HOW CONNECTED SHOULD A STREAM BE TO ITS CATCHMENT?
ASSESSING STREAM-GROUNDWATER INTERACTIONS AND HYPORHEIC
EXCHANGE IN STREAM ECOSYSTEM RESTORATION

A Thesis in
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by
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ABSTRACT

Stream classification systems used today, particularly when applied to stream restoration, do not take into account stream-groundwater interactions, hyporheic flows, or landscape characteristics. They generally ignore hydrological connectivity of a stream to its catchment by focusing on channel morphology. Thus resulting restoration approaches do not necessarily promote proper hydrologic function of a reach. Stream-groundwater interaction is important to stream ecosystem function and hyporheic exchange, in particular, has a significant influence on stream water quality. Therefore, it is proposed that stream restoration techniques need to address the subsurface interactions with streams, as much as the morphology of the channel.

The goal of this research is to determine which of the commonly used restoration practices is superior at enhancing the stream-groundwater interactions of the stream. Two main types of restoration efforts were explored using tracer studies and a two-storage zone transient storage model. The first type, which focused on reconnecting the floodplain (RTF), was expected to have a more positive effect on hyporheic exchange than restoration approaches that make use of in-stream structures (ISS) alone. However, both methods were found to produce no significant differences when compared with the unrestored reaches. This was not found to be an entirely robust conclusion and other methods are discussed which may lead to one.
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Chapter 1

Introduction

Stream restoration is becoming an increasingly popular practice in the United States. It is estimated that over $15 billion has been spent on it since 1990 (Bernhardt et al. 2005). With this has come a growing realization for the need of a deeper scientific foundation for stream ecosystem restoration. This includes incorporating ecology into hydrologic considerations and vice versa. Integrating the hyporheic zone, the interface of groundwater and surface water around streams, and hyporheic exchange of water through the subsurface into restoration strategies is one way to enhance a degraded stream ecosystem. This is because the hyporheic zone has a substantial affect on the biogeochemistry of the stream (Findlay 1995, Boulton et al. 1998, Gooseff et al. 2003).

One of the first steps in most stream restoration project is to determine the class of a stream. Classification methods used today are often based on the fluvial geomorphology (channel form, substrate size). This means they do not take into account stream-groundwater interactions, hyporheic flows, or landscape characteristics. Streams restored based on these classification methods tend to ignore stream-groundwater interactions and sometimes focus on creating in-stream habitats (Beechie et al. 2010). However, a few are restoring streams in a more holistic sense such as those that include connecting the stream to its floodplain. In this approach, it is often legacy sediments that have been removed from the channel corridor to promote connection of the stream channel and a lowered floodplain surface adjacent to the channel. The purpose of this thesis is to inform stream ecosystem restoration by determining how much hyporheic exchange should occur in a given reach and what techniques are best at enhancing stream-groundwater interactions.
Motivation

Many people attempt to organize streams according to common physical traits in order to predict how these ‘like’ streams will behave. Stream classification is a useful tool, but most systems do not take into account important aspects. They generally focus on surface characteristics, which ignores hydrological connectivity of a stream to its catchment. This can lead to restoration approaches that do not promote proper hydrologic function of a reach. The streams examined in the study were chosen based on such a classification system and are evaluated here to see if streams of the same class had any similarities in their subsurface flows.

Although many studies have proven that stream-groundwater interaction is important to stream ecosystem function, (Stanford and Ward 1993, Boulton et al. 1998, Dahm et al. 1998) little is known about how much exchange should occur. Further, there is also an insufficient amount of quantitative information that can be used to calculate possible benefits of stream restoration for nutrient transport (Bukaveckas 2007). This study compares restored and unrestored reaches of several streams in Pennsylvania in order to establish a basis for how much exchange should be occurring. We then compare these streams against each other in order to determine which restoration types resulted in a greater enhancement of hyporheic exchange.

In the past and still today most in-stream restoration projects have focused solely on restoring the surface form of the channel and have neglected to take the subsurface environment into account (Kasahara and Hill 2007). Kasahara and Hill (2007) stated that no studies have addressed the effects of in-stream structure restoration projects and few have done so since. Even fewer recent studies have investigated how structures may affect hyporheic exchange (Hester and Gooseff 2010; but see Crispell and Endreny, 2009 for example). Bukaveckas (2007) pointed out that transient storage can be a useful measurement of restoration success because of the
consistency of the method used to quantify transient storage and its potential to be a gauge of hydrologic processes important to stream performance.

Several studies have shown that restoration techniques that control the hydraulics of the channel through in-stream structures (referred to as ISS restoration) fail to improve stream ecosystems (Palmer et al. 2005). Meanwhile, new information on improved methods of stream restoration has come about, and yet ISS restoration remains dominant in the field. These improved methods include a range of techniques, some of which have been available for many years (Beechie et al. 2010). If we work towards improving our knowledge of the composition and processes of natural stream systems, we will ultimately advance restoration ecology and ecosystem management. Exchange of information between hydrologists, ecologists, and practitioners combined with the proper use of data from previous restorations will benefit the field tremendously (Moerke et al. 2004).

**Background**

The chosen study sites are all located within the state of Pennsylvania. Pennsylvania has had a vastly growing number of stream restoration projects since the mid 1990’s (NRRSS 2006). The foundation for many of these projects has been the evaluation or classification of the streams. A commonly used stream classification system is based on a stream’s geomorphic properties. However, classification by channel morphology can have its drawbacks. This type of classification does not take into consideration specific hydraulic, sediment-transport, and geotechnical processes. Therefore, the schema is simply a prediction of how the stream channel has evolved with time based on channel width, depth, slope, etc. It does not predict how the stream will be affected by processes such as erosion, transport, and deposition (Simon et al. 2007). Also, streams having considerable variation of physical characteristics can be sometimes
placed in the same class due to differences among how observers evaluate streams even within the same framework (Roper et al. 2008).

The classification of streams is often the first step in restoring them. For this study, stream restoration can be defined as the return of a stream to its original state, before human interference and degradation, in order to improve the ecosystem health of the stream. Many of those who restore streams in Pennsylvania use the same techniques as the majority of the country, placing in-stream structures to control stream hydraulics. There are, however, a few practitioners who have revamped stream restoration techniques in order to work on restoring stream ecosystem and hydrologic processes. This type of restoration focuses on reconnecting the floodplain of the stream to its main channel and it will be referred to as (RTF restoration).

ISS restoration uses artificial and unnatural habitat creation in order to control stream processes and dynamics. These efforts attempt to fix the results of degradation rather than attack what is causing the degradation to begin with. Examples of this type of restoration include bank stabilization using rip-rap or matting, pool or riffle building using rock weirs, direction of flow with rock and log cross vanes, and planting non-endemic riparian species (Beechie et al. 2010). Many restoration efforts have included reshaping a channel or adding wood or rocks, yet no more than a few of these have led to improved water quality or biodiversity (Palmer and Filoso 2009). The placement of in-stream structures such as rock and log vanes should be done if it is the only remaining option because they are seldom self-sustaining (Beechie et al. 2010).

RTF restoration aims to return a river or river reach to its original state by re-establishing natural processes that maintain its habitat and ecology (Beechie et al. 2010). Examples of RTF restoration include reconnecting the floodplain by excavating down to the historical elevation, channel relocation, and the creation of wetland areas with native plants along the floodplain. These methods are intended to restore stream processes rather than control them. By restoring stream processes, RTF restoration advances the improvement of habitat and biological diversity
while taking river dynamics such as bank erosion, channel migration, and flooding into account (Beechie et al. 2010). Within a stream there are physical, chemical, and biological processes, and RTF restoration looks to restore all of these. It uses more sustainable and elastic methods than ISS restoration. These methods require much less maintenance over time and allow for the stream environments to adjust to lasting strains such as climate change (Beechie et al. 2010).

One way in which we can inform stream ecosystem restoration is by determining how much hyporheic exchange should occur in a given reach. The hyporheic zone is a section of the subsurface of a stream where water from the main channel mixes with water that is temporarily stored in the streambed until returning to the main channel (Bukaveckas 2007). The rate of movement between the hyporheic zone and the main channel is referred to as hyporheic exchange. Processes that affect hyporheic mixing include molecular diffusion, advective pumping, shear-driven flow, and turbulence (O’Conner and Harvey 2008).

Hyporheic exchange has a major influence on biogeochemical processing. This is because sediments close to the streambed are crucial for nitrification and denitrification, as well as for total primary productivity and community respiration (Mulholland et al. 2001, Peterson et al. 2001, O’Conner and Harvey 2008). An example of hyporheic restoration includes the placement of substrate within the entire channel. However, if the riverbed is groomed to a flat surface, than there will likely be no exchange. The amount of exchange is dependent on streambed permeability and geometry (Vaux 1968). The added substrate creates a hyporheic zone that is vital for the biological communities and for chemical processing (Seger 2008). Specifically, it is necessary for the transport of dissolved oxygen to pre-emergent fish (Vaux 1968). However, it is the form of the channel and the resulting head gradients that will drive patterns of potential exchange through the hyporheic zone.

Transient storage is defined as the short-term retention of water and solutes within a stream reach. Hyporheic exchange only accounts for the part of transient storage in a stream
channel. The counter-part of hyporheic transient storage (HTS) is referred to as surface transient storage (STS). STS or in-stream storage includes the storage zones within the active channel (Bucaveckas 2007). Bencala and Walters (1983) described STS as zones of stationary water that are not moving downstream. These pockets of water are generally found behind in-stream obstructions (such as logs, boulders and rock and log cross vanes), in shallow water vegetation, on the sides of slow pools, and in the gravel and cobble beds of faster moving riffles (Bencala and Walters 1983). A depiction of surface and subsurface flowpaths throughout a stream can be seen below in Figure 1-1.

![Surface and Subsurface Flowpaths](image)

Figure 1-1: Surface and Subsurface Flowpaths (redrawn from Findlay 1995).

Transient storage is important to consider when measuring nutrient uptake and retention (O’Connor et al. 2010). Nutrient retention is very important because it limits the amount of nutrients which travel downstream causing harm to the ecosystem (Bucaveckas 2007). The hydrologic and geomorphic characteristics of a stream are what determine the amount of time
water remains in a stream reach and therefore a stream’s nutrient retention capacity (Bucaveckas 2007). Restored streams are expected to have greater nutrient retention than impacted streams due to reduced velocities within the restored reaches. RTF and ISS restoration both include features which alter the hydrologic and biological properties of a stream which can lead to increased nutrient retention. Modifying a channel can result in a more complex flow pattern, which may enhance hyporheic exchange and therefore transient storage (Bucaveckas 2007).

Transient storage and solute transport within a stream can be simulated by numerical models that relate solute concentrations to advection, dispersion, groundwater and tributary inputs, and transient storage (Stream Solute Workshop 1990). There are currently several of these models for determining transient storage dynamics using the above equations.

**Research Objectives**

There are three main objectives to this paper: [1] to determine pre-existing hyporheic exchange rates (from unrestored reaches) and how they differ from rates in reaches that have been restored; [2] to determine if streams of same geomorphic class have differing or similar amounts of stream-groundwater interactions; and [3] to determine which restoration approach (ISS or RTF) induces more hyporheic exchange.

**Hypotheses**

1. Current classification systems organize streams into various types solely according to the stream geomorphology. Within each stream type, the influence of the hyporheic zone should vary widely and therefore cause major dissimilarities between streams of the same class.
2. The in-channel storage (surface transient storage) of the unrestored reaches is much smaller than the in-channel storage of the restored reaches.

3. The restoration approaches that consider the floodplain and the subsurface of the stream in their design are more effective at enhancing hyporheic exchange than those that do not.
Chapter 2

Methods and Study Region

Streams

In order to maintain uniformity and to complete the study in one summer, all of the chosen study sites are located in the state of Pennsylvania. Their specific locations within the state can be seen in Figure 2-1. The reaches are spread throughout Pennsylvania and therefore are located in varying geographic settings. Two are located in the Appalachian Plateau region, two in the Ridge and Valley region, and five are located in the Piedmont region. The Appalachian Plateau and Ridge and Valley provinces are sedimentary (sandstone, shale, limestone). The Piedmont region is crystalline (gneiss) and sedimentary.

Figure 2-1: Stream Locations and Geology within Pennsylvania.
The studies were performed on two main types of restored reaches and their corresponding unrestored reaches. Four of the streams were restored with ISS methods (most have rock and log cross vanes as well as matting, root wads, etc.). Five of the streams were restored using the RTF method. The specific restoration techniques present in each of the streams can be seen in Table 2-1. The nine streams were chosen not only by the type of restoration done but also by their geomorphic class. As a result, each of these streams had widely varying characteristics.

Table 2-1: 10 Pennsylvania streams according to restoration approach.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Approach</th>
<th>Restoration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wallace Run</td>
<td>ISS</td>
<td>Rock and Log Cross Vanes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Matting</td>
</tr>
<tr>
<td>Bald Eagle Creek</td>
<td>ISS</td>
<td>Rock and Log Cross Vanes</td>
</tr>
<tr>
<td>Canoe Creek</td>
<td>ISS</td>
<td>Rock Wads</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mud Sill</td>
</tr>
<tr>
<td>Kelly Run</td>
<td>ISS</td>
<td>Re-meandering of Stream Channel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gravel and Sand bars</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mud Sill</td>
</tr>
<tr>
<td>Santo Domingo Creek</td>
<td>RTF</td>
<td>Floodplain restoration (sediment removed)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straightened reach made into meandering</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wetlands Created</td>
</tr>
<tr>
<td>Lititz Run</td>
<td>RTF</td>
<td>Channel Relocation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wetland pockets created</td>
</tr>
<tr>
<td>McIlvaine Run</td>
<td>RTF</td>
<td>Relocation of stream channel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spawning habitat for brown trout</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Native trees and shrubs planted</td>
</tr>
<tr>
<td>Rife Run</td>
<td>RTF</td>
<td>Stream channel relocation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Restored floodplain and stream bed returned to</td>
</tr>
<tr>
<td></td>
<td></td>
<td>historical elev.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wetland areas created</td>
</tr>
<tr>
<td>Shobers Run</td>
<td>RTF</td>
<td>Restored stream to more natural pattern</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Excavate floodplain to historical elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Native plants installed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Create wetland areas</td>
</tr>
</tbody>
</table>
Classification

The geomorphic classification of the streams was done on a first order, very general basis following the Rosgen Geomorphic Channel Design from Chapter 11 of the National Engineering Handbook. This ensured that there was no variability in stream class due to previous observer discrepancy. Each stream was classified using surveys collected from various companies providing restoration services. These surveys allowed us to quantify the entrenchment ratio, width/depth ratio, and sinuosity of all the restored stream reaches. The entrenchment ratio (ER) is the width of the floodplain ($W_{fpa}$) which is the width at two times the maximum bankfull depth divided by the bankfull width ($W_{bhf}$):

$$ER = \frac{W_{fpa}}{W_{bhf}}$$

(2.1)

The width/depth ratio ($W/d$) is simply the ratio of a streams bankfull width to the average depth ($d_{avg}$):

$$\frac{W}{d} = \frac{W_{bhf}}{d_{avg}}$$

(2.2)

The sinuosity of a stream (SR) is equal to the channel length ($L_{channel}$) divided by the valley length ($L_{valley}$) (Leopold et al. 1964):

$$SR = \frac{L_{channel}}{L_{valley}}$$

(2.3)

A visual of the classification system used can be seen below in Figure 3-1.
The contributing area, annual mean discharge, and Strahler stream order were also all considered before finalizing stream choices. The wide ranges in magnitude of several of the stream characteristics can be seen in Table 2-2. This makes evident the high variation between the streams. Represented is a wide range of geomorphic characteristics, size, and restoration approaches. Each of these restored reaches was paired with an unrestored reach of an equal or, in some cases, similar size. These were generally located somewhere upstream of the restored reach but close enough to be of the same order. Unrestored reaches were located along each stream where no form restoration had previously occurred. This was verified from the surveys given by the companies that performed each restoration.
Tracer Studies

Stream tracer studies are often used to calculate solute transport characteristics of a stream (Stream Solute Workshop 1990). The application of conservative tracers is a well-established method for determining the rate at which water moves through the stream channel and exchanges with the HTS and STS zones (Briggs et al. 2009). Sodium chloride, NaCl, was the nonreactive tracer chosen for this study because it is considered to be the most conservative of all the easily accessible solutes. The background concentrations of salt were very low and NaCl does not react chemically or biologically, nor does it compete with other ions (Stream Solute Workshop 1990).

Table 2-2: Varying characteristics of restored stream reaches.

<table>
<thead>
<tr>
<th>Restored Reach</th>
<th>Length (m)</th>
<th>Strahler Stream Order</th>
<th>Mean Discharge (m³/s)</th>
<th>Sinuosity</th>
<th>W/D Ratio</th>
<th>Entrench. Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bald Eagle Creek</td>
<td>20</td>
<td>3</td>
<td>0.0106</td>
<td>1.03</td>
<td>12.28</td>
<td>3.13</td>
</tr>
<tr>
<td>Canoe Creek</td>
<td>60</td>
<td>2</td>
<td>0.0182</td>
<td>1.21</td>
<td>32.29</td>
<td>1.59</td>
</tr>
<tr>
<td>Kelly Run</td>
<td>60</td>
<td>3</td>
<td>0.0290</td>
<td>1.1</td>
<td>7.36</td>
<td>1.1</td>
</tr>
<tr>
<td>Lititz Run</td>
<td>100</td>
<td>2</td>
<td>0.3009</td>
<td>1.02</td>
<td>6.89</td>
<td>2.31</td>
</tr>
<tr>
<td>McIlvaine Run</td>
<td>20</td>
<td>1</td>
<td>0.0080</td>
<td>1.2</td>
<td>7.35</td>
<td>1.28</td>
</tr>
<tr>
<td>Rife Run</td>
<td>40</td>
<td>2</td>
<td>0.0472</td>
<td>1.1</td>
<td>3.19</td>
<td>1.82</td>
</tr>
<tr>
<td>Shober's Run</td>
<td>60</td>
<td>4</td>
<td>0.0219</td>
<td>1.21</td>
<td>17.11</td>
<td>2.16</td>
</tr>
<tr>
<td>Santo Domingo Creek</td>
<td>40</td>
<td>2</td>
<td>0.0111</td>
<td>1.36</td>
<td>28.7</td>
<td>1.36</td>
</tr>
<tr>
<td>Wallace Run</td>
<td>160</td>
<td>3</td>
<td>0.2111</td>
<td>1.04</td>
<td>13.08</td>
<td>1.26</td>
</tr>
</tbody>
</table>
Salt was injected as a slug or single pulse into a well-mixed section of each stream. This was generally done at a riffle if one was available. A slug was used instead of a constant rate injection because it is much easier to set-up and execute, and it provided the level of accuracy needed. A simple slug injection is enough to measure the main channel flow and the amount of solute which is stored in short-term subsurface or surface storage zones (Stream Solute Workshop 1990).

The stream tracers studies were all conducted during the summer months of 2010 (late May to early September). The low flows found in streams during the summer present favorable conditions for detecting hyporheic flow (Harvey et al. 1996). There was also no significant rainfall which occurred during the tracer studies therefore the stage height remained constant for the duration of each. Tracer studies were conducted on the restored and unrestored reach for seven of the streams. Tracer studies were performed on the unrestored reaches in order to detect how much streamflow gain or loss should occur and how much exchange should be taking place through the hyporheic zone. For two of the streams, the studies could only be completed on the restored reaches. The mass of salt injected varied for each stream by its size. They ranged from 100g to at most 10kg. Increases in conductivity were very large for most streams (0.2-5.3 mS/cm).

We present short term STS and HTS storage of streams as the tracer studies conducted were between approximately 1 and 6 hours long. The length of study was determined through observation in the field; when the concentration spike had passed through the final downstream logger as well as the dead zones (STS) and returned to background concentration.

A typical field setup for each tracer study conducted is shown in Figure 2-4. Each reach had a length equivalent to twenty bankfull widths. This was determined to be adequate enough to capture the stream’s morphology (Briggs et al. 2009). Four data loggers, each having two Campbell Scientific 547A probes, were setup along the reach. Each probe measured stream
electrical conductivity (mS/cm) every second and data loggers averaged and recorded these values for every 30 seconds. These were later converted to solute concentrations (mg/L). The first data logger was placed at the most upstream point with one probe above the injection gathering background conductivities and the other one to two bankfull widths below the injection in order to ensure adequate mixing. The second and third data loggers were placed at seven and fourteen bankfull widths downstream of the injection point with one probe in the main channel and one in a STS zone. A picture of Santo Domingo Creek which depicts the difference between the main channel and the surface transient storage zone as well as the placement of the two probes can be seen in Figure 2-4. The final logger was placed at the end of the reach (twenty bankfull widths downstream) with both probes gathering main channel concentrations, each a third of the way in from either stream edge.

Figure 2-3: Diagram of field setup for each stream reach.
Prior to injecting the salt, twenty cross-channel velocity measurements were taken each a bankfull width apart. These were gathered using a FlowTracker ADV which is a handheld acoustic Doppler velocimeter with a resolution of 0.0001 m/s. Several velocities were taken across each cross-section at a depth 60% from the top. This applied to all cross-sections except for the first and last where they were taken for a longer period (40 sec. instead of 20 sec.) and averaged between the 20% from the top and 80% from the top velocities. The velocity measurements were used to determine what is the average main channel area and what is the average STS area where velocities are <0.01 m/s. This data is important for entering into the model, which is discussed below.
Modeling

The tracer studies can be used in conjunction with a transport model to estimate hydrologic and solute retention parameters (Stream Solute Workshop 1990). In this study, a two-storage zone (2-SZ) transient storage model was used to determine these transport parameters (Briggs et al. 2010). This approach takes the concentrations (C), main channel areas (A), flows (Q), obtained in the field and attempts to reproduce them with the advection-dispersion equation:

\[
\frac{\partial C}{\partial t} = -\frac{Q}{A} \frac{\partial C}{\partial x} + \frac{1}{A} \frac{\partial}{\partial x} \left[ AD \frac{\partial C}{\partial x} \right] + \frac{Q_L}{A} (C_L - C) + \alpha_{STS} (C_{STS} - C)
\]  (2.4)

Other terms seen in the equation are coefficient of dispersion (D), lateral inflow (Q_L), lateral concentrations (C_L), STS exchange rate (\alpha_{STS}), and STS concentrations (C_{STS}). The model is a version of the One-Dimensional Transport with Inflow and Storage (OTIS) model (Runkel 1998). A general depiction of how the model works is shown in Figure 2-5. Specifically, OTIS uses the Crank-Nicolson finite-difference solution to solve the advection-dispersion equation. This version of the model also includes both STS and HTS by adding the equations below (Fischer et al. 1979, Stream Solute Workshop 1990):

\[
\frac{\partial C_{STS}}{\partial t} = -\alpha_{STS} \frac{A}{A_{STS}} (C_{STS} - C)
\]  (2.5)

\[
\frac{\partial C_{HTS}}{\partial t} = -\alpha_{HTS} \frac{A}{A_{HTS}} (C_{HTS} - C)
\]  (2.6)

Main channel area (A), STS area (A_{STS}), HTS area (A_{HTS}), main channel concentration (C), concentration of STS (C_{STS}), concentration of HTS (C_{HTS}), exchange rate of STS (\alpha_{STS}), and exchange rate of HTS (\alpha_{HTS}) are all included in the storage zone equations.
A 2-SZ model version of OTIS was used for improved characterization of transient storage. It is possible to differentiate between the ‘slow’ and ‘fast’ exchange zones by having both an HTS zone and a STS zone within the model (Harvey et al. 2005). It is important to decipher between these two zones since the biogeochemical processing within each varies greatly (Briggs et al. 2010). A conceptual model of the two-storage zones is included in the figure above.

Several assumptions were made during the modeling process. The model assumes that there are uniform flow conditions, hence why injections following rain events were avoided. Lateral inflow of concentration through the sides of the channel is assumed to be zero ($C_{\text{LATin}} = 0$). It assumes that there is complete mixing of the injected salt and that the flows at the most upstream and most downstream points of the reach are constant across. Major assumptions regarding main channel processes are that advection, dispersion, lateral inflow, lateral outflow,
and transient storage all influence solute concentrations. Also all main channel model parameters are spatially variable but only parameters describing advection and lateral inflow are temporally variable (Runkel 1998). Assumptions related to the storage zones are: the solute in the storage zone is uniformly and instantaneously distributed, the zones are stationary, and advection, dispersion, lateral inflow, and lateral outflow do not occur in the storage zones (Bencala and Walters 1983, Runkel 1998).

This rendition of the OTIS model requires data on discharge and an upstream injection in the form of a concentration step input calculated from the amount of salt added. The parameters which the model solves for are dispersion coefficient, MC area, STS area, HTS area, STS exchange coefficient, and HTS exchange coefficient \( (D, A, A_{STS}, A_{HTS}, \alpha_{STS}, \alpha_{HTS}) \). Ranges were input for each of these parameters based on field observations and sampled 50,000 times using uniform random sampling. Estimates of \( A, A_{STS}, \) and \( D \) were calculated from the FlowTracker measurements taken in each stream reach. These values can all be seen below in Table 2-3. Net gains \( (q_{gain}) \) and losses \( (q_{loss}) \) are also listed in the table and are described in more detail below.

The best-fit parameters were determined using a root mean squared error (RMSE) and one minus the coefficient of determination \( (1-R^2) \):

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (C_{sim} - C_{obs})^2}{\sum_{j=1}^{n} C_{obs}^2 / n}} \tag{2.7}
\]

\[
1 - R^2 = \frac{SS_{err}}{SS_{tot}} \tag{2.8}
\]

\( SS_{err} \) is the sum of the squares of residuals and \( SS_{tot} \) is the total sum of squares. These best-fitting parameters simulated a solute concentration time series \( (C_{sim}) \), which had the closest match to the observed \( (C_{obs}) \) downstream breakthrough curve (BTC).
The original estimates for the dispersion coefficient ($D$) were found using equation:

$$D = \frac{0.01\sigma^2 W^2}{du^*}$$ \hspace{1cm} (2.9)

where $\omega$ is the mean velocity ($\text{ms}^{-1}$), $W$ is equal to the average width (m), $d$ is the mean depth (m), and $u^*$ is equal to the shear velocity ($\text{ms}^{-1}$). The estimates of discharge ($Q$ in $\text{m}^3\text{s}^{-1}$) which were calculated using the FlowTracker ADV were compared against dilution gauging estimates found using equation:

$$Q = \frac{M}{C_{avg} T_s}$$ \hspace{1cm} (2.10)

Table 2-3: Observed and calculated values from field studies.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Reach</th>
<th>D</th>
<th>A</th>
<th>A_STS</th>
<th>q_loss</th>
<th>q_gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bald Eagle Creek</td>
<td>Unrestored</td>
<td>0.0539</td>
<td>0.0252</td>
<td>0.0124</td>
<td>8.76E-05</td>
<td>3.48E-04</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>0.6297</td>
<td>1.0475</td>
<td>0.0280</td>
<td>1.10E-04</td>
<td>2.60E-04</td>
</tr>
<tr>
<td>Canoe Creek</td>
<td>Unrestored</td>
<td>0.5417</td>
<td>0.2134</td>
<td>0.0940</td>
<td>2.14E-05</td>
<td>2.51E-04</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>0.7199</td>
<td>0.1661</td>
<td>0.0905</td>
<td>2.11E-04</td>
<td>1.27E-04</td>
</tr>
<tr>
<td>Kelly Run</td>
<td>Restored</td>
<td>0.9062</td>
<td>0.2265</td>
<td>0.0843</td>
<td>3.00E-04</td>
<td>2.33E-04</td>
</tr>
<tr>
<td>Lititz Run</td>
<td>Restored</td>
<td>1.2998</td>
<td>1.6690</td>
<td>0.1183</td>
<td>6.29E-05</td>
<td>1.51E-04</td>
</tr>
<tr>
<td>McIlvaine Run</td>
<td>Unrestored</td>
<td>0.4662</td>
<td>0.0610</td>
<td>0.0353</td>
<td>6.97E-06</td>
<td>2.97E-04</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>0.0355</td>
<td>0.0533</td>
<td>0.0216</td>
<td>1.47E-04</td>
<td>7.02E-04</td>
</tr>
<tr>
<td>Rife Run</td>
<td>Unrestored</td>
<td>2.8167</td>
<td>0.2024</td>
<td>0.0097</td>
<td>1.99E-04</td>
<td>1.76E-04</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>0.2693</td>
<td>0.4156</td>
<td>0.0956</td>
<td>2.01E-04</td>
<td>9.78E-04</td>
</tr>
<tr>
<td>Santo Domingo Creek</td>
<td>Unrestored</td>
<td>0.7925</td>
<td>0.1397</td>
<td>0.0477</td>
<td>1.32E-05</td>
<td>7.21E-05</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>1.1171</td>
<td>0.0798</td>
<td>0.0143</td>
<td>1.86E-05</td>
<td>-4.70E-06</td>
</tr>
<tr>
<td>Shobers Run</td>
<td>Unrestored</td>
<td>1.3036</td>
<td>0.4492</td>
<td>0.1908</td>
<td>2.64E-04</td>
<td>3.94E-04</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>0.0335</td>
<td>0.2322</td>
<td>0.1052</td>
<td>4.36E-04</td>
<td>1.51E-04</td>
</tr>
<tr>
<td>Wallace Run</td>
<td>Unrestored</td>
<td>7.1795</td>
<td>1.3867</td>
<td>0.1607</td>
<td>2.81E-04</td>
<td>-4.63E-04</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>1.0071</td>
<td>1.0475</td>
<td>0.2450</td>
<td>1.09E-04</td>
<td>4.43E-04</td>
</tr>
</tbody>
</table>

RTF
where $M$ is the mass injected (mg), $C_{\text{avg}}$ is the average concentration at the downstream end of the reach following the injection (mg/L), and $T_s$ is the total number of seconds it took the solute to reach the downstream end of the reach.

Quantitative comparison of streams of different sizes can be made because the model normalizes solute retentions for parameters such as discharge and channel area (Stream Solute Workshop 1990). Lateral inflow ($Q_{\text{LATin}}$) and outflow ($Q_{\text{LATout}}$) were added to account for the gains ($q_{\text{gain}}$) and losses ($q_{\text{loss}}$) occurring along the stream reaches. Net gains and losses were found using the following set of equations (Harvey and Wagner 2000, Payn et al. 2009):

$$\Delta Q = Q_2 - Q_1$$

(2.11)

$$M_{\text{rec}} = Q_2 \int_0^t C(t) dt$$

(2.12)

$$q_{\text{loss}} = Q_1 \left( \frac{M_1 - M_{\text{rec}}}{M_1} \right)$$

(2.13)

$$q_{\text{gain}} = \Delta Q + q_{\text{loss}}$$

(2.14)

$Q_1$ is the most upstream discharge taken from the FlowTracker measurements, $Q_2$ is the most downstream FlowTracker discharge, and $M_{\text{rec}}$ is the amount of mass that has retained in the main channel. The discharges were taken from the FlowTracker estimates in case of incomplete mixing within the channel, which could cause inaccurate dilution gauging values.

The transient storage modeling approach is accompanied by a general residence time distribution (RTD) analysis. The RTD’s were found for each stream reach and compared using the following formula (Payn et al. 2008):

$$G_{\text{RTD}}(t) = \frac{C_{\text{out}}(t)}{\int_0^\infty C_{\text{out}}(\tau) d\tau}$$

(2.15)
where time began when the tracer was released. A cumulative sum was then taken of these values. This gave a cumulative RTD for both the restored and unrestored reaches and could be used to compare the average time water spent in storage in each reach. The results found from the RTD analysis were consistent with the results found in the 2-SZ TS modeling. An example of cumulative RTD’s for a restored and an unrestored reach can be seen in Figure 2-6.

Figure 2-6: Cumulative RTD’s for Bald Eagle Creek.
Chapter 3

Results

The BTC’s of the best fitting parameters were plotted for each reach to visualize how well these matched the observed curves. Figures 3-1 and 3-2 display two of many of these plots.

Figure 3-1: Observed and Simulated best fit downstream BTC’s for 1-SZ model of Rife Run restored.
Figure 3-2: Observed and Simulated best fit downstream BTC’s for 2-SZ model of Rife Run restored.

All of the best fitting parameters for each reach can be seen in Table 3-1 below.
Table 3-1: Model parameter results for the 1-SZ and 2-SZ models.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Reach</th>
<th>1-SZ Model-Optimized Parameters</th>
<th>2-SZ Model-Optimized Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>D (m$^2$s$^{-1}$)</td>
<td>A (m$^2$)</td>
</tr>
<tr>
<td>Bald Eagle Creek</td>
<td>Reference</td>
<td>1.9859</td>
<td>0.0124</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>1.7870</td>
<td>0.0529</td>
</tr>
<tr>
<td>Canoe Creek</td>
<td>Reference</td>
<td>0.0490</td>
<td>0.1448</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>0.0838</td>
<td>0.1334</td>
</tr>
<tr>
<td>Kelly Run</td>
<td>Reference</td>
<td>0.0691</td>
<td>0.2184</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>0.7513</td>
<td>1.3641</td>
</tr>
<tr>
<td>Lititz Run</td>
<td>Reference</td>
<td>0.0256</td>
<td>0.1093</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>1.9966</td>
<td>0.0229</td>
</tr>
<tr>
<td>McIlvaine Run</td>
<td>Reference</td>
<td>0.0774</td>
<td>0.2294</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>0.3647</td>
<td>0.3330</td>
</tr>
<tr>
<td>Rife Run</td>
<td>Reference</td>
<td>0.0071</td>
<td>0.2533</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>0.2755</td>
<td>0.0719</td>
</tr>
<tr>
<td>Santo Domingo Creek</td>
<td>Reference</td>
<td>0.0931</td>
<td>0.6710</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>0.1203</td>
<td>0.2781</td>
</tr>
<tr>
<td>Shoberns Run</td>
<td>Reference</td>
<td>0.4016</td>
<td>1.2540</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>6.1761</td>
<td>0.1174</td>
</tr>
</tbody>
</table>
Four metrics were used to assess which reach had greater hyporheic exchange:

\[ T_{STO} = \frac{A_s}{\alpha A} \]  

(3.1)

\[ F_{MED} = \frac{t_{MED} - t_{MED}^m}{t_{MED}} \]  

(3.2)

\[ q_{STS} = \alpha A \]  

(3.3)

\[ A_{STS} / A \]  

(3.4)

\( T_{STO} \) is the mean storage zone residence time (minutes) determined for both STS and HTS (Briggs et al. 2009) and \( F_{MED} \) is the fraction of median transport time due to storage (Runkel 2002). \( t_{MED} \) is the median reach travel time determined from the lower boundary MC BTC simulation with transient storage exchange and \( t_{MED}^m \) is the median travel time calculated from the lower boundary MC BTC simulation without transient storage exchange (\( \alpha = 0 \)) (Briggs et al. 2009, Runkel 2002). \( t_{MED} \) and \( t_{MED}^m \) were found by applying a trapezoidal integration to each breakthrough curve, dividing that in half, and then calculating the time at which that amount of concentration had passed. \( q_{STS} \), the average water flux through the surface transient storage zone per unit length (Harvey et al. 1996, Runkel 2002), is equal to the surface storage exchange flux. \( F_{MED} \) is used to compare the transient storage of reaches because it quantifies the interaction between advective velocity and transient storage parameters (\( A_{STS}, A_{HTS}, \alpha \)). Finally, \( A_{STS}/A \) gives the ratio of storage-zone area to main channel area for each stream (Thackston and Schnelle 1970, Harvey and Wagner 2000).

The Damköhler number (\( DaI \)) was calculated from the 1-SZ model results for all of the reaches and a friction factor (\( f \)) was looked at for each of the restored reaches. These were calculated by the following equations:
\[ DaI = \alpha \frac{(1 + A/A_{STS})L}{u} \]  
(3.5)

\[ f = \frac{8gdS}{u^2} \]  
(3.6)

DaI is a dimensionless number which evaluates the adequacy of the experimental reach lengths. The DaI values closest to 1.0 represent the highest sensitivity to storage processes and therefore most reliable parameter estimates. A DaI value much greater than 1.0 suggests that timescales of solute transport are much longer than the storage timescales (Harvey and Wagner 2000). In those cases, parameter uncertainty is higher because the movement of tracer due to storage has already reached equilibrium and therefore the effect of storage-zone exchange can no longer be detected (Harvey and Wagner 2000). None of the DaI values found here are much smaller than one which would infer that very little tracer has mixed with the storage zones and therefore the effect of storage exchange on the tracer is not recognized (Harvey and Wagner 2000). The following tables (3-2 and 3-3) display values for all of the model metrics discussed above:
<table>
<thead>
<tr>
<th>Stream</th>
<th>Reach</th>
<th>1-SZ Model Metrics</th>
<th>2-SZ Model Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bald Eagle Creek</td>
<td>Reference</td>
<td>MC Sim. 1-R²: 0.5812, RMSE: 44.9617, F_MED (%): 0.0000, T_{STO} (min): 1.4097</td>
<td>MC Sim. 1-R²: 0.0188, RMSE: 31.8406, F_MED STS(%): 0.0000, T_{STO} STS(min): 1.3250, F_MED HTS(%): 0.0000, T_{STO} HTS(min): 0.0780</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>MC Sim. 1-R²: 0.6185, RMSE: 212.4072, F_MED (%): 0.0000, T_{STO} (min): 4.0099</td>
<td>MC Sim. 1-R²: 0.4502, RMSE: 87.6832, F_MED STS(%): 0.0000, T_{STO} STS(min): 0.0178, F_MED HTS(%): 0.0000, T_{STO} HTS(min): 1.2944</td>
</tr>
<tr>
<td>Canoe Creek</td>
<td>Reference</td>
<td>MC Sim. 1-R²: 0.0455, RMSE: 23.1889, F_MED (%): 0.0455, T_{STO} (min): 3.8838</td>
<td>MC Sim. 1-R²: 0.0898, RMSE: 14.1780, F_MED STS(%): 0.0243, T_{STO} STS(min): 0.0192, F_MED HTS(%): 0.0024, T_{STO} HTS(min): 0.9242</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>MC Sim. 1-R²: 0.0154, RMSE: 16.4988, F_MED (%): -0.1507, T_{STO} (min): 1.7575</td>
<td>MC Sim. 1-R²: 0.0436, RMSE: 10.9800, F_MED STS(%): 0.0000, T_{STO} STS(min): 0.0192, F_MED HTS(%): 0.0095, T_{STO} HTS(min): 0.6047</td>
</tr>
<tr>
<td>Kelly Run</td>
<td>Reference</td>
<td>MC Sim. 1-R²: 0.0657, RMSE: 14.7610, F_MED (%): -0.0063, T_{STO} (min): 0.4138</td>
<td>MC Sim. 1-R²: 0.0800, RMSE: 16.0814, F_MED STS(%): 0.0095, T_{STO} STS(min): 0.1571, F_MED HTS(%): 0.0095, T_{STO} HTS(min): 0.1773</td>
</tr>
<tr>
<td>Littitz Run</td>
<td>Restored</td>
<td>MC Sim. 1-R²: 0.8682, RMSE: 10.4835, F_MED (%): -0.0833, T_{STO} (min): 3.0606</td>
<td>MC Sim. 1-R²: 0.8635, RMSE: 10.4789, F_MED STS(%): 0.0000, T_{STO} STS(min): 0.0198, F_MED HTS(%): 0.0000, T_{STO} HTS(min): 0.0237</td>
</tr>
<tr>
<td>McIlvaine Run</td>
<td>Reference</td>
<td>MC Sim. 1-R²: 0.0801, RMSE: 20.8486, F_MED (%): -0.0220, T_{STO} (min): 3.1031</td>
<td>MC Sim. 1-R²: 0.0818, RMSE: 20.6715, F_MED STS(%): 0.0054, T_{STO} STS(min): 0.0138, F_MED HTS(%): 0.0054, T_{STO} HTS(min): 2.3725</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>MC Sim. 1-R²: 0.0671, RMSE: 71.3982, F_MED (%): 0.0000, T_{STO} (min): 3.3497</td>
<td>MC Sim. 1-R²: 0.0841, RMSE: 68.5782, F_MED STS(%): 0.0000, T_{STO} STS(min): 0.0657, F_MED HTS(%): 0.0000, T_{STO} HTS(min): 0.2801</td>
</tr>
<tr>
<td>Rife Run</td>
<td>Reference</td>
<td>MC Sim. 1-R²: 0.1383, RMSE: 19.0464, F_MED (%): -0.0083, T_{STO} (min): 0.3006</td>
<td>MC Sim. 1-R²: 0.1207, RMSE: 14.0235, F_MED STS(%): 0.0000, T_{STO} STS(min): 1.2479, F_MED HTS(%): 0.0000, T_{STO} HTS(min): 0.0669</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>MC Sim. 1-R²: 0.0677, RMSE: 5.2137, F_MED (%): 0.0562, T_{STO} (min): 0.8876</td>
<td>MC Sim. 1-R²: 0.0313, RMSE: 4.6702, F_MED STS(%): 0.0000, T_{STO} STS(min): 0.0703, F_MED HTS(%): 0.0000, T_{STO} HTS(min): 2.5509</td>
</tr>
<tr>
<td>Santo Domingo Creek</td>
<td>Reference</td>
<td>MC Sim. 1-R²: 0.0411, RMSE: 18.2688, F_MED (%): -0.0316, T_{STO} (min): 1.5983</td>
<td>MC Sim. 1-R²: 0.0569, RMSE: 22.6687, F_MED STS(%): 0.0201, T_{STO} STS(min): 0.1576, F_MED HTS(%): 0.0201, T_{STO} HTS(min): 0.0249</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>MC Sim. 1-R²: 0.0305, RMSE: 10.7203, F_MED (%): -0.0097, T_{STO} (min): 3.2452</td>
<td>MC Sim. 1-R²: 0.0677, RMSE: 16.5276, F_MED STS(%): 0.0098, T_{STO} STS(min): 53.0556, F_MED HTS(%): 0.0098, T_{STO} HTS(min): 0.0343</td>
</tr>
<tr>
<td>Shobers Run</td>
<td>Reference</td>
<td>MC Sim. 1-R²: 0.0610, RMSE: 4.3120, F_MED (%): -0.0511, T_{STO} (min): 39.3360</td>
<td>MC Sim. 1-R²: 0.0174, RMSE: 7.2347, F_MED STS(%): 0.0039, T_{STO} STS(min): 1.9409, F_MED HTS(%): 0.0039, T_{STO} HTS(min): 0.1640</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>MC Sim. 1-R²: 0.0378, RMSE: 7.2751, F_MED (%): -0.0130, T_{STO} (min): 14.1960</td>
<td>MC Sim. 1-R²: 0.0805, RMSE: 10.2258, F_MED STS(%): 0.0000, T_{STO} STS(min): 3.8591, F_MED HTS(%): 0.0000, T_{STO} HTS(min): 0.0141</td>
</tr>
<tr>
<td>Wallace Run</td>
<td>Reference</td>
<td>MC Sim. 1-R²: 0.0855, RMSE: 5.6887, F_MED (%): 0.0017, T_{STO} (min): 0.7093</td>
<td>MC Sim. 1-R²: 0.0750, RMSE: 4.5920, F_MED STS(%): 0.0018, T_{STO} STS(min): 0.5957, F_MED HTS(%): 0.0018, T_{STO} HTS(min): 0.0229</td>
</tr>
<tr>
<td></td>
<td>Restored</td>
<td>MC Sim. 1-R²: 0.1739, RMSE: 4.3783, F_MED (%): 9.58E-07, T_{STO} (min): 2.1663</td>
<td>MC Sim. 1-R²: 0.0395, RMSE: 1.8415, F_MED STS(%): 0.0020, T_{STO} STS(min): 6.7852, F_MED HTS(%): 0.0020, T_{STO} HTS(min): 0.4221</td>
</tr>
</tbody>
</table>

RTF: best fit metric
The above data tables depict that there was more dispersion in the restored reaches of every stream except for in Bald Eagle Creek. The ratio of hyporheic storage-zone area to main channel area was greater for the restored reaches of every stream with the exception of Santo Domingo Creek and Shober’s Run. The average $q_{STS}$ from the 1-SZ model for all the ISS restored streams is approximately equal to the average for RTF restored streams. The 2-SZ model shows that the RTF streams more closely matched the average flux in and out of the hyporheic zone ($q_{HTS}$) of their unrestored reaches. However, the exchange rate for the surface transient storage zone ($q_{STS}$) is closer to unrestored reaches of the ISS restored streams.

According to the 2-SZ model, the ratio of surface storage-zone area to main channel area is...
slightly more for the RTF streams while the ratio of hyporheic storage-zone area to main channel area is higher for ISS restored streams. In the 1-SZ model, the ratio of surface storage-zone area to main channel area is greater for the ISS streams.

The average 1-R² and average RMSE for the 1-SZ model as well as the RMSE for the 2-SZ model are lower for the RTF streams; this suggests that the parameter sets for those reaches are more accurate than the ISS stream parameters. The ISS restored streams have shorter mean residence times (T_{STO}) according to the 1-SZ model. Yet, the RTF streams have shorter surface and hyporheic residence times according to the 2-SZ model. Although the RTF residence times are shorter overall according to the 2-SZ model, RTF restored streams have, on average, a T_{STO} HTS which is closer to their unrestored reaches. On average, both RTF and ISS have F_{MED}’s (1-SZ) which are greater in the restored reach than the unrestored reach. However, more ISS restored streams have improved F_{MED}HTS and F_{MED}STS (2-SZ) when compared with their unrestored reaches. A visualization of how the ISS and RTF restored reaches compared to each other in each metric (with respect to their unrestored reaches) can be seen in Figure 3-3 below.
Figure 3-3: Model metric ranking based on differences between restored reaches and reference reaches of each stream.
A t-test was performed on three groups of reaches. First the unrestored reaches were compared with the ISS restored reaches. Then the unrestored reaches were tested against the RTF restored reaches. Finally, the ISS restored reaches were compared with the RTF restored reaches. The Fisher-Snedecor F-test (or F-distribution) was used first since the sample sizes were unequal. This assessed the equality of the variance. If the variances were not equal, then Satterthwaite’s approximate t-test was performed (Satterthwaite 1941). These results can be seen in Table 3-4.
Table 3-4: Results of the statistical t-test.

<table>
<thead>
<tr>
<th>Model Metric</th>
<th>Test</th>
<th>F</th>
<th>p-value</th>
<th>t</th>
<th>p-value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>F&lt;sub&gt;med&lt;/sub&gt; 1-SZ</td>
<td>Ref. vs. ISS</td>
<td>5.9099</td>
<td>0.0636</td>
<td>0.9585</td>
<td>0.3629</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>Ref. vs. RTF</td>
<td>2.6368</td>
<td>0.2777</td>
<td>0.0247</td>
<td>0.9808</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>ISS vs. RTF</td>
<td>2.2413</td>
<td>0.4515</td>
<td>0.7097</td>
<td>0.5008</td>
<td>not statistically significant</td>
</tr>
<tr>
<td>F&lt;sub&gt;med&lt;/sub&gt; STS</td>
<td>Ref. vs. ISS</td>
<td>2.4474</td>
<td>0.4945</td>
<td>0.4919</td>
<td>0.6345</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>Ref. vs. RTF</td>
<td>2.5774</td>
<td>0.3786</td>
<td>0.7946</td>
<td>0.4453</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>ISS vs. RTF</td>
<td>1.0532</td>
<td>0.9223</td>
<td>0.3030</td>
<td>0.7707</td>
<td>not statistically significant</td>
</tr>
<tr>
<td>F&lt;sub&gt;med&lt;/sub&gt; HTS</td>
<td>Ref. vs. ISS</td>
<td>2.4474</td>
<td>0.4945</td>
<td>0.4919</td>
<td>0.6345</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>Ref. vs. RTF</td>
<td>2.5774</td>
<td>0.3786</td>
<td>0.7946</td>
<td>0.4453</td>
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</tr>
<tr>
<td></td>
<td>ISS vs. RTF</td>
<td>1.0532</td>
<td>0.9223</td>
<td>0.3030</td>
<td>0.7707</td>
<td>not statistically significant</td>
</tr>
<tr>
<td>T&lt;sub&gt;sto&lt;/sub&gt; 1-SZ</td>
<td>Ref. vs. ISS</td>
<td>91.8906</td>
<td>0.0035</td>
<td>0.9402</td>
<td>0.3822</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>Ref. vs. RTF</td>
<td>6.3378</td>
<td>0.0954</td>
<td>0.4191</td>
<td>0.6840</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>ISS vs. RTF</td>
<td>14.4988</td>
<td>0.0529</td>
<td>0.7691</td>
<td>0.4670</td>
<td>not statistically significant</td>
</tr>
<tr>
<td>T&lt;sub&gt;sto&lt;/sub&gt; STS</td>
<td>Ref. vs. ISS</td>
<td>4.6584</td>
<td>0.1043</td>
<td>0.8571</td>
<td>0.4137</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>Ref. vs. RTF</td>
<td>2.7190</td>
<td>0.2637</td>
<td>0.6392</td>
<td>0.5371</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>ISS vs. RTF</td>
<td>1.7133</td>
<td>0.6029</td>
<td>0.2485</td>
<td>0.8109</td>
<td>not statistically significant</td>
</tr>
<tr>
<td>T&lt;sub&gt;sto&lt;/sub&gt; HTS</td>
<td>Ref. vs. ISS</td>
<td>3.3432</td>
<td>0.3495</td>
<td>0.2134</td>
<td>0.8358</td>
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</tr>
<tr>
<td></td>
<td>Ref. vs. RTF</td>
<td>1.5934</td>
<td>0.5804</td>
<td>0.1028</td>
<td>0.9202</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>ISS vs. RTF</td>
<td>5.3271</td>
<td>0.2007</td>
<td>0.0734</td>
<td>0.9436</td>
<td>not statistically significant</td>
</tr>
<tr>
<td>q&lt;sub&gt;5&lt;/sub&gt; 1-SZ</td>
<td>Ref. vs. ISS</td>
<td>2.5131</td>
<td>0.4807</td>
<td>0.2869</td>
<td>0.7807</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>Ref. vs. RTF</td>
<td>8.2381</td>
<td>0.0607</td>
<td>0.5926</td>
<td>0.5666</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>ISS vs. RTF</td>
<td>3.2781</td>
<td>0.2814</td>
<td>0.3612</td>
<td>0.7286</td>
<td>not statistically significant</td>
</tr>
<tr>
<td>q&lt;sub&gt;5&lt;/sub&gt; STS</td>
<td>Ref. vs. ISS</td>
<td>1.9242</td>
<td>0.6317</td>
<td>0.4176</td>
<td>0.6861</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>Ref. vs. RTF</td>
<td>3.5938</td>
<td>0.2361</td>
<td>1.0437</td>
<td>0.3212</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>ISS vs. RTF</td>
<td>1.8677</td>
<td>0.5517</td>
<td>0.6649</td>
<td>0.5274</td>
<td>not statistically significant</td>
</tr>
<tr>
<td>q&lt;sub&gt;5&lt;/sub&gt; HTS</td>
<td>Ref. vs. ISS</td>
<td>18.8496</td>
<td>0.0352</td>
<td>1.1383</td>
<td>0.2922</td>
<td>not statistically significant</td>
</tr>
<tr>
<td></td>
<td>Ref. vs. RTF</td>
<td>2.5430</td>
<td>0.2949</td>
<td>0.3465</td>
<td>0.7362</td>
<td>not statistically significant</td>
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<td>ISS vs. RTF</td>
<td>47.9339</td>
<td>0.0095</td>
<td>0.9797</td>
<td>0.3802</td>
<td>not statistically significant</td>
</tr>
</tbody>
</table>
Chapter 4

Discussion

Streams within the same class were found to have significantly different quantities of exchange. This is most clear when comparing Canoe Creek and Shober’s Run, which were both classified as steam type B. Both of these stream reaches were 60 m in length. According to the 1-SZ model, Shober’s Run had a significantly higher $T_{STO}$ than Canoe Creek. The 2-SZ model showed the reverse and Canoe Creek had much greater $T_{STO}$’s as well as much lower exchange rates ($\alpha_{STS}, \alpha_{HTS}$). Although these outcomes are contradictory, both display huge differences in storage retention times between two streams of the same class. Another comparison can be made between two streams which were classified as type E. Lititz Run and Rife Run were both restored using RTF techniques. The 2-SZ model estimated that Lititz Run has a much longer $T_{STO}$ in the STS than the HTS while Rife Run has just the opposite. Although we did find significantly different outcomes for streams of the same class, we only had two of each to compare against. This is a key limitation to the study because one or both of the streams could simply be outliers in that class.

The $Dai$ values found in Table 3-3 were calculated following the field studies. The lengths of each reach were determined by the widths of each steam and we believe this to have accounted for the differences in stream size. Therefore, we believe the length of each steam did not affect the outcome of the parameters.

It is not entirely clear from the results which restoration induces more hyporheic exchange but we can make general conclusions from some of the metrics. According to the 1-SZ model, the average $T_{STO}$’s of RTF restored streams was longer which could result in more nutrient retention. The 1-SZ model also resulted in a higher average $F_{MED}$ for the RTF restored streams which means that, on average, the solute stays in storage longer in those streams than in the ISS
restored streams. The 2-SZ model showed that the RTF restored streams had $q_{HTS}$’s closer to their unrestored reaches than the ISS restored streams. A $q_{HTS}$ close to the unrestored value means that the restored reach was able to nearly match the amount of hyporheic storage exchange flux occurring in each meter of the unrestored reach. It was expected that RTF restored streams would have more hyporheic exchange occurring than ISS restored streams because they considered the hyporheic zone in the design. Since restoration is focused on reconnecting the stream to its floodplain, the flow is expected to interact with the floodplain more frequently and as a result those areas should become biogeochemically active (Bukaveckas 2007). However, a pattern which was detected from the 2-SZ modeling shows that, on average, the ISS restored reaches had $F_{MED} HTS$ values closer to their unrestored reaches than the RTF restored streams. This result implies that ISS restoration is better at enhancing hyporheic storage. Along with this, the t-test of all of the metrics gave results that were not statistically significant for every pair. If these results had been significant then there would be strong evidence that the values in the three groups differ. The t-test confirms that all of the reaches, whether unrestored, ISS, or RTF, had similar metric values. Therefore we cannot say if one approach did a better job at connecting the main channel to the subsurface than the other.

A limitation of the model metrics used to compare the three groups of reaches stems from the model which calculated the parameters ($D$, $A$, $A_{STS}$, $A_{HTS}$, $\alpha_{STS}$, $\alpha_{HTS}$) for every reach. The model was able to find well-defined values of $A$ and $D$ for each reach much better than values of $A_{STS}$, $A_{HTS}$, $\alpha_{STS}$, and $\alpha_{HTS}$ (as seen on dotty plots in Appendix C). Since all of the parameters are related to one another and $A$ and $D$ tend to dominate the results, a model which can separate parts of the breakthrough curve in order to determine different parameters would be useful for future analysis.

The simple cumulative RTD distributions and plots of downstream observed BTC’s for unrestored and restored reaches gave the best view of comparisons between the different reaches.
A summary of all of these for each stream can be found in Appendix D. With the exception of McIlvaine Run (which had very similar unrestored and restored BTC’s), all of the restored reaches had a wider observed BTC as well as a longer tail. This can be interpreted to mean that there was more dispersion in the restored reach and the tracer also stayed in storage longer. The cumulative RTD’s for most of the streams were higher and longer for the restored reaches. This agrees with the previous statement that restored reaches had higher tracer retentions. These long residence times are characteristic of a stream subsurface which has a lot of contact between sediments and therefore higher microbiological activity (Payn et al. 2008, Triska et al. 1989).

While these experiments were completed during low flows, they still only capture the fastest exchange timescales and cannot detect the hyporheic flow paths in the deeper alluvium (Harvey et al. 1996). It is becoming broadly acknowledged that stream restoration efforts should be monitored in the long-term in order to advance the knowledge and management of stream ecosystems (Moerke et al. 2004, Bernhardt et al. 2005). In most cases, the tracer studies performed were performed well after the stream restoration took place (up to 8 years). The ISS techniques can sometimes induce higher in-stream and hyporheic storage in the long-term through the accumulation of woody debris and the extra sorting of bed materials (Bukaveckas 2007). Experiments done in the natural stream system tend to have the least control but also the most realistic insights on how restoration has affected hyporheic exchange (Stream Solute Workshop 1990).
Chapter 5

Conclusions

The disparities found here between streams of the same class suggest that the classification system used does not consider the hyporheic and surface transient storage zones when determining stream type. This is merely a suggestion and cannot be taken as a decisive result until examined further with a greater numbers of streams of the same classes as those presented here.

According to the two-storage zone model used in this analysis, both types of restoration resulted in levels of stream-groundwater interaction close to those found in the unrestored reaches. Analysis of the observed breakthrough curves illustrated that, for most streams, restoration led to greater residence times and would likely therefore result in higher nutrient retention. Therefore, as a whole, restoration was found to have a positive impact on a stream’s ecosystem since it led to hyporheic exchange levels close to the unrestored reaches. An increase in hyporheic exchange improves the potential for enhanced biogeochemical processing in the stream.

However, these results are not robust enough to support a guaranteed conclusion. There is a high amount of uncertainty in some of the parameters that could only be improved through the use of another model or other form of analysis. The uncertainty is highest in the two storage-zone areas and both storage-zone rates. These parameters are crucial for identifying the amount of stream-groundwater interactions and hyporheic exchange. Although this outcome severely limits the number of concrete results, we can still make some general conclusions.

Overall, if the goal of restoration is to restore natural stream processes, the projects have a much greater potential for providing a long-term solution. Stream restoration using the creation of habitats through in-stream structures has often been found to be unsuccessful at dealing with
the source of habitat degradation, leading to restoration projects which fall short of attaining 
environmental goals (Beechie et al. 2010). However, ISS techniques have been found here to 
increase the amount of solute retention in a stream, which is found to be beneficial for a stream’s 
ecosystem. In-stream structure techniques are important to know because it is not always 
possible to restore natural processes (i.e. excavate down to the historical floodplain) especially in 
heavily developed areas (Beechie et al. 2010). Successful stream ecosystem restoration will 
result from a perspective that embraces connecting the river channel to its floodplain, corridor, 
and even catchment in order to ensure that restoration techniques at the local scale are sustainable 
on a regional scale and into the future.
Chapter 6

Future Work

A potential follow up to this study could look at a greater number of streams within each stream class in order to find a clearer and more complete view of how the streams differ within each class in regards to their stream-groundwater interactions. Another future consideration for this work would be to use a different model which will better characterize the parameters of each stream reach. The model would have to be more sensitive to the values of $A_S$ and $\alpha$ in order to improve the reliability of the model metric outcomes.

The effects of restoration on the surface and hyporheic transient storage of a stream vary across each project. Although a wide range of projects was investigated here, they all were in similar geologic settings in the same state. All restoration projects should be continuously monitored in order to gain knowledge on how stream processes are being affected by restoration. This knowledge is imperative for advancing the practice of stream ecosystem restoration.
Appendix A

Acronyms and Descriptions of Symbols Used

Table A-1: Acronyms and Descriptions of Symbols Used (Briggs et al. 2010).

<table>
<thead>
<tr>
<th>Symbol (units)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>D (m²s⁻¹)</td>
<td>Main channel longitudinal dispersion coefficient</td>
</tr>
<tr>
<td>A (m²)</td>
<td>Main channel cross-sectional area</td>
</tr>
<tr>
<td>A_STS (m²)</td>
<td>Surface storage-zone cross-sectional area</td>
</tr>
<tr>
<td>A_HTS (m²)</td>
<td>Hyporheic storage-zone cross-sectional area</td>
</tr>
<tr>
<td>α_STS (s⁻¹)</td>
<td>Surface storage-zone exchange coefficient</td>
</tr>
<tr>
<td>α_HTS (s⁻¹)</td>
<td>Hyporheic storage-zone exchange coefficient</td>
</tr>
<tr>
<td><strong>Model Storage Metrics</strong></td>
<td></td>
</tr>
<tr>
<td>T_STO (h)</td>
<td>Mean storage zone residence time</td>
</tr>
<tr>
<td>F_MED (%)</td>
<td>Fraction of median travel time due to storage</td>
</tr>
<tr>
<td>Dal</td>
<td>Damkohler number, evaluates experimental reach length based on the relationship of storage exchange to advective transport</td>
</tr>
<tr>
<td>q_STS (m²/s)</td>
<td>Storage exchange flux per meter stream length</td>
</tr>
<tr>
<td>f</td>
<td>Storage zone friction factor</td>
</tr>
<tr>
<td>A_S/A</td>
<td>Ratio of storage-zone area to stream cross-sectional area</td>
</tr>
<tr>
<td><strong>Commonly Used Acronyms</strong></td>
<td></td>
</tr>
<tr>
<td>ISS</td>
<td>In-stream structures</td>
</tr>
<tr>
<td>RTF</td>
<td>Reconnecting the floodplain</td>
</tr>
<tr>
<td>MC</td>
<td>Main channel</td>
</tr>
<tr>
<td>STS</td>
<td>Surface transient storage</td>
</tr>
<tr>
<td>HTS</td>
<td>Hyporheic transient storage</td>
</tr>
<tr>
<td>BTS</td>
<td>Solute tracer break-through curve</td>
</tr>
</tbody>
</table>
Figure A-1: Cross section of a stream displaying geomorphic measurements used in analysis.

\[
\begin{align*}
\text{dbkf} &= \text{depth to bankfull} & \text{Abkf} &= \text{area at bankfull} \\
\text{dmbkf} &= \text{depth to maximum bankfull} & \text{Wbkf} &= \text{bankfull width} \\
& & \text{Wfpa} &= \text{flood-prone width}
\end{align*}
\]

\[
P_{bkf} = \text{wetted perimeter at bankfull}
\]

\[
R_{bkf} = \text{hydraulic radius at bankfull} = \frac{\text{Abkf}}{P_{bkf}}
\]
Appendix B

Model Inputs

Concentration - Step

IBOUND = 1

Figure B-1: Type of injection input (Runkel 1998).

Figure B-2: Calculation of $Q_{LAT\text{in}}$ and $Q_{LAT\text{out}}$.

$$\Delta q = \frac{Q_2 - Q_1}{20W_{b kf}}$$

$$\text{conc. injected} \left[ \frac{mg}{L} \right] = \frac{M_1 \frac{10^6 mg}{kg}}{Q_1 \times 30 \text{sec} \times \frac{1000L}{m^3}}$$

$$M_{rec} = Q_2 \int_{t_{inj}}^{t_{finish}} C(t) \, dt$$

$$q_{loss} = \frac{Q_1 \left( \frac{M_1 - M_{rec}}{M_1} \right)}{20W_{b kf}}$$

$$q_{gain} = \Delta q + q_{loss}$$
Appendix C

Observed versus Modeled Parameter Values

Table C-1: Corresponding numbers and streams for graphs below.

<table>
<thead>
<tr>
<th>Number</th>
<th>Stream Reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bald Eagle Creek Unrestored</td>
</tr>
<tr>
<td>2</td>
<td>Bald Eagle Creek Restored</td>
</tr>
<tr>
<td>3</td>
<td>Canoe Creek Unrestored</td>
</tr>
<tr>
<td>4</td>
<td>Canoe Creek Restored</td>
</tr>
<tr>
<td>5</td>
<td>Kelly Run Restored</td>
</tr>
<tr>
<td>6</td>
<td>Lititz Run Restored</td>
</tr>
<tr>
<td>7</td>
<td>McIlvaine Run Unrestored</td>
</tr>
<tr>
<td>8</td>
<td>McIlvaine Run Restored</td>
</tr>
<tr>
<td>9</td>
<td>Rife Run Unrestored</td>
</tr>
<tr>
<td>10</td>
<td>Rife Run Restored</td>
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<tr>
<td></td>
<td>Santo Domingo Creek Unrestored</td>
</tr>
<tr>
<td>11</td>
<td>Santo Domingo Creek Restored</td>
</tr>
<tr>
<td>12</td>
<td>Santo Domingo Creek Unrestored</td>
</tr>
<tr>
<td>13</td>
<td>Shober's Run Unrestored</td>
</tr>
<tr>
<td>14</td>
<td>Shober's Run Restored</td>
</tr>
<tr>
<td>15</td>
<td>Wallace Run Unrestored</td>
</tr>
<tr>
<td>16</td>
<td>Wallace Run Restored</td>
</tr>
</tbody>
</table>
Figure C-1: Ranges of values for Observed and Modeled parameters.
Appendix D

Typical 1-SZ and 2-SZ TS Modeling Results

Figure D-1: 1-SZ Dotty plots of 1-\(r^2\) values for Rife Run unrestored reach.
Figure D-2: 1-SZ Dotty plots of RMSE values for Rife Run unrestored reach.
Figure D-3: 1-SZ best fit BTC from the minimum RMSE and 1-$r^2$ for Rife Run unrestored reach.
Figure D-4: 2-SZ Dotty plots of 1-$r^2$ values for Rife Run unrestored reach.

Figure D-5: 2-SZ Dotty plots of RMSE values for Rife Run unrestored reach.
Figure D-6: 2-SZ best fit BTC from the minimum RMSE and 1-$r^2$ for Rife Run unrestored reach.
Figure D-7: 1-SZ Dotty plots of $1-r^2$ values for McIlvaine Run unrestored reach.

Figure D-8: 1-SZ Dotty plots of RMSE values for McIlvaine Run unrestored reach.
Figure D-9: 1-SZ best fit BTC’s from the minimum 1-\( r^2 \) and RMSE for McIlvaine Run unrestored reach.

Figure D-10: 2-SZ Dotty plots of 1-\( r^2 \) values for McIlvaine Run unrestored reach.
Figure D-11: 2-SZ Dotty plots of RMSE values for McIlvaine Run unrestored reach.

Figure D-12: 2-SZ best fit BTC from the minimum $1-r^2$ and RMSE for McIlvaine Run unrestored reach.
Figure D-13: 1-SZ Dotty plots of 1-$r^2$ values for Santo Domingo Creek restored reach.

Figure D-14: 1-SZ Dotty plots of RMSE values for Santo Domingo Creek restored reach.
Figure D-15: 1-SZ best fit BTC’s from the minimum 1-\(r^2\) and RMSE for Santo Domingo Creek restored.

Figure D-16: 2-SZ Dotty plots of 1-\(r^2\) values for Santo Domingo Creek restored reach.
Figure D-17: 2-SZ Dotty plots of RMSE values for Santo Domingo Creek restored reach.

Figure D-18: 2-SZ best fit BTC from the minimum 1-$r^2$ and RMSE for Santo Domingo Creek restored reach.
Appendix E

General RTD Results

Bald Eagle Creek
Appendix F

Analysis of Modeling Results

Fmed for 1-SZ

Fmed STS for 2-SZ
STS Exchange Flux for 2-SZ

HTS Exchange Flux for 2-SZ
Figure F-1: Comparison graphs of model metrics for unrestored, ISS, and RTF reaches
Appendix G

Stream Locations and Pictures

Bald Eagle Creek Restored:

General address and lat/long of stream:

- **Address:** Pennsylvania 425
  Airville, PA 17302
- **Latitude:** 39.780139
- **Longitude:** -76.414589

Location of restored reach:
Pictures of Reach:
Bald Eagle Creek Unrestored:

General address and lat/long of stream:

Address: Pennsylvania 425
          Airville, PA 17302
Latitude: 39.780139
Longitude: -76.414589

Location of unrestored reach:
Pictures of Reach:
Canoe Creek Restored:

General address and lat/long of stream:

Address: Beaver Dam Rd
Hollidaysburg, PA 16648
Latitude: 40.496489
Longitude: -78.2659

Location of restored reach:
Pictures of Reach:
Canoe Creek Unrestored:

General address and lat/long of stream:

Address: Beaver Dam Rd
Hollidaysburg, PA 16648
Latitude: 40.496489
Longitude: -78.2659

Location of unrestored reach:
Pictures of Reach:
Kelly Run Restored:

General address and lat/long of stream:

Address: 28801-28877 Miller Station Rd
          Cambridge Springs, PA 16403
Latitude: 41.804039
Longitude: -79.969308

Location of restored reach:
Pictures of Reach:
Lititz Run Restored:

General address and lat/long of stream:

Address: 813 Rothsville Rd
Lititz, PA 17543
Latitude: 40.149536
Longitude: -76.281719

Location of restored reach:
Pictures of Reach:
McIlvaine Run Restored:

General address and lat/long of stream:

Address: 1444 S Whitford Rd
West Chester, PA 19380
Latitude: 40.014514
Longitude: -76.414589

Location of restored reach:
Pictures of Reach:
McIlvaine Run Unrestored:

General address and lat/long of stream:

Address: 1444 S Whitford Rd
           West Chester, PA 19380
Latitude: 40.014514
Longitude: -76.414589

Location of unrestored reach:
Pictures of Reach:
Riff Run Restored:

General address and lat/long of stream:

Address: 59 Rettew Ln
Manheim, PA 17545
Latitude: 40.155872
Longitude: -76.404272

Location of restored reach:
Pictures of Reach:
Rife Run Unrestored:

General address and lat/long of stream:

Address: 59 Rettew Ln
Manheim, PA 17545
Latitude: 40.155872
Longitude: -76.404272

Location of unrestored reach:
Pictures of Reach:
Santo Domingo Creek Restored:

General address and lat/long of stream:

Address: Lutz Ln
Lititz, PA 17543
Latitude: 40.160628
Longitude: -76.298356

Location of restored reach:
Pictures of Reach:
Santo Domingo Creek Unrestored:

General address and lat/long of stream:

Address: Lutz Ln
Lititz, PA 17543
Latitude: 40.160628
Longitude: -76.298356

Location of unrestored reach:
Pictures of Reach:
Shober’s Run Restored:

General address and lat/long of stream:

Address:  
Sweet Root Rd  
Bedford, PA 15522

Latitude:  39°59'25.45"N  
Longitude:  78°30'58.49"W

Location of restored reach:
Pictures of Reach:
Shober’s Run Unrestored:

General address and lat/long of stream:

Address: Sweet Root Rd  
Bedford, PA 15522
Latitude: 39°59'25.45"N
Longitude: 78°30'58.49"W

Location of unrestored reach:
Pictures of Reach:
Wallace Run Restored:

General address and lat/long of stream:

Address: 930-946 Sycamore St
Bellefonte, PA 16823
Latitude: 40.954693
Longitude: -77.836552

Location of restored reach:
Pictures of Reach:
Wallace Run Unrestored:

General address and lat/long of stream:

Address: 930-946 Sycamore St
Bellefonte, PA 16823
Latitude: 40.954693
Longitude: -77.836552

Location of unrestored reach:
Pictures of Reach:
Literature Cited


