

HYDROLOGIC RESPONSE TO CHANNEL RECONFIGURATION ON SILVER
BOW CREEK: SCIENCE TO INFORM THE RESTORATION PROCESS

by

Seth James Kurt-Mason

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Land Resources and Environmental Sciences

MONTANA STATE UNIVERSITY

Bozeman, Montana

November 2010

©COPYRIGHT

by

Seth Kurt-Mason

2010

All Rights Reserved

APPROVAL

of a thesis submitted by

Seth James Kurt-Mason

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency and is ready for submission to the Division of Graduate Education.

Dr. Brian L. McGlynn (Co-Chair) and Dr. Geoffrey C. Poole (Co-Chair)

Approved for the Department of Land Resources and Environmental Sciences

Dr. Tracy M. Sterling

Approved for the Division of Graduate Education

Dr. Carl A. Fox

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Seth James Kurt-Mason

November 2010

ACKNOWLEDGEMENTS

I would like to thank my committee members, Dr. Geoffrey Poole and Dr. Brian McGlynn for the considerable amount of time they invested in helping to develop and implement this study. Their unwavering commitment to my intellectual and personal development not only provided me with the support needed to produce a high-quality body of scientific work, but helped me further myself as a budding scientist. The mentoring I received from both Geoff and Brian will continue to motivate me to strive for excellence in the years to come. Committee members Dr. Clifford Montagne and Dr. Wyatt Cross provided thoughtful feedback and demonstrated a gracious willingness to assist me whenever needed. I greatly appreciate their friendship. Robert Payne from the Fluvial Landscape Lab at Montana State University contributed considerably to this project through many patient conversations and thoughtful comments. Amanda Hyman, Matt Mitchell, Jessica Mason, Bill Hoblitzell, Jordan Kurt-Mason, Galen Laird , and Patrick della Croce aided me in collection of field data and never complained about broken equipment, cold water, or inclement weather. Access to the field study site was generously granted by the Montana Department of Environmental Quality. This research was majority funded by the Montana Department of Justice's Natural Resource Damage Program. Additional funding was provided by the United States Geological Survey through the Montana Water Center. Special thanks to Greg Mullen from MDOJ, Joel Chavez and Ben Quinones from MDEQ, and Stewart Smith from Pioneer Technical Services, Inc. for their assistance and support of this project.

TABLE OF CONTENTS

1. INTRODUCTION	10
Problem Statement	10
An Imperative for Process-Based Restoration and Assessment	10
Restoring and Assessing Hydrologic Processes in Surface- and Groundwater	11
Scientific Background	12
First Order Controls on Hydrologic Behavior	12
Ecological Significance of Hydrologic Storage and Exchange	13
Human Impacts on Hydrologic Retention	15
Site Characterization	17
Purpose and Broader Impacts.....	20
2. HYDROLOGIC RESPONSE TO CHANNEL RECONFIGURATION ON SILVER BOW CREEK, MONTANA: SCIENCE TO INFORM THE RESTORATION PROCESS	24
Introduction	24
Site Description	28
Methods.....	30
Hydrogeomorphic Data Collection	30
Geomorphic and Hydraulic Characterization of Stream Channels.....	32
Stream Tracer Experiments.....	36
Results	40
Hydrogeomorphic Comparisons	40
Geostatistical Comparisons.....	41
Stream Tracer Experiments.....	44
Discussion	46
Restoration and Stream Channel Complexity.....	47
Restoration and Hydrologic Transport Dynamics	50
Conclusion.....	57
3. SUMMARY	70
REFERENCES CITED.....	73

LIST OF TABLES

Table	Page
2.1: Hydrogeomorphic characteristics of experimental reaches	58
2.2: Semivariance modeling results for longitudinal and cross-sectional depth profiles	58
2.3: Semivariance modeling results for longitudinal velocity profiles collected at three flow states.	59
2.4: Semivariance modeling results for aggregated cross-sectional velocity data collected at three flow states	59

LIST OF FIGURES

Figure	Page
1.1: Stream disturbance cascade for conceptualizing disturbance propagation through stream ecosystems.	22
1.2: Silver Bow Creek study site.....	23
2.1: Pathways by which perturbations may cascade through stream systems.....	60
2.2: Patterns of hydrologic storage and exchange at a range of spatial scales.	61
2.3: Aerial of study site highlighting the spatial scale of plan-form changes to stream channel segments resulting from realignment activities.	61
2.4: Data collected from the ADCP during longitudinal and transverse channel surveys.	62
2.5: Idealized experimental and modeled semivariogram for a given spatial data set.	62
2.6: Characterization of cross-sectional channel geometry.	63
2.7 (A-D): Pre-realignment velocity and depth profiles collected (A) along the channel thalweg and (B) from a representative cross-section. Post-realignment velocity and depth profiles collected (C) along the channel thalweg and (D) from a representative cross-section	64
2.8 (A-D): Frequency distributions of (A) longitudinal velocity, (B) cross-sectional velocity, (C) longitudinal depth, and (D) cross-sectional depth collected during summer baseflow conditions.....	65
2.9 (A-D): Experimental semivariograms of (A) longitudinal velocity, (B) cross-sectional velocity, (C) longitudinal depth, and (D) cross-sectional depth collected during summer baseflow conditions.....	66

LIST OF FIGURES-CONTINUED

Figure	Page
2.10 (A-B): (A) Average solute transport time calculated for the length of the thalweg between the upstream solute injection point and the downstream observation point in pre- and post- channels across a range of flow states. (B) Pre- and post-realignment RTDs observed after injected solute traversed approximately 1000 m of thalweg length in a pre-realignment and a post-realignment channel segment during baseflow conditions.....	67
2.11 (A-B): (A) Average solute transport times calculated for the straight-line distance between the upstream solute injection point and the downstream observation point in pre- and post- channels across a range of flow states. (B) Pre- and post-realignment RTDs observed after injected solute traversed approximately 500 m of valley length in a pre-realignment and a post-realignment channel segment..	68
2.12 (A-B): (A) Index of transient storage as a function of average channel residence time in pre- and post-realignment channels. (B) RTDs observed after approximately 27 minutes of downstream transport in a pre-realignment and a post-realignment channel segment.....	69

ABSTRACT

Hydrologic residence time in streams is rarely considered as a response variable for assessing restoration design strategies. However, residence time is a useful index of hydrologic controls on ecosystem processes that may facilitate or limit the achievement of project goals. Interactions between the physical structure of streambeds and the patterns of flow through the channel determine hydrologic residence time and largely control solute transport and exchange among the various physical and biological components of the stream ecosystem. The influence of reach-scale channel reconfiguration on these complex interactions are not well characterized despite well-documented linkages between individual channel features, hydrologic retention, water quality, and in-stream habitat quality. This study documented changes in solute transport and variation in channel water velocity prior to and immediately following large-scale channel realignment along Silver Bow Creek in southwestern Montana. Channel restoration increased water residence time in the channel by increasing sinuosity, decreasing channel slope, and introducing frequent slow-moving pools. However, channel realignment yielded a reduction in the fine-scale variation in streambed topography. Therefore, post-realignment channel water velocities were more uniform, yielding a reduction in transient storage within the system, which could offset some of the beneficial effects of slower advective velocities. Restoration actions may be more effective at recovering normative hydrologic function if planning and design efforts consider the hydrologic effects and ecological benefits of fine-scale topographic variation and the bio-geomorphic processes that create and maintain such fine-scale variation over time.

CHAPTER ONE

INTRODUCTION

Problem StatementAn Imperative for Process-Based
Restoration and Assessment

Rivers and streams in Montana constitute some of the state's most valuable aesthetic, economic and recreational resources, yet due to the cascading effects of land use practices and channel engineering in streams (Figure 1.1), many Montana waterways are in need of restoration. Nationwide, spending estimates for stream restoration projects top \$14 billion since 1990 [Bernhardt, et al., 2005]. Similar trends are observed in Montana. In 1999, the state earmarked \$130 million for restoration of resources in the Upper Clark Fork River Basin. By the close of 2007, 72 restoration projects totaling \$66 million were approved for use of these funds [MDOJ, 2008]. As more attention and resources are devoted to improving the condition of riverine resources, the need grows for tools and assessment strategies that evaluate physical and ecological stream processes and interface with adaptive management frameworks that optimize restoration outcomes.

Understanding the extent to which restoration alters the dynamic ecological, biogeochemical and hydrologic processes that ultimately determine future stream attributes is necessary for the development self-sustaining restoration strategies [Beechie and Bolton, 1999]. Current restoration strategies frequently assume structural modifications to the stream/floodplain system are followed by improved functionality of

those biotic and abiotic processes most valued by society. This paradigm and the restoration approaches that it ultimately begets are deeply rooted in the complex social, institutional, legal, and economic realities facing planners and practitioners. The incredible complexity of natural systems is often overlooked because of the need for clearly defined goals and easily assessed benchmarks. However, an oversimplified view of the processes at work in natural systems is problematic and may lead to the formation of tacit assumptions about the efficacy of individual restoration techniques at meeting stated goals. Thus, monitoring efforts that evaluate the physical components of a restored stream (e.g., morphological heterogeneity, extent of habitat units, species presence/absence, or aesthetic appeal) without explicitly considering the system interactions that ultimately dictate the condition of those components are of limited use. More effective restoration approaches are apt to emerge if monitoring protocols shift away from evaluating immediate changes in ecosystem *structures and characteristics* and toward evaluating ecosystem *processes* that may predict long-term ecological health. Such a process-based approach will ultimately be more directly useful for informing the firms, managers, and policy makers guiding restorative action [Palmer, et al., 2005].

Restoring and Assessing Hydrologic Processes in Surface- and Groundwater

Few monitoring or assessment strategies investigate how restoration design influences the patterns of movement of water and solutes throughout the stream system that may exert a significant influence on stream ecology. Complex interactions between the physical structure of the streambed and the hydraulic characteristics of overlying

surface-waters govern storage and exchange processes responsible for transporting water and solutes among the stream, riparian zone, and alluvial aquifer [Brunke and Gonser, 1997; Poole *et al.*, 2008]. Importantly, these interactions may influence water temperature extremes [Arrigoni *et al.*, 2008] and the in-stream retention and transformation of pollutants [Findlay and Sobczak, 1996] (e.g., nitrate, pesticides, pharmaceuticals, etc.). Exchanges between the stream channel, surface dead-zones, hyporheic zones, and groundwater exist at multiple spatial (centimeter to kilometer) and temporal (seconds to months) scales and are most prevalent where channel morphology is complex (e.g., high sinuosity, frequent side channels and mid-channel bars, well-formed pool/riffle sequences, and variable channel slope) [Ensign and Doyle, 2005; Gooseff *et al.*, 2007]. Degraded streams tend to have simplified channel patterns and are therefore expected to exhibit reduced rates of exchange, yielding associated losses in habitat complexity, depressed capacity for buffering against temperature and discharge fluctuations, and cumulative or synergistic effects from downstream advection of pollutants. Thus, it is likely that channel response to dynamic hydrologic exchange, transport, and storage mechanisms along the streambed and across the floodplain are critical controls on restoration's success.

Scientific Background

First Order Controls on Hydrologic Behavior

Physical controls on groundwater-surface water interactions exist at multiple scales. At the valley-scale (100s of meters to kilometers), hydrogeomorphic setting

constrains the floodplain and stream channel and governs patterns of stream gains and losses to regional groundwater systems [Woessner, 2000]. At the reach scale (10s to 100s of meters), morphologic characteristics of the channel, floodplain hydrogeology, and the position of the alluvial aquifer in the catchment govern the magnitude and temporal dynamics of groundwater connectivity, and solute retention in surface and subsurface zones [Ensign and Doyle, 2005; Poole *et al.*, 2006]. Research employing a range of methodologies from stream tracer experiments to numerical simulation modeling suggests that large slope breaks, convexities and concavities in streambed topography, sinuosity, and longitudinal roughness promote hydrologic storage and exchange at the reach scale [Gooseff *et al.*, 2007; Harvey and Bencala, 1993; Kasahara and Hill, 2006; Wondzell, 2006]. At the bedform scale (centimeters to meters), geomorphic structures along the streambed, stream stage, and hydraulic conductivities of subsurface sediments are useful predictors of the arrangement of subsurface flowpaths and rates of hyporheic exchange [Boano *et al.*, 2007; Fernald *et al.*, 2006; Kasahara and Hill, 2006; Sophocleous, 2002].

Ecological Significance of Hydrologic Storage and Exchange

Storage of channel water by in-channel storage zones and near-stream hyporheic and parafluvial zones influences stream biogeochemical cycling by increasing the residence time of water-borne solutes in the stream systems and opportunities for these solutes to interact with bioreactive sediments and microbial communities in the channel [Ensign and Doyle, 2005; Gooseff *et al.*, 2007]. The mixing water by way of vertical and

lateral advection moves solutes along gradients in redox potential [*Fernald et al.*, 2006; *Hinkle et al.*, 2001; *Storey et al.*, 2004], creating patches of elevated biogeochemical activity along the streambed [*Boulton et al.*, 1998; *Duval and Hill*, 2007]. Chemical transformations occurring in these storage zones are functional pathways by which nutrients, oxygen, heavy metals, and pollutants are delivered, transported, and transformed [*Baker and Vervier*, 2004; *Boulton et al.*, 1998; *Burt and Pinay*, 2005; *Findlay*, 1995; *Hill et al.*, 1998; *Hinkle et al.*, 2001; *Holmes et al.*, 1996; *McClain et al.*, 2003; *Mulholland and DeAngelis*, 2000; *Storey et al.*, 2004]. The size of transient storage zones and the rates of exchange between the channel and these zones have significant effects on nutrient dynamics, uptake lengths, and in-stream processing of major-ions and metals [*Bencala*, 2005]. Streambed metabolism, an important control on rates of biological processing, is likely driven by the physical controls on the residence time of water within the stream and associated hyporheic zone [*Boulton et al.*, 1998; *Fernald et al.*, 2006; *Storey et al.*, 2004]. Patterns of hyporheic exchange at a variety of scales have been shown to govern the spatial patterns of abundance for several species of algae and aquatic insects and spawning habitat quality for trout, charr, and endangered salmonids in Montana streams [*Baxter and Hauer*, 2000; *Wyatt et al.*, 2008]. *Poole and Berman* [2001] show these exchanges to moderate stream temperature cycles, which directly influence rates of metabolic processes, physiology and behavior of aquatic species, nutrient cycling, and primary productivity [*Poole and Berman*, 2001].

Human Impacts on Hydrologic Retention

Some recent progress has been made developing frameworks for understanding stream hydrologic function in undisturbed, impacted, or restored streams. This new area of research is developing in response to an increasing awareness of the data gaps left by most post-restoration monitoring and recent calls to investigate restoration's effect on stream processes [*Bash and Ryan, 2002; Bernhardt et al., 2005; Boulton, 2007; Hester and Gooseff, 2010; Kondolf et al., 2006; Palmer et al., 2005*]. The vector of human impact (degradation vs. restoration) on a stream is expected to directly relate to the system's structural complexity and hydrologic functionality. Degraded streams are expected to exhibit reduced structural complexity and a depressed capacity for transient storage and hydrologic retention exchange. The restoration of degraded streams frequently aims to enhance structural complexity of the stream by installing individual channel features or by completely realigning the streambed to mimic some reference state. Enhanced complexity in these restored systems is expected to increase the propensity for exchanges between the channel, surface dead-zones, and groundwater. By altering patterns of movement for water and solutes, patterns of degradation and restoration in stream systems may indirectly influence spatial and temporal patterns in habitat quality, the distribution and composition of biotic communities, as well as buffering and assimilation capacities for excess nutrients, heavy metals, and other pollutants as they are advected downstream.

Numerous research efforts have focused on elucidating the connections between human modification of stream structure and hydrologic behavior. Qualitative

observations of nitrogen processing rates in arid urban and natural streams link channel complexity and transient storage characteristics [*Grimm et al.*, 2005]. Gooseff et al. [2007] found that channel complexity and transient storage varied as a function of land use in the surrounding catchment. Streams located in urban and agricultural settings showed significantly reduced channel complexity and transient storage residence times when compared with undisturbed reference streams. D'Angelo et al. [1993] also noted a reduced capacity for transient storage in simple artificial flumes when compared with reference streams. Conversely, Salehin [2003] found that simplification of channel morphology and subsequent lining of a streambed with clay resulted in longer timescale transient storage due to reduced hydraulic conductivity of bed sediments. In addition to established ties between structural degradation and solute transport dynamics, restoration activities have also been linked to patterns of water and solute movement. Construction of riffle-steps on a suite of urban and agricultural streams in Ontario, Canada induced greater localized hyporheic exchange, temporarily increasing streambed dissolved oxygen levels and rates of nitrate uptake [*Kasahara and Hill*, 2006]. Recent research on a California stream showed that restoration activities enhanced long spatio-temporal hydrologic retention by encouraging storage of early season discharge in subsurface zones and increasing discharge during baseflow via groundwater seepage [*Tague et al.*, 2008]. Knust and Warwick [2009] integrated a hydraulic and solute transport model to assess changes in solute transport characteristics following restoration of the Truckee River in Nevada. Their investigation suggested that restoration increased hyporheic residence times in the vicinity of constructed riffle-steps features. Bukaveckas [2007]

found that channel realignment increased advective transport times but decreased transient storage in surface and subsurface storage zones at the reach-scale. Although not all of the existing research supports the same conclusions, it is clear that structural modification consistently alters patterns of movement for water and solutes.

Despite documented linkages between individual channel structures/features, hydrologic retention, water quality, and in-stream habitat quality, and some preliminary work investigating the effects of large-scale restoration activities, the influence of reach-scale channel reconfiguration on the complex interactions between streambed structure, channel hydraulics, and hydrologic behavior are not well characterized. Therefore, designing restoration efforts to enhance hydrologic retention across a range of spatial and temporal scales remains difficult. This research investigated relationships between stream restoration activities and solute transport dynamics. In several channel segments prior to and immediately following complete channel realignment we examined relationships between measures of hydraulic and topographic complexity and solute transport characteristics and identify useful metrics for evaluating the condition of hydrologic behavior and its trajectory toward or away from baseline conditions.

Site Characterization

Silver Bow Creek (SBC) is located in the Upper Clark Fork River Basin. It extends 23 miles from the town of Butte to the Warm Springs Ponds near Opportunity, Montana. The floodplain and streambed were heavily impacted by mining activities over the past century. In 1983, Silver Bow Creek was designated as a federal Superfund site.

Remediation and restoration activities, including extensive excavation of tailings and soils from the floodplain, reconstruction of the stream channel, and bank stabilization began along select sub-reaches in 1999. Completion of all restorative action in the SBC corridor is anticipated in 2011.

The legacy of impact and restorative action on SBC in southwestern Montana makes it ideal for examining the cascading effects of shifting land use practices and channel engineering on the hydrologic function of streams. SBC is situated at the headwaters of the Clark Fork River watershed, and drains an area heavily impacted by more than a century of hard-rock mining activities. During this time, the stream channel underwent a succession of biological, chemical, hydrologic and morphologic transformations. Notably, a series of floods in the early 1900s transported metal-rich mine tailings along the stream corridor, burying floodplain soils with up to two meters of contaminated sediments [Gammons *et al.*, 2006]. The presence of contaminated sediments along more than 26 miles of SBC prompted the Environmental Protection Agency (EPA) to designate it as a federal superfund site. Remedial and restorative actions along the SBC corridor were designed to remove contaminated sediments, improved aquatic habitat, enhance the aesthetic appeal of the floodplain, and promote the function of dynamic riverine processes [MNRDP *et al.*, 2005]. Due to extensive historical modifications to the stream/floodplain system, meeting project goals required the removal and replacement of contaminated floodplain soils and complete realignment of the stream channel.

Floodplain remediation and channel realignment activities took place on successive valley sections between 200 m and 1.0 km in length. After a given construction zone was delineated, contaminated floodplain soils were removed and replaced with clean material. A new stream channel was then constructed through this material. Restored channels were cut to a depth such that the streambed ran through the native valley-fill sediments. After each section of the new channel was completed, water was redirected from the old channel to the new channel. The historic channel was then filled with clean material and work proceeded to the next downstream valley section. The large spatial scale of restoration activities and a construction strategy that worked incrementally downstream provided a fortuitous setting for testing hypotheses regarding the interplay between channel form and hydrologic transport processes.

We studied approximately 2 km of Silver Bow Creek near Fairmont, Montana at the south end of the Deer Lodge Valley (Figure 1.2). This section of the creek was being actively restored during the study period. At a stream gauge immediately downstream of the study site (USGS gauge 12323600, Lat. 46°06'28", Long. 112°48'17"), SBC drains an area of 940 km². Prior to remediation, the floodplain at the site was composed of Quaternary alluvium, overlain with mining-derived sediment deposits [*Pioneer Technical Services and Applied Geomorphology*, 2008]. In addition to impacts associated with the historic flooding events described above, this section of SBC was subject to large-scale placer mining activities, which manifested in the excavation and channelization of the streambed, yielding a single-threaded, relatively straight channel with moderate slope (0.07%). The channel flowed over coarse, embedded native alluvium and was

characterized primarily as run habitat throughout its length [*Pioneer Technical Services and Applied Geomorphology*, 2008]. The extent of the active floodplain was restricted to the near-channel zone by the presence of dikes, spoils berms, and downcutting through fine-grained tailings deposits. Following restorative realignment, the stream channel was more sinuous, and therefore longer, and exhibited a reduced channel slope. Post-realignment channels remained single threaded but were narrower, deeper, and the uniform run morphology of pre-realignment channels was replaced by regularly spaced riffle-pool-run sequences. Data were collected from both pre- and post-alignment channels in consecutive reaches along the study segment. Delineation of reaches corresponded to the serial implementation of construction activities, reach by reach, as restoration work progressed downstream.

The legacy of impact and restorative action on Silver Bow Creek makes it ideal for examining the relationships between stream processes and restoration activities in the context of the stream disturbance cascade (Figure 1.1) because restoration activities on Silver Bow Creek are large in scope and will inevitably influence the physical streambed characteristics that control solute transport dynamics at the reach and sub-reach scales.

Purpose and Broader Impacts

Our study investigated relationships between measures of hydraulic and topographic complexity and solute transport characteristics in the context of a large-scale stream restoration project. We hypothesized that changes in channel structure due to

large-scale channel realignment can cause dramatic changes in the nature of hydraulic retention within the restored reaches. In particular, we predicted that:

(1) Measures of hydrogeomorphic channel complexity are greater in restored channel segments.

(2) Restored reaches exhibit corresponding increases in hydrologic retention as evidenced by lower advective transport velocities and increased transient storage.

Work conducted on SBC contributes directly to the advancement of stream restoration science and practice by elucidating feedbacks between restoration design and dynamic hydrologic stream processes. Project results are relevant to the local, state (e.g. Montana DEQ, Montana DOJ) and federal agencies (USDA, USFS, USGS, BLM), stakeholder groups, NGOs, consulting and engineering firms, and policy makers involved in various aspects of stream restoration planning and implementation. Furthermore, the results of this project are directly applicable to stated goals regarding the fate and transport of pollutants and habitat quality on Silver Bow Creek and the Upper Clark Fork River Basin. Enhanced understanding of the influence of channel reconfiguration on solute transport and hydrologic retention along restored streams may lead to more cost effective restoration approaches, while providing new avenues for improving long-term water quality, ecological and economic value of restored rivers and streams across the region.

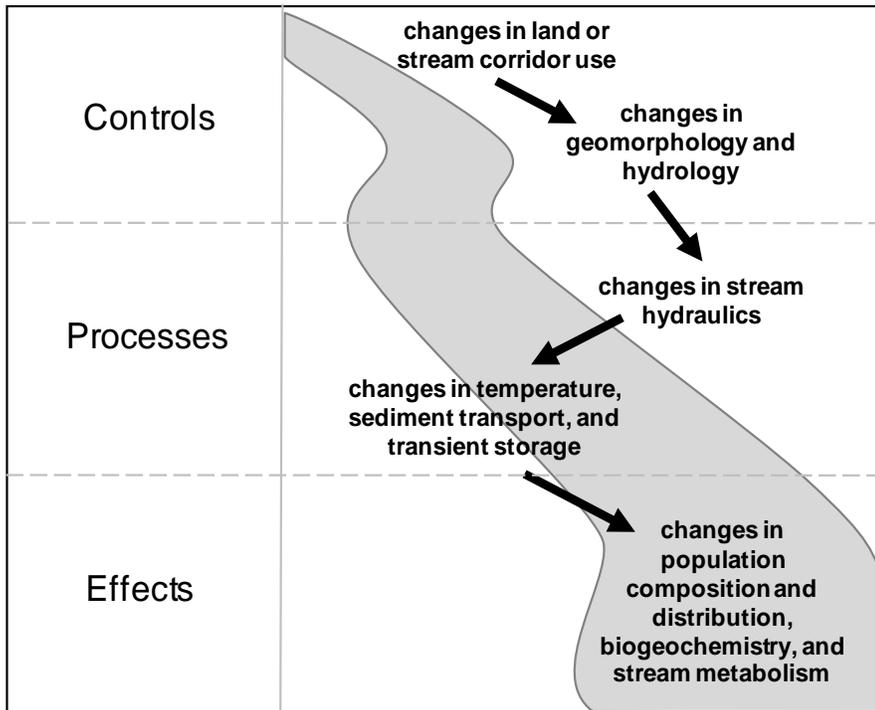


Figure 1.1: Stream disturbance cascade for conceptualizing disturbance propagation through stream ecosystems (Similar to FISRWG [1998]).

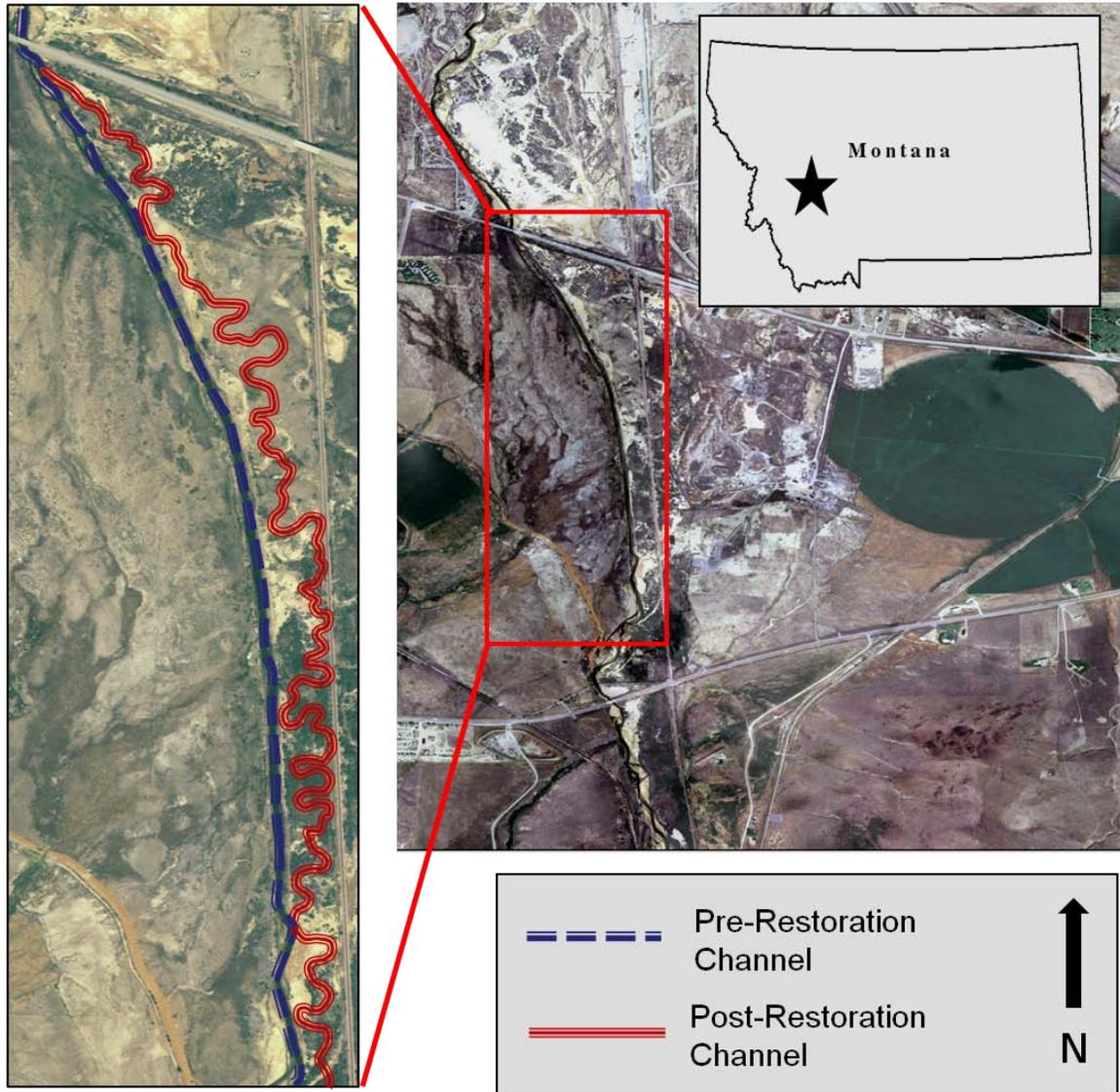


Figure 1.2: Silver Bow Creek study site. Hydrogeomorphic surveys and stream tracer experiments were conducted on various segments on both pre- and post-restoration channels.

CHAPTER TWO

HYDROLOGIC RESPONSE TO CHANNEL RECONFIGURATION
ON SILVER BOW CREEK, MONTANA: SCIENCE TO INFORM THE
RESTORATION PROCESSIntroduction

The role of physical structure in governing patterns of water and solute movement is important to restoration strategies that seek to improve the ecological function of stream systems. Hydrologic transport and transient storage dynamics influence biogeochemical cycling by controlling the residence time of solutes in the stream system and mediating opportunities for these solutes to interact with bioreactive sediments and microbial communities residing in the stream channel. The movement of water between components of the stream exhibiting different residence time characteristics moves solutes along gradients in redox potential [Fernald *et al.*, 2006; Hinkle *et al.*, 2001; Storey *et al.*, 2004] and creates ecologically significant hotspots of elevated biogeochemical activity [Boulton *et al.*, 1998; Duval and Hill, 2007; McClain *et al.*, 2003] that may have a disproportionate influence on whole-system ecological function. Chemical transformations occurring in these areas are pathways by which nutrients, oxygen, heavy metals, and pollutants are transformed [Baker and Vervier, 2004; Bencala, 2005; Boulton *et al.*, 1998; Findlay, 1995; Hinkle *et al.*, 2001; McClain *et al.*, 2003; Mulholland and DeAngelis, 2000]. Ensign and Doyle [2005] demonstrated that in-channel storage of water can constitute a significant fraction of total reach-scale solute retention and may be the dominant mechanism for the uptake of ammonium and

phosphate in some streams. Other research concluded that exchange flows between the stream channel, hyporheic zones, and saturated anoxic riparian sediments can function as a nitrate sinks in lowland streams [*Fernald et al.*, 2006; *Hill et al.*, 1998; *Kasahara and Hill*, 2006]. Hydrologic exchanges between the channel and subsurface storage zones at a variety of scales have also been shown to directly influence temperature regimes [*Arrigoni et al.*, 2008], physiology and behavior of aquatic species [*Baxter and Hauer*, 2000], and rates of metabolic processes [*Fellows et al.*, 2001]. Thus, channel response to dynamic hydrologic transport, storage, and exchange mechanisms along the streambed and across the floodplain can be critical controls on the achievement of many stream restoration goals.

The spatial arrangement and temporal scales of connections between the stream channel, in-channel storage zones, hyporheic zones, and groundwater systems are influenced by channel hydraulics and structural elements of the stream/floodplain system. Hydrologic exchanges between advection-dominated and storage-dominated zones exist at several spatial scales: the valley scale (10^2 to 10^3 meters), channel-unit scale (10^0 to 10^1 meters), and bedform scale (10^{-2} to 10^0 meters) (Figure 2.2). Hydrogeomorphic setting constrains the floodplain and stream channel and governs patterns of stream gains and losses to regional groundwater systems at the valley scale [*Woessner*, 2000]. Channel-unit spacing [*Cardenas*, 2008a; *Cardenas et al.*, 2004], sinuosity [*Gooseff et al.*, 2006], the presence of channel obstructions [*Ensign and Doyle*, 2005], and the characteristics of the alluvial aquifer in the catchment [*Poole et al.*, 2006] govern the spatial organization and temporal dynamics of hyporheic exchange and storage in

surface-water zones (jointly referred to as transient storage) at the channel-unit scale. Geomorphic structures along the streambed and banks [*Cardenas et al.*, 2004; *Kasahara and Hill*, 2006], breaks in slope [*Anderson et al.*, 2005; *Gooseff et al.*, 2006], and hydraulic conductivities of subsurface sediments [*Packman and Salehin*, 2003] can be useful predictors of the arrangement and persistence of hyporheic flowpaths at the bedform scale. Stream restoration often modifies patterns of hydrologic storage and exchange at a variety of spatial and temporal scales because restoration activities typically entail the modification of stream/floodplain structure.

Human activities on floodplains and along stream corridors may have unintended or undesirable impacts on the arrangement and persistence of hydrologic connections with cascading impacts on hydrologic transport and storage dynamics and other ecosystem functions. Generally, exchanges between the advective portion of the stream channel, surface storage zones, hyporheic zones, and groundwater are assumed to be most prevalent where channel morphology is complex (e.g., high sinuosity, frequent side channels and mid-channel bars, well-formed pool/riffle sequences, and variable channel slope). Degraded streams—those often targeted for restoration—tend to have simplified channel patterns and are thus expected to exhibit reduced rates of storage and exchange, yielding associated losses in habitat complexity, depressed capacity for buffering against temperature and discharge fluctuations and cumulative or synergistic effects from downstream advection of pollutants. Despite documented linkages between individual restoration structures/features, hydrologic retention, and solute transport characteristics [*Crispell and Endreny*, 2009; *Kasahara and Hill*, 2006; *Mutz et al.*, 2007], very few

studies have investigated the role of reach-scale geomorphic channel restoration on hydrologic transport processes. Contradictory conclusions from existing research on restored streams [Bukaveckas, 2007; Knust and Warwick, 2009] make it difficult to predict the influence of channel realignment on patterns of water and solute movement.

As more attention and resources are devoted to improving the condition of riverine resources, the need grows for new tools and assessment strategies. Increasing awareness of research gaps and data gaps left by most post-restoration monitoring efforts has led to a recent call by Hester and Gooseff [2010] to investigate the effect of stream restoration on spatio-temporal patterns of water movement. Here, our study investigated relationships between measures of hydraulic and topographic complexity and patterns of water and solute movement in the context of a large-scale stream restoration project. We hypothesized that changes in stream structure due to channel realignment cause dramatic changes in the nature of water and solute retention within the restored reaches. In particular, we predicted that: (1) measures of hydrogeomorphic channel complexity are greater in restored channel segments, and that (2) restored reaches exhibit corresponding increases in hydrologic retention evidenced by lower advective transport velocities and increased transient storage. We tested these predictions on Silver Bow Creek (SBC) in southwestern Montana by conducting hydrogeomorphic surveys and stream tracer experiments in channel segments prior to and following channel realignment.

Site Description

The legacy of impact and restorative action on SBC in southwestern Montana makes it ideal for examining the cascading effects of channel engineering on the hydrologic behavior of streams. SBC is situated at the headwaters of the Clark Fork River watershed, and drains an area heavily impacted by more than a century of hard-rock mining activities. During this time, the stream channel underwent a succession of structural and chemical transformations. Notably, a series of floods in the early 1900s transported metal-rich mine tailings along the stream corridor, burying floodplain soils with up to two meters of contaminated sediments [Gammons *et al.*, 2006]. The presence of contaminated sediments along more than 26 miles of SBC prompted the Environmental Protection Agency (EPA) to designate it as a federal superfund site. Remedial and restorative actions along the SBC corridor were designed to remove contaminated sediments, improved aquatic habitat, enhance the aesthetic appeal of the floodplain, and promote the function of dynamic riverine processes [MNRDP *et al.*, 2005]. Due to extensive historical modifications to the stream/floodplain system, meeting project goals required the removal and replacement of contaminated floodplain soils and complete realignment of the stream channel.

Floodplain remediation and channel realignment activities took place on successive valley sections between 200 m and 1.0 km in length. After a given valley section was delineated, contaminated floodplain soils were removed and replaced with clean material. A new stream channel was then constructed through this material. Restored channels were cut to a depth such that the streambed ran through the native

valley-fill sediments. After each section of the new channel was completed, water was redirected from the old channel to the new channel. The historic channel was then filled with clean material and work proceeded to the next downstream valley section. The large spatial scale of restoration activities and a construction strategy that worked incrementally downstream provided a fortuitous setting for testing hypotheses regarding the interplay between channel form and patterns of water and solute movement.

We studied approximately 2 km of Silver Bow Creek near Fairmont, Montana at the south end of the Deer Lodge Valley (Figure 2.3). This section of creek was being actively restored during the study period. At a stream gauge immediately downstream of the study site (USGS gauge 12323600, Lat. 46°06'28", Long. 112°48'17"), SBC drains an area of 940 km². Prior to remediation, the floodplain at the site was composed of Quaternary alluvium, overlain with mining-derived sediment deposits [*Pioneer Technical Services and Applied Geomorphology*, 2008]. In addition to impacts associated with the historic flooding events described above, this section of SBC was subject to large-scale placer mining activities, which manifested in the excavation and channelization of the streambed, yielding a single-threaded, relatively straight channel with moderate slope (0.72%). The channel flowed over coarse, embedded native alluvium and was characterized primarily as run habitat throughout its length [*Pioneer Technical Services and Applied Geomorphology*, 2008]. The extent of the active floodplain was restricted to the near-channel zone by the presence of dikes, spoils berms, and downcutting through fine-grained tailings deposits. Following restorative realignment, the stream channel was more sinuous, and therefore longer, and exhibited a reduced channel slope. Post-

realignment channels remained single threaded but were narrower, deeper, and the uniform run morphology of pre-realignment channels was replaced by regularly spaced riffle-pool-run sequences. Data were collected from both pre- and post-alignment channels in consecutive reaches along the study segment. Delineation of targeted sub-reaches corresponded to the serial implementation of construction activities, reach by reach, as restoration work progressed downstream.

Methods

Data were collected on SBC over a range of flow states during the summer and fall of 2009. The geomorphic, hydraulic, and hydrologic character of individual channel reaches were assessed prior to and following channel realignment. Data collected from all reaches were aggregated according the structural state of the channel (pre-realignment vs. post-realignment). This approach was deemed reasonable as channel hydraulics and geomorphology of pre-realignment channels were observed to be relatively constant across the study area. Similarly, the design principles and construction techniques used to construct restored channels did not vary between the sub-reaches selected for this study.

Hydrogeomorphic Data Collection

Water velocity vector fields and stream depths were measured using a StreamPro acoustic Doppler current profiler (ADCP) mounted on a floating platform (Teledyne RD Instruments, Poway, California, USA¹). The operating principles of ADCPs are described in greater detail elsewhere [*Gordon, 1996*]. Briefly, the ADCP measures a Doppler

¹ Manufacturers are listed for informational purposes only and do not constitute an endorsement by the authors.

frequency shift in the column of water beneath it to calculate three-dimensional water velocity, stream depth, and instrument position in X,Y coordinate space. Velocities recorded for discrete depth cells were calculated by Teledyne's proprietary WinRiver II software (Figure 2.4). Data were recorded at 1 second intervals, regardless of instrument speed. Depth cell size was varied between individual cross-sections and thalweg segments based on channel morphology to provide the most complete spatial data coverage at the highest possible resolution. Bottom-tracking was used to correct velocity values for instrument motion. The instrument was operated in the field by attaching a long aluminum handle to the downstream side of the floating platform and pushing it at a constant rate. This approach was used for collecting velocity and depth profiles perpendicular to the main direction of flow (cross-sectional profiles) and along the channel thalweg (longitudinal profiles).

Estimates of stream discharge were also obtained using the ADCP. Measurements were completed along cross-sections exhibiting relatively uniform bathymetry and low-shear velocity profiles, as recommended by the manufacturer. At least four cross-section passes were completed to provide estimates of variance in measured discharge. Additional passes were completed if the coefficient of variation for the original four passes exceeded 4%. An average discharge was calculated from all passes once a coefficient of variation below this threshold value was obtained, as recommended by the manufacturer. We frequently made supplemental passes along cross-sections upstream or downstream of the measurement site to ensure that discharge estimates were not biased by channel geometry.

Geomorphic and Hydraulic Characterization of Stream Channels

We conducted hydrogeomorphic comparisons of pre- and post-realignment channels to help identify those mechanisms responsible for restoration-derived differences in patterns of water and solute movement. Hydrogeomorphic characterizations have previously been used in conjunction with tracer studies because the methodological constraints of the stream tracer approach necessitate some degree of speculation about the mechanisms responsible for observed hydrologic transport and storage processes [Gooseff *et al.*, 2007]. To calculate changes in channel sinuosity (S), thalweg lines were digitized from aerial photos and planform channel design plans within a GIS for pre-realignment and post-realignment stream channels. Changes in reach-averaged channel slope were derived from pre-restoration floodplain surveys and design plans for restored channels. Changes in channel width (w), cross-sectional area (A), hydraulic depth (D), wetted perimeter (P), hydraulic radius (R), and Froude number (F) were assessed by comparing ADCP data collected from 27 randomly selected cross-sections on each of two adjacent channel segments—one pre-realignment and one post-realignment—during summer baseflow conditions ($Q \approx 800$ l/s). Metrics w and A were measured directly by the ADCP. Hydraulic depth was calculated as w/A . Wetted perimeter (P) was calculated by summing incremental channel bed measurements over the length of a given cross-section:

$$P = \sum_{i=2}^n \sqrt{((x_n - x_{n-1}))^2 + (d_n - d_{n-1})^2} \quad (1)$$

where $d_{2..n}$ are the stream depth measurements recorded at the incremental cross-sectional lengths $x_{2..n}$. Hydraulic radius was computed as A/P . Channel Froude number was computed as follows:

$$F = \frac{Q}{A\sqrt{gD}} \quad (2)$$

where Q is stream discharge measured with the ADCP at the downstream end of the reach and g is gravitational acceleration.

Frequency distributions of stream depth along the channel thalweg and along individual cross-sections was calculated by summing the lengths of streambed that fell within various depth ranges and dividing by the total measured thalweg or cross-sectional length. Therefore, the probability that stream depth fell within a given depth range was calculated as:

$$P[d_{min} < d < d_{max}] = (\sum_{i=1}^n x_i)/L \quad (3)$$

where d_{min} and d_{max} define the minimum and maximum of the depth range, respectively, d is the stream depth measured over some distance x , $x_{1..n}$ are the lengths of stream that have depths within the depth range, and L is the total measured stream length (2.4). Cross-sectional data collected along a given channel segment was aggregated into a single distribution.

Frequency distributions of stream velocity were calculated by summing the measured longitudinal and cross-sectional profile area fractions falling within various velocity ranges and dividing by the total measured profile area. The probability that velocity fell within a given range was calculated as:

$$P[vmin < v \leq vmax] = (\sum_{i=1}^n a_n)/A_l \quad (4)$$

where v_{min} and v_{max} define the minimum and maximum of the velocity range, respectively, v is the stream velocity measured over some longitudinal or cross-sectional profile area a , $a_{l..n}$ is the profile area falling within the velocity range, and A_l is the total area of the profile. Cross-sectional data collected along a given channel segment was aggregated into a single velocity distribution.

Spatial patterns indicated by visual inspection of velocity and depth data were investigated through application of geostatistical methods. These methods, including calculations of semivariance, are gaining popularity as a tool for assessing the spatial organization of stream hydraulics and bathymetry [Legleiter *et al.*, 2007; Shields *et al.*, 2003]. We calculated semivariance for depth and velocity data as:

$$\gamma(h) = \frac{1}{2n_h} \sum_{i=1}^{n_h} (z(x_i + h) - z(x_i))^2 \quad (5)$$

where h is the lag distance between pairs of ordered data of some variable z measured at points $x_{l..n}$. Plots of semivariance against lag distance called experimental semivariograms (Figure 2.5) were used to explore the spatial organization of measured depth and velocity values. Semivariograms were calculated for longitudinal velocity and depth data collected on 400 m long pre- and post-realignment channel segments. Cross-sectional semivariograms were created by aggregating semivariance values calculated at various lag distances from multiple cross-sections. Semivariograms for longitudinal and cross-sectional velocity data were calculated for three flow states: 800 l/s, 1100 l/s, and 1400 l/s. Differences in the structure of spatial data were assessed through visual examinations of semivariance data and through fitting mathematical models to the

experimental semivariograms. We fit spherical covariance model structures or pure nugget effect model structures to observed data:

$$\gamma_{spherical}(h) = n + (s - n) * \left[\left(\frac{3h}{2r} \right) - 0.5 \left(\frac{h^3}{r^2} \right) \right] \quad (6)$$

$$\begin{aligned} \gamma_{nugget}(h) &= 0 \text{ when } |h| = 0 \\ &= s \text{ when } |h| \neq 0 \end{aligned} \quad (7)$$

Where the sill s is equal to the maximum variance of the data set, n is the nugget, and r is the range. Model type was selected by visual assessment of experimental semivariograms. Best-fit model parameters were obtained for spherical models through Monte Carlo sampling. One thousand random samples for r and n were drawn from uniform distributions whose upper and lower bounds were determined by visual inspection of experimental semivariograms. Models were constructed for each sampling run. The parameter set that produced the model with the smallest sum of squared errors when evaluated against the experimental semivariogram was selected as the optimal set. The calculated semivariance $\gamma(h)$ at a given lag h describes the complexity of the data surface at the spatial scale defined by h . Low semivariance values at a given lag distance indicate low spatial variability (or low complexity) at that scale. The range represents the distance at which the variable of interest is no longer spatially correlated. The slope of the semivariogram between a lag distance of zero and the range describes how data values co-vary with increasing distance. Increasing semivariance values occur at spatial scales where variability approaches the sill. The height of the sill indicates the overall variability present in the system but does not, by itself, contain information about the spatial

structure of the data. The nugget represents a discontinuity at the origin of the semivariogram and results either from measurement error or a lack of correlation at fine spatial scales [Legleiter *et al.*, 2007]. The presence of a large nugget effect in an experimental semivariogram indicates a system where the variable of interest exhibits very little fine-scale spatial correlation and, thus, greater structural complexity. Each component of the semivariogram was related back to the physical organization of stream topography or velocity fields.

Stream Tracer Experiments

Stream tracer experiments have been used extensively to characterize hydrologic residence time distributions (RTD) and identify mechanisms of solute storage and exchange in streams [Anderson *et al.*, 2005; Gooseff *et al.*, 2008; Haggerty *et al.*, 2002; Harvey *et al.*, 1996; Wondzell, 2006]. We conducted fifty-six stream tracer experiments on pre-realignment (n=34) and post-realignment (n=22) study reaches during the summer and fall of 2009. The sequential downstream implementation of channel realignment permitted data collection to occur several times prior to and in the days and weeks immediately following restoration on multiple channel segments. Reach lengths for tracer experiments were selected such that pre-realignment and post-realignment RTDs could be compared across similar channel distances, valley distances, and average in-channel residence times. Each experiment consisted of an instantaneous release of sodium chloride (NaCl) at a site sufficiently upstream of the downstream monitoring location(s) to ensure complete vertical and lateral mixing. Fluorescent dyes were periodically co-injected with salt slugs so that mixing lengths could be assessed visually. Electrical

conductivity (EC) and stream temperature data were collected at all monitoring locations. Data were collected at 5 second intervals with CS547A probes connected to CR1000 dataloggers (Campbell Scientific Inc., Logan, Utah, USA¹). Probes were fixed to stakes in the thalweg at approximately 50% of channel depth. Independent calibration curves, developed for each probe in the lab prior to the 2009 field season, were applied to convert field measurements of temperature and EC into NaCl concentration breakthrough curves (BTCs). Changes in background EC over the duration of an individual experiment were assumed to be linear and were corrected by subtraction.

For instantaneous tracer releases, BTCs are a direct reflection of the hydrologic RTD of the system, provided the system is linear. Previous studies of the stream tracer approach show that the peak of a RTD contains information about the advective portion of flow, while the tail contains information about transient storage behavior [*Harvey et al.*, 1996]. The timing of the peak of the RTD represents the average solute velocity in the system and is commonly interpreted as the advective transport time, while the slope and thickness of the RTD tail is associated with transient storage processes. The length and thickness of tails are positively correlated with the size of transient storage zones and the frequency of exchange with them. Characterization of RTD peak timing and tailing for each stream tracer experiment allowed us to directly compare patterns of water movement in pre- and post-realignment channels across a range of flow states.

The effect of channel realignment on hydrologic transport processes can be investigated by comparing the shape of hydrologic RTDs in pre- vs. post-realignment channels. However, because sinuosity changes markedly from pre- to post-realignment, a

case can be made for comparing RTDs where water has flowed over the same channel distance, the same down-valley distance, or after water has spent the same amount of time in each channel. The “channel distance” comparison is useful for understanding changes in solute transport along the channel. The “valley distance” comparison is useful for understanding changes in solute transport within a drainage network, and the “residence time” comparison is useful for documenting temporal rates of advection, dispersion, and transient storage within the channel. To carry out these comparisons, we calculated modal stream channel velocity, modal down-valley velocity (down-valley travel rate, excluding sinuosity), and an index of transient storage for each RTD. The modal stream channel velocity for a given RTD was calculated as the time to peak divided by the thalweg distance between the injection and observation points. The modal down-valley velocity was calculated as the time to RTD peak divided by the straight line distance between the injection and observation points. The bivariate relationship between the time to RTD peak and the time at which 99% of the recovered tracer mass passed by the solute observation point was used as a measure of the effect of transient storage on each RTD. The time at which 99% of the recovered tracer mass passed the observation point was assumed to be sufficiently distal to the mode of the RTD to be an independent measure of transient storage, unaffected by dispersion. Other investigators have similarly compared RTD tailing behavior directly by normalizing the time axis of observed BTCs to the median solute transport time. Gooseff [2007] plotted such normalized BTCs from morphologically distinct reaches so that differences in tailing behavior could be assessed visually. We chose not to use this approach because we were concerned with distortions

in RTD shape that may occur when applying such normalizations to data collected at different time scales. For channel distance, valley distance, and residence time comparisons, ANCOVA methods were used to assess the significance of observed differences in transport characteristics between pre- and post-realignment channels. For each between-group comparison, four model structures were tested (single mean, two means, parallel lines, and separate lines) and F-tests were used to identify the most parsimonious model that adequately described the variability of the data sets.

Stream tracer data is most frequently assessed by parameterization and curve-fitting of a numerical transient storage model like OTIS-P. We initially endeavored to analyze our data in this manner. However, application of the Generalized Likelihood Uncertainty Estimation [*Beven and Freer, 2001*] approach to the OTIS model showed output to be fairly insensitive to large ranges in parameter values. This may have been the result of our tracer injection strategy (instantaneous rather than constant rate), scaling issues in our system—evidenced by Damkohler numbers much greater than unity—or may be a reflection of general inadequacies in model structure noted by others [*Camacho and González, 2008; Wagener et al., 2002*]. Regardless of the cause, we present direct comparisons of RTD characteristics rather than data from the modeling approach because of the high degree of uncertainty associated with parameter estimates.

Results

Hydrogeomorphic Comparisons

Comparisons of channel geometry and frequency distributions of stream depth and stream velocity for pre- and post-realignment channels highlighted the distinct changes in longitudinal and cross-sectional structure illustrated in Figure 2.7. Shifts in cross-sectional channel geometry are illustrated by Figure 2.6. Results from ANOVA comparisons of cross-sectional data are summarized in Table 2.1. The distribution of longitudinal stream depths in pre-realignment channels was unimodal and very peaked, reflecting the relatively planar morphology of these reaches at the channel-unit scale and the low overall variability in depth (Figure 2.8c). Examination of pre-restoration cross-sectional distributions indicated that the planar morphology of these channels was not limited to the longitudinal axis, but also extended laterally from the channel thalweg to stream banks. Conversely, longitudinal depth distributions in post-realignment channels were bimodal and exhibited a larger overall variance. The bimodal behavior of these distributions coincided with the distinct differences in the depth of engineered riffle-run sequences and pools. Cross-sectional depth distributions mirrored those collected along the channel thalweg (Figure 2.8d).

Observed differences in channel form were correlated with shifts in the characteristics of velocity distributions. In pre-realignment reaches, longitudinal and cross-sectional distributions of channel velocities were near Gaussian (Figure 2.8a and 2.8c). These channels exhibited relatively consistent run morphology and contained roughness elements (e.g. cobbles and boulders) that were large relative to stream depth.

Mean velocities of longitudinal distributions were higher than those from post-realignment reaches. This reduction in mean velocity following restoration coincided with both decreased channel slope and the introduction of frequent slow-moving pools in restored channels. Longitudinal velocity distributions from post-realignment channels exhibited a characteristic positive skew that was reflective of the large fraction of stream volume contained in deep pools. Post-realignment cross-sectional velocity distributions did not exhibit this characteristic, which likely resulted from a random sampling strategy that selected a greater number of riffles and runs than pools. Variability in stream discharge did not affect general conclusions reached from comparisons of velocity distributions. While mean velocity values were found to increase with discharge in both pre- and post-realignment channels, the patterns of differences in mean, variance, and skewness shown in Figure 2.8 remained relatively unchanged.

Geostatistical Comparisons

Visual assessment of raw data surfaces and semivariograms, and inter-reach comparisons of best-fit model parameters indicated strong correlations between scales of bedform complexity and the organization of longitudinal and cross-sectional velocity fields. Comparison of experimental semivariograms for longitudinal depth profiles illustrated differences in topographic structure at a range of spatial scales (Figure 2.9b). The experimental semivariogram of longitudinal stream depth in pre-realignment channels was best fit with a pure nugget effect model. These spatial data exhibited a very low sill, reflecting a low overall variability in depth. This was corroborated by field observations and the reach-averaged variance in depth illustrated by frequency

distributions in Figure 2.8c. Longitudinal data from post-realignment reaches were best fit with spherical covariance model structure. These data exhibited a much higher sill than pre-realignment data structures. The higher overall variability in stream depths observed in these reaches coincided with the introduction of riffle/pool/run morphology. Examination of semivariograms supported visual assessments of raw data surfaces and field observations. Stream depths within a given channel-unit were self-similar and the differences in stream depth between channel-units were large. Therefore, the greatest differences in depth were found at thalweg distances associated with the spacing of riffle/run sequences and pools (15-20 m). There was essentially no nugget effect observed in post-realignment depth data. The calculated semivariance value for lag distances between 0 and 10 cm was slightly larger in pre-realignment channels ($\gamma = 2.73 \times 10^{-4}$) than in post-restoration channels ($\gamma = 1.19 \times 10^{-4}$), indicating that more fine-scale variability existed in channel bedform structure before restoration took place. This difference is a conservative representation of differences in bedform variability because large absolute changes in depth occurring in the relatively smooth transition zones between channel units are likely responsible for a significant portion of the observed semivariance at lag distances less than one meter. The change in fine-scale topographic structure was noted in the field as restoration shifted the bed material from large embedded cobbles in pre-realignment channels to sands and gravels in post-realignment channels. Cross-sectional depth semivariograms displayed similar characteristics to their longitudinal counterparts (Figure 2.8d). Pre-realignment data exhibited a low sill that reflected the low overall variance in cross-sectional stream depth in these channels. The

experimental semivariogram was best described by a pure nugget effect model. Post-realignment data exhibited a much higher sill value and were best-fit with a spherical model structure. The range value fit to post-realignment data corresponded approximately to the average channel width (approx. 4 m).

Spatial patterns illustrated by velocity and depth semivariograms for both pre- and post-realignment channels were similar, indicating strong relationships between velocity fields and the characteristics of streambed topography. Longitudinal velocity semivariograms from both pre- and post-realignment channels (Figure 2.8a) were fit with spherical covariance model structures. The sill characterizing data from both channels was similar across all three observed flow states (Table 2.3). The wide range of longitudinal velocity values associated with steep bed slopes and the presence of large relative roughness elements in pre-realignment channels was likely achieved in post-realignment channels by the regular spacing of very high velocity riffles/runs and very low velocity pools as illustrated by Figure 2.7. The nugget effect in pre-realignment channels was much larger than in post-realignment channels. Post-realignment longitudinal semivariograms had a larger range than pre-realignment semivariograms. The distance over which longitudinal velocity values co-varied in pre-restoration reaches increased from 2 m at a discharge of 800 l/s to 5 m at a discharge of 1100 l/s and 8 m at a discharge of 1400 l/s. This shift toward larger range values suggested that increases in discharge produced more organized longitudinal velocity fields in pre-realignment channels. Fitted range values remained relatively constant (≈ 15 m) and approximately equal to average channel unit spacing across all three flow states in post-realignment

channels. Spatial structure existed in longitudinal velocity fields at a coarser scale (i.e. less spatial complexity) in post-realignment reaches than in pre-realignment reaches. In pre-realignment reaches, the spatial structure of velocity fields broke down quickly with increasing distance. High water velocities near the stream surface rapidly transitioned toward much lower velocities near the stream bed due to bed friction. In post-realignment channels, thalweg velocity values within a given channel-unit exhibited strong spatial correlation, while differences in velocity between channel-units were large. Differences in cross-sectional semivariograms were similar to those observed in longitudinal data structures (Figure 2.8b). Both pre- and post-realignment cross-sectional data were fit with spherical covariance model structures (Table 2.4). Pre-realignment cross-sectional data exhibited higher nugget and higher sill than post-realignment cross-sections at low flow, indicating spatial correlation existed across larger distances in post-realignment cross-sections. Interestingly, the respective values of these parameters for pre- and post- channels converged as discharge increased.

Stream Tracer Experiments

Direct comparisons of hydrologic RTDs provided insights into changes in hydrologic transport and retention resulting from restoration for a given channel length, a given valley length, and a given channel residence time. We plotted modal stream velocity against discharge for 56 stream tracer experiments and grouped data by channel type (Figure 2.10a). ANCOVA methods were used to assess the significance of observed differences in modal velocity between pre- and post-realignment channels (Table 2.4). A parallel lines model was found to adequately characterize trends in the data, indicating

that channel type and discharge were significant predictors of modal velocity (F-stat = 220.26, p-value ≈ 0). The model estimated modal stream velocity to be 0.11 m/sec greater in pre-realignment channels at any given discharge. This difference is illustrated in Figure 2.10b by plotting individual RTDs from each channel type that characterize solute transport over a given thalweg distance at a given discharge. Channel realignment increased hydrologic retention by slowing advective transport along a given stream segment.

A similar approach was used to compare differences in hydrologic transport over a given valley length. We plotted modal valley velocity against discharge for the same 56 stream tracer experiments (Figure 2.11a). ANCOVA techniques were once again used to assess differences between pre- and post-realignment channels. A parallel lines model was found to adequately characterize trends in the data, indicating that both discharge and channel type were significant predictors of modal valley velocity (F-stat = 816.40, p-value ≈ 0). The model estimated modal valley velocity to be 0.27 m/sec greater in pre-realignment channels at any given discharge. This difference was illustrated by plotting individual RTDs for each channel type that characterized solute transport over a given valley length at a given discharge (Figure 2.11b). Restoration on SBC increased hydrologic retention by slowing advective transport along a given valley length. These changes coincided with increases in channel length between upstream-downstream valley points following channel realignment.

Comparisons of modal velocities from the perspectives of the channel thalweg and valley segment were useful for understanding the way in which restoration activities

affected the advective portion of solute transport processes — those expected to control the bulk of hydrologic retention along a stream corridor. However, these approaches did not provide information about the RTD tailing behavior that is typically associated with transient storage dynamics. We assessed differences in RTD tailing by plotting the modal hydrologic residence time against the time at which 99% of the recovered tracer mass passed by the solute observation point for all 56 tracer experiments (Figure 2.12a). This comparison yielded an index of transient storage reflecting the persistence of RTD tailing as a function of the average solute residence time in the stream channel. ANCOVA comparisons produced a separate lines model that adequately described the differences in the data trends (F-stat = 28.62, $p \ll 0.001$). The modeled slope that best characterized pre-realignment data (1.33 min/min) was greater than the slope that characterized best post-realignment data (1.13 min/min). This difference in modeled slope indicated that RTD tails were thicker and exhibited a lower slope in pre-realignment channels than in post-realignment channels for a given in-channel residence time. These differences in tailing behavior were illustrated by plotting RTDs from pre- and post- channels that exhibited the same median solute residence time in the stream channel (Figure 2.12b).

Discussion

Research investigating the relationships between elements of stream structure and the movement of water and solutes throughout stream corridors [*Anderson et al.*, 2005; *Cardenas*, 2008b; *Packman et al.*, 2004; *Poole et al.*, 2006; *Wondzell*, 2006] has largely informed recent work exploring the effects of anthropogenic modification of the

streambed on measures of hydrologic and biogeochemical function [Bukaveckas, 2007; Gooseff *et al.*, 2007; Knust and Warwick, 2009] and guided the development of our research questions on Silver Bow Creek. The burgeoning understanding of the interplay between channel form and function provides a foundation for research questions investigating pathways of human degradation and restoration in stream ecosystems. We related the structure of pre- and post-realignment stream channels (as structure is frequently modified by restoration activities) to characteristics of hydrologic RTDs. This research compliments the existing body of literature by 1) integrating common hydrogeomorphic comparisons, geostatistical analyses, and stream tracer experiments and 2) suggesting new frames of reference for considering patterns of water and solute movement along stream corridors in an effort to provide unique insights into the relationship between stream restoration, channel form, and the functional attributes of stream ecosystems.

Restoration and Stream Channel Complexity

Our investigations showed that restoration increased channel complexity at the channel-unit scale (10^0 to 10^1 meters) while reducing it at the bedform scale (10^{-2} to 10^0 meters). Relatively straight channels with no channel-unit variability were replaced by highly sinuous channels with regular channel-unit spacing. Depth semivariance increased substantially, peaking at a lag distances near 20 m in post-realignment channels due to the introduction of regular riffle-pool-run sequences (Figure 2.9). However, field observations and covariance modeling of spatial data indicated that restoration reduced variability in streambed topography at very fine scales (< 10 cm). While our methodology

did not explicitly quantify the correlations between bed topography and velocity, the strong relationships observed between semivariograms of channel bed structure and velocity fields (Figure 2.9) in the overlying water column allowed us to relate streambed topography to velocity field complexity. Legleiter [2007] utilized a similar geostatistical approach to identify correlations between stage, streambed topography and the organization of overlying velocity fields. Our findings on SBC support Legleiter's conclusion that stream depth, relative to the height of roughness elements in the streambed, is a fundamental control on velocity field structure. The shallow channel and high bed-roughness present in pre-realignment channels were associated with poorly-organized (i.e. highly-complex) velocity fields (Figure 2.7). Increases in discharge and corresponding increases in stream depth in these channels reduced the relative size of roughness elements and enhanced the spatial organization of velocity fields, as noted by changes in covariance modeling parameters (Tables 2.3 and 2.4). The regular channel-unit spacing, a hydraulically efficient channel geometry (i.e. hydraulic radius in Table 2.1), and relatively low bed roughness present in post-realignment channels were correlated with velocity fields exhibiting strong spatial correlation at the scale of the average pool-riffle sequencing (Tables 2.3 and 2.4). The spatial patterns of longitudinal post-realignment velocity fields persisted through changes in discharge (Table 2.3), while the spatial correlation of cross-sectional velocity fields broke down with increased flow (Table 2.4). No clear ranking based on metrics of complexity was produced by hydrogeomorphic comparison of the pre- and post-realignment channels. However, this

approach did identify several mechanisms that were expected to differentially influence patterns of water and solute movement on our study reaches.

The connection between stream structure and spatio-temporal patterns in water and solute transport is supported by numerous modeling efforts [*Cardenas et al.*, 2004; *Cardenas*, 2008b; *Salehin et al.*, 2004] field investigations on natural streams [*Anderson et al.*, 2005; *Kasahara and Wondzell*, 2003; *Wondzell*, 2006] and experimental stream manipulations [*Ensign and Doyle*, 2005]. *Ensign and Doyle* [2005] found positive correlations between the velocity field heterogeneity and the propensity for surface storage zone development. We assumed similar relationships existed on SBC, although we did not make direct measurement of the residence time characteristics of surface water zones across a range of velocities. Velocity field characteristics suggested surface storage was greater on pre-realignment reaches at low discharges, and the propensity for such storage on pre- and post- reaches began to converge as discharge increased (Tables 2.3 and 2.4). Longitudinal velocity profiles exhibited weaker spatial correlation in pre-realignment reaches than post-realignment reaches at lag distances less than 5 m across all observed flow states, suggesting that fine-scale surface eddying may have been more prevalent prior to restoration. Even if strong relationships exist between velocity field correlation lengths, surface eddying, and water retention, the effects of surface storage on patterns of water and solute movement were likely confounded by the presence and activity of subsurface storage zones.

Changes in channel geometry (Table 2.1 and Figure 2.6) and streambed topography (Table 2.2 and Figures 2.7-2.9) suggested that subsurface storage in pre-

realignment channels could have been dominated by high-frequency exchange along relatively short hyporheic flowpaths, while subsurface storage in post-realignment channels could have been dominated by lower frequency exchange along relatively long hyporheic flowpaths. Structural changes to the stream channel following restoration were expected to reduce stream-subsurface hydraulic head gradients created by bedform features (e.g. beneath individual cobbles in the streambed) and increase head gradients at the channel-unit scale, promoting the development of subsurface flowpaths across meander bends and beneath riffles. If subsurface flowpaths are assumed to be hierarchically nested [Poole *et al.*, 2008], then these structural changes would reduce the frequency of hyporheic exchange and increase the average residence time of water and solutes in subsurface storage zones in post-realignment channels. Although the methods employed by this study did not allow us to identify the exact location of transient storage or the proportional roles played by surface and subsurface solute retention, significant changes in transport behavior following restoration suggested that channel structure played a large role in dictating hydrologic RTD characteristics.

Restoration and Hydrologic Transport Dynamics

The study of water and solute movement in streams is germane to restoration science because improvements in water quality or in-stream mitigation of pollutants are an important component of many restoration plans. Silver Bow Creek, along with many other streams targeted for restoration, is negatively impacted by nutrient loading (e.g. waste-water effluent, agricultural runoff) and/or contamination by major ions and metals (e.g. acid mine drainage, industrial effluent, urban runoff). Thus, as discussed in the

Introduction, hydrologic transport dynamics likely play a crucial role in dictating the effectiveness of restoration design at improving the ecological condition of streams.

We utilized stream tracer data to present three frames of reference for considering restoration-induced changes in solute transport behavior: 1) the stream length perspective (transport characteristics for a given stream channel length), 2) the valley length perspective (transport characteristics for a given downstream valley length), and 3) the residence time perspective (transport characteristics for a given average solute transport time along the stream channel). Characterization of RTDs from each of the above perspectives led to different conclusions about hydrologic transport dynamics on pre- and post-realignment reaches. This highlights the need for careful consideration of the question of interest when selecting a methodology for stream tracer data collection and subsequent analysis. The richest understanding of patterns of water and solute movement, especially in the context of a comparative analysis like the one used here, is likely to come from the integration of all three perspectives.

Comparisons of results based on stream channel length are typical to hydrologic transport studies. We conducted such comparisons to identify the effects of restoration on hydrologic RTDs over a given channel length. Restoration of channels on SBC increased advective transport time within the stream channel by average of 17% across all observed flow states (Figure 2.10). Synergies created by decreased channel slope and low thalweg velocities in frequent slow-moving pools provided a mechanism for slowing the average downstream advection of water in post-realignment channels. Our findings are consistent with those of Bukaveckas [2007] who noted that channel realignment on Wilson Creek

reduced reach-averaged water velocity and increased the median transport time of conservative solutes by 50%. Increased in-channel transport time in restored reaches of SBC likely increased opportunities for solutes to be degraded, transformed, or removed from the system via biological or abiotic processes. Utilization of this channel length based comparative approach may be useful in studies of natural streams or cases where restoration does not alter channel length. However, in systems like SBC where restoration design entails modification channel length, additional information may be gleaned from valley-length based comparisons.

Assessment of down-valley hydrologic transport characteristics is well-suited to evaluating the impact of restoration on the movement of water and solutes across a floodplain or through a channel network. Many restoration designs alter the length of the stream channel within a set project boundary by enhancing sinuosity. This alters transport characteristics between pairs of upstream-downstream valley points. Down-valley solute advection rates in our study reaches were decreased by an average of 42% across all observed flow states following restoration activities (Figure 2.11). This difference can be explained largely by increases in channel sinuosity that lengthened the channel, but was further enhanced by the reduction in water velocity per unit channel length, due to reduced reach-averaged channel slope and the presence of frequent pools in restored channels. Restoration was much more effective at retaining water and solutes when considering down-valley rates of solute transport than would otherwise be concluded by comparing advection rates along a given thalweg distance. This result convoluted straightforward interpretations about restoration's affect on biogeochemical processes

and ecological function. Implications for biogeochemistry and stream ecology were further complicated because interactions between the advective portion of flow and transient storage zones—where elevated rates of biogeochemical activity often occur—were lower in restored channels.

Transient storage was reduced in post-realignment channels when compared to pre-realignment channels, for a given in-channel residence times (Figure 2.12). If a positive relationship exists between transient storage and the retention and transformation of nutrients and other pollutants, then restoration activities on SBC reduced the stream's capacity for assimilating these solutes per unit time spent in the stream channel, though this effect was likely counteracted by the increased hydrologic residence time across a given stream or valley length afforded by channel realignment. The observed differences in RTD tailing behavior may have been affected both by the physical arrangement of the system and by the sensitivity of the employed methodology to various timescales of exchange.

The reduced RTD tailing observed in restored channels may have been related to a channel design that increased flow efficiency (i.e. hydraulic radius in Table 2.1). Post-restoration velocity fields were nearly laminar, exhibited long correlation lengths, and were oriented in a primarily downstream direction over relatively smooth bed surfaces. Conversely, the presence of large relative-roughness elements in shallow pre-realignment channels produced velocity fields with much shorter correlation lengths (Figure 2.7). The formation of storage zones associated with streambed roughness elements may have been responsible for some portion of the observed differences in RTD tailing behavior. The

relationship between bed structure and transient storage has been reported by others. A meta-analysis of tracer experiments conducted on streams across the U.S. showed transient storage to be positively correlated with channel friction factor, a measure to bed roughness [*Jones and Mulholland, 2000*]. Roughness can affect transport dynamics by creating opportunities for solute storage in boundary layer vortices and eddies located behind large elements in the streambed. Irregular bed surfaces also facilitate advective pumping mechanisms that lead to surface-subsurface exchange [*Wörman et al., 2002*]. The reduction of streambed slope and reduced bedform topographic variability in restored channels likely weakened hydraulic head gradients at the bedform scale, limiting the frequency of hyporheic flow along short spatio-temporal subsurface flowpaths. Although the introduction of large pool-riffle sequences and meander bends likely produced an abundance of longer hyporheic flowpaths, the methodological sensitivities typical to our experiments and the ratio of stream discharge to the volume/rate of water conveyed along these flowpaths likely made their presence and influence on RTD tailing difficult to detect. This effect may have been compounded upon by the smaller contact area between stream water and the streambed in restored channels. Reductions in the size of this interface relative to the volume of water conveyed through the stream channel at any given time would have resulted in reduced rates of exchange between the channel and subsurface storage zones. Changes in the hydraulic conductivity of streambed sediments may have also contributed to observed differences. Although post-realignment channels were constructed in the same alluvial material that pre-realignment channels flowed through, sufficient time may not have passed between channel construction and

field observations for any meaningful sediment sorting to occur. As a result, hydraulic conductivities in restored streambeds may have been lower, increasing the residence time of hyporheic flow but preventing rates of flow along subsurface from achieving rates similar to those in pre-realignment channels. These explanations are, of course, speculative because no solute concentration measurements or estimates of hydraulic conductivity were made in the streambed.

Our results may indicate pathways for improving the effect of stream restoration on hydrologic transport processes. Channel realignment in SBC decreased advective transport times along a given channel length and a given downstream-valley length. These increases in water and solute retention should benefit biotic uptake of solutes, but decreased bed roughness and highly organized velocity fields are apt to offset the beneficial effects of slower advective velocities by limiting transient storage. Incorporation of roughness elements that produce chaotic velocity fields into channel designs that inherently slow water velocity through increased sinuosity, decreased channel slope, and enhanced channel-unit variability could further enhance contact time between solutes, bio-reactive streambed sediments, and microbial communities in surface-water storage zones. Such approaches could, thus, provide additional ecological benefits over traditional channel realignment techniques that frequently aim enhance hydraulic conveyance by making channels narrower, deeper, and reducing the roughness of the streambed.

While our work suggested that restoration activities on SBC had the immediate impact of decreasing transient storage, it is important to note that we did not investigate

the temporal evolution of restored channels. In valley-bottom, low-gradient streams like SBC, measures of transient storage may increase as channels are exposed to a range of discharge events and natural geomorphic processes begin to reorganize and reshape the streambed. Wondzell and Swanson [1999] report that flood-induced changes in channel form are a significant control on the spatial organization of hyporheic flow at a variety of scales. These findings are supported by a modeling study by Poole et al. [2006] that concludes cut and fill dynamics, channel avulsion, and the presence of paleo-channels on a floodplain are critical controls on the development and maintenance of subsurface transient storage zones. Furthermore, the deformation of channel banks is necessary for the formation of eddies and backwaters, locations that Bukaveckas [2007] and Ensign and Doyle [2005] note can play a large role in controlling reach-scale solute transport. Therefore, we predict that the degree to which solute transport dynamics in restored systems can recover and surpass normative conditions is directly tied to the channel's ability to self-organize. Long-term monitoring and research designs built around this prediction will help inform discussions about what 'ideal' streams look and act like and may provide a foundation for dialogue regarding the role of deformable channels and planned design-failure in constructed channels. Continued work relating the geomorphic evolution of restored stream channels to the condition and persistence of hydrologic retention and transient storage will be a valuable contribution to both restoration science and restoration practice.

Conclusion

Restoration of stream segments on SBC slowed advective transport velocities for a given stream length and across a given valley length by reducing average streambed gradient and increasing stream length. Restoration was more efficient at retarding transport across a given valley length than a given stream length, indicating that adding sinuosity to stream channels is an important component of restoration design where slowing the advective transport of water and solutes along the stream corridor is a stated or implied goal. Despite increased water and solute retention due to changes in advective velocities, channel restoration reduced the influence of transient storage on hydrologic residence time distributions in our study reaches. Our findings caution that the increases in residence time associated with increased sinuosity and pool frequency may be offset to some extent by a loss in surface-zone storage and near-channel hyporheic exchange in restored channels. Considering stream-bed complexity and the hydrologic effects of channel roughness and topographic heterogeneity may be a critical but commonly overlooked factor in the design of those stream restoration projects that incorporate channel realignment.

Table 2.1: Hydrogeomorphic characteristics of experimental reaches. Sinuosity and slope values are derived from channel design surveys/plans. All other metrics are reported as the mean plus or minus the standard deviation where n=27 cross-sections from each channel type. Reported p-values are results from one-way ANOVA comparisons.

	Sinuosity	Reach Avg. Slope (%)	Width (m)	Cross-Sectional Area (m ²)	Hydraulic Depth (m)	Wetted Perimeter (m)	Hydraulic Radius (m)	Froude Number
Pre	1.04	0.72	8.67 ± 1.38	1.89 ± 0.27	0.22 ± 0.02	10.35 ± 1.31	0.18 ± 0.03	0.33 ± 0.06
Post	1.64	0.41	5.53 ± 1.24	2.2 ± 0.96	0.41 ± 0.18	6.36 ± 1.29	0.35 ± 0.13	0.28 ± 0.17
p-value	-	-	7.84E-12	0.1139	1.86E-06	1.44E-15	1.10E-07	0.1437

Table 2.2: Semivariance modeling results for longitudinal and cross-sectional depth profiles collected along 400 m of channel thalweg and 27 randomly selected cross-sections on both pre- and post-realignment channel segments.

Profile Type	Channel Type	Covariance Model	nugget g(h)	range (m)	sill g(h)
Longitudinal	Pre	Nugget	-	-	0.011
	Post	Spherical	0.003	18.509	0.178
Cross-Sectional	Pre	Nugget	-	-	0.003
	Post	Spherical	0.000	3.953	0.075

Table 2.3: Semivariance modeling results for longitudinal velocity profiles collected at three flow states.

Channel Type	Q (l/sec)	Model	nugget g(h)	range (m)	sill g(h)
Pre	800	Spherical	0.043	2.127	0.060
	1100	Spherical	0.048	5.107	0.058
	1400	Spherical	0.053	8.032	0.065
Post	800	Spherical	0.015	16.531	0.056
	1100	Spherical	0.032	12.671	0.070
	1400	Spherical	0.023	15.241	0.070

Table 2.4: Semivariance modeling results for aggregated cross-sectional velocity data collected at three flow states.

5

Channel Type	Q (l/sec)	# of x-sections	Model	nugget g(h)	range (m)	sill g(h)
Pre	800	12	Spherical	0.060	4.995	0.077
	1100	8	Spherical	0.044	4.724	0.078
	1400	12	Spherical	0.038	3.711	0.070
Post	800	12	Spherical	0.013	1.477	0.042
	1100	8	Spherical	0.030	3.275	0.060
	1400	12	Spherical	0.042	4.935	0.098

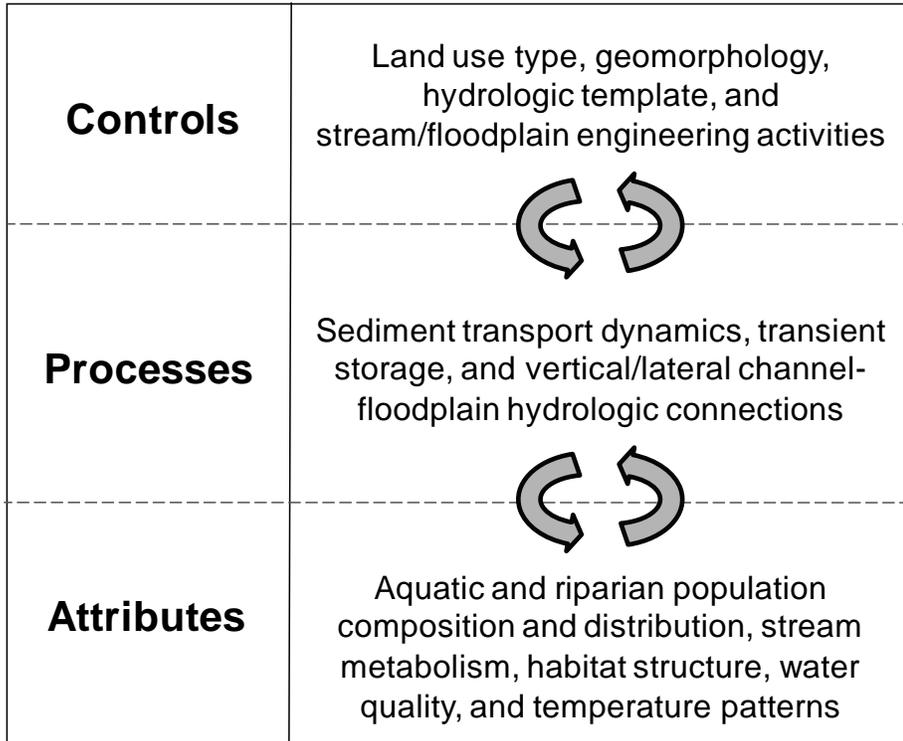


Figure 2.1: Pathways by which perturbations may cascade through stream systems. The presence of feedbacks at each level may buffer or propagate disturbances. Restoration strategies often fail to explicitly consider the role of stream *processes* in mediating connections between *controls* and *attributes*.

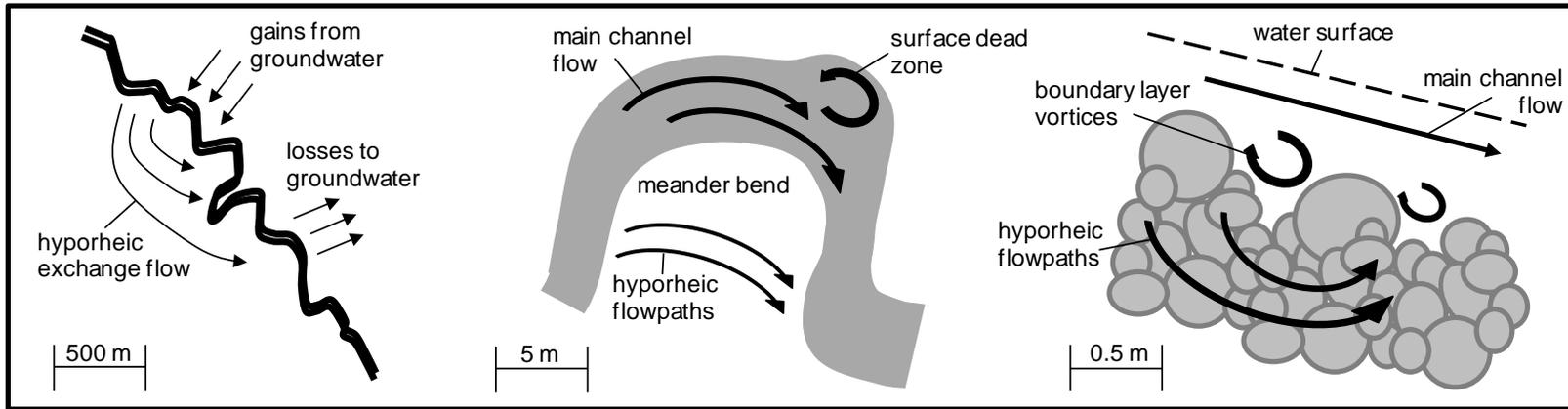


Figure 2.2: Patterns of hydrologic storage and exchange at a range of spatial scales.

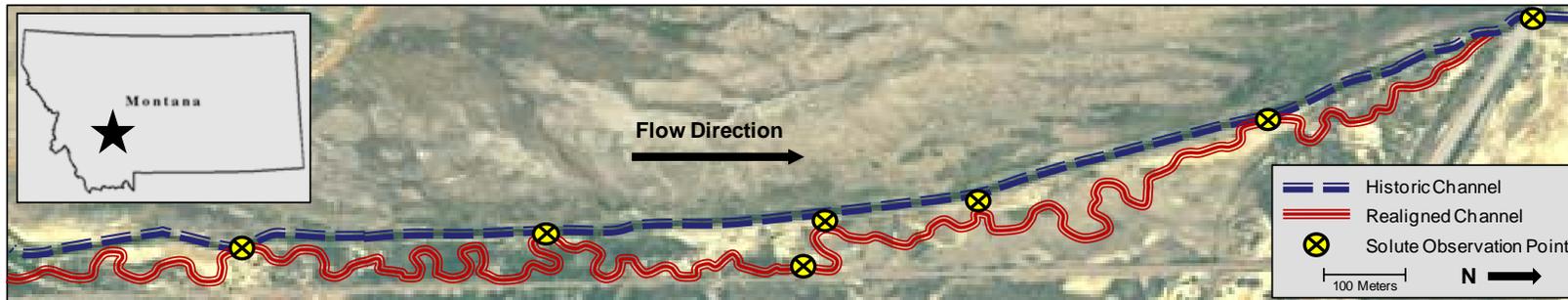


Figure 2.3: Aerial of study site highlighting the spatial scale of plan-form changes to stream channel segments resulting from realignment activities. Solute observation points are noted.

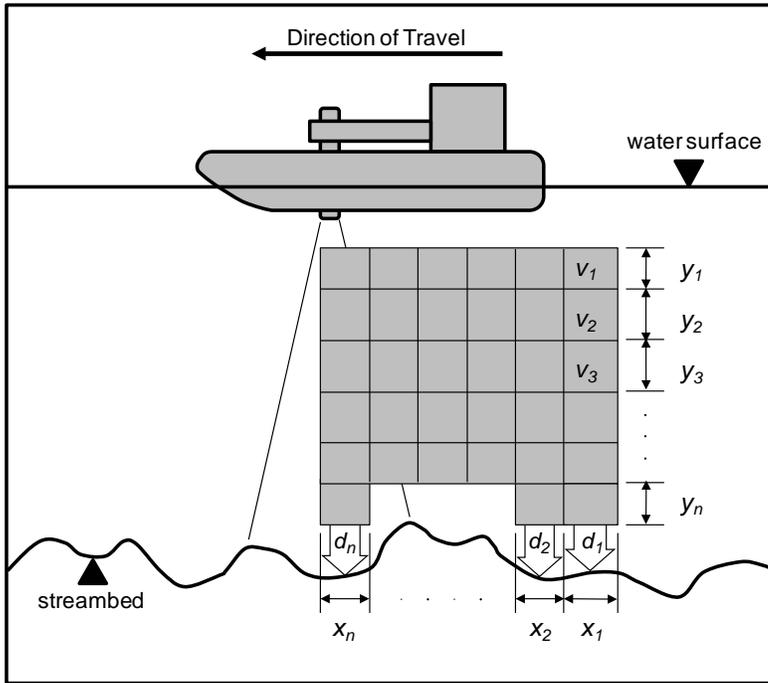


Figure 2.4: 1 Hz data collected from the ADCP during longitudinal and transverse channel surveys includes distance traveled (x), total stream depth (d), velocity cell depth (y), and average cell velocity (v).

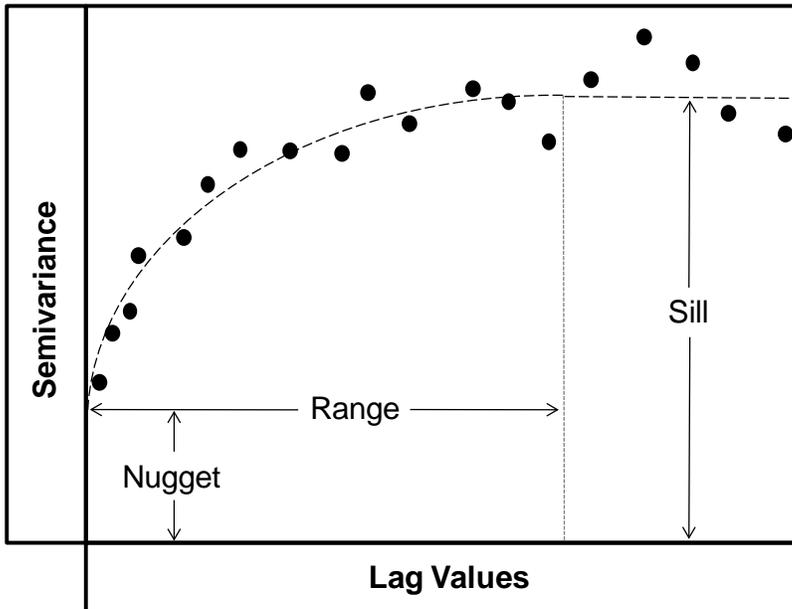


Figure 2.5: Idealized experimental (black dots) and modeled (dashed line) semivariogram for a given spatial data set. Model parameters of interest are noted.

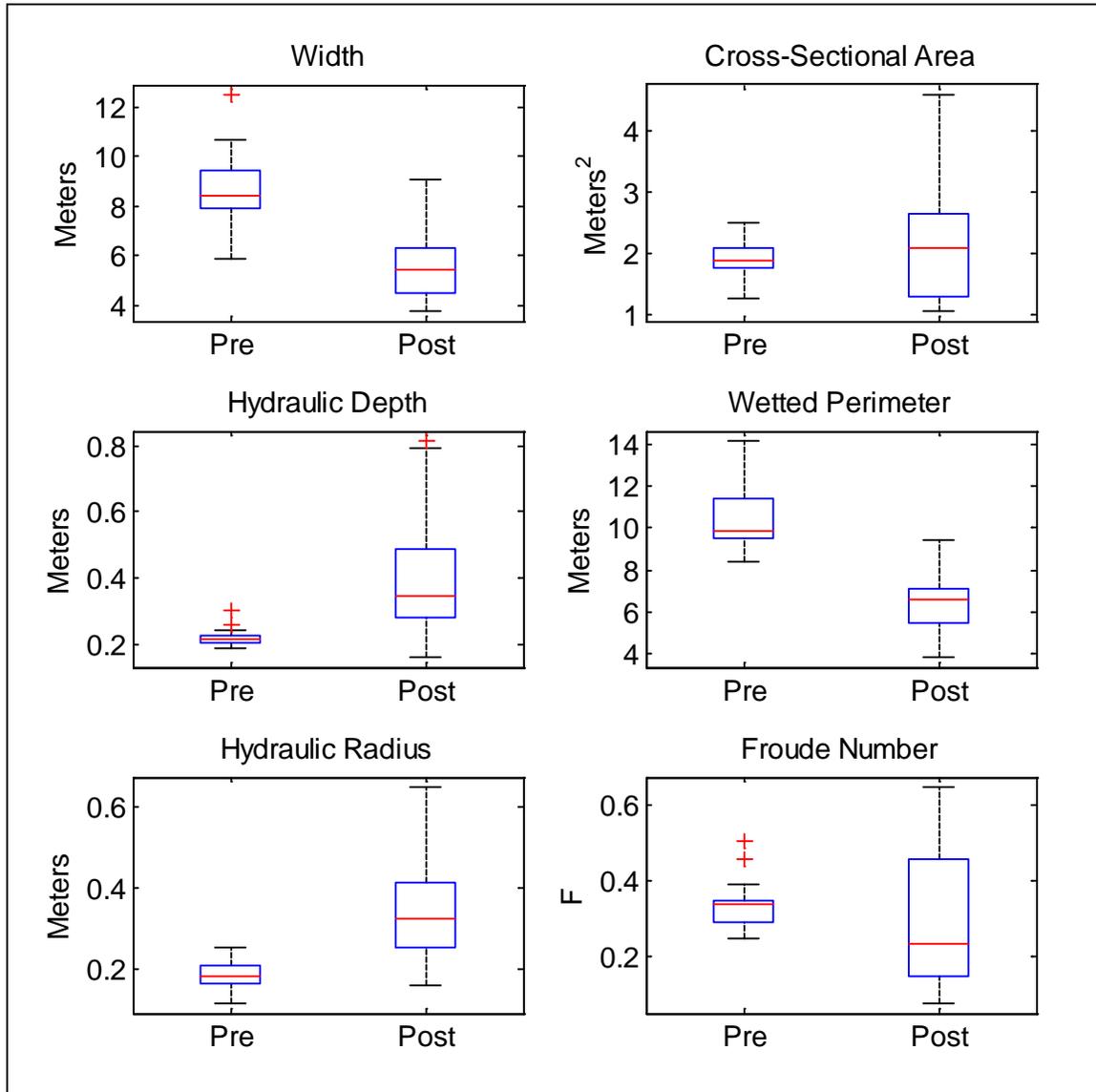


Figure 2.6: Characterization of cross-sectional channel geometry. Data was collected from pre- and post-realignment stream channels during summer baseflow conditions (n=27 pre-restoration cross-sectional depth profiles and 27 post-restoration cross-sectional depth profiles).

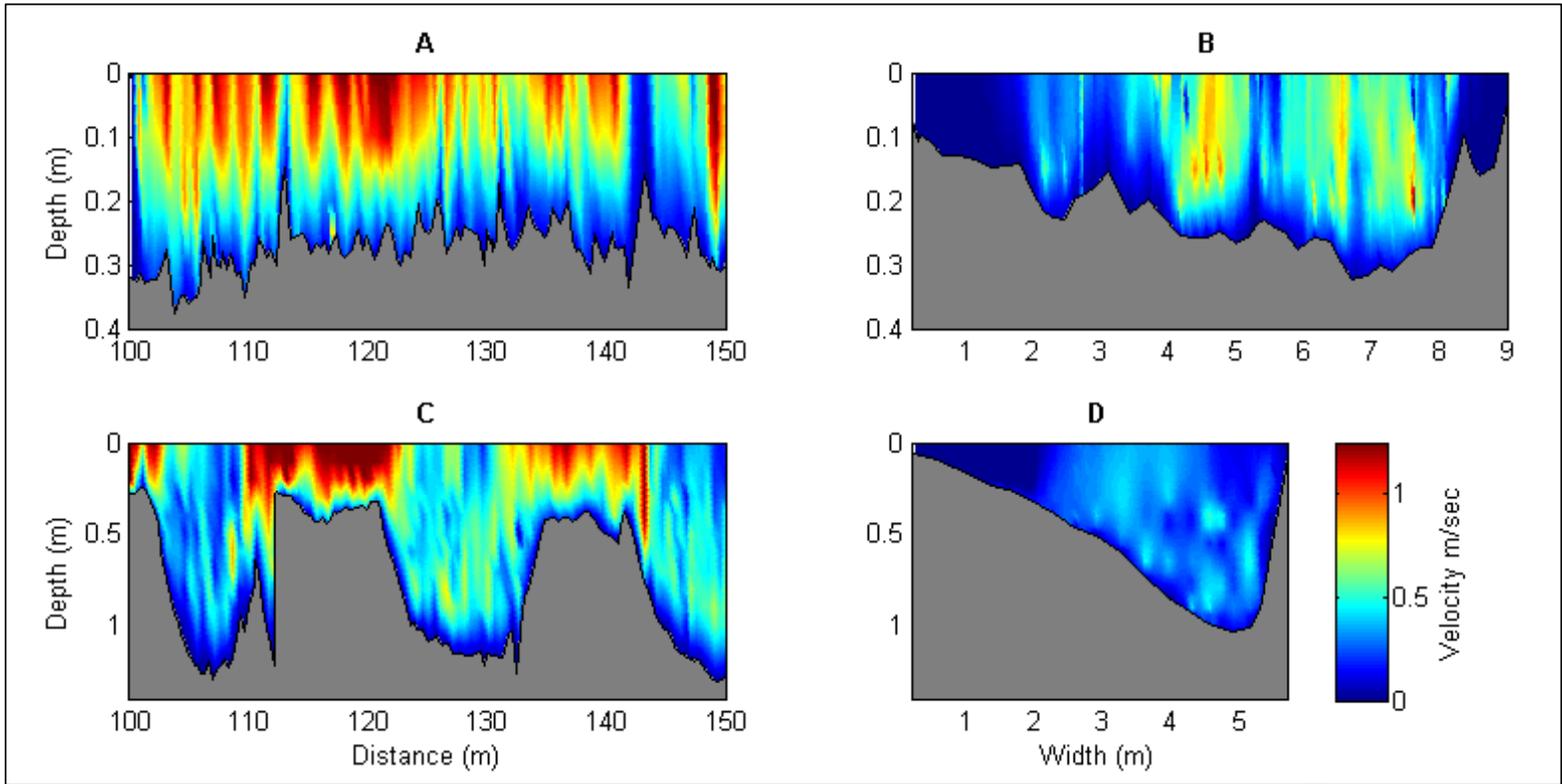


Figure 2.7: Pre-realignment velocity and depth profiles collected (A) along the channel thalweg and (B) from a representative cross-section. Post-realignment velocity and depth profiles collected (C) along the channel thalweg and (D) from a representative cross-section. Continuous surfaces were krigged with the spatial covariance structures defined by a best-fit spherical model for each data set's experimental semivariogram. Vertical axes are scaled for clarity.

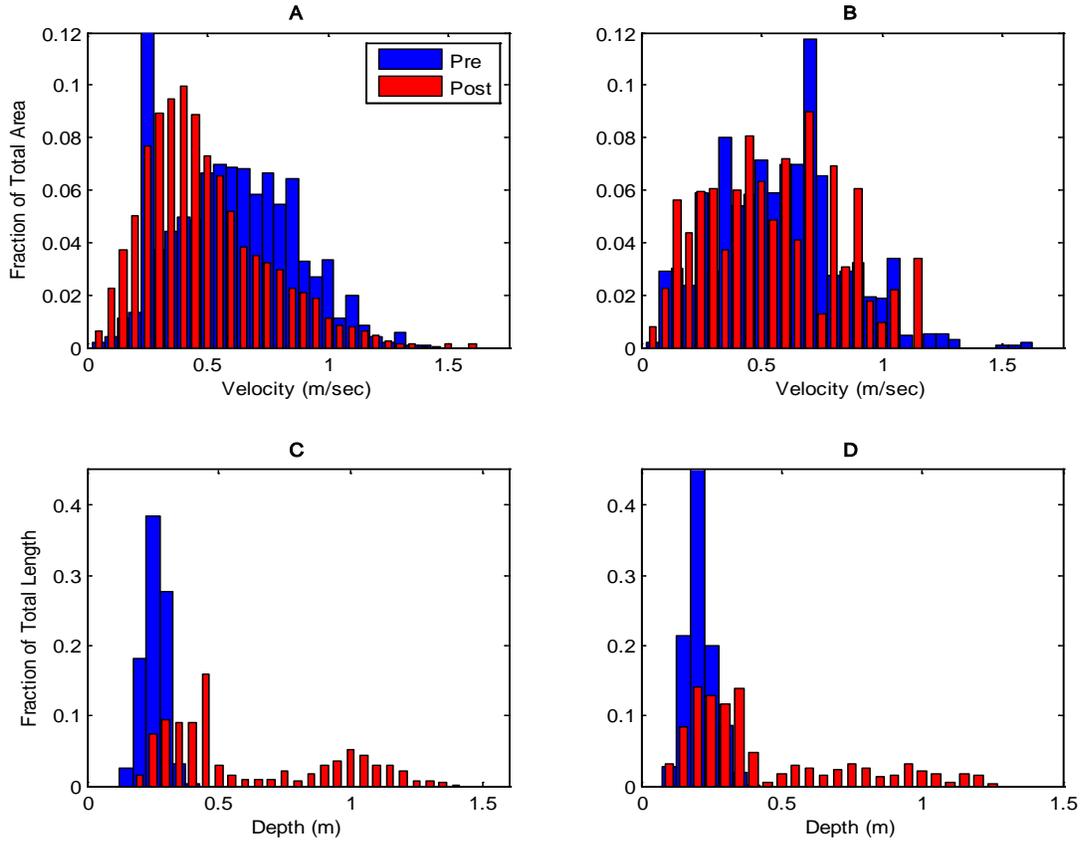


Figure 2.8: Frequency distributions of (A) longitudinal velocity, (B) cross-sectional velocity, (C) longitudinal depth, and (D) cross-sectional depth collected during summer baseflow conditions. Cross-sectional distributions represent aggregated data from 12 pre-realignment cross-sections and 12 post-realignment cross-sections.

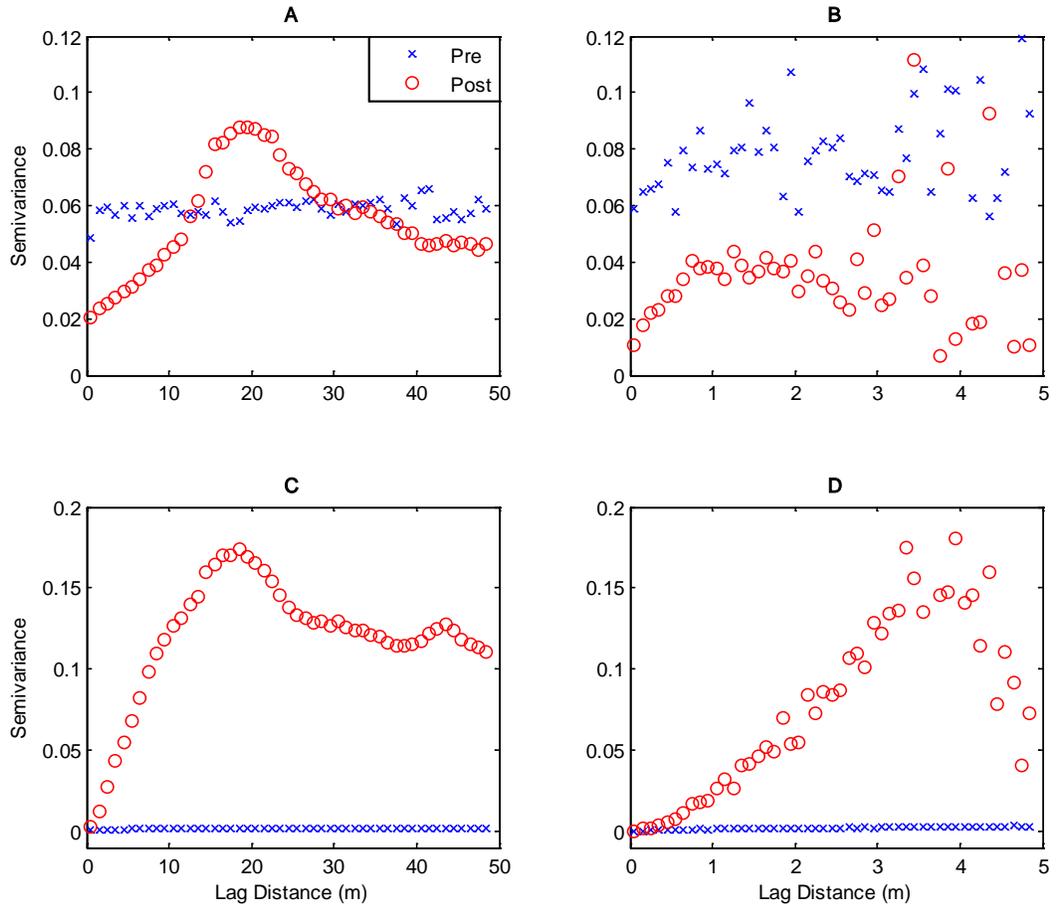


Figure 2.9: Experimental semivariograms of (A) longitudinal velocity, (B) cross-sectional velocity, (C) longitudinal depth, and (D) cross-sectional depth collected during summer baseflow conditions. Cross-sectional semivariograms represent aggregated data from 12 pre-realignment cross-sections and 12 post-realignment cross-sections.

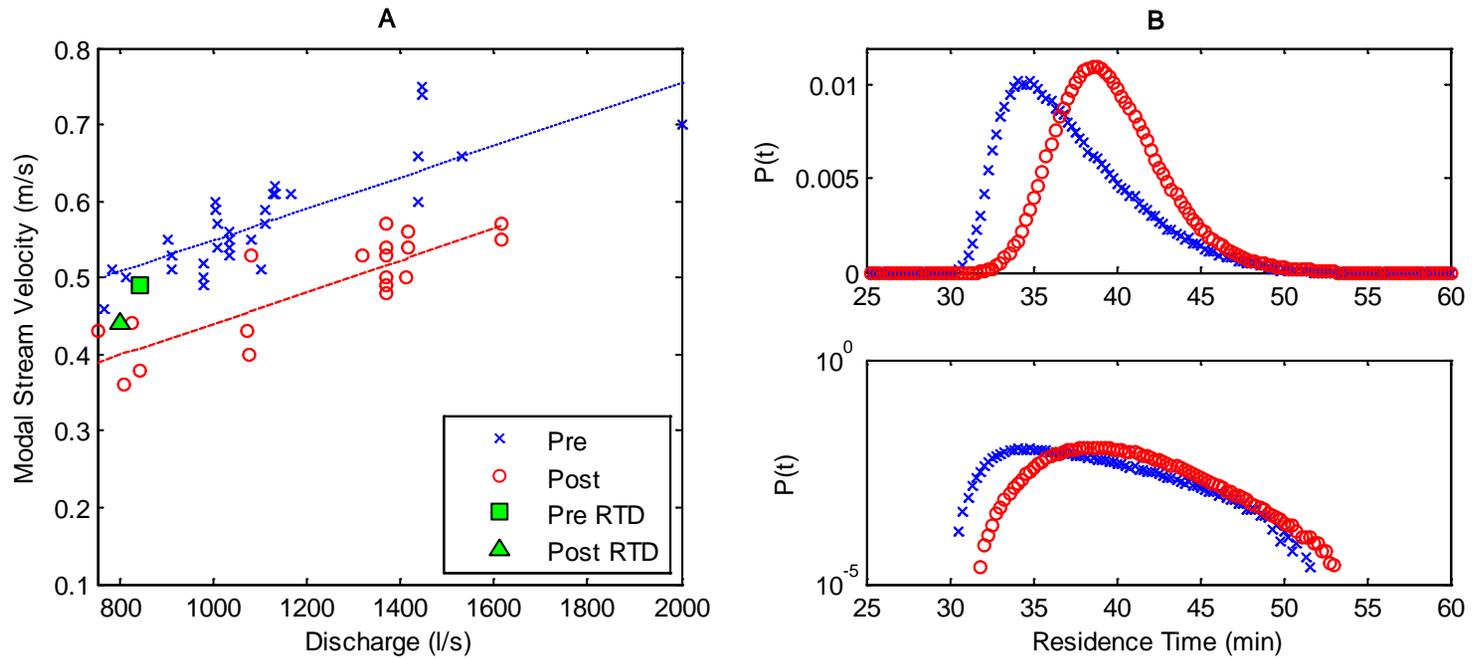


Figure 2.10: (A) Average solute transport time calculated for the length of the thalweg between the upstream solute injection point and the downstream observation point in pre- and post- channels across a range of flow states. (B) Pre- and post-realignment RTDs observed after injected solute traversed approximately 1000 m of thalweg length in a pre-realignment and a post-realignment channel segment during baseflow conditions. RTDs are displayed in normal and semi-log space.

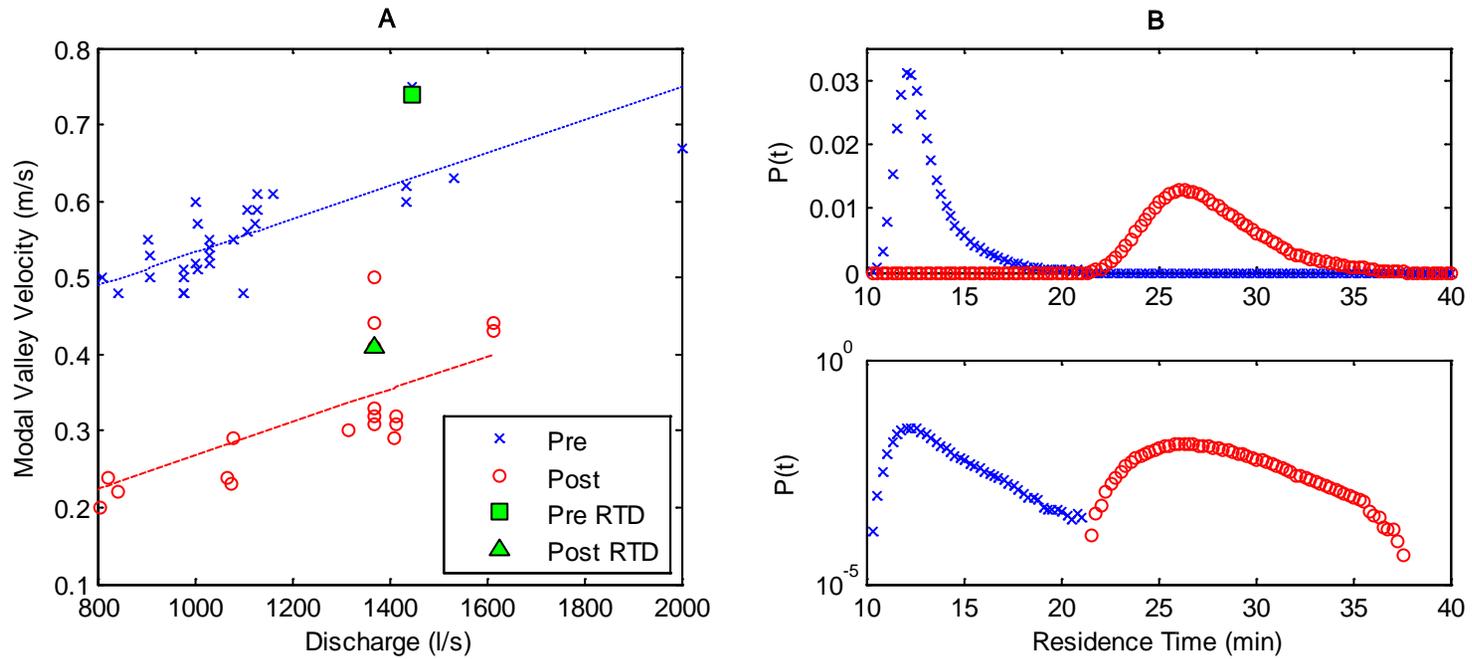


Figure 2.11: (A) Average solute transport times calculated for the straight-line distance between the upstream solute injection point and the downstream observation point in pre- and post- channels across a range of flow states. (B) Pre- and post-realignment RTDs observed after injected solute traversed approximately 500 m of valley length in a pre-realignment and a post-realignment channel segment. RTDs are displayed in normal and semi-log space.

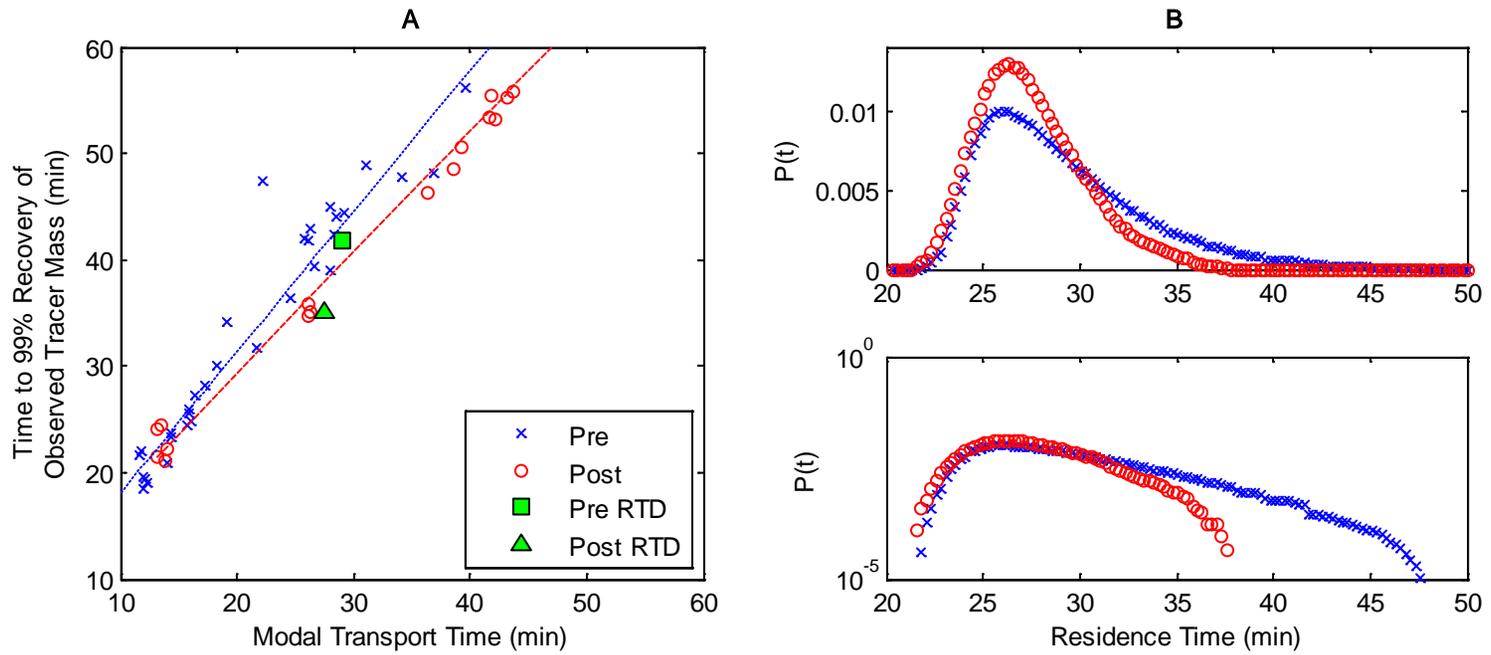


Figure 2.12: (A) Index of RTD tailing length and thickness as a function of average channel residence time in pre- and post-realignment channels. (B) RTDs observed after approximately 27 minutes of downstream transport in a pre-realignment and a post-realignment channel segment. RTDs are displayed in normal and semi-log space.

CHAPTER THREE

SUMMARY

The influence of reach-scale channel restoration activities on the behavior of many stream ecosystem processes remains poorly understood. This impedes the development of efficient and self-sustaining stream restoration strategies. Research that elucidates relationships between various restoration activities and those ecosystem processes that may dictate the condition and evolutionary trajectory of the ecosystem attributes considered by long-term project goals will be valuable to both restoration science and practice. This body of research was conducted on a stream targeted for and subjected to restoration. Our results provide insight into the way that channel engineering can alter the solute transport processes that may exert a significant influence on stream ecological processes.

This study combined hydrogeomorphic channel surveys with stream tracer experiments on Silver Bow Creek in southwestern Montana to answer the following questions:

- (1) How does channel realignment alter structural complexity across a range of spatial scales?
- (2) How does channel realignment impact solute transport dynamics for a given stream length, for a given valley length, and for a given channel residence time?

- (3) Are there correlations between shifts in hydraulic and topographic complexity and changes in solute transport behavior?

Integration of results from longitudinal and cross-sectional velocity and depth surveys and stream tracer experiments conducted on pre- and post-realignment stream channels suggested that:

- (1) Channel realignment on Silver Bow Creek increased channel unit scale topographic and velocity field complexity, but decreased complexity at the bedform scale.
- (2) Channel realignment decreased rates of downstream advection for a given stream length and a given valley length, and also decreased transient storage of water and solutes for a given in-channel residence time.
- (3) Channel designs that decrease bed roughness and alter channel geometry to increase the efficiency of flow may have the unintended consequence of decreasing the effects of transient storage.

The real-dollar, social, and aesthetic value gained from restoration activities through increased quality of use of a restored stream by wildlife, fishermen, agricultural users, and municipalities is inextricably tied to that stream's ecological, biogeochemical, and hydrologic functioning. As such, solute transport dynamics may be an important consideration for managers and practitioners engaged in functional restoration of stream

ecosystems. The movement of water and solutes between the stream channel, groundwater, and hyporheic storage zones are critical controls on a stream's ability to provide many ecosystem goods and services. Channel-realignment activities—like those on Silver Bow Creek—alter the structure of the streambed and will inevitably influence the fluvial characteristics that control solute transport dynamics at the reach and sub-reach scales.

Despite the critical role that solute transport may play in stream restoration strategies, the understanding of restoration's affect on reach-scale hydrologic behavior and subsequent effects on aquatic habitat quality is incomplete. This is likely a fruitful area for future research. Enhanced understanding of the influence of channel realignment on solute transport dynamics will lead to more efficient and cost effective restoration approaches, while likely providing new avenues for improving long-term habitat quality, water quality, ecological and economic value of restored rivers and streams.

REFERENCES CITED

- Anderson, J. K., et al. (2005), Patterns in stream longitudinal profiles and implications for hyporheic exchange flow at the H. J. Andrews Experimental Forest, Oregon, USA, *Hydrological Processes*, 19(15), 2931-2949.
- Arrigoni, A. S., et al. (2008), Buffered, lagged, or cooled? Disentangling hyporheic influences on temperature cycles in stream channels, *Water Resources Research*, 44, W09418, doi:10.1029/2007WR006480
- Baker, M. A., and P. Vervier (2004), Hydrological variability, organic matter supply and denitrification in the Garonne River ecosystem, *Freshwater Biology*, 49(2), 181-190.
- Bash, J. S., and C. M. Ryan (2002), Stream restoration and enhancement projects: is anyone monitoring?, *Environmental Management*, 29(6), 877-885.
- Baxter, C. V., and F. R. Hauer (2000), Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (*Salvelinus confluentus*), *Canadian Journal of Fisheries and Aquatic Sciences*, 57(7), 1470-1481.
- Beechie, T., and S. Bolton (1999), An approach to restoring salmonid habitat-forming processes in pacific northwest watersheds., *Fisheries* 24, 6-15.
- Bencala, K. E. (2005), Hyporheic exchange flows, edited, Encyclopedia of Hydrological Sciences.
- Bernhardt, E. S., et al. (2005), Ecology: Synthesizing US River Restoration Efforts, *Science*, 308(5722), 636-637.
- Beven, K., and J. Freer (2001), Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology, *Journal of Hydrology*, 249(1-4), 11-29.
- Boano, F., et al. (2007), Bedform-induced hyporheic exchange with unsteady flows, *Advances in Water Resources*, 30(1), 148-156.
- Boulton, A. J., et al. (1998), The functional significance of the hyporheic zone in streams and rivers, *Annual Review of Ecology and Systematics*, 29(1), 59-81.
- Boulton, A. J. (2007), Hyporheic rehabilitation in rivers: restoring vertical connectivity, *Freshwater Biology*, 52(4), 632-650.
- Brunke, M., and T. Gonser (1997), The ecological significance of exchange processes between rivers and groundwater, *Freshwater Biology*, 37(1), 1-33.

- Bukaveckas, P. A. (2007), Effects of Channel Restoration on Water Velocity, Transient Storage, and Nutrient Uptake in a Channelized Stream, *Environ. Sci. Technology*, 41(5), 1570-1576.
- Burt, T. P., and G. Pinay (2005), Linking hydrology and biogeochemistry in complex landscapes, *Progress in Physical Geography*, 29(3), 297-316.
- Camacho, L. A., and R. A. González (2008), Calibration and predictive ability analysis of longitudinal solute transport models in mountain streams, *Environmental Fluid Mechanics*, 8(5), 597-604.
- Cardenas, B. M. (2008a), The effect of river bend morphology on flow and timescales of surface water-groundwater exchange across pointbars, *Journal of Hydrology*, 362(1-2), 134-141.
- Cardenas, M. B., et al. (2004), Impact of heterogeneity, bed forms, and stream curvature on subchannel hyporheic exchange, *Water Resources Research*, 40(8), W08307, doi:10.1029/2004WR003008.
- Cardenas, M. B. (2008b), Surface water-groundwater interface geomorphology leads to scaling of residence times, *Geophys. Res. Letters*, 35, L08402, doi:10.1029/2008GL033753.
- Crispell, J. K., and T. A. Endreny (2009), Hyporheic exchange flow around constructed in-channel structures and implications for restoration design, *Hydrological Processes*, 23(8), 1158-1168.
- Duval, T. P., and A. R. Hill (2007), Influence of base flow stream bank seepage on riparian zone nitrogen biogeochemistry, *Biogeochemistry*, 85(2), 185-199.
- Ensign, S. H., and M. W. Doyle (2005), In-channel transient storage and associated nutrient retention: evidence from experimental manipulations, *Limnology and Oceanography*, 50(6), 1740-1751.
- Fellows, C. S., et al. (2001), Whole-stream metabolism in two montane streams: contribution of the hyporheic zone, *Limnology and Oceanography*, 46(3), 523-531.
- Fernald, A. G., et al. (2006), Water quality changes in hyporheic flow paths between a large gravel bed river and off-channel alcoves in Oregon, USA, *Regulated Rivers: Research and Management*, 22(10), 1111-1124.
- Findlay, S. (1995), Importance of Surface-Subsurface Exchange in Stream Ecosystems: The Hyporheic Zone, *Limnology and Oceanography*, 40(1), 159-164.

- Findlay, S., and W. V. Sobczak (1996), Variability in Removal of Dissolved Organic Carbon in Hyporheic Sediments, *Journal of the North American Benthological Society*, 15(1), 35-41.
- Federal Interagency Stream Corridor Restoration Working Group (FISRWG) (1998), Stream Corridor Restoration - Principles, Processes, and Practices. GPO Item No. 0120-A; SuDocs No. A 57.6/2:EN 3/PT.653. ISBN 0-934213-59-3.
- Gammons, C. H., et al. (2006), An overview of the mining history and geology of Butte, Montana, *Mine Water and the Environment*, 25(2), 70-75.
- Gooseff, M. N., et al. (2006), A modelling study of hyporheic exchange pattern and the sequence, size, and spacing of stream bedforms in mountain stream networks, Oregon, USA, *Hydrological Processes*, 20(11), 2443-2457.
- Gooseff, M. N., et al. (2007), Relating transient storage to channel complexity in streams of varying land use in Jackson Hole, Wyoming, *Water Resour. Res.*, 43, W01417, doi:10.1029/2005WR004626.
- Gooseff, M. N., et al. (2008), Comparison of in-channel mobile-immobile zone exchange during instantaneous and constant rate stream tracer additions: Implications for design and interpretation of non-conservative tracer experiments, *Journal of Hydrology*, 357(1-2), 112-124.
- Gordon, R. L. (1996), Acoustic Doppler Current Profiler Principles of Operation, a Practical Primer, RD Instruments, San Diego, California.
- Grimm, N. B., et al. (2005), Nutrient retention and transformation in urban streams, *Journal of the North American Benthological Society*, 24(3), 626-642.
- Haggerty, R., et al. (2002), Power-law residence time distribution in the hyporheic zone of a 2nd-order mountain stream, *Geophys. Res. Lett.*, 29(13), 1640, doi:10.1029/2002GL014743.
- Harvey, J. W., and K. E. Bencala (1993), The effect of streambed topography on surface-subsurface water exchange in mountain catchments, *Water Resources Research*, 29(1), 89-98.
- Harvey, J. W., et al. (1996), Evaluating the reliability of the stream tracer approach to characterize stream-subsurface water exchange, *Water Resour. Res.*, 32(8), 2441-2451.
- Hester, E. T., and M. N. Gooseff (2010), Moving Beyond the Banks: Hyporheic Restoration Is Fundamental to Restoring Ecological Services and Functions of Streams, *Environ. Sci. Technol.*, 44(5), 1521-1525.

- Hill, A. R., et al. (1998), Hyporheic zone hydrology and nitrogen dynamics in relation to the streambed topography of a N-rich stream, *Biogeochemistry*, 42(3), 285-310.
- Hinkle, S. R., et al. (2001), Linking hyporheic flow and nitrogen cycling near the Willamette River—a large river in Oregon, USA, *Journal of Hydrology*, 244(3-4), 157-180.
- Holmes, R. M., et al. (1996), Denitrification in a nitrogen-limited stream ecosystem, *Biogeochemistry*, 33(2), 125-146.
- Jones, J. B., and P. J. Mulholland (Eds.) (2000), *Streams and Ground Waters*, Academic Press, San Diego, California.
- Kasahara, T., and S. M. Wondzell (2003), Geomorphic controls on hyporheic exchange flow in mountain streams, *Water Resources Research*, 39(1), 1005.
- Kasahara, T., and A. R. Hill (2006), Effects of riffle-step restoration on hyporheic zone chemistry in N-rich lowland streams, *Canadian Journal of Fisheries and Aquatic Sciences*, 63(1), 120-133.
- Knust, A. E., and J. J. Warwick (2009), Using a fluctuating tracer to estimate hyporheic exchange in restored and unrestored reaches of the Truckee River, Nevada, USA, *Hydrological Processes*, 23(8), 1119-1130.
- Kondolf, G. M., et al. (2006), Process-based ecological river restoration: visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages, *Ecology and Society*, 11(2), 5.
- Legleiter, C. J., et al. (2007), Geostatistical analysis of the effects of stage and roughness on reach-scale spatial patterns of velocity and turbulence intensity, *Geomorphology*, 83(3-4), 322-345.
- McClain, M. E., et al. (2003), Biogeochemical Hot Spots and Hot Moments at the Interface of Terrestrial and Aquatic Ecosystems, *Ecosystems*, 6(4), 301-312.
- MDOJ (2008), Funded Restoration Projects, edited, Montana Department of Justice, Helena, MT.
- MNRDP, (2005), Silver Bow Creek Watershed Restoration Plan (Final), Montana Department of Justice, Helena, MT.
- Mulholland, P. J., and D. L. DeAngelis (2000), Surface-subsurface exchange and nutrient spiraling, in *Streams and Ground Waters*, edited by J. B. Jones and P. J. Mulholland, pp. 149–166, Academic Press, San Diego, California.

- Mutz, M., et al. (2007), Effect of instream wood on vertical water flux in low-energy sand bed flume experiments, *Water Resources Research*, 43(10), W10424, doi:10.1029/2006WR005676.
- Packman, A. I., and M. Salehin (2003), Relative roles of stream flow and sedimentary conditions in controlling hyporheic exchange, *Hydrobiologia*, 494(1), 291-297.
- Packman, A. I., et al. (2004), Hyporheic Exchange with Gravel Beds: Basic Hydrodynamic Interactions and Bedform-Induced Advective Flows, *Journal of Hydraulic Engineering*, 130, 647-656.
- Palmer, M. A., et al. (2005), Standards for ecologically successful river restoration, *Journal of Applied Ecology*, 42(2), 208-217.
- Payn, R. A., et al. (2008), Comparison of instantaneous and constant-rate stream tracer experiments through non-parametric analysis of residence time distributions, *Water Resources Research*, 44(6), 44-53.
- Pioneer Technical Services, I., and I. Applied Geomorphology (2008), Subarea 4 Channel Stability Analysis and Conceptual Design Report, Montana Department of Environmental Quality, Mine Waste Cleanup Bureau, Helena, MT.
- Poole, G. C., and C. H. Berman (2001), An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-Caused Thermal Degradation, *Environmental Management*, 27(6), 787-802.
- Poole, G. C., et al. (2006), Multiscale geomorphic drivers of groundwater flow paths: subsurface hydrologic dynamics and hyporheic habitat diversity, *Journal of the North American Benthological Society*, 25(2), 288-303.
- Poole, G. C., et al. (2008), Hydrologic spiraling: the role of multiple interactive flow paths in stream ecosystems, *River Research and Applications*, 24(7), 1018-1031.
- Salehin, M., et al. (2003), Comparison of transient storage in vegetated and unvegetated reaches of a small agricultural stream in Sweden: seasonal variation and anthropogenic manipulation, *Advances in Water Resources*, 26(9), 951-964.
- Salehin, M., et al. (2004), Hyporheic exchange with heterogeneous streambeds: laboratory experiments and modeling, *Water Resources Research*, 40(11), W11504, doi:10.1029/2003WR002567.
- Shields, F. D., et al. (2003), Use of acoustic doppler current profilers to describe velocity distributions at the reach scale, *Journal of the American Water Resources Association*, 39(6), 1397-1408.

- Sophocleous, M. (2002), Interactions between groundwater and surface water: the state of the science, *Hydrogeology Journal*, 10(1), 52-67.
- Storey, R. G., et al. (2004), Nitrogen processing in the hyporheic zone of a pastoral stream, *Biogeochemistry*, 69(3), 285-313.
- Tague, C., et al. (2008), The Effect of Geomorphic Channel Restoration on Streamflow and Groundwater in a Snowmelt Dominated Watershed, *Water Resour. Res.* 44, W10415, doi:10.1029/2007WR006418.
- Wagener, T., et al. (2002), Dynamic identifiability analysis of the transient storage model for solute transport in rivers, *Journal of Hydroinformatics*, 4(3), 199-211.
- Woessner, W. W. (2000), Stream and Fluvial Plain Ground Water Interactions: Rescaling Hydrogeologic Thought, *Ground Water*, 38(3), 423-429.
- Wondzell, S. M., and F. J. Swanson (1999), Floods, channel change, and the hyporheic zone, *Water Resources Research*, 35(2), 555-567.
- Wondzell, S. M. (2006), Effect of morphology and discharge on hyporheic exchange flows in two small streams in the Cascade Mountains of Oregon, USA, *Hydrological Processes*, 20(2), 267-287.
- Wörman, A., et al. (2002), Effect of flow-induced exchange in hyporheic zones on longitudinal transport of solutes in streams and rivers, *Water Resources Research*, 38(1), 2.1-15.
- Wyatt, K. H., et al. (2008), Benthic algal response to hyporheic-surface water exchange in an alluvial river, *Hydrobiologia*, 607(1), 151-161.