KnickerbockerFloodPlain/index.htm)

Another important aspect of the projects was pre- and post-project monitoring to determine the effectiveness of restoration. The lack of pre- and post-project assessment is routinely cited as a major issue in the field of stream restoration (Shoredits and Clayton, 2013). Seattle Public Utilities has made project assessment a top priority and has invested significant resources in pre- and post-project monitoring with help from U.S. Fish and Wildlife Service (USFWS) and NOAA Fisheries. The pre-project surveys took place between 2005 and 2009 at both treatment sites and also the nearby control sites. Initial monitoring of the Knickerbocker and Confluence restoration sites began soon after project completion in fall of 2014. An important element of the post-project monitoring is evaluating the impacts of restoration on HZ function. Due to limited resources, post-project monitoring of the hyporheic zone was only budgeted for the summer months. The primary objective of this research project is to collect data in the winter months, which will provide us with an understanding of how hyporheic function compares during different seasons. This study is the first to be completed at the two treatment sites and provides an initial look at HZ exchange post-restoration. The results of this research will be made available to SPU and USFWS to compare with the summer season surveys that are expected to continue for the next (3-5) years. In sum, this project will add to the wealth of research that will be used to evaluate the effectiveness of the Thornton Creek restoration projects.

Conclusion

Hyporheic zone restoration is a novel approach, especially in an urban stream system such as Thornton Creek. In result, there are few studies that have examined the viability of hyporheic restoration for improving vertical connectivity in a highly urbanized stream setting. The overall goal of this study is to identify a data collection method that is effective at determining levels of hydrological exchange. This study is designed to gauge how flow dynamics vary between stream systems with perceived differences in the hyporheic health. This study supports a growing effort to measure and quantify hyporheic exchange to better understand how to preserve and restore hyporheic zones. Furthermore, this study provides the initial data needed for identifying the possibilities and limitations of hyporheic restoration.

Chapter 3: Methods and Analysis

Field Study Overview

The primary objective of this study was to identify the locations of upwelling and downwelling at individual habitat units (pools, glides, riffles) and to determine the relative strength of these processes at both the treatment (restored) sites and control (unrestored) sites on Thornton Creek. To achieve this objective, six intensive streambed temperature surveys were completed at multiple stream reaches on the South Fork of Thornton Creek in the late winter of 2015 (Figure 5). The survey methods closely followed those used in pre-project surveys, which were developed by Paul Bakke, a Geomorphologist from USFWS. The surveys took place between February 24th and March 20th. Dates were chosen to survey during baseflow conditions, and were also based on survey crew availability. Survey times varied, but most of the surveys were completed between 10 A.M. and 4 P.M. Crews of two completed surveys, in which one person recorded data, while the other measured temperatures.

There were six surveys in total completed at two distinct treatment sites, Knickerbocker & South Fork Confluence, as well as, two control sites, which were located just upstream of the treatment sites (Figure 5). At each treatment site, one survey was conducted at an upstream and downstream reach for a total of two surveys at each site. At each control site, one survey was completed. The rational for conducting two surveys at the treatment sites was to obtain a more detailed analysis of how hyporheic exchange differed or remained the same between the upstream and downstream section of the restored sites.

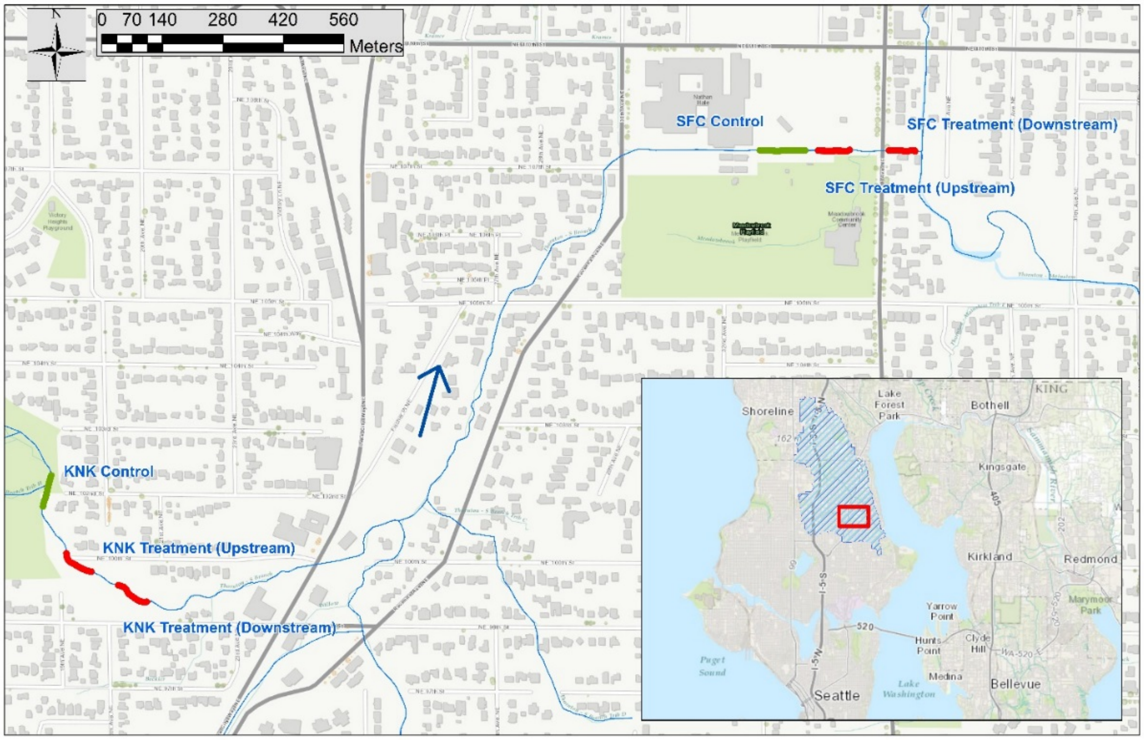

Figure 5: Above is a map showing approximate survey locations of each reach at both the Knickerbocker (KNK) and South Fork Confluence (SFC) sites located on Thornton Creek, in the city of Seattle. The blue arrow indicates stream flow direction.

Survey Procedures

For the temperature surveys, 60-80 short, 0.375” inner diameter polyethylene tube segments were installed into the streambed. Multiple transects (12-17) consisting of 3-5 tubes were installed laterally from one stream bank to the other at each site (Figure 6). The number of tubes and transects used for each site varied based on stream characteristics and conditions at each site. For example, wider stream reaches typically required more tubes to ensure sufficient survey coverage. Transects were placed at the beginning, middle, and end of each habitat unit type (riffle, pool, and glide) (Figure 6), which were defined at the site by the surveyors. The spacing of transects varied from reach to reach, but transects were generally placed every 2-4 m longitudinally down the reach. The tubes (approx. 33 cm in length) were inserted about 10 cm into the streambed using a soil probe. The distance between each tube also varied, but most of the tubes were placed 1 m to 2.5 m apart laterally across the stream channel. In certain situations, tubes were dislodged during the survey and were reinstalled in the original location.

Figure 6: Photograph of South Fork Confluence treatment (downstream) study site. Shows the characteristic transect and tube arrangement used for all six surveys. The photograph shows transects placed at the upstream, middle, and downstream section of a riffle unit.

At the start of each streambed temperature survey, the air temperature was first recorded using an Omega HH-41 digital thermometer (±0.01 ºC). For the two surveys at the Knickerbocker treatment site, the stream gage height at an upstream and downstream location was recorded, using two gauging stations that were previously placed at the site. Next, the temperature at the bottom of each tube (10 cm below the streambed) was recorded once after the reading stabilized (approximately 30 seconds) using the Omega HH-41 digital thermometer. Surface water temperature was recorded by holding the probe about just above the streambed in the middle of the channel. This occurred approximately every 10 tubes or 2-3 transects, in order to quicken the pace between transects and also due to the limited variability of stream temperature between adjacent tubes and transects. Additionally, surveyors noted the substrate type (cobble, gravel, sand) at each specific tube, using visual observation. The surveyors cycled through each array of tubes three times, starting each round within about an hour from each other. In result, between 50 and 70 tubes were surveyed three times during the course of one field day for each particular stream. The three replicate measurements were later averaged, in order to reduce the impacts of survey error and also the confounding temperature variability that occurs due to differences in survey times.

Flow surveys were conducted on each survey day at the upstream and downstream section of each site. The surveys were conducted using methods adopted from (Harrelson et al., 1994) in which discharge was determined from 20 velocity measurements that were recorded laterally across the stream channel in equal intervals. Each measurement was taken at 0.6 times the total depth. The equipment used was a top-setting rod and a Marsh-McBirney Flo-Mate 2000 meter. The flow surveys were intended to show changes in discharge from the upstream and downstream section of each reach. Changes in discharge could indicate whether a particular site is a gaining or losing stream reach. A gaining reach is one where upwelling of water is more prevalent; whereas, a losing reach is the opposite with a predominance downwelling of water. For example, areas in which discharge is lower downstream, might indicate surface water is being lost to downwelling. In sum, flow surveys provide useful information that can be used along with the streambed temperature surveys to better understand to what degree HZ exchange is occurring at each of the survey sites.

GPS Surveys

Prior to the actual survey day, each transect was located and marked with a flag on both the left and right stream bank and was labeled with a specific transect number. Each flag was then surveyed using a Trimble GeoExplorer 6000 handheld GPS receiver. The accuracy of the GPS surveys ranged from 10 cm to about 1 m, based on location and particular satellite conditions. The bankfull edge on each side of the stream was also surveyed longitudinally along each reach in order to create a plan-view map of the stream channel. On the survey day, the distance of the tube to the right and left bank flag markers was recorded using a measuring tape. Also, the distance between the left and right bank flags were measured for each transect. These measurements were important for later determining the approximate location of each tube.

Spatial and Statistical Analysis

The first step in the data analysis was to compute the difference between the streambed temperature and the surface water temperature, which is called the temperature anomaly. The temperature anomalies were computed by subtracting the temperature recorded at the bottom of each tube from the surface water temperatures recorded just above the streambed. It was expected that areas with greater temperature anomalies are locations of upwelling, while areas with lower temperature anomalies are locations of downwelling. In result, sites that have the greatest range in temperature anomalies, are thought to have the greatest hyporheic exchange. To compare ranges at each of the sites, the temperature anomaly data was used to create box-and-whisker plot graphs.

Next, a plan-view contour map was created for each survey reach using ArcGIS software that shows the temperature anomaly data at each individual habitat unit. The GPS survey data that was collected in the field was first downloaded and placed on a blank map in ArcGIS. The survey data contained points that showed the locations of transect flag markers and lines that showed the bankfull edge at each particular stream reach. Then using the field measurements collected for each tube, points were manually measured and placed on the map, which showed the approximate location of each tube along each particular transect. After adding the tube point locations the temperature anomaly value for each tube was also assigned to each point in the attribute table. Finally, a Triangulated Irregular Network (TIN) was created using the temperature anomaly data, which resulted in a contour map of temperature anomaly distribution throughout each reach. The plan-view maps were used to compare the survey results at each site, looking for differences in streambed temperature anomalies. Also, the maps were useful for identifying particular locations of upwelling and downwelling and proximity of these zones to in-stream hyporheic structures.

All statistical analysis, which includes the creation of the box-and-whisker plots, was conducted using JMP 12.0 (SAS Institute). Using JMP 12.0, descriptive statistics were computed to summarize the data and begin to uncover patterns. The primary dependent variable used was the average temperature anomalies at each tube for each reach. The descriptive statistics include measures of central tendency (i.e. mean and median) and measures of spread (i.e. quartiles, variance, and standard error of the mean).

In addition to the descriptive statistics, Kruskal-Wallis tests were run to test for significant differences between several different variables. The Kruskal-Wallis test was chosen due to the non-normal distribution of the temperature anomaly data, which was determined after running a series of Shapiro-Wilk W tests on the data. Data transformations had no effect on the non-normal distribution of the data; therefore, Kruskal-Wallis tests were viewed as the best statistical test. The Kruskal-Wallis test was first used to determine if there was a significant difference between the survey sites at both Knickerbocker and the South Fork Confluence. Second, a Steel-Dwass test was run to determine which sites differed from each other. A Steel-Dwass test is the nonparametric equivalent of the Tukey's HSD test. The Kruskal-Wallis test was next used to determine if there were differences between habitat type (i.e. riffle, glide, pool) in determining average temperature anomalies at both the treatment and control reaches. A Steel-Dwass test was again used to determine which habitat types differed from each other. Box-and-whisker plots were created to visually interpret how average temperature anomalies varied based on habitat type. Last, a Kruskal-Wallis test was run again, but instead using substrate type (i.e. sand, cobble, gravel) as the independent variable. The substrate test was run with combined data from all six survey sites because of the unequal sample size of the data.

Chapter 4: Results

Knickerbocker

The results of the streambed temperature surveys at the three Knickerbocker sites showed that the Knickerbocker control site had the greatest range of temperature anomalies followed by the Knickerbocker treatment (downstream) reach and then the Knickerbocker treatment (upstream) reach (Figure 7). A Kruskal-Wallis test showed that there was a statistically significant difference in average temperature anomalies between the different survey sites, ($\chi^2(2) = 50.921$, $p = <0.001$). Post hoc comparisons using the Steel-Dwass test indicated that the Knickerbocker control average anomaly values were significantly different than the Knickerbocker treatment (upstream) anomalies ($p = <0.001$) and also the Knickerbocker treatment (downstream) anomalies ($p = <0.001$). However, the anomalies at the Knickerbocker treatment (upstream) site did not did not significantly differ from the temperature anomalies at the Knickerbocker treatment (downstream) site ($p= 0.57$).

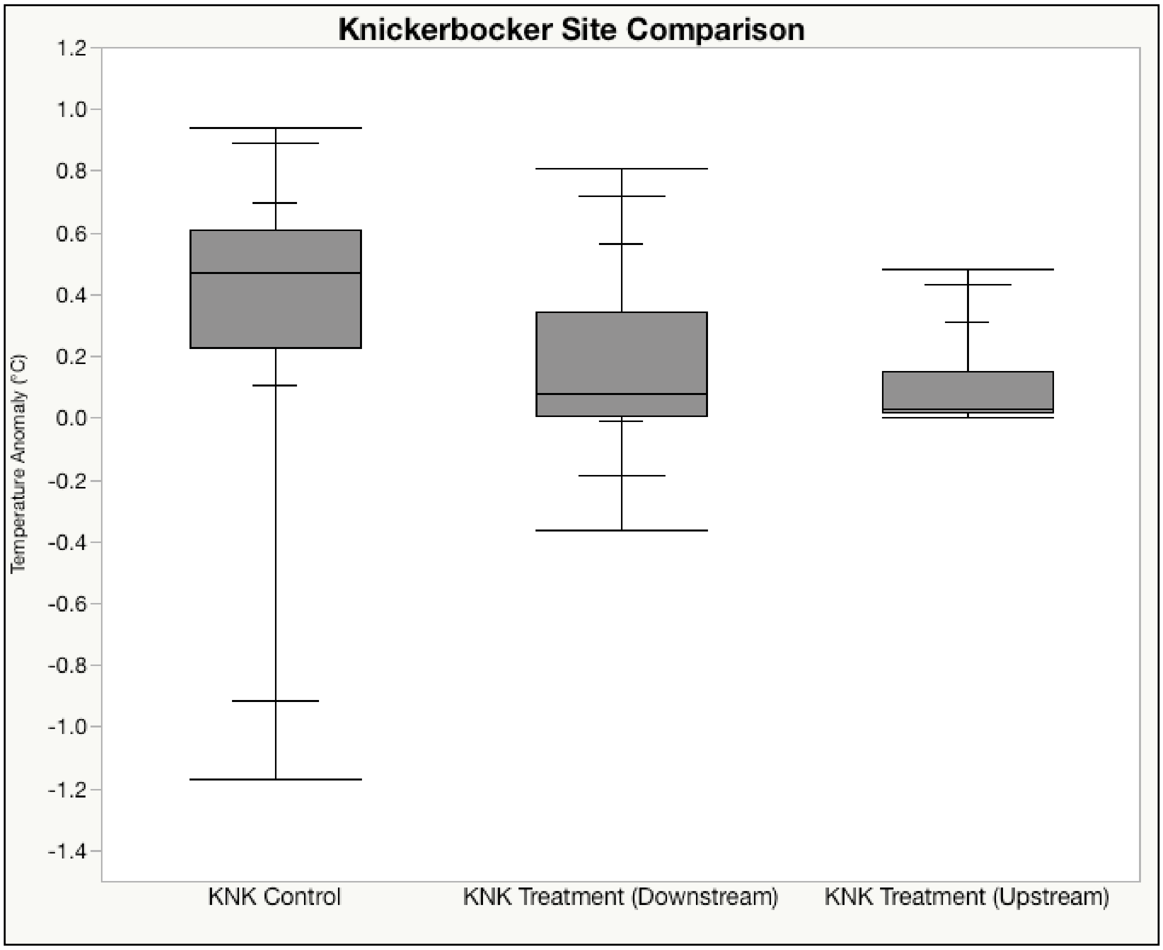

Figure 7: Shows box-and-whisker plots of temperature anomalies (°C) at each of the Knickerbocker sites. Temperature anomalies are the difference in temperature between the water just below the streambed (10 cm) and the surface water. Anomaly values above zero indicate that the streambed was colder than the surface water and anomaly values below zero indicate the opposite. Includes results of surveys that were completed at the Knickerbocker (KNK) control reach, Knickerbocker (KNK) treatment upstream (US) reach, and the Knickerbocker (KNK) treatment downstream (DS) reach. The line in the middle of each box (interquartile range) represents the median (50^{th} percentile). The upper boundary line of each box marks the 75th percentile and lower boundary marks the 25th percentiles. The whisker lines from top to bottom mark the 100%, 97.5%, 90%, 10%, 0.5%, and 0% quantiles.

Knickerbocker Control

On March 1, 2015, an intensive streambed temperature survey was completed at the Knickerbocker control reach. The survey was conducted during baseflow conditions. The weather conditions were sunny and relatively warm for a day in late winter. The air temperature was 11.62°C at the start of the survey at 1:10 PM and 10.43°C at the completion of the survey at 3:35PM. The stream discharge at the upstream reach of the survey site was 0.046 m^3/s (1.62 ft^3/s) and 0.051 m^3/s (1.82 ft^3/s) at the downstream reach. The slight increase in discharge could partially be due to a small tributary that enters the site in the upper portion of the stream reach. The average surface water temperature was 9.65°C (Standard error of the mean (SEM) = 0.04°C), with the lowest recorded temperature of 9.26°C and the highest of 9.98°C. The average streambed temperature was 9.24°C (SEM= 0.03°C), with a minimum temperature of 8.51°C and a maximum temperature of 10.73°C.

	Knickerbocker Control	**Knickerbocker Treatment (Upstream)**	**Knickerbocker Treatment (Downstream)**
Start Time	1:10 PM	2:00 PM	2:44 PM
End Time	3:35 PM	4:50 PM	6:20 PM
Start Air Temp	11.62°C	10.31°C	11.5°C
End Air Temp	10.43°C	6.31°C	9.11°C
Surface Water Temp. (avg.)	9.65°C	9.54°C	9.19°C
Streambed Temp. (avg.)	9.24°C	9.44°C	9.02°C
Temperature Anomaly (avg.)	0.41°C	0.10°C	0.17°C
Temperature Anomaly (75% quartile)	0.62°C	0.15°C	0.34°C
Temperature Anomaly (50% median)	0.47°C	0.03°C	0.08°C
Temperature Anomaly (25% quartile)	0.23°C	0.02°C	0.01°C
Upstream Discharge	0.046 m^3/s	0.049 m^3/s	0.043 m^3/s
Downstream Discharge	0.051 m^3/s	0.043 m^3/s	0.034 m^3/s

Table 1: Survey data and averages at Knickerbocker sites.

Total temperature anomalies (n=153) at the Knickerbocker control reach averaged 0.41°C (SEM= 0.03°C). Temperature anomalies of 0.62°C, 0.47°C, and 0.23°C represent the 75th, 50th, and 25th percentiles, respectively (Figure 7). It is important to note that positive anomaly values indicate that the temperature at the bottom of the tube is colder than the above surface water temperature. Negative anomaly values indicate that the temperature at the bottom of the tubes is warmer than the surface water temperatures. The largest anomaly values were observed at transect #3 (tube #2) and transect #7 (tube #2), with anomalies of -1.17°C and 0.94°C, respectively (Figure 8). Transect #3 was unique in that it was the location of the largest temperature anomaly, but also because it was the only location with negative anomaly values, where surface water was colder than the streambed. Transect #3 was located along the upstream section of a glide. There were other areas with large temperature anomalies; such as along transect #14, which had two tubes with anomalies of (0.77°C). Transect #14 was located along a riffle feature. The lowest average temperature anomalies were found at transect #8 (tube #4) and transect #9 (tube #2), with anomalies of 0.03°C and 0.06°C, respectively. Both of these transects were located along glide units.

As previously mentioned, there is a small tributary that enters the Knickerbocker control site in the upstream section of the stream reach (see figure 8). The plan-view map (Figure 8) shows that streambed temperature transects are located an extended distance (>2 meters) away from tributary. This was done deliberately to reduce the impacts of the tributary on temperature anomalies. However, it is possible that the tributary had some influence on temperature anomalies, and especially to the adjacent transects #4 and #5.

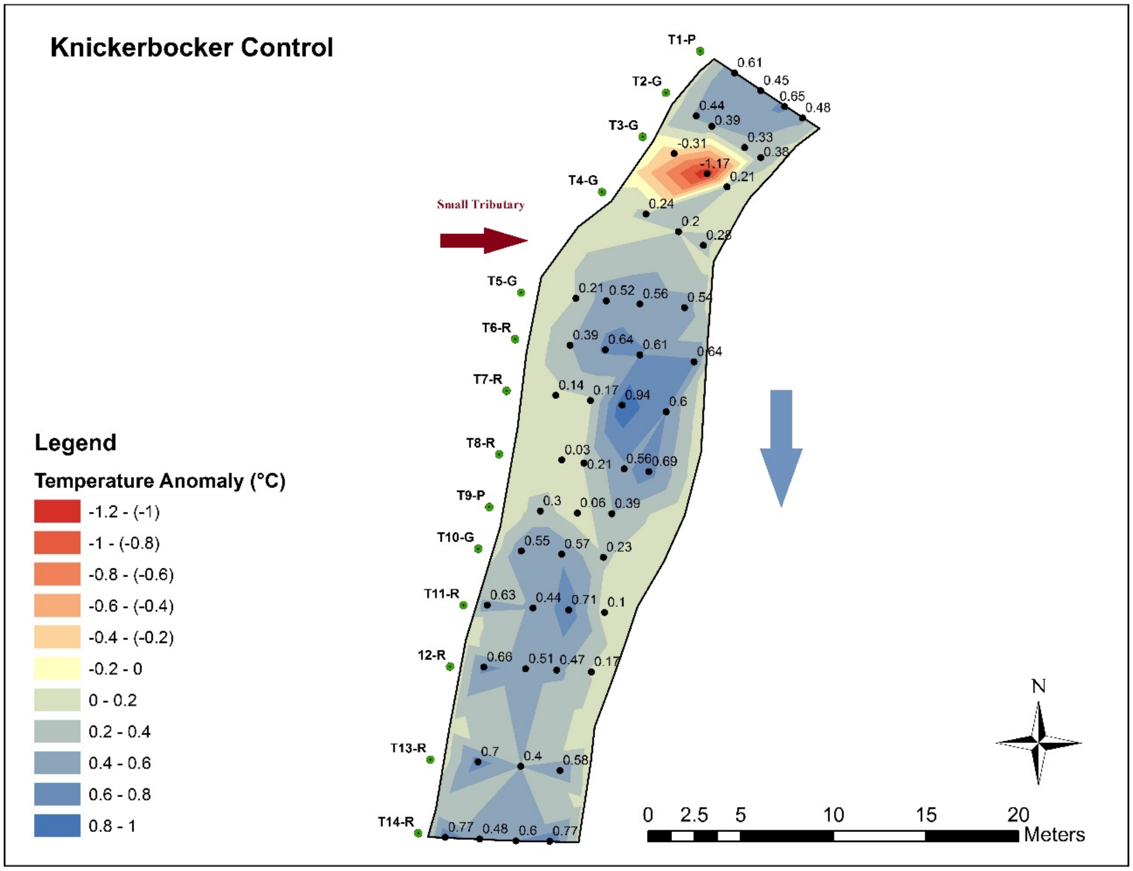

Figure 8: Plan-view map shows temperature anomaly patterns along survey reach and shows the average anomaly at each specific tube. Map also includes points, which are labeled with transect number (i.e. transect #1 [T1]) and also habitat type (pool (P), glide (G), and riffle [R]). The blue arrow indicates stream flow direction. Borders of stream reach indicate the approximate location of bankfull. Red arrow indicates location where small tributary enters the Knickerbocker control site. Notice that the streambed temperature transects are placed an extended distance away from tributary. This was done deliberately to reduce the impacts of the tributary on temperature anomalies.

Knickerbocker Treatment (Upstream)

On February 28, 2015, an intensive streambed temperature survey was completed at the Knickerbocker treatment (upstream) reach. The survey was conducted during baseflow conditions and relatively mild weather conditions. The weather on the survey day was sunny to partly cloudy. At the survey start time of 2:00 PM, the air temperature was 10.31°C. By the end of the survey at 4:50 PM, the temperature had dropped to

6.31°C. The stream discharge at the upstream reach of the survey site was 0.049 m^3/s (1.74 ft^3/s) and 0.043 m^3/s (1.53 ft^3/s) at the downstream reach. The average surface water temperature was 9.54°C (SEM= 0.01°C), with the lowest recorded temperature of 9.46°C and the highest of 9.62°C. The average streambed temperature was 9.44°C (SEM= 0.01°C), with a minimum temperature of 9.00°C and a maximum temperature of 9.59°C.

Total temperature anomalies between the streambed and surface water (n=138) at the Knickerbocker treatment reach (upstream) averaged 0.10°C (SEM= <0.01°C). Temperature anomalies of 0.15°C, 0.03°C, and 0.02°C represent the 75th, 50th, and 25th percentiles, respectively (Figure 7). The largest average anomaly values were observed at tube #2 (0.48°C) and tube #3 (0.35°C) along transect #4. These tubes were located in the center of the stream channel at the head of a pool (Figure 9). Large anomalies were also observed along transect #1, which was located just downstream of a step-pool restoration feature. Much of the reach consisted of low temperature anomalies. The lowest average temperature anomalies were found at transect #9 (tube #3) and transect #12 (tube #2), both at 0.00°C. Unlike the other reaches in this study, there weren’t any tubes at the Knickerbocker Treatment (Upstream) site that had an average negative anomaly, which means that the streambed temperature was almost always colder than the above surface water.

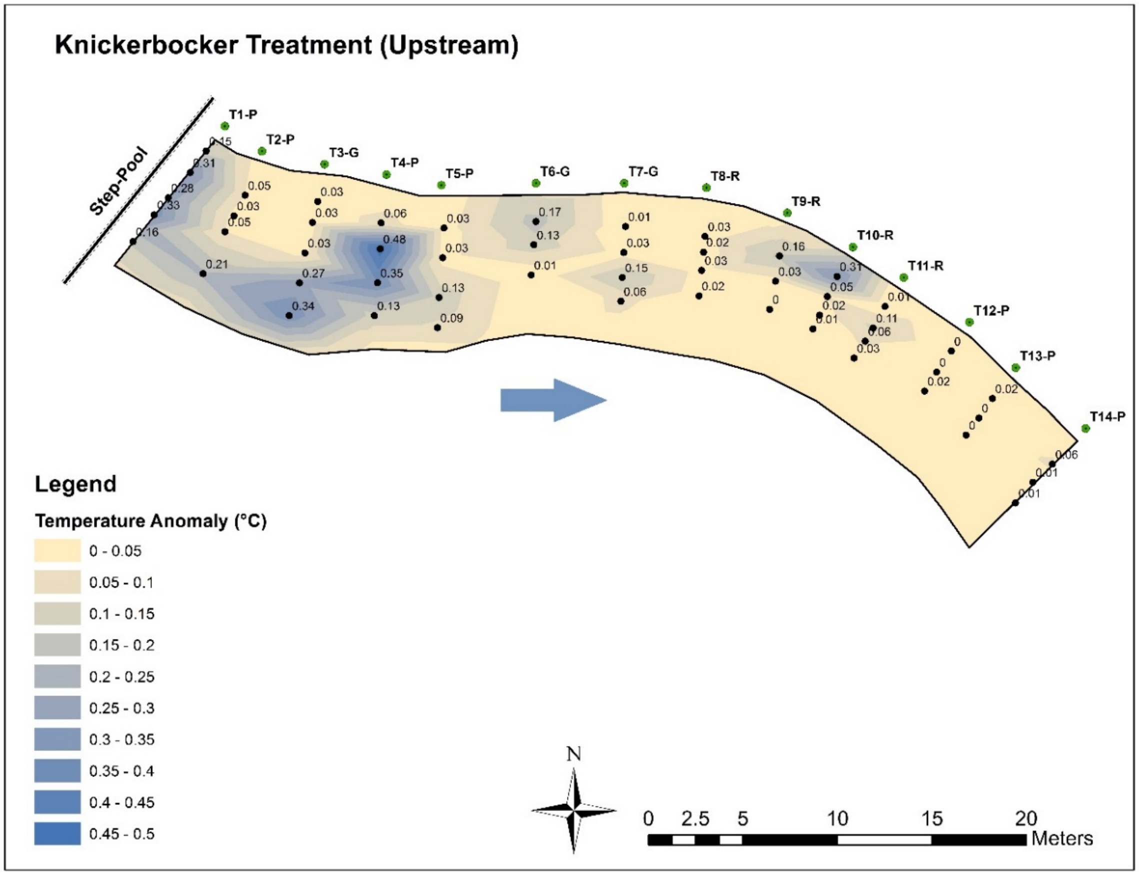

Figure 9: Plan-view map shows temperature anomaly patterns along survey reach and shows the average anomaly at each specific tube. Map also includes points, which are labeled with transect number (i.e. transect #1 [T1]) and also habitat type (pool (P), glide (G), and riffle [R]). Lines show approximate location of large restoration structures. The blue arrow indicates stream flow direction. Borders of stream reach indicate the approximate location of bankfull.

Knickerbocker Treatment (Downstream)

On February 22, 2015, an intensive streambed temperature survey was completed at the Knickerbocker treatment (downstream) reach. The survey was conducted during baseflow conditions and relatively mild weather conditions. The weather on the survey day was mostly overcast with no precipitation. At the survey start time of 2:44 PM, the air temperature was 11.5°C. By the end of the survey at 6:20 PM, the temperature had decreased to 9.11°C. The stream discharge at the upstream reach of the survey site was

0.043 m^3/s (1.53 ft^3/s) and 0.034 m^3/s (1.23 ft^3/s) at the downstream reach. The average surface water temperature was the coldest of the Knickerbocker sites at 9.19°C (SEM= 0.01°C), with the lowest recorded temperature of 9.13°C and the highest of 9.33°C. The average streambed temperature was 9.02°C (SEM= 0.02°C), with a minimum temperature of 8.26°C and a maximum temperature of 9.51°C.

Total temperature anomalies (n=183) at the Knickerbocker treatment (downstream) reach averaged 0.17°C (SEM= 0.02°C). Temperature anomalies of 0.34°C, 0.08°C, and 0.01°C represent the 75th, 50th, and 25th percentiles, respectively (Figure 7). The largest temperature anomaly values were observed at tube #3 (0.81°C) along transect #17, which is located near the right bank at the end of a riffle (Figure 10). Other high average anomalies were recorded along transect #5 and transect #10, which are both located downstream of two different step-pool restoration features. Again, much of the reach had relatively low average temperature anomalies, such as that of transect #13 (tube #3) and transect #15 (tube #2), both with anomalies of 0.00°C. There were 7 tubes that had negative temperature anomalies, meaning the streambed temperature was warmer than the surface water temperature. The largest negative temperature anomaly occurred at transect #11 (tube #3) with a value of -0.36°C.

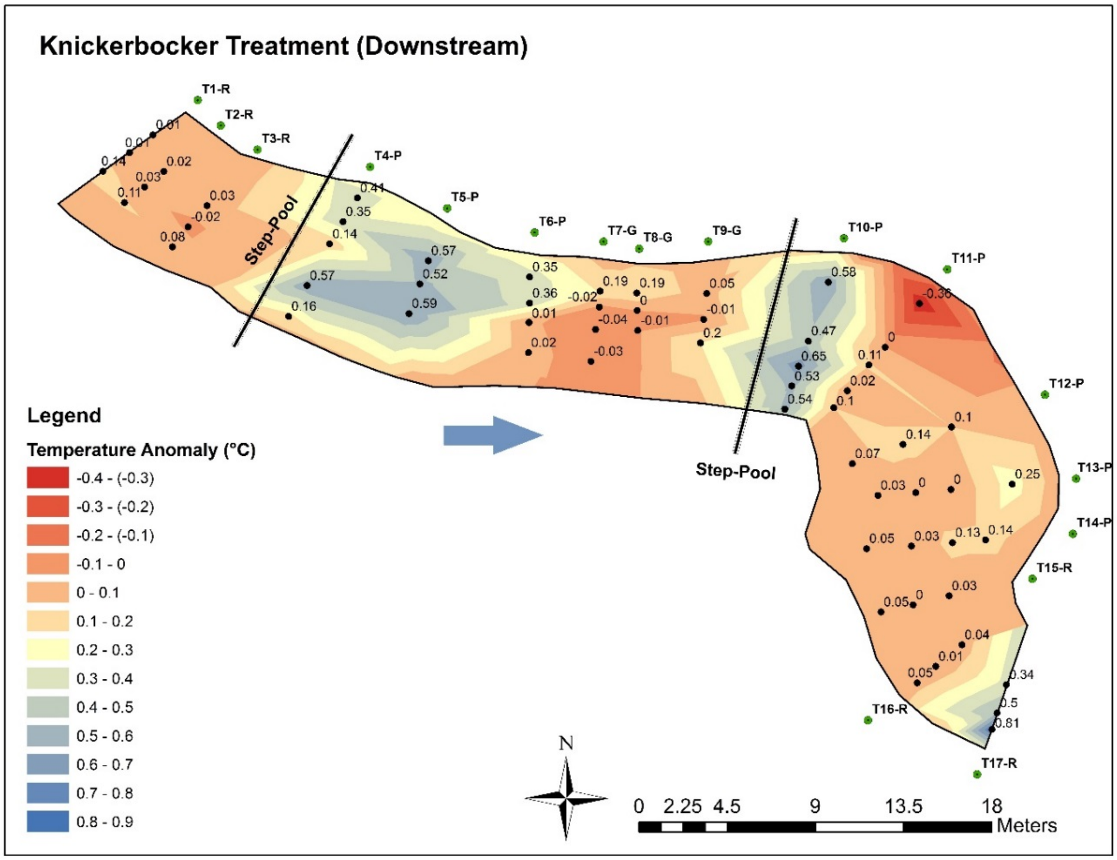

Figure 10: Plan-view map shows temperature anomaly patterns along survey reach and shows the average anomaly at each specific tube. Map also includes points, which are labeled with transect number (i.e. transect #1 [T1]) and also habitat type (pool (P), glide (G), and riffle [R]). Lines show approximate location of large restoration structures. The blue arrow indicates stream flow direction. Borders of stream reach indicate the approximate location of bankfull.

South Fork Confluence

The results of the streambed temperature surveys at the three South Fork Confluence (SFC) sites found that the SFC control site had the greatest range of temperature anomalies followed by the SFC treatment (downstream) reach and then the SFC treatment (upstream) reach (Figure 11). A Kruskal-Wallis test showed that there was a statistically significant difference in average temperature anomalies between the different survey reaches, ($\chi^2(2) = 48.01$, p = <0.001). Post hoc comparisons using the

Steel-Dwass test indicated that temperature differences were significantly different between all the SFC sites: SFC control and SFC treatment (upstream) (p = <0.001), SFC control and SFC treatment (downstream) (p= <0.001), SFC treatment (upstream) and SFC treatment (downstream) (p= 0.007).

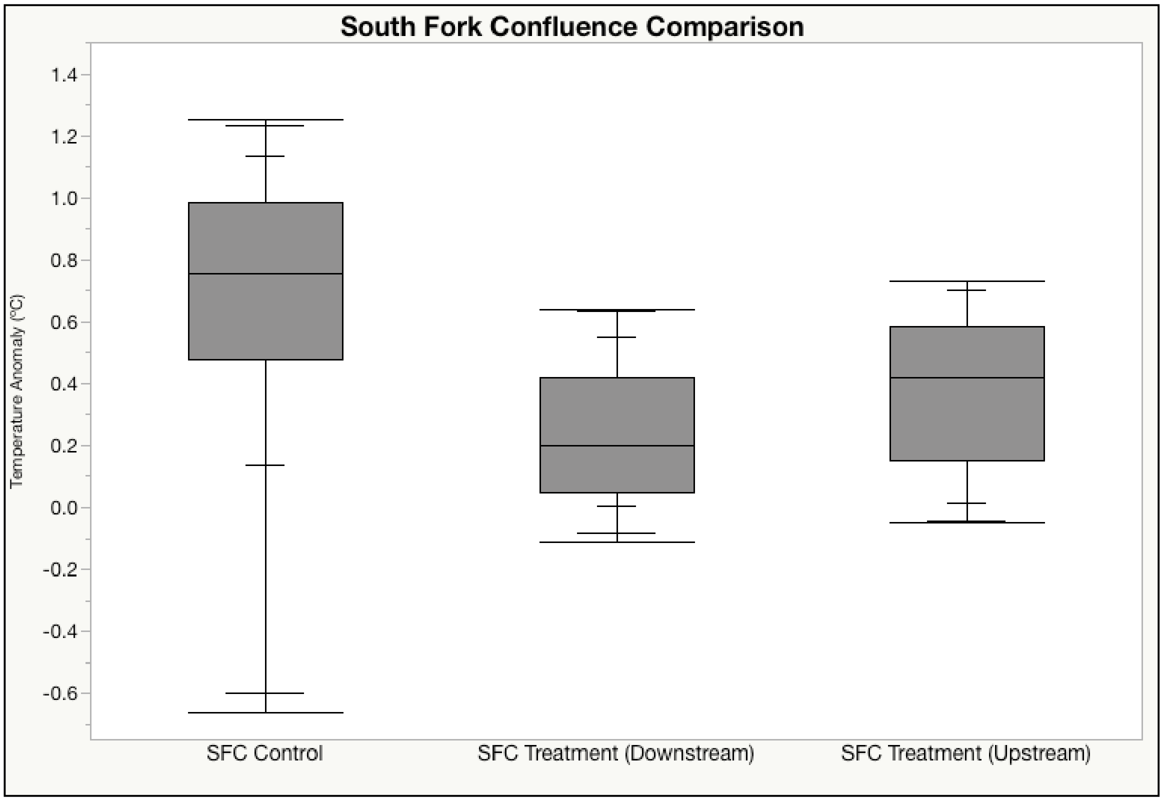

Figure 11: Shows box-and-whisker plots of temperature anomalies (°C) at each of the South Fork Confluence sites. Temperature anomalies are the difference in temperature between the water just below the streambed (10 cm) and the surface water. Anomaly values above zero indicate that the streambed was colder than the surface water and anomaly values below zero indicate the opposite. Includes results of surveys that were completed at the South Fork (SFC) control reach, South Fork Confluence (SFC) treatment (upstream) reach, and the South Fork Confluence (SFC) treatment (downstream) reach. The line in the middle of each box (interquartile range) represents the median (50th percentile). The upper boundary line of each box marks the 75th percentile and lower boundary marks the 25th percentile. The whisker lines from top to bottom mark the 100%, 97.5%, 90%, 10%, 0.5%, and 0% quantiles.

South Fork Confluence Control

On March 8, 2015, an intensive streambed temperature survey was completed at the South Fork Confluence control reach. The survey was conducted during baseflow conditions with partly sunny weather conditions. The air temperature was 14.81°C at the start of the survey at 1:00 PM and 17.62°C at the completion of the survey at 3:30 PM. The stream discharge at the upstream reach of the survey site was 0.049 m^3/s (1.73 ft^3/s) and 0.055 m^3/s (1.93 ft^3/s) at the downstream reach. The average surface water temperature was 10.36°C (SEM= 0.05°C), with the lowest recorded temperature of 9.73°C and the highest of 10.76°C. The average streambed temperature was 9.67°C (SEM= 0.04°C), with a minimum temperature of 8.97°C and a maximum temperature of 11.24°C.

	SFC Control	**SFC Treatment (Upstream)**	**SFC Treatment (Downstream)**
Start Time	1:00 PM	1:35 PM	11:56 AM
End Time	3:30 PM	4:24 PM	2:15 PM
Start Air Temp	14.81°C	16.66°C	11.47°C
End Air Temp	17.62°C	16.4°C	15.69°C
Surface Water Temp. (avg.)	10.36°C	11.36°C	11.59°C
Streambed Temp. (avg.)	9.67°C	11.00°C	11.36°C
Temperature Anomaly (avg.)	0.69°C	0.38°C	0.23°C
Temperature Anomaly (75% quartile)	0.98°C	0.58°C	0.42°C
Temperature Anomaly (50% median)	0.76°C	0.42°C	0.2°C
Temperature Anomaly (25% quartile)	0.48°C	0.15°C	0.05°C
Upstream Discharge	0.049 m^3/s	0.053 m^3/s	0.074 m^3/s
Downstream Discharge	0.055 m^3/s	0.072 m^3/s	0.082 m^3/s

Table 2: Survey data and averages at South Fork Confluence sites.

Total temperature anomalies (n=138) at the South Fork Confluence control reach averaged 0.69°C (SEM= 0.04°C). Temperature anomalies of 0.98°C, 0.76°C, and 0.48°C represent the 75th, 50th, and 25th percentiles, respectively (Figure 11). The largest anomaly value was observed at transect #11 (tube #1) with an average anomaly of 1.25°C (Figure 12). The next two largest average anomalies were observed at transect #12 (tube #4) and transect #13 (tube#1) with anomalies of 1.15°C. Transect #12 and #13 were located along riffle habitats, whereas, transect #11 was located along the downstream section of a glide feature. The lowest anomalies were found at transect #2 (tube #1) and transect #4 (tube #1), with anomalies of 0.11°C and 0.12°C, respectively. Both of these transects were located in the riffle habitats. There were two locations, transect #5 (tube #1) and transect #6 (tube #1) where average streambed temperatures were warmer than surface water temperatures. Transect #5 (tube #1) had a negative anomaly of (-0.66°C) and transect #6 (tube #1) had an average anomaly of (-0.32°C). Both of these transects were located along glide habitats.

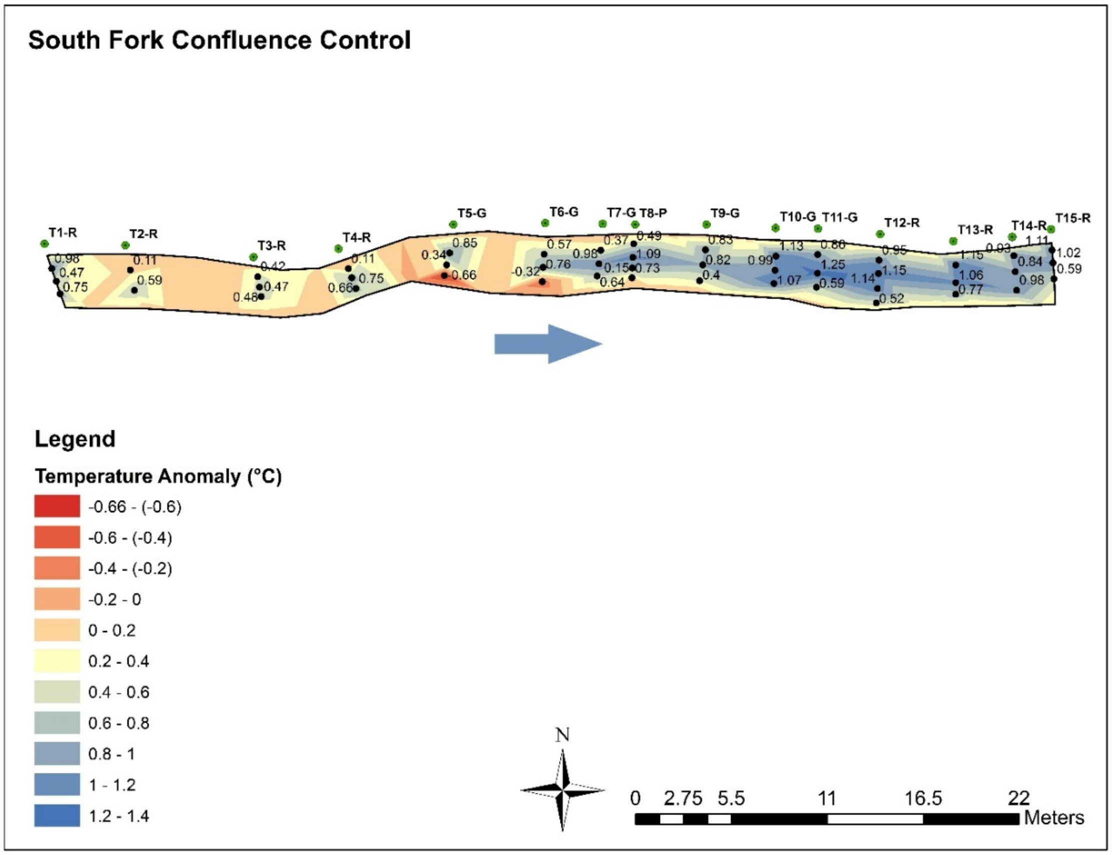

Figure 12: Plan-view map shows temperature anomaly patterns along survey reach and shows the average anomaly at each specific tube. Map also includes points, which are labeled with transect number (i.e. transect #1 [T1]) and also habitat type (pool (P), glide (G), and riffle [R]). The blue arrow indicates stream flow direction. Borders of stream reach indicate the approximate location of bankfull.

South Fork Confluence Treatment (Upstream)

On March 19, 2015, an intensive streambed temperature survey was completed at the South Fork Confluence treatment reach (Upstream). The survey was conducted during baseflow conditions and mild and overcast weather. The air temperature was 16.66°C at the start of the survey at 1:35 PM and 16.4°C at the completion of the survey at 4:24 PM. The stream discharge at the upstream reach of the survey site was 0.053 m^3/s (1.87 ft^3/s) and 0.072 m^3/s (2.53 ft^3/s) at the downstream reach. The relatively large increase in discharge is most likely attributed to the small tributary that enters the stream in the downstream portion of the survey reach. The tributary enters downstream of the last transect; therefore, it likely did not impact temperature measurements. However, the tributary likely influenced discharge measurements, which were recorded just downstream of the tributary. The average surface water temperature was 11.36°C (SEM= 0.02°C), with the lowest recorded temperature of 11.14°C and the highest of 11.5°C. The average streambed temperature was 11.00°C (SEM= 0.02°C), with a minimum temperature of 10.47°C and a maximum temperature of 11.48°C.

Total temperature anomalies (n=168) at the South Fork Confluence treatment (upstream) reach averaged 0.38°C (SEM= 0.02°C). Temperature anomalies of 0.58°C, 0.42°C, and 0.15°C represent the 75th, 50th, and 25th percentiles, respectively (Figure 11). The largest anomaly values were observed at transect #5 (tube#2), transect #13 (tube #3) and transect #14 (tube #3), both with anomalies of 0.73°C (Figure 13). Transect #5 was located in the middle section of a riffle, whereas both transect #13 and #14 were located just downstream of a step-pool feature. The lowest anomalies were found at transect #12 (tube #3) and transect #1 (tube #3), with anomalies of 0.01°C and 0.02°C, respectively. Both of these transects were located in the riffle habitats and towards the sides of the channel. Only 4 tube locations had warmer streambed temperatures than the surface water temperatures and all of these negative anomaly values were small (between -0.03°C and -0.05°C).

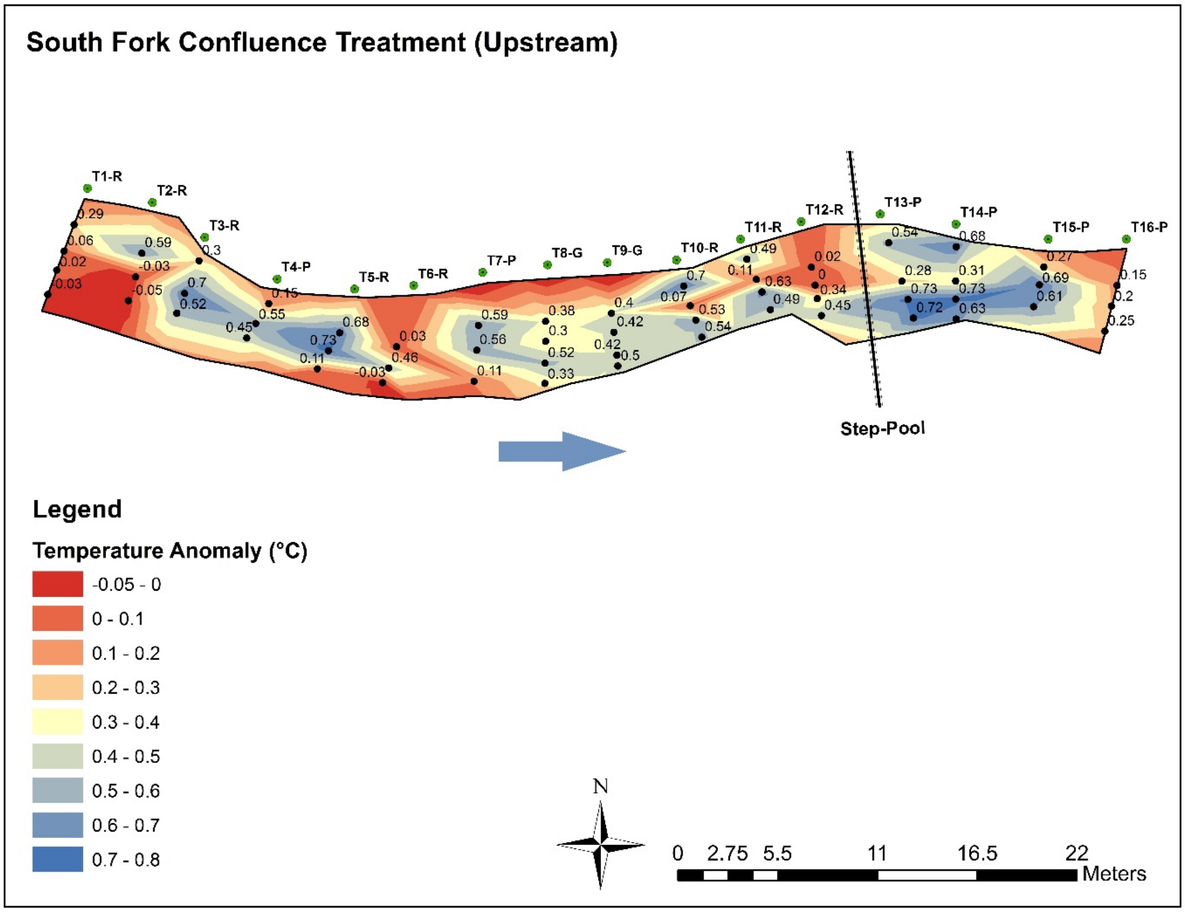

Figure 13: Plan-view map shows temperature anomaly patterns along survey reach and shows the average anomaly at each specific tube. Map also includes points, which are labeled with transect number (i.e. transect #1 [T1]) and also habitat type (pool (P), glide (G), and riffle [R]). Lines show approximate location of large restoration structures. The blue arrow indicates stream flow direction. Borders of stream reach indicate the approximate location of bankfull.

South Fork Confluence Treatment (Downstream)

On March 20, 2015, an intensive streambed temperature survey was completed at the South Fork Confluence treatment (downstream) reach. The survey was conducted during baseflow conditions and overcast weather with light rain towards the end of the surveys. The air temperature was 11.47°C at the start of the survey at 11:56 AM and 15.69°C at the completion of the survey at 2:15 PM. The stream discharge at the upstream reach of the survey site was 0.074 m^3/s (2.60 ft^3/s) and 0.082 m^3/s (2.89 ft^3/s) at the downstream reach. The average surface water temperature was 11.59°C (SEM= 0.01°C), with the lowest recorded temperature of 11.4°C and the highest of 11.71°C. The average streambed temperature was 11.36°C (SEM= 0.02°C), with a minimum temperature of 10.92°C and a maximum temperature of 11.8°C.

Total temperature anomalies (n=54) at the South Fork Confluence treatment (downstream) reach averaged 0.23°C (SEM= 0.02°C). Temperature anomalies of 0.42°C, 0.2°C, and 0.05°C represent the 75th, 50th, and 25th percentiles, respectively (Figure 11). The largest average temperature anomalies were observed at transect #8 (tube #3) and transect #11 (tube #1), with anomalies of 0.64°C and 0.62°C, respectively (Figure 14). Both of these transects are located in the middle and tailout sections of pools. The lowest average temperature anomalies were found at transect #13 (tube #2) and transect #6 (tube #1), with anomalies of 0.01°C. Both of these transects were located in the riffle habitats. There were four tube locations with negatives anomaly values. The largest negative anomaly value was observed at transect #13 (-0.11°C), which was located along the middle portion of a riffle.

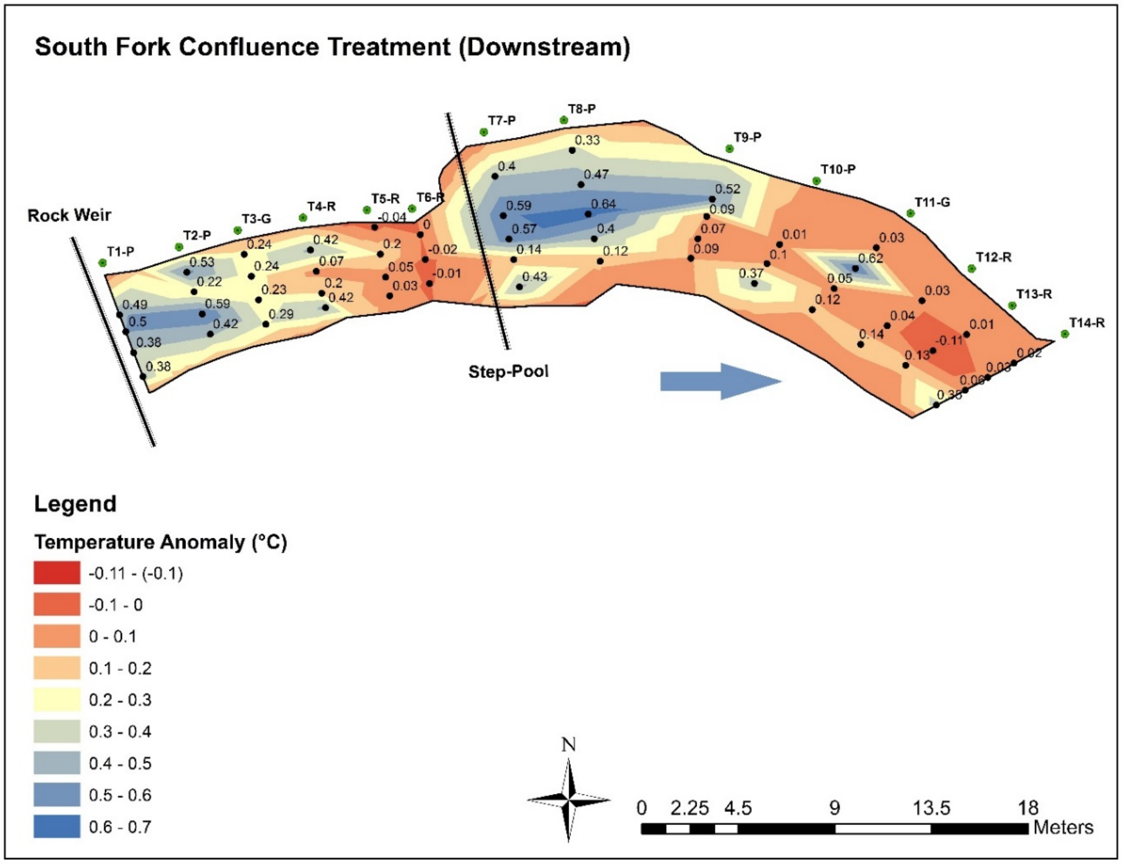

Figure 14: Plan-view map shows temperature anomaly patterns along survey reach and shows the average anomaly at each specific tube. Map also includes points, which are labeled with transect number (i.e. transect #1 [T1]) and also habitat type (pool (P), glide (G), and riffle [R]). Lines show approximate location of large restoration structures. The blue arrow indicates stream flow direction. Borders of stream reach indicate the approximate location of bankfull.

Influence of Habitat Type on Temperature Anomalies

Knickerbocker Sites

The most common habitat type at the Knickerbocker Control site were riffles (n=27), followed by pools (n=7), and glides (n=17). The highest average anomalies occurred along riffle habitats with a mean value of 0.50°C (SEM= 0.05°C), followed by pools 0.42°C (SEM= 0.08°C) and glides 0.24°C (SEM= 0.10°C). A Kruskal-Wallis test found that there was a significant effect of habitat type on average temperature anomalies

($\chi^2(2) = 7.1742$, $p = 0.0277$). Temperature anomalies at riffle habitats were statistically different than the temperature anomalies at glides based on a post hoc comparison using the Steel-Dwass test (p=0.028). However, the temperature anomalies at pool habitats did not significantly differ from the temperature anomalies at riffles (p = 0.549) or glides (p= 0.468).

The most common habitat type at the two Knickerbocker treatment sites were pools (n=59), followed by riffles (n=36), and glides (n=19). The highest average anomalies occurred along pool habitats with a mean value of 0.18°C (SEM= 0.03°C), followed by riffles 0.10°C (SEM= 0.03°C) and glides 0.07°C (SEM= 0.03°C). Pool habitats also had a greater spread of temperature anomalies, followed by glides and then riffles (Figure 15). A Kruskal-Wallis test found that there was a significant effect of habitat type on average temperature anomalies ($\chi^2(2) = 8.46$, $p = 0.0146$).

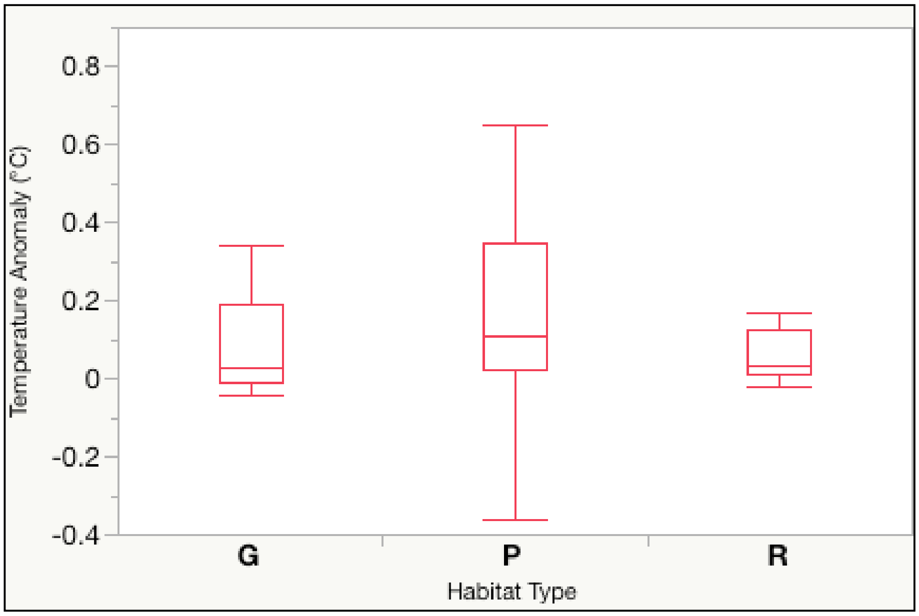

Figure 15: Shows spread of temperature anomalies among different habitat types [riffles (R), glides (G), and pools (P)] at the two Knickerbocker treatment sites.

Temperature anomalies at pool habitats were statistically different than the temperature anomalies at glides based on a post hoc comparison using the Steel-Dwass test (p=0.032). However, the temperature anomalies along riffles did not significantly differ from the temperature anomalies at glides (p = 0.545) or pools (p= 0.096).

South Fork Confluence Sites

The most common habitat type at the South Fork Confluence Control site were glides (n=25), followed by riffles (n=18), and pools (n=3). The highest average anomalies occurred along glide habitats with a mean value of 0.70°C (SEM= 0.09°C), followed by riffles 0.69°C (SEM= 0.08°C) and pools 0.62°C (SEM= 0.24°C). A Kruskal-Wallis test found that there was not a significant effect of habitat type on average temperature anomalies ($\chi^2(2) = 0.7687$, $p = 0.681$).

The most common habitat type at the South Fork Confluence treatment sites were riffles (n=52), followed by pools (n=47), and glides (n=11). The highest average anomalies occurred along glide habitats with a mean value of 0.41°C (SEM= 0.04°C), followed by pools 0.37°C (SEM= 0.03°C) and riffles 0.22°C (SEM= 0.04°C). However, the greatest range of anomalies were associated with riffle and then pool habitats (Figure 16). A Kruskal-Wallis test found that there was a significant effect of habitat type on average temperature anomalies ($\chi^2(2) = 12.1836$, $p = 0.0023$).

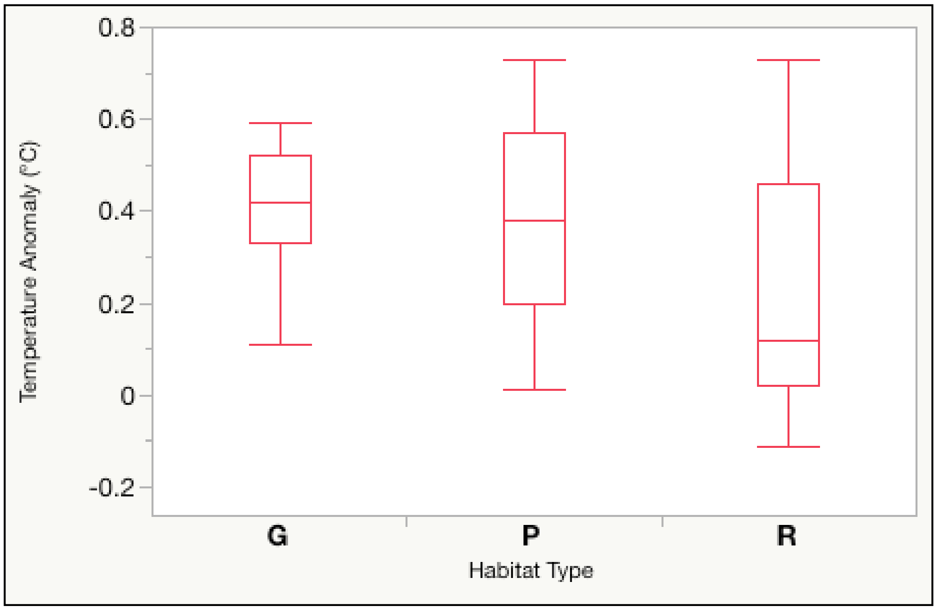

Figure 16: Shows spread of temperature anomalies among different habitat types [riffles (R), glides (G), and pools (P)] at the two South Fork Confluence treatment sites.

Temperature anomalies at riffle habitats were statistically different than the temperature anomalies at pools based on a post hoc comparison using the Steel-Dwass test (p=0.004). However, the temperature anomalies along glides were not significantly different from the temperature anomalies at pools (p = 0.817) or riffles (p= 0.067).

Influence of Substrate Type on Temperature Anomalies

The most common substrate types among all the reaches surveyed were cobble (n=253), sand (n=45), and gravel (n=23). The predominance of cobble substrate was not unexpected, since cobble was added to the treatment sites during hyporheic zone restoration. Regions with sandy substrate had the highest anomalies with a mean value of (0.41°C), followed by gravel (0.34°C) and cobble (0.31°C). However, a Kruskal-Wallis test found that there was no significant effect of substrate on average temperature anomalies ($\chi^2(2) = 2.4527$, $p = 0.724$). A more detailed substrate analysis broken up by sites was not performed due to the unequal distribution of sample size among the different substrate types.

Chapter 5: Discussion

Summary of Findings

The streambed temperature surveys along Thornton Creek produced some important and surprising results. Most notably, the surveys found that both control sites had a greater range in temperature anomalies than their respective treatments sites. These results reject the hypothesis that temperature anomalies would be greater overall at the treatment sites than at the control sites. This hypothesis is based on the assumption that the treatment sites would have greater morphological complexity and high hydraulic conductivity (K_h), resulting in greater hyporheic water and heat exchange, which would be indicated by a large range of temperature anomalies (Leavy et al., 2010). Generally, lower temperature anomaly values indicate lower hyporheic exchange (Leavy et al., 2010). Therefore, the results of this study would initially indicate that hyporheic exchange is greatest at the control reaches. However, there are other possible explanations provided below that should be considered before making any conclusions.

A potential explanation could have to do with water residence time. In a properly functioning hyporheic zone it is expected that downwelling water will travel into the hyporheic and groundwater zones where it will remain trapped for an unspecified amount of time. Under the streambed, the water temperature either warms (typical of winter) or cools (typical of summer). Longer residence times will likely mean greater difference between the surface water temperatures and the groundwater temperatures. Similar studies (Kasahara and Hill, 2006b; Hester and Doyle, 2008) have discussed the impact of stream restoration on residence time. These studies found that sites with finer sediment typically have longer residence times. Conversely, stream reaches with coarser substrate typically consisted of brief residence times due to the higher hydraulic conductivity (K_h). The Kasahara and Hill (2006b) study found that constructed riffle sections that used boulders and cobbles created a zone of high K_h values, which produced rapid hyporheic flux with quickened residence times. Furthermore, Hester and Doyle (2008) found that residence time was also influenced by weir structure size, with greater residence time associated with smaller structures. This finding is significant because the control sites consisted of predominantly small in-stream structures in comparison with those at the treatment sites.

The treatment sites at Knickerbocker and the South Fork Confluence were designed with the desired effect of improved hyporheic exchange. The step-pool features and coarse sediment that were added to the sites were thought to be ideal for improving hyporheic flux of water, which likely minimizes residence time. So, in the restored sites water may be travelling up and down through the hyporheic zone so rapidly that it doesn’t get a chance to change temperatures below the streambed before being forced back into the surface water zone. In result, lowered residence times may explain the relatively low anomaly values observed at the treatment sites when compared to the control sites. Although no formal grain size analysis was conducted for this study, the control sites generally consisted of finer sediment. The streambed at the control sites was also more uniform and lacked many morphological features. Thus, it is expected that residence time at these sites will be prolonged, which results in an increase in temperature anomalies.

The primary limitation of this study was that the survey methods only provide the relative strength of upwelling and downwelling at the restored sites, but does not provide an actual measure of hyporheic flux or residence time. In result, comparing between sites becomes difficult due to differing factors, such as residence time, which can strongly influence temperature differences and hyporheic zone flow volumes. Consequently, it is recommended that future surveys at the Thornton Creek sites, include an examination of residence time and HZ flow volumes, in order to better understand the results of the streambed temperature surveys.

Knickerbocker

The greatest range of temperature anomalies were observed at the Knickerbocker Control reach, followed by the Knickerbocker treatment (downstream) reach, and the Knickerbocker treatment (upstream) reach. As previously mentioned, the large range of temperature anomalies at the control sites could be due to prolonged residence times. Another explanation specific to the Knickerbocker control site could be that groundwater is penetrating the hyporheic zone laterally from the stream banks. The Knickerbocker control site is located in a narrow valley and pre-project surveys found that groundwater was coming into the hyporheic zone from the surrounding hillsides (Leavy et al., 2010).

Furthermore, when looking at the Knickerbocker control plan-view map created for this study, some of the largest anomalies are observed nearest to the banks, which indicates cool groundwater may be entering the hyporheic zone laterally.

At all three of the sites, there were spatial thermal patterns where hyporheic exchange was occurring. These spatial patterns were most often associated with habitat unit type. Often, areas with the greatest temperature anomalies were associated with pools, whereas transects along riffles often had the lowest temperature anomalies. The influence of step-pool structures on temperature anomalies is most apparent at the Knickerbocker treatment (downstream) reach (see Figure 10). The plan-view map shows that low temperature anomalies occur along a riffle and glide habitat just upstream of the two step-pool structures, which indicates downwelling is occurring. Downstream of each structure, large temperature anomalies were recorded, which indicates upwelling is occurring at the pool habitats. These results closely followed the results of similar past studies (Daniluk et al., 2013; Kasahara and Hill, 2006b). In sum, the results of the surveys at the Knickerbocker treatment sites indicate that hyporheic exchange is influenced by the step-pool structures installed during restoration.

The Knickerbocker treatment sites are unique in that they both seem to be losing reaches. This speculation is supported by the stream discharge surveys that were conducted before each of the temperature surveys, which found that surface water flow was greater at the upstream section of the reach than at the downstream section, indicating surface water is likely being lost to the groundwater and hyporheic zone through the process of downwelling. Areas of downwelling generally have lower temperature anomaly values than areas of upwelling (Leavy et al., 2010) and thus could partly explain why temperature anomalies were relatively low at the treatment sites. If this explanation were confirmed, it would indicate that the benefits of hyporheic recharge might be manifested further downstream out of the study area. Though, it should be noted that discharge surveys were conducted only once at the upstream and downstream sections of each site without replication; therefore, more surveys are needed to further support these speculations.

There were few locations across all the Knickerbocker reaches where streambed temperatures were warmer than the above surface water. These few locations did not follow an obvious pattern and in result are difficult to explain. For example, two locations along transect #3 at the Knickerbocker control reach had warm streambed temperatures (see Figure 8). The warm streambed temperatures appeared random with no visible morphological characteristics that could explain the phenomenon. Another example occurred at the Knickerbocker treatment (downstream) site at transect #11 (tube #1) (see Figure 10) where the average temperature anomaly was (-0.36°C). A possible explanation for the warm streambed temperatures could be direct solar radiation that penetrated through the riparian vegetation and warmed small sections along the streambed. During the baseflow conditions, much of the stream reach at the treatment sites and control site was shallow, meaning less than 1 meter in depth. Therefore, direct solar radiation could influence streambed temperatures, especially at a small-scale. This explanation is most attractive for the results at the Knickerbocker control site due to the mostly sunny conditions during the survey.

South Fork Confluence

The South Fork Confluence control reach had a greater range of temperature anomalies than the South Fork Confluence (upstream) treatment reach, and the South Fork Confluence treatment (downstream) reach. The streambed temperature anomalies at the South Fork Confluence control site were particularly high and were the highest of all six stream reaches. This result was surprising due to the lack of morphological complexity at this reach. Much of reach is straightened with quick and uniform flow and consists of a rather homogenous streambed. The anomalies at the control site failed to follow any easily distinguishable patterns and neither habitat type nor substrate type were found to have a significant impact on temperature anomalies. However, the plan-view map of the reach clearly shows that the greatest anomalies occurred in the downstream section of the reach, which would indicate substantial upwelling is occurring. The only explanation for this phenomenon could be related to differences in stream gradient between the upstream and downstream section of the reach. The stream gradient becomes more gradual as you transition downstream. The change in gradient may be forcing water down in the upstream section and then back up in the downstream section. This explanation is highly speculative; however, other studies (Kasahara and Hill, 2006b; Hester and Doyle, 2008) have noted similar patterns of upwelling and downwelling that were caused by changes in stream gradient. More detailed gradient and hyporheic flux surveys are needed, which could be used to support the above explanation.

The location of the largest temperature anomalies were often linked with habitat unit type and proximity to restoration structures at both the South Fork Confluence treatment sites. At the SFC treatment (upstream) reach, the largest temperature anomalies were located at transects #13 and #14. These two transects were located downstream of a step-pool weir structure (see Figure 13). At the SFC treatment (downstream) reach, the largest temperature anomalies were located at transects #1, #7, and #8. These transects were also located in pool habitats, just downstream of large restoration structures (see figure 14). As previously mentioned, it was expected that the greatest anomalies would be found in pools and specifically pool tailouts due to upwelling of water.

Warm Winter Temperatures

At all the surveyed reaches, the streambed temperatures were mostly colder than the surface water temperatures, which was unexpected for the winter months. The literature (Conant, 2004; Stonestrom and Constantz, 2003; Leavy et al., 2010) suggests that streambed temperatures should be warmer than the surface water in the winter months due to the insulating effects of soil and then colder in the summer months. The Leavy et al. (2010) study, conducted similar surveys at the same treatment and control sites before the restoration projects were completed in 2006 and 2007. They observed an autumnal crossover along Thornton Creek, which occurred somewhere between late August and mid-October. The autumnal crossover marks the transition from cold streambed temperatures (relative to surface water temps.) in the summer months to warmer streambed temperatures in the winter. The results of this study contradict their finding, and suggests that autumnal crossover was weakened or may not have occurred at all in the winter of 2015. However, summer and fall streambed temperature data would be needed to confirm this speculation.

The discrepancy in the temperature reported in this study with that of Leavy et al. (2010) could be due to the warm winter season that the Pacific Northwest region experienced in 2014-2015. The winter was one of the warmest on record for Seattle. Between November 2014 and March 2015, each month recorded an average air temperature well above monthly mean temperatures for the city (Table 3). Warm air temperatures translate to warmer surface water temperatures, which may explain why the groundwater temperatures were consistently colder than the surface water at all six surveys reaches. Also, the surveys were conducted in the late winter season when surface water temperatures are usually warmer, which may also partly explain this occurrence.

	Nov	**Dec**	**Jan**	**Feb**	**Mar**
Mean Air Temps. (1945-2015) (C°)	7.2	4.8	4.5	6.0	7.4
Winter of 2014-2015 Temps. (C°)	7.8	7.4	7.3	9.3	10.3

Table 3: Average monthly temperatures (C°) of 2014-2015 compared with mean monthly air temperatures over the past 70 years (1945-2015). Source: Data taken from National Weather Service Office website (http://www.weather.gov/climate/xmacis.php?wfo=sew)

Substrate Clogging

Another consideration, which is mentioned often throughout the literature, is the problem of siltation and clogging. The hyporheic zone can become clogged through sediment deposition that fills the interstices of the substrate, which reduces hydraulic conductivity (K_h) and subsequently reduces hyporheic exchange (Daniluk et al., 2013; Kasahara and Hill, 2006a). Substrate clogging would also simultaneously increase water residence time by decreasing vertical hyporheic flow. The substrate at the two treatment sites was purposely constructed without the input of fine sediment because it was expected that fine sediment would quickly deposit on top of the restored reaches. In result, the coarse sediment to fine sediment ratio is probably lower than would be expected in future years. Thus, future field surveys may have considerably different results due to the influence that fine sediment has on hyporheic flux and water residence time.

Post-restoration Equilibrium

An additional consideration for this study, is the shortened time between restoration completion and the streambed surveys conducted at the treatment sites. As discussed in other similar studies (Daniluk et al., 2013; Kasahara and Hill, 2006a), a stream system will take an unspecified amount of time following restoration to reach a sort of equilibrium. This is due to the high degree of disturbance that restoration causes. The treatment reaches at Knickerbocker and the South Fork Confluence were both completed in late fall of 2015. The field surveys for this study were completed only a few months after the completion of the restoration projects and in such, likely took place before the stream reaches were able to stabilize. In result, future field investigations are needed to determine how hyporheic zone exchange varies over time. This study provides the early implementation data set that will make testing of post-restoration equilibrium possible in the future.

Chapter 6: Conclusion and Implications for Future Research

This study was designed as an initial investigation into hyporheic zone exchange at the two treatment sites on Thornton Creek. The study was not intended to be a stand-alone study and does not provide conclusive results that determine the overall success of stream restoration for HZ exchange. Therefore, the results of this study do not yet indicate a failure of the hyporheic zone restoration. Instead, this study provides beneficial data that can be compared with subsequent studies to better understand how hyporheic zone exchange changes over time at the treatment sites.

Future surveys are planned for both restoration sites at Thornton Creek. The future surveys will also use streambed temperature surveys to examine hyporheic exchange on a reach scale. However, future surveys will also include the installation of piezometers that will be used to measure vertical thermal gradients within the streambed. The data collected will then be modeled to calculate the flux of water through the hyporheic zone. Furthermore, groundwater level, piezometric head, and hydraulic conductivity will also be measured, providing a much more detailed analysis of HZ exchange than what is offered by this study. Unfortunately, due to the constraints in time and resources, these more detailed surveys could not be incorporated into this study. However, the results of this study will be correlated with these future surveys, which combined should result in a more definitive answer as to the effectiveness of hyporheic zone focused restoration for improving water exchange.

A key issue raised by the literature that should be considered for future hyporheic investigations is the problem of restoration sustainability. The hyporheic features installed at the restored sites will likely change and shift over time. For example, significant scouring around step-pool structures at the Knickerbocker site occurred during high flow events in the winter of 2015. Scouring could lead to a total failure of these structures in the near future, which could lead to dramatic changes in HZ exchange. In sum, it is important to monitor these changes in order to better interpret the results of the hyporheic zone surveys. Furthermore, futures hyporheic zone investigations may also inform management decisions at the restored sites, indicating where hyporheic features may need to be replaced or restored.

There are few studies that have similarly examined hyporheic exchange after stream restoration. The lack of comparable studies made it difficult to understand and explain the results of this study. Future studies are needed to determine how hyporheic zone exchange is impacted by stream restoration, which will help to inform ways to better design restoration projects in the future. Improving hyporheic restoration design is arguably most important in urban watersheds, in which streams are highly degraded. As population continues to grow and cities are increasingly developed, it is important that we consider the hyporheic zone, so that we may better protect and restore these important stream ecosystems.

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