The Pennsylvania State University

The Graduate School

Department of Civil and Environmental Engineering

SOLUTE TRANSPORT DYNAMICS IN ALASKAN ARCTIC TUNDRA STREAMS

A Thesis in

Civil Engineering

by

Adam N. Wlostowski

© 2012 Adam N. Wlostowski

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

December 2012
The thesis of Adam N. Wlostowski was reviewed and approved* by the following:

Michael N. Gooseff  
Associate Professor of Civil and Environmental Engineering  
Thesis Advisor

Patrick Reed  
Associate Professor of Civil and Environmental Engineering

William ‘Breck’ Bowden  
Patrick Professor of Watershed Science and Planning

Peggy Johnson  
Processor of Civil and Environmental Engineering  
Head of the Department of Civil and Environmental Engineering

*Signatures are on file in the Graduate School
ABSTRACT

(Chapter 1)

One-dimensional solute transport modeling to simulate experimental tracer releases in rivers is common practice. There are generally two experimental designs employed for tracer (1) slug injections (SI), where a relatively large mass of dissolved tracer is instantaneously released into the stream to label a single parcel of stream water; and (2) constant rate injections (CRI), where a relatively small load of dissolved tracer is continuously introduced to the stream at a constant rate for a known duration of time, labeling (to a lesser extent than the SI approach) many parcels of stream water passing the injection location. However, relatively few studies have investigated the effect of experiment design on model parameter sensitivity and identifiability.

We conducted slug injection and constant-rate experiments in a low-gradient, alluvial, headwater tundra stream in northern Alaska. Each experimental data set was simulated with the One-dimensional Transport with Inflow and Storage (OTIS) model, and analyzed with Monte Carlo-based techniques to investigate differences in parameter sensitivity and time-varying identifiability. Slug injection data showed sensitivity to the longitudinal dispersion parameter, while constant-rate injection data exhibited sensitivity to the storage zone area parameter.

Constant rate injection data shows heightened identifiability for the storage zone area and storage zone – main channel exchange rate parameters during rising and tailing portions of the breakthrough curve, whereas slug injection data only show heightened identifiability to these parameters during the tailing portion of the breakthrough curve. Results show that experimental design affects parameter sensitivity and time-varying identifiability, and that experimental data may be easily analyzed to understand information contents associated with each parameter in a 1D transient storage model.

(Chapter 2)
Advvection, dispersion, and transient storage are three dominant solute transport processes in natural stream channels. One-dimensional numerical transient storage models are often used to simulate these processes along with stream flow gains and losses, in order to understand the relative spatial and temporal scales of each process. Here we describe a new approach to determine the influence of advection, dispersion, transient storage, and longer-term exchanges by directly analyzing the solute data collected from stream tracer experiments, with no parametric modeling required. The inherent challenges of using solute transport models include issues related to model appropriateness and parameter identification. Using this new approach, we are able to parse the timescales and quantity of labeled water (i.e., tracer mass) that experience each process. We are better able to discern the relative influence of advection/dispersion, transient storage, and long time-scale exchange across conditions in a single stream, and across different stream systems. We apply our approach to many slug injections of dissolved salt in lake-inlet and lake-outlet stream reaches in arctic Alaska, and are able to compare and contrast the characteristic transport processes of each reach.

(Chapter 3)

Lakes have been shown to alter basic geomorphic and hydrologic characteristics of outlet streams, compared to inlet streams. However, it is not well understood how lake-influenced differences in channel structure, open-channel hydrology, and subsurface hydrology affect solute transport mechanisms in inlet and outlet streams. Two arctic headwater streams, underlain by continuous permafrost, on Alaska’s North Slope were intensively monitored from June to September 2011. Sites were selected to focus on the influence of a single high arctic lake, known as I8-Lake. I8-Inlet, a 555m reach directly upstream of the lake is un-influenced by any upstream lakes, while I8-Outlet is a 386m reach located directly downstream of the lake. Width:depth ratio at I8-Outlet was 33 and 20 at I8-Inlet. I8-Outlet had consistently higher Manning’s n values at all discharge conditions. Water temperatures along I8 Outlet were consistently higher than water
temperature along I8 Outlet. Outlet:inlet discharge ratio declined from 4 to 1 over a 4 month period (June through September of 2011) as lake storage from snowmelt drained throughout the thawed season. Shallow groundwater table dynamics at I8-Inlet were largely controlled by precipitation events, whereas I8-Outlet had a more stable shallow groundwater table, which rose quickly in the spring and remained relatively stable throughout the season. A non-parametric analysis based on objective breakthrough curve decomposition methods was used to analyze many small conservative slug injections from each stream to characterize solute transport differences. We found that more tracer mass was associated with the transient storage timescale on I8-Outlet compared to I8-Inlet (p = 0.005), while more tracer mass was associated with advection/dispersion timescales on I8-Inlet compared to I8-Outlet. we concluded that 1) a high arctic lake imposes measurable hydrologic and geomorphic changes along the down-valley river continuum, and 2) hydrogeomorphic differences amongst streams above and below a small arctic lake create significantly different solute transport environments. More specifically, the contribution of transient storage in I8 Outlet is greater than was observed in I8 Inlet.
# TABLE OF CONTENTS

List of Figures .................................................................................................................... v

List of Tables ...................................................................................................................... vi

Acknowledgements ........................................................................................................... vii

Chapter 1 The influence of experimental design on parameter identifiability in a 1D
transient storage model for stream solute transport ....................................................... 1

1.1 Introduction .................................................................................................................... 1
1.2 Methodology .................................................................................................................. 2
1.3 Results & Discussion ................................................................................................. 5
1.4 Conclusions .................................................................................................................. 9

Breakthrough curve decomposition: A framework for analyzing solute transport
processes in rivers, independent of numerical transport models .................................... 10

Chapter 2 ............................................................................................................................... 10

2.1 Introduction .................................................................................................................... 10
2.2 Methodology .................................................................................................................. 12
2.3 Results and Discussion ............................................................................................... 16
2.4 Conclusions .................................................................................................................. 19

Chapter 3 Hydrogeomorphic contrasts between inlet and outlet streams of a high arctic
lake and subsequent solute transport implications ......................................................... 20

3.1 Introduction .................................................................................................................... 20
3.2 Study Site ...................................................................................................................... 22
3.3 Methodology ................................................................................................................ 24
3.4 Results .......................................................................................................................... 30
3.5 Discussion ..................................................................................................................... 36
3.6 Conclusions .................................................................................................................. 43

References ........................................................................................................................... 45
LIST OF FIGURES

Figure 1-1: Regional Sensitivity Analysis using the OTIS model structure ................................................................. 5
Figure 1-2: DYNIA analysis for OTIS model structure ................................................................................................. 6
Figure 2-1: An example of observed BTC (a) decomposed into a combination of advective/dispersive (b) and transient storage (c) components. ......................................................................................... 13
Figure 2-2: A box and whisker representation of the portion of injected tracer mass associated with advection/dispsersion, transient storage, and lost mass components of the total observed BTCs from I8 Inlet and I8 Outlet streams ........................................................................................................ 16
Figure 2-3: modal velocities on I8 Inlet compared to I8 Outlet ....................................................................................... 17
Figure 3-1: Toolik field station is located in the northern foothills of Alaska's Brooks Range ..................................... 22
Figure 3-2: I8-Inlet and I8-Outlet located upstream and downstream, respectively, of I8-Lake within the greater Toolik Lake watershed ........................................................................................................... 23
Figure 3-3: well stage logger schematic cartoon ............................................................................................................. 26
Figure 3-4: slug injection example photo ....................................................................................................................... 27
Figure 3-5: slug injection experimental set up and data schematic ................................................................................... 28
Figure 3-6: Stream-bed elevation profiles of I8 Inlet and I8 Outlet ............................................................................... 31
Figure 3-7: Manning's n as a function of discharge for I8 Inlet and I8 Outlet ................................................................. 32
Figure 3-8: time series of steam temperature, discharge and outlet:inlet flow ratios for I8 Inlet and I8 Outlet ................. 33
Figure 3-9: time series of temperatures at 1m depth beneath the streambed on I8 Inlet and I8 Outlet ................. 33
Figure 3-10: frequency plots of wells containing water for I8 Inlet and I8 Outlet ................................................................. 35
Figure 3-11 18 Inlet and 18 Outlet grain size distributions ............................................................................................. 37
LIST OF TABLES

Table 2-1. 18 Inlet and 18 Outlet sub-reach lengths 13

Table 3-1. 18 Inlet and 18 Outlet sub-reach lengths 27

Table 3-2. 18 Inlet and 18 Outlet wetted width and width:depth ratios 34
ACKNOWLEDGEMENTS

This thesis was made possible by support from a suite of good people and organizations, which helped in various ways throughout data collection, analysis, and writing processes. First and foremost, Michael N. Gooseff provided continued support, guidance, and enthusiastic encouragement as my primary advisor and co-author, without his assistance none of this would be possible. William ‘Breck’ Bowden and Wil Wollheim contributed greatly to this work as principal investigators, co-authors, and academic role models. Thanks to Thorsten Wagener for his academic advisory, co-authorship, and terrific teaching abilities. Patrick Reed assisted me greatly in understanding parameter sensitivity and optimization, while providing guidance and advisory when needed. Toolik Field Station and its amazing staff assisted with remote field logistics in northern Alaska. Kyle Whittinghill, Malcolm Herstand, Erika Smull, Sam Parker, Ryan Sleeper, Claire Treat, Genna Woldvogel, Chris Bakey, and Sarah Godsey all contributed in some way to field data collection. Jon Herman, Joe Kasporyzk, Christa Kelleher, and Adam Ward all assisted greatly with the analysis of field data. Thanks to all current and past Penn State WRE students and faculty for creating a top-notch working environment. Also a very special thanks to my amazing family: Paul Wlostowski, Judith Wlostowski, Matthew Wlostowski, Colleen Wlostowski, and Raymond Blatner for their ongoing love and support through 24 years of life and counting!

This material is based upon work supported by The National Science Foundations Office of Polar Programs under collaborative grant nos. 0902029, 0902113, and 0902106. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.
Chapter 1
The influence of experimental design on parameter identifiability in a 1D transient storage model for stream solute transport

1.1 Introduction

Stream solute transport models that account for advection, dispersion, and transient storage are commonly used to simulate observations from experimental releases of conservative tracers. A set of best-fit model parameters, which maximize the match of simulated to observed data, can be found by manual calibration or using automated search algorithms. The best-fit parameter set may then be used to characterize the spatial and temporal extent of advective, dispersive, and transient storage properties of a given stream reach [Briggs et al., 2010; Harvey et al., 1996; Wondzell, 2006b]. There are generally two experimental designs used for solute additions: (1) slug injections (SI), where a relatively large mass of dissolved tracer is instantaneously released into the stream to label a single parcel of stream water; and (2) constant rate injections (CRI), where a relatively small load of dissolved tracer is continuously introduced to the stream at a constant rate for a known duration of time, labeling (probably to a lesser extent than the SI approach) many parcels of stream water passing the injection location.

Experimentalists are faced with a decision of which injection method to use – SI or CRI? Payn et al. [2008] addressed this question by comparing SI and CRI experiments through non-parametric residence time distribution (RTD) analysis. They determined that both CRI and SI data have similar RTDs and hydrologic retention characteristics, and concluded that linear transport models (e.g. OTIS) are appropriate for modeling both data sets. On the other hand, Wagner and Harvey [1997] compared both experiment types parametrically using synthetically
generated concentration data and a 1D transient storage model. They concluded that experimental design has a profound affect on model results due to differences in parameter sensitivities and information content between SI and CRI data sets. However, to the best of our knowledge, there has not yet been a study that interrogates experimental data for transient storage model parameter sensitivity and time-varying identifiability using global sensitivity techniques.

This note expands on a methodology presented by Wagener et al. [2002, 2003] to elucidate the influence of experimental design on parameter sensitivity and time-varying identifiability (i.e. parameter uniqueness), using two field data sets collected in injections of contrasting design. We also seek to add to previous work by Wagner and Harvey [1997] by evaluating a 1D solute transport model with global sensitivity analysis strategies and applying these methods to real, rather than synthetic experimental data.

1.2 Methodology

Experimental work was carried out on a 265 m reach of I8-Outlet, a low gradient, alluvial tundra stream. This work was part of a larger study of hydroecological characteristics of tundra streams. However, during mid-simmer, tundra streams physically behave similarly to stream in temperate areas [Edwardson et al., 2003; Greenwald et al., 2008; Zarnetske et al., 2007]. Thus this the methodologies described in this note are extensible to other biomes and is not restricted to arctic environments.

CRI and SI experiments were completed July 15 and 16, 2011, respectively. Dissolved NaCl was used as the conservative tracer: 12 kg for the SI, and 200 g/L injected for 3.5 hrs for the CRI. Discharge during the SI was 20% higher (133 L/s) than discharge during the CRI (110 L/s). Continuous specific conductance measurements were logged (HOBO Conductivity Data Logger –
U240-001) at five-second intervals at the top and bottom of the reach throughout each experiment.

Tracer data was simulated with the One-dimensional Solute Transport with Inflow and Storage (OTIS) model (equations 1 and 2) [Runkel, 1998].

\[
\frac{\partial C}{\partial t} = -\frac{Q}{A} \frac{\partial C}{\partial x} + \frac{1}{A} \frac{\partial}{\partial x} \left( AD \frac{\partial C}{\partial x} \right) + \frac{q_{LIN}}{A} \left( C_L - C \right) + \alpha (C_s - C) \quad (1)
\]

\[
\frac{\partial C_s}{\partial t} = \alpha \frac{A}{A_S} (C - C_S) \quad (2)
\]

where \( Q \) is stream discharge (m\(^3\)/s), \( C \) is main channel solute concentration (mg/m\(^3\)), \( A \) is channel area (m\(^2\)), \( D \) is the dispersion coefficient (m\(^2\)/s), \( q_{LIN} \) is the lateral inflow discharge (m\(^3\)/s/m), \( C_L \) is the storage zone solute concentration (mg/L), \( A_S \) is the storage zone area (m\(^2\)), and \( \alpha \) is the main channel – storage zone exchange rate (1/s).

This analysis is based on Monte-Carlo sampling of 2000 points in the feasible parameter space, of \( A, D, A_S, \) and \( \alpha \). \( A, D, \) and \( A_S \) were uniformly sampled, while \( \alpha \) was uniformly sampled from the log-transformed space because its feasible range spans several orders of magnitude. The performance of each parameter set was evaluated with a root mean squared error (RMSE) objective function (equation 3),

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (c_{sim,i} - c_{obs,i})^2}{n}} \quad (3)
\]

where, \( c_{sim,i} \) and \( c_{obs,i} \) are the simulated and observed concentrations at the \( i^{th} \) sample, and \( n \) is the total number of samples. Smaller RMSE values indicate a better fit of simulated to observed data. Parameter sets were ranked by RMSE performance and the top 10% parameter sets were selected to discern behavioral (good performing) from non-behavioral (poor performing) parameter sets (even though we accepted that more than 10% might provide acceptable simulations). We
selected the 10% threshold because we are only investigating whether or not the top of the parameter distribution is variable across the feasible parameter range (see discussion in Wagener et al., 2003).

Sensitivity is a measure of a parameter’s influence on a model’s output. Parameters with higher sensitivity have a greater influence on the model output. We determined the sensitivity of the four model parameters using Regional Sensitivity Analysis (RSA) [Freer et al., 1996; Spear and Hornberger, 1980]. RSA compares the cumulative distribution functions (CDF) of behavioral and non-behavioral parameters. If the CDFs are similar in shape to the uniform CDF, then no particular range of values for this parameter is preferable to another, hence indicating a parameter that is not sensitive. However, if the shapes of the CDFs are very different, better parameters values are distributed across a narrower range of feasible values, indicating higher parameter sensitivities.

A parameter is globally identifiable if it is uniquely locatable within the parameter space, where a lack of identifiably makes it impossible to accept of reject constituent model hypotheses, given observed data [Kleissen et al., 1990]. In this note, we analyze the identifiability of each model parameter through time along the concentration-time profile with DYNAmic Identifiability Analysis (DYNIA) [Wagener et al., 2002, 2003]. The objective of the DYNIA framework is to locate times of high identifiability, and thus high information content, along the concentration-profile (or some other time series) for each parameter. DYNIA is a direct extension of RSA as implemented by Freer et al. [1996]. Instead of generating a behavioral parameter set by evaluating RMSE across the entire concentration profile (RSA), DYNIA evaluates RMSE across a moving window. Here we chose a four-minute window size. So, at each time step the slope and 90% confidence interval of the behavioral CDF is evaluated for each parameter. Narrower confidence intervals and steeper gradients correspond to times of higher identifiability.
1.3 Results & Discussion

The CDFs of the behavioral parameter populations for SI and CRI data are shown in Figure 1-1. The most sensitive parameter by far for both experimental designs was channel area $A$ (Figure 1-1a), as shown by the greatest skew of the behavioral CDF. The median value for $A$, as indicated by dashed lines, lies between 7.5 and 8 m$^2$ for the SI data and between 6.5 and 7 m$^2$ for the CRI data. This difference is likely due to the higher discharge conditions and enhanced advection during the SI experiment. Dispersion $D_x$ is slightly more sensitive using the SI data compared to the CRI data (Figure 1-1b). Storage zone area $A_S$ shows greater sensitivity and a smaller behavioral parameter range using the CRI data (Figure 1-1c). Storage zone – main channel exchange rate $\alpha$ is the least sensitive of all parameters for both the SI and CRI data sets (Figure 1-1d).

Figure 1-1: Regional Sensitivity Analysis using the OTIS model structure for parameters channel area $A$ (a), longitudinal dispersion $D_x$ (b), storage zone area $A_S$ (c), and storage zone exchange rate $\alpha$ (d). CRI data results are displayed by grey lines and SI data results are displayed as black lines. Dashed lines on plot (a) indicate the median $A$ values for each experiment type.
The disproportionate sensitivity of $A$ relative to all other parameters, in both experiment types, is likely a function of the RMSE objective function, when the error is accumulated over the whole breakthrough curve. RMSE is far more sensitive to timing errors than amplitude errors, because a slight difference in timing will create a significant error during the highest concentration periods. Because $A$ controls the advective component of transport, it has a strong influence on peak concentration (SI) and plateau (CRI) timing at the downstream monitoring location. Following the continuity equation, if $A$ is too high for a particular discharge, the simulated breakthrough curve will arrive late at the downstream monitoring location; likewise, if $A$ is too small, the simulated breakthrough curve will arrive early at the downstream monitoring location. Thus, $A$ is the most sensitive parameter. Compared to $A$, other parameters are minimally sensitive for both experimental data sets, ultimately leading to unreliable parameter estimates for $D_x$, $A_S$, and $\alpha$ for the river reach studied.

Figure 1-2: DYNIA analysis for OTIS model structure with SI (a, c, e, g) and CRI (b, d, f, h) data. The parameters are channel area $A$ (a-b), longitudinal dispersion coefficient $D$ (c-d), storage zone area $A_S$ (e-f), and storage zone exchange coefficient, $\alpha$ (g-h). Bold dashed lines (plots a and b) correspond to median best performing $A$ values from RSA analysis. Bold boxes (1-12) highlight regions of increased parameter identifiability.
Figure 1-2 shows the results of the DYNIA analysis for both SI and CRI data sets. The CDF gradient at each time step is shown as grayscale and 90% confidence intervals are displayed as dashed lines bounding the grayscale, or simply the vertical extent of the grayscale. Darker colors and narrower 90% confidence intervals correspond to periods of higher parameter identifiability. The vertical location of the darker colors indicates in what range most of the behavioral parameters are located (the number of parameter sets found in this range is proportional to the color – all sets in one grid cell would turn the cell black). The normalized concentration profile is superimposed on the plots to show changes in relative concentration through time.

For the SI data set, $A$ shows a region of well identified parameter values on the rising limb of the concentration profile through the peak concentration (Figure 1-2a, region 1). Shortly after the peak value and through the tail, parameter identifiability deteriorates and good-performing parameter values are widely distributed over the feasible range. The CRI data set shows well identified values of $A$ on the rising limb (Figure 1-2b, region 2) and falling limb (Figure 1-2b, region 3) of the concentration profile, with more poorly identified parameter values through the leading plateau shoulder and concentration tail. The $A$ values corresponding to regions of highest identifiability for both the SI and the CRI data sets, as shown by the dashed lines (Figure 1-2a and b), agree with the median best performing values from the RSA analysis (Figure 1-1a). This somewhat intuitive observation illustrates the connection of these two analyses, as DYNIA is simply a time-varying extension of RSA.

Dispersion, $D$, shows well-identified values prior to the arrival of tracer for both SI (Figure 1-2c, region 3) and CRI (Figure 1-2d, region 4) experiments. Following the arrival of tracer the analysis exhibits a rapid deterioration in parameter identifiability, where the 90% confidence intervals abruptly widen and more optimal parameter values are broadly distributed across the parameter space. A possible explanation for the early time identifiability of this
parameter is that $D$ mechanistically controls the spreading of the solute front. Thus, $D$ will control the initial arrival time of tracer at the downstream monitoring location, given that $A$ is appropriately identified.

Storage zone area $A_s$, for the SI data set, is poorly identified throughout the arrival, peak, and early tail periods. However during the late tail times (Figure 1-3e, region 6), better performing parameter values are distributed over a narrower portion of the parameter space. On the other hand, the CRI data set shows regions of increased $A_s$ identifiability on the rising and falling shoulder regions and tailing segments of the concentration-time profile. Similar to findings by Wagener et al. [2002], the CRI data set highlights an interaction between $A$ and $A_s$, where $A_s$ is best identified when $A$ is most poorly identified – across the plateau shoulders and late tail times (Figure 1-2f, regions 7, 8, & 9). This interaction if forced by the contrasting functionality of $A$ and $A_s$ Channel area, $A$, controls the advective transport and thus heavily influences the timing of peak concentration values, whereas $A_s$ controls the late time release of solute from storage as well as the early-time filling of storage zones, hence the shape of the concentration profile tail.

Storage zone – main channel exchange rate $\alpha$ is well identified in the tailing portions of both SI data (Figure 1-2g, region 10) and CRI data (Figure 1-2h, region 12). Thus, $\alpha$ has partial control on the late time release of tracer from storage zones to the main channel. The CRI data set also shows well-identified periods across the leading shoulder and early plateau times of the concentration profile (Figure 1-2h, region 11). This is likely due to the initial, early time, saturation of storage zones with tracer.

The results found in this study largely corroborate findings by Wagner and Harvey [1997]. However, we used experimentally gathered tracer data in combination with robust global Monte Carlo sensitivity analyses to highlight basic differences in parameter sensitivity and identifiability between SI and CRI modeled tracer data. Given the use of real experimental tracer
data, the results shown in this note can be better used for experimental design and to understand modeling limitations/capabilities of field data from tracer experiments.

1.4 Conclusions

This technical note aims to elucidate the influence of experimental design on transient storage model parameter sensitivity and time-varying identifiability, using Monte Carlo based analysis methods, and experimental data from tracer experiments in a low gradient, alluvial headwater tundra stream in northern Alaska. We arrived at the following three conclusions: (1) Experimental design has a profound influence on the global sensitivity and the time-varying identifiability of parameters in the OTIS model structure. (2) Data from the SI method are associated with increased model sensitivity to the $D_x$ parameter, while data from the CRI method are associated with increased model sensitivity to the $A_S$ parameter. (3) Data from the CRI method show heightened identifiability for $A_S$ and $\alpha$ parameters during rising and tailing portions of the concentration-time profile, whereas slug injection data only show heightened identifiability to these parameters during the tailing portion of the concentration-time profile.

These results are specific to the two injections simulated and to the characteristics of the reach analyzed. Wagener et al. [2002] came to similar conclusions based on slug injections in a low gradient UK stream and Scott et al. [2003] reported low sensitivities for transient storage parameters ($\alpha$ and $A_S$) using CRI methods on 3 of 5 reaches on a small, steep mountain stream in CA, USA. The techniques described here may be applied to comparative studies of breakthrough curve behavior to investigate the role of, for example, morphology on solute transport model parameter sensitivity. Our Monte Carlo based approach is straightforward and can be applied to determine whether or not a parameter is sufficiently sensitive for solute transport modeling.
Chapter 2

Breakthrough curve decomposition: A framework for analyzing solute transport processes in rivers, independent of numerical transport models

2.1 Introduction

Advection, dispersion, and transient storage are three dominant processes controlling solute transport in natural stream channels. Advection is due to bulk fluid movement along the primary longitudinal flowpath of a stream channel. Dispersion is the spread of particles resulting from the combined influence of complex velocity distributions (mechanical mixing) and particle diffusion [Fischer, 1973]. Transient storage describes physical processes, which retain streamwaters and associated solutes for some period of time before releasing them back to the primary longitudinal flow path of the main channel. It has become common practice to simulate these three basic mechanisms via a set of partial differential model equations, simulating the transport of solute through space and time using a numerical model.

The development of our current mathematical understanding of solute transport in rivers has been constructed over time by several important literature contributions. Early solute transport models were developed to simulate the movement of solutes through a pipe, only considering advection and dispersion processes (equation 2-1) [Taylor, 1954, 1921],

\[
\frac{\partial C_{av}}{\partial t} + v \frac{\partial C_{av}}{\partial x} = D \frac{\partial^2 C_{av}}{\partial x^2}
\]  

(2-1)

where, \( t \) is time [T], \( x \) is longitudinal distance [L], \( C_{av} \) is the cross-section average solute concentration \([M/L^3]\), \( v \) is the average cross-sectional velocity \([L/T]\), and \( D \) is the dispersion coefficient \([L^3/T^2]\). This model, which only considers advection and dispersion, assumes that the
concentration-time breakthrough curves (BTC) takes a Gaussian distribution, where the plume spread (from an Eularian perspective) increases with the square root of time.

Later work, most notably from Chatwin [1971], Day and Wood [1976], Day [1977], Beltaos and Day [1978] challenged the efficacy of a simple advection-dispersion model as applied to simulating solute transport in natural river channels. The Gaussian advection-dispersion model was able to accurately simulate solute transports data prior to the advective timescale. However, at late-time, systematic tailing was observed, displaying a consistent deviation from Gaussian behavior. Thackston and Schnelle [1970] followed up on late-time solute tailing observations by proposing one of the first transient storage models, by considering solute dead-zone interactions. Dead-zone theory stated that tracer could be trapped in pockets of little to no flow, which temporarily retain tracer while the bulk of the tracer plume passes. Dead-zone theory provided a logical explanation for the consistent post-advection time-scale deviation of the Taylor models from field observation in natural channels.

Bencala and Walters [1983] used Thackston and Schnelle’s [1970] model in a landmark paper, thoroughly explaining the development and application of what is now known as the transient storage model (TSM). This specific TSM uses a single rate mass transfer configuration, and an exponential residence time distribution (RTD). However, other configurations exist, employing different RTDs, such as a lognormal, gamma, or power law RTD [Haggerty and Reeves, 2000; Haggerty et al., 2000, 2002; Worman et al., 2002]. Experimental in-stream tracer methods in combination with 1D numerical transient storage models [Stream Solute Workshop, 1990] are now widely used for characterizing spatial and temporal extent of advection, dispersion, and transient storage processes [Bencala and Walters, 1983; Briggs et al., 2009; Choi et al., 2000; Harvey et al., 1996; Wagner and Harvey, 1997b; Zarnetske et al., 2007].

Despite the ease and accessibility of modeling solute injection data with 1D numerical solute transport models, interpretation of inverse model results can be problematic. Transient
storage model parameters, particularly those representing transient storage – main channel exchange, have been shown to lack parameter sensitivity and identifiability [Scott et al., 2003; Wagener et al., 2002]. Furthermore, transient storage model parameters have been found to lack physical meaning [Marion et al., 2003; Wondzell, 2006a]. Recent efforts have been made to use simple metrics as a way to characterize and compare solute transport mechanisms across spatial and temporal scales [Gooseff et al., 2007; Mason et al., 2012; Payn et al., 2009; Schmid, 2003].

As an expansion of this work, the goal of this note is to put forth a simple framework to parse quantitatively the relative influence of advective/dispersive and transient storage processes without requiring transport models and their inherent limitations. We apply our new methodology to several solute injections performed in two Alaskan tundra streams, based on an objective decomposition of residence time distributions into basic principle components by injectate mass.

2.2 Methodology

Solute injections were carried out on experimental reaches of I8-Inlet and I8-Outlet, two low-gradient, alluvial, headwater tundra streams located on Alaska’s North Slope. I8 Inlet and I8 Outlet are the inlet and outlet, respectively, of a small high arctic lake known as I8. From June to September 2011, we established a database of residence time distributions from many small slug injections of dissolved NaCl, completed across a wide range of discharge conditions.

Injections were completed along 3 sub-reaches, which together compose the greater experimental reach (table 2-1). The analyses presented here employ data from 37 injections on I8-Outlet, and 35 injections on I8-Inlet. Although many injections were complete, we only selected the aforementioned BTCs, which were well-sampled all the way through the tail to the detection limit of the data loggers used. Furthermore, this analysis does not discern injections by sub-reach.
We assume that each sub-reach is an adequate representation of the combined morphologic and hydrologic features of the greater stream reach. So, all BTCs, regardless of sub-reach, are lumped together from each stream (I8 Inlet and I8 Outlet).

Table 2-1: I8-Inlet and I8-Outlet were broken into sub-reaches, over which small slug injections were completed

<table>
<thead>
<tr>
<th>Sub-reach 1 (m)</th>
<th>Sub-reach 2 (m)</th>
<th>Sub-reach 3 (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I8 Inlet</td>
<td>190</td>
<td>150</td>
</tr>
<tr>
<td>I8 Outlet</td>
<td>140</td>
<td>125</td>
</tr>
</tbody>
</table>

Figure 2-1: An example observed BTC (a) decomposed into a combination of advective/dispersive (b) and transient storage (c) components.

The analysis proposed in this note is based on the objective decomposition of slug injection BTCs into three basic components by mass of injected tracer: Advective/dispersive, transient storage, and lost tracer components. We will hereinafter use the term BTC ‘component’ to refer to portions of the BTC, which represent some amount of conservative solute mass.
Following the Taylor [1921] dispersion model, we can accurately reproduce solute injection data prior to the advective timescale using a Gaussian distribution. Thus, we delineate the advective/dispersive component of the BTC as a Gaussian shape resulting from the temporal mirroring of the rising limb of the BTC about the peak concentration and time (figure 2-1b). We can then quantify the amount of tracer mass recovered within the advective/dispersive component, as a percentage of injected mass (equation 2-2),

\[
\% M_{\text{adv/disp}} = \left( \frac{Q \int_{0}^{t} C(t)_{\text{adv/disp}}}{M_{\text{INJ}}} \right) \times 100 \quad (2-2)
\]

where, \(\% M_{\text{adv/disp}}\) is the percentage of injected mass recovered within the advective/dispersive component of the BTC, \(Q\) is the discharge at the sampling location \([L^3/T]\), \(C(t)_{\text{adv/disp}}\) is the advective/dispersive component concentration time-series \([(M*T)/L^3]\), and \(M_{\text{INJ}}\) is the mass of NaCl tracer added at the upstream injection location \([M]\).

The transient storage component of the BTC is defined as the advective/dispersive component subtracted from the entire observed BTC (figure 2-1c). Again, we are able to quantify the amount of tracer mass recovered within the transient storage component, as a percentage of injected mass (equation 2-3),

\[
\% M_{TS} = \left( \frac{\int_{0}^{t} C(t)_{TS}}{M_{\text{INJ}}} \right) \times 100 \quad (2-3)
\]

where, \(\% M_{TS}\) is the percentage of injected mass recovered within the transient component of the BTC, \(Q\) is the discharge at the sampling location \([L^3/T]\), \(C(t)_{TS}\) is the transient storage component concentration time-series \([(M*T)/L^3]\), and \(M_{\text{INJ}}\) is the mass of NaCl tracer added at the upstream injection location \([M]\).
Lastly, the third component of the BTC is the injected mass that we were unable to detect with simple in-stream auto-sampling methods (i.e. lost tracer). There are several reasons why injected tracer might not be detected at the downstream sampling site. Tracer may be unrecovered due to (1) labeled water leaving the study reach along flow paths that will never return to the spatial extent of the reach, or (2) labeled water leaving the study reach along long timescale flow paths, which may return to the spatial extent of the reach beyond the temporal detection capacity of slug methodology and thus below detection limits of automatic conductivity samplers. This component therefore represents a combination of hydrologic losses and long timescale transient storage. For a more detailed explanation of un-recovered tracer mass, see Payn et al. [2009]. This BTC component is unseen, meaning that we are unable to measure an explicit concentration time-series using in-stream sampling methods. However, we are able to quantify the mass associated with this component as the difference between total recovered mass by the observed BTC and the total injected mass (equation 3-4).

\[
\% M_{\text{loss}} = \left( \frac{M_{\text{INJ}} - Q \int_0^t C(t)_{\text{BTC}}}{M_{\text{INJ}}} \right) \times 100 \quad (3-4)
\]

where, \(\% M_{\text{loss}}\) is the percentage of injected mass not recovered within the observed BTC, \(Q\) is the discharge at the sampling location \([L^3/T]\), \(C(t)_{\text{BTC}}\) is the transient storage component concentration time-series \([(M*T)/L^3]\), and \(M_{\text{INJ}}\) is the mass of NaCl tracer added at the upstream injection location \([M]\).
2.3 Results and Discussion

Figure 2-2: A box and whisker representation of the portion of injected tracer mass associated with advection/dispersion, transient storage, and lost mass components of the total observed BTCs from I8 Inlet and I8 Outlet streams

Results from BTC decomposition analysis described above are displayed in figure 2-2. Median percentage of injected tracer mass associated with advection/dispersion is 52% and 49% for I8 Inlet and I8 Outlet, respectively. Median percentage of injected tracer mass associated with transient storage is 37% and 42% for I8 Inlet and I8 Outlet, respectively. Median percentage of tracer mass not recovered by the total observed BTC is 8% and 7% for I8 Inlet and I8 Outlet, respectively.

Both streams display similar relative portions of solute transport timescales. The majority of tracer mass was recovered within the Gaussian shaped advective/dispersive component of the BTCs. The transient storage and lost tracer components make up the remainder of the mass balance. This result indicates that combined advective/dispersive processes, which are of a shorter timescale than transient storage, are the dominant transport mechanisms in both I8 Inlet and I8 Outlet.
Although both streams appear to have similar dominant transport mechanisms, differences are observed in the relative percentage of tracer mass associated with advective/dispersive to transient storage portions of observed BTCs. A paired t-test of the mean transient storage component groups on I8 Inlet and I8 Outlet is statistically different (p = 0.005). I8 Inlet has less tracer mass associated with transient storage timescales than I8 Outlet. Although not statistically significant, the data also show that the median percentage of tracer mass associated with the advective/dispersive component of the total observed BTC is greater on I8 Inlet than I8 Outlet. This result highlights slight differences in contributing solute transport mechanisms between the two studies streams. I8 Inlet is more advective/dispersive than I8 Outlet, while I8 Outlet is more influenced by longer timescale transient storage processes. This result is particularly intriguing because it shows that ability of the BTC decomposition method to quantify small differences in transport mechanisms between systems.

Figure 2-3: Greater modal velocities on I8 Inlet compared to I8 Outlet over a wide range of discharge conditions. Reflective of differences advective in solute transport processes
Advective travel time over sub-reaches, $t_{adv}$, was calculated as the time between peak concentration time at the upper boundary, $t_{pk,upper}$, and peak concentration time at the lower boundary, $t_{pk,lower}$ (equation 3-5).

\[ t_{adv} = t_{pk,lower} - t_{pk,upper} \] (3-5)

Modal velocity, $v$, was then calculated as the distance between the upper and lower sub-reach boundary, $x$, divided by $t_{adv}$ (equation 3-6).

\[ v = \frac{x}{t_{adv}} \] (3-6)

Modal velocity was calculated from 43 slug injections on I8 Outlet and 39 slug injections on I8 Inlet. We were able to use more BTCs for this analysis because modal velocity calculations can be made without “complete” BTCs, containing late-time data. Results show greater modal velocities on I8 Inlet than I8 Outlet over a wide range of discharge conditions (figure 2-3). This result is further confirmation of differences in solute transport characteristics between the two streams; I8 Inlet is more dominated by advection than I8 Outlet.

I8 Inlet and I8 Outlet showed similar lost tracer components of observed BTCs. This portion of the injected mass, which was not recovered, represents a combination of long timescale hyporheic flowpaths and hydrologic losses to groundwater systems. We did not expect to see measurable lost tracer components on either stream because of the confined nature of stream channels underlain by continuous permafrost. Permafrost separates streams from deep groundwater systems by posing a no flow boundary both vertically, beneath the channel, and laterally, to either side of the channel [Brosten et al., 2006].

Another non-parametric approach to analyzing solute BTCs is temporal moment analysis. Temporal moment routing has been used to predict the shape of observed BTCs by several previous studies [Schmid, 2003; Worman et al., 2002]. However, the BTC decomposition methods move beyond the use of temporal moments for two reasons. First, BTC decomposition
allows for the isolation of process specific time domains, specifically advection/dispersion and transient storage BTC components. Temporal moments provide a broader shape characterization of BTCs, which do not isolate specific time domains of observed breakthrough curves. Second, BTC decomposition quantifies the mass of injected tracer associated with different components of observed BTCs, which by itself permits comparison of the relative contribution of specific transport mechanisms. Previous temporal moment routing techniques employed the first through fourth temporal moments to fit observed BTCs, and link temporal moments to Transient Storage Model transport parameters [Schmid, 2003]. However it is the non-unique and non-physically based nature of Transient Storage Model transport parameters that we wish to escape by using BTC decomposition methods in the first place.

2.4 Conclusions

The main goal of this note was to present a conceptual model for parsing the relative influence of advective/dispersive from transient storage solute transport processes using an objective decomposition of experimental BTCs. We were able to demonstrate that solute transport along both I8 Inlet and I8 Outlet is dominated by shorter timescale advection and dispersion processes due to the fact that the majority of tracer mass was recovered within the advective/dispersive component of the BTC. Furthermore, our results from the BTC decomposition methods were able to highlight differences in solute transport process between I8 Inlet and I8 Outlet to a statistically significant degree. The relative contribution of advective/dispersive processes along I8 Inlet is greater than I8 Outlet, while the relative contribution transient storage processes is greater along I8 Outlet compared to I8 Inlet.
Chapter 3

Hydrogeomorphic contrasts between inlet and outlet streams of a high arctic lake and subsequent solute transport implications

3.1 Introduction

Geomorphologists and aquatic ecologists alike, explain large-scale spatial and temporal patterns with popular continuum paradigms [Leopold and Maddock, 1953; Vannote et al., 1980]. For example, the River Continuum Concept [Vannote et al., 1980] states that combined physical and hydrologic catchment function creates biological response patterns along the length of a river. However, certain watershed features pose a disturbance to geomorphic and ecological patterns along longitudinal valley gradients [Wohl, 2004], such as hillslopes, bedrock outcrops, and lakes. Lakes have been shown to influence differences in channel-structure [Arp et al., 2007], discharge dynamics [Arp et al., 2006], water chemistry [Kling et al., 2000; Marcarelli and Wurtsbaugh, 2009], habitat [Dorava and Milner, 2000; Richardson and Mackay, 1991], temperature [Dorava and Milner, 2000; Richardson and Mackay, 1991; Wotton, 1995], and sedimentation [Arp et al., 2007] between lake-inlet and lake-outlet streams.

Many arctic Alaskan stream networks located north of the Brooks Range can be characterized as lake-stream systems. Lakes in arctic catchments have been shown to significantly alter streamwater chemical composition between inlet and outlet streams, due to lentic chemical processing [Kling et al., 2000]. Also, increased temperatures in lake outlets, compared to lake inlets [Dorava and Milner, 2000; Wotton, 1995], may influence sub-channel architecture and associated shallow groundwater dynamics in arctic stream systems. Sub-stream seasonally frozen sediments are preferentially thawed by conductive and convective heat transfer
from the open channel into subsurface sediments [Brosten et al., 2006, 2009]. Brosten et al., [2006] showed deeper annual maximum thaw depths beneath a lake outlet, compared to a lake inlet. However, the study did not explore differences in thaw dynamics due to lake influences, specifically.

Combined hydrologic and morphologic characteristics of streams have been shown to influence dominant solute transport processes: advection [Leopold and Maddock, 1953], dispersion [Beltaos and Day, 1978; Fischer, 1973], and transient storage [Cardenas, 2009; Kasahara and Wondzell, 2003; Wondzell and Swanson, 1999; Wondzell, 2006b]. We conducted channel structure surveys, measured open channel discharge, stream temperature, sub-stream temperature, shallow-groundwater dynamics, and grain size distributions to investigate hydrogeomorphic differences between lake inlet and outlet streams. We also conducted many small injections of conservative tracer to elucidate differences in solute transport dynamics (advection, dispersion, and transient storage) between lake inlet and outlet streams. To our knowledge, no work has been done to investigate geomorphic and hydrologic differences between lake inlets and outlets within arctic stream networks underlain by continuous permafrost. Moreover, this study is the first of its kind, to compare solute transport dynamics between lake inlets and lake outlets.
3.2 Study Site

Field research was conducted within the Toolik Research Natural Area, located in the northern foothills of Alaska’s Brooks Range (figure 3-1). River drainages were formed by glacial outwash from the greater Wisconsonian glaciations [Hamilton and Walker, 2002]. Dominant vegetation consists of sedges, grasses, and mixed dwarf birch. Hydrology is largely dominated by spring snowmelt, occurring in May. Ice-out initiates a brief runoff period lasting from mid to late May through late September or early October [Kane et al., 1989]. Average annual rainfall is 18cm, a large percentage of which occurs during July and August [Kane et al., 1989; McNamara et al., 1997, 1998]. Runoff ratios vary greatly and are largely dependent on rainfall intensity and
antecedent moisture conditions [Kane et al., 1989]. The entire region is underlain by continuous permafrost. Conductive and convective heat transfer from the open channel into sub-stream sediments creates a seasonally evolving, preferentially thawed region beneath stream channels, commonly referred to as a thaw bulb [Brosten et al., 2006, 2009]. Rivers located in regions of continuous permafrost are disconnected from deep groundwater networks, but shallow groundwater above frozen ground can be connected to streamwaters. All shallow groundwater activity is confined to the active layer, the near surface mineral soil and organic layer above the frost table, which experiences seasonal freezing and thawing.

Figure 3-2: 18-Inlet and 18-Outlet are upstream and downstream, respectively, of 18-Lake within the greater Toolik Lake watershed. Map credit: Toolik Field Station GIS http://toolik.alaska.edu/gis/maps/maps.php?category=general

Experimental work for this study was done on two streams, 18 Inlet and 18 Outlet, the inlet and outlet, respectively, of a small lake known as 18 (figure 3-2). These streams may be generally classified as low gradient, alluvial, headwater tundra streams [Brosten et al., 2006; Greenwald et al., 2008; Zarnetske et al., 2007, 2008]. 18 Inlet is completely un-influenced by upstream lakes, while 18 Outlet is located directly downstream of 18 Lake. Total stream reaches
(I8 Inlet: 555 m, I8 Outlet: 386 m) were selected such that they encompassed a representative sample of stream features (pools, riffles, runs, meanders). Total stream reaches on I8 Inlet and I8 Outlet were divided into 3 sub-reaches (table 3-1). Sub-reaches were delineated such that they were each an appropriate representation of the total stream reach morphology. It should be noted that analyses within this study did not discern results between sub-reaches. We assume that each reach is an adequate representation of combined morphologic and hydrologic features of the greater stream reach. So, all results, regardless of sub-reach, are lumped together from each stream (I8 Inlet and I8 Outlet). The purpose of this study is to compare two different streams, not different reaches within the same stream.

Table 3-1: sub-reach lengths within the total stream reaches studied on I8 Inlet and I8 Outlet

<table>
<thead>
<tr>
<th></th>
<th>Sub-reach 1 (m)</th>
<th>Sub-reach 2 (m)</th>
<th>Sub-reach 3 (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I8 Inlet</td>
<td>190</td>
<td>150</td>
<td>215</td>
</tr>
<tr>
<td>I8 Outlet</td>
<td>140</td>
<td>125</td>
<td>121</td>
</tr>
</tbody>
</table>

3.3 Methodology

3.3.1 Surface water gauging

A HOBO U20 Water Level Data Logger, positioned in deep-pool locations, gauged water level continuously at 10-minute intervals on I8 Inlet and I8 Outlet. Data was collected from June 6 through September 20, 2011. A rating curve was established between water height and stream discharge, using a power-law relationship (equation 3-1) for I8 Inlet (n=18, $R^2=0.98$) and I8 Outlet (n=17, $R^2=0.80$)

$$Q = cd^b$$  \hspace{1cm} (3-1)
where, $Q$ is stream discharge (L/s), $d$ is depth (m), and $c$ and $b$ are constant real numbers. For I8 Inlet $c = 45607$ and $b = 5.8$. For I8 Outlet, $c = 18640$ and $b = 6.81$. These relationships were used to transform continuous stage measurements into continuous discharge measurements for the 2011 season.

### 3.3.2 Shallow Groundwater Monitoring

Shallow well networks were installed along I8 Inlet and I8 Outlet during July 2010 and June 2011. 8 Wells were installed on each stream in 2010, and then 2 additional wells were installed on each stream in 2011. Wells were made of 1” slotted PVC piping. Each well was manually inserted by first using a hand auger to remove a soil core of slightly smaller diameter than the well. Wells were then inserted until depth of refusal at the frozen-ground interface.

Wells were placed as evenly as possible laterally along the total study reach and on alternating sides of the channel. 5 wells were within the left-bank near-stream hillslope area, and 5 wells were within the right-bank near-stream hillslope area. Locations were chosen such that wells were located in apparent regions of preferential groundwater flow from the landscape toward the stream (near-channel hillslope swales). Each well was instrumented with a HOBO U20 Water Level Data Logger to continuously measure water depth at 10-minute intervals. The data logger was attached to a chain and hung into the well from the well cap.

Because the depth of the active layer is constantly changing, wells were continuously maintained throughout the season by adjusting the depth at which the stage logger was positioned, such that it was consistently at the frozen ground boundary or true bottom of the well. If this adjustments was not made several times each month, we would risk having the stage logger hanging above the shallow groundwater surface, thus recording no water, when there was indeed water at some level below the detection of the logger (figure 3-3). During the late fall and early winter the active layer re-freezes, however we did not monitor this late into the season, and thus did not need to adjust the wells accordingly.
Figure 3-3: As the frost table deepens throughout the season, stage loggers inside of wells need to be consistently adjusted, such that the logger is constantly at the frost table – active layer interface, and able to record the presence of water in the well. As shown in this cartoon, if the logger was not lowered, it would fail to ‘see’ any water in the well during August, when soils are more deeply thawed relative to June.

Due to the logistical difficulties of maintaining well networks in regions of continuous permafrost, we were unable to monitor specific groundwater elevations in each well throughout the season. Furthermore, we observed many dry wells, which remained dry for most of the season (no measurable water level within the well above frost table). Our analysis of well data was simplified by tracking the number of wells on each stream containing water throughout the 2011 season, and using this as proxy for shallow groundwater dynamics within the active layer. A similar use of shallow groundwater wells was made by Jensco et al., [2009, 2010] to monitor hydrologic connectivity along hillslope-riparian-stream transects.

3.3.3 Solute Injections

Between June and September 2011, we completed many small slug injections (37 on I8 Outlet and 35 on I8 Inlet) of approximately 1 kg of sodium chloride (NaCl). Injections were carried out over three shorter sub-reaches (table 3-1) on both I8 Inlet and I8 Outlet. A known
mass of solute was dissolved into a 5-gallon bucket of stream water and injected near instantaneously across the channel width, one “mixing length” above the upper boundary of each reach (figure 3-4). “Mixing lengths” were visually determined reaches, where solutes encountered sufficient turbulent mixing conditions over a sufficiently long reach, to completely mix throughout the water column.

![Figure 3-4: Dissolved NaCl is poured across the waters of I8 Inlet, one “mixing length” above the upper boundary of sub-reach 1 using a 5-gallon bucket. Following the injection both the bucket and mixing stick are rinsed in the flowing stream water.](image)

Specific conductance was continuously monitored at 2-second resolution throughout each injection, using HOBO U24 conductivity loggers at the upper and lower boundaries of each sub-reach. Thus, each injection provided two breakthrough curves (BTCs). The upper boundary logger recorded the first BTC and the lower boundary logger recorded the second (figure 3-5).
Figure 3-5: Two BTCs are recovered from each solute injection, the first at the upper reach boundary, and the second at the lower reach boundary.

Slug injection data was used for several analyses and calculations. Advective travel time, $t_{adv}$, was calculated as the time between peak concentration at the upper boundary, $t_{pk, upper}$, and peak concentration at the lower boundary, $t_{pk, lower}$ (equation 3-2). $t_{pk, upper}$ and $t_{pk, lower}$ are illustrated in figure 3-5.

$$t_{adv} = t_{pk, lower} - t_{pk, upper} \quad (3-2)$$

Modal velocity, $v$, was calculated as the distance between the upper and lower reach boundary, $x$, divided by $t_{adv}$ (equation 3-3).

$$v = \frac{x}{t_{adv}} \quad (3-3)$$

Discharge was calculated at the upper boundary of each sub-reach using dilution gauging techniques [Kilpatrick and Cobb, 1985].
Breakthrough curves collected at the lower boundary of each sub-reach were analyzed using BTC decomposition methods. Breakthrough curve decomposition is an analysis, which objectively breaks BTCs into basic components: advective/dispersive, transient storage, and tracer-loss. The portion of injected tracer associated with each component is calculated and used to infer the relative influence of different transport processes. A detailed explanation of this method is outlined in chapter 2 of this work. This analysis considered 35 injections on I8 Inlet and 37 injections on I8 Outlet. Although many injections were completed, BTC decomposition analysis requires BTCs that are well sampled all the way through late-time solute “tails” to the detection limit of the data loggers used.

3.3.4 Geomorphic Characterization

Detailed surveys of the channel bottom along the thalweg were completed using a TOPCON GTC-240NW total station during June 2011. A graduated wading rod was used to measure stream width and depth every 10cm across transects. Transects were located approximately 20m apart along the total-reach length. Transect measurements were made May 9, 2011 (35 L/s), August 6, 2011 (43 L/s), and July 21, 2010 (574 L/s) on I8 Inlet, and May 9, 2011 (247 L/s), August 9, 2011 (82 L/s), and July 18, 2010 (242 L/s) on I8 Outlet. Average wetted width and width:depth ratio (w:d) was calculated using these data.

As discharge conditions changed, we assumed that wetted width would remain close to the average wetted width, as calculated by the transect measurements. This assumption is justified by the incised nature of these streams. Both I8 Inlet and I8 Outlet have near-vertical peat banks, within which the channel has incised over time. Rating curve relationships between discharge and depth (equation 3-1), were rearranged to compute reach average depths at different discharge conditions (equation 3-4).

\[
d = \left( \frac{Q}{b} \right)^{\frac{1}{a}}
\]  

(3-4)
Hydraulic radius as a function of discharge, \( R_h(Q) \), was computed using equation 3-5,

\[
R_h(Q) = \frac{w \left[ \left( \frac{Q}{b} \right)^{\frac{1}{a}} \right]}{w + 2 \left[ \left( \frac{Q}{b} \right)^{\frac{1}{a}} \right]}
\]  (3-5)

where, \( w \) is the reach average wetted width (m), which was assumed to remain constant across discharge conditions. Manning’s roughness coefficient was estimated using the following relationship (equation 3-6),

\[
n = \frac{1}{v} R_h^{2/3} S_o^{1/2}
\]  (3-6)

where, \( n \) is the dimensionless Manning’s roughness coefficient, \( v \) is modal velocity (m/s) (equation 3-3), \( R_h \) is the hydraulic radius (m) (equation 3-5), and \( S_o \) is the total reach average bed slope (m/m).

### 3.3.5 Temperature

HOBO U24 loggers continuously logged stream temperature at 10-minute intervals in I8 Outlet and I8 Inlet, throughout the 2011 flow season. Additionally, temperatures were continuously monitored 1m beneath the streambed at one site beneath I8 Inlet and one site beneath I8 Outlet. Sites on each stream were both beneath shallow riffles. Temperature measurements were logged with a Campbell Scientific CR10X data logger at 3-hour intervals.

### 3.4 Results

#### 3.4.1 Channel-structure comparison
I8 Inlet has a reach-averaged slope of 1.26%, while I8 Outlet has a reach-average slope of 1.38% (figure 3-6). Our survey covered 600m of I8 Inlet and 425m of I8 Outlet. Each survey began at the top of the total-reach and extended slightly beyond the bottom of the total-reach. The average wetted width on I8 Inlet is 4.12m, whereas I8 Outlet has wider average width of 4.43m (table 3-2). I8 Outlet is a wider, shallower channel, with a w:d of 33.33, while I8 Inlet is narrower, deeper channel, with a w:d of 20.

![Stream-bed elevation profiles as surveyed along the thalweg. I8 Inlet is shown by red triangles and I8 Outlet is shown by black circles.](image)

**Figure 3-6:** Stream-bed elevation profiles as surveyed along the thalweg. I8 Inlet is shown by red triangles and I8 Outlet is shown by black circles.

**Table 3-2:** average wetted width and width:depth ratio results from 3 channel surveys spanning a wide range of discharge conditions during the 2010 and 2011 flow seasons.

<table>
<thead>
<tr>
<th></th>
<th>I8 Inlet</th>
<th>I8 Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average wetted width, w (m)</td>
<td>4.12 (σ=1.5)</td>
<td>4.43 (σ=1.5)</td>
</tr>
<tr>
<td>Average width:depth</td>
<td>20</td>
<td>33.33</td>
</tr>
</tbody>
</table>

Manning’s $n$ values, as a function of discharge for I8 Inlet and I8 Outlet, show increased roughness across all discharge values (figure 3-7). Each discrete point represents Manning’s
roughness as calculated from a single slug injection. Although not explicitly calculated, roughness declined exponentially on both stream as discharged increased.

![Manning's n as a function of discharge for I8 Inlet and I8 Outlet.](image)

**Figure 3-7: Manning's n as a function of discharge for I8 Inlet and I8 Outlet.**

### 3.4.2 Open channel temperature and discharge dynamics

During early June, after spring thaw, temperatures in I8 Inlet are lower than I8 Outlet (Figure 3-8). However by the end of June, temperatures in I8 Outlet exceed temperatures on I8 Inlet. Stream temperatures in I8 Outlet remain higher than I8 Inlet temperatures throughout the duration of our temperature monitoring. Diurnal temperature variations are greatest during low flow periods on both I8 Inlet and I8 Outlet. However, I8 Inlet temperatures experience greater diurnal variability than I8 Outlet temperatures over the entire monitoring period.

Peak flow timing following storm events, occurs consistently later on I8 Outlet than on I8 Inlet. We selected 6 clear storm events (labeled in figure 3-8) to calculate lag times. Storm events 1, 2, and 3 peak approximately 60 hrs later on I8 Outlet than I8 Inlet. Storm event 4 peaks approximately 38 hrs later on I8 Outlet than I8 Inlet. Storm events 5 and 6 both peak approximately 11 hrs later on I8 Outlet than I8 Inlet. Outlet:Inlet discharge ratio declines
throughout the 2011 flow season from approximately 4 to 1. Abrupt declines in discharge ratio occur during storm events.

### Figure 3-8: time series of steam temperature, discharge and outlet:inlet flow ratios for I8 Inlet and I8 Outlet during the 2011 flow season. Storm event, labeled 1 through 6, were analyzed for differences in peak flow timing.

#### 3.4.3 Subsurface Temperature Dynamics

### Figure 3-9: time series of temperatures at 1m depth beneath the streambed on I8 Inlet and I8 Outlet
Similar to surface water temperatures, I8 Inlet temperatures at 1m depth beneath the streambed show more variability than I8 Outlet temperatures at 1m depth beneath the streambed (figure 3-9). During 2011, both streams attained sub-surface temperatures above zero around the same time (early June). I8 Inlet had greater maximum sub-surface temperatures during July of 2010 and 2011. During September of 2010 and 2011, sub-surface temperatures on I8 Inlet decline more rapidly towards freezing than I8 Outlet. During the winter of 2010-2011 I8 Inlet sub-surface temperatures drop well below freezing to approximately -3°C, while sub-surface temperatures on I8 Outlet remain near 0°C.

### 3.4.3 Groundwater Dynamics

Groundwater dynamics showed seasonal differences on each stream (figure 3-10). Surrounding I8 Inlet, the groundwater regime is strongly correlated with individual storm pulses. Major rain events during June, July and September wet up to 8 wells for a relatively brief period of time, before returning to dryer conditions between storms, where only 1 to 2 wells contain water. Groundwater dynamics surrounding I8 Outlet show a greater seasonal trend than I8 Inlet. During early June, between 1 and 3 wells contain water, however by late June and early July, an average of 4 wells contained water. An average of 4 wells remain wet throughout the majority of the flow season until late September, when a large rain-on-snow precipitation event caused 8 wells to become wet. I8 Outlet had a seasonal average of approximately 4 wells containing water, while I8 Inlet had a seasonal average of 3 wells containing water.
Figure 3-10: semi-log streamflow hydrographs and frequency plots of wells containing water for I8 Inlet and I8 Outlet over the 2011 flow season.

3.4.4 Solute transport comparison

Recovered tracer mass, compartmentalized into principle BTC components, reveals similarities and differences between solute transport mechanisms on I8 Inlet and I8 Outlet (figure 2-2). Both streams display similar relative portions of solute transport timescales. The majority of tracer mass, for both systems, was recovered within the Gaussian shaped advective/dispersive component of the BTCs. Median percentage of injected tracer mass associated with advection/dispersion is 52% and 49% for I8 Inlet and I8 Outlet, respectively. The transient storage and lost tracer components make up the remainder of the mass balance. Median percentage of injected tracer mass associated with transient storage is 37% and 42% for I8 Inlet and I8 Outlet, respectively. Median percentage of tracer mass not recovered by the total observed BTC is 8% and 7% for I8 Inlet and I8 Outlet, respectively.

Although both streams display generally similar dominant transport mechanisms, differences are observed in the relative portion of tracer mass associated with advective/dispersive to transient storage components of observed BTCs. A paired t-test of the
transient storage component groups on I8 Inlet and I8 Outlet shows statistically different mean values \( p = 0.005 \), assuming normally distributed data. I8 Inlet has less tracer mass associated with transient storage timescales than I8 Outlet. Although not statistically significant, the data also show that the median percentage of tracer mass associated with the advective/dispersive component of the total observed BTC is greater on I8 Inlet than I8 Outlet.

3.5 Discussion

3.5.1 Channel Structure

Lake inlets have been shown to have narrower and deeper channels than lake outlets [Arp et al., 2007]. Our results corroborate this, where geomorphic surveys showed higher average w:d on I8 Outlet compared to I8 Inlet. Arp et al.,[2007] also observed larger median grain sizes at lake outlets, compared to lake inlets. Our sites showed similar patterns, where grain size distributions on I8 Outlet were dominated by larger grain sizes, and distributions on I8 Inlet were dominated by smaller grain sizes [Zarnetske and Greenwald, 2005 unpublished data] (figure 3-12). This is likely due to the sediment-trapping effects of I8 Lake. Fine particles on I8 Inlet, mobilized during higher flows, are trapped within the lake and never reach I8 Outlet.
Figure 3-11: I8 Inlet and I8 Outlet have very different grain size distributions, where I8 Inlet has a greater portion of finer particles than I8 Outlet.

Higher Manning’s $n$ values were observed in I8 Outlet compared to I8 Inlet, across a wide range of discharge conditions (figure 3-7). Manning’s roughness coefficient of stream channels has been shown to be related to the size and distribution of streambed particles [Limerinos, 1970], where higher Manning’s $n$ values correspond to streams with higher median grain sizes. Grain size distributions from I8 Inlet and I8 Outlet (figure 3-12) justify higher Manning’s $n$ values observed on I8 Outlet. Channel composition and roughness differences have implications for the geomorphic potential of lake inlet and outlet streams in stream-lake systems. Because smaller substrate material is more easily mobilized during high flow events, it is likely that inlet streams will undergo more rapid geomorphic transitions than lake outlet streams, given sufficiently high flows.

3.5.2 Surface water dynamics

Current understanding of hydrologic processes in catchments underlain by continuous permafrost has come at two contrasting scales of study. First, the individual hillslope-scale of study has been used to understand runoff processes through the active layer at discrete locations
within a catchment [Carey and Woo, 2002; Quinton et al., 2000, 2009]. Second, a larger watershed-scale of study has been used to understand hydrologic function in catchments underlain by continuous permafrost using hydrograph analysis at the catchment outlet [McNamara et al., 1997, 1998]. However, hydrologic linkages smaller than the watershed-scale, but larger than the hillslope-scale, are important to whole catchment hydrologic understanding [Beven and Kirkby, 1979].

A goal of this study was to work between the hillslope and catchment scale, by focusing on a larger lake-stream hydrologic linkage within the Toolik Inlet watershed. It must be noted that I8 Lake is drained by a single stream (I8 Outlet), however I8 Lake is fed by two streams: I8 Inlet and a much smaller un-named tributary. I8 Lake acts a large reservoir within the greater catchment. The declining outlet:inlet flow ratio throughout the season is likely due to the seasonal depletion of lake storage via I8 Outlet. During ice-out, influent waters rapidly increase lake storage [Whalen and Cornwell, 1985], approximately 40% of arctic lake inflow has been shown to occur while a lake is ice covered [O’Brien et al., 1997]. Although we were not able to measure ice-out discharges, we believe similar early season discharge dynamics occurred on I8 Lake. Our data show that spring lake storage is slowly deteriorated over the season as lake outflows exceed inflows until mid August when outlet:inlet ratio reaches 1 (approximate steady state, assuming I8 Inlet is the dominant input of water to I8 Lake).

The reservoir influence on I8 Lake can also be noticed during storm events. We analyzed peak flow timing of 6 storm events during the 2011 flow season, and observed a delay in peak flow timing on I8 Outlet compared to I8 Inlet for all events. The magnitude of the delay decreased throughout the season. This may be due to the compounding nature of storms 4, 5 and 6, where precipitation events and associated storm responses occur in fairly rapid succession. Whereas storms 1, 2, and 3 are separated by enough time, such that stream flow conditions can return to near-baseflow, before the onset of the next storm. This result is intriguing because other
lake-stream hydrologic studies have not observed peak flow timing differences between inlet and outlet streams [Arp et al., 2006].

3.5.3 Surface Temperature Differences

A general description of seasonal lake temperature dynamics in temperate to cool climates is given by Wetzel [1983]. Following ice-out, lakes undergo spring stratification, where warmer waters are isolated within the upper epilimnion layer, which overlays a much cooler hypolimnion below. The extent of the epilimnion expands throughout the summer months due to solar heat inputs. During the fall, cold air temperatures return the lake water to a uniform temperature of maximum density, 4°C, where further cooling of surface waters can easily form ice-cover. After winter ice formation, lakes experience an inverse thermal stratification, where cooler shallow waters overlay warmer, deeper waters.

Specific thermal dynamics for Toolik Lake, a larger arctic lake located <2 km from I8 Lake, were outlined by O’Brien et al., [1997]. The lake is ice covered for 9 months (October – June). Following a quick ice-out, the lake thermally stratifies within one week, creating an epilimnion approximately 5m deep. The epilimnion is warmed by solar radiation, occurring 24hrs during summer months. Whalen and Cornwell [1985], observed a 10°C temperature difference between the warmer epilimnic waters and cooler hypolimnic waters by late July. The eilimnion deepens throughout the summer before another complete mixing event in late August. Ice formation begins in September, forming a complete cover by October.

Our temperature data show that I8 Outlet is considerably warmer than I8 Inlet for most of the flow season. Because I8 Outlet is a surface flow release of I8 Lake, the effluent water is likely composed primarily of warmer epilimnic waters. During the month of June we observed a gradual warming of I8 Outlet waters from approximately 5°C to 15°C, this warming is likely due to the formation of the epilimnion and its expansion via solar radiation. I8 Outlet waters remain consistently warmer than I8 Inlet waters for the remainder of the flow season; this is also likely
due to warm epilimnic waters composing the majority of I8 Outlet discharge. I8 Lake has a similar thermal influence on I8 Outlet as small surface release dams have on downstream waters. Surface release dams have been shown to increase water temperatures above natural conditions in effluent streams [Wotton, 1995].

I8 Lake also provides thermal buffering during storm events. I8 Inlet water temperature drops when discharge increases and cooler rainwater runoff is mixed with warmer surface waters [Brown and Hannah, 2007; Poole and Berman, 2001]. However, this phenomenon is not nearly as strong in I8 Outlet, likely due to thermal dilution of cooler runoff water with much warmer epilimnic water.

3.5.4 Groundwater dynamics

A frequency analysis of wetted wells revealed very different groundwater dynamics on I8 Outlet compared to I8 Inlet. There were more event-controlled groundwater responses on I8 Inlet than I8 Outlet, where more wells would become wet immediately following storm events, and then dry out afterwards. However, I8 Outlet showed a more seasonal trend, where early in the season, few wells contained water, but by the middle of summer, more wells took on water and remained wet throughout the observation period.

Subsurface temperatures can provide valuable insight towards groundwater dynamics beneath streams [Hatch et al., 2006]. Temperatures beneath I8 Outlet decline less rapidly than I8 Inlet during September and October of 2010 and 2011 (figure 3-9). Furthermore, it appears that temperatures beneath I8 Outlet remain above freezing for a longer period of time than I8 Inlet, however, because of missing data during late September and early October on I8 Inlet, we cannot say this for sure. Also, during winter months, I8 Outlet temperatures barely dip beneath freezing, whereas I8 Inlet temperatures drop to approx -3°C. This temperature evidence suggests that I8 Outlet sustains a groundwater system for longer in the year than I8 Outlet and possibly remains
active throughout winter months. This difference in subsurface temperature, may be due to a constant input of warm lake water into the shallow groundwater system of I8 Outlet.

I8 Outlet seems to have a very different groundwater environment than I8 Inlet. Groundwater in regions of continuous permafrost in confined to the active layer. Active layer depth and extent is enhanced around stream channels, this increased zone of seasonal thaw is referred to as the thaw bulb [Brosten et al., 2006]. The thaw bulb is formed by combined conductive and convective heat transport into sub-stream sediments. We propose that warm epilimnic effluent water from I8 Lake, as well as the constant head boundary provided by the lake, increases thaw bulb extent, spatially and temporally, beneath I8 Outlet. This would provide a possible explanation for the contrasting groundwater dynamics observed between I8 Inlet and I8 Outlet, and is a suggested topic of future research. Differences in groundwater regimes among arctic lake inlets and outlets may have implications for important biogeochemical processes occurring within riparian and hyporheic waters.

### 3.5.5 Contrasting solute transport dynamics

A large body of literature has related solute transport dynamics to combined geomorphic, hydraulic, and hydrologic characteristics of stream systems [Beltaos and Day, 1978; Cardenas, 2009; Fischer, 1973; Kasahara and Wondzell, 2003; Leopold and Maddock, 1953; Wondzell and Swanson, 1999; Wondzell, 2006b]. Furthermore, several studies have established that lake inlets and outlets have distinctly different channel structure, geomorphic, and hydrologic characteristics [Arp et al., 2006, 2007]. However, no study, to our knowledge, has “bridged the gap” between lake-stream geomorphic/hydrologic characteristics and solute transport dynamics.

This study applied new BTC decomposition methods to a suite of residence time distributions from I8 Inlet and I8 Outlet. For both I8 Inlet and I8 Outlet, The majority of tracer mass recovered at downstream boundary locations was within the advective/dispersive BTC
component. This result indicates that combined advective/dispersive processes, which are of a shorter timescale than transient storage, are dominant transport mechanisms in both streams.

BTC decomposition analyses also revealed transport differences between I8 Inlet and I8 Outlet. I8 Inlet showed a smaller portion of tracer mass associated with transient storage timescales than I8 Outlet, to a statistically significant degree (p = 0.005). Also, modal velocity data (figure 2-3) show that I8 Inlet is more advective than I8 Outlet. Wider, shallower channel structure and increased Manning’s n values on I8 Outlet, may facilitate more surface-water groundwater exchange on I8 Outlet, which could explain the greater portion of recovered solute mass associated with the transient storage BTC component. Likewise, high modal velocities and narrow, deep channel-structure on I8 Inlet may explain the greater portion of recovered solute mass associated with the advective/dispersive BTC component. The observed differences in solute transport processes observed between I8 Inlet and I8 Outlet likely facilitates differences in biogeochemical processing between each stream, specifically the cycling of inorganic nutrients [Ensign and Doyle, 2005; Triska et al., 1993].

Because this study only considers a single high arctic lake-stream system (I8) the results of the study are not immediately transferable to all arctic lake-stream systems. However, because lake-stream systems are so common in arctic catchments, this study justifies the consideration of lentic influences on lotic ecosystems. We provide evidence that lakes influence the hydrology and morphology of downstream river channels, which in turn influences solute transport dynamics. The findings in this study will be useful in understanding how arctic catchments will respond to increasing temperature and associates landscape changes.
3.6 Conclusions

The goal of this study was to investigate differences in channel-structure and morphology, open-channel hydrology, water temperature, and subsurface hydrology between two arctic alluvial tundra stream, I8 Inlet and I8 Outlet, separated by a small arctic lake, I8 Lake. Additionally, we aimed to elucidate differences in dominant solute transport mechanisms between the two streams. Our results are able to support two main conclusions.

I8 Lake imposes measurable water temperature, hydrologic, geomorphic changes along the down-valley river continuum. Water temperatures in I8 Outlet were higher than water temperatures in I8 Inlet for the majority of the 2011 flow season. I8 Inlet had a wider and shallower channel structure with higher Manning’s roughness coefficients and a grain size distribution dominated by finer particles. I8 Lake acted as a large storage reservoir, affecting seasonal stream flow dynamics and storm responses in I8 Outlet compared to I8 Inlet. Also, I8 Inlet and Outlet displayed very different seasonal shallow groundwater dynamics, which we propose, is partially due to large temperature differences between the two streams.

Hydrogeomorphic differences between I8 Inlet and I8 Outlet create significantly different solute transport environments. Results of a BTC decomposition analysis revealed differences in the relative contribution of solute transport mechanisms. Transport along I8 Inlet is more advective/dispersive than I8 Outlet, while transport along I8 Outlet is more influenced by longer timescale transient storage processes.

To our knowledge this is the first study to highlight basic hydrogeomorphic differences between lake inlet and outlet streams in a high arctic catchment, underlain by continuous permafrost. Furthermore, this study was the first of its kind to specifically investigate solute transport differences between lake inlets and outlets. This work not only contributes to a more
complete understanding of solute transport mechanisms in stream networks, but also adds to our understanding of the role of stream-lake interactions in high arctic catchments.
References


