Appraisal of suspended sediment sources and fluxes in Marsh Creek, SE Idaho: complexities revealed by high-resolution spatial and temporal data

By

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Abstract

Excessive suspended sediment loading of streams is one of the most common causes for ecological and recreational stream impairment in the US (USEPA, 2016). Identifying the primary sources of sediment, which may be a function of a suite of geomorphic characteristics specific to a watershed or human-induced disturbances, is an important first step in the effective mitigation of sediment sources through conservation practices or retention techniques. This study first sets out to understand sources of sediment in an impaired watershed, Marsh Creek in southeast Idaho. It takes a novel approach, using a dense longitudinal array of water quality sensors collecting continuous data, coupled with conventional approaches of sediment fingerprinting and event-scale flow and sediment load analyses. Bank erosion is determined to be the primary sediment source based on multiple lines of evidence: a generally accumulating flux profile, minor tributary sediment inputs, stable isotope fingerprinting, and moderate event-scale first-flush patterns. Interestingly, a complicated pattern of sediment production, storage and remobilization emerges during this study. When compared to a longitudinal census of bank instabilities, there is poor correlation between areas that appear to be actively eroding and local, instream sediment fluxes. This has important implications on the interpretation of sediment flux data from continuous stations as well as the residence time of fine sediment in riverine systems.

Chapter 1. Introduction

1.1.1. Problem Statement

In agricultural settings, sources of suspended sediment are commonly non-point sources with broad areal distributions within the landscape (USEPA, 2016). Given the diffusive nature of these sources, mitigating them can be a challenge. Most suspended sediment monitoring studies employ one or a few sites within a basin to characterize the magnitude and timing of sediment flux. The use of multiple longitudinal sensors measuring turbidity in sequence is novel and is employed in this study in order to characterize sources of sediment in an impaired watershed. Additionally, this study employs a kayak survey to determine potential sources of sediment. The natural laboratory for this study is Marsh Creek, a turbidity-impaired stream in southeast Idaho.

1.1.2. Summary and Recommendations in Appendix A

For those interested in a concise summary of the results, conclusions, and sediment mitigation prescriptions for Marsh Creek, please refer ahead to **Appendix A: Recommendations for Improving Water Quality**. Please also refer to the proceeding figures in Appendix B, especially Figure B.1., where this figure provides information on the amount and continuity of data used in this project.

1.2. Sediment Dynamics Background

1.2.1. Suspended Sediment Background

From a physical perspective, the transport modes of sediment in rivers can be broken up into two fractions: (1) *bed load* and (2) *suspended load*. Important to the discussion of the relationship between hydrodynamics and transport mechanisms is the

Rouse number. The Rouse number (P) is a non-dimensional ratio describing competing forces of the *downward* particle settling velocity and *upward* turbulent shear forces depicted in Equation 1.1 below,

$$P = \frac{w_s}{ku_*} \qquad \text{Equation 1.1}$$

where w_s is the settling velocity (in m/s), k = 0.4 (Von Karman's constant), and u_* is the shear velocity (in m/s). Bed load has a P > 2.5 and thus represents the coarser fraction (gravels to cobbles) of sediment that persistently contacts the bed and moves through processes such as rolling, saltation, and sliding. Suspended load is the finer portion (clays to sands) that undergoes various degrees of suspension and mixing in the turbulence of the flow. Load that undergoes approximately 50% suspension during transport has a 1.2 < P < 2.5 and 100% suspension a 0.8 < P < 1.2. When P approaches or is less than 1, particles are said to be positively or neutrally buoyant and the likelihood that these particles will interact with the bed during transport is diminished. Notice that these ratios can be greater than 1, indicating that suspended load can undergo transient storage on the bed, especially in coarser fractions or when turbulent energy is diminished in the channel (Vanoni, 1975). The finest endmember of suspended load is referred to as the *wash load*, which maintains a P > 0.8 and is therefore positively buoyant and concentrated closer to the surface of the flow (Shah-Fairbank *et al.*, 2011). Therefore, this finest fraction of particles seldom undergoes storage and quickly transmits through the system.

Suspended sediment can be broken up into two general classes: non-cohesive and cohesive suspended sediments. Non-cohesive suspended sediments are the coarser fractions larger than 0.0062 mm in diameter which are not influenced by electrostatic interparticle forces (Kuhnle, 2013). Cohesive suspended sediments are those smaller than 0.004 mm, with particle sizes composed of clays and silts where electrostatic interparticle forces are greater than gravity forces. Intermediate silts between these two grain sizes (0.0062 – 0.004) are still considered to be strongly influenced by interparticle forces and are considered to belong to the cohesive realm (Kuhnle, 2013). It is noted that much of the suspended sediment that is observed and measured in this study are silt-sized and finer, therefore much of this sediment is considered to be cohesive suspended (Kuhnle, 2013). Therefore, when referring to suspended sediments, it is implicit that the bulk behavior of these sediments are cohesive, however, this is not directly evaluated in this study. More information on challenges of doing so are discussed below.

Suspended sediments, herein referred to as SS, are not usually singular mineral particles, especially from a hydrodynamic standpoint. Through the electrochemical properties of fine grain sizes, flocculation of silts and clays occurs to from aggregates known as flocs that maintain large and permeable pore networks. These pore networks house microbiota that produce extracellular structural material and allow for the constant advection of water in and out of the network. This means that these flocs are constantly communicating chemically and physically with the flow environment (e.g., Droppo, 2001, 2004). Given their large pore volumes composed primarily of trapped water, the effective density of these particles approaches that of water. This decreased floc density results in settling velocities that are much lower than expected Stokes' settling velocities computed from singular grain sizes extracted from SS (Droppo, 2004). Given the sum of these effects on *in situ* hydrodynamic behavior, it has been well-documented that typical grain size analyses will erase these complexities and cannot alone account for the settling behavior of SS particles (Williams *et al.*, 2008).

1.2.2. Supply and Capacity Behavior of Suspended Sediments

SS, both in terms of bed-interacting coarser suspended load and wash load, maintain nonlinear relationships with stream discharge. This is attributed to the fact that streams generally maintain transport capacities much greater than those required to transport fine sediment (Walling and Collins, 2016). The primary controlling factor of SS flux in many cases is the supply of SS to the channel network. This results in time-dependent nonlinear lag relationships between peak flow and peak sediment concentration, termed *hysteresis*, which can result in order of magnitude differences in suspended concentrations at the same flow (e.g., Hickin, 2004; Bača, 2008; Oeurng and Sauvage, 2010). Inferences of SS delivery mechanisms made between the types of hysteresis (clockwise, Figure 1.1a. vs. counter-clockwise loops, Figure 1.1b). In a clockwise loop, the sediment concentration peak precedes the discharge peak. This indicates local channel supply exhaustion prior the peak of a hydrologic event. The opposite relationship (counter-clockwise) may indicate upland-derived sources due to a longer sediment transit time (Oeurng and Sauvage, 2010; Gellis, 2013). It has also been shown in many systems that the magnitude and type of hysteretic behavior may be well-correlated with seasonality and time since last hydrologic forcing, where lower flow periods may be times of channel-network storage and higher flow periods may flush this supply through the network (Hickin, 2004; Gellis, 2013; Walling and Collins, 2016; Kamarinas *et al.*, 2016).

Additional non-linear legacy effects may also exist that can modulate the timing and magnitude of SS transport in a drainage. Though this list is not completely exhaustive, these include interrelated spatial variables such as the degree of disturbance, land use type, hillslope-channel connectivity, permeability of soils, riparian corridor continuity and basin geology (Walling, 1983; de Vente *et al.*, 2007; Gellis, 2013). Temporal variables which impact SS supply through cause-and-effect sequences include antecedent soil moisture conditions, recent high flow events, and timing of land cover disturbance related to cultivation (Kamarinas *et al.*, 2016).

1.2.3. Ecological Impacts of Suspended Sediment Loads

Given their high geochemical affinity, SS are primary vectors of nutrients, pollutants, and pathogens, which bind to the surface of the particles or flocs (Edwards and Withers, 2008). The timing and magnitude of SS routing modulates aquatic biodiversity within channel systems (Palmer *et al.*, 2000). Chronic excessive SS loading in streams is a leading cause of ecological impairment throughout watersheds in the U.S. (USEPA, 2016). High SS concentrations and associated turbidity have detrimental ecological impacts **–** such as the reduction of light availability in the water column, which fuels the primary productivity of aquatic ecosystem (Palmer *et al.*, 2000). Excessive turbidity has also been shown to negatively affect the growth of salmonids (Sigler *et al.*, 1984; Sweka and Hartman, 2000).

1.3. Measurement Techniques and Management of Suspended Sediment

1.3.1. Suspended Sediment Monitoring Techniques

Measuring SS involves taking physical samples, usually depth and width integrated with an isokinetic sampler and quantifying both the total suspended solids and mineral sediment concentration through combustion of the sample. In many traditional studies, once a sufficient number of sediment concentrations are obtained for all flow regimes, these values are correlated to discharge using a linear or power law regression (Hickin, 2004). This approach of estimating sediment concentrations using flow regime as a proxy has been largely discredited as being too inaccurate (Loperfido *et al.*, 2010). Given the inherent nonlinearities discussed in the previous sections above that result, flow can be a poor estimate for sediment concentrations and this warrants the collection of continuous data (Horowitz, 2003; Jones *et al.*, 2012).

Measuring SS transport rates generally involves taking advantage of sensors, which measure the transmissivity and scattering of either light or acoustic waves in a water column as a surrogate for SS concentrations (e.g., Gippel, 1995; Lewis, 1996; Voichick and Topping, 2014; Czuba *et al.*, 2015). Many contemporary studies use cost-effective sensors that measure *turbidity*, which is the optical clarity of a water body and is usually found to be well-correlated with SS concentrations (Gippel, 1995; Lewis, 1996; Wren *et al.*, 2000; Minella *et al.*, 2008; Rasmussen *et al.*, 2011). A very common form of turbidity measurement known as *nephelometry*, employed in this study, emits infrared light and measures the amount of particle-backscattered light.

1.3.2. Sediment Fingerprinting and Tracing

Given that most SS sources are diffusive and non-point in nature, it is difficult to pinpoint their areal distribution and geomorphic position using traditional monitoring techniques. Significant portions of sediment in transit may be remobilized from the bed. The use of sediment fingerprinting for source type and area apportionment has recently been implemented in many studies in the last couple decades (Walling and Collins, 2016). Sediment fingerprinting involves the comparison of physical and/or chemical characteristics of a sediment to soil sources on the landscape, in order to understand relative contributions of sources to a sediment budget (Walling, 2005; Walling, 2013; Collins *et al.*, 2016). Important to this analysis is the assumption that sediments are a composite of these sources and that the tracer properties of the particles are conservative they are delivered through the drainage. Examples of fingerprints include mineral magnetic properties, trace element compositions, radiogenic isotope concentrations, and spectroscopic characteristics (Papanicolaou *et al.*, 2003; Walling, 2005; Mukundan *et al.*, 2010; Collins *et al.*, 2016).

Sediment fingerprinting may also be used as a tracing technique to understand the magnitude and timescales of catchment-scale sediment redistribution by utilizing particle-bound concentrations of manmade fallout radionuclides (^{210}Pb-ex, ^{137}Cs, ^{7}Be) and cosmogenic radionuclides of sediments (Walling and Collins, 2016). To overcome the tendency that different stocks of sediment (distal versus proximal) are transported on the rising limb versus the falling limb of a hydrograph based on variable hydrologic connectivity, and differing transit times, these samples are commonly taken as long time-integrated samples (Phillips *et al.*, 2000). Additionally, bed samples – if representative of the transport conditions of interest, may also act as a time-integrated sample of sediment flux (Walling, 2013). The use of autosamplers or repeated sampling can also be implemented to document this variability.

1.3.3. Management of Fine Sediment Sources

Conservation and sediment mitigation practices are expensive (Belmont *et al.*, 2011; Walling and Collins, 2016). In the Portneuf watershed, where this study takes place, past TMDLs have estimated that conservation practices costing $20 million are required for the reduction of sediment loads to recreationally and ecologically beneficial levels (IDEQ, 2010). Given the high stakes at play, effective returns on investment in the management of fine sediment sources requires a sound understanding of the spatial distribution and linkages between these sources and the channel network.

1.4. Study Area, Historical Context, and Motivation

This section will introduce the study design, methods, and research questions which are conveyed in Chapters 2 and 3.

1.4.1. Geomorphic Setting

Marsh Creek (MC), the largest tributary in the Portneuf River subbasin, drains ~1100 km^2 of land in SE Idaho. The drainage is located in a N-S trending basin ranging in elevations from 1380 to 2700 meters. Runoff in MC is primarily dominated by the snowmelt derived from higher elevations, with the largest historical events being driven by rain-on-snow events. Flow in MC is generally from south to north.

MC exists as an underfit channel in a wide alluvial valley flanked by abandoned alluvial surfaces on the east and west, with a basalt plateau acting as the western divide in the downstream-most northern reaches (Thackray *et al.*, 2011). Work done mapping Quaternary deposits longitudinally along MC reveal significant paludal deposits distal to fan surfaces on the east and west side of MC dating back to the middle Pleistocene (Thackray *et al.*, 2011). Therefore, it is inferred that the basin has maintained poor drainage for a significant period of time dating back into the Pleistocene, likely due to Quaternary motion along faults bounding the basin (Thackray *et al.*, 2011). This poor drainage coupled with loess deposits that cap the surrounding benches, has left a considerable supply of fine sediment in the modern MC system.

MC is a highly land use-impacted watershed, with much of the alluvial valley and portions of the foothills being utilized for both agriculture and grazing. Given this demand, there is significant allocation of surface water in the MC watershed. This manifests itself as very low summer baseflows and wholesale disconnection of tributaries with the channel. To assist in the delivery of surface water to benches on the east side of MC, a transbasin diversion known as the Marsh Valley Canal, was built in the early 20th century (PMVCC, 2017). This diversion delivers water from the middle Portneuf River into the MC watershed, where a potentially significant amount of water that is not lost to evapotranspiration either runs off or infiltrates into groundwater.

1.4.2. Historical Accounts of Water Quality and Motivation

Marsh Creek (MC) has been historically identified as a hotspot of poor water quality in relation to its high SS output to the lower Portneuf River. Adjacent floodplain and significant proximal uplands are utilized for dryland farming, irrigated agriculture, and grazing. Evidence from past reports produced by cooperative watershed partnerships have indicated multiple different sources of fine sediment delivery (McSorley, 1977). This includes coarse resolution data and anecdotal descriptions of tributaries delivering disproportionately high amounts of fine sediment from lateral upland sources during spring runoff and intense rainstorms. Most recently, an Idaho Association of Soil Conservation Districts (IASCD, 2013) report indicated a landslide-dammed, anthropogenically-modified shallow lake feature, termed the ‘Rat Pond’, as a significant source of fine sediment using quasi-monthly measurements of discharge and sediment concentration. However, the sampling site used to track the amount of sediment at the inlet of the Rat Pond is located ~3.4 channel kilometers upstream of the true inlet. While there is no perennial tributary junction along this upstream stretch, bank erosion and intermittent surface runoff could be consistently supplying fine sediment to the channel above the Rat Pond. Therefore, this data may not represent a true bracketing of sediment flux through the Rat Pond. Additionally, in their analysis, they plotted their average load data on a logarithmic scale (Figure 1.2a). This gave the visual appearance, in logarithmic space, that the Rat Pond was the largest conveyor of fine sediment in Marsh Creek. Back-transforming this data reveals that this is an optical illusion (Figure 1.2b). Even if one accepts the premise that these samples represent a true accounting of sediment loads of the Rat Pond alone, these data show that the Rat Pond contributes only ~18% to the total budget of MC at the most. Therefore, the idea that the Rat Pond is the primary driver of excessive sediment loads in MC is unlikely. Given this, no definitive data on fine sediment sources exist for MC; yet, effective management of these sources requires this understanding.

A study done by Cusack using a continuous dataset over four years at a monitoring station in Marsh Creek close to the confluence occupied during this study (Site 2, see Chapter 2 Figure 2.1) revealed interesting and complex transport dynamics using a comparison of high resolution sediment concentration to discharge data (2016). Most strikingly, this analysis revealed the persistence of a diel signal of elevated turbidity that peaked nocturnally. This signal, strongest in the summer and fall, was observed to occur independent of more complex daily variations in discharge. It was argued that these variations could be explained through bioturbation. Specifically, nocturnal feeding of aquatic biota (i.e., carp, crayfish) which acted to stir up sediment on the bed, resulting in the nighttime peaks and daytime troughs. Additionally, Cusack analyzed hysteretic patterns of flow versus sediment concentration and found that no single type of hysteresis (clockwise, counter-clockwise, random) dominated in Marsh Creek (2016). The author argued that this could be indicative of complex sourcing of sediment from both distal and proximal sources but was uncertain about using such inferences from a single point in the basin. It was ultimately determined in this study that an understanding of sourcing could be more confidently achieved using a longitudinal array of sensors to understand the spatial extent and magnitude of erosion and fine sediment delivery along the mainstem.

Chapter 1 Figures

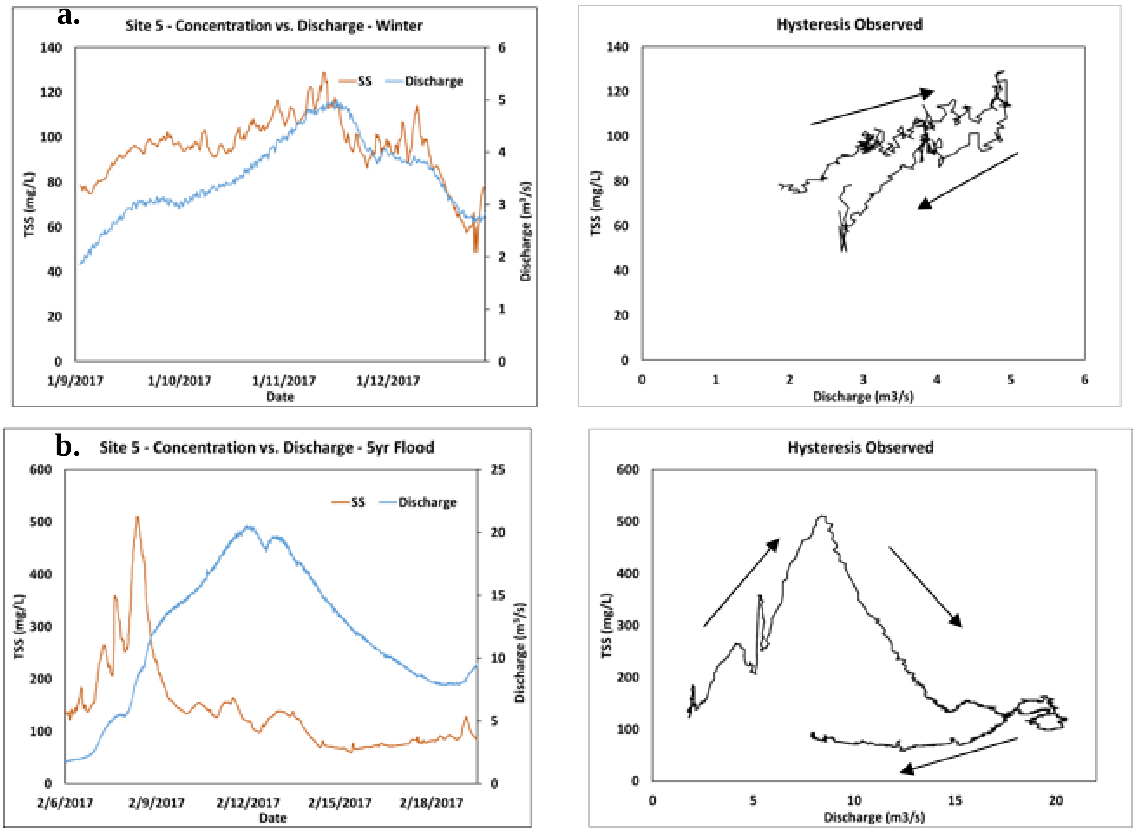

Figure 1.1. Types of Hysteresis Observed in Marsh Creek a. Example of counter-clockwise hysteresis where the discharge peak precedes the sediment concentration peak. Loop formed in discharge-SS space forms a counter-clockwise loop. b. Example of a strong clockwise loop where the sediment concentration peak precedes the discharge peak. Loop formed in discharge-SS space forms a clockwise loop.

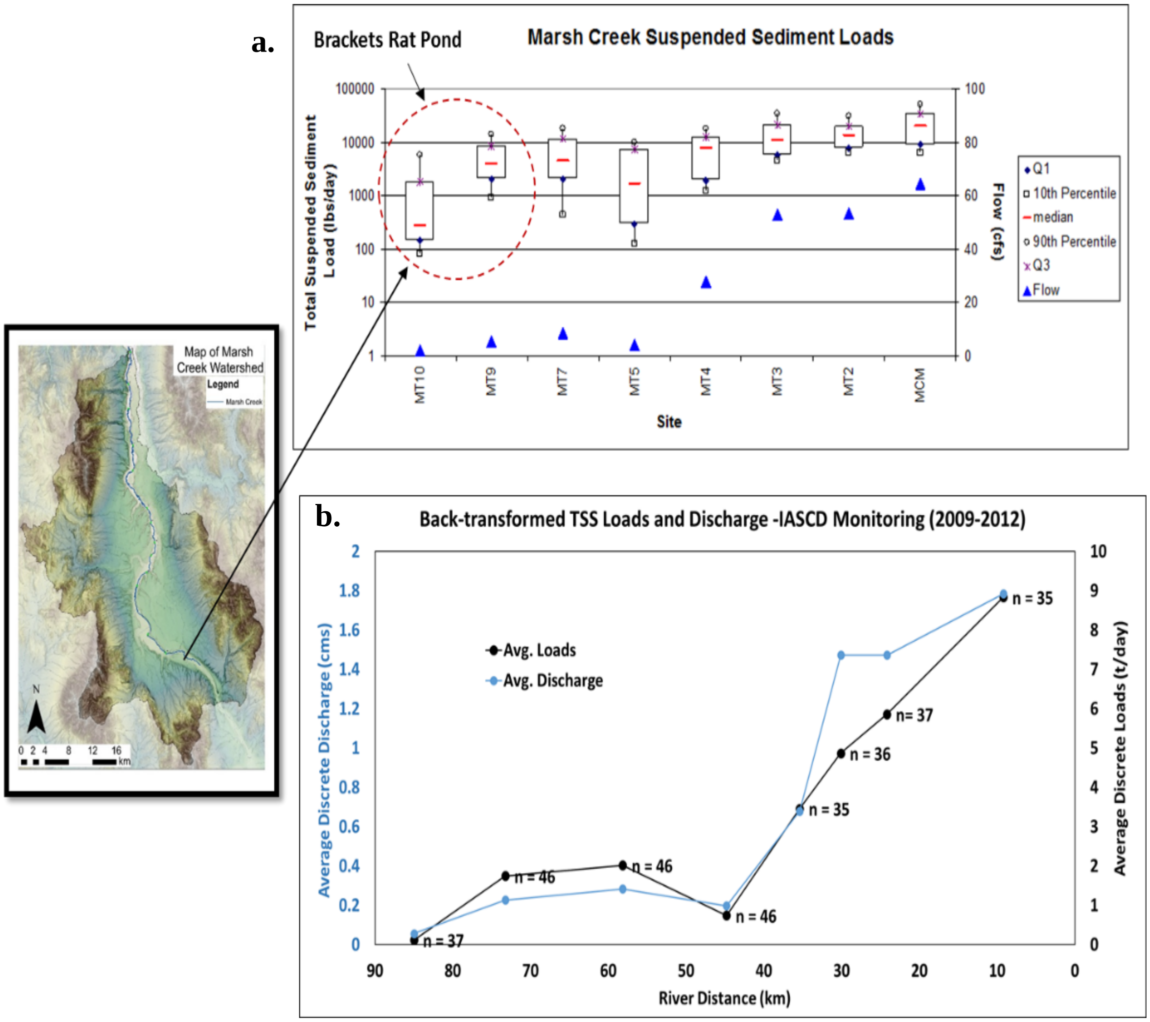

Figure 1.2. IASCD Flux and Discharge Data. a. Raw IASCD data of average longitudinal sediment flux and flow in MC from 2009-2013 with sediment flux data plotted on a logarithmic scale. Based on the logarithmic scale, it appears as though the Rat Pond is a major source of SS on MC. An inset map shows the approximate location of the Rat Pond. b. Data back-transformed. Note that the relative importance of the Rat Pond drops. Significant sediment recruitment occurs downstream in the lower stations.

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Chapter 2: Primary bank sourcing revealed through high resolution load data and stable isotope fingerprinting

Abstract

A dense longitudinal array of water quality sensors were used to characterize sediment sources in Marsh Creek, an impaired and intensively-managed stream in southeast Idaho. Additionally, sediment fingerprinting was performed using stable isotope data of sources versus sediment. Seasonal and annual downstream accumulating trends in flux, event-scale loading patterns, and sediment fingerprinting revealed banks to be the primary source of sediment in Marsh Creek. This detailed characterization of the competition between erosion, storage, and remobilization of fine sediment will help inform local stakeholders on how to best mitigate sediment sources.. Short-term observations of longitudinal patterns reflect local sediment remobilization rather than actual sediment sources. Only over annual timescales can these in-stream fluxes accurately reveal sources.

2.1. Introduction

Fine sediment, comprising the suspended load portion of riverine sediment, was traditionally thought of as having little interaction with the river, being quickly transmitted relative to bedload components of sediment in transport. However, it has gained recognition in the past couple decades as being an extremely important component of the physical, chemical, and ecological makeup of riverine systems worldwide (Walling and Collins, 2016). Suspended sediment has a high chemical activity owing to larger free mineral surface areas commonly composed of electrochemically-active clay phases (Droppo, 2001, 2004). This higher reactivity makes fine sediment a key vector of important ecological elements such as nutrients and bacteria as well as pollutants including heavy metals, pharmaceutical byproducts, and other carcinogens (Walling, 2005).

Total suspended solids or suspended sediments, herein referred to as SS, are a key factor in the light availability of aquatic ecosystems. Turbidity, defined as the optical clarity of a water column, is highly correlated with SS concentration (e.g., Gippel, 1995; Wren *et al.*, 2000; Horowitz, 2003; Minella *et al.*, 2008). Excessive turbidity can choke out benthic ecosystem function by decreasing the amount of light used for photosynthesis. Many studies have also implicated excessive SS concentrations with decreased health in salmonids through a cascade of impacts on function of physical habitat, negative effects on gills, and feeding patterns (Sigler *et al.*, 1984; Sweka and Hartman, 2000). In the US, one of the most common causes for ecological and recreational impairment is excessive turbidity (USEPA, 2016).

The successful mitigation of excessive SS requires a sound understanding of sediment sources, delivery, and fluvial conveyance mechanisms so that conservation practices, commonly referred to as best management practices (BMPs), may effectively sequester problematic sediment in riparian and/or terrestrial zones on the landscape. There are generally high stakes involved with these projects, which commonly cost millions of dollars and involve taxpayer investment (Belmont *et al.*, 2011; Walling and Collins, 2016). Therefore, a clear understanding of the source-transport relation of fine sediment is extremely important during the undertaking of BMPs.

Humans exert a strong influence on fine sediment delivery to channels through activities such as agriculture, irrigation, hydraulic mining, and channelization (Gilbert, 1917; Grabowski and Gurnell, 2016; Voichick and Topping, 2014; Walling and Collins, 2016). It is important to recognize when anthropogenic forcing is a key contributor to high SS loading so that these influences may be addressed through targeted BMPs and adaptive management strategies.

2.1.1. Types of Fine Sediment Sources

SS sources can generally be thought of in terms of their erosive processes and proximity to channels on the landscape (e.g., Walling, 2005; Gran *et al.,* 2009). Sediment sources that are distal to channels belong to hillslope process domains. In agricultural-intensive watersheds, these areas are typically utilized for grazing or crop cultivation. These practices create disturbances to the upper layers of soil, which can contribute to the likelihood of sediment runoff (Russell *et al.*, 2001; Walling, 1983). Runoff processes that deliver fine sediment involve surface detachment of soil particles through overland flow. Examples of specific processes in this domain include sheetwash, dry and wet ravel, rilling, and if concentrated into single flow paths- the formation of gullies (Dietrich *et al.,* 2003; Lavé and Burbank, 2004). Dominant human influences on these SS sources include construction sites, tillage, grazing, exacerbated wildfire regimes and irrigation drainage that act to decrease surface shear strength of soils through the removal of vegetation and degradation of soil structure (Vanoni, 1970; Russell *et al.,* 2001; Kamarinas *et al.*, 2016). Connectivity of these sources to the channel is intermittent and requires runoff generation that depends on a multitude of surficial and hydrologic factors.

These include antecedent conditions that increase soil moisture such as rainfall and snowmelt. When coupled with land disturbances (i.e., crop harvest, tillage), these can exert a strong nonlinear control on the magnitude of SS loading events (Gellis, 2013; Kamarinas *et al.*, 2016).

Proximal SS sources are those peripheral to the channel network - the bed and banks of the channel. Sediment from these sources usually enters the channel through direct hydrodynamic interactions. This involves direct fluvial entrainment by the flow from shear stresses exerted on the bed and banks where recruitment of material is greatest during higher flows when the wetted perimeter and flow depths are greatest. Mass wasting processes, through lateral flow and cantilever-driven failures can occur irrespective of flow conditions, stochastically supplying sediment to the channel (Bull, 1997; Gran and Czuba, 2017). This sediment does not necessarily experience immediate transport and may undergo transient storage in the channel system locally or in depositional zones downstream (Bull, 1997; Green *et al.*, 1999).

As transport capacity increases during hydrologic events (i.e., rainfall, snowmelt), these transient stores of sediment are entrained and undergo export out of the basin. Some studies have also shown that dewatering of bank faces on the receding limb of hydrographs can drive bank slumping that may be observed as a coherent signal downstream (Bull *et al.*, 1995; Russell *et al.*, 2001). Additionally, subaerial erosion of bank faces through freeze and thaw processes in mountainous rivers has shown to be an important component of bank destabilization and subsequent sediment recruitment in channels (Yumoto *et al.*, 2006). Bed material, which usually involves the conveyance of upstream-supplied sediment, is only considered a SS source if long-term channel incision is occurring (Gran, 2009). Channelization and a more flashy hydrograph caused by land use changes can increase the effective erosive power of channels and exacerbate near-channel sourcing from bank material or may lead to longer-term incision (Vanoni 1975; Belmont *et al.*, 2011).

2.1.2. Sediment Tracing Techniques

SS sources, especially in agricultural settings, have broad spatial distributions and differing magnitude-frequency domains of sediment supply connectivity to the channel (Fryirs, 2013). The logistics of sensor maintenance usually limit monitoring of erosive processes and channel gauging to a small number accessible points in the watershed, usually near the outlet of a catchment or within a study reach. If the aim of monitoring is to characterize sources, this approach is limited in its spatial resolution, and depending on the duration of monitoring, temporal scope of sediment delivery to the channel (Collins and Walling, 2004). In the absence of sensors, the use of physical or geochemical fingerprints can be a powerful tool in determining river sediment sources.

This typically involves the selection of a discriminant physical or chemical characteristic of different source soils and matching it to a river sediment sample, which represents a composite of these sources. Discriminant fingerprints are used to unravel the location and relative importance of these sources in terms of their total delivery of fine sediment to the channel. These characteristics can include magnetic properties, trace element compositions, radiogenic isotope concentrations, and spectroscopic characteristics (e.g., Papanicolaou *et al.*, 2003; Walling, 2005; Mukundan *et al.*, 2010). Sediment sources, particularly in agricultural settings, are generally separated into cropland domains distal to the channel versus near-channel bank sources as described previously. Rilling and sheetwash generally access only the upper few centimeters of soil through surface detachment, whereas bank erosion sources material deeper into the soil profile. Discriminating between surface and deeper-profile sources can be done with a suite of tracers, such as fallout radionuclides from nuclear testing, which concentrate in the upper horizons of soil (Quine *et al.*, 1994), or nitrogen stable isotopes have been shown to systematically change with depth (Mukundan *et al.*, 2010). The effectiveness of fingerprints such as these can be determined statistically through methods such as mixing models (Walling, 2013).

2.1.3. Sediment Routing in Fluvial Networks

Understanding the supply and propagation of sediment from singular and distributed sources in a fluvial network has been of particular interest in many studies in geomorphology over its history (e.g., Benda and Dunne, 1997; Gilbert, 1917; Cui, 2003, Cui and Parker, 2005; Gran and Czuba, 2017). Terms for the description of a downstream propagation of a sediment parcel take on multiple meanings within the literature. It is important to clearly define sediment delivery and fluvial conveyance in the context of this study. Many studies have addressed sediment routing in mountainous rivers in which the primary mode of transport is bedload (e.g., Benda and Dunne, 1997; Cui and Parker, 2005; James, 2010). These differ fundamentally from SS-dominated systems because bedload is generally transport-limited whereas most rivers maintain a transport capacity exceeding those required to move SS, making these systems more supply-limited (Walling and Collins, 2016; Kuhnle, 2013). Therefore, sediment conveyance episodes dominated by bedload entail a much greater degree of transient storage on the bed (James, 2010; Gilbert, 1917). Sediment pulses in SS-dominated settings involve increases in discharge and associated increases in sediment concentration that propagate as a package downstream (e.g., Bull, 1997). Sediment pulses can be derived from either a disturbance acting broadly over a substantial portion of a watershed (i.e., non-point sources, land-use changes, climatic shifts) or as a singular high magnitude event delivered to a point in a channel network such as a landslide (Jacobson and Gran, 1999; Sutherland *et al.*, 2002; Gran and Czuba, 2017).

Sediment pulses, in the context of this study, involve snowmelt and precipitation-driven increases in discharge and sediment concentration that propagate downstream. Sediment pulses of either bed material or suspended load have been shown to undergo dispersion (broadening and flattening of the waveform) and downstream translation (Gran and Czuba, 2017). Intuitively, results from empirical data and modeling have both indicated that dispersion of sediment pulses occurs as the signal moves through low transport capacity zones (Benda and Dunne, 1997; James, 2010; Gran and Czuba, 2017).

Longitudinal studies comparing the progression of waves of elevated SS concentration and discharge pulses of a flood through a river network have had differing results in many studies. Studies conducted at very large spatial scales on high-order rivers have observed flow increases ahead of associated SS pulses, arguing that this lag is due to higher velocities of flood pulses compared to sediment pulses (e.g., Lewis, 1921; Heidel, 1956; Petts *et al.*, 1985). Studies conducted on smaller watersheds at the event-scale have shown that SS concentration pulses precede discharge pulses, an opposite relationship (e.g., Bull, 1997; Bača, 2008; Oeurng and Sauvage, 2010). These lags were traditionally thought of as disparities in the celerity of sediment packages and water (Lewis, 1921; Heidel, 1956). However, it has been generally accepted that these may be explained instead by relative transit times of sediment to the observation point. Channel-derived sediment, which is generally exhausted on the rising limb of the hydrograph, results in a peak of sediment concentration preceding a peak in discharge. This premise of local source exhaustion is confirmed in many studies by field observations of primary sourcing from eroding banks in watersheds that display this behavior (e.g., Bull *et al.*, 1995; Bull, 1997; Gellis, 2013).

An opposite relationship, where discharge maxima precede sediment concentration peaks, have been explained by sediment derived from upland delivery to tributaries which have a longer relative transit time than locally-derived stocks (Baca, 2008; Gellis, 2013; Oeurng and Sauvage, 2010). This relationship is time-dependent and non-linear resulting in hysteresis loops of concentration-discharge. This is a practical issue from the standpoint of estimating sediment loads via linear or power-law discharge-SS rating curves, where hysteretic effects can produce considerable inaccuracies in total budgets (Horowitz, 2003; Hickin, 2004). Though there is an extensive treatment of SS-discharge hysteresis in the literature, few studies have explicitly estimated continuous loads across multiple storm events longitudinally as is explored in this study.

2.2 Study Area and Focus

2.2.1. Study Area Setting

The focus of this study is the Marsh Creek, herein referred to as MC, the largest tributary of the Portneuf River (see Figure 2.1). The Portneuf supports recreation and agriculture in the Pocatello region of SE Idaho. The stream has been identified as a large contributor of fine sediment and has been TMDL-classified as an impaired stream for excessive turbidity (McSorley, 1977; IDEQ 2010). Based on the National Landcover

Database, ~25% of the MC watershed is currently used for crop cultivation and cattle grazing (USGS, 2011). Most of this agricultural land is concentrated within the alluvial valley near the channel or located on bluffs above the channel close to irrigation infrastructure. The dominant soil texture class is silt loam (NRCS, 2016).

Marsh Creek (MC), the largest tributary in the Portneuf River subbasin, drains ~1100 km^2 of land in SE Idaho. The MC drainage ranges in elevations from 1380 to 2700 meters. Runoff in MC is dominated by snowmelt derived from higher elevations, with the largest historical events being driven by rain-on-snow events.

MC is located in a north-south trending basin with a full graben system at its southern extent, inset in a larger and more recently active half-graben oriented NNE-SSW (Kruger *et al.,* 2003). MC is an underfit channel in a broad alluvial plain. Paludal, fluvial, and lacustrine Pleistocene stratigraphy of the bluffs flanking Marsh Valley indicates that the basin hosted a low energy depositional environment grading between marsh and playa systems with climate shifts in the Middle to Late Pleistocene (Thackray *et al.,* 2011). This, coupled with younger loess deposits mantling much of the upslope alluvial surfaces, provides a large potential stock of fine sediment to the contemporary riverine system.

The stream likely underwent drainage integration with pluvial Bonneville Lake during its highstand ~50 ka (Thackray *et al.,* 2011). MC most famously acted as the initial floodway of the catastrophic 17.4 calibrated years BP Bonneville Flood at Red Rock Pass, the SE drainage divide of the basin (H. E. Malde, 1968; O’Connor, 1993). The flood peaked at approximately 24,000-32,500 cubic meters per second (O’Connor, 1993). As the flood entered southern Marsh Valley, it is inferred from the valley’s broad width and leftover extensive boulder lag bars sourced from Red Rock Pass that the flood was primarily in a depositional mode. Therefore, it is speculated that most of the downcutting that accommodated the formation of the wide alluvial valley was through non-catastrophic drainage of Lake Bonneville that maintained high stream power relative to the stream today (Thackray *et al.*, 2011).

2.2.2. Study Overview and Rationale

Conservation practices and sediment mitigation projects in the MC subbasin date back to the 1980s, beginning with the Idaho State Agricultural Water Quality Program (IDEQ, *personal communication*). In the 1990s, the Conservation Reserve Program (CRP) resulted in the significant easement of agricultural land located on the west benches above southern MC (NRCS, 2007). This has apparently resulted in a reduction of soil erosion of ~3 tons/acre/year on CRP, pasture, and crop land since the 1980s for the Portneuf watershed, which has remained relatively static in the 1990s (NRCS, 2007). In the past decade, USEPA 319 grants were funneled towards cost-sharing BMP implementation on projects related to exclosure fencing, corral relocations, and establishment of off-site water troughs (IASCD, 2013). In all, millions of dollars have already been spent in the past decade on conservation, yet no definitive data exists on sediment source apportionment (IASCD, 2013). The Idaho Department of Environmental Quality total maximum daily loads (TMDLs) studies have listed middle and lower MC as being impaired, with one of the largest concerns being elevated turbidity levels (IDEQ, 2010).

The City of Pocatello and other stakeholders in the lower Portneuf basin have expressed interest in sediment mitigation strategies aimed at reducing poor water quality associated with chronically high SS. To date, no study has explicitly determined primary sources and delivery mechanisms of suspended sediment in the MC subbasin. Therefore, a clear understanding of the type and location of SS sources must be made so that these may be targeted with appropriate sediment control practices and could also provide an evaluation of the effectiveness of past practices.

To achieve the aims outlined above, we characterize high spatial and temporal resolution SS fluxes along the main stem of MC through the implementation of a longitudinal array of 13 water quality monitoring stations over full water year (March 2016-March 2017). These stations collect 15-minute time series data on flow and sediment concentration to characterize mass balance trends and SS concentration-discharge relationships at various timescales longitudinally along the mainstem of MC. Secondly, we use cost-effective stable isotopes and geochemistry for endmember mixing to separate the relative contribution of upland sources versus bank sources.

2.2.3. Observations of Prevalent Bank Erosion

Based on kayak surveys and observations at various sites along Marsh Creek, there are numerous bank failures present along the full study transect of MC. Woody riparian vegetation is less common along the creek with pasture and agricultural land running adjacent to the channel through much of its reaches. The primary mode of failure is bank slumping along lower angle detachment planes which appear to incrementally slip. (Figure 2.2a). Material calving off the toes of the failures has been observed during diurnal freeze-thaw periods. Additionally, especially along the outsides of bends, cantilever failure driven by undercutting is another common mode of failure (Figure 2.2b). In addition to these geotechnical bank failures, there are also livestock trampled zones that act to further destabilize bank material and reduce vegetative cover (Figure 2.2c). Livestock, being adapted to mesic habitats similar to humans, prefer shady cool environments with water and food readily accessible (Fleischner, 1994). Thus, they prefer to graze in riparian settings, leading to the degradation of physical habitat and loss of bank stability in these zones. The most extreme of these are scallop-shaped terraces ranging from 1m to tens of meters of completely trampled bare ground (Figure 2.2d). These are commonly formed by cattle scratching, who utilize the terrace edges as a scratching surface (Peppler and Fitzpatrick, 2005).

Given that bank failures are so common along Marsh Creek, it is hypothesized that the primary source of sediment is through bank erosion. A majority of banks observed during this study are primarily composed of silt-clay soils that could easily undergo suspension once delivered to channel. In order to evaluate this, this study utilizes high resolution time series data of sediment transport rates from 13 monitoring stations in a longitudinal array along the mainstem creek and stable isotope geochemistry used for fingerprinting bank and upland sources. These data were collected over a full calendar year and were analyzed at various scales in order to characterize source and transient storage of SS along ~80 km of channel (see Figure 2.1).

2.3. Methods

2.3.1. Monitoring Stations

Monitoring stations were established at 13 accessible points in a longitudinal array along the mainstem of MC (Figure 2.1). These monitoring stations consisted of a YSI 6900-series sonde equipped with a conductivity-temperature probe and a 6139 turbidity sensor housed within a protective 4-inch diameter PVC pipe with 1.5” diameter holes anchored to rebar with hose clamps and suspended in the channel at about one-half of the average baseflow stage (see Figure 2.3). At a coarse scale, sites are chosen based on their longitudinal positions bracketing major tributaries to evaluate whether these acted as significant lateral SS inputs. Other important considerations for the selection of water quality stations that are representative of natural flow conditions are generally hydraulically homogeneous reaches (i.e., not within a major meander bend), sites located upstream of major human infrastructure that may act to modulate the amount of water or sediment, and sites that maintain a generally stable cross-section (Wilde, 2008). Turbidity is reported in nephelometric turbidity units (NTU) and calibrated with SS, using paired samples from a IDEQ dataset from previous monitoring as well as isokinetic samples collected during this study (Wilde, 2005, see Figure 2.4). This study's calibration samples were collected at Site 2, Site 6, and Site 16, bracketing the longitudinal transect of the study (Figure 2.4). It was determined that there was no statistically significant difference in the slope of the regression line for each site - indicating that the SS-turbidity relationship is consistent longitudinally and temporally over varying flows in the study reaches. It was determined during various flow conditions that turbidity measured at a point was within analytical error both laterally and vertically in the cross section, implying that the SS load was extremely well mixed in this system. Biweekly to monthly QA-QC and maintenance were performed on these instruments to account for instrument drift due to fouling as well as calibration errors (Wilde, 2008).

Additionally, stage-discharge relationships were established following USGS methods using HOBO water level loggers (Model # U20-011-04) set up in a similar fashion to sonde stations (Braca, 2008; Sauer and Turnipseed, 2010). Given that most sites were upstream of bridge crossings with hardpoints and rip-rap, these bridge crossings were chosen due to a lower likelihood of bed aggradation or degradation. Discharge was measured using wading rod acoustic doppler velocimeters in lower flow conditions and with an acoustic doppler current profiler trimaran during higher flows. It was found that during the study, aquatic vegetation growth during warmer periods greatly influenced both channel roughness and displaced non-trivial volumes of water at monitoring cross-sections. This degraded some stage-discharge relationships at six of the 13 stations and synoptic discharge surveys were performed within a single day, three times, to determine corrected rating relationships in discharge during various flow conditions in the summer and fall during the study. This information, along with lag times determined from flow-peak offset correlations, was used to interpolate flows during these periods of poor ratings (see relationship in Appendix B, Figure B.4.). These data were combined to calculate loads using the product of discharge and concentration, which are then converted to units of tons/day. For a complete view of the continuity of load, discharge, and turbidity data, please see Appendix B, Figure B.1.

Idaho Department of Environmental Quality (IDEQ) data on discharge and TSS of major tributaries of MC were collected during this study’s monitoring period and shared generously with the author. These data were converted to loads and compared to time-lagged load differences using sites bracketing the tributary confluences. Paired t-tests were run on tributary contributions and load differences to evaluate whether a tributary could explain the load difference between longitudinal main stem stations.

2.3.2. Stable Isotope Sediment Fingerprinting

Stable isotope fingerprinting took place in 2016 and three potential source endmembers are evaluated: (1) pasture and (2) alfalfa hay, both cropland topsoil sources, as well as (3) vertically-integrated streambank sources. Pasture and alfalfa hay topsoils were collected by extracting material 4 cm^2 in area and 2.5 cm deep. A total of seven of these samples are analyzed at 5 sites ranging from river km 72 to river km 14.7 (see Figure 2.1 for locations) Additionally, actively failing bank profiles were sampled vertically and a depth-weighted average value is extracted. In all, 7 bank faces are evaluated longitudinally along the channel with a total of 38 samples ranging in depth increments ranging from 2.5cm-10cm. 6.4 micrometer sieves are used to separate the silt and clay portions of single samples from each endmember in order to apply corrections for grain size to these samples. Sediment samples were collected isokinetically at a cross-section and bed samples are collected down to ~8cm as an estimate of longer-term composites of erosion and deposition. Endmember samples are root-picked to remove macro-scale organic inputs. All samples are acidified with 1M HCl to remove inorganic carbon from carbonates prevalent in the field area and freeze-dried for 48 hours. Finally, samples are run through an elemental analyzer and stable isotope ratio mass spectrometer at the Idaho State University CAMAS Lab. All values for $\delta^{15}N$ are relative to nitrogen atmospheric compositions of 0 ‰.

2.4. Results

2.4.1 Seasonal and Annual Longitudinal Trends

Seasonally-averaged longitudinal data show that in general from the upper-most site towards the confluence of MC with the Portneuf River, sediment flux increases substantially (Figure 2.5). This downstream accumulation of sediment flux is especially apparent during the spring and winter monitoring periods when hydrologic connectivity is the greatest. During the summer months, lower baseflows associated with the dry season, irrigation withdrawal, and fluid drag induced by aquatic vegetation greatly reduce sediment fluxes (Figure 2.5). Summer irrigation drastically draws down the seasonal average flows of the upper reaches (Sites 13-11), meaning there is very little conveyance from the upper-most 20 km to the lower-most 50 km.

Readily apparent in these longitudinal data are also storage points along the course of the channel. Sites 11 and 12 are particular points where long-term sediment flux is decreased relative to the upstream sites. This is corroborated with lower transport capacity zones bracketed by the next site upstream. Within these reaches, diversion points create backwaters induced by culverts for the purpose of irrigation and connection of grazing pasture through earthen bridges or retrofitted rail cars.

Figure 2.6 shows a cumulative sum of SS flux during a period of late winter through summer of 2016. Interestingly, Site 5, the downstream site, does not always maintain a larger cumulative flux (Figure 2.6). These periods represent times of in-channel storage between these sites. Subsequent remobilization of SS from transient storage zones results in a steepening of this curve until its position is equal to or greater than the adjacent upstream site.

2.4.2. Event-Scale Loading Patterns

In all, 10 distinct hydrograph events with flow peaks exceeding the 75th percentile of flow occurred during the monitoring period. Most of these events occurred as either runoff in response to snowmelt in the spring or rainstorms in the fall, winter, and spring. At Site 2, located near the confluence, two events could be classified as having clockwise hysteresis, three events classified as having counter-clockwise hysteresis, and the remaining five are too complex to be classified into any hysteretic looping pattern. Only five were directly comparable due to fouling and instrumentation, which are shown in Figure 2.7. One major rain-on-snow event in February 2016 produced multiple hydrographic peaks (2-3 depending on the site), likely accounting for ~80% of the event-based SS export of MC.

In the centroid analysis shown in Figure 2.7., five of the event comparisons have analytically indistinguishable values, six have load values greater for the first-half of the storm event, and the remaining four comparisons have values greater for the second half of the storm event. Cumulative totals from these five storms show that 3,240 tons of sediment are collectively transported during the first half while 1,750 are transported during the second half. However, when error is propagated through the summation of the 15-minute data, analytical error balloons to approximately 25 times the estimate. On average, for sites 5 and 2 especially, it appears that sediment flux is greater during the first half of the event than the second half. For site 15, located much further up-basin, loads for four out of five of the events are about the same once considering analytical error.

2.4.3. Lack of Significant Tributary Contributions

A comparison between IDEQ tributary load data and mass balance estimates of SS flux along main stem MC show that tributaries do not explain the additional sediment inputs along the reach containing the junction. During the times in which additional sediment flux increases between an upstream and downstream station, tributary inputs were much smaller in magnitude (see Table 2.1). For the seven loading times where there is increased flux along MC in the downstream direction evaluated for four major tributaries, loads along tributaries accounted for only 14.9% of the additional flux gained in junction reaches.

Additionally, there were certain times in which net storage took place between stations - implying that tributary contributions were completely stored between sites in addition to main stem loads. In addition to these data, it is clear both from the author's observations, that streams did not maintain perennial connection with the MC trunk stream. Drying of these tributaries appears to be modulated by irrigation withdrawals in the summertime as well as stream intermittency of lower-order tributaries.

2.4.5. Fingerprinting Results

Stable isotope fingerprinting shows sufficient separation of endmembers when plotted in C:N and $\delta^{15}N$ space (Figure 2.8). Interestingly, the two agricultural topsoil endmembers, alfalfa hay and pasture, plot with more enriched (higher) $\delta^{15}N$ values compared to profile-integrated bank samples. This is an opposite relationship to other studies (Mukundan *et al*., 2010; Vervaet *et al.*, 2002), where $\delta^{15}N$ values increased with increasing depth. Bed and suspended sediment samples collected in the summer and fall plot within +/-1 standard error of bank samples.

2.5. Discussion

2.5.1. Flux Accumulation and Storage Patterns

Cumulative and seasonal average flux plots show a general increase in SS loads in the downstream direction in MC. Fall 2016 data show a deviation from this trend, where high flux is persistent along the 60-40 km corridor, with values similar to those closer to the outlet (Figure 2.5). These values could be explained by summer storage and subsequent fall remobilization within these reaches that is attenuated downstream via storage. This is corroborated by observations of large irrigation-induced backwaters and a possible withdrawal signal of irrigation encompassed within this zone. Irrigation activity peaks in the summertime, enhancing storage of fine sediment. As flows increase in the fall in response to greater rainfall and cessation of water withdrawal, these transient stores can be remobilized.

2.5.2. Mainstem Channel Bank Sourcing from Monitoring Data

Overall, especially in the spring and winter months when snowmelt drives the greatest hydrologic connectivity, flux increases in the downstream direction. This is consistent with longitudinal non-point sources. These sources act to deliver SS to the channel that may be transmitted downstream as throughput wash load and, as shown in a comparison of cumulative flux patterns, a significant component may be transiently stored and later remobilized. Given the highly agriculturally-modified nature of MC, these patterns of remobilization do not exclusively coincide with hydrologic events. Remobilization of lateral bars formed from a backwater at an agricultural check-dam between Sites 1 and 2 is observed and acts a significant short-term control on the sediment flux relationship between these sites. Additionally, influences of livestock such as large group crossings likely also act to sporadically remobilize significant amounts of sediment.

Tributaries do not appear to have an influence on this trend, maintaining a much lower sediment supply and, in many cases, do not perennial connection with the main stem. These data rule out the potential of lateral upland sources as being important to the overall sediment budget of MC (Table 2.1).

Event-scale flux data show that there is slightly more sediment transported on the first half of hydrographs than the latter half following the flow centroid. This signifies that likely a significant degree of sediment supplied during these events is proximal (Gellis, 2013). Independent evidence shows that upland derived sources are unlikely a major contributor to sediment sources during the monitoring period. Additionally, the collapse of banks immediately following the passage of a flood peak as has been observed in previous studies could explain much of the remaining load on the latter half of hydrologic events (Sarma, 1986; Russell *et al.*, 2001). This shows that the analysis of hysteresis and decomposition of loads into halves based on the centroid is not alone a useful diagnostic tool for sediment source. It does show, in the case of this study, that sediment is not completely exhausted during first-flush portions of a hydrograph event but that there is still an overall greater flux of sediment during the first half of an event, especially during larger events.

2.5.3. Remobilization Signal Dominates

Within the temporal scope of this study, both at event timescales and seasonal to annual scales, remobilization of sediment appears to be an extremely important component of SS transmission at water quality stations. This storage and remobilization signal makes a simple assessment of SS loads at various hierarchal timescales in order to pin down spatially explicit sources very difficult. The remobilization signal dominates, especially at smaller temporal scales.

It should be noted that this is a very common limitation and has been observed across many watersheds where linkages between estimates of watershed-scale erosion rates and export out of a basin are completely decoupled (e.g., Walling, 1983; Kirchner *et al.,* 2001; Lu *et al.,* 2005). This is encompassed by the *sediment delivery ratio* (SDR), which is a ratio of area-normalized sediment delivery out of the basin outlet point to the gross erosion rate acting over the landscape (Walling, 1983). SDRs for basins vary over both time and space, with a time dependence linked to the variable magnitude-frequency relationships of erosion processes and a spatial dependence linked to the transit time of parcels of sediment from source to outlet (Walling, 1983; Fryirs, 2013). In other words, the transient storage of sediment while it is en route to the outlet point is extremely important.

Based on the conservation of mass, the export of sediment out of a basin must balance the amount of sediment production (Sadler and Jerolmack, 2015). This means that the SDR must approach one over sufficiently long timescales (Lu *et al.,* 2005). In a monitoring project such as this one, these timescales may not be achieved but these are extremely important consideration when interpreting flux data such as those introduced in this paper. Analysis of longer-term data loading data in various watersheds has shown that sediment loading responses to a disturbance regime that increases erosion (Owens and Xu, 2011) or significant conservation effort that attempts to mitigate erosion (Brooks *et al.,* 2010) have a marked lag time associated with them. These lag times are the result of the sediment storage either in transit on the hillslope or in conveyance in a channel. This study highlights that in-channel storage, even in fine-grained systems, is a critical disruptor of sediment source identification in monitoring studies.

2.5.4. Fingerprinting – Bank Source Evidence and Temporal Weaknesses

Stable isotope fingerprinting results of sediment in the endmember mixing space strongly suggest a majority bank source for SS in MC. These data were collected during a singular season, so it is highly probable that a direct connection between sources and SS exists. These values changed with season, and SS samples taken in the winter during a high magnitude event deviated outside of the mixing triangle (Appendix B, Figure B.2.). This could be reflective of seasonally-driven non-stationary behavior of ^{15}N due to changes in the organic breakdown or additional inputs of nitrogen into the system (organic or inorganic) not considered through the endmembers analysis, a weakness in the application of such results beyond their temporal scope of sampling.

2.6. Conclusions and Future Work

Based on longitudinally prevalent observations of bank erosion through both hydrodynamic and land-use related processes, it is hypothesized that banks are the primary source of high SS to MC. An overall accumulating sediment flux in the downstream direction, lack of significant lateral inputs, a moderate first-flush signal during events, and fingerprinting data all confirm bank material as the primary producer of sediment in MC. The delivery and transmission of sediment from bank sources at the event-scale is not obvious and likely confounded by storage along transient depositional centers located along the course of MC.

Past conservation efforts, which put a significant portion of upland agricultural operations into fallow during the CRP program in the past three decades, could have reduced fine sediment delivery into the channel network during snowmelt and precipitation events. Though no definitive analyses or high quality data exist to track changes in sediment flux from this period to the present, the strong evidence of primary bank sourcing put forth by this study seem to indicate very little sedimentological connectivity of the uplands to the mainstem channel.

Future work should involve tracking potential improvements in turbidity trends in response to conservation and BMP implementation in the MC basin. This data could prove useful in tracking the trajectory of turbidity trends in response to upland farming conservation practices and provide context on the potential shift of relative contributions of banks compared to surface sediment runoff. Additionally, analysis of historical imagery could provide an additional dimension in identifying hotspots of channel migration and areas that have undergone significant channelization. These analyses could help land managers and stakeholders prioritize areas in which to improve riparian and bank stability conditions through conservation projects and BMPs.

Chapter 2 Figures

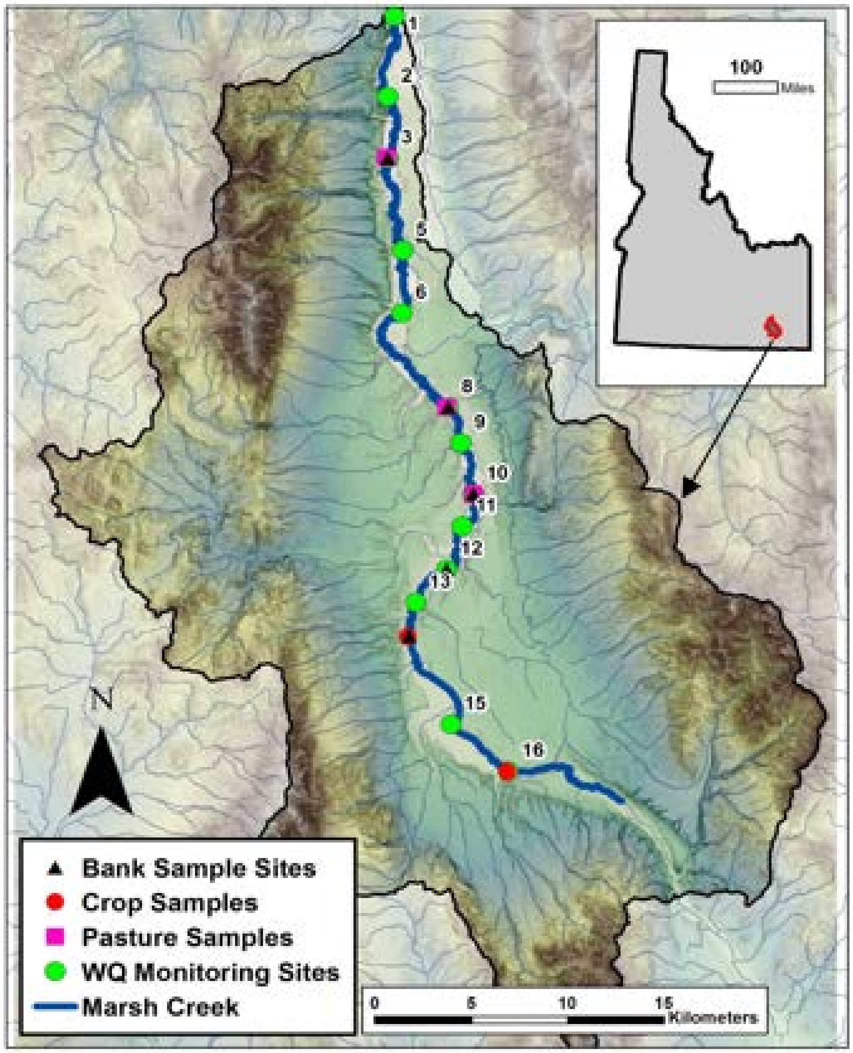

Figure 2.1. Map showing the location of Marsh Creek watershed in SE Idaho. Locations shown are monitoring sites (green) and geochemistry samples, which are color-coded according to the key.

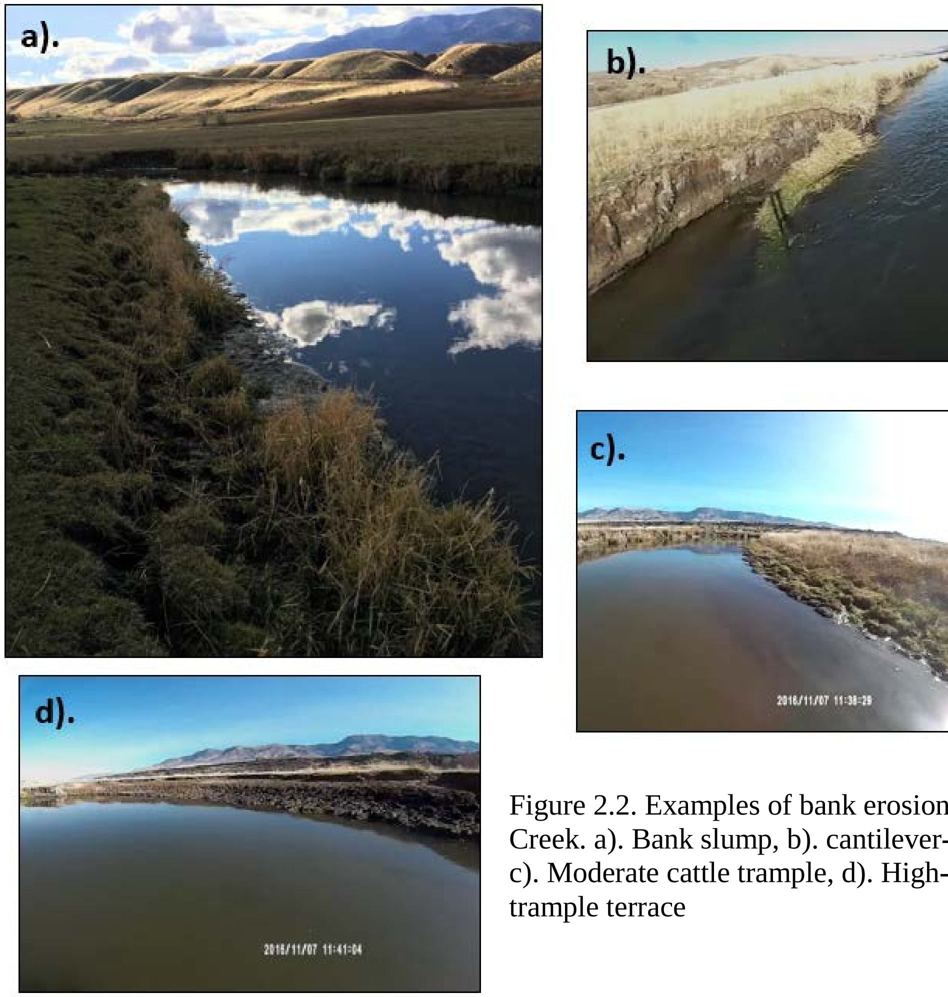

Figure 2.2. Examples of bank erosion in Marsh Creek. a). Bank slump, b). cantilever-driven failure, c). Moderate cattle trample, d). High-intensity cattle trample terrace

Figure 2.3. Example of a sonde deployment in 4-inch diameter PVC anchored to the banks.

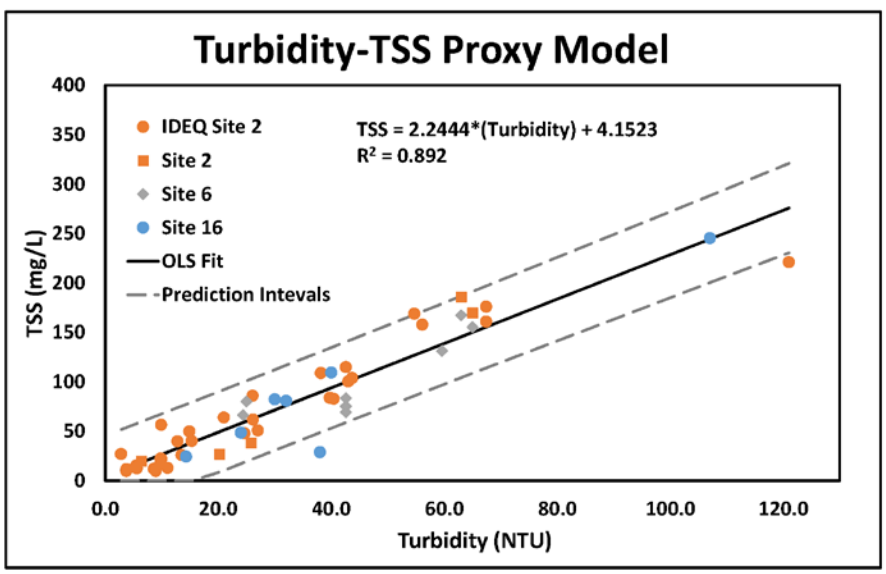

Figure 2.4. Regression line between total suspended solids (TSS, referred to as SS in text) and turbidity. Best fit line and equation shown with prediction intervals bracketing spread. Regression significant at $p < 0.001$. Regression equation is used to convert continuous turbidity into estimated SS concentration.

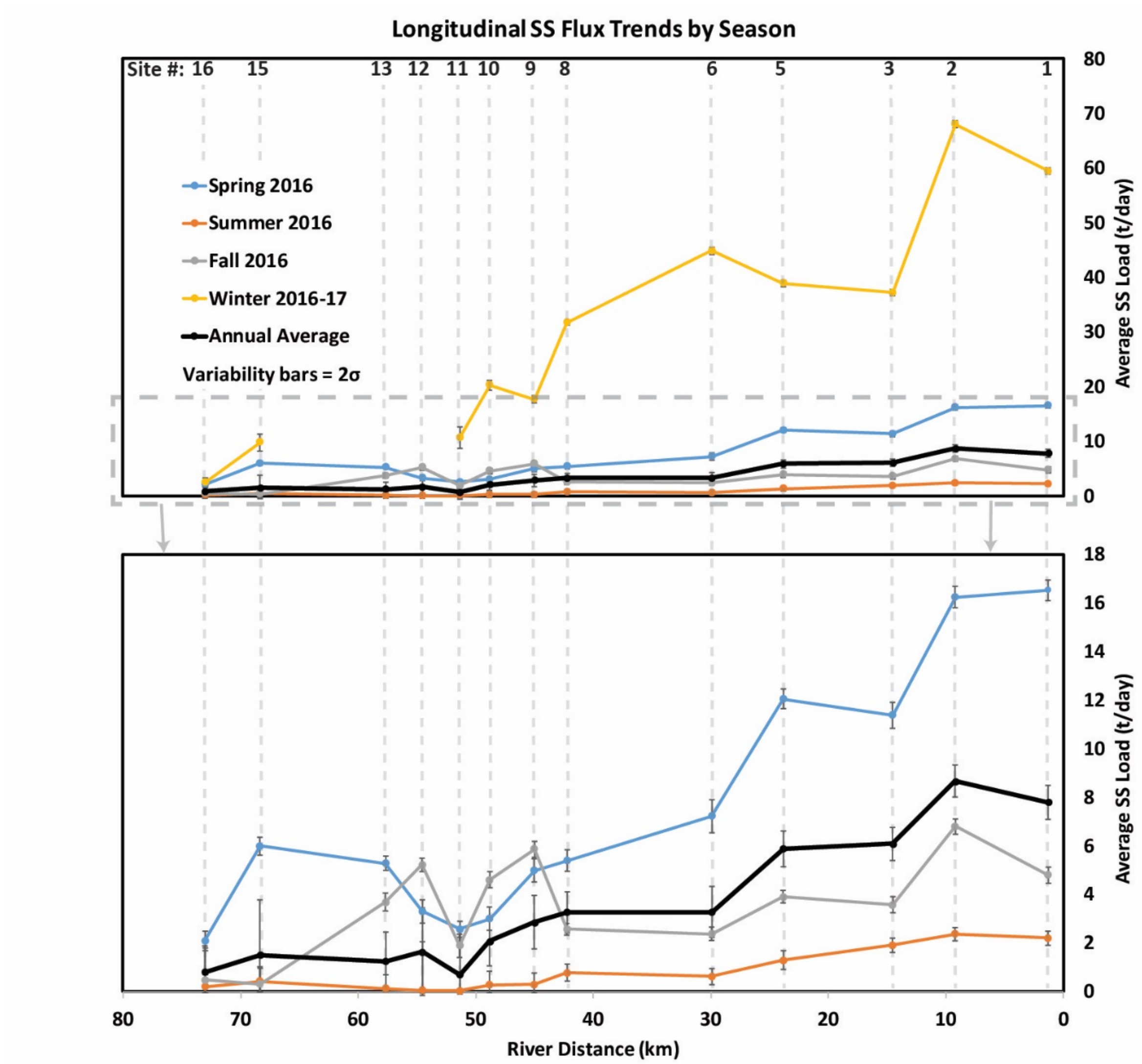

Figure 2.5. Longitudinal trends of suspended sediment flux for Marsh Creek. Top figure is inclusive of winter data, which is skewed by a large 5-year flood event. Lower figure, outlined by dotted box in top figure, omits winter data in order to scale load axis to see differences between season. Gaps in winter records at sites 12 and 13 were due to instrument failure/late installation, etc. Overall sediment flux accumulates in downstream direction. Averages and uncertainties are done as back-transformed logarithmic averages based on sufficient normality of the logarithmically-transformed data. Note overall increasing loads towards the confluence, except during the fall period where elevated sediment loads occur along the 60-45 km corridor.

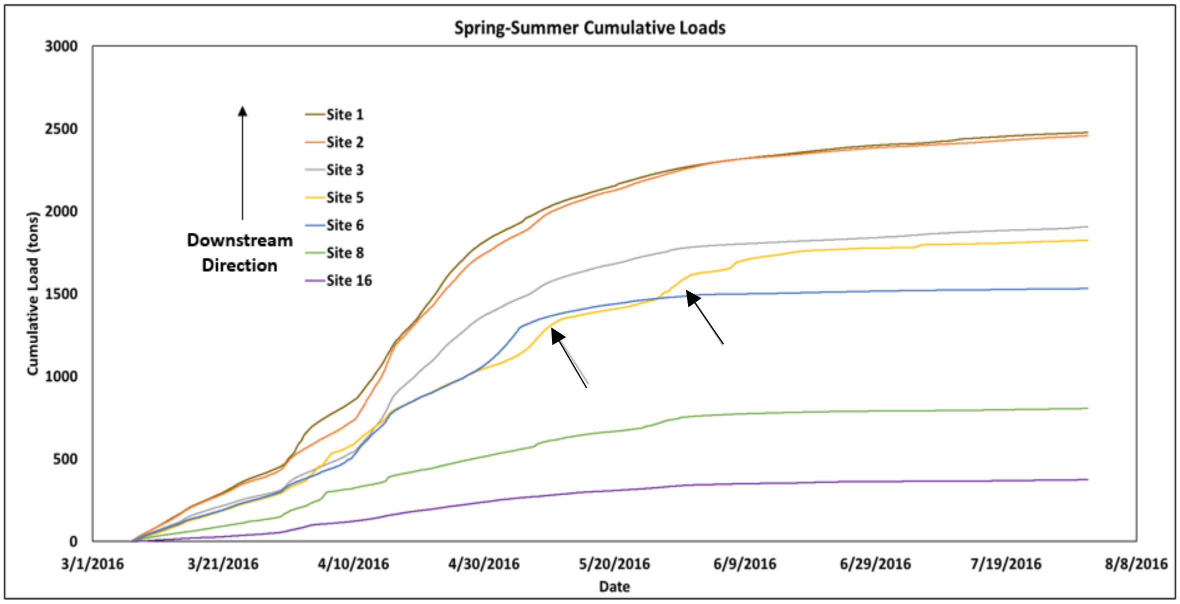

Figure 2.6. Cumulative load (flux) trends for selected sites. Total cumulative flux for spring and summer period resulting in downstream increasing total loads. Arrows show examples of lines crossing each other, indicative of storage then subsequent remobilization in reaches bracketed by sites 5 and 6.

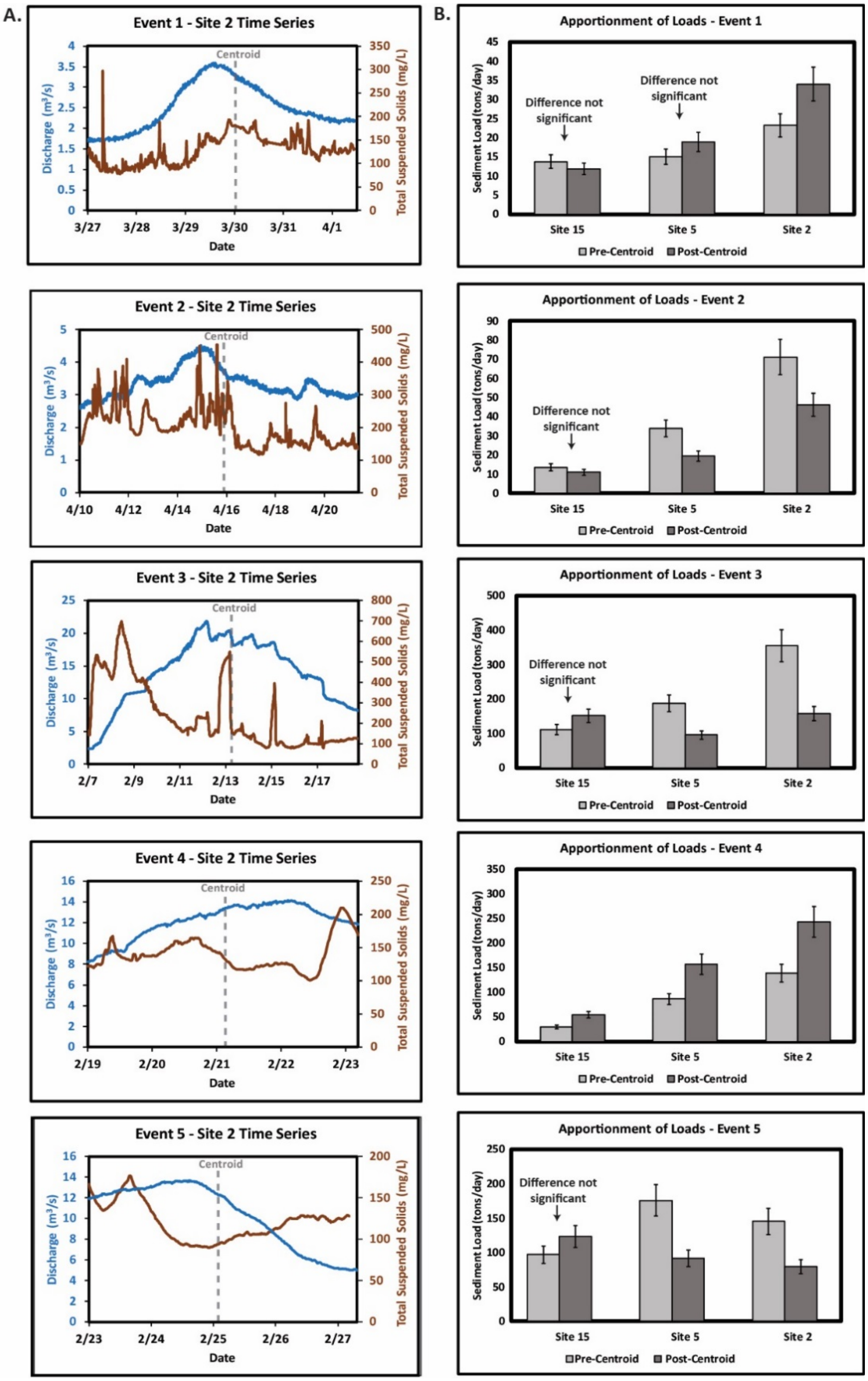

Figure 2.7. Event-scale loading before and after flow centroids. A. This column of graphs is the load and flow time series for each event with flow centroids shown. B. Average loads separated into pre-centroid and post-centroid values. Values with no significant analytical differences are noted (overlapping standard errors), all other values significantly different (*p<0.001*). Six comparisons have greater loads during the first half, five are analytically indistinguishable, and four have greater loads during the last half.

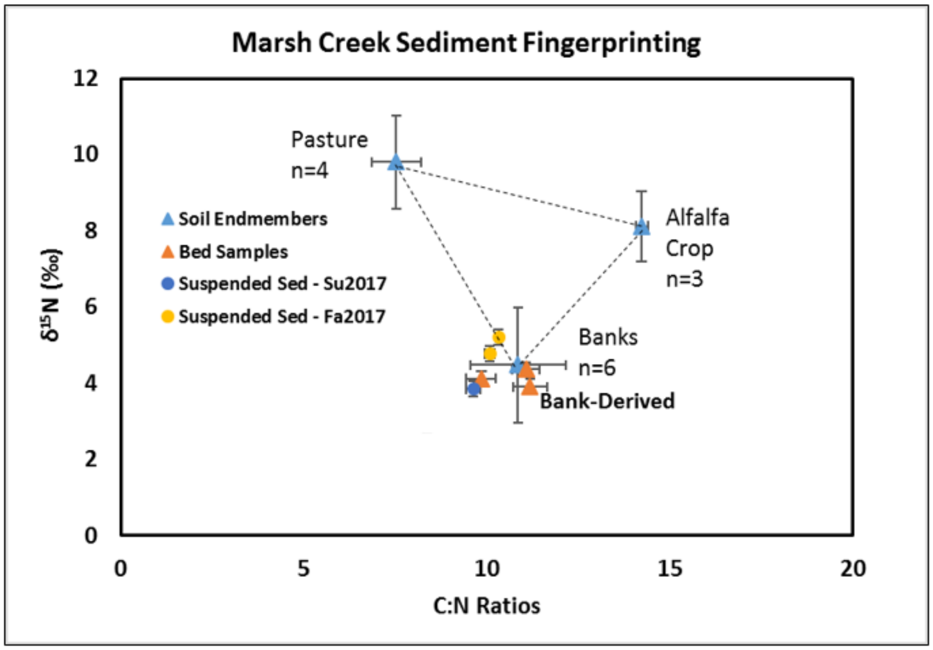

Figure 2.8. Sediment fingerprinting plot with $\delta^{15}N$ values plotted against C:N concentration ratios. Blue triangles are soil source endmembers in a triangular mixing diagram with bed samples (orange triangles) and suspended sediment samples for fall and summer plotted (circles). Error bars are standard errors for individual samples and endmember averages. Most notably, the bed and suspended sediment samples plot within uncertainty of bank endmember.

Chapter 2 Table

Tributary Name	**Tributary Load (t/day)**	Date in 2016	MC Load Downstream of Junction (t/day)	MC Load Upstream of Junction (t/day)	**MC Reach Difference [Downstream-Upstream] (t/day)**	*p*-value to test if MC difference greater than tributary input (shaded if significant)
Walker	**0.34**	4/20	38.69	36.48	**2.21**	0.098
	0.28	6/6	3.94	1.44	**2.50**	0.021
Goodenough	**0.11**	4/20	4.61	0.53	**4.08**	0.011
	0.03	6/6	17.38	13.15	**4.22**	0.027
Garden	**2.64**	4/20	13.15	4.90	**8.26**	0.017
	0.54	5/18	4.80	3.07	**1.73**	0.052
	0.01	7/20	0.41	0.61	**-0.20**	N/A-Storage in Reach
Hawkins	**0.12**	6/2	2.40	4.70	**-2.30**	N/A-Storage in Reach
	0.02	7/11	0.24	0.04	**0.20**	0.060
	0.61	6/6	1.54	2.98	**-1.44**	N/A-Storage in Reach

Table 2.1. Tributary load data compared against bracketing station loads. Tributary loads and reach difference loads, in bold, are reported in tons/day. Reach loads are computed as downstream load minus upstream load, where a negative value represents storage of sediment in that reach, and by extension, storage of tributary inputs. Statistical significance of MC reach loads versus tributary data is evaluated at the $\alpha = 0.1$ level based on analytical uncertainties of each measurement. In the case of all times when loads were compared, tributary inputs could not explain additional gains in flux in the bracketed reach.

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Chapter 3: Suspended sediment fluxes are decoupled from their sources – transport complexities revealed in space and time

Abstract

Suspended sediment is an integral influence on water quality in many watersheds, especially in agricultural settings (USEPA, 2016). Marsh Creek, a watershed impaired by high turbidity with evidence of ubiquitous bank erosion, is the site of a unique water quality study pairing spatially continuous bank imagery from a kayak survey with a dense longitudinal array of water quality sensors. We find that the spatial pattern of sources poorly correlates with the longitudinal pattern of sediment in transport. Storage and remobilization are recognized as a key influence on subsequent sediment fluxes, acting to largely mask source areas. Stream power, estimated from high spatial resolutions LiDAR data has a slightly improved correlation with reach-scale sediment recruitment patterns compared to bank quality data. This chapter details the difficulty of inferring sediment sources from longitudinal measurements and the importance of understanding transport dynamics when monitoring non-point source turbidity in an agricultural setting.

3.1. Introduction

Non-point source erosion and fine sediment delivery is a major problem in rivers worldwide, especially in agricultural settings (USEPA, 2016; Walling and Collins, 2016). Fine sediment, modally transported as the suspended load in rivers, is generally thought of as being supply-limited. This is attributed to the fact that most channels maintain transport capacity far exceeding the threshold for entrainment and transport of these particles, although the finest fraction sediment will generally retain a high cohesive strength owing to electrochemical properties of clays and silts (Hjulstrom, 1939; Sundborg, 1956). When suspended sediment undergoes delivery to the channel, it is readily transportable and transmits downstream only being seldom deposited in very low energy conditions. The finest fraction of this, the wash load, generally never undergoes settling and is quickly exported out of the system.

Given that fine sediment generally has electrochemically-active mineral surfaces, it is constantly in communicative feedback with streamwater solutes (Droppo, 2001). This makes understanding suspended sediment, herein referred to as SS, an integral part of nutrient fluxes and other constituent loads. Additionally, SS in riverine systems generally modulate turbidity, the optical clarity of water, and therefore have a direct influence on photosynthetic conditions of aquatic flora (Palmer *et al.,* 2000). Higher and persistent turbidity has also been shown to have a direct impact on the biomass accumulation and overall health of salmonids (Sigler *et al.,* 1984; Sweka and Hartman, 2000). On top of this, surface-subsurface water exchanges may be deleteriously influenced. Fine sediment infiltration of gravels has been shown to inhibit hyporheic exchange that provides oxygenated waters to benthic organisms (Kondolf *et al.,* 2006). Additionally, where municipal water supplies are surface-derived, considerable money can be spent on filtering out SS, especially when it is excessive. Given all this, there is a considerable economic, social, and ecological benefit to understanding and mitigating SS sources when it is proven that these sources are detrimental (Belmont *et al.,* 2011).

3.1.1. Bank Erosion and Transport Linkages

Bank erosion, bar accretion, and floodplain construction are natural processes of channel-floodplain material exchanges and control the geometry of channels. Bank erosion in particular is an integral part of dynamic habitat development along aquatic-riparian interface (Florsheim *et al.*, 2008). Bank erosion, when a significant contributor to the overall sediment budget of a river, can provide coarse sediment and woody material that drives the creation of beneficial hydraulically complex aquatic habitat (Florsheim *et al.*, 2008). Therefore, bank erosion should not be thought of as being deleterious in all conditions. When fine sediment derived from banks is determined to be in excess and affecting organisms mal-adapted to higher turbidity conditions, it can be viewed as ecologically detrimental (Palmer *et al.*, 2000).

There are many factors which influence the degree of bank erosion at the scale of a river reach, including local hydrodynamics associated with lateral flow, saturation conditions, freeze-thaw potential (Yumoto, 2006), material type as related to its internal shear strength (Gatto, 1995; Lawler, 1993), angle of the bank face (Rosgen, 2001), and intensity of riparian vegetation (Micheli and Kirchner, 2002; Micheli *et al.*, 2004). Many methods may be employed to quantify bank erosion and the timescale under consideration is important in the decision of which method to use. At longer timescales, repeated aerial and satellite imagery as well as stratigraphic investigations are commonly utilized techniques of understanding migration and bank erosion rates (Lawler, 1993). These timescales are beyond the scope a study such as this, so methods more appropriate at shorter timescales are used.

Techniques at annual to decadal scales attempt to quantify bank erosion through the estimation of volumetric or surficial changes of a bank face surface relative to a fixed datum. The most common method to estimate bank surface loss is through the deployment of erosion pins (Lawler, 1993). More sophisticated, but costly, techniques include the use of change detection via photogrammetric methods or terrestrial laser scanning (Longoni *et al.*, 2016). These techniques generally focus on the temporal aspects of bank erosion, but a recently emerging technique involves mapping the longitudinal distribution of bank failures from kayak surveys (Connell, 2012). A tradeoff in applying this technique is that finer temporal resolutions of bank erosion are sacrificed at the expense of spatially continuous longitudinal data. This practice of favoring rapid assessment of the spatial distribution of sources of erosion and the potential linkage to transport will be explored in this study.

Quantification of bank erosion and its manifestation in channel migration or overall sediment budgets is quite difficult, given the stochastic space-time dependencies that have emerged in such studies (Couper, 2004). Essentially, as with many other depositional and erosional processes, when considered at various nested spatial and temporal scales, quantification of bank erosion is controlled by the Sadler effect (Sadler, 1981; Couper, 2004). The Sadler effect is a realization of the irregular rates of erosion and deposition over shorter averaging windows (Sadler, 1981). For example, a short averaging window that takes into account higher magnitude erosion events may be skewed towards high values relative to a longer-term background rate. The opposite may also be true, where an averaging window that is dominated by very few events will be skewed towards values much lower than the average background rate (Sadler, 1981). Bull

(1997) explored bank erosion in a river with high fine sediment loads and monitored fluxes from study reaches with continuous data. In this study, it is found that the total material delivered did not in fact undergo immediate transport and was highly dependent on transport conditions at the time of failure, as well as the timescales over which rates of erosion and transport are considered (Bull, 1997).

3.1.2. Problem Statement

This project seeks to understand primary sources of fine sediment for the purpose of recommending mitigation strategies for the improvement of ecosystem services, the benefits of an ecosystem to a group or individual, available to downstream stakeholders. Given the resources to understand the longitudinal sediment budget at high spatiotemporal resolutions - can erosive signals, either transient or persistent in time, be tracked to their approximate spatial position on the landscape? Does significant in-channel storage and remobilization of SS act to obscure these primary erosive signals? It has been shown in Marsh Creek, the location of this study, that banks are the probable primary contributor of excessive SS to the channel (Chapter 2). The purpose of this study is to understand the longitudinal spatial frequency and magnitude of bank failures and explore potential spatiotemporal linkages between these failures and downstream SS flux in a turbidity-impaired watershed.

3.2. Study Area

Marsh Creek (MC) is a semiarid channel utilized for agriculture that drains ~1100 km^2 of land in SE Idaho (Figure 3.1a). The drainage is located in a N-S trending fault-bounded basin with mountain summits reaching up to 2500-2700 meters along the south, west, and east divides. The watershed receives much of its precipitation in the winter months and the mountainous portions of the basin build and ablate deep snowpacks that feed spring runoff, generally resulting in the highest flows for MC during this time. The basin has a broad, low valley floor (0.5-2km) that is susceptible to rain on snow events, which contribute to the highest discharge events. In the drier summer and early fall months, many tributaries lose connectivity to the channel and much of the perennial flow accumulations come from proximal spring inputs.

3.2.1. Geomorphic Setting

MC is a low gradient, underfit channel flowing generally to the north until its confluence with the Portneuf River (Thackray *et al.*, 2011). It occupies a wide alluvial valley (Figure 3.1a). This valley is flanked on either side by Pleistocene-aged fan surfaces, which have been partially or fully dissected by E-W trending tributaries (Thackray *et al.*, 2011). This abandoned fan surface and its relief above the MC floodplain is the result of a drop in base level and associated downcutting following the progressive formation of the eastern Snake River Plain by the Yellowstone Hotspot Track (Kruger *et al.*, 2003; Thackray *et al.*, 2011). Northern MC is located in a slightly more confined valley bordered on the east by the Portneuf Valley Basalt (430ka +/- 70 ka; Thackray *et al.*, 2011). It is inferred from middle and late Pleistocene stratigraphy that MC has hosted a low energy environment prior to emplacement of this basalt as evidenced by thick paludal deposits dated to ~637 +/- 3ka. Given this, MC has maintained poor drainage connection to the Portneuf and this is inferred to be a result of middle to late Pleistocene subsidence of the basin along local N-S trending faults (Thackray *et al.*, 2011). This, coupled with loess-rich deposits mantling much of the upper fan surfaces, has supplied contemporary MC with a large stock of fine sediment (DeVecchio *et al.*, 2002).

Most recently, MC is well known for being the spillway of the catastrophic Bonneville Flood at its SE divide 17.4 cal yr BP, evidenced by extensive melon gravel bars interspersed along the valley floor and south central benches (Malde, 1968; O'Connor, 1993). Prior to the Bonneville Flood, Thackray *et al.* (2011) infer that non-catastrophic drainage of Lake Bonneville during its highstand could have also accommodated much of the recent downcutting that formed the present alluvial valley.

3.2.2. Fine Sediment Impairment

MC has long been known to be a hotspot of fine sediment generation and delivery to the lower Portneuf River, which is utilized for ecosystem services by the Pocatello metropolitan area (McSorley, 1977). Historical reports sponsored by watershed partnerships using anecdotal observations and low frequency water quality data in the 1960s and 1970s indicated tributaries draining upland surfaces heavily utilized for grazing and farming as being the primary sediment conveyor to MC (McSorley, 1977). Born out of this report and regional efforts to target agricultural nonpoint sources was a patchwork of conservation practices, led by the State Agricultural Water Quality Program, focusing on mitigating sediment runoff from these operations, culminating in the USDA-sponsored Conservation Reserve Program, which has put a significant portion of this land into easements (NRCS, 2007).

Despite these efforts, MC continues to be listed as an impaired stream for various water quality parameters, including excessive turbidity, in the Portneuf Subbasin TMDL

(IDEQ, 2010). This current study is born out of a need to understand if there is a primary source of SS and how to best address it through conservation practices.

3.3. Methods

3.3.1. Bank Stability Kayak Survey

Bank instabilities and their relative magnitudes were mapped using tandem kayak survey crews on ~57 km of navigable channel on MC. Kayaks were equipped with Kodak SP360 cameras that capture forward-looking timelapse photography with full 180-degree fields of view. YSI 6900-series sondes logging turbidity at 5 second increments are strapped to the submerged portion of the bow of each kayak. Position was tracked continuously using GPS-enabled smartphones. In addition to this survey, ground crews measured discharge at every accessible point, including all long-term monitoring stations. Flow conditions were ~76% of the daily median as measured at the USGS gauging station at Site 6 (Station 13075000).

Turbidity data was cleaned using a median filter using a window of five points (equal to 25 seconds of float time) and a visual evaluation and removal of erroneous data due to bed disturbances or extreme biofouling. Resting periods greater than 30 seconds and portages were removed from the photo data. Turbidity and timelapse frames were georeferenced by matching the time of each observation with the clock of the continuous GPS track. The bank images are classified using a score of intensity scaled from 0-10 (Figure 3.2). A zero implies that no failure is present, while values at the lower end (1-3) imply a lower magnitude failure and values greater than 5 implied higher magnitude failures associated with a large surface area with little vegetation and stability (see Table 3.1). Additionally, if banks had evidence of cattle trample, this was noted. In addition to the accounting of bank instability surveys, the amount of riparian vegetative cover is also documented on a similar scale, where zero represents dense riparian forest, 5 represents some woody vegetation present, and 10 implies very little vegetative cover on the banks (Table 3.1).

Load data were calculated continuously along the transect using the synoptic discharge measurements paired with the roving turbidity data. In addition to these data, spatially continuous estimates of unit stream power are computed using median flows from March 2016-March 2017 at each monitoring station and channel slopes extracted from aerial LiDAR data acquired for the study area. This is summarized by the following equation:

$$\boldsymbol{\omega} = \frac{\boldsymbol{\rho g Q S}}{\boldsymbol{W}} \qquad \text{Equation 3.1}$$

where $\boldsymbol{\omega}$ is unit stream power (W/m^2), $\boldsymbol{\rho}$ is density of water (1,000 kg/m^3), **g** is the gravitational acceleration (9.8 m/s^2), **Q** is discharge (m^3/s), **S** is channel slope, and **W** is active channel width (m) as determined from ½-meter NAIP imagery (USGS, 2013). It should be noted that discharges during the NAIP acquisition are within ~80% of those determined during the kayak survey.

3.3.2. Monitoring Stations

13 monitoring stations were established in a longitudinal network along the mainstem of MC. These stations were equipped with 6900-series continuously logging turbidity, conductivity, and temperature every 15 minute. These data were paired with physical measurements of total suspended solids (TSS), herein referred to as suspended sediment (SS) and fit using a linear regression shown below.

$$\textbf{SS Concentration} = 2.2444 \times \textbf{Turbidity} + 4.1523 \; (r^2 = 0.89, \; p < 0.0001) \qquad \text{Equation 3.2}$$

HOBO water level loggers were also deployed at these sites in order to estimate flow using stage-discharge relationships. Flow data that had poor rating relationships due to high magnitude emergence of aquatic vegetation or changes in the bed level were interpolated using sites upstream and downstream with a characteristic time-lag. For more detailed information on monitoring techniques, see section 2.3.1.

3.4. Results

3.4.1. Longitudinal Profile and Stream Power

Figure 3.1 shows a 90-degree rotated map of MC with a longitudinal profile and continuous stream power plot lined up along the direction of flow. The longitudinal profile (Figure 3.1b) shows a strongly stepped profile with lower slope zones separated by local increases in gradient. Though these steeper gradient zones only cover one-quarter of the centerline distance, they accommodate ~71% of the total elevation drop of MC along our study reaches. Nine out of 14 of these drops are associated with major agricultural infrastructure (i.e., checkdams, culverts, bridges, diversions). Overall, this irregular spiking pattern in stream power reflects local increases in power coincident with these steps. Lower gradient zones settle out to values ranging from 0.5-1 W/m^2, 6-10 times lower than stream along the higher gradient zones.

3.4.2. Bank Instability Surveys

A majority of banks observed during this study are primarily composed of silt-clay soils that could easily undergo suspension once delivered to channel. Bank instabilities, variable in their overall magnitude, are present throughout all reaches of MC

(Figure 3.3a-b). A census of stable versus unstable banks show that a majority of banks in MC are undergoing some degree of erosion, with a majority of this manifested as lower magnitude bank slumps (Figure 3.3c). Grazing appears to have a significant impact on exacerbating preexisting instabilities (44.1% of all instabilities). It appears that grazing impacts on banks occurs more frequently in the 60-30 km range (Figure 3.3a). This is corroborated by observations of larger parcels used for grazing in the broader valleys of these reaches compared to the narrower valleys of the lower 30km that have smaller parcel sizes with smaller herds observed during field operations. Grazing-induced failures, solely caused by degradation related to cattle scratching and/or access for drinking, constitute a small portion of total failures at 7%. However, when averaging the left and right banks, these result in the single highest average scores (~4.5 versus 3 for cantilever-type failures, the next highest average score).

Interestingly, riparian vegetation cover is greater in the lower reaches, likely resulting in the apparent decrease in bank instability magnitude (Figure 3.3a-b). Field observations both during the survey and station maintenance showed that much more robust riparian buffer is present in these lower reaches at a greater frequency. Loads recorded on the day of the survey (Figure 3.3b) showed that the upper reaches were overall net transport reaches with some deposition centered around 50-40 river km while the largest increases in load occurred nearer to the confluence (12-10 km and 5-7 km). These load data, along with annual averages, are not obviously visually correlative with bank instability data. The largest single increase in load at 5-7 km is coincident with unstable longitudinal bars that extended a few km upstream of a checkdam that was in a lowered position at the time of the survey. It is important to note, however, that this represents a zone of storage that is currently being remobilized following an artificial rise in erosive power as the dam was lowered. This is not the signal of primary erosion of bank material, only a transient signal associated with remobilization. Figure 3.3c showed that evidence for livestock trample is present in more than half of areas with some degree of bank erosion.

3.4.3. Station Connectivity During a 5-year Flood Event

By and large, the highest magnitude event during the monitoring period was an approximately five-year flood lasting ~75% of February 2017 (Figure 3.4). Three high magnitude protracted flow peaks with amplitudes of 21 m^3/s, 13.2 m^3/s, and 14 m^3/s as measured at site 2 were fueled by a series of rain on snow events in which infiltration capacities were diminished by frozen ground which later reverted to oversaturated conditions as thaw occurred (Figure 3.4). This provided a unique opportunity to document the complete exhaustion of bed-stored sediment and track sediment pulses as the event progressed. Figure 4b shows staggered SS load time series for each site in operation. Nonlinear patterns emerge in the generation and translation of SS pulses at each site. A ‘first-flush’ exhaustion signal, displaying clockwise hysteresis, is traced from Site 9 to the confluence. This signal appears to amplify in the downstream direction as additional sediment is entrained by the translating discharge wave.

During the incipient rising limb Feburary 7-10, streamflow is primarily contained within the banks. After peak discharges are reached February 10-11, flow begins to spill out onto the floodplain. It is inferred that following the storage-amplified first-flush, much of the ensuing sediment transport observed is inferred to be primarily bank-sourced. A pattern of signal generation and immediate or progressive attenuation appears to emerge during this phase. An example of this is shown during the days of 2/21 – 2/22 where two high magnitude pulses are generated at site 9 and site 10 but signal dispersion and attenuation occurs. One probable explanation for this phenomenon could be advective storage of a portion of this slug on the floodplain. Significant floodplain deposits are observed following this event. Site 11 was also an area that likely experienced significant storage, as evidenced by storage between sites 15 and 10 (Figure 3.4) based on estimates of cumulative SS flux at as well as burial of the sensor at this site. Downstream of this point, however, sediment flux generally increased towards the confluence through the integration of basin-wide non-point sources.

3.5. Discussion

3.5.1. Distributed Bank Sources

Bank instability data from the kayak survey detail a heterogeneous but longitudinally dense series of bank failures. These bank failures appear to be strongly enhanced by both the absence of riparian buffer and grazing activity. Overall, most

reaches appear to have bank instabilities. Recently, projects in the MC basin have been implemented to mitigate the direct impact of cattle on the channel. These projects include the installation of off-channel watering troughs, exclosure fencing, and riparian planting. These projects are cost-share collaborations between local government organizations and landowners (e.g., NRCS, 2009; IASCD, 2013). One dimension not captured in this assessment is the temporal aspect of bank failures and the timing of inputs into the channel.

3.5.2. Decoupling of Suspended Sediment Flux from Bank Sources

When comparing daily or seasonal SS flux data to various estimates, it is evident that there is no clear connection between bank sources and interstation increases in flux. Figure 3.5 shows station differencing of average fluxes over (a) the full annual period and (b) the February 2017 5-year flood compared to bank instability averages bracketed by these stations. No matter the state of connectivity, it appears that no discernable signal exists between the spatial magnitude distribution of bank failures and reach-scale downstream SS fluxes. This seems to suggest that these when these sources turn on, downstream transmission is mitigated by temporary sediment storage centers. This complex relationship of transient storage is not captured in this simple comparison of sources to flux.

3.5.3. Comparison of Suspended Sediment Flux to Stream Power

As suggested above, given sufficient supply, the state of erosive power and transport capacity may be an important determinant of total flux. Figure 3.5 shows station flux differencing at a reach-scale compared to average unit stream power between differenced stations. The spring 2016 data shows a slight positive correlation between sediment storage and/or recruitment. This relationship is extremely weak during the flood event, potentially due to a strong remobilization signal associated with the incipient first flush. Additionally, floodplain-channel exchanges occurring at the scale of this event, evidenced in signal attenuation in Figure 3.4, would not be captured by a comparison to stream power alone.

3.5.4. Integration of Storage and Remobilization

These patterns of storage and remobilization of SS suggest that a significant portion of sediment dynamics, even in fine-grained systems, are controlled the position, trapping efficiency, and capacity of depositional zones. Figure 3.6a-b illustrate a conceptual model of source, sink, and longitudinal SS flux where storage zones, most effective during times of lower transport capacity (i.e., summer baseflows, induced backwaters), act to attenuate the integrated signal of non-point sources of sediment. When transport capacity rises (i.e., storm response, dam lowering), these transient storage zones become activated as sediment sources. Taken at face value, these perform as punctuated point-source regions (Figure 3.6b). An analysis of the relationship between flow and sediment concentration can help to clarify potential modes of sourcing. Higher magnitude events have the potential to prevent transient storage and sediment pulses may be effective tracers of erosive signals. This does appear to have a limit, as floodplain storage may also act as a form of signal attenuation and storage which could act to sequester such signals on the order of millennia through floodplain construction (e.g., Walling and Owens, 2002; James, 2010; Fryirs, 2013).

In the analysis done on bank imagery, one dimension not considered during bank instability analysis was bank height, as this was difficult to determine with hemispherical cameras. Bank heights, coarsely derived from LiDAR using 100-m spaced cross-sections showed no definitive trend of increasing bank heights in the downstream direction (Appendix B, Figure B.3.). When compared to slope, bank heights do appear to respond by increasing downstream of inflection points (Appendix B, Figure B.3). It is clear that higher slopes and increased discharge resulting in greater stream power the lower 40 km of MC (Figure 3.1) and that this increased erosive energy is coincident with increased flux of SS annually (Figure 2.5, 3.5).

3.5.5. Important Considerations for Monitoring

What this bulk behavior results in is an obfuscation of sediment sources whereby the patterns of sediment in transport completely fail to reveal incoming erosive signals. Therefore, given these complex transport dynamics, a water quality array of any density may not provide the adequate means to pin down spatially explicit sources during most flow conditions. In fact, over shorter timescales (i.e., during a more constrained flow regime), transport dynamics may be completely dominated by sediment remobilization depocenters – potentially leading to an erroneous understanding of where sediment sources may arise on the landscape. The idea of supply limitations dominating SS transport dynamics that has been suggested in previous studies (e.g., Gellis, 2013; Walling, 2005; Walling and Collins, 2016) may only give part of the story – it appears that within this riverine domain, longitudinal variations in transport capacity are also important, especially at timescales shorter than a full year.

Another important aspect of the non-triviality of transient storage of SS is the potential for a time-lagged response between the implementation of sediment mitigation strategies and improvements in water quality. It is clear that both in this study and previous studies, that there are non-linear thresholds and dependencies which may alter the timescales over which SS stored in a watershed may be exported (e.g., de Vente, 2007; Kamarinas *et al.*, 2016; Owens and Xu, 2011). Therefore, management of the expectations of stakeholders over the timescales in which water quality may respond to conservation projects is important.

3.6 Future Work

Further analysis of monitoring station data could involve the analysis of sediment pulses transmitted through stations using signal processing techniques such as cross-correlation or spectral analyses. Though it is revealed that these signals are complex and undergo serious transformations while under transmission in the system, a robust time-series analysis of SS concentrations signals could reveal important dynamics about mobilization and storage of SS pulses as they move through a riverine system.

Additionally, given the richness of the SS load dataset produced, the author believes that novel approaches to sediment source identification could be done using inverse modeling. Inverse models use a set of observations in to derive a model that explains their causal mechanisms. In modeling physical systems, such as the SS load time series as presented here, a set of inverse model outcomes may be constrained using physically possible parameters.

Additionally, erosion pin or surface change detection studies could be implemented in reaches that have higher stream power that have been identified to have greater amounts of SS conveyance. This would provide more quantitative data on the rate of delivery of sediment to the channel and could be extrapolated across reaches of interest. This would ultimately assist in more site-specific prioritization of sediment mitigation projects targeting bank erosion.

3.7. Conclusions

In this study, an exploration of the potential spatiotemporal linkages between bank erosion and sediment flux is explored via a kayak survey paired with data from a dense longitudinal water quality array. It was initially expected that segments with visual evidence of more bank erosion would be reflected within flux data at various timescales but a very poor correlation between these two was found. Additionally, evidence of signal attenuation related to channel network and/or floodplain storage was explored for a high magnitude event. It is clear that sediment transport dynamics (e.g., primary erosion, storage, and remobilization) exert a complex control on the character of observed sediment flux, even in fine-grained systems. Given the considerable time and effort required to maintain a water quality network, if the aims of a project are to identify sediment sources, other means of tracing sediment such as sediment fingerprinting may yield a more efficient and complete understanding of the relationship between potential sources and sediment flux.

Chapter 3 Figures

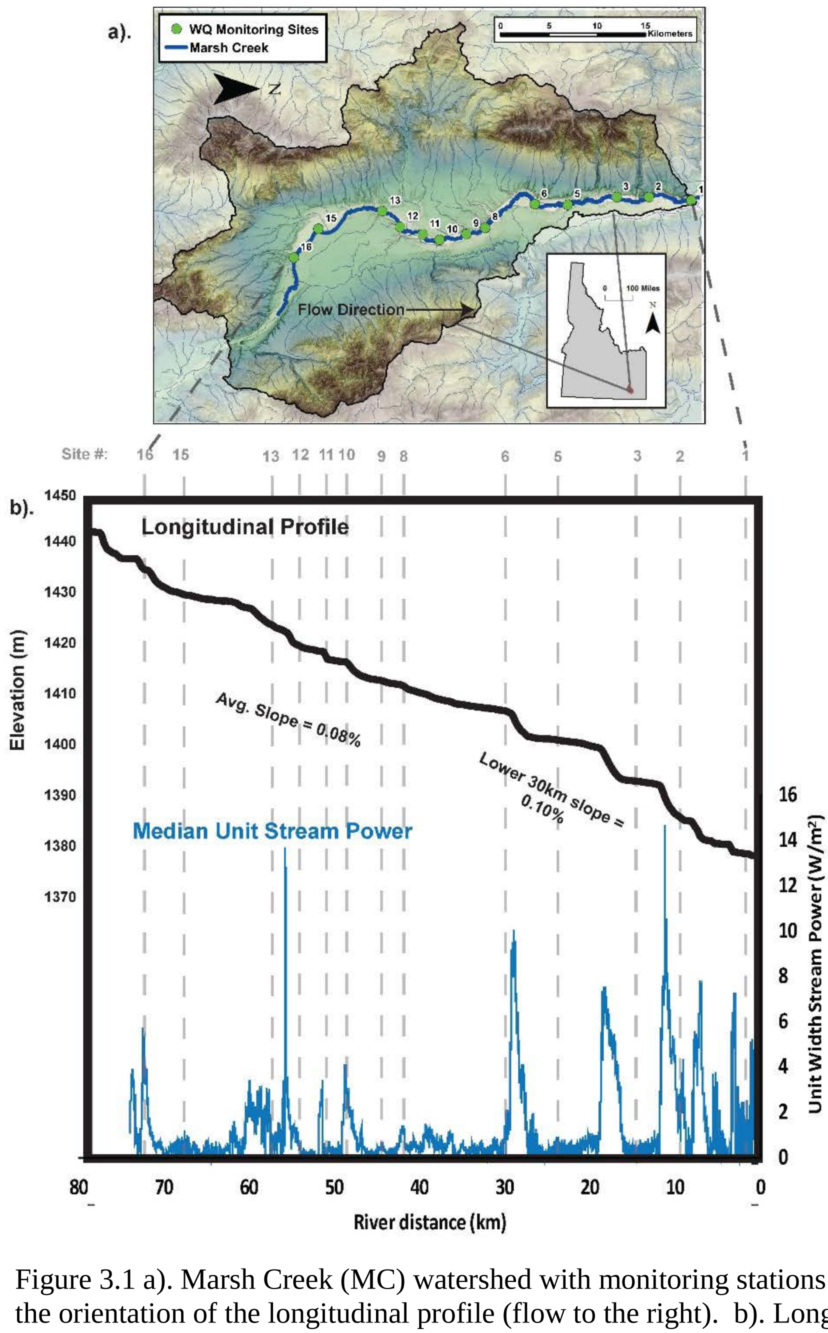

Figure 3.1 a). Marsh Creek (MC) watershed with monitoring stations tilted in the orientation of the longitudinal profile (flow to the right). b). Longitudinal profile and continuous estimates of unit stream power. Note the stepped profile of MC; these high gradient zones accommodate three-quarters of the elevation drop of MC.

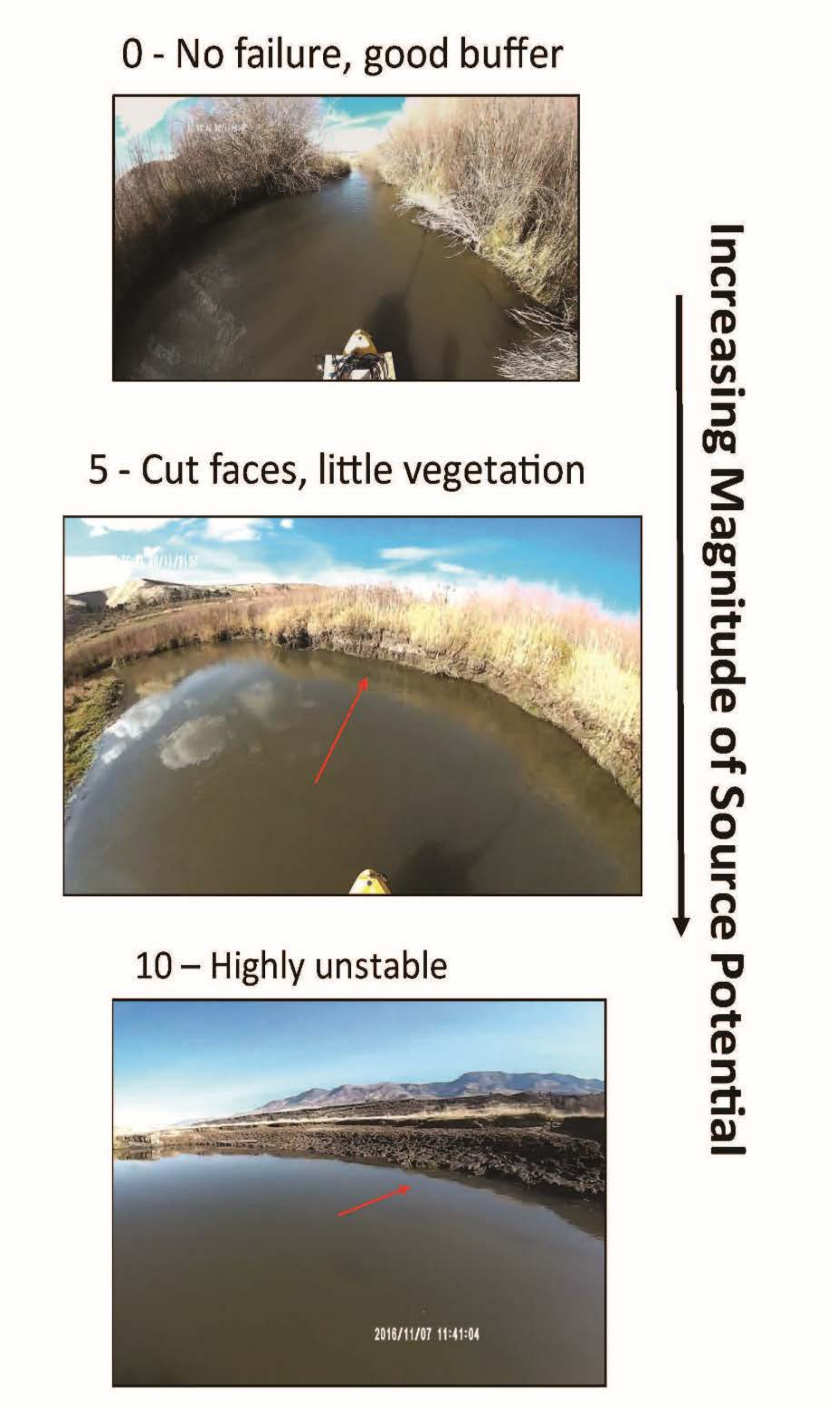

Figure 3.2. Visual examples of classification scores of bank instabilities from kayak survey images. Values range from 0 (no erosion) to 10 (very severe erosion). Red arrows pointing at erosive features. See Table 3.1 for more details.

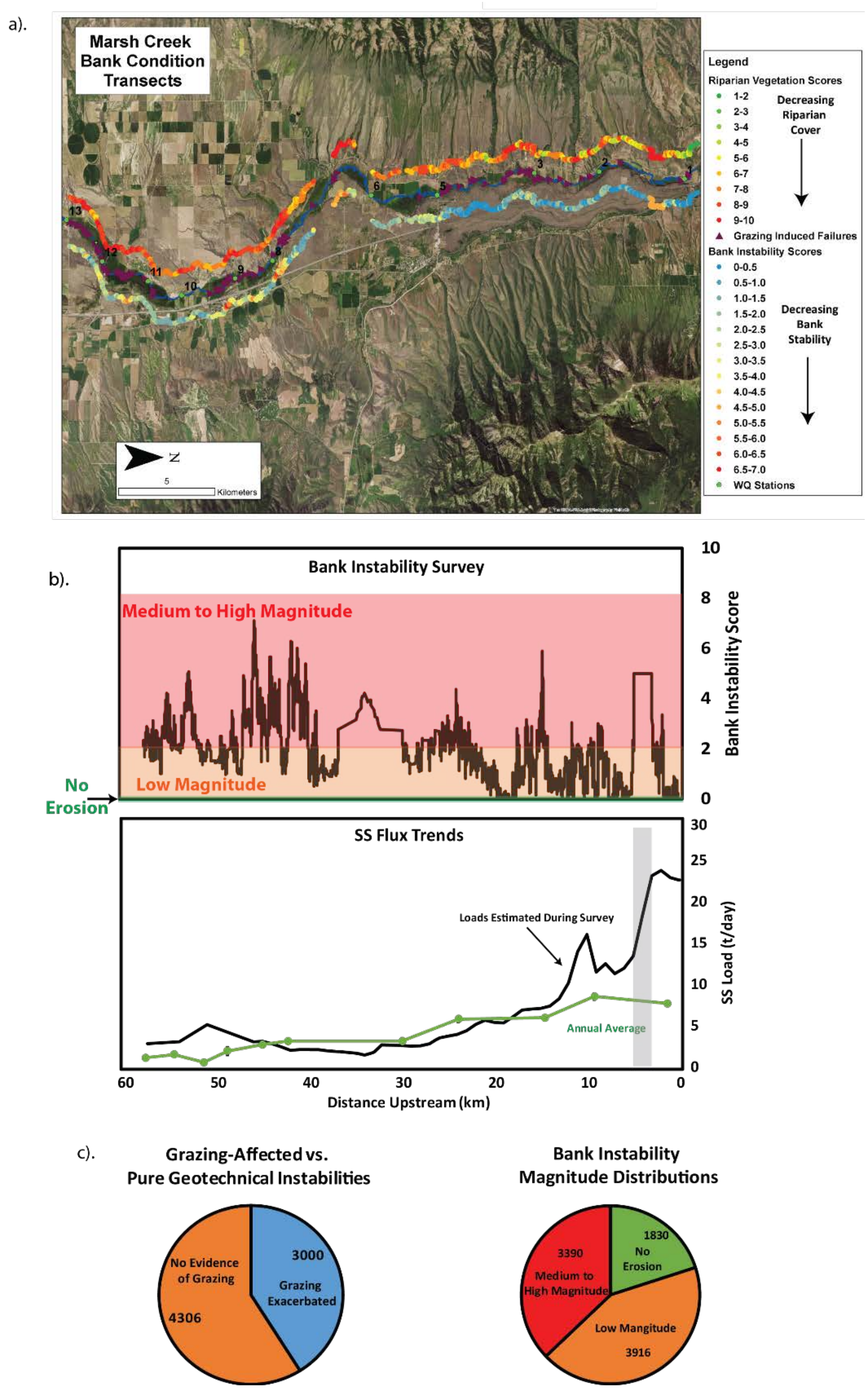

Figure 3.3. Map view of staggered transects of riparian vegetation scores, cattle-induced failures, and bank failures along Marsh Creek. Note that riparian condition generally improves in the downstream direction. b). Comparison of bank instabilities to continuous estimates of flux during the survey and annual load average by site. The grey bar shows an increase in load associated with a remobilizing depositional zone within a checkdam backwater. c). Bank failure statistics related to grazing and a breakdown of bank instability magnitudes. Scores are broken down according to magnitude divisions as delineated in graph b.

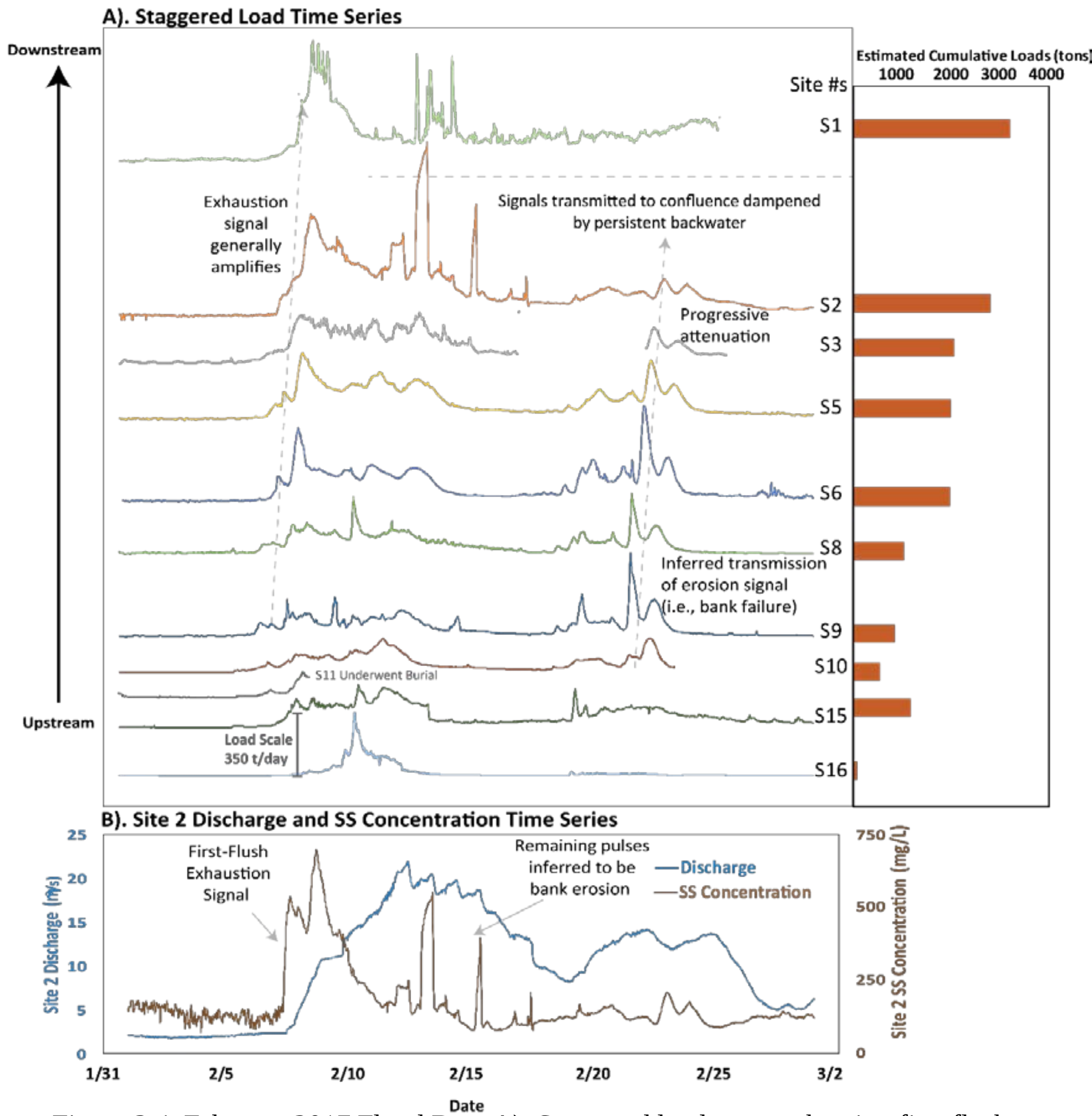

Figure 3.4. February 2017 Flood Data A). Staggered load curves showing first flush pulses and subsequent. Total estimates of flux estimated by bars on the right. Note that flush signals appear to amplify while remaining erosive signals attenuate. Truncated or missing data due to instrument malfunction. B). Comparison of sediment concentration for Site 2 showing evidence for exhaustion vs. inferred erosion based on strength and type of hysteretic patterns.

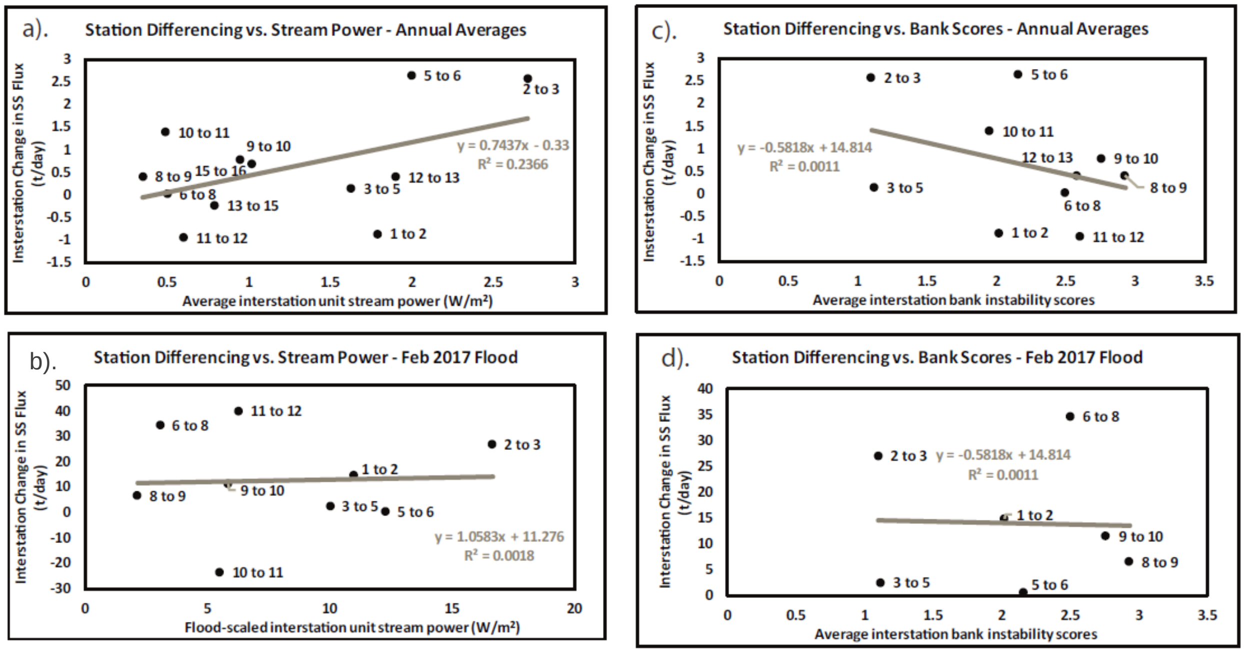

Figure 3.5. a). Inter-station unit stream power plotted against annual inter-station change in SS flux. b). Scaled inter-station unit stream power plotted against February 2017 5-year flood change in SS flux. c). Inter-station bank instability scores plotted against annual changes in flux. d). Inter-station bank instability scores plotted against a 5 year recurrence interval flood. These data show that flux data is primarily uncorrelated with both stream power and bank instability density, except for a minor positive correlation between annual flux and stream power.

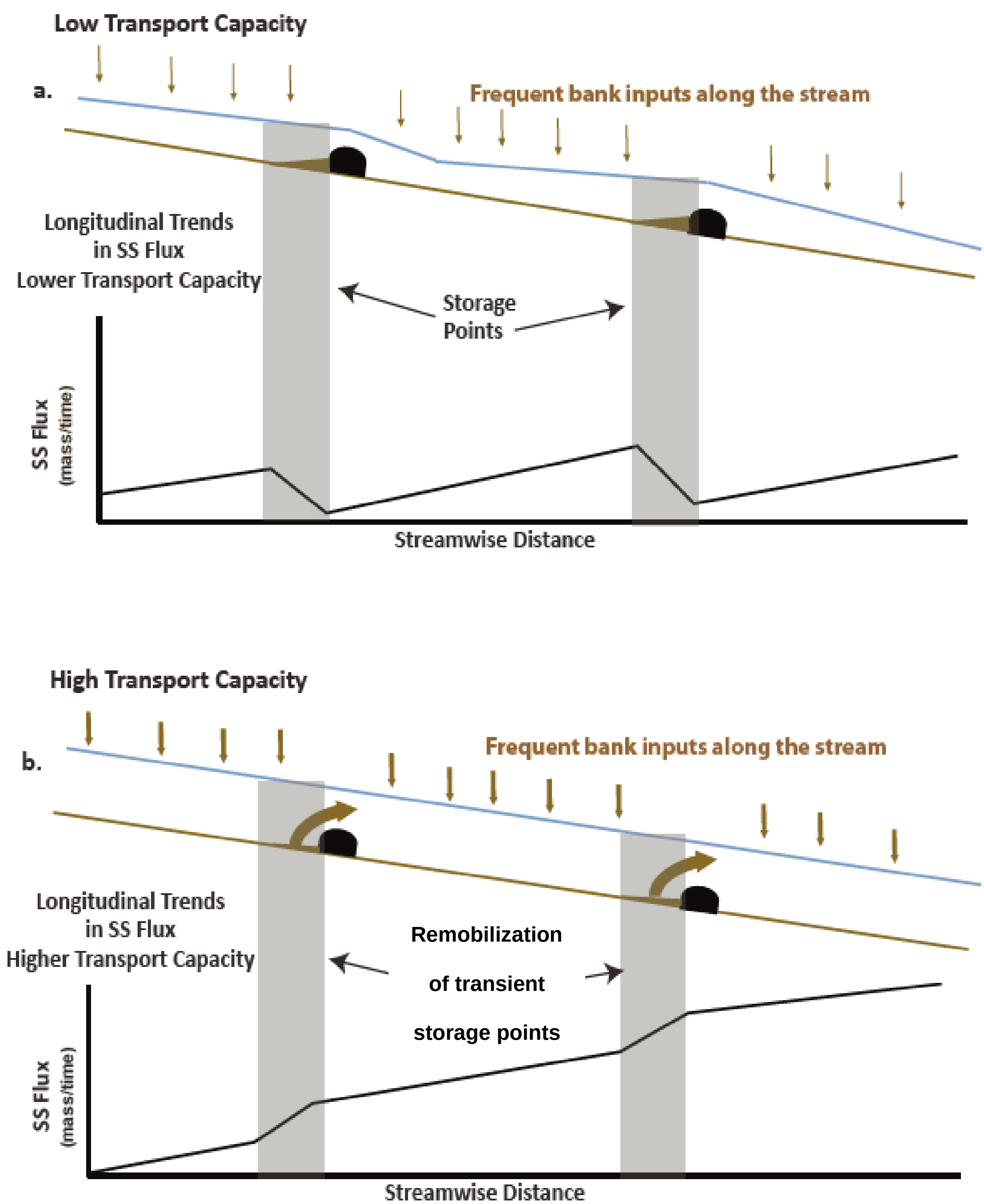

Figure 3.6. Conceptual model of sediment delivery, storage, and remobilization. A. Lower energy conditions promote bed storage in low gradient reaches. B. Higher flow conditions remobilize storage points along with increased bank inputs. Overall, the export of sediment is composed of that which is primarily eroded as well as significant remobilized suspended sediment.

Chapter 3 Table

Bank Erosion Image Classification Score Explanation Table			
Bank Erosion Magnitude Score	**Bank Characteristics**	**Riparian Vegetation Score**	**Vegetation Characteristics**
0	No evidence of bank erosion, well-vegetated	0	Dense riparian forest
1	Very minor bank erosion, usually associated with minor slumping that is well-vegetated	1	Riparian forest
2	Minor bank erosion, area affected less than 25 centimeters in height, usually associated with slumping, somewhat well-vegetated, bank trample may be evident in scores 2 or greater	2	Thin, continuous riparian forest
3	Moderate bank erosion, significant, area affected less than 25 centimeters in height, slump or minor cut face, some grass present on bank area	3	Continuous strip of woody riparian vegetation, dense shrubs present
4	Moderate bank erosion, height affected ranging from 25-50 centimeters, significant bank slump or minor cut face, little grass present on bank area	4	Discontinuous strip of woody riparian vegetation, dense shrubs present
5	Moderate bank erosion, bank heights 50-100 centimeters above water surface, major cut face, very little grass present on bank area	5	Sparse woody riparian vegetation, shrubs present
6	Moderate bank erosion, bank heights 50-100 centimeters, major cut face, bare soil	6	Shrubs present and/or dense grass
7	Severe bank erosion, area is greater than 1 meter, usually induced or exacerbated by cattle trample, bare soil	7	Some shrubs present with continuous grass coverage
8	Severe bank erosion, area affected is greater than 1 meter above water surface, usually induced or exacerbated by cattle trample, bare soil	8	Continuous grass coverage
9	Very severe bank erosion, area affected greater than 1.5 meters in height above water surface, only induced by cattle trampling, bare soil	9	Discontinuous grass coverage
10	Very severe bank erosion, area affected greater than 2 meters in height above water surface, only induced by cattle trampling, bare soil	10	Bare soil, vegetation absent

Table 3.1. Explanation of image classification scores for both bank instabilities and density/presence of riparian vegetation. Bank scores range from 0 (no evidence of erosion) to 10 (significant erosion and source of sediment). Vegetation scores follow a similar related trend where 0 represents very dense vegetation and increasing values imply less vegetation leading up to 10 (the complete absence of vegetation).

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Chapter 4. Conclusions and Recommendations

4.1. Chapter 2 Summary

In this study, a dense longitudinal array of water quality is used to characterize sediment sources in Marsh Creek, an impaired and intensively-managed stream. High-resolution suspended sediment flux data show that there is a general downstream accumulation in sediment flux at the annual scale. Additionally, a moderate degree of SS supply exhaustion is observed during hydrographic events, implicating local bed and bank sediment sources. Through comparing mass balances of sediment flux in tributaries and stations bracketing their confluences, it is also found that tributaries account for insignificant contributions to the total loads in Marsh Creek. Sediment fingerprinting is performed using stable isotopes and organic contents on three source endmembers: (1) agricultural topsoil, (2) pasture topsoil, and (3) vertically-integrated bank profiles. Sediment samples are collected at a downstream station and compared to these endmembers. Sediment samples appear to strongly reflect the bank characteristics in terms of their $\delta^{15}N$ and C:N ratios.

These spatiotemporal load and geochemical data indicate that banks are the primary source of sediment. Interestingly, it is found in the temporal analysis of stations that a load passing through one station may not be seen passing through a paired downstream station both at the event-scale and at season scales. These represent times of sediment storage between stations where an impulse upstream of sediment above the upper measurement point is sequestered in the reach between the two stations. This implies that a significant amount of eroded sediment is transiently stored and remobilized while undergoing export out of the basin. This has serious implications on the interpretation of load data in longitudinal studies, where a significant component of the translation of SS signals between stations is representative of remobilization. Importantly, these results also provide a case study where a longitudinal downstream accumulation in sediment flux is found in a watershed with evidence of non-point bank erosion present in most reaches. This accumulating signature could prove useful to other studies that have implemented longitudinal arrays in a channel network.

4.2. Chapter 3 Summary

In order to understand the potential linkages between source and associated transport signals, we characterize the spatial distribution and frequency of bank instabilities longitudinally along Marsh Creek. This involves a roving kayak survey using hemispherical cameras that are classified and georeferenced. These data show that bank instabilities are longitudinally distributed throughout MC with a significant amount of spatial heterogeneity. When these values were averaged by reaches between stations and compared to annual estimates, there is poor correlation between the apparent magnitude of bank erosion and reach-scale sediment conveyance. Additionally, stream power is determined using gradients derived from LiDAR topographic data and median stream flows. A similar comparison using interstation changes in flux and average stream power shows poor but more improved correlation.

This apparent disconnection between evaluation of bank sources, transport capacity, and observed transport patterns lends more evidence to transient storage and remobilization being a critical factor in flux trends, even at the annual scale. This has important implications on the limitations of using high-resolution spatiotemporal data to trace out fine-scale spatial locations of source areas. Additionally, it provides compelling evidence of the importance of transient storage, even in fine-grained systems. This is important for managing the temporal expectations of stakeholders after conservation practices targeting non-point sources have been implemented. Additionally, it provides an excellent framework for the evaluation of reach-scale persistent sediment sources through the analysis of channel migration using historical imagery as well as a contemporary snapshot of sediment sources to compare against historical sources using geochemical stratigraphic analyses.

4.3. Recommendations for Stakeholders

It is clear through this work that bank sources are the primary source of sediment in Marsh Creek and that they are widely distributed across its entire mainstem. Zones of greater transport capacity in the lower 30 km of the channel have resulted in larger amounts of sediment delivered through bank erosion in these reaches. Predisposed by its Quaternary geology, this watershed has a large potential supply of fine sediment mantling its surface and stored within its banks. The utilization of the benches and floodplain for farming and grazing have resulted in the progressive clearing of riparian corridor and some significant bank destabilization related in part to grazing (with ~44% of the channel length surveyed being cattle-impacted to some degree as indicated in this project). No single group or individual is the main contributor to poor water quality in Marsh Creek and the Lower Portneuf. Instead, these results show that this problem is systemic. Hundreds to thousands of banks may be contributors of sediment for a given period, which ultimately become integrated through time and space as one moves further downstream. A systemic problem requires a systemic approach in order to address it. This next section details approaches to address sources of high turbidity. Please see

Appendix A for a more detailed treatment of these concepts and suggested recommendations.

4.3.1. Project Types and Framework Summary

Please see, Appendix A: Recommendations for Improving Water Quality in Marsh Creek, for a full overview of general recommendations to reduce sediment conveyance and improve water quality in Marsh Creek and the lower Portneuf River. A brief synopsis of recommendation strategies is given below.

Given that Marsh Creek derives much of its suspended sediment load from bank erosion, it is recommended that approaches to mitigate bank erosion be applied to Marsh Creek. Projects that act to harden the banks (e.g., installation of cement walls, rip-rap, etc.) are not recommended as these projects commonly act to increase bank erosion locally. Practices that discourage cattle activity near the channel and utilize bioengineered designs for bank stabilization are recommended. Please see Appendix A for more details.

Additionally, given that Marsh Creek is a low-gradient system that was likely historically integrated into a riverine wetland floodplain complex, sediment retention projects that increase the amount of wetland/floodplain deposition of sediment throughout the water year are recommended. Many intermittently-connected wetlands exist in Marsh Creek and could be perennially reintegrated with the channel. Also, low-lying areas in the floodplain could be used as sites for constructed wetlands. As with both bank erosion mitigation and sediment retention projects, it is clear that a large bulk of sediment (>60%) is derived from the lower 30 km of Marsh Creek, so these reaches should be prioritized for such projects. Please see Appendix A for more details.

4.4. Future Work

As has been emphasized in the preceding chapters, this project is limited in its temporal scope. Long-term studies that could characterize sediment hotspots through historical image analysis of channel migration are recommended. Additionally, given the considerable effort and resources already put into conservation practices, time series analysis of historical water quality data could help elucidate whether these practices have made gains in the improvement of turbidity in Marsh Creek.

Additional projects with a broader temporal scope also could include the analysis of floodplain and bank stratigraphy using radiometric dating techniques such as depth profiles of ^{7}Be, excess ^{210}Pb and ^{137}Cs. Based on the concentrations of these radiometric tracers with depth, inferences can be made about the antiquity of these deposits. This has important implications on whether the current Marsh Creek system is reworking ancient sediments or legacy sediments related to land use shifts in the 19th and 20th centuries.

4.5. Project Limitations and Lessons

As with any scientific endeavor attempting to understand complexities that arise in natural systems, there are limitations. Of course, as has been iterated before, this study is limited in terms of its temporal scope. There could exist a significant lag time between sediment production and basin export, even from proximal sources (as this study shows). This makes inferring areas of greater sediment production using a longitudinal mass balance much more difficult the smaller the timescale may be. This effect is similar to the Sadler effect encountered in quantitative stratigraphy, where smaller averaging windows of stratigraphic section are subject to greater bias from larger (or persistently smaller) depositional or erosional events (Sadler, 1981). Longer averaging windows are required to attain a baseline rate of erosion and/or sediment flux, especially when trying to make a comparison to a historical baseline or evaluate whether human activities have exacerbated increased erosion and sediment flux from a basin.

Given the considerable effort put into monitoring and some in-house instrumentation problems associated with analyzing grain size distributions of fine sediment, estimates of grain sizes were never documented during this project. This information is useful in determining the entrainment and transport potential of sediments. Is sediment in Marsh Creek primarily silt and clay and subject to considerable grain-to-grain cohesive forces (greater than gravitational ones)? This has implications on the transport and storage behavior of these sediments. Even with this information in hand, however, the behavior of cohesive suspended sediment is highly complex and constantly evolving based on chemical and biological interactions between water and cohesive aggregates (Droppo, 2001). It is also extremely difficult to analyze these, given that suspended sediment aggregates (known as flocs) can be easily destroyed by these analytical techniques (Woodward and Walling, 1992). The use of elutriation techniques that preserve floc characteristics of suspended sediments (Walling and Woordward, 2007) or *in-situ* laser diffraction techniques (Czuba *et al.*, 2015) attempt to circumvent this, but are generally cost-preventative for most government-funded monitoring studies.

Additionally, it is clear that analysis of bulk stable isotopes of sediment and soil, are subject to the seasonality of biological nitrogen transformations and/or additional inputs from nitrogen deposition that could mitigate trans-seasonal comparisons (see Appendix B, Figure B.2.). The ability to use stable isotopes, is however, cost-effective and does appear to be applicable when samples are collected in a single season. If given additional resources, the use of more conservative tracers (i.e., fallout tracers, compound-specific stable isotopes) would be preferred.

Additionally, to follow up to the realization of the importance of transient bed storage of SS, it would be interesting to develop a project to understand bed aggradation and degradation using cheaper ‘DIY’ (do-it-yourself) sensors attached to anchored rebar that could log time series data on the amount of light or some other parameter sensitive to being buried in sediment. Given the cost efficiency of such sensors, these could be deployed at an even finer spatial scale and could help quantify residence times of storage, spatial distributions of transient storage, and the fraction of SS on the bed in a sediment budget during a given year.

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Appendix A: Recommendations for Improving Water Quality in Marsh Creek

Disclaimer: This report is intended for interdisciplinary scientists, engineers, and planners interested in improving water quality in Marsh Creek and the lower Portneuf River. Conclusions from this study are intended to guide future remediation and sediment mitigation efforts at the scale of both local reaches and the entire mainstem. This recommendation is a general guide on how to best reduce suspended sediment sources and/or enhance sediment deposition based on a one year, longitudinal water quality dataset, source identification from a single kayak survey, and an isotopic sediment fingerprinting campaign over a single season. Prior to the implementation of remediation and sediment mitigation efforts, appropriate actions should be assessed and prioritized based on stakeholder feedback. This report, in no way, outlines or recommends site-specific projects in Marsh Creek. Detailed, site-specific analyses should be conducted by professionals in their respective fields. They will identify the most appropriate suite of actions, refine conceptual plans, and develop comprehensive plans for implementation and effectiveness monitoring. The authors assume no responsibility for actions taken in response to this document.

Introduction

This recommendation report is the culmination of data collection and interpretation from an Idaho State University M.S. Geology project led by James Guilinger and advised by Dr. Ben Crosby. It is intended to serve as a coarse-scale recommendation framework on how to improve water quality conditions in Marsh Creek (and by extension, the lower Portneuf River) as it relates to excessive suspended sediment and turbidity. Please carefully review the disclaimer above and understand that this recommendation report does not serve as a site-specific guide to restoration or remediation projects and only attempts to advise stakeholders on suites of actions that have the potential to improve water quality in Marsh Creek.

Study Design

In this project, we use three techniques to identify the primary sources of suspended sediment in Marsh Creek, which has been classified as impaired due to excess TSS under the clean water act. First, we deployed water quality monitoring stations at 13 locations along Marsh Creek, equipped with sensors that continuously measure the amount of sediment being transported along all reaches of the channel between March 2016 and March 2017 (Figure A.1.). Second, we executed a kayak survey equipped with hemispherical cameras and GPS-enabled smartphones to collect ‘Google-Street View’-like data on the spatial distribution and magnitude of bank erosion along ~57 km of channel. Third, a sediment fingerprinting sampling campaign was performed to determine if there was a distinct chemical stable isotopic signature for in-stream sediment that could be correlated to one of three local sources: eroding bank profiles, crop topsoils, and pasture topsoils. LiDAR topographic data acquired for this study and conclusions from a previous geological study (Thackray et al., 2011) were used to infer the pre-settlement geomorphic conditions of Marsh Creek. Detailed below are the results and conclusions of this study pertinent to the characterization of sediment sourcing and transport in the channel and what suite of actions are deemed appropriate to reduce high levels of suspended sediment in the channel.

Summary of Pertinent Results and Conclusions

1. Based on our in-stream monitoring of sediment flux, frequent observation of trampled and collapsing banks, and sediment fingerprinting, we conclude that the primary source of fine sediment in Marsh Creek is mainstem bank erosion. Sediment delivery from the banks is not equal in all reaches. For example, reaches in the lower 40% of Marsh Creek contribute more than 60% of total annual sediment load (Figure A.2.).

2. Insight from previous workers (Thackray et al., 2011) and analysis of high resolution topographic data indicate that pre-settlement, broad riverine wetlands occupied large expanses of Marsh Creek's floodplain. These wetlands were disconnected from the mainstem through leveeing and channelization and filled in to create arable land beginning in the late 19th century (Figures A.2., A.3., and A.4.).

Chronic and excessive suspended sediment in Marsh Creek is primarily derived from mainstem bank erosion and exacerbated by mainstem disconnection with floodplain wetland complexes following historical leveeing and channel modification.

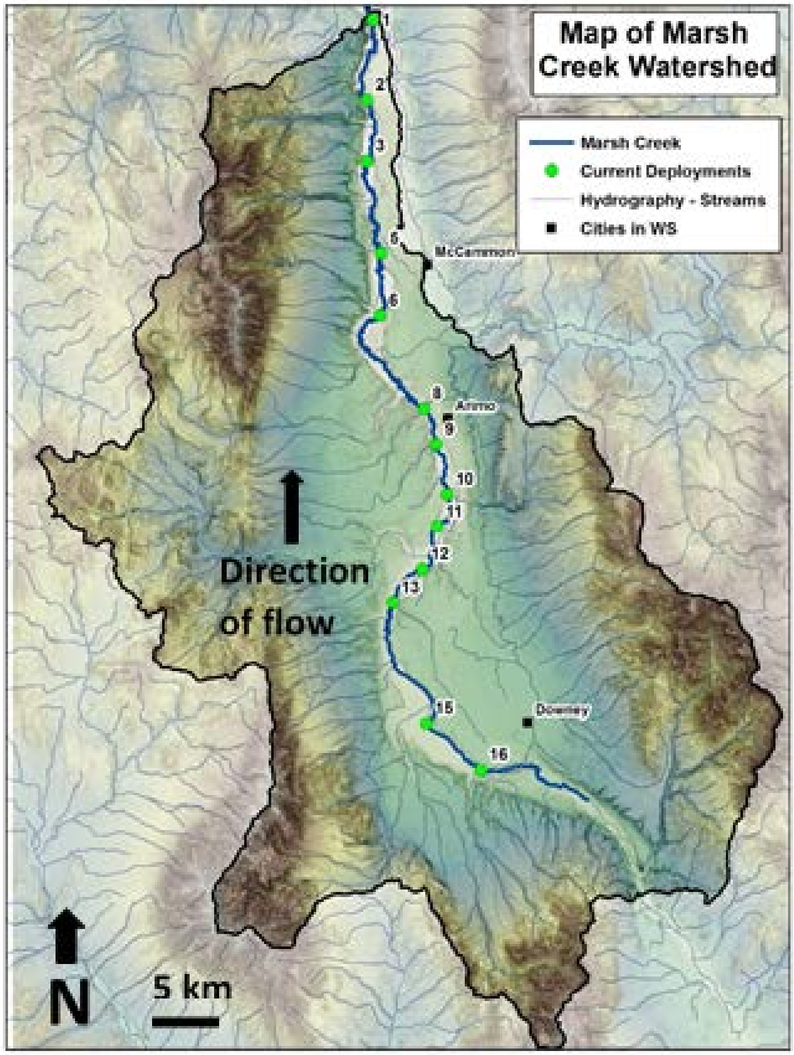


Figure A.1. Map of Marsh Creek subbasin with channel and locations of the 13 water quality monitoring stations shown. Mainstem channel is bold blue line. Direction of flow along the creek is from south to north.

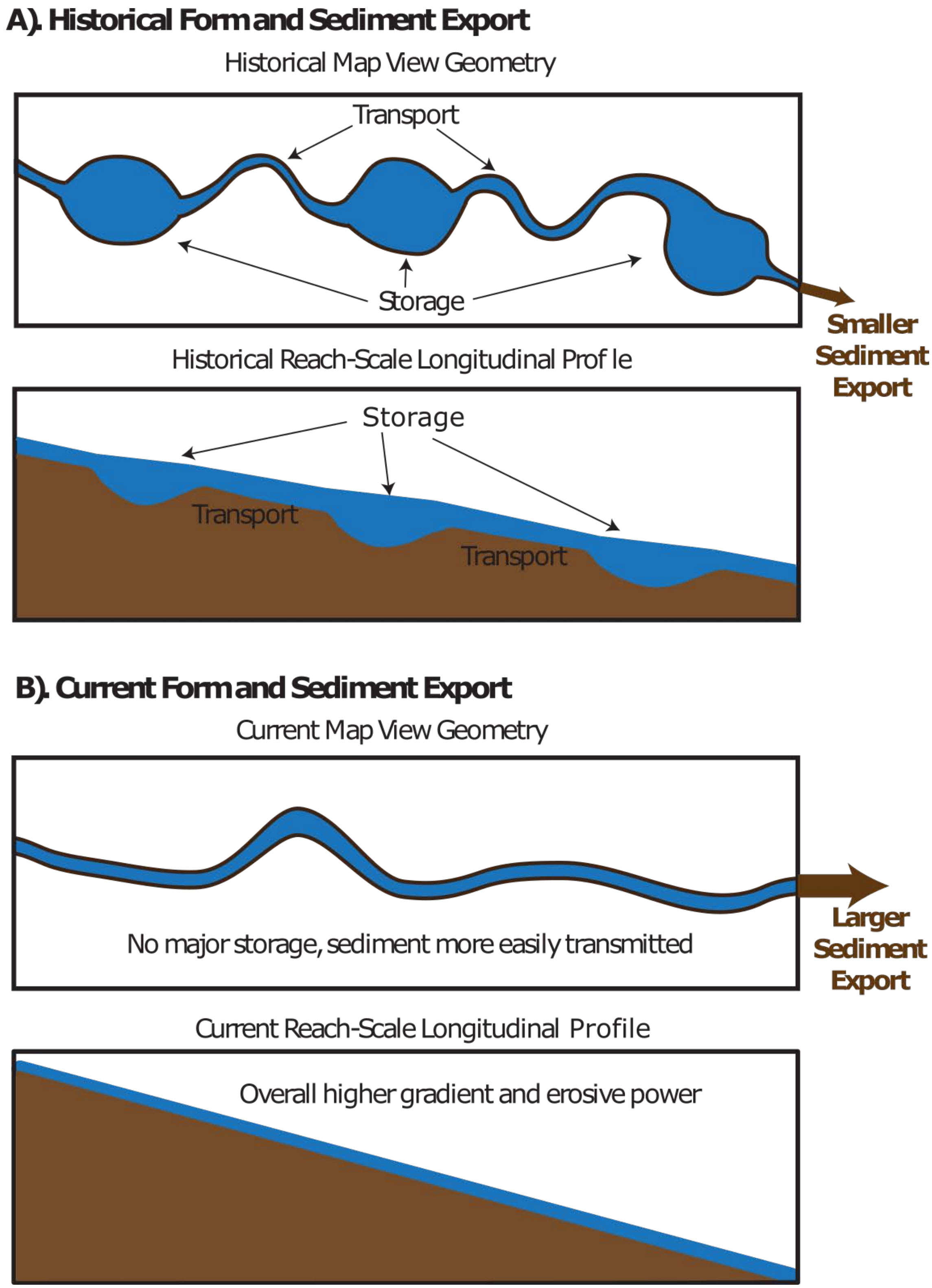


Figure A.2. Conceptual figure of historic conditions and current conditions in Marsh Creek in relation to channel geometry and its controls on sediment transport.

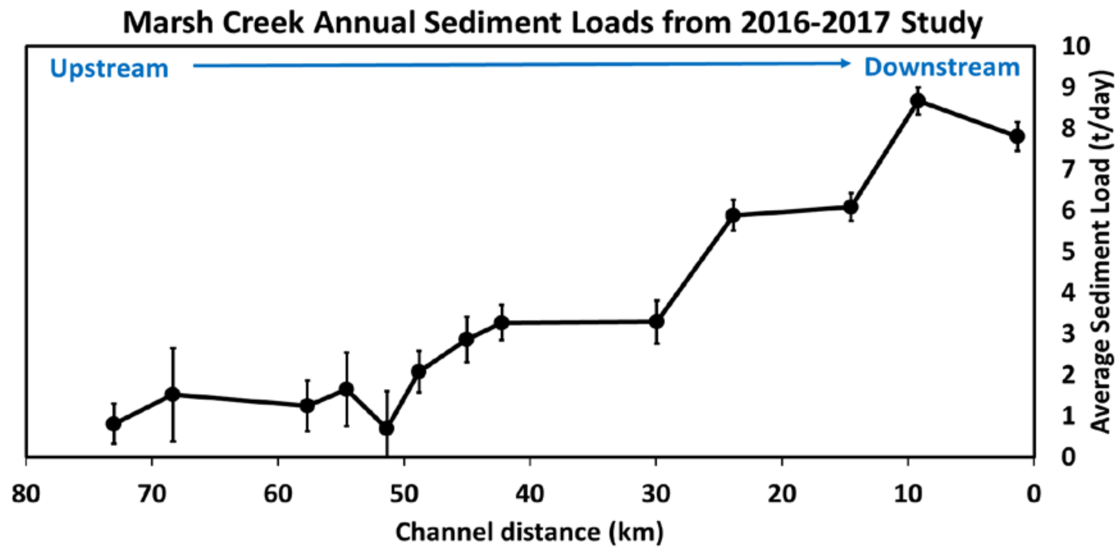


Figure A.3. Annual average suspended sediment load for Marsh Creek at each of the 13 monitoring sites for the period of March 2016 to March 2017. Distance is along the channel centerline and is in downstream descending order, where zero is the confluence with Portneuf River and larger numbers are further upstream. Error bars represent annual variability of one standard deviation. Overall accumulation of sediment flux in the downstream direction, indicative of integrated non-point sources.

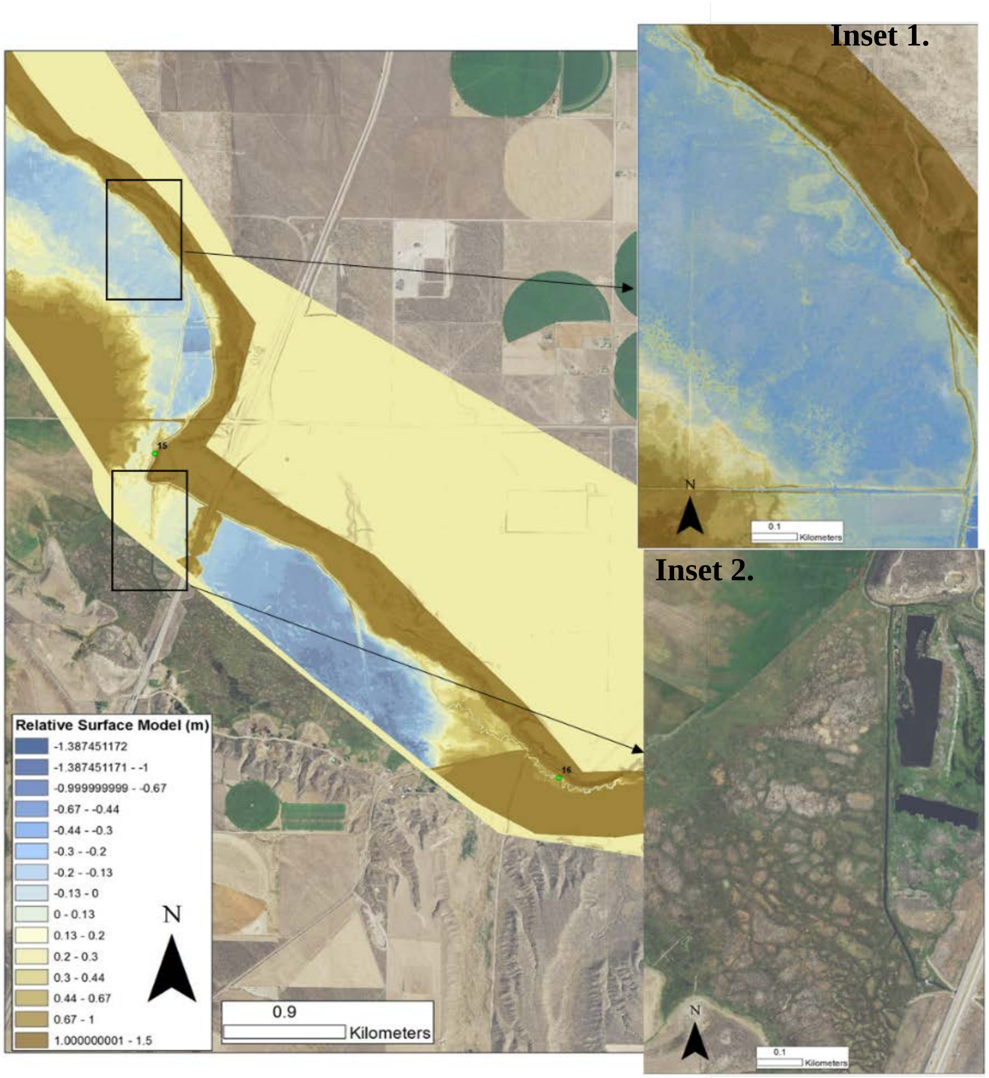


Figure A.4. Relative surface model and aerial imagery of Marsh Creek near sites 15 and 16. The relative surface model is LiDAR (light detection and ranging) topography relative to a downstream trending channel water surface. Blue colors represent zones below the channel height and brown represents zones above the channel height. Inset 1 shows an example of levied channel super-elevated above the floodplain (some minor meander scars present). Inset 2 shows mounded topography of marshy peat bogs common along these reaches.

Bank Erosion Mitigation Recommendation Table					
Name	**Summary**	**Advantages**	**Disadvantages**	**Relative Costs**	**References**
Off-Channel Watering	Installation of off-channel water sources (commonly groundwater wells) and troughs to prevent cattle from accessing the channel and trampling the banks.	Even when done alone, will reduce the amount of cattle trample of channels. Improves overall health of cattle not drinking from less healthy stream water.	Expense and labor of installing a groundwater well and non-freezing watering troughs, cows may still freely access channel (fencing recommended as additional measure)	Moderate	Beschta et al., 2013
Cattle Exclosure Fencing	Installation of fencing to prevent cattle from constantly accessing the channel in order to prevent trampling. Commonly supplemented with seasonal flash-grazing to prevent spread of noxious weeds.	Directly prevent cattle activity that destabilizes streambanks. Allows native riparian plants to revegetate and provide stream	Minor losses of grazing land adjacent to the stream. Expenses in building and maintaining fences. If noxious weeds are local problem, flash-grazing is required.	Moderate	Keller et al., 1979; Fleischner, 1994; Beschta et al., 2013
Riparian Seeding or Planting	Planting or seeding of endemic riparian plants along a buffer zone. Provides bank cohesion through root material and additional hydraulic roughness.	When appropriately planted with correct vegetation, riparian zones may recover very quickly. Provides natural bank cohesion through a reestablished riparian zone.	Cows may still freely access channel (fencing recommended as additional measure). Additional costs of monitoring.	Low to Moderate	Fleischner, 1994; Beschta et al., 2013
Biotechnical Protection	Involves the streamside integration of organic biomass (usually woody or herbaceous) and inorganic structure to increase the cohesive strength of bank soils. This material also acts as a hydraulically rough surface to extract momentum from the flow and reduce streambank erosion. See Li and Eddleman, 2002 for a comprehensive list of project types and Bentrup and Hoag, 1998 for a careful review of the planning and implementation of bioengineering projects.	In general, bioengineering is less costly and more effective than bank hardening projects even with maintenance costs factored in. Bioengineering projects 'blend in' with the surrounding ecosystem and directly provide riparian and aquatic habitat. These projects do not require specialized technical expertise beyond planning, installation can be done by volunteer groups (high school groups, Boy/Girl Scouts, watershed partnerships, etc.). Provide the greatest protection and strength.	Bioengineering projects, though providing the most effective bank stabilization and protection, are the most costly measures provided in this table. There are additional costs for monitoring and maintenance to ensure continued effectiveness of such projects.	High	Li and Eddleman, 2002; Bentrup and Hoag, 1998

Table A.1. Streambank erosion mitigation measures, includes summary definitions of each mitigation type, advantages versus disadvantages, relative costs, and references to literature pertaining to the mitigation measure.

Suspended Sediment Reduction Strategies

1. Source Mitigation

Mitigation projects act to directly reduce sediment inputs from the banks. Given the amount of actively eroding banks along all of Marsh Creek, reductions in turbidity would likely require expansive, broad-scale implementation of projects. To reduce sediment delivery from the banks to the river, we recommend soft physical bank stabilization projects and shifts in grazing practices. This includes practices that discourage cattle activity around channel banks, the creation or enhancement of riparian vegetation, and biotechnical bank stabilization. Listed in Table A.1. are some examples of these bank erosion mitigation techniques, relative costs, pertinent literature, and benefits of each project type. As stated in the foreword disclaimer, site-specific analyses should be done prior to the implementation of any project to determine the efficacy and appropriateness of each measure being proposed.

It should be noted that not all bank erosion should be viewed as negative or as an unnatural process. Bank erosion is an important component of any river, one example being the maintenance and migration of meander bends, which add to the hydrologic complexity and maintains important physical habitat. Channels are naturally complex features that undergo shifts in their form over time during periodic disturbances. Bank erosion due to human disturbances such as the complete loss of riparian vegetation, channel straightening, and cattle trample fall under the purview of unnatural exacerbation of bank erosion occurring in Marsh Creek.

It should be noted that bank erosion mitigation through engineered bank hardening (i.e., rip-rap, gabions, retaining walls) is <u>not recommended</u>, unless site specific analyses determine it is appropriate. Inappropriate bank hardening can locally exacerbate bank erosion by reducing hydraulic roughness and can commonly lead to costly destruction of the infrastructure designed to protect the banks. For examples of this and a geomorphic perspective on the benefits and detriments of bank erosion, please see Florsheim et al., 2008 and Li and Eddleman, 2002.

2. Sediment Retention

Sediment retention projects encourage deposition by allowing flow to slow down and/or spread laterally. This typically involves the connection of channels to existing floodplain wetlands, the engineering of new floodplain wetlands, or the construction of retention dams. These features improve water quality by sequestering suspended sediment in low energy, depositional environments.

As is highlighted in Figure A.2., ~60% of the sediment in Marsh Creek is derived from the lower 30 km of channel and >80% of the sediment is derived from downstream of the Rat Pond outlet. This means that projects which only target the upper portions of the watershed, as has been suggested in a previous study (IASCD, 2013), would not address the significant sediment sources downstream. Therefore, it is the author’s opinion that the most effective location for sediment retention and streambank stabilization projects be in the lower 30 km of the channel. An example of an area that could be utilized as a wetland complex is shown in Figure A.5., however it should be noted that this figure is not a comprehensive plan but is for conceptual illustrative purposes only. Listed below is a general framework for the types of sediment retention projects that could be implemented. As stated in the foreword disclaimer, site-specific analyses should be done prior to the implementation of any project to determine the efficacy and appropriateness of each measure being proposed.

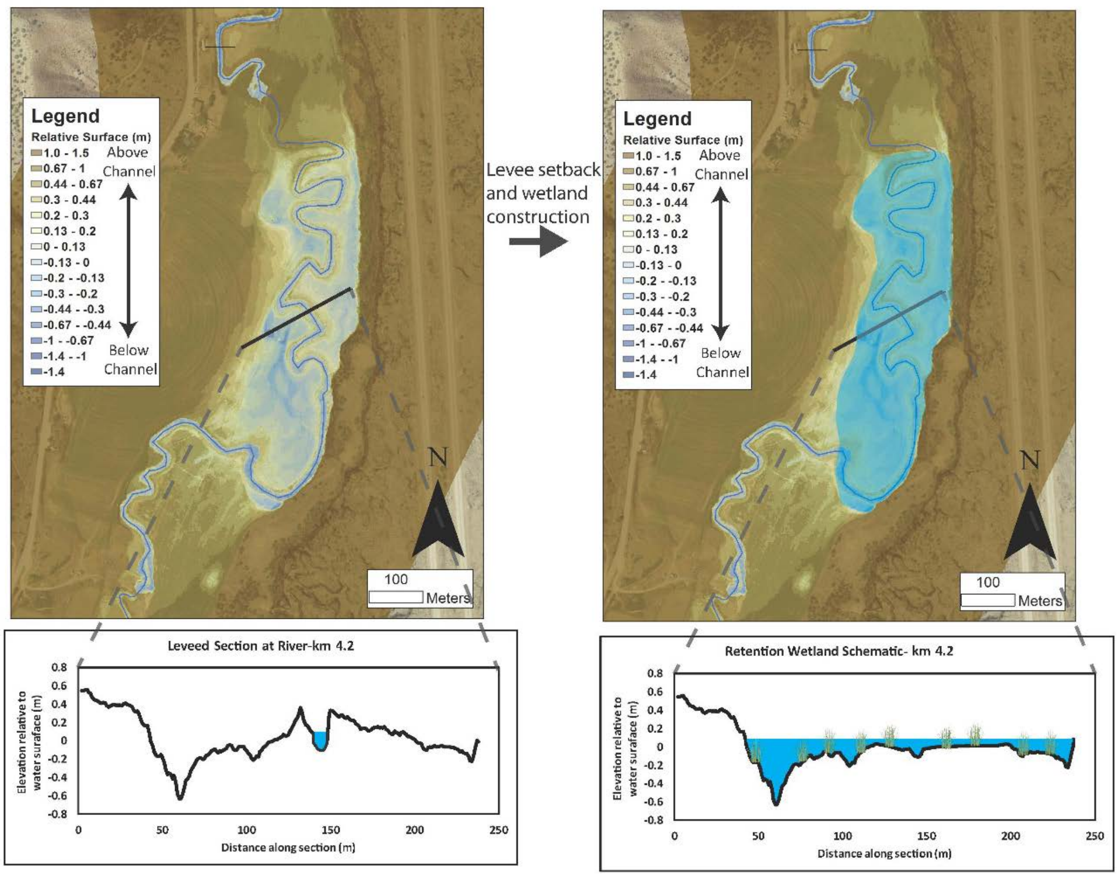


Figure A.5. Conceptual figure of a wetland project in Marsh Creek closer to the mouth of the channel (River-km 4.2). Shaded relief is a relative surface model with blue colors lying below channel water surface elevation and brown colors perched above. A. Superelevated channel cross-section with lower-lying adjacent floodplain. B. Levee removal and channel-connected wetland retention area. *Disclaimer: please note that A.4.B. is purely conceptual, appropriate permissions, permitting, and site-specific analyses should be done prior to the initiation of such plans.*

Sediment Retention Framework

Less costly. Uses existing or partially functioning wetlands. Less control over hydraulics.

1. Protect Existing Wetlands: Stakeholders should identify wetlands that maintain intermittent or perennial connection with Marsh Creek and protect these areas from land use practices that may disconnect or remove these features. One example located between sites 12 and 11 is a zone of floodplain intermittently connected to the channel due to an irrigation diversion backwater (Figure A.5.). This had a noticeable effect on the 2016-2017 sediment budget of Marsh Creek, where a decrease of sediment flux is reported between these two sites (Figure A.1.).

2. Reconnect and Enhance Existing Wetlands: Wetlands that are largely disconnected from the channel could be reintegrated with the channel. Historically, these areas have functioned as wetland habitats that encouraged deposition of fine sediment, precluding the costs of constructing a wetland and ensuring a greater likelihood of success in such projects. Areas in the Marsh Creek floodplain that contain significant disconnected wetlands are shown in Figure A.5.

3. Constructed Wetlands: The construction of engineered wetlands can effectively remove suspended sediments from turbid flows. This involves the creation of a wetland area with native macrophytes, which may be utilized as effective aquatic habitat. Previous evaluation of wetland projects show that much smaller wetlands (less than 1% of the watershed area) are insufficient at retaining enough sediment and that a wetland comprising approximately 5% of the watershed may provide sufficient retention (Koskiaho, 2003).

4. Constructed Retention Basins: This includes projects that involve construction of gravel or concrete-lined basins for the purpose of depositing and retaining fine sediment. These basins are constructed by creating a wide, low gradient zone that attenuates incoming flows and encourages sediment deposition. In order to increase the trapping efficiency of such basins, they are commonly augmented with baffles, which are permeable barriers that act to reduce flow velocities and disperse incoming turbulent energy across the basin (Thaxton *et al.*, 2005). Infrastructure-based designs such as these allow for the most control over hydraulic parameters, which can be optimized for higher trapping efficiencies. However, relative to the last three wetland options, retention basins are the most costly investment given the amount of infrastructure and maintenance required. Deposited sediment needs to be dredged, creating a recurring cost. Additionally, compared to wetlands, additional investments would be required in order for these areas to be aesthetically pleasing and/or house suitable riparian habitat.

More costly. Engineered structures allow more control over hydraulics.

Paired Approaches to Water Quality Improvements

Sediment mitigation and sediment retention projects both act to target sources of high turbidity in Marsh Creek directly, with streambank stabilization projects mitigating the sediment sources and retention projects restoring processes of wetland and floodplain sediment deposition. It is recommended by this author that an approach to water quality improvements in the Marsh Creek subbasin utilize both streambank erosion mitigation and sediment retention projects.

Given the fact that a majority of land adjacent to Marsh Creek is private and that bank erosion is distributed along all reaches, it is unlikely that a wide adoption of mitigation projects will happen in the shorter term. The establishment and/or reestablishment of sediment deposition centers along the creek, especially in the lower-most reaches, can be concentrated on a small number of properties with interested landowners and enhance deposition in the shorter-term. Therefore, retention projects, once enough wetlands and/or basins are created to accommodate enough deposition, could provide relatively quick improvements in water quality. Sediment load records can be used to determine the amount of parcel space required and the geometry of constructed retention projects can be designed using sediment transport models that have been utilized for wetland studies (e.g., SED2D [Koskiaho, 2003], MARSED [Newcomer *et al.*, 2014]).

Following the planning and implementation phase, it is also highly recommended that stakeholders monitor the features and downstream water quality to track project effectiveness. As demonstrated in this thesis, monitoring over annual timescales will tend to represent longitudinal sediment source inputs as opposed to seasonally or event-scale driven storage and remobilization. Given this, longer term monitoring is recommended following the implementation of projects.

Additionally, a paired approach of both methods could involve constructing inset floodplain and lower angle banks could be an additional recommendation integrating both the benefits of retention and bank stabilization (see Figure A.5.). A significant barrier for broader-scale implementation of in terms of implementation and land acquisition along significant portions of Marsh Creek.

Mutual Benefits to Local Stakeholders and Project Aims

All of the aforementioned projects have one thing in common: they require projects on private land and the permission of willing landowners. The loss of grazing space and arable land adjacent to channel can be a financial burden to landowners who work the land. This can pose a significant barrier to such projects. Therefore, one of the most important aspects of site selection for these projects is targeting projects where mitigation or retention are mutually beneficial to both landowners and to the aims of improving water quality.

One example from the Portneuf watershed is cattle exclosure fencing and the installation of groundwater pumps for off-channel watering troughs. Landowners report improved overall health of their herd due to cleaner water sources (Banks, personal communication).

Another example of mutual benefit is areas of land that undergo prolonged seasonal inundation during larger runoff years. These areas can be much less valuable as cropland and could be suitable for wetland projects. The lease, purchase or establishment of easements in such areas is a financial benefit to the landowner. Additionally, projects that act to stabilize banks provide long-term benefits by protecting productive land against bank erosion and lateral migration.

Conclusions

Please see Figure Marsh Creek, a stream impaired by high levels of turbidity and sediment, primarily derives its sediment from bank erosion, Most of the sediment is delivered in the more energetic lower 30 km of the mainstem. This bank source is exacerbated by land use practices and channel modification that have largely disconnected Marsh Creek from access to historically prevalent floodplain wetland complexes that accommodated deposition of fine sediment. Given the affirmation of primary streambank sources and wetland disconnection, it is recommended by the author that two approaches be implemented. First, the mitigation of streambank erosion across a wide scale, prioritizing the lower 30 km where much of the sediment during this study is delivered. Second, the creation of sediment retention projects prioritized in reaches closer to the mouth where they could accommodate a basin-wide integration of suspended sediment sources. In either case, it is recommended that routine monitoring of the projects takes place to evaluate their effectiveness and rectify any issues that may arise over time. Additionally, long-term water quality data should be collected close to the mouth of the channel to track how mitigation is improving water quality for Marsh Creek. Please see summary Figure A.5. for a comprehensive overview of what is addressed in this recommendation report.

PROBLEM:
Chronic and excessive suspended sediment in Marsh Creek is primarily derived from bank erosion and exacerbated by a lack of deposition in floodplain wetland complexes that were disconnected from the channel following historical leveeing and channel modif cation.

SOLUTION 1
Bank Stabilization

PROS:
- Treats the source of the problem (bank erosion) directly
- Would improve water quality locally
- Directly improves aquatic and riparian habitat
- Also retains sediment from overland runoff
- Does not require dredging like retention projects
- Exclusion can prevent pathogen inputs to stream
- Saves arable land from bank erosion and channel migration

CONS:
- Requires wider adoption to be largely effective
- Does not immediately improve water quality, sediment already in storage in system will require time to flush
- As with both solutions, will require the loss of farm/grazing land adjacent to channel

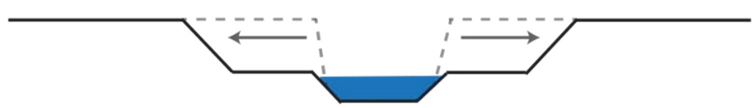
SOLUTION 2
Wetland Sediment Retention

PROS:
- Retains sediment immediately upon completion of project
- Does not require widespread adoption
- Can be focused to a few areas
- Constructed wetlands provide valuable habitat
- Returns it to a system that historically had interconnected riverine wetlands
- Preexisting wetlands could be connected at smaller cost
- Could attenuate impacts of flooding through water storage

CONS:
- Only improves water quality for reaches downstream of retention areas
- Requires dredging due to sediment infilling
- Less preexisting wetlands in the lower reaches of Marsh Creek, where much of the sediment is derived, making retention projects here more difficult

HYBRID SOLUTION:
Floodplain Construction

Set back preexisting oversteepened banks or levees and regrade banks, providing accessible floodplain during moderate to high flows



PROS:
- Mitigates bank erosion and provides f oodplain retention of sediment
- Improves aquatic and riparian habitat
- Local improvements in water quality
- Maintains flood protection

CONS:
- Requires widespread adoption
- Likely the most costly solution
- Requires more contribution of grazing/farmland than bank stabilization projects

Figure A.6. Summary chart of recommendations for reduced sediment in Marsh Creek.

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Appendix B: Additional Figures

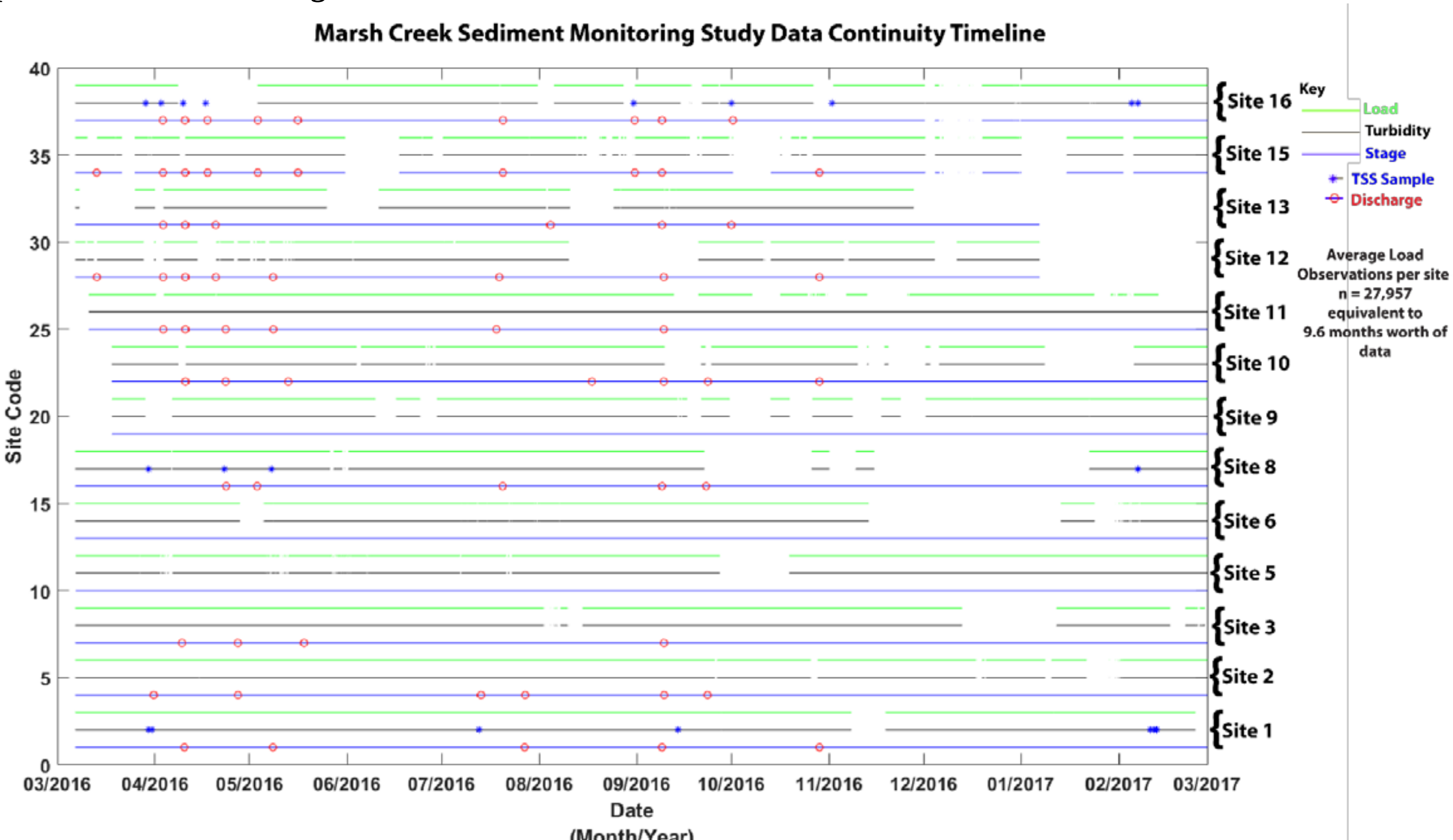

Figure B.1. Data continuity plot by site. Three continuous data types shown: turbidity, stage, and derived load (see key). Discrete data, discharge and TSS, that are used for calibration of models are shown as points (see key). Given that load is a product of the preceding two, if one is absent, then load will also be absent. Common issues leading to loss of data in order of decreasing abundance include: irreconcilable sensor fouling, loss of battery power, instrumental error, and user error. These data represent the full temporal extent of quality-assured, shift-corrected, filtered, and smoothed data. Site code is an internal code used to separate data by site, therefore, refer to right side of y-axis for site numbers for triplicate data types.

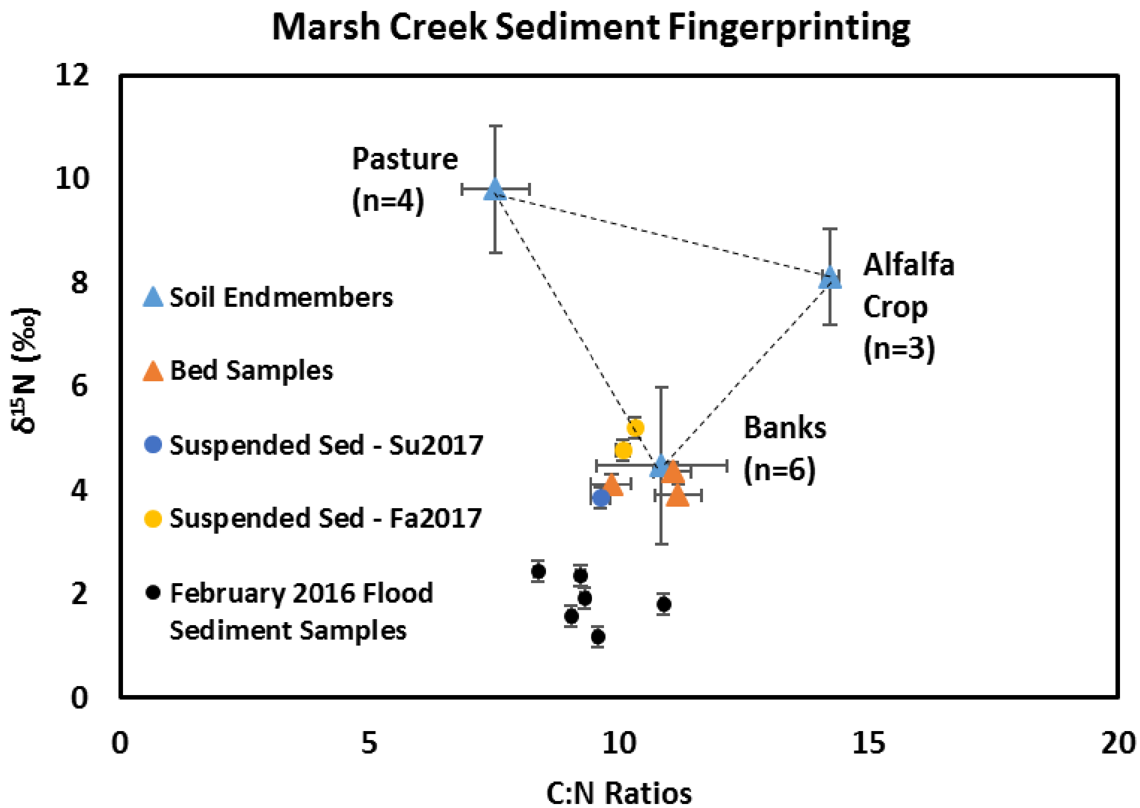

Figure B.2. Nitrogen isotope and elemental sediment fingerprinting plot with February 2016 flood data included. Blue triangles with overall larger mixing triangle show endmember averages and mixing space. All other symbols denote sediment samples. Note that most samples fall within uncertainty of bank endmember values. The black circles, representing February 2016 flood samples taken during a different part of the year than all of the other samples (winter vs. late summer and fall for other samples), fall outside of this mixing triangle. This implies an inherent seasonality in the endmembers that may shift the values of the endmembers. Additionally, additional endmembers may not be represented, one example being atmospheric deposition during the rainfall event that may have skewed data to lighter values. This shows an inherent temporal non-stationarity in the data, a weakness with this method.

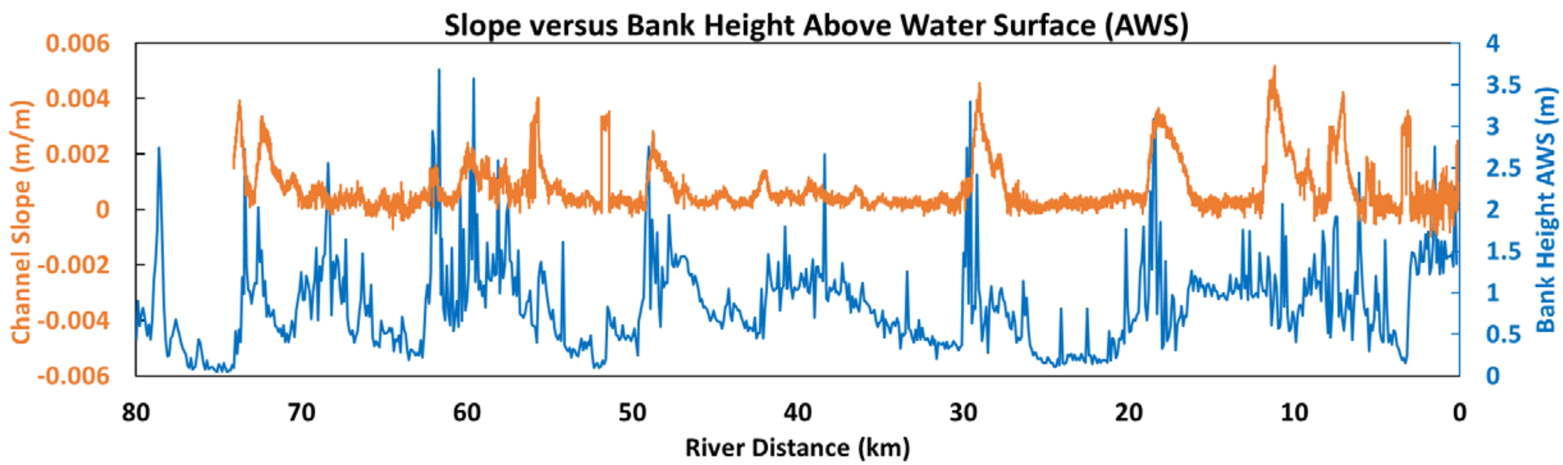

Figure B.3. Bank height above water surface (blue) and LiDAR-derived slope derived (orange) plotted longitudinally along Marsh Creek. Cross-sections to derive bank heights are spaced at 100-m increments along the centerline. Note the apparent concomitant increases in bank height with increased slope. These higher gradient inflections appear to have a control on bank height, where high bank heights and slopes occurring together may exert a strong control on which banks may be eroding to a higher degree. The apparent spatial ‘periodicity’ of the data is also interesting, and appears to be controlled by the spacing of disconnected wetland complexes. It may be that some higher gradient zones with larger banks may be outlet points for wetlands and lower gradient zones with smaller banks may be historical riverine wetland systems.

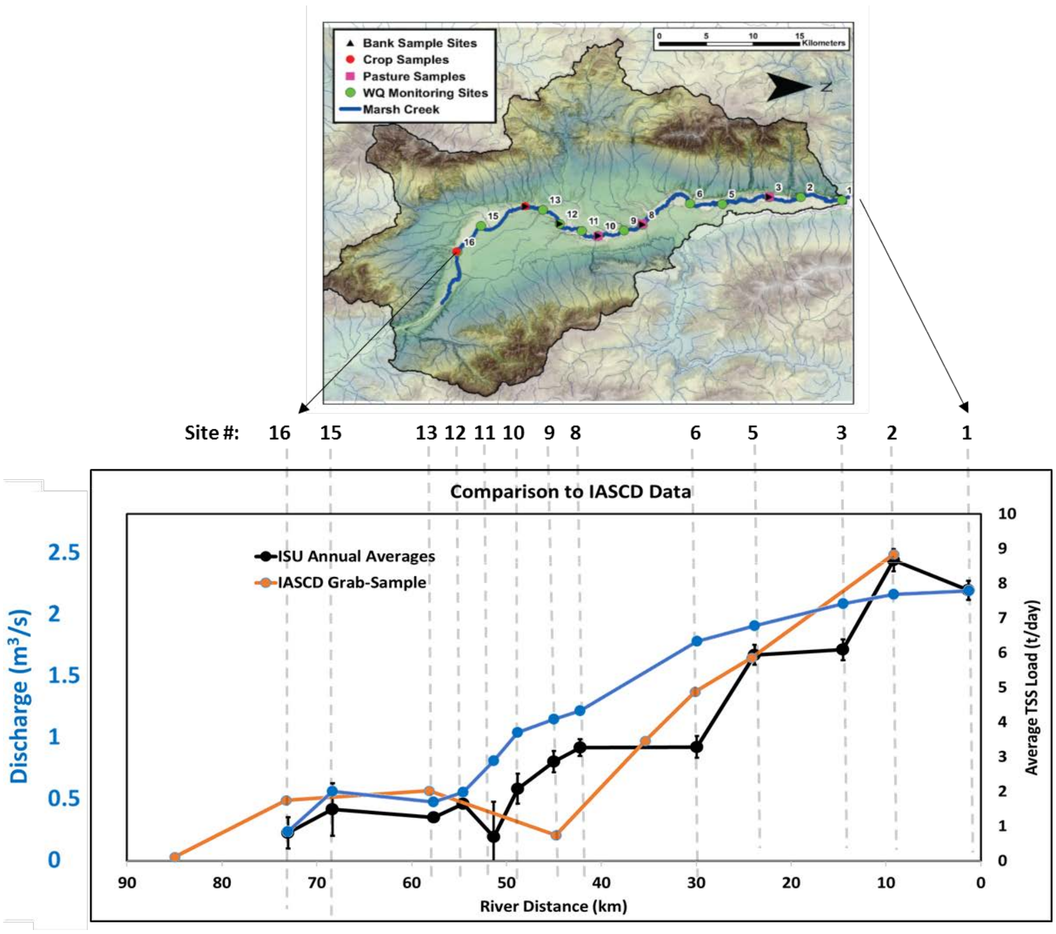

Figure B.4. Longitudinal annual trends in flux from this study (black), 4-year discrete sampling from the IASCD study (orange), and annual discharge (blue) from this study. Note the similarity of the flux data in trend and magnitude. This implies a relatively consistent downstream accumulation of sediment flux, especially in the lower ~30 km.