**Stream-Subsurface Exchange and Hyporheic Zone Influence on Reach-scale
Water Budgets within a Boreal Shield Catchment of Quebec, Canada**

by

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fulfillment of the requirements for the degree of

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in

Geography

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ABSTRACT

Mass loss of solute and gross channel water losses and gains were quantified to understand the influence of hyporheic exchange on water budgets of boreal shield catchments. Six series of tracer injections were performed on 9 reaches of a stream network within a subwatershed of Gatineau Park, Quebec from July to November, 2011. Solute loss was substantial and increased throughout the summer baseflow recession to a maximum of 88% at reach 4. High solute exchange exists for all reaches despite most exhibiting slight positive net discharge values, resulting in minimum gross channel water loss no less than 34% during low flow conditions. Strong power law relationships for most reaches ($R^2 > 0.9$) suggest discharge as the most important variable on the magnitude of mass loss. Although inter-reach variability in mass loss could implicate watershed-scale controls on exchange potential, there was no correlation between LiDAR DEM-derived watershed morphometrics and mass loss.

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1. INTRODUCTION

Stream discharge is arguably the most frequently studied, measured, and expressed parameter in the field of watershed hydrology, yet there remains a need to understand the dynamic link between channel flow (discharge) and processes that operate within the stream zone. During baseflow recession periods, streamflow is sustained by stored groundwater in alluvial catchment aquifers and surrounding connected hillslope aquifers. Research suggests that even during an input event of rainfall or snowmelt to the catchment, large portions of streamflow can be derived from pre-event groundwater that is displaced by newer input water through mechanisms of subsurface flow (Sklash and Farvolden, 1979; Rodhe, 1981; MacLean et al., 1995). Surface water-groundwater interactions are the most commonly studied and dominant process influencing runoff generation in headwater catchments, particularly in boreal catchments (Wels et al., 1991; Waddington et al., 1993; Devito et al., 1996; Spence and Woo, 2006). However, interactions and exchanges between the stream and the subsurface exist at a range of spatial scales that have a varying effect on water quantity, quality, and ecosystem structure within the catchment. These stream-groundwater interactions are poorly understood.

Small-scale surface-subsurface exchange, referred to as hyporheic exchange and occurring within the near stream zone, is considered an important water transfer process across the channel bed. Even at this relatively small scale, considerable volumes of surface water can be lost from or gained to channel flow resulting in marked changes in total and unit discharge along different portions of the stream. This exchange suggests that a greater total amount of water is involved in streamflow discharge over time than is

often assumed from net discharge within the catchment. This has caused the hydrological community to recognize multiple catchment contributions to channel flow (Harvey and Bencala, 1993; Payn et al., 2009). In addition to influencing discharge, hyporheic exchange also affects stream solute concentrations and has forced re-evaluation of several biogeochemical processes operating within the watershed, such as nutrient cycling and respiration of benthic organisms within the subsurface (Ingendahl et al., 2009; Gooseff, 2010).

This research examines the nature of surface-subsurface exchange of water through time and space and its effect on regulating longitudinal stream water budgets within a 2.9 km² catchment of Gatineau Park, Quebec, Canada. While sometimes acknowledged within the scientific literature, hyporheic contributions to channel flow are rarely reported and this study is unique in that it quantifies gross gain and loss of channel water over reaches 100 to 200 m in length. These values were determined using the recently developed method of conservative tracer injection and mass recovery analysis outlined by Payn et al. (2009). Furthermore most research has taken place within mountain catchments of western North America, yet this study seeks to determine if similar relationships between the magnitude of solute loss or water exchange and catchment morphology exist within a boreal shield watershed of eastern Canada.

The purpose of this research is to enhance our existing knowledge on the potential role of hyporheic exchange in influencing water and solute budgets of streams, focusing on small spatial scales through application of a reach based approach. Understanding small scale water exchange is important in our overall concept of runoff generation and stream discharge variation along the channel in boreal shield catchments. The hyporheic

zone and residence time of water in transient storage has an important influence on subsurface hydrochemistry and meiofaunal ecosystem productivity (Valett et al., 1994; Gooseff, 2010). Determining locations of exchange will aid in watershed management, particularly with regards to the exposure to pollution and its effect on aquatic ecology (Kimball et al., 2002). Quantification of timing and magnitude of solute concentrations provides a better understanding of hyporheic influence (Harvey et al., 1996), which in turn can be used to help assess water quality degradation and mitigate damage to stream ecosystem health (Runkel et al., 1999). Findings may assist the National Capital Commission (NCC) in their effort to preserve and maintain the environmental integrity of Gatineau Park.

1.1 Research Objectives

This study used conservative tracer injections and mass recovery analysis to determine solute mass loss and infer gross discharge gains and losses in order to assess the influence of hyporheic exchange on longitudinal stream water budgets at the reach scale. The research specifically sought to answer the following questions:

- 1 What are the proportions of solute mass loss and gross water gain and loss of the selected reaches over the course of the summer recession period?
- 2 Does surface-subsurface exchange vary across time and space?
- 3 Does catchment structure or any physical watershed factors relate to magnitudes of exchange?

Question 1 will be assessed from tracer loss results using the methods of Payn et al. (2009) while question 2 will examine the relationship between solute mass loss and downstream discharge throughout the summer recession in baseflow, and the variation in

gross discharge exchanges between reaches located in the catchment. Several catchment parameters were derived quantitatively for each reach using geographic information systems software and plotted against mass loss results to answer question 3. Background research and development of the methodology led to the inquiry and examination of two supplementary research questions:

- 4 Is there a significant difference between discharge measurements using the methods of dilution gauging and velocity-area?
- 5 Does the injection of multiple amounts of solute mass result in different proportions of mass loss over the same reach length assuming constant discharge?

1.2 Thesis Structure

This thesis is composed of six chapters. The introduction is followed by Chapter 2 which provides background information on the concept of surface-subsurface exchange and its influence on streamflow, the numerous methods of quantifying contributions to channel flow from hyporheic flowpaths, and several scales of physical watershed control on exchange potential. Chapter 3 describes the study site and location of the reaches within the catchment, as well as the field methods utilized in this study. Chapter 4 illustrates the results observed for each research question while Chapter 5 discusses them. Chapter 6 concludes the thesis by summarizing the key results and offering suggestions for future hyporheic research.

2. BACKGROUND

Interpretation and understanding of runoff generation in terms of the dominant mechanisms and flowpaths within boreal catchments of the Canadian Shield has evolved with time and what have been viewed as the ultimate controlling factors have indeed been intensively studied and debated. Catchment runoff varies with landscape structure and streamflow generation has been linked to not only surface inputs of overland flow (Horton, 1933; Betson, 1964; Pearce et al., 1986) but also subsurface processes including groundwater ridging (Sklash and Farvolden, 1979), translatory flow (Hewlett and Hibbert, 1967), and macropore drainage (Beven and Germann, 1982). Runoff response and source area contributions to discharge during both stormflow and baseflow conditions have been assessed using a suite of hydrometric, isotopic, and geochemical analyses (McDonnell et al., 1990; MacLean et al., 1995; Peters et al., 1995). While these studies acknowledge the link between channel flow and zones of groundwater storage within the catchment, there is little understanding of the effect of small-scale surface-subsurface exchange (hyporheic flowpaths) on stream discharge.

2.1 Stream-Groundwater Connection and Net Discharge

It is common knowledge now that surface streamflow is linked to water stored in the subsurface, yet it is no longer assumed that the channel acts as a pipe in which all water that drains from a catchment and contributes to channel flow remains in surface transport until it exits at the outlet (Bencala et al. 2011). Channel flow in small alluvial streams is often sustained by groundwater within the surrounding catchment during baseflow conditions. The stream-subsurface connection is multi-directional and depends

on the hydraulic gradient from the elevation of the water table in the hillslope relative to the stream surface (Morrice et al., 1997; Winter et al., 1998).

Movement of groundwater towards and into the surface flow results in an increase in discharge from the upstream to the downstream end of the channel. Such conditions are referred to as net gaining streams. Alternatively when hillslope water tables fall below the elevation of the stream surface water moves from channel flow into the subsurface recharging catchment aquifers. This results in a decrease in discharge from the upstream to the downstream end of the channel and is referred to as a net losing stream in this thesis. These two scenarios are illustrated in Figure 2.1.

Figure 2.1. Net gaining streams (left) experience groundwater discharge along their channels as water tables are located at higher elevations relative to the stream surface, and net losing streams (right) result in groundwater discharge as water tables are below the stream surface elevation. From Winter et al. (1998).

The general perception is that this net loss or gain of water is attributed to groundwater recharge or discharge respectively and that the amount of water determined from this change in discharge is solely what is being transferred across the stream-subsurface boundary. More recently however, stream zone research has recognized that gain and loss of water to and from the stream occurs at smaller scales (across stream lengths of centimeters to meters) often simultaneously and varying along the length of the channel (Ruehl et al., 2006; Szeftel et al., 2011). Water associated with these small-scale losses and gains originates not from deeper groundwater sources but from channel water itself.

2.2 The Hyporheic Zone and Exchange Process

The process whereby water exits the stream, penetrates the subsurface, remains in transient storage for a period of time, and returns back to the channel is referred to as hyporheic exchange. These flowpaths are confined to the stream zone subsurface, and collectively make up what is known as the hyporheic zone (Figure 2.2, Triska et al., 1989). Previous research in mountain catchments has recognized the essential role of the hyporheic zone in storing and transporting water into and out of the stream channel (Bencala and Walters, 1983; Wondzell, 2006; Covino and McGlynn, 2007; Payn et al., 2009).

Gooseff (2010) provides an extensive review of the hyporheic zone documenting multiple definitions based on hydrological, chemical, and biological controls while detailing the challenge in defining its boundaries according to the catchment environment. The hyporheic zone, while subject to debate, can be defined as the area encompassing the

subsurface beneath and to the sides (banks) of the stream in which water from the stream penetrates the porous channel bed and returns back into the channel downstream via subsurface flowpaths (Kennedy et al., 1984; Triska et al., 1989; Bencala, 2005; Tonina and Buffington, 2009). The zone will differ in scale depending on the longest flowpath of interest (Gooseff, 2010).

Figure 2.2. Illustration of the hyporheic zone bounded by the dashed blue lines as distinguished from regional groundwater and surface water. Dashed orange arrows indicate subsurface hyporheic flow paths (laterally and vertically) and hyporheic exchange (turnover). Black arrows represent surface water lost to groundwater recharge whereas yellow arrows represent groundwater inflow. The inset box displays the influence of channel morphology on the initiation of exchange. From Tonina and Buffington (2009).

Hyporheic flow is considered local groundwater flow independent of regional groundwater which originates or terminates in the surrounding catchment (Toth, 1963). Hyporheic water will mix with stored groundwater in the local aquifer, however it will

maintain a portion of channel water based on its hydrochemical signature. It is considered a separate source of streamflow contribution with its own distinct flowpaths situated within a larger network of deeper groundwater flowpaths both of which are actively exchanging water (Harvey and Bencala, 1993).

Payn et al. (2009) outline different types of flowpaths contributing to loss and gain of water (Figure 2.3). Under net losing scenarios channel water can be lost to deep groundwater flowpaths which do not return to the channel (E). This water is stored for long periods and mixes readily with previously stored groundwater such that when or if it returns to the stream it will no longer resemble surface water. Under net gaining scenarios along the channel water is gained from these deep groundwater flowpaths (A).

Figure 2.3. Cross section of a stream with a study reach (dashed rectangle) showing variation in hyporheic flowpath length (B,C,D,F) and flow lost to (E) or gained from (A) groundwater. At the small, reach scale net loss or gain of water includes hyporheic water gained from flowpaths originating upstream of the reach upstream point (B) and that lost from large spatial scale flow paths (D) or from flow paths with long retention (storage) times (C) in which case water re-enters the reach but only after the study period. Water that is both lost from and returned to the reach over the length of study (F) usually does so along flowpath distances of centimeters to meters. From Payn et al. (2009).

Water is also lost to three different types of hyporheic flowpaths (Figure 2.3), (1) those that return to the channel within the study period (F), (2) long flowpaths which exit the reach but return to the stream at a position downstream from the study reach (D), and (3) large flowpaths which exit and return to the study reach but have residence times longer than the injection period or time of study (C). Sources of hyporheic gain are similar and result from (1) small flowpaths returning to the reach (F), (2) long flowpaths that return to the study reach but originate at greater distances upstream (B), and (3) water in large flowpaths with long retention times but was lost from the reach before the experimental time period (C).

2.3 Gross Hydrological Gains and Losses

While all of the water from the large hyporheic flowpaths usually returns to the stream or makes up a small portion of water loss at larger spatial and temporal scales of study, at reduced scales of interest (e.g. stream reach) hyporheic flowpaths will have a greater influence on stream water budgets. Harvey and Wagner (2000) refer to this reduced length of study as the “window of detection” and is represented in Figure 2.3 as the dashed rectangle. Net discharge at these smaller scales therefore will not reflect the true nature of water exchange within the catchment. Loss and gain of water from long hyporheic flowpaths both spatially and temporally will also affect net discharge. Therefore as a result of this exchange process, net discharge at small spatial scales is the difference between larger magnitude gross discharge losses and gains.

The gross gains and losses are themselves a function of both hyporheic and groundwater flow. The longitudinal stream water balance equations for baseflow conditions, adapted from Harvey and Bencala (1993) are provided for both net losing (Equation 2.1) and gaining (Equation 2.2) reaches:

$$Q_N = q_{in} - [Q_{out} + q_{out}] - E \quad \text{net losing} \quad (2.1)$$

$$Q_N = [Q_{in} + q_{in}] - q_{out} - E \quad \text{net gaining} \quad (2.2)$$

where

- Q_N -net discharge
- Q_{out} -gross loss due to deep regional groundwater recharge
- Q_{in} -gross gain due to deep regional groundwater discharge
- q_{out} -gross loss due to hyporheic outflow
- q_{in} -gross gain due to hyporheic inflow
- E -evaporation.

For net losing reaches Q_N is negative as the gross losses outweigh the gross gains. Thus Q_N is positive for net gaining reaches as the gross gain is greater than the gross loss. Gross values may be negligible at large scales (i.e. assessing the water balance at the catchment scale along the entire stream length) and equal to the net loss or gain (Harvey and Bencala, 1993). The relative magnitudes of these gross discharge values will be greater at smaller scales of study and the net loss or gain can no longer be considered the only transfer of water within the system. The channel is not simply gaining from groundwater discharge in net gaining reaches, nor is it only losing water due to groundwater recharge in net losing reaches.

Few studies have concluded that spatial variation in streamflow exists at large scales (Toth, 1963; Freeze and Witherspoon, 1967; Covino and McGlynn, 2007). However results from recent reach-based initiatives have shown that streams can indeed both gain and lose water intermittently and at different rates along varying sections of the

channel (Zellweger et al, 1989; Harvey and Bencala, 1993; Payn et al., 2009). Spatial variation in discharge due to heterogeneity of the channel is recognized at smaller spatial scales, with channel reaches themselves exhibiting concurrent gain and loss across different portions of their profile (Harvey and Bencala, 1993; Szeftel et al., 2011). Net discharge of the catchment provides no indication of the gross (total) gains and losses of water over time and space within the watershed (Szeftel et al., 2011) and thus scale represents an important and sometimes problematic component of streamflow research. Understanding how streamflow varies in response to the hyporheic exchange process, and quantifying these gross estimates of surface-subsurface exchange is important to consider when performing catchment water budget analysis.

2.4 Methods of Identifying and Quantifying Hyporheic Exchange

2.4.1 Hydrochemical Differentiation

The substantial turnover of water associated with surface-subsurface exchange suggests that the hyporheic exchange process will undoubtedly have an effect on solute transport; influencing solute budgets in the stream and regulating water chemistry along different parts of the channel (Jackman et al., 1984; Findlay, 1995; Temnerud et al., 2007). Solute loss occurs in areas of water loss whereas an influx of solutes and nutrients into the stream occurs in areas of water gain within the reach or stream (Harvey and Bencala, 1993; Triska et al., 1993). Longer retention times may result in changes to the chemical composition of hyporheic water if solute is subjected to greater exposure and interaction with the subsurface or groundwater (Findlay, 1995). Biogeochemical alterations to channel water in the subsurface will consequently change the compositional

structure of the stream at locations of return flow. As a result, concentration differences of natural water quality parameters including temperature (Hoehn and Cirpka, 2006; Westhoff et al., 2011), pH (Fowler and Scarsbrook, 2002), ions (Banzhaf et al., 2011), and nutrients (Hendricks and White, 1991; Hinkle et al., 2001) are an adequate tool for identifying regions of exchange along the channel.

2.4.2 End-Member Mixing Analysis

End-Member Mixing Analysis (EMMA) is a technique which uses isotope and/or ion data in mass balance equations to calculate the fraction of runoff or streamflow which originates from different areas of the catchment (Pearce et al., 1986; McDonnell et al., 1990). Deep groundwater, riparian aquifers, and stream water (within the channel or hyporheic zone) may experience different isotopic and chemical concentrations due to their respective locations and time spent within the catchment (McDonnell et al., 1990). Different soil horizons and layers within horizons may have similar isotopic signatures however they may have different concentrations of ion tracers allowing for identification of geographic source areas (Hoeg et al., 2000).

Application of EMMA to groundwater in the near stream subsurface can determine if it is hyporheic in nature based on the geochemical definition requiring no less than 10% stream water contribution (Triska et al., 1989; Gooseff, 2010). Furthermore, the relative concentrations of ions and other chemical constituents in the stream may help to yield estimates of groundwater inflow and determine if hyporheic flowpaths represent the dominant source of streamflow over the course of the study

period (Battin et al., 2003). For a more comprehensive description of EMMA the reader is referred to Buttle (1998) and Hinton et al. (1994).

2.4.3 Tracer Injection and Mass Recovery Analysis

Measurement of physiochemical stream concentration fluxes and EMMA demonstrates the advantage of using water chemistry for hyporheic research. Moreover the conservative nature of some solutes (e.g. sodium chloride, lithium chloride) illustrates their effectiveness in actually quantifying estimates of gross channel water loss and gain. As such, experimental tracer studies have become popular among those investigating the hyporheic exchange process (Zellweger et al., 1989; Zellweger, 1994; Morrice et al., 1997; Payn et al., 2009; Ward et al., 2010).

Steady (constant rate) or instantaneous (slug) injections of tracer are commonly used as a means of discharge measurement through dilution gauging over short lengths of the channel (Kilpatrick and Cobb, 1985; Moore, 2004; Moore, 2005). A known mass of solute tracer is injected at the upstream end of a reach and the concentration of the in-stream solute cloud is measured at the downstream end of the reach. Breakthrough curves (Figure 2.4) illustrate the change in concentration of solute over time at a location within the study reach as it increases from and returns to background concentration. Over longer distances the shape of the curve provides insight into the magnitude and duration of subsurface storage (Bencala and Walters, 1983; Harvey and Bencala, 1993). Changes in solute concentration have been linked to the hyporheic zone (Findlay, 1995).

Figure 2.4. Breakthrough curve illustrating the concentration of rhodamine over time (circles, diamonds, and squares), a slug injected tracer, at three different locations downstream (RM 11.0, 9.5, and 8.0). From Runkel et al. (1999).

Payn et al (2009) with reference to Rieckermann et al (2005) acknowledge that the mass of solute recovered at this downstream end can be quantified as the integration of the product of downstream tracer concentration and downstream discharge. Loss of mass and hence a decrease in concentration of a nonreactive solute indicates loss of water to one or more of the aforementioned flowpaths (Larkin and Sharp, 1992; Ruehl et al., 2006; Payn et al., 2009).

2.4.4 Transient Storage Modelling

Time-concentration data from tracer injections is commonly used for numerical modelling purposes. Transient storage models (TSM) have been developed to simulate the life cycle of solute transport within a specified reach and to quantify transport processes including dispersion, lateral inflow, and subsurface exchange (Bencala and

Walters, 1983; Gooseff et al., 2005; Szeftel et al, 2011). The most commonly used TSM is the One Dimensional Transport with Inflow and Storage (OTIS) model developed by the United States Geological Survey (USGS).

OTIS establishes a ‘best fit’ to the observed tracer concentration data over time plotted as the breakthrough curve (Harvey et al., 1996). Concentration in both the stream (Equation 2.3) and subsurface (Equation 2.4) is determined using two mathematical models (Runkel, 1998):

$$\frac{\partial C}{\partial t} = -\frac{Q}{A} \frac{\partial C}{\partial x} + \frac{1}{A} \frac{\partial (AD \frac{\partial C}{\partial x})}{\partial x} + \frac{q_{LIN}}{A} (C_L - C) + \alpha (C_S - C) \quad (2.3)$$

$$\frac{dC_S}{dt} = \alpha \frac{A}{A_S} (C - C_S) \quad (2.4)$$

where

- A - main channel cross-sectional area (m²)
- A_S - storage zone cross-sectional area (m²)
- C - main channel solute concentration (μS/cm)
- C_L - lateral inflow solute concentration (μS/cm)
- C_S - storage zone solute concentration (μS/cm)
- D - dispersion coefficient (m²/s)
- Q - volumetric flow rate (m³/s)
- q_{LIN} - lateral inflow rate (m²/s)
- t - time (s)
- x - distance (m)
- α - storage zone exchange coefficient (1/s)

OTIS determines optimal hydrological parameters (such as the exchange coefficient and cross-sectional storage area) unique to those study reaches (Gooseff et al., 2005; Runkel et al., 1999). This is usually done through a user specified trial-and-error input approach. However, the addition of a Nonlinear Least Squares algorithm to the model and the use of observed time-concentration data at the downstream boundary of the reach allows for these parameters to be determined automatically (Runkel, 1998). This edition of the

model is known as OTIS-P. Parameter estimates can be used to provide insight into the nature of exchange by measuring two important metrics such as the relative size of the storage zone area, A_s/A (Fernald et al., 2001; Wondzell, 2006), and residence time of water in storage zone flowpaths, $t_s = A_s/A\alpha$ (Harvey et al., 1996; Szeftel et al., 2011). While equations 2.3 and 2.4 describe the fate of conservative solute as governed by physical processes, OTIS can also account for mass loss of non-conservative (reactive) tracer from chemical reactions within the subsurface.

One of the limitations of OTIS however is its inability to distinguish in-stream storage from subsurface storage (Bencala et al., 2011; Szeftel et al., 2011) – loss of solute mass can result from both (Fernald et al., 2001). In-stream storage refers to retention of mass in areas of the stream separated from the main flow (Runkel et al., 1999). These are often attributed to stagnant pockets of water usually along the sides of pools, trapped in circulation (eddies), and behind flow obstructions such as boulders, logs, and vegetation (Bencala and Walters, 1983). Subsurface storage refers to the hyporheic zone or deep groundwater recharge (Gooseff, 2010). As a result gross discharge estimates from tracer experiments may overestimate hyporheic or groundwater flow depending on the magnitude of in-stream storage.

2.4.5 Stream-Subsurface Hydraulic Head Differences and Hydraulic Gradient

Surface-subsurface exchange is ultimately driven by pressure variations between the water and channel bed (Findlay, 1995, Harvey and Bencala, 1993). Water will enter the subsurface along regions of the channel in which the pressure of the water on the surface side of the bed is greater than the pressure within the subsurface (Savant et al,

1987; Woessner, 2000). Consequently, water exits from the subsurface and enters the channel when the pressure is greater beneath the bed (Thibodeaux and Boyle, 1987).

Direction of both vertical and lateral water movement between the surface and subsurface can be inferred from measurement of hydraulic gradients or water level differences using piezometers and wells respectively within the near stream zone. The equation for vertical hydraulic gradient (VHG) as expressed by Baxter et al. (2003) and Anderson et al. (2005) is,

$$VHG = \frac{h_{piezometer} - h_{stream}}{\Delta l} \quad (2.5)$$

where $h_{piezometer}$ and h_{stream} refer to the total hydraulic head of the piezometer and stream respectively, and Δl is the depth between the channel bed and the top of the piezometer screen. If the water level in the piezometer is below the stream surface VHG will be negative and water will flow downwards into the subsurface, whereas if the water level is greater than the stream surface, VHG is positive and water will flow upwards into the stream (Figure 2.5). The methods employed in this research include tracer injection and mass recovery using a conservative tracer, and stream-subsurface hydraulic head differences using piezometers.

Figure 2.5. If the difference in hydraulic head (Δh) between the piezometer and water surface is negative (left) downwelling will occur as indicated by the black arrows. If the difference in hydraulic head is positive (right) upwelling will take place. From Baxter et al. (2003).

2.5 Watershed Control on Exchange Potential

The net gain or loss of water from a stream is composed of the gross gains and losses of water over different reaches over time, which are in turn dependent on the characteristics of the channel and their linkage to the surrounding landscape (Harvey and Bencala, 1993; Harvey et al., 1996; Payn et al., 2009). Wondzell (2006) and Tonina and Buffington (2009) acknowledge that variation in streamflow and water exchange is controlled by a number of factors operating within the watershed. These factors such as valley confinement (Boulton et al., 1998), channel sinuosity (Cardenas et al., 2004), and dune morphology (Wörman et al., 2002) are present at the catchment, reach, and channel bed scales respectively (Figure 2.6).

Buffington and Tonina (2009) recognized multiple hyporheic exchange mechanisms and found a relationship between the type of mechanism at work and the type of channel. Channel types have been classified according to differences in streambed properties which determine pressure gradients of flow between the channel bed and subsurface influencing the scale of exchange (Grant et al., 1990; Wörman et al., 2002; Tonina and Buffington, 2009). Variation in pressure gradients results in a range of spatial and temporal scales in flow and hence a myriad of flowpath lengths and storage areas (Figure 2.6, Dent et al., 2001; Cardenas, 2008).

Figure 2.6. Catchment factors at a range of scales (micro, channel-unit, channel-reach, and valley-segment) influence the magnitude of exchange both spatially and temporally. Micro-scale hyporheic exchange takes place at very small scales through sediment particles by means of turbulent mixing and bedload transport. Channel-unit hyporheic flow may result from step-pool sequences for instance, while meandering represents a channel-reach factor. In addition to these scales valley-segment hyporheic flow can result from changes in valley width or slope and produce the largest hyporheic flowpaths (tens to hundred of meters in length). From Buffington and Tonina (2009).

The relationship between catchment scale (valley-segment) characteristics and hyporheic exchange has garnered much investigation over the last few decades. The scale of surface-subsurface exchange and hence size of the hyporheic zone has been associated with several of these factors including (1) transport potential (i.e. hydraulic conductivity, Morrice et al., 1997) and (2) volume of soil medium (Tonina and Buffington, 2009), (3) slope of the channel bed (Tonina, 2005; Buffington and Tonina, 2009), and (4) transition in valley width or confinement (Stanford and Ward, 1993; Baxter and Hauer, 2000).

The proportion of hyporheic flow contributing to gross channel loss and gain of water has been related to discharge conditions, hillslope water table elevations and hence magnitude of regional groundwater flow into the stream (Boulton et al., 1998; Harvey and Bencala, 1993). Water table drawdown into soil layers with slower transmittance of water and reduced hillslope-stream hydraulic gradients results in less groundwater contribution (Hinton et al., 1993; Spence, 2010) increasing the volume of subsurface available for hyporheic flow (Storey et al., 2003). Jencso et al. (2009) found that in mountain catchments the duration of water table connection across the major landscape units, hillslope – riparian area – stream, was proportional to the size of the local contributing area (LCA). The LCA consists of the entire area of the catchment which drains to a point along the stream. It is hypothesized that longer durations of water table connection lead to greater gross inputs of hillslope groundwater and thus less space for hyporheic flow. Basing their study off the work of Jencso et al. (2009) and Bond et al. (2002), Wondzell et al. (2010) also suggest that reductions in lateral inputs of groundwater from hillslopes combined with greater evapotranspiration could lead to

greater loss of water due to hyporheic flow during baseflow periods. Therefore a fifth catchment scale factor influencing reach scale surface-subsurface exchange could be local contributing area (5).

While research has been intensive, a thorough understanding of these large scale processes in different catchment environments remains necessary for advancing the current conceptual models of surface-subsurface exchange. This study focused on several catchment scale watershed parameters, including factors 3, 4, and 5, for select reaches (as opposed to reach or channel bed scale factors) in an effort to determine if similar relationships exist between catchment properties and magnitudes of exchange.

3. METHODOLOGY

3.1 Study Area

Watershed 8 (W8) is a 2.94 km² catchment in central Gatineau Park, Quebec, Canada (45°32'04.90''N, 75°53'55.10''W) lying above the Eardley Escarpment draining northeast into Meech Lake (Figure 3.1 and 3.2). W8, situated 20 km northwest of Ottawa, Ontario, is located within the boreal shield region of Canada with thin humo-ferric podzolic soils and Precambrian bedrock outcrops. Soil depth within the channel ranged from 0.4 to 1.0 m as is inferred from long piezometer installation base measurements, however bedrock coverage is also nonexistent along portions of the stream network. Elevation from the outlet to the top of the watershed ranges from approximately 160 to 360 m.

Figure 3.1: Location of Watershed 8 (in red) within Gatineau Park (area covered by the DEM). The lighter the pixel colour on the DEM the greater the elevation.

Figure 3.2: Location of reaches within Watershed 8.

Nine reaches were selected for study with reaches: 1 to 6 on the main channel which branches to the west upstream from the outlet, while reaches 7 to 9 are located in a separate subwatershed to the south at a higher elevation. Reach 1 is located approximately 250 meters upstream from the outlet and is separated from reach 2 by a confluence. Reaches 2 to 4 are consecutive and separated from reaches 5 and 6 by another confluence (Figure 3.3). Reaches 7, 8, and 9 are also consecutive (Figure 3.4). The reason for separation of the reaches between confluences was to eliminate the dilution effect of increased discharge. Any positive change in discharge therefore is attributed to groundwater or hyporheic gains avoiding the need to measure discharge of the additional surface water and hence reducing error in gross estimates.

A transition zone associated with a large change in elevation exists running northwest-southeast within the catchment. Reaches 4, 5, 7, and 8 lying along the transition have steeper slopes and may be classified as step-pool channels while reaches 6 and 9 have similar low-grade, meandering morphologies. The abutment of reaches 5 and 6 are similar to that of reaches 8 and 9. Reaches 1-3 below the transition can also be considered step-pool or riffle-pool channel types. Only reach 3 experienced surface water input from tributary development, however this occurrence was restricted to the highest flow week. Large open, pooled wetlands drain into the upstream ends of reaches 6 and 9 providing the source of streamflow.

Figure 3.3: Cross profile of the main channel in Watershed 8 with location of study reaches 1 to 6 and the two confluences. Vertical exaggeration is approximately 2.5x.

Reaches 7 - 9

Figure 3.4: Cross profile of the stream length in the upper subwatershed of W8 with location of study reaches 7 to 9. Vertical exaggeration is approximately 2.5x.

3.2 Field Methods

Six series of tracer injections were performed on the 9 reaches throughout the summer baseflow recession period from July to November 2011; each series occurring over a duration of 2 to 4 days. Slug injections consisted of 200 grams (g) pre-dissolved sodium chloride (NaCl, table salt) in 2 litres (L) of stream water using 1 L plastic Nalgene bottles. The salt was weighed in the lab prior using a scale with an accuracy of ± 0.01 g. Solute concentrations were measured at reach upstream and downstream ends using temperature-corrected Onset HOB0 U24 temperature/specific conductance probes logging at 2 second (s) intervals with a low range of 0-1000 $\mu\text{S}/\text{cm}$ and ± 5 $\mu\text{S}/\text{cm}$ accuracy. A YSI Professional Plus Handheld Multiparameter Instrument was used in the field to measure real-time background concentrations before and after each pulse passed reach downstream end. The loggers were calibrated at the beginning of the study period using stream water and a specific conductance ($\mu\text{S}/\text{cm}$) to concentration (g/L) relationship was modeled for each and concentrations were calculated using the following:

$$c_t = \frac{(SC_t - SCb)}{S_H} \quad (3.1)$$

where,

- c_t -concentration at given point in time expressed in grams per litre (g/L)
- SC_t -specific conductance at given point in time expressed in microsems per centimeter ($\mu\text{S}/\text{cm}$)
- SCb -background specific conductance of the stream water ($\mu\text{S}/\text{cm}$)
- S_H -slope of the concentration-specific conductance relationship for the given HOB0 determined in the lab before the study period (all slopes are derived from linear relationships and are reported at the bottom of Appendix F)

3.2.1 Discharge

Two methods of discharge measurement were utilized: i) velocity-area using a SonTek Flo Tracker, and ii) dilution gauging (equation 3.2), assuming complete mass recovery, with mixing lengths ranging from 15 to 45 meters. Mixing lengths differed in response to flow conditions and channel characteristics. Lengths were reduced during low flow weeks in some reaches for the purpose of minimizing solute loss prior to reaching the HOBO logger. Larger distances at greater baseflows were used to ensure sufficient travel time for complete mixing. Furthermore, both reach lengths and mixing distances varied in order to locate ideal injection points within the channel free from braided stream sections and pockets of slow moving water.

$$Q = \frac{M_i}{\sum_{t=1}^n c_t T} \quad (3.2)$$

where,

- Q -discharge expressed in litres per second (L/s)
- M_i -injection mass expressed in grams (g) and is constant at 200g
- c_t -concentration at given point in time expressed in grams per litre (g/L)
- T -logging interval expressed in seconds (s) and is constant at 2s

Each slug injection for discharge measurement at the upstream end of the reach was used to measure solute loss at the downstream end of the reach. For consecutive reaches, discharge measured at the upstream of a reach (e.g. reach 2) was subsequently used as the discharge measurement at the downstream end of the next reach (e.g. reach 3). Similar to Payn et al. (2009) this method conserved time and salt and as a result the first injection of the field week began at reach 1 near the outlet with each succeeding injection taking place as the team progressed upstream.

3.2.2 Solute mass loss

Mass recovery was quantified from the downstream concentration pulses for each upstream injection assuming constant discharge at the downstream end (equation. 3.3).

Concentration refers to the solute content in g/L as opposed to specific conductance.

$$M_r = \sum_{t=1}^n c_t T Q_d \quad (3.3)$$

where,

M_r - mass recovered at the downstream end of the reach from the upstream injection pulse (g) using the concentration of the pulse at the downstream end
 Q_d - reach downstream discharge (L/s)

The mass lost from the reach over the length of study becomes the difference between the amount injected and the amount recovered at the downstream end, as follows:

$$M_l = M_i - M_r \quad (3.4)$$

M_l - mass lost from the channel to hyporheic or groundwater flowpaths (g)

3.2.3 Gross hydrological loss and gain

Gross potential maximum and minimum hydrological losses and gains (L/s) were calculated following the methods of Payn et al. (2009). A range of loss and gain is in relation to the nature of exchange within the channel and where mass loss takes place along the reach. Minimum estimates assume all solute loss occurs upstream before the dilution effect of gross gains into the stream along the channel.

$$Q_{lmin} = \frac{M_l}{\sum_{t=1}^n c(u)_t T} \quad (3.5)$$

$$Q_{gmin} = Q_n - Q_{lmin} \quad (3.6)$$

$$Q_n = Q_d - Q_u \quad (3.7)$$

where,

- Q_{lmin} -minimum gross loss from the channel (L/s)
- $c(u)_t$ -the concentration of the solute pulse at the upstream end of the reach (g/L)
- Q_{gmin} -minimum gross gain to the channel (L/s)
- Q_n - net discharge (L/s)
- Q_d -discharge at the downstream end of the reach (L/s)
- Q_u -discharge at the upstream end of the reach (L/s)

Whereas maximum loss and gain takes place at the far downstream end of the reach theoretically when the reach is subjected to the greatest contribution of inflow along its length (Payn et al., 2009):

$$Q_{lmax} = \frac{M_l}{\sum_{t=1}^n c(d)_t T} \quad (3.8)$$

$$Q_{gmax} = Q_n - Q_{lmax} \quad (3.9)$$

where,

- Q_{lmax} -maximum gross loss from the channel (L/s)
- $c(d)_t$ -the concentration of the solute pulse at the downstream end of the reach (g/L)
- Q_{gmax} -maximum gross gain to the channel (L/s)

A range in potential gross water loss and gain is possible. Mass loss depends on specific conductance and is therefore a measure of solute concentration of the water. If it is assumed that all mass loss occurred upstream before any gross discharge gains to the reach then this represents the minimum proportion of gross water loss from the reach over the period of study. The solute concentration of the injection at the upstream end $c(u)_t$ is used to quantify this proportion of gross water loss, as is expressed in Equation 3.5. The solute concentration will decrease as more water enters the reach from subsurface flow, diluting the injection mass as it travels downstream. As a result if solute mass loss occurs after or during gross water gain to the channel it will take a substantially

greater proportion of gross water loss in order to account for that same percentage of solute mass loss. The reduced solute concentration of the injection at the downstream end of the reach assumes a condition of complete dilution within the study period and hence represents the maximum potential proportion of gross water loss from the reach. As can be inferred from Equation 3.8 it will require greater gross water loss (Q_{lmax}) to produce the same mass loss value (M_l) because the solute concentration at the downstream end $c(d)_t$ is much less than the concentration at the upstream end $c(u)_t$. Minimum and maximum proportions of gross water loss and gain refer to the ratio of gross discharge to discharge at the upstream end of the channel providing a measure of how much water was added to or lost from channel flow over the reach length and course of the study period. In this study baseflow recession and gross discharge loss due to evaporation was assumed negligible within the time of contact, however their effect could lead to overestimates of gross gain and underestimates of gross loss as indicated by Payn et al. (2009).

3.2.4 Contact Time

The time for each solute cloud to travel the reach and completely pass the downstream HOBO logger, referred to as the time of contact, was also recorded using HOBOWARE PRO software and Microsoft Excel. Mass loss was normalized to reach length as reach distance varied from 102 to 225 m (mass loss/reach length, ML/RL). These values were further normalized to contact time (ML/RL/T) as it is suggested that mass loss is dependent upon the amount of time solute is exposed to exchange along the channel. High losing reaches with the shortest lengths and contact times should have the greatest exchange potential.

3.2.5 Piezometers

Two piezometers were placed next to one another in each reach except for 7 and 8 (due to insufficient soil depth) in order to determine magnitudes of hydraulic head.

Water level differences between the stream and each piezometer were measured and used to indicate the direction of vertical subsurface water flow:

$$\Delta h_{stream-long} = h_{stream} - h_{long} \quad (3.10)$$

$$\Delta h_{stream-short} = h_{stream} - h_{short} \quad (3.11)$$

$$\Delta h_{short-long} = h_{short} - h_{long} \quad (3.12)$$

where,

h_{stream}	- hydraulic head of the stream water surface
h_{long}	- hydraulic head of the water in the long piezometer
h_{short}	- hydraulic head of the water in the short piezometer
$\Delta h_{stream-long}$	- head difference between the stream and long piezometer
$\Delta h_{stream-short}$	- head difference between the stream and short piezometer
$\Delta h_{short-long}$	- head difference between the short and long piezometers

If the difference in hydraulic head is positive then water is lost from the stream downwards into the subsurface. Consequently if the difference in head is negative then water is gained to the channel upwards from the subsurface into the stream.

One piezometer was inserted deeper than the other and placement location varied among reaches. Piezometric dimensions and installation depths are provided in Table 3.1 and 3.2 respectively. Water level within the piezometers was measured immediately before upstream injection using one of two methods: an electronic water level meter, or through the use of a plastic blow tube and measuring the length of tube from water level to piezometer head. The blow tube method was employed when piezometer access ports

damaged during installation prohibited beeper insertion. Water levels were first measured from the top of each respective piezometer. Hydraulic head was then determined as the difference between the distance from the top of the piezometer and the datum (the base of the long piezometer at each site in this study), and the water level measurement. Stream surface water levels were measured from the top of each piezometer to the stream surface along the outside of the piezometer.

Table 3.1: Piezometric Dimensions (in centimeters).

	Short Piezometer	Long Piezometer
Drive point:	22	22
Shaft:	45.9	122.2
Total length:	67	143.3

Table 3.2: Piezometer installation depths (in centimeters).

Reach	Short Piezometer	Long Piezometer
1	38.8	103.8
2	36.1	57.5
3	27.8	56.4
4	24.2	36.5
5	34.9	72.8
6	40.8	94.3
7	----	----
8	----	----
9	47.6	84.8

3.2.6 Multiple tracer mass experiment

Four series of tracer injections were conducted on reach 2 using four different injection masses (50, 100, 200, and 400 grams) each field week in order to assess the influence of tracer mass on interpretation of hyporheic exchange. This experiment was

carried out during weeks 1, 2, 5, and 6. The experiment began with an injection at the downstream end of the reach to measure downstream discharge. An injection of the same mass was then conducted at the upstream end of the reach. Passage of this upstream injection solute cloud was observed at the downstream end using the YSI and immediately following a return to near background concentration the team proceeded with the downstream injection of the second injection mass. The first injection mass to be released was 50 g followed in order by 100 g, 200 g, and 400 g. Each injection was conducted under the same weekly discharge and over the same reach distance and mixing lengths.

3.3 Software Methods

3.3.1 Watershed properties in Arcmap10 and SAGA

Several watershed topographic parameters were determined for each reach using ArcMap10 (ESRI, 2011) and System for Automated Geoscientific Analyses (SAGA, Olaya and Conrad, 2009):

- A. Channel Slope
- B. Local Contributing Area
- C. Average Valley Width (at 3m elevation above water surface)
- D. Mean Catchment Slope or Downslope Distance Gradient
- E. Drainage Slope ($\text{Vertical Overland flow Distance} / \text{Overland flow Distance}$)
- F. Wetness Index ($\text{Local Contributing Area} / \text{Valley Slope}$)
- G. Reach Length / Channel Slope
- H. $[\text{Reach Length} \times \text{Average Valley Width}] / \text{Channel Slope}$
- I. Local Contributing Area / Reach Length

A LiDAR based digital elevation model (DEM) of Gatineau Park with a spatial resolution of 5 meters was imported to SAGA as a grid file from ESRI Arc/Info. The grid was subsequently clipped to a larger scale encompassing W8 and all sinks were

filled using the *Planchon and Darboux (2002)* method with minimum slope angle of 0.01. Following the preprocessing stage catchment area for the grid was established using the *recursive* module with deterministic 8 method and 1.1 convergence. Channel network and direction were then formed with an initiation threshold greater than 45000 m² of upstream watershed area, and maximum divergence and minimum segment length of 5 and 50 cells respectively.

Reach endpoints were recorded in the field as a point shapefile with the use of a handheld Trimble Global Positioning System (GPS) and NAD 1983 NSRS 2007 UTM Zone 18N as the projected coordinate system. Each reach was created as its own feature or line shapefile in ArcMap10, delineated with the aid of the imported endpoints and a pre-existing stream network shapefile for the park. The reach shapefiles were loaded into SAGA and channel slope was determined from applying the *Profiles From Line* module. Contributing watershed areas for each reach endpoint were created from the *Upslope Area (Interactive)* module again using the deterministic 8 method with a 1.1 convergence. *Vectorizing Grid Classes* module altered area grids to shapefiles after converting each to no data with the grid calculator.

Each reach shapefile was further converted to a grid using the *Shapes To Grid* module and threshold buffers created of all cells up to 3 m above the reach. The 3 m buffers were clipped at their upstream ends using the watershed polygons and areas were calculated from the remaining cell count. Dividing the 3 m areas by their respective reach lengths equates to an average valley width at the specified height above reach cell. Local contributing area, mean catchment slope, drainage slope, and wetness index for each reach were all calculated using the *Grid Statistics From Polygons* module.

Parameters D, E, and F are measures of both runoff and storage potential within the catchment and the potential effect they might have on surface-subsurface exchange was examined in this study.

3.3.2 General Statistical Approach

Solute mass loss values and gross discharge loss and gain estimates were quantified using Microsoft Excel and statistical analysis was performed using R statistical software (R Development Core Team, 2009). Discharge measurements for each method were plotted against each other and a series of test statistics (Wilcoxon Rank Sum test and T-test, paired and unpaired) were used to evaluate the precision of each method of discharge measurement. Linear regression was applied to the relationship mass loss per reach length (ML/RL) vs. discharge (Q), and ML/RL vs. time of contact (T), and for all relationships between GIS based catchment parameters and ML/RL with a significance level of 5%. Variability in mass loss between injection amounts for each week was assessed and the ANOVA test was performed using the results of the multi-mass experiment to determine if the mean mass loss (%) values for each week were significantly different from one another.

4. RESULTS

4.1 Discharge Measurements

Discharge (Q) decreased throughout the study period ranging 82 to 5 L/s at the downstream end of reach 1 and subsequently increased during week 6 in response to more frequent fall precipitation events (Figure 4.1). Dates of each field week and their corresponding reach 1 downstream discharge are presented in Table 4.1. Variation in downstream discharge among each reach decreased as flow rates decreased. Weeks 4 and 5 had the lowest baseflow and smallest range in discharge across all reaches.

The lower reaches within the watershed exhibited greater rates of baseflow drawdown and hence greater ranges in discharge (Figure 4.2). Discharge was not measured at reaches 7, 8, and 9 on week 5 due to long contact times and time constraints in the field, however it is expected that discharge rates would be similar to week 4. For all field weeks the spatial series of discharge showed the distinct separation of reaches along the stream, most noticeable on week 1. Large decreases in discharge that occurred between reaches 1 and 2, and reaches 4 and 5 and were due to confluences (Figure 2.2 and 2.3). The decrease in discharge between reach 6 and 7 illustrated in Figure 4.2 reflects the differences between sub watersheds where reaches 7, 8, and 9 are separated from the main channel (Figure 2.2).

Table 4.1: Field week dates and discharge near the outlet.

Field Week	Field Dates, 2011	Reach 1 Downstream Discharge (L/s)
1	July 4-8	82
2	July 19-22	26
3	August 15-17	14
4	August 29 – September 2	5
5	October 10-13	5
6	October 31 – November 3	36

Figure 4.1: Downstream discharge rates for each reach.

Figure 4.2: Downstream discharge rates by field week.

Net discharge (ΔQ), defined as the difference in discharge between the downstream and upstream end of the reach, approached 0 L/s for all reaches as baseflow receded (Figure 4.3). The range in ΔQ across all reaches was greater under higher flow conditions. Reach 1 remained a net losing reach for all six weeks (Figure 4.4). All other reaches were net gaining throughout the summer with the exception of reach 7 during week 1, reaches 6 and 7 during low flow week 4, and reach 3 for weeks 4 and 5. Reach 3 also experienced the greatest change in discharge during the two highest flow weeks and the much greater inflow associated with week 1 may in part be related to additional water input from development of a small ephemeral tributary. As a result this reach seems to be the most responsive to changes in baseflow.

Figure 4.3: Change in discharge for each reach from upstream to downstream end

Figure 4.4: Change in discharge for each field week.

Discharge was determined via two methods: dilution gauging and the velocity-area method. Most of the points on the plot (Figure 4.5) lie close to the 1:1 line, which would suggest good agreement in the measurements between the two methods. Spearman's correlation ($r=0.95$) is strong and significant and the slope of the best-fit line is 0.98 which implies a very strong near 1-to-1 relationship between the two sets of observations. The coefficient of determination is significant and close to 1 ($R^2=0.95$). However the residuals of this relationship violate the assumptions of normality and homoscedasticity, suggesting these measures may be unreliable when assessing the precision of both methods. As a result the difference of the distributions of each method were tested for significance.

Both samples have positively skewed distributions. Variance is not significantly different between the distributions ($F = 0.96$, $p = 0.87$). The unpaired Wilcoxon Rank Sum (Mann-Whitney U) test also indicated that there is no significant difference between the two distributions ($p = 0.48$). However, the paired Wilcoxon test indicates that there is indeed a significant difference ($p = 0.04$).

Figure 4.5: Observation data from the two methods of discharge measurement plotted against one another with the 1:1 line running through the points.

Both samples were transformed in order to produce normal distributions using an $x^{0.08}$ transformation with insignificant differences between variances ($F = 0.76$, $p = 0.24$). Mean discharge is not significantly different using an unpaired two sample t-test ($p = 0.38$), but they are different using a paired two sample t-test ($p = 0.0002$). The mean of

the differences between paired observations is 0.7 L/s for the original untransformed discharge values and 2.3 L/s for the absolute differences between observation pairs. Discharge differences were smaller during low flows and most less than the mean difference (Figure 4.6). However the low flow differences represent greater proportions of surface discharge upon standardizing to their respective average discharge values between each method (Figure 4.7). The majority of the discharge differences at intermediate and high baseflow periods were much lower and represent only a small portion of the surface discharge.

Figure 4.6: Absolute discharge differences plotted against the downstream discharge value using dilution gauging and their values relative to the mean of the absolute discharge differences (2.3 L/s) depicted as the horizontal line.

Figure 4.7: Absolute discharge differences standardized to their respective average discharge value of the two methods, and plotted against downstream discharge (dilution gauging). The dependent variable represents the proportion of discharge represented by the difference observed between methods.

Despite a strong correlation between observations of the two methods there remains discrepancy in discharge values and distributions. Only one set of discharge measurements is required for mass recovery analysis. As a result and in light of the fact that the discharge measurements differed, the discharge values obtained from dilution gauging were used in mass loss quantification as the Flow Tracker was sometimes met with measurement error and high discharge uncertainty, often during low flows.

Velocity-area methods have also been found to be less accurate in small streams in other studies (e.g. Day, 1977). Flow Tracker data is included in Appendix G.

4.2 Solute Mass Loss

High solute exchange existed for all reaches despite most exhibiting slight positive net discharge values. Mass loss of solute varied for each reach and for each field week. Loss of solute mass increased in all reaches as discharge decreased (Table 4.2). Percentages were small (0 – 10%) during high flows with the exception of reach 7 that lost nearly 40%. Large increases in mass loss occurred during low flow weeks, with a maximum loss of 88% occurring at reach 4 during week 5. Missing data was the result of contact times exceeding the time available for field study and hence an incomplete record of recovered solute. Additional mass loss data is presented in Appendix A and specific conductance data is reported in Appendix F..

The pooled data in Figure 4.8 suggests a power law relationship between discharge and mass loss per reach length (ML/RL). Generally as discharge decreased ML/RL increased. Mass loss increases greatly at low discharge and piecewise regression analysis determined a change in the slope of the relationship (mass loss rate) at ~10.6 L/s. For individual reaches, the relationships become much stronger (Table 4.3). Reaches 1 to 6 showed significant correlation between the log transform of mass loss and discharge with Pearson's R ranging from -0.95 to -0.99. The R^2 values for linear regressions range from 0.88 to 0.99 (all significant). Reaches 7 and 8 do not have enough observations to make reliable inferences. The correlation and linear relationship between $\log(Q)$ and $\log(ML/RL)$ for reach 9 ($r=-0.68$, $R^2=0.28$) are not significant. A breakdown of significance testing for each relationship is provided in Appendix B.

Table 4.2: Mass loss (%) data for each reach on each field week with corresponding reach 1 downstream discharge.

Reach	Week 1 82L/s	Week 2 26L/s	Week 3 14L/s	Week 4 5L/s	Week 5 5L/s	Week 6 36L/s
1	4.3	13.0	24.6	51.0	33.8	9.9
2	7.0	29.8	34.9	76.8	68.1	22.3
3	4.5	20.0	27.5	64.9	64.2	21.3
4	13.2	30.4	37.7	79.1	87.6	24.8
5	6.8	18.4	23.5	39.7	48.4	15.7
6	0.9	15.4	16.2	62.0	62.8	9.9
7	37.5	--	--	--	--	41.5
8	2.1	8.9	--	--	--	28.9
9	12.6	14.1	16.8	66.8	--	23.3

Figure 4.8: Mass loss per reach length data plotted against discharge for all reaches.

Table 4.3: Coefficient of determination and associated P value for each reach log ML/RL vs. log discharge relationship.

Reach	Adjusted r ²	P value
1	0.95	0.0006
2	0.95	0.0001
3	0.93	0.001
4	0.99	<0.0001
5	0.97	0.0002
6	0.88	0.004
7	--	--
8	0.42	0.64
9	0.28	0.21

Spatial and temporal variability in solute mass loss existed along the stream channel. The lowest flow weeks (4 and 5) exhibited the greatest amounts of loss for all reaches with loss ratios noticeably greater than the other weeks (Figure 4.9a). During week 4 the HOBOS were inadvertently removed from reaches 2 to 4 before the injection pulses completely passed the downstream end of reaches 3 and 4. Injections were performed a second time for these three consecutive reaches during this field week. Mass loss results for both injections to reach 2 were included in the plot as downstream discharge was the same on both days.

Trends can be interpreted among reaches. When mass loss was normalized to reach length, reaches 1, 4, and 7 lost the greatest solute mass. The boxplots of each reach and their mean mass loss values confirmed this observation (Figure 4.9b). Reach 7 lost the most mass for the two high flow weeks sampled and if mass recovery was possible during weeks 2 to 5 it is hypothesized that it would also lose the most solute for all weeks.

Reach 2 also lost more mass relative to the other remaining reaches (3, 5, 6, 8, and 9), which was more pronounced for the weeks with intermediate flows (2 and 3). While reach 2 lost a large amount of mass (in grams), its magnitude of loss decreased becoming less relative to others because it is one of the longer reaches. Reach 6 experienced a high proportion of loss during the lowest flow weeks compared to the others despite losing the least during higher flow states. Reach 9 is similar in that respect.

Figure 4.9: (a) Mass loss per reach length (ML/RL) by reach for each field week, and (b) boxplots of ML/RL by reach.

The proportion of net discharge ($\Delta Q/Q_u$) entering or exiting the channel for each reach was compared with its associated mass loss per reach length for all six field weeks (Figure 4.10 and 4.11). Under high flow conditions the greatest loss of mass occurred in reach 7, coinciding with a large fraction of water loss from the stream. It is important to note that reach 7 also had the longest solute contact times. During weeks 1 and 6 reaches with the greatest proportion of water added to their channels lost the least solute with the exception of 9. Reaches 2, 4, and 5 all lost greater amounts of solute mass, which coincided with their lower fractions of water input. The opposite was true for reaches 3, 6, and 8. This relationship however between fraction of incoming discharge and proportion of mass leaving the channel experienced at high discharge is not found for week 2 to 5 during intermediate and low flow conditions.

Reaches 1, 2, and 4 continued to have the greatest loss for each week. The fraction of water leaving reach 1 increased as discharge decreased. Reaches 4 and 9 both had a high fraction of water input to the channel, however their relative mass loss values were high compared to the other reaches during this period of recession. Furthermore, in subsequent low flow weeks, reaches with a small fraction of channel water input had reduced proportions of mass loss. During low flows, both net losing reaches 3 and 6 had a larger increase in the proportion of mass loss, that were close yet still less than reaches 2 and 4. Reaches 2 and 4 remained the largest losing reaches despite the fact that they had positive fractions of water input.

4.3 Gross Hydrological Gains and Losses

High percentages of solute mass loss coupled with small changes in discharge (ΔQ) from upstream to downstream end for most reaches resulted in large magnitudes of both gross discharge loss and gain along the channel. For instance, on week 2, reach 2 had a net gain of 0.7 L/s but lost 30% solute mass. This 30% gross channel water loss equates to 4.6 L/s discharge loss from the reach. A gain of 5.3 L/s was subsequently needed to balance out the loss. Net discharge (ΔQ) is the difference between the gross gains and losses of water that occur concurrently along the reach due to water exchange from both groundwater and hyporheic flowpaths. Gross values refer to the total unit discharge of both incoming and outgoing water to and from the channel respectively over the duration of the study period.

Gross discharge losses and gains generally decreased for all reaches as baseflow receded, however these values represent increased proportions of subsurface input and output as a fraction of the upstream surface discharge. For example, minimum gross gain and loss for reach 4 decreased from 9.5 and 6.4 L/s (week 1) to 5.8 and 3.9 L/s respectively (week 2). However, these values represent increased proportions of channel flow from 21 and 14 % (week 1) to 45 and 30 % respectively (week 2). Minimum gross channel water loss during low flow conditions ranged from 34% to 88% of reach upstream discharge with maximum potential gross losses exceeding 100% for most reaches.

Figure 4.10: Barplots of proportion of upstream discharge ($\Delta Q / Q_u$) added to or lost from the channel (blue), and mass loss per reach length (red) for weeks 1 to 3. Time of contact is added as a line graph (green).

Figure 4.11: Barplots of proportion of upstream discharge ($\Delta Q/Q_u$) added to or lost from the channel (blue), and mass loss per reach length (red) for weeks 4 to 6. Time of contact is added as a line graph (green).

Gross discharge loss and gain along the channel is expressed as a proportion of upstream discharge in Figure 4.12 and 4.13. Appendix C contains both maximum and minimum values for discharge gain and loss in three different water budget measurement units – litres per second, percentage of upstream discharge, and litres (total volume). The proportions of gross gain and loss increased for each reach as discharge decreased throughout the summer to the lowest flow conditions during weeks 4 and 5. These proportions decreased as discharge increased from week 5 to week 6. There was negligible gross gain to reach 1 during higher flow weeks 1,2, and 6, however at intermediate to low flow the net loss of water from this reach could not account for all solute exchange. Gross loss from reach 1 was much greater than net loss in discharge during weeks 3, 4, and 5 resulting in considerable gross gain to this reach. Reaches 2, 4, and 7 lost considerable mass because they had the largest fractions of upstream discharge loss from their channels. Such reaches under net gaining conditions exhibited large magnitudes of gross discharge loss in order to exchange such high percentages of solute. These losses are counteracted by even greater magnitudes of gross gain.

4.4 Contact Time

The pooled set of data showed a positive correlation between contact time and ML/RL – the longer the time spent in the channel the more mass that was lost from the solute cloud (Figure 4.14). Reaches 1 to 6 showed significant correlation between mass loss and contact time with Pearson's R ranging from 0.84 to 0.99. The r^2 values range from 0.63 to 0.96 (all significant, Table 4.4). Reaches 7 and 8 did not have sufficient observations for statistical testing. The coefficient of determination for reach 9 ($r^2=0.33$)

is insignificant. An extensive breakdown of significance testing for each relationship is provided in Appendix D.

The slope of the relationship between contact time and ML/RL is greatest for reaches 1, 4, and 2 (similar to ML/RL vs. Q in Figure 4.8). The larger the slope, the greater the mass loss per reach length value per unit time (ML/RL/T). The slopes for these three reaches lie above those for reaches 3, 5, 6, 8, and 9 for similar contact times and hence were more conducive to mass loss, or had greater exchange potential. Only two observations were found for reach 7 making definitive statements about mass loss rate difficult.

When normalized to contact time reaches 2, 4, and 7 still maintained high magnitudes of solute mass loss, however reach 1 experienced the greatest magnitude of loss for most weeks (Figure 4.15a). The means of the ML/RL/T for each reach (Figure 4.15b) confirm the interpretation from Figure 4.15a. The variation in loss among weeks for each reach also decreased, removing the large increase in loss associated with low flows and low flow mass loss ratios were no longer the greatest. A strong inverse relationship exists between discharge and travel time of channel water. This would lead to a positive correlation between contact time and mass loss. However the reduction in variability of normalized mass loss between weeks suggests mass loss within a reach has some dependence upon time of contact.

Gross gain (%) - Q_g / Q_u , Gross loss (%) - Q_l / Q_u , Downstream Discharge (L/s)

Time of Contact (s)

Figure 4.12: Barplots of gross proportions of upstream discharge gained to (Q_g/Q_u , red) and lost from (Q_l/Q_u , blue) the channel for weeks 1 to 3. Whiskers extended above and below the bars represent the maximum proportional gains and losses respectively. Time of contact (green) and downstream discharge (purple) are added as lines.

Figure 4.13: Barplots of gross proportions of upstream discharge gained to (Q_g/Q_u , red) and lost from (Q_l/Q_u , blue) the channel for weeks 4 to 6. Whiskers extended above and below the bars represent the maximum proportional gains and losses respectively. Time of contact (green) and downstream discharge (purple) are added as lines.

Figure 4.14: Mass loss per reach length data plotted against time of contact for all reaches.

Table 4.4: Coefficient of determination and associated P value for each reach ML/RL vs. time of contact relationship.

Reach	Adjusted r^2	P value
1	0.63	0.04
2	0.79	0.004
3	0.96	0.0003
4	0.95	0.0001
5	0.95	0.0006
6	0.74	0.02
7	--	--
8	0.4	0.63
9	0.33	0.18

Figure 4.15: (a) Mass loss per reach length normalized to contact time (ML/RL/T) by reach for each field week, and (b) boxplots of ML/RL/T by reach.

4.5 Vertical Water Flow

Water level comparisons (change in hydraulic head) were initially determined between the stream surface and each piezometer, and between the short and long piezometers. Water levels were measured from the base of the long piezometer drive point, which also acted as the datum. Differences in direction were common at each reach and between methods. As a result hydraulic head and direction of vertical water

flow was determined using the difference between the stream surface and water level within the long piezometer. In addition all measurements were derived from applying the blow tube method as the measurement beeper could only be inserted in 6 of the 14 piezometers.

Water flow directions were consistent at each site with loss of water from the stream to the subsurface occurring in reaches 1, 2, 3, and 4 during all field weeks (Table 4.5). Reach 9 lost water at its piezometer location for the first three weeks, which gradually reversed to a groundwater recharge site during week 6. Reaches 5 and 6 gained water to their channels at their respective piezometric locations throughout the study period. Hydraulic head differences and general flow rates of water loss were large and constant for net losing reach 1. Large, positive differences were present during the first two flow weeks at reach 9, however these decreased with baseflow drawdown towards a no vertical flow state. Similar to reach 1, head differences were fairly constant (1 to 2 cm fluctuations) for reaches 2, 3, and 4 but were of much smaller magnitude. Gaining reaches 5 and 6 also experienced large water level and hydraulic head differences. These decreased substantially in magnitude however as baseflow receded suggesting a decrease in the rate of gross discharge gain into the reach at those locations.

Table 4.5: Weekly hydraulic head (cm) differences and corresponding direction of water flow for each reach. Positive water level differences imply flow from the stream into the subsurface, whereas negative differences imply the opposite.

Reach	Week 1		Week 2		Week 3		Week 4		Week 5		Week 6	
1	13.8	Loss	14.3	Loss	13.6	Loss	12.1	Loss	14.6	Loss	16.5	Loss
2	1	Loss	0.7	Loss	1.4	Loss	1.9	Loss	2.2	Loss	3.8	Loss
3	2	Loss	1.2	Loss	2.7	Loss	2.9	Loss	3.8	Loss	3.5	Loss
4	0.9	Loss	1.2	Loss	-0.3	Gain	0.3	Loss	2.1	Loss	1.3	Loss
5	-17.9	Gain	-13.5	Gain	-12.4	Gain	-9.8	Gain	-7.9	Gain	-12.5	Gain
6	-20.6	Gain	-15	Gain	-13.1	Gain	-9.2	Gain	-7.6	Gain	-6.7	Gain
7												
8												
9	34.6	Loss	17.7	Loss	3.2	Loss	0	No Flow			-1.6	Gain

4.6 Multi-mass Experiment

Mass loss data for the multiple tracer load experiment is reported in Table 4.6. The percentage of mass loss should theoretically be the same for each injection for each field week given the same downstream discharge and reach length, as this experiment was only conducted on reach 2. However there was high variability in mass loss (10 to 20%) between injection amounts for each field week with weeks 1 and 4 showing overlap in mass loss data (Figure 4.16a and b). The 50 g injection from week 1 resulted in mass loss percentages greater than the 100, 200, and 400 g injections during the lower flow period week 4.

Table 4.6: Mass loss values (%) for each injection mass on each field week. Downstream discharge is provided beside each week.

Injection Mass (g)	Week 1 – 36.9L/s	Week 2 – 10.7L/s	Week 3 – 3.3L/s	Week 4 – 18.7L/s
50	28.2	46.2	52.2	29.8
100	7.3	36.0	59.4	11.3
200	10.9	36.4	66.7	16.4
400	13.7	42.9	68.8	25.9

Results from both tests suggest a significant difference of means/distributions for all four weeks ($p < 0.05$). However both a t-test (Table 4.7) shows that weeks 1 and 4 are not significantly different in terms of their means ($p > 0.05$) despite an 18L/s difference (50% reduction) in downstream discharge.

Figure 4.16: (a) Mass loss (%) data for each injection amount by field week, and (b) boxplots of mass loss (%) by week.

Table 4.7: T-test P values between mass loss (%) means for each week pair of the multi-mass experiment and their significance ($p < 0.05$, Yes or No).

	Week 1	Week 2	Week 3	Week 4
Week 1		0.006	0.0003	0.39
Week 2	YES		0.005	0.01
Week 3	YES	YES		0.0004
Week 4	NO	YES	YES	

The purpose of the multi-mass experiment was to determine if injecting different amounts of tracer into the same reach under similar flow conditions would lead to different proportions of mass loss. It was found in this study that different injection amounts did lead to a high degree of variability in percent mass loss, despite a constant reach length and discharge. The 50 g injection mass lost the most for all weeks except the lowest flow week (week 3) in which the 400 g injection lost the maximum (Figure 4.16a). The 400 g injection lost the second most for the three other weeks. It was hypothesized that contact time has some influence on mass loss and may account for the variability among injection amounts. When normalized to contact time (Figure 4.17) the percentage for each injection is still not the same for each field week and the variation is not reduced, with increases observed for the high flow weeks.

Figure 4.17: Mass loss normalized to contact time for each injection by each respective field week.

4.7 Catchment Parameters and Relation to Mass Loss

Inter-reach variability in mass loss has been previously ascribed to watershed control on exchange potential (Payn et al., 2009). However, all watershed properties analyzed in this study showed no significant relationship with mass loss result after assuming and applying linear regression to the pooled data. Plots for each of the 9 watershed variables tested in this study show no discernible correlations with mass loss over the entire study period (Figure 4.18, 4.19, and 4.20). Catchment parameter values for each reach are provided in Appendix E.

Figure 4.18: Mass loss per reach length plotted against GIS-derived watershed parameters (a) channel slope, (b) local contributing area, and (c) average valley width at 3m elevation above the stream surface, for each reach by field week. Reach 1 downstream discharge is provided for each field week in the legend.

Figure 4.19: Mass loss per reach length plotted against GIS-derived watershed parameters (a) mean catchment slope, (b) drainage slope, and (c) wetness index, for each reach by field week. Reach 1 downstream discharge is provided for each field week in the legend.

Figure 4.20: Mass loss per reach length plotted against GIS-derived watershed parameters (a) reach length/channel slope, (b) [reach length x average valley width] / Channel Slope, and (c) local contributing area/reach length, for each reach by field week. Reach 1 downstream discharge is provided for each field week in the legend.

5. DISCUSSION

The purpose of this study was to observe and quantify surface-subsurface exchange of channel flow in order to gain a better understanding of the dynamics of two-way water exchange along small streams during baseflow conditions. Tracer injections were applied at the reach scale and mass recovery analysis of conservative solute (NaCl) was used to quantify simultaneous gross water gains and losses along the channel. These stream zone, reach scale measurements of concurrent discharge and recharge along the surface-subsurface boundary provide an indication of the relative magnitude of hyporheic exchange within different areas of the catchment.

Several studies have focused on the hyporheic zone and exchange process, in particular their relation to channel morphology (Anderson et al., 2005; Wondzell, 2006; Crispell and Endreny, 2009; Rosenberry et al., 2012) and effect on subsurface water chemistry (Fowler and Scarsbrook, 2002; Greenwald et al., 2008; Argerich et al., 2011; Sawyer et al., 2012). However there has been limited research that actually quantifies hyporheic contributions through a longitudinal stream water balance approach. Typically, these studies determined gross gains and losses from hydraulic gradients and water flux estimates using a series of wells and piezometers (Harvey and Bencala, 1993; Hinkle et al., 2001; Covino and McGlynn, 2007).

In addition to their extensive use in discharge measurement, solute tracers have frequently been used in surface-subsurface exchange research. Qualitatively tracer concentrations are used as markers in wells to delineate the extent of storage zone areas while quantitatively they are used for transient storage modelling in order to determine residence times of stream water in hyporheic flowpaths (Harvey and Bencala, 1993; Wondzell, 2006). Unlike most others, the research methods presented here (adapted from

Payn et al, 2009) used conservative tracer concentrations (i.e. specific conductance) to estimate both the mass loss of solute and the subsequent gross gains and losses of water to and from the channel.

The importance of this study was to enhance our understanding of the hyporheic exchange process in Precambrian Shield environments and to determine its significance in controlling water budgets of small streams. Relative magnitudes of exchange across different portions of the channel aid in identifying areas of the watershed with greater exchange potential and transient storage which translate to locations more sensitive to water turnover and longer exposure to subsurface contamination from pollutants. Furthermore, while hyporheic exchange has been well documented in headwater catchments of mountain streams in the Northwestern United States, this study pertained to the Canadian Boreal Shield, investigating the process in a different catchment environment, focusing on similar relationships between exchange and hydrological and physical watershed parameters.

5.1 Methods of Discharge Measurement

An important aspect of this study was to provide insight into the precision and accuracy of discharge measurements in small streams. Statistical analysis suggests there were significant differences in this study between the dilution gauging and velocity-area discharge measurements. The 0.7 L/s mean of the differences may represent a substantial difference between discharge measurements at very low flows. Figures 4.6 and 4.7 illustrate that while low flow discharge differences are small, they actually represent greater proportions of surface discharge (greater than 100% in some instances) suggesting that some of these differences are well outside of the measurement error.

Some standardized values from Figure 4.7 are in fact greater than the Statistical Uncertainty registered by the Flow Tracker during velocity-area discharge measurement (Appendix H), attesting to this suggestion. Further analysis (i.e. replication of discharge measurements at each reach) would have to be done to interpret the significance of the results with greater certainty. Discharge values obtained from dilution gauging were used for mass recovery quantification due to the high uncertainty and error involved in VA measurement, especially during low flows. Furthermore, others have reported noticeable differences between the two methods, concluding that dilution gauging is a more accurate measure of discharge in streams of similar size (Day, 1976; Day, 1977; Jarrett, 1992; Zellweger, 1994; Moore, 2003). Therefore, like Payn et al. (2009) it was decided that dilution gauging results would be used for subsequent mass recovery analysis.

5.2 Solute Mass Loss and Gross Water Loss and Gain

Hyporheic exchange is an important hydrological process in this catchment environment. Most reaches experienced solute losses greater than 10% for weeks 2 to 6 which are considered substantial (Payn et al., 2009). Others have measured significant tracer loss from the stream to transient storage in the near stream zone which they attribute to hyporheic exchange (Zellweger, 1994; Jonsson et al., 2003; Payn et al., 2009). Gross gains and losses of water (as a percentage of upstream discharge) along the channel were high, increasing with baseflow drawdown and as absolute values of net discharge approached 0 L/s, which is similar to the results of Payn et al. (2009). Mass loss percentages represent the same percentage of minimum water loss from channel flow over the study period under a scenario in which all solute and water loss occurs before any discharge gains. Thus, channel water loss was equivalent to and just as substantial as

the solute mass loss ($>10\%$). Gains and losses exceeding 100% of upstream discharge during low flows indicates that the volume of surface water that entered the reach over the time of contact was lost to the subsurface and an equivalent amount gained. Such percentages were well within the minimum-maximum gross discharge ranges and pertained to most reaches during the low flow weeks 4 and 5. Large proportions of gross inflow and outflow of water suggest a high degree of turnover.

Gains can be attributed to either hyporheic flowpaths or deeper groundwater flowpaths for net gaining reaches, however these two sources cannot be partitioned from the gross discharge measurements using methods of tracer recovery. Head measurements using wells and piezometers have been previously applied to produce flow nets capable of distinguishing hyporheic flowpaths from groundwater connections to regional hillslope aquifers (Harvey and Bencala, 1993). Here, it cannot be stated with confidence that any or all of the gross gain in the W8 reaches is attributable to hyporheic flowpaths, however their presence is implied from the fact that these net gaining reaches lose mass – amounts greater than can be accounted for by in-stream storage (Harvey et al., 1996) – in addition to the development of a shoulder-and-tail appearance on the concentration breakthrough curves for each solute injection (Figure 5.1). A long tail illustrates not only the longitudinal dispersion of the solute cloud but also the return of tracer to the stream from small scale hyporheic flowpaths slightly increasing the specific conductance of the stream water (Bencala and Walters, 1983; Jonsson et al., 2003).

Most of the concentration curves from the injections in this study reduced to specific conductance levels close to background concentration but still greater at the end of the logging period. This suggests greater exchange and the influence of tracer labeled

water in long spatial or temporal hyporheic flowpaths, which returns to the reach after the time of study. Reaches with limited exchange along their lengths, during high flow periods, have curves with short tails and a shorter return to near background conductance levels. Mass loss is the result of these longer spatial or temporal hyporheic flowpaths which do not return to the stream within the study reach length or the injection period when specific conductance returns to near background levels (Payn et al., 2009).

Figure 5.1: Reach 1 concentration breakthrough curves for (a) week 1 during high flow conditions (4% solute mass loss), and (b) week 4 during low flow conditions (51% solute mass loss). The week 4 curve takes longer to reach peak concentration and the tail is longer and drawn out, both indicators of greater hyporheic exchange. It took approximately 4 times longer for the solute pulse to pass the downstream end of the reach during low flow.

Net losing reaches act as groundwater recharge sites within catchments. In this case, gross loss may be due to both hyporheic and groundwater flowpaths. Gross loss was much greater than the net loss of water for reaches in this study, indicating large magnitudes of gross gain associated with returning water from hyporheic flowpaths. Recall that net discharge is the difference between gross discharge gain and gross discharge loss. The gain balances out most of the loss resulting in a reduced magnitude of net discharge loss from the channel. With the exception of reach 1 during weeks 1 and 2 which had negligible gross gains, net loss of water could not account for all solute loss, suggesting that a fraction of this gross loss is related to hyporheic flow. For example reach 7 lost 38% of solute during the highest flow week and while it was a net losing reach, the proportions of gross water gain and loss (minimum 19 and 39% of upstream discharge respectively) suggest this catchment experiences a high magnitude of exchange within the local stream valley aquifer. Payn et al. (2009) stress the importance of quantifying gross inflow and outflow which are underestimated from net discharge and often neglected in longitudinal stream water balance studies.

5.3 Hydrological Factors Controlling Mass Loss and Magnitudes of Exchange

Surface-subsurface exchange increased throughout the summer baseflow recession period for all reaches. The strong relationship between discharge and ML/RL for each reach suggests discharge is a primary factor influencing hyporheic exchange, which supports the work of Morrice et al. (1997), Boulton et al. (1998) and more recently Payn et al. (2009) who identified similar relations between exchange and discharge. However, Wondzell (2006) does report that some studies have concluded that the

magnitude of exchange has no dependence on flow conditions. Discharge of both subsurface inflow and outflow along the channel decreased in magnitude as discharge at the outlet declined, however the percentage of channel flow represented by these gross gains and losses increased dramatically (refer to Appendix C) for all reaches illustrating how reduced baseflows permit greater exchange of channel water. To conclude, both the amount of mass loss and corresponding proportions of gross discharge loss and gain are a function of discharge. Hence, bidirectional channel water balance is temporally dependent in this catchment with a large seasonal response (increase) in the magnitude of exchange as baseflow progressively recedes throughout the summer

The relationship observed between solute loss and discharge could be explained by a link between baseflow discharge and groundwater contribution from the surrounding hillslope. During high flow conditions early in the summer season the catchment is still relatively wet from snowmelt recharge and streamflow is sustained from recently stored groundwater. Inflow to the stream from groundwater flowpaths is substantial and reduces the area of hyporheic exchange, in effect limiting the proportion of gross water loss along the channel (Wroblicky et al., 1998). As baseflow decreases, groundwater contribution also decreases due to water table drawdown which is reflected here in the formation of net losing conditions for reaches 3, 6, and 7 during low flow weeks 4 and 5. Less regional groundwater input from the hillslopes allows for development of longer hyporheic flowpaths and expansion of the hyporheic zone leading to greater exchange of stream water (Tonina and Buffington, 2009). However less groundwater contribution may not necessarily result in a change to the hyporheic process. The magnitude of gross discharge loss (L/s) did not change substantially nor did it decrease for every reach as

baseflow receded. This relatively unchanging rate of water loss and gain may represent greater amounts of channel flow involved in exchange however it does not mean that the zone of exchange has expanded. The cross sectional area of the exchange zone relative to the cross sectional area of the reach (A_e/A) is likely to increase as surface discharge decreases as a result of a decrease in A as opposed to an increase in A_s .

The power law relationship between discharge and mass loss demonstrates the substantial increase in the rate of mass loss at very low discharge. This may result from excessive hillslope water table drawdown and a large reduction in inflow from regional groundwater as previously mentioned. Results also suggest that a decrease in discharge leads to an increase in the slope of the stream water surface as it conforms to the slope of the channel bed, and is associated with an increase in gross water loss (Harvey and Bencala, 1993; Wondzell, 2006). Decreases in discharge result in water level drawdown and greater contact with the channel bed. In effect water can more easily penetrate the subsurface subsequently causing greater solute loss.

Hyporheic exchange studies have yet to examine mass loss and the response to travel time of the solute pulse within the water column. The significant relationship between mass loss and time of contact for most reaches arises from a strong negative correspondence between discharge and contact time. While contact time has received little attention in previous work, Thibodeaux and Boyle (1987) and Payn et al. (2009) reported on the varying effect velocity might have on the magnitude of exchange. Reduction in discharge is associated with a decline in velocity due to friction with greater channel bed contact. Not only does a larger proportion of streamflow have the ability to exchange at the surface-subsurface boundary, but the exponential decrease in discharge

and associated velocity reduction increases the amount of time available for solute contact and exchange along the bed.

While the relationship of mass loss with contact time for each reach is not as strong as the relationship with discharge, it is evident that greater loss occurs under longer travel times. It was believed that the longer the solute pulse takes to pass through the reach then the greater the potential for mass loss and as such ML/RL was normalized to contact time. The variability in mass loss per reach length that exists between field weeks for each reach in Figure 4.9a was greatly reduced upon normalizing. The range in mass loss decreased for each reach and low flow loss values were no longer the greatest for all reaches as is shown in Figure 4.15a. This illustrates the dependence of mass loss and surface-subsurface exchange on the time of contact. Thus, contact time may also account for the large increase in mass loss associated with low discharge. While the variability in solute loss between weeks decreases, differences in mass loss values among the reaches themselves still exists, which apparently implies watershed control on exchange potential.

Solute mass loss was typically greatest in reaches 1, 2, 4, and 7, however relative magnitudes of gross hydrological loss and gain displayed complex temporal variations. During high flow conditions (weeks 1 and 6) those reaches with the greatest proportion of water added to their channels ($\Delta Q/Q_u$) experienced the least amount of loss, implying a high rate of water movement into the channel from groundwater or larger upstream hyporheic flow paths (Harvey and Bencala, 1993; Wroblicky et al., 1998; Tonina and Buffington, 2009). This correlation between proportion of net inflow and mass loss potential is related to the concept of stream-hillslope groundwater connection discussed

previously and the ability of groundwater flowpaths to outcompete hyporheic flowpaths in the stream zone. However this relationship does not persist for intermediate and low flow conditions.

Under higher-discharge baseflow conditions, reaches with the greatest amount of solute loss had the lowest proportions of net discharge gain. However, during weeks 2 to 5 reaches with the greatest magnitudes of solute loss exhibited large positive fractions of water input. This not only suggests that the gross discharge gains are much greater than the gross losses, but that the gross discharge losses for these reaches must be of very high magnitude to cause substantial mass loss from the channel. In order to lose that much mass and still have the largest positive proportion of discharge input reaches 2, 4, and 9 require much larger gross loss values of hyporheic flow, which would themselves be counteracted by larger gross gains. The proportions of gross loss and gain to these reaches were indeed of much greater magnitude (Figure 4.12 and 4.13, Appendix C). This demonstrates greater exchange, which may be reflected in the size of the storage zone area. Groundwater contribution to all reaches may be greatly reduced during week 2 to 5 as water tables lower. As a result, a greater proportion of the gross discharge gains to net gaining reaches likely originates from large scale hyporheic flowpaths during intermediate and low flow periods.

5.4 Vertical Water Flow and Direction

Piezometers were installed in 7 of the 9 reaches for the purpose of determining direction of vertical water flow. Water flux measurements were not calculated due to the assumed large spatial variability of heads along the reach, however results support the

general exchange behaviour of each reach. Large magnitudes of recharge correspond to the consistently net losing nature of reach 1. Smaller magnitudes of recharge inferred from hydraulic head differences between stream surface and piezometer were consistent for all weeks in reaches 2, 3, and 4. The longer persistence of downwelling for these lower reaches reflects the greater proportions of solute mass loss and water turnover exhibited by reaches 1, 2, and 4, and presented in the results. The water loss associated with piezometers in reaches 2, 3, 4, and 9 may be sites of gross loss despite the net gaining nature of these reaches.

Large negative differences in hydraulic head (indicating an area of upwelling) at piezometer locations coincide with low magnitudes of exchange within reaches 5 and 6, suggesting these reaches could be gaining water along the majority of their lengths. Persistent upwelling reflects the reduced proportions of solute and water mass loss in reaches 5 and 6 compared to reaches 1 to 4. While hydraulic head differences remained relatively constant at piezometer sites for reaches 1 to 4, they approached 0 for reaches 5, 6, and 9 as baseflow declined, reflecting the decrease in gross loss or gain (expressed in litres per second) to each reach. It is important to note that while the water flow directions support the general spatial variability of exchange within this catchment from tracer recovery analysis, results may not be representative of the entire reach in each case. For instance, reaches 2 and 4 show consistent water loss from head measurements and while they lose the greatest amounts of solute mass and channel water they are net gaining reaches throughout the study period and hence gain water along some portions of their beds. Therefore the downwelling at piezometer only represents the localized nature of exchange within each reach.

5.5 Multi-mass Experiment

The purpose of the multi-mass experiment was to determine if injecting different amounts of tracer (salt) into the same reach under similar flow conditions would lead to the same proportions of mass loss. The experiment was performed four times using four different injection masses, always carried out on reach 2. The percentage of mass loss should theoretically be the same for each injection for each field week given a constant reach length and discharge value however it was found in this study that different injection amounts did indeed lead to a high degree of variability in percent mass loss. Test results indicate significant overlap in mean percent mass loss for two field weeks despite a 50% reduction in discharge. It was expected that there would be a little variability between mass loss values using different injection amounts however it was not expected that the variability would be this high for each week, in which mass loss values between weeks overlapped. Normalizing to contact time failed to reduce or account for the variability between injection mass. It may be to beneficial to use a constant injection mass when performing hyporheic experiments within a reach, however replication of solute mass recovery for the same injection mass should be performed under the same discharge conditions at different times throughout the baseflow recession. It is important to determine if there is variability associated with using the same injection amount for a given discharge.

5.6 Catchment Parameters Controlling Mass Loss and Magnitudes of Exchange

Analysis of watershed parameters using Arcmap10 and SAGA indicated that there were no significant relationships between solute mass loss and catchment structure,

which was an unexpected result. Also, no association can be made between mass loss results and location of the reaches relative to the transition zone running through W8. Reaches with a higher wetness index, smaller values for mean catchment slope and drainage slope were hypothesized to have lower magnitudes of surface-subsurface exchange as they are expected to maintain greater antecedent moisture conditions from increased storage and less efficient surface runoff. This would lead to persistent water table connections between the stream and surrounding hillslope (Allan and Roulet, 1994; Buttle and Turcotte, 1999; Buttle et al., 2004; Jencso et al., 2009), however these reaches did not have the smallest magnitudes of exchange.

While these parameters showed no significant correlations with solute loss the local contributing area for reach 3 is greater than both reaches 2 and 4. In fact, this reach has the greatest local contributing area among all nine reaches. Jencso et al. (2009) found that channel sections with larger LCA had a more sustained connection to their hillslope water tables throughout the baseflow recession period. Greater contributions of hillslope groundwater to surface streamflow would result from longer connections, limiting the potential for hyporheic exchange in reaches with large LCA. This relationship may be present in reach 3 and the low solute losing, high LCA reach 6. Furthermore small tributary development at reach 3 during high flow conditions would suggest greater connection to the hillslope water table and larger lateral hydraulic gradients in this area of the catchment. However, as was established there was no relationship between LCA and ML/RL. Moreover Jencso et al. (2010) suggest hillslope contributions to streamflow depend not only on the size of the local contributing area but also on the size of the riparian zone relative to the hillslope. They found that areas along the stream with

greater riparian to hillslope ratios responded more slowly to inputs of hillslope groundwater and solutes. Larger relative riparian zones in mountain catchments appear to buffer hillslope contributions and could represent an important landscape factor prolonging the time it takes for complete turnover of select reaches in Watershed 8, permitting greater hyporheic exchange regardless of the size of their LCA.

While a larger contributing area may reduce the zone of exchange due to channel-hillslope water table connection, Buffington and Tonina (2009) suggest that a more confined valley leads to a reduction in exchange and mass loss. A broader valley allows for larger scales of flowpaths both spatially and temporally (Stanford and Ward, 1993). Average valley widths at 3 meters elevation above the stream surface for reaches 3 and 6 happen to be shorter than 2 and 4 which supports the reduced amounts of mass loss. Additional width measurements at varying elevations should be measured in order to validate this assumption.

Reach 5 is similar in character to reach 4, located along the transition and together may represent a zone of high exchange or groundwater loss to the watershed that is returned to reach 3. Covino and McGlynn (2007) and Payn et al. (2009) found similar patterns of gross loss at the landscape transition zone in their respective mountain-to-valley study sites, with gross hydrological gains at downstream locations, which they attribute to large scale groundwater or hyporheic flowpaths. Furthermore reaches 4 and 5 have much steeper channel slopes which facilitate longer flowpaths that drive water downwards through the substrate, particularly in channels with large pressure gradients due to bed structures such as steps (Buffington and Tonina, 2009). However this explanation is not supported by data. While gross gains in reach 3 increase throughout

the recession period, it transitions to a net losing reach at low flow and the relative proportions of gain remain less than that of reach 4.

Results of this study demonstrate how catchment scale physical watershed properties are not definitive controlling factors on surface-subsurface exchange in this boreal shield catchment. This is not the first study to acknowledge a lack of significant evidence linking catchment factors to magnitudes of exchange (Ward et al., 2012). Relationships between the catchment scale factors introduced in Chapter 2 and hyporheic exchange potential have been proposed and observed in mountain catchments. These settings tend to have spatially uniform soil cover and are composed of three main landscape elements – the hillslope, riparian zone, and stream (Jencso et al., 2009). This simple structure is in contrast to boreal shield catchments and as such hydrological processes including hyporheic exchange may differ in their response to catchment morphology.

The boreal shield is non-uniform with respect to surficial geology. Basins often display transitions from areas of soil cover to zones of Precambrian bedrock sometimes found with patches of forest stands and a variety of wetlands including peatlands and raised bogs (Branfireun and Roulet, 1998; Spence and Woo, 2002, 2006). Many have alluded to the fact that spatial variation in catchment properties results in multiple landscape elements or units coupled together to form a series of runoff processes defining the hydrological response of the catchment (Devito et al., 1996; Metcalfe and Buttle, 2001; Buttle et al., 2004; Spence, 2010). Bedrock or forested plots upland represent distinct elements with their own runoff mechanisms and hillslopes themselves may be composed of a group of units (e.g. bedrock outcrops, soil-filled valleys, wetlands, forest

patches) each with its own runoff regime (Spence and Woo, 2006). The heterogeneous distribution of these landscape elements determines the length of time required for the contribution of hillslope groundwater to streamflow and runoff generation.

Runoff response in the catchment is ultimately a function of three factors; the ability for water to travel through the subsurface (typology), the influence of gravity and storage capacity associated with bedrock topography, and the location of each landscape unit relative to one another (topology) (Hinton et al., 1993; Buttle, 2006). Spence and Woo (2002) and Allan and Roulet (1994) highlight the significance of bedrock depressions in hindering runoff generation above and below the surface in boreal catchments. Bottomley et al. (1986) and Buttle et al. (2004) suggest groundwater elevation must rise above high points in the underlying bedrock in order to satisfy depression storage and allow subsurface flow to continue laterally downslope towards the stream, a concept which Spence and Woo (2003) refer to as “fill-and-spill”. Microtopography therefore will cause water table fluctuations over time and space with the potential for landscape elements to remain disconnected.

The boreal shield thus is not just a connection between streams, riparian zones, and hillslopes within the local contributing area. Water table connection and duration of subsurface flow towards the channel also depends on the topology or landscape orientation of these smaller hillslope units. Hillslope units, which have high storage capacities and require greater precipitation input in order to sustain the groundwater connections will allow for large scale hyporheic flowpaths and greater surface-subsurface exchange along the near-stream zone. Therefore it may be worth investigating the unit-

to-unit transitions within hillslopes draining into different portions of the channel as it could be related to the degree of water exchange in boreal catchments.

Loss of solute and water and multiple scales of exchange in this setting may be under greater influence from small-scale reach or channel bed characteristics. Water loss into the subsurface tends to occur over pressure inducing obstructions including steps, riffles, boulders, logs, etc. and increases as the water surface slope steepens (Wondzell, 2006). Reaches 1 through 5 can be classified as step-pool channels and these small scale features may be driving such large magnitudes of exchange. Reaches 6 and 9 are located above the transition zone and are low-slope meandering streams characterized by a riffle-pool morphology. Increases in relative mass loss at low flow conditions may be enhanced by the meandering structure which has been associated with high rates of loss due to contact of water with the channel banks (Boano et al., 2006). Similar behaviour occurs in divided streams (Kasahara and Wondzell, 2003), a characteristic common to reach 3.

Previous research in mountain catchments has identified soil type and extent as another possible parameter affecting the size and residence time of hyporheic flowpaths (Wroblicky et al., 1998; Tonina and Buffington, 2009). In general, the lack of stream zone soil cover in boreal shield catchments as opposed to western mountain catchments would suggest that hyporheic exchange and solute loss would not be substantial (Wondzell, 2006), unlike the results found in Watershed 8. Soil surveys were not conducted as part of this study however boreal shield catchments are known for their sporadic bedrock exposures and fracturing and exposed bedrock was observed along portions of reaches 7 and 8. During week 1 reach 7 – located just upstream from a tall,

steep scarp marking the transition boundary – lost 38% of solute mass compared to 13% for reaches 4 and 9, and less than 7% for the rest. This substantial difference in mass loss between reach 7 and the other reaches, similarly found on week 6, suggest the presence of fracture-induced channel water loss to deeper groundwater. Spence and Woo (2002) observed that fractures on bedrock surfaces of shield catchments can have an influence on runoff generation, while Buffington and Tonina (2009) acknowledge the potential for hyporheic exchange through such features. This process could also be responsible for some of the gross loss inherent to net losing reach 1, which is divided by an approximately 2 meter high waterfall.

6. CONCLUSION

This study examined the role of small-scale surface-subsurface water exchange in determining longitudinal reach water budgets in a 2.9 km² watershed of Gatineau Park, Quebec, Canada. Solute mass loss was measured from conservative tracer injections in an effort to quantify gross discharge gains and losses. Proportions of solute loss and water exchange at each reach were related to changes in baseflow discharge as well as catchment morphology for the purpose of understanding what factors control magnitudes of hyporheic exchange within areas of this boreal shield catchment. Results of the three main research questions are summarized as follows:

- 1) Solute mass loss was substantial (>10%) for most reaches during weeks 2 to 6 and reached a maximum of 88% at reach 4 during week 4. High solute exchange exists for all reaches despite most exhibiting slight positive net discharge values. Minimum gross channel water loss during low flow conditions ranged from 34% to 88% of reach upstream discharge with maximum potential proportions of gross loss and gain exceeding 100% for most reaches.
- 2) Both solute loss and the proportions of gross discharge gain and loss increased throughout the summer baseflow recession. A distinct power law relationship exists between mass loss and discharge for the 6 main channel reaches ($R^2 > 0.9$) with a large increase in the rate of loss associated with flows less than 10L/s. Variation in mass loss between reaches was present with reaches 1, 2, 4, and 7 exhibiting greater amounts of exchange over their lengths relative to the others during most weeks.
- 3) No patterns in exchange can be found between reaches above and below the steep transition zone. All nine catchment parameters analyzed in this study showed no significant relationship with mass loss.

Mass recovery analysis was capable of estimating a range of gross discharge loss and gain for each reach. Substantial solute mass loss and large values of gross discharge loss and gain suggests a high degree of surface-subsurface exchange occurs within this catchment. The increase in proportion of channel flow involved in the exchange process in response to a decrease in baseflow for all reaches indicates that both discharge and

time of contact influence the magnitude of hyporheic exchange. These results support the idea that reductions in groundwater contribution to streamflow throughout the summer baseflow recession period allow for greater exchange of water through hyporheic flowpaths, constituting the majority of gross loss and gain.

The relationships discovered in mountain basins between catchment morphological parameters and the magnitude of exchange (e.g. Payn et al., 2009) were not found in this catchment environment. Boreal shield catchments are different from mountain catchments in structure and organization of their landscape units resulting in different modes of runoff generation which may be responsible for the differences observed in this study. Despite the lack of evidence suggesting catchment control on exchange potential, magnitudes of solute loss over the course of the entire study period were still much greater than expected for a boreal shield catchment. These results could be associated with reach or channel bed scale factors known to induce surface-subsurface exchange.

Results of the two supplementary research questions are summarized as follows:

- 4) The results between dilution and velocity-area discharge methods were significantly different using a paired t-test with the mean of the differences being 0.7 L/s before transformation.
- 5) Variation existed in mass loss percentages between injection amounts (in the range of 10-20%) for each week with weeks 1 and 4 having significantly similar mass loss values ($p > 0.05$) despite a 50% reduction in downstream discharge.

After investigation into research question 4 it is suggested that, in streams of similar size, discharge be measured using dilution gauging as opposed to the velocity-area method which was associated with high measurement error. Secondly it is recommended that mass recovery experimentation use a constant injection mass for

multi-reach hyporheic study, based on results from question 5. Conservative tracer injection and mass recovery analysis is also incapable of partitioning hyporheic flow from regional groundwater contributions to and from channel flow. Therefore other methods should be employed in conjunction with tracer injections to differentiate proportions of streamflow derived from both hyporheic and groundwater flowpaths. End member mixing analysis and a larger system of well/piezometer transects installed within the near stream zone would aid in determining gross discharge values involved in hyporheic exchange specifically. A combination of all three methods would provide adequate interpretation of bidirectional channel water exchange.

In conclusion, quantification of gross discharge values provides insight into the magnitude of small scale water exchange in a boreal shield catchment and provides an indication of where and when water turnover is most prevalent. Estimates of concurrent gain and loss along reaches shows that greater amounts of water contribute to channel flow than is often assumed from net discharge. This research helps to advance understanding of hyporheic exchange influence on streamflow across different watershed environments and is a reminder that consideration of small scale hydrological processes are important for improving conceptual models of streamflow generation.

APPENDIX A: Reach discharge and mass loss data by field week.

Week 1 – July 4-8

Reach	Downstream Discharge (L/s)	Upstream Discharge (L/s)	Net Discharge (L/s)	Downstream Mass (g)	Upstream Mass (g)	Recovered Mass (g)	Mass Loss (g)	Mass Loss (%)	Reach Length (m)	Mass Loss per Reach Length (g/m)	Time of Contact (s)	Mass Loss per Reach Length per Contact Time (g/m/s)
1	81.8	86.0	-4.2	198.6	198.2	189.6	-8.6	4.3	101.6	0.08	1271	6.6E-05
2	59.7	57.9	1.8	198.8	198.9	185.1	-13.9	7.0	220.5	0.06	2059	3.1E-05
3	57.9	48.7	9.2	198.9	200.0	191.1	-8.9	4.5	225.2	0.04	2042	1.9E-05
4	48.7	45.6	3.1	200.0	200.2	173.7	-26.5	13.2	155.8	0.17	1932	8.8E-05
5	19.7	18.1	1.6	199.5	199.0	185.5	-13.5	6.8	155.0	0.09	2665	3.3E-05
6	18.1	15.7	2.3	199.0	198.7	196.9	-1.8	0.9	149.2	0.01	3176	3.9E-06
7	8.7	10.9	-2.2	200.0	197.1	123.2	-73.9	37.5	144.9	0.51	6071	8.4E-05
8	10.9	9.0	1.9	197.1	199.1	194.9	-4.2	2.1	133.6	0.03	4706	6.7E-06
9	9.0	7.2	1.8	199.1	199.1	174.1	-25.0	12.6	130.0	0.19	2979	6.5E-05

Week 2 – July 19-22

Reach	Downstream Discharge (L/s)	Upstream Discharge (L/s)	Net Discharge (L/s)	Downstream Mass (g)	Upstream Mass (g)	Recovered Mass (g)	Mass Loss (g)	Mass Loss (%)	Reach Length (m)	Mass Loss per Reach Length (g/m)	Time of Contact (s)	Mass Loss per Reach Length per Contact Time (g/m/s)
1	25.6	30.0	-4.4	200.1	199.9	173.8	-26.0	13.0	101.6	0.26	2444	1.0E-04
2	16.1	15.4	0.7	200.0	199.6	140.1	-59.5	29.8	220.5	0.27	3669	7.4E-05
3	15.4	14.7	0.7	199.6	200.0	160.0	-40.0	20.0	225.2	0.18	4026	4.4E-05
4	14.7	12.8	1.9	200.0	200.0	139.2	-60.8	30.4	155.8	0.39	3529	1.1E-04
5	5.8	5.4	0.4	200.0	199.2	162.6	-36.6	18.4	155.0	0.24	5008	4.7E-05
6	5.4	4.8	0.6	199.2	200.3	169.5	-30.8	15.4	149.2	0.21	5517	3.7E-05
7	3.0	3.0	0.0	200.0	198.4				144.9			
8	3.0	2.8	0.2	198.4	199.7	181.8	-17.9	8.9	133.6	0.13	10115	1.3E-05
9	2.8	2.4	0.4	199.7	199.5	171.4	-28.1	14.1	130.0	0.22	7574	2.9E-05

Week 3 – August 15-17

Reach	Downstream Discharge (L/s)	Upstream Discharge (L/s)	Net Discharge (L/s)	Downstream Mass (g)	Upstream Mass (g)	Recovered Mass (g)	Mass Loss (g)	Mass Loss (%)	Reach Length (m)	Mass Loss per Reach Length (g/m)	Time of Contact (s)	Mass Loss per Reach Length per Contact Time (g/m/s)
1	14.0	16.1	-2.1	200.2	200.1	150.7	-49.3	24.6	101.6	0.49	3155	1.5E-04
2	9.7	9.0	0.8	200.0	200.0	130.2	-69.9	34.9	220.5	0.32	5009	6.3E-05
3	9.0	8.8	0.2	200.0	200.0	145.1	-54.9	27.5	225.2	0.24	5507	4.4E-05
4	8.8	7.0	1.8	200.0	200.5	124.8	-75.7	37.7	155.8	0.49	5467	8.9E-05
5	2.7	2.4	0.3	199.9	200.0	152.9	-47.1	23.5	155.0	0.30	8000	3.8E-05
6	2.4	1.9	0.4	200.0	200.0	167.5	-32.5	16.2	149.2	0.22	9622	2.3E-05
7	1.3	1.4	0.0	200.1	200.1				144.9			
8	1.4	1.3	0.0	200.1	199.7				133.6			
9	1.3	0.8	0.5	199.7	199.6	166.0	-33.6	16.8	130.0	0.26	16796	1.5E-05

Week 4 – August 29 – September 2

Reach	Downstream Discharge (L/s)	Upstream Discharge (L/s)	Net Discharge (L/s)	Downstream Mass (g)	Upstream Mass (g)	Recovered Mass (g)	Mass Loss (g)	Mass Loss (%)	Reach Length (m)	Mass Loss per Reach Length (g/m)	Time of Contact (s)	Mass Loss per Reach Length per Contact Time (g/m/s)
1	5.2	6.7	-1.5	199.6	199.0	97.5	-101.5	51.0	101.6	1.00	5602	1.8E-04
2	3.4	2.7	0.6	199.6	200.0	46.4	-153.6	76.8	220.5	0.70	9515	7.3E-05
3	2.5	2.6	-0.1	200.2	200.0	70.3	-129.7	64.9	225.2	0.58	11065	5.2E-05
4	2.6	2.0	0.6	200.0	200.0	41.8	-158.2	79.1	155.8	1.02	15692	6.5E-05
5	1.4	1.3	0.1	200.0	199.9	120.4	-79.4	39.7	155.0	0.51	11539	4.4E-05
6	1.3	1.5	-0.2	199.9	200.0	76.0	-124.0	62.0	149.2	0.83	11965	6.9E-05
7	0.8	0.9	-0.1	198.3	198.5				144.9			
8	0.9	0.8	0.1	198.5	200.0				133.6			
9	0.8	0.5	0.3	200.0	200.0	66.3	-133.7	66.8	130.0	1.03	19169	5.4E-05

Week 5 – October 10-13

Reach	Downstream Discharge (L/s)	Upstream Discharge (L/s)	Net Discharge (L/s)	Downstream Mass (g)	Upstream Mass (g)	Recovered Mass (g)	Mass Loss (g)	Mass Loss (%)	Reach Length (m)	Mass Loss per Reach Length (g/m)	Time of Contact (s)	Mass Loss per Reach Length per Contact Time (g/m/s)
1	5.2	5.7	-0.5	200.0	200.0	132.3	-67.7	33.8	101.6	0.67	7327	9.1E-05
2	3.6	2.9	0.7	200.0	199.7	63.7	-136.0	68.1	220.5	0.62	12890	4.8E-05
3	2.9	3.0	-0.1	199.7	199.1	71.3	-127.8	64.2	225.2	0.57	13051	4.3E-05
4	3.0	2.4	0.6	199.1	199.4	24.7	-174.6	87.6	155.8	1.12	14521	7.7E-05
5	1.2	1.1	0.1	200.0	200.2	103.4	-96.9	48.4	155.0	0.63	16391	3.8E-05
6	1.1	0.9	0.2	200.2	199.9	74.4	-125.5	62.8	149.2	0.84	17803	4.7E-05
7												
8												
9												

Week 6 – October 31 – November 3

Reach	Downstream Discharge (L/s)	Upstream Discharge (L/s)	Net Discharge (L/s)	Downstream Mass (g)	Upstream Mass (g)	Recovered Mass (g)	Mass Loss (g)	Mass Loss (%)	Reach Length (m)	Mass Loss per Reach Length (g/m)	Time of Contact (s)	Mass Loss per Reach Length per Contact Time (g/m/s)
1	35.9	38.7	-2.8	200.0	200.0	180.2	-19.8	9.9	101.6	0.19	2370	8.2E-05
2	20.5	19.3	1.2	200.0	200.0	155.5	-44.5	22.3	220.5	0.20	4500	4.5E-05
3	19.3	16.8	2.5	200.0	200.0	157.3	-42.7	21.3	225.2	0.19	4803	3.9E-05
4	16.8	15.1	1.7	200.0	200.0	150.4	-49.6	24.8	155.8	0.32	4727	6.7E-05
5	7.0	6.5	0.5	200.0	200.0	168.5	-31.5	15.7	155.0	0.20	6310	3.2E-05
6	6.5	5.6	0.8	200.0	200.0	180.3	-19.7	9.9	149.2	0.13	7481	1.8E-05
7	6.2	5.8	0.4	200.0	200.0	116.9	-83.1	41.5	144.9	0.57	10653	5.4E-05
8	5.8	5.5	0.3	200.0	200.0	142.3	-57.7	28.9	133.6	0.43	9045	4.8E-05
9	5.5	4.8	0.7	200.0	200.0	153.4	-46.6	23.3	130.0	0.36	7901	4.5E-05

APPENDIX B: Statistical breakdown of reach based relationships between discharge and mass loss per reach length.

Reach	Spearman's Rank Correlation Coefficient (r) and p-value	Spearman's Correlation (+/- ve) Significant (Yes/No)	Pearson's Product Moment Correlation Coefficient (r) and p-value	Pearson's Correlation (+/- ve) Significant (Yes/No)	Model Coefficients y-intercept slope	Coefficient p-values and significance (Yes/No) y-intercept slope	P-value of model and significance (Yes/No) Adjusted r-squared
1	-0.99	-ve	-0.98	-ve	1.25	0.008 (YES)	0.0006 (YES)
	0.0003	YES	0.0006	YES	-0.82	0.0006 (YES)	0.95
2	-0.89	-ve	-0.98	-ve	0.54	0.038 (YES)	0.0001 (YES)
	0.01	YES	0.0001	YES	-0.76	0.0001 (YES)	0.95
3	-0.94	-ve	-0.97	-ve	0.33	0.26 (NO)	0.001 (YES)
	0.02	YES	0.001	YES	-0.8	0.001 (YES)	0.93
4	-0.96	-ve	-0.99	-ve	0.69	0.0002 (YES)	<0.0001 (YES)
	0.003	YES	<0.0001	YES	-0.63	<0.0001 (YES)	0.99
5	-1	-ve	-0.99	-ve	-0.41	0.007 (YES)	0.0002 (YES)
	0.003	YES	0.0002	YES	-0.65	0.0002 (YES)	0.97
6	-1	-ve	-0.95	-ve	0.17	0.69 (NO)	0.004 (YES)
	0.003	YES	0.004	YES	-1.44	0.004 (YES)	0.88
7	-1	-ve	NA	NA	0.04	NA	NA
	1	NO			-0.33	NA	NA
8	-0.5	-ve	-0.54	-ve	-0.18	0.96 (NO)	0.64 (NO)
	1	NO	0.64	NO	-1.11	0.64 (NO)	-0.42
9	-0.7	-ve	-0.68	-ve	-0.65	0.19 (NO)	0.21 (NO)
	0.23	NO	0.21	NO	-0.46	0.21 (NO)	0.28

Previous table continued

Reach	Skewness and p-value of Residuals	Skewness (+/-ve) and significance (Yes/No)	Kurtosis and p-value of Residuals	Kurtosis (Lepto/Platy) and significance (Yes/No)	Shapiro-Wilk normality test p-value and significance (Yes/No)	Breusch-Pagan homoscedasticity test p-value and significance (Yes/No)	Comments
1	-0.43 0.34	-ve NO	-1.6 0.23	Platy NO	0.6 NO	0.2 NO	Possible outliers
2	-0.04 0.48	-ve NO	-1.56 0.22	Platy NO	0.96 NO	0.09 NO	1 extreme outlier
3	0.24 0.41	+ve NO	-1.4 0.26	Platy NO	0.97 NO	0.09 NO	1 extreme outlier
4	0.54 0.29	+ve NO	-1.5 0.23	Platy NO	0.36 NO	0.09 NO	1 extreme outlier
5	-0.18 0.43	-ve NO	-1.8 0.21	Platy NO	0.69 NO	0.98 NO	
6	0.22 0.42	+ve NO	-1.88 0.2	Platy NO	0.68 NO	0.05 YES/NO	Heteroscedastic Possible outlier
7	NA	NA	NA	NA	NA	NA	Only two observations
8	0.38 0.42	+ve NO	-2.33 0.28	Platy NO	0.02 YES	0.95 NO	Non-normal using S-W test, only 3 observations
9	0 0.5	NO	-2.1 0.2	Platy NO	0.62 NO	0.04 YES	Coefficients are not significant, No relationship, Extreme outlier

APPENDIX C: Maximum and minimum gross hydrological gains and losses.

Gross Gains and Losses (total L/s)

Reach	Week 1				Week 2				Week 3			
	Min Gain	Min Loss	Max Gain	Max Loss	Min Gain	Min Loss	Max Gain	Max Loss	Min Gain	Min Loss	Max Gain	Max Loss
1	-0.3	-3.9	-0.3	-3.9	-0.5	-3.9	-0.6	-3.8	1.9	-4.0	5.2	-7.3
2	6.0	-4.2	6.6	-4.8	5.3	-4.6	7.5	-6.8	3.9	-3.1	6.0	-5.2
3	11.5	-2.3	12.0	-2.8	3.7	-2.9	4.6	-3.9	2.6	-2.4	5.5	-5.3
4	9.5	-6.4	11.0	-7.8	5.8	-3.9	8.3	-6.4	4.5	-2.6	7.2	-5.3
5	2.9	-1.3	3.1	-1.5	1.4	-1.0	1.7	-1.3	0.9	-0.6	1.1	-0.8
6	2.5	-0.2	2.5	-0.2	1.3	-0.7	1.6	-1.0	0.8	-0.3	0.9	-0.5
7	2.1	-4.2	3.4	-5.6								
8	2.1	-0.2	2.1	-0.2	0.5	-0.3	0.5	-0.3				
9	2.7	-1.0	3.1	-1.4	0.7	-0.3	0.9	-0.5	0.7	-0.1	0.8	-0.3

Previous table continued

Reach	Week 4				Week 5				Week 6			
	Min Gain	Min Loss	Max Gain	Max Loss	Min Gain	Min Loss	Max Gain	Max Loss	Min Gain	Min Loss	Max Gain	Max Loss
1	1.9	-3.4	3.9	-5.4	1.4	-1.9	2.2	-2.7	1.0	-3.8	1.1	-3.9
2	2.7	-2.1	11.8	-11.2	2.6	-1.9	8.4	-7.7	5.5	-4.3	7.1	-5.9
3	1.6	-1.7	4.5	-4.6	1.8	-1.9	5.1	-5.2	6.1	-3.6	7.7	-5.2
4	2.2	-1.6	10.6	-9.9	2.7	-2.1	21.7	-21.1	5.5	-3.7	7.3	-5.5
5	0.6	-0.5	1.1	-0.9	0.6	-0.5	1.2	-1.1	1.5	-1.0	1.8	-1.3
6	0.7	-0.9	1.8	-2.1	0.8	-0.6	2.3	-2.1	1.4	-0.6	1.5	-0.7
7									2.8	-2.4	4.8	-4.4
8									1.9	-1.6	2.7	-2.4
9	0.7	-0.3	2.0	-1.7					1.8	-1.1	2.4	-1.7

Gross Gains and Losses (as a % of upstream discharge)

Reach	Week 1				Week 2				Week 3			
	Min Gain	Min Loss	Max Gain	Max Loss	Min Gain	Min Loss	Max Gain	Max Loss	Min Gain	Min Loss	Max Gain	Max Loss
1	-0.3	-4.6	-0.3	-4.6	-1.8	-13.0	-2.0	-12.8	11.8	-24.6	32.3	-45.2
2	10.3	-7.2	11.3	-8.2	34.2	-29.8	48.7	-44.4	43.5	-34.9	66.9	-58.3
3	23.5	-4.7	24.5	-5.7	24.8	-20.0	31.0	-26.2	29.4	-27.5	62.2	-60.3
4	20.9	-14.0	24.1	-17.2	45.3	-30.4	65.1	-50.2	64.0	-37.7	102.8	-76.5
5	15.9	-7.0	17.3	-8.4	26.0	-18.4	31.8	-24.2	37.0	-23.5	48.4	-34.9
6	15.9	-1.0	16.0	-1.1	28.1	-15.4	33.2	-20.5	39.6	-16.2	47.3	-23.9
7	18.8	-38.6	31.4	-51.2								
8	23.2	-2.2	23.7	-2.7	16.8	-8.9	18.5	-10.6				
9	37.8	-13.3	43.3	-18.9	30.1	-14.1	35.0	-19.0	85.6	-16.8	102.9	-34.2

Previous table continued

Reach	Week 4				Week 5				Week 6			
	Min Gain	Min Loss	Max Gain	Max Loss	Min Gain	Min Loss	Max Gain	Max Loss	Min Gain	Min Loss	Max Gain	Max Loss
1	28.3	-51.0	57.7	-80.4	25.5	-33.8	38.5	-46.9	2.6	-9.9	2.9	-10.2
2	99.8	-76.8	430.2	-407.2	89.8	-64.7	292.3	-267.2	28.5	-22.3	36.6	-30.4
3	59.7	-64.9	169.8	-175.0	60.5	-64.2	168.8	-172.5	36.1	-21.3	45.8	-31.1
4	110.8	-79.1	530.3	-498.6	110.1	-87.6	887.2	-864.7	36.2	-24.8	48.1	-36.7
5	50.9	-39.7	84.4	-73.3	57.7	-48.4	111.7	-102.4	23.9	-15.7	28.4	-20.2
6	46.3	-62.0	121.9	-137.6	87.5	-62.8	262.6	-237.9	24.3	-9.9	27.0	-12.5
7									48.0	-41.5	82.2	-75.7
8									34.1	-28.9	47.9	-42.7
9	129.7	-66.8	391.2	-328.3					38.2	-23.3	49.8	-34.9

Gross Gains and Losses (total volume of water over the time of study in Litres)

Reach	Week 1				Week 2				Week 3			
	Min Gain	Min Loss	Max Gain	Max Loss	Min Gain	Min Loss	Max Gain	Max Loss	Min Gain	Min Loss	Max Gain	Max Loss
1	-357	-4995	-345	-5006	-1308	-9561	-1504	-9365	5968	-12500	16371	-22903
2	12275	-8559	13509	-9793	19357	-16881	27583	-25107	19526	-15663	30007	-26143
3	23397	-4668	24400	-5671	14709	-11838	18382	-15511	14206	-13288	30082	-29165
4	18425	-12368	21189	-15132	20476	-13729	29414	-22667	24349	-14360	39109	-29120
5	7654	-3363	8339	-4049	7041	-4981	8627	-6567	6982	-4434	9130	-6582
6	7938	-486	8003	-551	7444	-4065	8794	-5415	7281	-2984	8693	-4396
7	12461	-25532	20754	-33825								
8	9831	-949	10027	-1145	4800	-2550	5272	-3021				
9	8140	-2876	9330	-4065	5535	-2592	6442	-3498	11326	-2228	13620	-4522

Previous table continued

Reach	Week 4				Week 5				Week 6			
	Min Gain	Min Loss	Max Gain	Max Loss	Min Gain	Min Loss	Max Gain	Max Loss	Min Gain	Min Loss	Max Gain	Max Loss
1	10592	-19102	21612	-30122	10601	-14088	16025	-19511	2421	-9074	2687	-9340
2	26033	-20036	112220	-106222	33363	-24036	108628	-99301	24755	-19362	31850	-26456
3	17340	-18856	49363	-50879	23635	-25081	65978	-67425	29155	-17249	37060	-25154
4	34679	-24752	165952	-156025	39077	-31089	314892	-306905	25859	-17696	34375	-26212
5	7416	-5795	12308	-10686	10345	-8677	20040	-18373	9752	-6409	11573	-8230
6	8307	-11117	21862	-24673	13670	-9811	41024	-37165	10252	-4166	11375	-5290
7									29835	-25801	51041	-47007
8									17072	-14470	24000	-21399
9	12818	-6608	38666	-32457					14546	-8889	18969	-13312

APPENDIX D: Statistical breakdown of reach based relationships between contact time and mass loss per reach length.

Reach	Spearman's Rank Correlation Coefficient (r) and p-value	Spearman's Correlation (+/- ve) Significant (Yes/No)	Pearson's Product Moment Correlation Coefficient (r) and p-value	Pearson's Correlation (+/- ve) Significant (Yes/No)	Model Coefficients y-intercept slope	Coefficient p-values and significance (Yes/No) y-intercept slope	P-value of model and significance (Yes/No) Adjusted r-squared
1	0.94 0.02	+ve YES	0.84 0.04	+ve YES	-0.02 0.0001	0.93 (NO) 0.04 (YES)	0.04 (YES)
2	0.8 0.02	+ve YES	0.91 0.04	+ve YES	0.04 <0.0001	0.67 (NO) 0.004 (YES)	0.004 (YES) 0.79
3	0.94 0.02	+ve YES	0.99 0.0003	+ve YES	-0.04 <0.0001	0.23 (NO) 0.0003 (YES)	0.0003 (YES) 0.96
4	0.93 0.007	+ve YES	0.98 0.0001	+ve YES	0.09 <0.0001	0.15 (NO) 0.0001 (YES)	0.0001 (YES) 0.95
5	0.94 0.02	+ve YES	0.98 0.0006	+ve YES	-0.006 <0.0001	0.88 (NO) 0.0006 (YES)	0.0006 (YES) 0.95
6	0.94 0.02	+ve YES	0.89 0.02	+ve YES	-0.2 <0.0001	0.29 (NO) 0.02 (YES)	0.02 (YES) 0.74
7	NA	NA	1 1	+VE NO	0.4 <0.0001	NA NA	NA NA
8	0.5 1	+ve NO	0.55 0.63	+ve NO	-0.1 <0.0001	0.85 (NO) 0.63 (NO)	0.63 (NO) -0.4
9	0.9 0.08	+ve YES	0.71 0.18	+ve NO	0.02 <0.0001	0.96 (NO) 0.18 (NO)	0.18 (NO) 0.33

Previous table continued

Reach	Skewness and p-value of Residuals	Skewness (+/-ve) and significance (Yes/No)	Kurtosis and p-value of Residuals	Kurtosis (Lepto/Platy) and significance (Yes/No)	Shapiro-Wilk normality test p-value and significance (Yes/No)	Breusch-Pagan homoscedasticity test p-value and significance (Yes/No)	Comments
1	0.44 0.34	+ve NO	-1.32 0.27	Platy NO	0.73 NO	0.05 YES/NO	Outliers Funnelling
2	0.82 0.21	+ve NO	1.85 0.32	Lepto NO	0.07 NO	0.51 NO	Outliers Slight neg. skew
3	0.26 0.41	+ve NO	-1.34 0.27	Platy NO	0.97 NO	0.03 YES	Outliers Funnelling
4	-0.13 0.45	-ve NO	-1.99 0.17	Platy NO	0.31 NO	0.09 NO	Possible outlier
5	0.29 0.39	+ve NO	-1.86 0.2	Platy NO	0.3 NO	0.93 NO	Possible outlier
6	0.57 0.3	+ve NO	-1.29 0.28	Platy NO	0.6 NO	0.5 NO	
7	NA	NA	NA	NA	NA	NA	Only two observations
8	0.21 0.45	+ve NO	-2.33 0.28	Platy NO	0.64 NO	0.14 NO	only 3 observations
9	-0.23 0.42	-ve NO	-1.52 0.27	Platy NO	0.81 NO	0.04 YES	Outliers, appears to funnel

APPENDIX E: GIS-derived parameter values for each reach.

Reach	Channel Slope	Local Contributing Area (m ²)	Average Valley Width at 3m above stream surface (m)	Mean Catchment Slope	Drainage Slope	Wetness Index
1	0.095	4800	33	0.28	0.34	9.06
2	0.071	79500	96	0.19	0.16	8.25
3	0.051	160400	81	0.23	0.20	7.79
4	0.088	139525	117	0.29	0.17	7.36
5	0.105	39975	76	0.30	0.27	7.71
6	0.042	115600	63	0.29	0.20	7.56
7	0.089	24825	46	0.23	0.27	7.6
8	0.066	19775	50	0.26	0.30	7.13
9	0.016	19975	30	0.17	0.15	8.05

Previous table continued.

Reach	Reach Length (m) Channel Slope	[Reach Length (m) * Valley Width (m)] Channel Slope	Local Contributing Area (m ²) Reach Length (m)
1	1066	35656	47
2	3112	299614	361
3	4438	358135	712
4	1773	207722	896
5	1483	112055	258
6	3513	221641	775
7	1629	74980	171
8	2028	100978	148
9	7921	234549	154

APPENDIX F: Specific Conductance ($\mu\text{S}/\text{cm}$) at the beginning of the time of contact (SC_B), at peak concentration during the injection period (SC_P), and at the end of the time of contact (SC_E). The Peak Range in specific conductance is the difference between the peak value and the beginning value. The End Range in specific conductance is the difference between the specific conductance value at the end of the injection period and the value at the beginning of the injection period.

Reach	Week 1					Week 2					Week 3				
	SC_B	SC_P	Peak Range	SC_E	End Range	SC_B	SC_P	Peak Range	SC_E	End Range	SC_B	SC_P	Peak Range	SC_E	End Range
1	172.5	186.5	14.0	173.1	0.6	189.6	209.0	19.4	191.1	1.5	204.4	225.0	20.6	207.5	3.1
2	187.7	198.9	11.2	188.9	1.2	207.0	224.8	17.8	210.0	3.0	223.3	244.9	21.6	225.9	2.6
3	189.2	201.6	12.4	190.4	1.2	208.5	227.5	19.0	211.1	2.6	227.6	251.6	24.0	229.7	2.1
4	196.1	207.9	11.8	197.3	1.2	212.5	228.1	15.6	217.5*	5.0	231.2	246.4	15.2	234.1	2.9
5	185.0	210.9	25.9	187.8	2.8	210.2	252.8	42.6	215.3	5.1	230.2	288.0	57.8	236.1	5.9
6	186.0	212.5	26.5	189.0	3.0	209.0	247.1	30.1	215.2	6.2	230.2	270.8	40.6	240.7	10.5
7	181.5	194.4	12.9	183.3	1.8										
8	183.2	204.3	21.2	183.2	0.0	206.7	236.4	29.7	219.4*	12.7					
9	197.1	242.1	45.0	197.1	0.0	208.1	259.0	50.9	216.6	8.5	207.5	250.1	42.6	218.3	10.8

*value obtained from modelling the breakthrough curve providing an extension of the tail

Previous table continued.

Reach	Week 4					Week 5					Week 6				
	SC _B	SC _P	Peak Range	SC _E	End Range	SC _B	SC _P	Peak Range	SC _E	End Range	SC _B	SC _P	Peak Range	SC _E	End Range
1	199.5	214.3	14.8	205.2	5.7	203.8	226.5	22.7	207.0	3.2	155.0	167.4	12.4	156.6	1.6
2	220.6	230.5	9.9	225.8	5.2	225.3	235.0	9.7	227.4	2.1	184.2	195.0	10.8	186.7	2.5
3	230.0	244.5	14.5	237.9	7.9	230.0	242.6	12.6	233.6	3.6	189.1	200.5	11.4	191.5	2.4
4	241.1	246.5	5.4	244.1	3.0	236.9	240.2	3.3	237.5	0.6	192.5	204.0	11.5	194.0	1.5
5	228.2	283.6	55.4	235.8	7.6	215.3	253.2	37.9	222.4	7.1	179.6	207.5	27.9	184.2	4.6
6	230.5	257.1	26.6	242.4	11.9	221.0	243.7	22.7	228.3	7.3	186.3	210.5	24.2	191.0	4.7
7											180.8	189.8	9.0	183.2	2.4
8											185.8	200.3	14.5	189.4	3.6
9	208.7	229.3	20.6	218.8	10.1						188.5	210.0	21.5	188.5	0.0

SpC vs. Concentration slopes: HOBO 1 = 1778.2, HOBO 2 = 1805.2, HOBO 3 = 1806.6, HOBO 4 = 1794.1

APPENDIX G: Flow Tracker data for each reach during each field week. The data includes discharge (Q), Statistical uncertainty (Stats Unc.) in the discharge measurement, the number of stations used by the Flow Tracker during each discharge measurement, and velocity of the water (Vel.). Under Reach, d represents the downstream end of a reach and u represents the upstream end of a reach.

Reach	Week 1				Week 2				Week 3			
	Q (L/s)	Stats Unc. (%)	# of stations	Vel. (m/s)	Q (L/s)	Stats Unc. (%)	# of stations	Vel. (m/s)	Q (L/s)	Stats Unc. (%)	# of stations	Vel. (m/s)
1d	84.4	9.1	18	0.278	23.1	16.1	14	0.133	13.3	8.6	17	0.109
1u	89.3	8.2	12	0.385	31.9	3.7	12	0.323	12.2	10.3	14	0.173
2d	58.2	10.3	16	0.318	26.6	10.9	16	0.241	11.8	12.9	13	0.130
3d	56.6	11.7	14	0.252	14.9	3.8	17	0.119	6.7	11.4	7	0.098
4d	56.9			0.331	16.8	16.0	19	0.124	7.6	16.8	21	0.060
4u	39.6	13.8	11	0.362	13.8	19.4	9	0.092	10.6	3.9	12	0.175
5d	21.8	15.9	8	0.336	6.2	45.4	10	0.085	1.4	34.1	9	0.025
6d	20.8	4.6	13	0.179	6.6	4.5	15	0.117	1.7	21.5	8	0.037
6u	15.2	7.1	9	0.420	3.2	16.2	9	0.165	1.4	21.3	10	0.031
7d	12.2	28.8	10	0.075	5.2	46.0	12	0.048	6.2	15.6	7	0.114
8d	10.0	3.5	13	0.042	3.1	44.8	6	0.037	0.4	18.8	8	0.005
9d	9.6	6.1	12	0.044	3.7	7.4	11	0.021	1.3	31.2	12	0.014
9u	9.7	36.9	8	0.095	3.2	23.3	6	0.070	0.7	15.6	11	0.018

Previous table continued.

Reach	Week 4				Week 5				Week 6			
	Q (L/s)	Stats Unc. (%)	# of stations	Vel. (m/s)	Q (L/s)	Stats Unc. (%)	# of stations	Vel. (m/s)	Q (L/s)	Stats Unc. (%)	# of stations	Vel. (m/s)
1d	4.2	9.6	17	0.050	2.8	8.6	18	0.041	19.1	11.8	15	0.097
1u	5.6	19.8	12	0.120	3.8	13.9	12	0.075	21.6	9.5	11	0.136
2d	1.7	40.2	11	0.045	2.1	83.3	12	0.032	15.4	19.6	14	0.081
3d	1.4	18.9	13	0.030	3.8	62.3	8	0.040	15.3	19.4	14	0.047
4d	1.4	27.8	12	0.023	1.8	34.2	15	0.016	10.2	25.3	14	0.063
4u	1.1	13.7	8	0.042	1.1	19.3	10	0.024	9.6	4.8	14	0.114
5d	0.7	26.4	8	0.013	0.5	22.7	7	0.018	4.7	6.7	12	0.067
6d	0.4	62.4	7	0.011	1.2	34.1	7	0.019	3.0	8.1	13	0.053
6u	0.7	9.0	10	0.017	0.2	37.3	9	0.005	4.6	7.2	13	0.064
7d	0.3	10.6	15	0.017					2.9	27.0	10	0.071
8d	0.3	11.3	9	0.007					4.6	19.9	11	0.042
9d	1.1	11.6	15	0.013					7.6	20.8	9	0.041
9u	0.4	8.0	21	0.014					4.2	17.3	8	0.046

APPENDIX H: Table columns from left to right: Absolute discharge differences between discharge measurement pairs (VA – Dilution Gauging, L/s), average discharge between each method (L/s), absolute differences standardized to their respective average discharges (%), and statistical uncertainty of the velocity-area Flow Tracker discharge observations (%).

Reach	Week 1				Week 2				Week 3			
	Abs. Q Diff. (L/s)	Avg. Q (L/s)	Abs. Q Diff / Avg Q (%)	Stats Unc. (%)	Abs. Q Diff. (L/s)	Avg. Q (L/s)	Abs. Q Diff / Avg Q (%)	Stats Unc. (%)	Abs. Q Diff. (L/s)	Avg. Q (L/s)	Abs. Q Diff / Avg Q (%)	Stats Unc. (%)
1d	2.6	83.1	3.1	9.1	2.5	24.4	10.3	16.1	0.7	13.6	5.1	8.6
1u	3.3	87.6	3.8	8.2	1.9	31.0	6.1	3.7	3.9	14.2	27.6	10.3
2d	1.5	59.0	2.5	10.3	10.5	21.4	49.2	10.9	2.1	10.6	19.5	12.9
3d	1.3	57.3	2.3	11.7	0.5	15.2	3.3	3.8	2.3	7.9	29.3	11.4
4d	8.2	52.8	15.5		2.1	15.8	13.3	16.0	1.2	8.2	14.6	16.8
4u	6.0	42.6	14.1	13.8	1.0	13.3	7.5	19.4	3.6	8.8	40.9	3.9
5d	2.1	20.8	10.1	15.9	0.4	6.0	6.7	45.4	1.3	2.1	63.4	34.1
6d	2.7	19.5	13.9	4.6	1.2	6.0	20.0	4.5	0.7	2.1	34.1	21.5
6u	0.5	15.5	3.2	7.1	1.6	4.0	40.0	16.2	0.5	1.7	30.3	21.3
7d	3.5	10.5	33.5	28.8	2.2	4.1	53.7	46.0	4.9	3.8	130.7	15.6
8d	0.9	10.5	8.6	3.5	0.1	3.1	3.3	44.8	1.0	0.9	111.1	18.8
9d	0.6	9.3	6.5	6.1	0.9	3.3	27.7	7.4	0.0	1.3	0.0	31.2
9u	2.5	8.5	29.6	36.9	0.8	2.8	28.6	23.3	0.1	0.8	13.3	15.6

Previous table continued.

Reach	Week 4				Week 5				Week 6			
	Abs. Q Diff. (L/s)	Avg. Q (L/s)	Abs. Q Diff / Avg Q (%)	Stats Unc. (%)	Abs. Q Diff. (L/s)	Avg. Q (L/s)	Abs. Q Diff / Avg Q (%)	Stats Unc. (%)	Abs. Q Diff. (L/s)	Avg. Q (L/s)	Abs. Q Diff / Avg Q (%)	Stats Unc. (%)
1d	1.0	4.7	21.3	9.6	2.4	4.0	60.0	8.6	16.8	27.5	61.1	11.8
1u	1.1	6.2	17.9	19.8	1.9	4.8	40.0	13.9	17.1	30.2	56.7	9.5
2d	1.7	2.6	66.7	40.2	1.5	2.9	52.6	83.3	5.1	18.0	28.4	19.6
3d	1.1	2.0	56.4	18.9	0.9	3.4	26.9	62.3	4.0	17.3	23.1	19.4
4d	1.2	2.0	60.0	27.8	1.2	2.4	50.0	34.2	6.6	13.5	48.9	25.3
4u	0.9	1.6	58.0	13.7	1.3	1.8	74.3	19.3	5.5	12.4	44.5	4.8
5d	0.7	1.1	66.7	26.4	0.7	0.9	82.4	22.7	2.3	5.9	39.3	6.7
6d	0.9	0.9	105.9	62.4	0.1	1.2	8.7	34.1	3.5	4.8	73.9	8.1
6u	0.8	1.1	72.7	9.0	0.7	0.6	127.3	37.3	1.0	5.1	19.6	7.2
7d	0.5	0.6	90.9	10.6					3.3	4.6	72.5	27.0
8d	0.6	0.6	100.0	11.3					1.2	5.2	23.1	19.9
9d	0.3	1.0	31.6	11.6					2.6	6.6	32.1	20.8
9u	0.1	0.5	22.2	8.0					0.6	4.5	13.3	17.3

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