TESTING THE APPLICABILITY OF THE PFANKUCH STABILITY INDEX IN CHARACTERIZING THE PHYSICAL INTEGRITY OF LOW-GRADIENT ALLUVIAL STREAMS IN MINNESOTA, USA AND EXPLORING ITS UTILITY FOR STRESSOR IDENTIFICATION OF BIOLOGICAL IMPAIRMENTS

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PROLOGUE

This thesis is comprised of three chapters:

Chapter 1 is a background of channel stability concepts and a literature review of the theoretical and empirical relationships among channel stability, habitat quality and biotic communities. The main elements of this chapter were published in the peer reviewed journal *Environmental Monitoring and Assessment* under the title "Physical integrity: the missing link in biological monitoring and TMDLs". This chapter outlines the rational for state biological monitoring programs to collect geomorphic measurements and application of channel stability assessments to aid reference or best attainable stream condition for biological index development, to record a baseline of channel condition to detect change over time, to diagnose biological impairment for Stressor Identification, and to identify sources of sediment related TMDLs.

Chapter 2 is an experimental test of the theoretical concepts described in Chapter 1. Specifically, I used correlation, regression, and multiple linear regression to explore the association between channel stability, habitat quality, and biotic integrity in two watersheds in Minnesota with contrasting geology, historical vegetation, and land use. The channel stability assessments tested were the *Stream Reach Inventory and Channel Stability Index* and a modified channel evolution model. These channel stability assessment tools were tested for their applicability to low-gradient streams that are typically dominated by fine substrates and their ability to explain a portion of the variability observed in fish community health and habitat quality.

Chapter 3 presents a modified channel stability assessment tailored to stream conditions observed during this study as well as observations from other research. The goal of the modified assessment is to provide a more informed and appropriate reach level assessment tool that can be used by biologists with limited training in geomorphology to quickly identify and characterize geomorphic conditions that reflect stable verses unstable stream conditions found in low-gradient streams. These modifications should provide for a more appropriate reach level assessment to aid researchers in characterizing stable verses unstable stream conditions for further exploring the association among channel stability, habitat quality, and biological communities in low-gradient streams in many regions in Minnesota as well as potentially much of Midwestern U.S.A.

ABSTRACT

The interaction between geomorpohology and hydrology forms and governs the type and quality of the habitat upon which biological communities are arranged. Effectively creating links between what controls and impacts stream biota and habitat quality as they relate to geomorphology and hydrology is complex and requires an interdisciplinary understanding. From the hydrologic-geomorphic perspective, knowledge of what dictates and controls fluvial geomorphic processes at the watershed to the reach scale have been identified and mechanisms that initiate changes in sediment supply and/or flow regime resulting in altered stream geomorphic condition have been documented. From the biota-habitat perspective, the knowledge of what biota require for their existence (e.g., thermal regime, water chemistry, habitat for feeding, reproduction, and protection) has been identified and numerous studies have documented an association between instream, near-stream, and watershed land use with changes in water quality, habitat quality, and loss of biological integrity. However, studies often have not always identified the mechanisms and intermediate pathways linking changes in watershed land use to biological impairments. One plausible link is channel stability and the effect on habitat quality. This causal link needs to be more fully explored and documented for Stressor Identification of biological impairments. Biologists, with knowledge related to species traits and habitat requirements may lack geomorphic training; conversely, geomorphologists with an understanding for flow and sediment dynamics may lack an understanding of habitat conditions required by biota. Assessment tools and training that incorporate an understanding of both of these perspectives are needed so that candidate causes and mechanisms associated a loss in channel stability, habitat quality, and consequently, biological integrity can be identified. Before that can occur, existing habitat and channel stability assessment tools need to be tested and tailored to appropriately rate conditions observed in different regions and stream types so that deviations from the best biologically supporting conditions can be assessed and managed.

This study aims to test the applicability of an existing channel stability assessment in rating channel stability indicators observed in low-gradient streams in Minnesota and explore its utility for Stressor Identification of biological impairments.

The objectives of this study were: 1) to test the applicability of a channel stability assessment, namely the Pfankuch Stability Index (PSI) in characterizing stream stability indicators observed in low-gradient streams consisting primarily of fine substrates, 2) to identify key channel stability and habitat quality variables and their level of association with stream health as characterized by a fish index of biotic integrity (FIBI), 3) to explore the level of association between indicators of channel stability and habitat quality, and 4) determine which metrics and variables seem appropriate for assessing and exploring the channel stability and habitat quality linkage in low-gradient streams.

Two watersheds were selected in which to pursue these objectives: the Snake River in the St. Croix River Basin and the Redwood River in the Minnesota River Basin. These watersheds contrasted in geology, historical vegetation, and intensity of anthropogenic land use. In total, 28 sites (14 sites in each watershed) were sampled for fish, channel stability, habitat quality, water chemistry, and geomorphic variables including substrate composition, percent stream features, and stream gradient. Watershed land use statistics were estimated in ArcGIS. Statistical tests applied included ANOVA, correlation, linear regression, and multiple linear regression.

My results suggest that: 1) modifications to PSI metrics are needed in order to more appropriately rate and characterize indicators of channel stability found in low-gradient streams. Metrics such as *rock angularity, brightness,* and *channel capacity* were problematic to score and should be removed or modified. Suggestions for a modified channel stability assessment include: adding metrics that rate the degree of incision and floodplain connectivity, tailoring metric descriptions to conditions observed, incorporating a channel evolution model, and estimating substrate composition, among others. 2) Subjective channel stability assessments can be useful for Stressor Identification of biological impairments. Specifically, metrics associated with the degree of substrate mobility and aggradation explained a significant portion of the variation in FIBI in both watersheds; although, the shape of the association differed between watersheds and should be re-examined in future studies. Habitat quality metrics related to channel morphology, cover, and substrate condition explained a significant portion of the variability in FIBI and were related to channel stability. 3) Other geomorphic variables such as *D50* and *percent pool and riffle* were associated with higher FIBI scores.

An ancillary benefit of this project was the development of a modified channel stability assessment tool that is currently being implemented and tested in different watersheds by the Minnesota Pollution Control Agency for their biological monitoring program.

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CHAPTER 1

Physical integrity: the missing link in biological monitoring and TMDLs

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Asmus, B., Magner, J. A., Vondracek, B., & Perry J. (2009). Physical integrity: the missing link in biological monitoring and TMDLs. *Environmental Monitoring and Assessment, 159,* 443–463. doi:10.1007/s10661-008-0642-6.

Introduction

The objectives outlined in the 1972 Clean Water Act and its amendments (PL 92-500, Section 101[a]) require that the "physical, chemical, and biological integrity" of our nation's waters be maintained and restored. Many of the terms within the Clean Water Act amendments were not explicitly defined, and as a consequence water quality managers and researchers have struggled with defining these terms for regulatory and management activities (Cairns 1977; Frey 1977; Karr 1981, 1993; Karr and Dudley 1981; Hughes et al. 1982; Aadler 1995; Whittier et al.1987; Barbour et al. 2000). The increased attention to Total Maximum Daily Loads (TMDLs) associated with biotic impairment now requires water quality managers and researchers to reflect and ask important questions, such as: Is our present definition sufficient to protect physical integrity as well as biological and chemical integrity of streams? If not, how should physical integrity be defined and assessed?

We propose that *physical integrity* be equated with *channel stability* and that *channel stability* is an integral component of *physical habitat integrity* in low-gradient alluvial streams. We argue that channel stability is the missing link in water quality monitoring programs and TMDL investigations of biotic impairments. To remedy this missing link, we highlight a suite of physical and visual assessments that could be used to assess channel stability. As a result, chemical, physical, and biological integrity would be better understood, protected, and restored.

Physical integrity defined

Graf (2001) asserted that water quality managers and researchers have focused on the chemical and biological integrity of streams, whereas physical integrity has been overlooked or ignored. This oversight may be the result of the lack of a formal definition of *physical integrity* in the original Clean Water Act. As a consequence, many water quality managers and researchers have chosen to define and monitor physical integrity in terms of *physical habitat integrity* (Reid and Hilton 1998; Goldstein et al. 1999; Rabeni 2000; Bauer and Ralph 2001). But can and should physical integrity be defined only in terms of physical habitat? Is this approach sufficient to monitor physical integrity and to ensure that the physical structure and function of stream ecosystems is maintained?

We use the term physical integrity to imply a consistency of structure and function of the physical attributes of a watercourse through time. This definition is consistent with that of Graf (2001) who offered the following definition for the term:

> "*Physical integrity* for rivers refers to a set of active fluvial processes and landforms wherein the channel, flood plains, sediments, and overall spatial configuration maintain a dynamic equilibrium, with adjustments not exceeding limits of change defined by societal values." (Italics inserted by authors for emphasis)

Graf's (2001) definition of physical integrity is similar to definitions of channel stability (e.g., Lane 1955; Rosgen 1996; Watson et al. 2002).

Lane (1955) defines channel stability as "the dynamic equilibrium that exists between stream power and the discharge of bed material sediment." This equilibrium concept is generally described by the following relationship (Lane 1955; *sensu* Rosgen 1996)

$$Q_s D_{50} \sim QS$$

where, equilibrium is maintained or achieved when there is a balance between the product of the current discharge (Q) and stream gradient (i.e., slope, S) and the product of sediment discharge (i.e., bed material load, Q_s) and median particle size of bed material sediment (D_{50}). In other words, channel stability is achieved when there is a balance between the scouring forces of flow (volume and velocity) and resistance to flow (degree of hydraulic shear stress due to sediment type and volume of mobilized sediment).

A similar definition for this equilibrium concept is provided by Rosgen (1996, p. 7-11) who defined channel stability as:

> "the ability of the stream, over time, to transport the flows and sediment of its watershed in such a manner that the dimension, pattern and profile of the river is maintained without either aggrading nor degrading."

Watson et al. (2002) provided a similar definition as Lane (1955) and Rosgen (1996). Watson et al. (2002) described channel stability as a function of *sediment continuity* (i.e., sediment supply is balanced by the sediment transport capacity). When the sediment transport capacity is greater than the sediment supply, sediment will be eroded from the channel banks and bottom (depending on the resistance of the bed and bank materials); when the sediment supply is greater than the sediment transport capacity, suspended sediment will settle out and aggrade the channel bed (Magner and Brooks 2007).

The definition that we accept for *physical integrity* is the same as definitions given for *physical integrity* by Graf (2001) and *channel stability* by Lane (1955), Rosgen (1996), and Watson et al. (2002). This definition for p*hysical integrity* is generally not used, one exception is by the Arizona Department of Environmental Quality, Monitoring and Assessment Program (http://www.azdeq.gov/environ/water/assessment/ongoing.html). We argue that *physical integrity* is synonymous with *channel stability* (i.e., hydrologic, hydraulic or geotechnical stability and sediment continuity); it is the foundational element that supports habitat quality in low-gradient alluvial streams and streams with erodible cohesive sediments. Thus, channel stability is a necessary ingredient for the support of optimal habitat quality.

Relationships among physical integrity, habitat quality, and stream biota

The structure and function of the physical stream is governed by the interaction between geomorphology and hydrology (Figure 1-1, Maddock 1999).

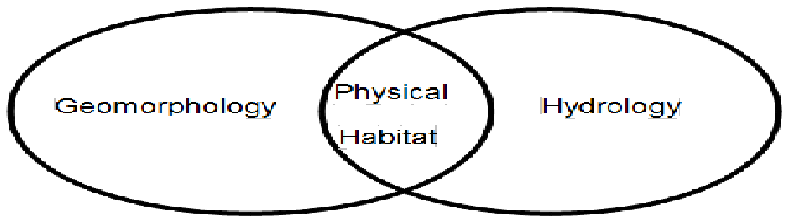


Figure 1-1: Stream physical habitat is determined by the interaction between channel geomorphology and hydrology. Figure modified from Maddock (1999).

The interaction among landform, surficial geology, and discharge creates the structural form of the channel that in turn governs the volume and quality of the aquatic habitat (Maddock 1999). This relationship dictates the type and kind of suitable habitat available for biotic organisms (e.g., substrate type, riffles and pools, flow variability, degree of embeddedness). Geomorphic condition (e.g., sinuosity, gradient, channel shape, cross-sectional area, substrate size) has also been shown to influence diversity and productivity of fish communities (Berkman and Rabeni 1987; Waters 1995; Sullivan et al. 2004b). Fish and macroinvertebrate functional groups are confined by water depth and velocity (Gorman and Karr 1978), as well as the availability, size, and sorting of substrates suitable for reproduction, feeding, and protection (Allan 1975, Karr and Chu 1999). When the stream channel is stable (i.e., not eroding or aggrading above expectation), the stream is able to maintain its form and structure and therefore, the stream, according to the definition we propose, demonstrates that it has *physical integrity.*

The resulting dynamically stable physical channel form provides the foundation upon which other elements of habitat are arranged (e.g., vegetation, large woody debris) and biological communities are structured (Southwood 1977; Ross et al. 2001). Large woody debris, riparian and instream vegetation, and depth variability, contribute to the heterogeneity of the habitat that supports biological diversity. Hence, habitat assessments typically focus on the presence of these physical elements (i.e., *physical habitat)* since biological potential is dependent on the quality of the habitat (Rabeni 2000). However, most habitat assessments only record the presence of these habitat elements (e.g., substrate size, woody debris, riffles, pools). What is typically not assessed is whether or not these structures were recently mobilized by high flow events, the degree of floodplain connectivity, and the ability of the stream to maintain riffle/pool complexes, thalweg depth, and stable banks during annual high flow events. A stream that is not able to maintain these stream features will have a reduced potential to support a diverse biologically community.

Fish and macroinvertebrates depend on specific habitats; a loss of habitat diversity can result in a loss of biotic diversity (Gorman and Karr 1978, Maul et al. 2004, Lau et al. 2006). For example, stream channelization reduces habitat diversity through removal of meander bends and in-stream vegetation (Lau et al. 2006) that creates uniform bed morphology (Brookes 1988) and altered flow regimes (Karr and Dudley 1981). Excess sediment that enters streams as a result of poor land use practices and unstable banks can embed or cover coarse substrates that are required by organisms for reproduction, feeding, and protection (Waters 1995; Nerbonne and Vondracek 2001; Berkman and Rabeni 1987). Increased embeddedness of coarse substrates reduces habitat area and results in reduced macroinvertebrate density (Lenat et al. 1981). Altered flow regimes may lead to degradation of habitat (e.g., high flows, mobility of coarse substrates, low flows, sedimentation) and water quality impairments that further impact biota. Fundamentally, if there is change in the hydrologic regime or change in sediment transport capacity, channel adjustment will be initiated (*sensu* Lane 1955), and the physical structure and biological function of the stream channel and its attendant floodplain will change. Consequently, habitat degradation and water quality impairments will occur and biotic communities will be affected. Thus, the fundamental interaction among geomorphology (geology, channel morphology, substrate size), hydrologic pathway (movement of water to the channel), and hydraulic forces (shear stress) forms the physical structure upon which habitat is developed (Maddock 1999). Theoretically, habitat quality will be at its optimum when watershed hydrology and stream sediment transport capacity are in balance within the context of regional geology, land use, and natural climate fluctuation. Conversely, when substrate supply and the flow regime are out of balance e.g., as could occur when changes in land use increase storm flow peaks (maximum discharge) the channel will undergo a period of instability during which habitat quality is diminished (e.g., excess scouring, embeddedness, loss of floodplain connectivity, loss of deep pool refugia). Therefore, we define the combination of habitat structures (i.e., *physical habitat*) and the structural and hydrologic stability of the channel (i.e., *physical integrity*) as *physical habitat integrity*. In our view, most habitat assessments do not adequately assess channel stability.

In the USA, habitat assessments have routinely been employed during regular biological water quality monitoring programs to assess river health (Karr and Dudley 1981; Karr 1999; Maddock 1999). Some of the more commonly used assessments include the Qualitative Habitat Evaluation Index (QHEI; Rankin 1989), the Rapid Habitat and Visual Reach Assessment (Barbour et al. 1999), and quantitative habitat assessments to reduce subjective bias (e.g., Sorenson et al. 1999). In general, these assessments evaluate local land use, riparian health, dominant sediment class per unit area, degree of embeddedness, bank erosion, variation in stream features, and cover for fish and macroinvertebrates. However, while these assessments characterize habitat types and quality of habitat available for aquatic biota, in our opinion, they do not stress the fluvial processes that control channel stability, which we argue is foundational to maintaining habitat quality and stream health, especially in low-gradient streams typical of the Midwestern USA. While national stream assessment protocols that include more quantitative assessments of geomorphic channel condition have been developed (e.g., Fitzpatrick et al. 1998; Kaufmann and Robison 1998), these assessments are generally not used by most state biological monitoring programs (Goodrich et al. 2004). Perhaps these geomorphic assessments have been perceived as difficult for some state agencies to implement for various reasons, such as additional field time and personnel costs, pressure to assess more streams in a shorter time-period, adequate training for field crews, equipment costs, and perceived lack of utility. However, TMDL investigations of biological and chemical stream impairments may soon change this perception.

TMDLs and limitations with habitat assessments

During condition monitoring (i.e., initial biological monitoring to assess stream health), a stream that does not meet water quality standards associated with its designated use (e.g., human consumption, aquatic recreation) is considered impaired and added to the Federal 303(d) list of impaired water bodies. Each listed reach, or identified Assessment Unit (AUID), requires completion of a TMDL assessment to identify the stressor(s) linked to the impairment (USEPA 2000a). Additional monitoring may by needed to target and identify suspected stressors, which may include continuous chemical monitoring, flow measurements, habitat assessments, and geomorphic condition assessments. The ultimate goal of a TMDL is to reduce loading of identified stressors associated with the listed impairment and subsequently return the AUID to compliance with water quality standards and designated uses.

When a stream is listed for impaired biota, previously collected chemistry and habitat data can be analyzed to tentatively identify potential stressors associated with the impairment (e.g., low dissolved oxygen (DO), turbidity, lack of cover, substrate embeddedness). If the pollutant is excess stream sediment, a habitat assessment may provide an indication of potential sources of sediment from unstable stream banks or local land use practices (Vondracek et al. 2005) such as cattle grazing in the riparian zone (Trimble and Mendel 1995). Unfortunately, other stressors associated with unstable channels are generally not quantified by most habitat assessments even though conditions such as excess bed-scouring and substrate mobility have been associated with *habitat instability* (Death and Winterbourn 1995) as a consequence of channel instability (Tipton et al. 2004). Additionally, the geomorphic condition of the channel as being incised and disconnected from the floodplain or overwidened and a potential cause of aggradation is not generally assessed. Consequently, most habitat assessments do not provide sufficient evidence that a channel is hydrologically, hydraulically, or geotechnically unstable; as such, the underlying mechanisms that may impact habitat and biota may not be identified. Therefore, we argue that there is a *missing link* in many state biological assessment protocols currently in use in the USA.

Channel stability: the missing link

Water chemistry, habitat quality and channel stability all are important drivers of biological integrity. As such, all three are required to maintain the ecological integrity of streams. Maddock (1999) asserted that river health should be evaluated based on water quality, hydrology, geomorphology and availability of physical habitat including assessments that measure flow regime and assess conditions of *channel stability*. Kaufmann (1993) and Kaufmann et al. (1999) identified and described seven stream attributes that influence stream ecology: channel dimensions, channel gradient, channel substrate size and type, habitat complexity and cover, riparian vegetation cover and structure, channel-riparian interaction, and anthropogenic alterations; an observed or measured change in any of these physical attributes can be used to detect an anthropogenic disturbance. At present, most condition monitoring programs generally assess water chemistry, habitat quality, and structure of the biotic community (Figure 1-2); however, it is not common to conduct a separate assessment of *channel stability* [i.e., the stream's ability to maintain its channel structure through assessing whether a balance between sediment (size and quantity) and the flow regime (sediment transport competence) is presently being achieved]. Consequently, state regulators who address sediment TMDLs are faced with a lack of information on channel geomorphic, hydraulic, and geotechnical conditions that would help identify mechanisms leading to sediment discontinuity, habitat degradation, and biological or chemical impairment. Determining the mechanisms of impairments is crucial to designing targeted and realistic remediation efforts. Channel stability assessments are the missing link in biological monitoring programs and TMDL investigations. We suggest that an increased understanding of channel geomorphic, hydraulic, and hydrologic processes by biological monitoring crews and supplementing habitat assessments with qualitative and/or quantitative measures of channel stability will remedy this missing link (Figure 1-2).

Natural stream processes are determined largely by climate, geology, vegetation, and basin morphology (Petts and Foster 1985); consequently, characterization of the stream's natural sediment and flow regime may vary widely by region and geologic stream type. In this paper, we focus our discussion on the natural stream processes of aggradation and degradation that typical for mid- to low-gradient alluvial streams (Lane 1955; Schumm 1977) and streams that contain cohesive silts and clays, particularly in the streambank. Alluvial streams naturally undergo dynamic processes of degradation and aggradation within a watershed network from headwater streams to large rivers at such slow rates and quantities that changes in stream character are not readily perceptible (Simon and Rinaldi 2000). These processes fluctuate temporally (i.e., wet season to dry season, annual variation), spatially (i.e., lateral migration), and stochastically (e.g., large floods or droughts). The balance among these natural shifts in sediment production and sediment transport capacity (Lane 1955) i.e., sediment continuity, is

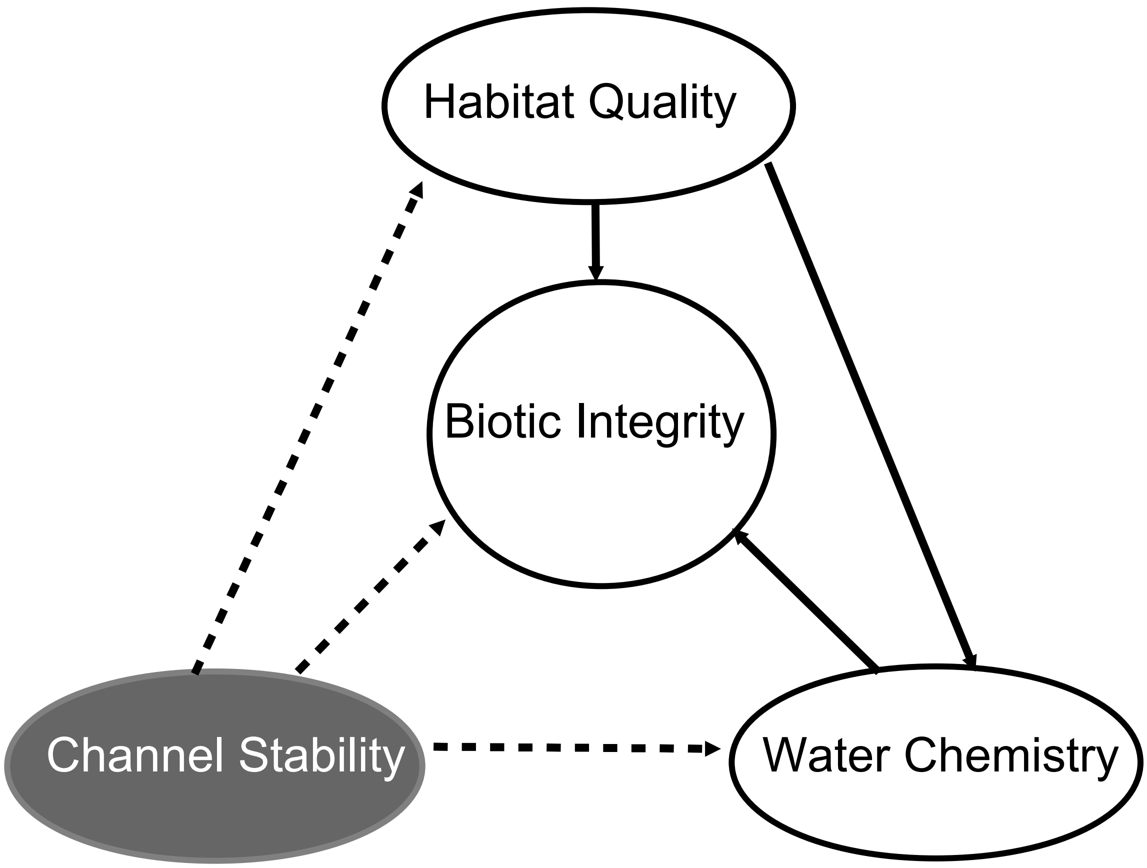


Figure 1-2: Diagram illustrating an initial TMDL stressor identification process for impaired biota. White circles represent the typical data collection strategy employed by most state biological monitoring programs while the gray circle represents channel condition and stability assessments that may be a missing link that would enhance the initial stressor identification process. A more focused assessment of channel stability (i.e., ability to maintain geomorphic shape and resist erosional forces) will identify stressors related to a sediment imbalance (sediment size & quantity) or changes in flow regime resulting in correctly prescribed remediation efforts. In our view, all components are needed to adequately assess the ecological integrity of low-gradient alluvial streams and address biological impairments.

Table 1-1: Potential anthropogenic causes of channel instability and resulting stream changes.

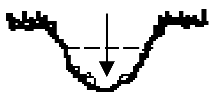
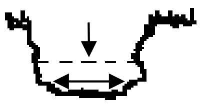
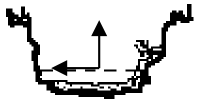
Alteration	**Direct Result**	**Change in stream channel hydrology or channel stability**	**Change in physical channel properties**
Damming	- interrupts natural flow regime	- hydrologic flood pulse dampened - sediment storage upstream; sediment transport downstream of dam	- riffle/run streams upstream changed to pool/glide streams - fish migration interrupted
Channelization	- reduced sinuosity - loss of instream vegetation - steepened, higher banks; channel incision[c] - channel bed below ground water base level	- contained peak flows; increased discharge - increased pore pressure and groundwater seeps at toe of bank	- increased gradient - bank instability; bed scouring - dewatered floodplains - loss of physical heterogeneity
Riparian disturbance	- tree removal - animal grazing	- tree roots decompose; shear strength reduced - evapotranspiration reduced, time of soil saturation increased - animals trample banks	- geotechnical bank failure - banks destabilize, collapse
Increase in impervious surfaces	- increased overland flows[d]	- increased magnitude and frequency of flooding events[d] - more erosive stream power	- overland sediment, chemicals, and nutrients transported to stream[e] - degradation of streambed; increased substrate instability
Increase in drain tile	- changed timing of water entering stream - less water storage in soil	- flashy discharge regime	- degradation of streambed; increased substrate instability - channel instability - aggradation in low flow
Change in land use (e.g., increase in impervious, change in watershed vegetation)	- less evapotranspiration - less soil infiltration	- increased groundwater pore pressure - increased overland flow and stream discharge - changed timing, magnitude and duration of peak flows [b]	- degradation of streambed[b] - bank instability[b] - habitat diversity reduced[f]
Change in climate	- more intense storms [a] - less rainfall, drought - reduced snow pack	- flashy discharge regime - low flows - reduced overbank floods	- degradation of streambed, bank instability = sediment production - aggradation

[a]Rapport et al. (1998); [b] Rosgen (1996); [c]Galay (1983); [d]USEPA (1997); [e]Pitt et al. (1995); [f] Rabeni and Jacobson (1993)

considered the stream's stable state (quasi-equilibrium; Simon 1989) within its current geology, land use, and climate (Rosgen 1996). In contrast, channel instability is defined as an imbalance between sediment production and sediment transport capacity (i.e., sediment discontinuity). Instability results from a combination of sources that involve both natural events and anthropogenic changes (Simon and Downs 1995; Simon and Rinaldi 2000). Examples of natural events that initiate channel instability in low-gradient alluvial streams include: glacial rebound, also referred to as uplift or subsidence (Schumm 1977; Riedel et al. 2005); knickpoint migration between lowland rivers and higher elevation headwaters; and meander cut-offs that periodically occur in sinuous channels (Hooke 2004). Natural channel adjustment processes can be accelerated and magnified by human activities (Table 1-1), such as mechanical alteration or indirectly through activities that change watershed hydrology (Simon and Downs 1995) as could occur due to changes in vegetation (Anderson et al. 2006), increases in impervious area, and hydrologic alterations induced by climate change (Poff et al. 1996; Rapport et al. 1998). Altered climate and landscape conditions can lead to a change in the magnitude, timing, and duration of peak flows (Rosgen 1996) subsequently initiating periods of channel instability and adjustment (Simon and Downs 1995).

Annual peak stream flow events and sediment mobility are considered important natural disturbances essential to maintaining healthy biological communities (Resh et al. 1998, Allan 1995). Periodic disturbances, such as floods, can benefit habitat conditions for biota (Allan 1995). Occasional higher flows have more erosive power to scour away fines embedding substrates and pools, overbank flows introduce large woody debris (Kline et al. 2004) and organic matter (Cuffney 1988) from riparian corridors. Biological communities are largely adapted to occasional disturbances that are part of the natural cycle of streams (Allan 1995); however, when the magnitude and frequency of disturbance is altered, a threshold is breached after which biological communities may be negatively impacted (Connell 1978, Townsend et al. 1997a). Periods of drought, water diversion, or reductions in annual snow-melt may interrupt the annual periodicity of scouring flows to remove fines embedding coarse substrates thereby impacting lithophilic spawners (Brouder 2001). Anthropogenic channel alterations and changes in watershed hydrology (Table 1-2) can accelerate and magnify the intensity of disturbance and initiate system-wide disequilibrium (Schumm et al. 1984; Simon 1989; Simon and Rinaldi 2000; Ross et al. 2001; Magner et al. 2004b; Lenhart 2008) during which channel geomorphic changes may occur (e.g., channel incision, widening, aggradation) and habitat quality and biological integrity may be affected.

Table 1-2: Stages of the Channel Evolution Model (Schumm et al. 1984, Thorne et al. 1997) with descriptions of the associated channel condition and the theoretical impacts to biota [conditions considered beneficial (+) or detrimental (-) to fish and/or macroinvertebrates]. Dashed lines on figures indicate height of channel forming flow; arrows indicate direction and magnitude of baselevel change (degradation or aggradation) or bank retreat. Figures modified from Bledsoe et al. (2002) after Schumm et al. (1984).

CEM stage/ Process	**Channel Condition**	**Impact to Biota**
I. Sinuous, premodified 	heterogeneous channel bottoms; deep pools, shallow edge habitat, backwaters floodplain connectivity = energy of peak annual flows dissipated into floodplain	(+) presence of refugia during spates benefits young-of-year and weak swimmers (+) reproductive zone for floodplain adapted species (+) overwintering pools benefit large fish; supports trophic complexity (+) for nutrient limited streams, nutrient recharge from floodplains = periphyton growth that supports algal grazers; for streams receiving excess nutrients, floodplain attenuation limits excessive plant growth = stabilizes DO fluxes
II. Degradation 	loss of floodplain connectivity = fewer overbank flows into floodplain increased channel capacity = increased shear stress during channel forming flows scouring = mobilization of stable substrates and macrophytes	(-) loss of refugia for young-of-year and weak swimmers during spates (-) increased macroinvertebrate drift; increased mortality (-) for nutrient limited streams, periphyton growth limited = reduced food supply for grazers; for streams receiving excess nutrients, plant growth increases = increased DO fluxes and potential for low DO (-) loss of stable substrates and macrophytes; impacts reproduction, rearing, feeding, protection (-) loss of diversity and abundance
III. Degradation and widening 	mass wasting, bank erosion, increased sediment supply = increased turbidity, increased temperature and reduced dissolved oxygen	(-) irritated gill tissues, respiratory and feeding stress (-) increased drift; decreased abundance (-) loss of sensitive species = loss of species diversity
IV. Aggradation and widening 	velocity reduced, suspended sediments settle and embed coarse substrates pool infilling and loss of habitat heterogeneity sediment bars at bends build up and divert flow to outer bank causing bank collapse	(-) reduced reproductive success of lithophilic spawners (-) loss of food availability for grazers, scrapers, and net builders (-) loss of interstitial spaces used for protection (-) loss of deep overwintering pool refuge; loss of habitat for large fish = trophic level impacts
V. Quasiequilibrium 	new channel forms in aggraded sediment; reintroduced floodplain within channel trees and plants root in freshly deposited alluvial sediment and stabilize banks narrower channel cuts into aggraded sediment, pools deepen, bottom complexity returns	(-) high flows still concentrated within terraces of former channel; harsher flood-flow conditions for biota than original channel (+) energy flow of nutrients from floodplain reconnected with stream; supports within stream periphyton and food web dynamics (+) new refuge during spates; overwintering pools (+) trophic complexity returned (+) species diversity returned, abundance returned

Incision, also referred to as downcutting or bed-level lowering, often follows an increase in sediment transport capacity (i.e., increased stream discharge) above mean annual sediment supply (Lane 1955; Galay 1983; Magner et al. 2004b). Processes of downcutting and channel widening can cause long-term changes in the structure and function of stream channels and riparian corridors (Shields et al. 1994); subsequently, habitat and biotic degradation occur (Table 1-2). Incising channels disconnect from their floodplains (Schumm et al. 1984; Thorne et al. 1997, Watson et al. 2002), consequently reducing low flow refuge for young-of-the-year fish and weak swimmers during high discharge events (Junk et al. 1989). Annual high flows that used to spill out into the floodplain are now concentrated within the deeper channel profile thereby magnifying the degree of degradation or bottom scouring. As a result, larger substrates upon which organisms rely for reproduction, feeding, and protection are now mobilized, thereby causing a reduction in species diversity (Death and Winterbourn 1995) and density (Death and Winterbourn 1995; McIntosh 2000). Incised stream banks tend to evolve by hydraulic toe slope erosion and subsequent geotechnical failure resulting in excess in-stream sediment and loss of habitat heterogeneity through infilling of pools and interstitial spaces. Aggradation in pools can result in greatly reduced pool depth, thereby limiting the availability of late-summer and over-winter refugia for large fish (Schlosser 1987). Excessive sediment delivery from unstable banks can trigger violations of numeric water quality standards for chemical impairments (e.g., total suspended solids (TSS), turbidity, temperature, low dissolved oxygen) and narrative standards (biotic integrity) leading to CWA Section 303(d) listing of streams (Lenhart 2008). Hence, when substrate supply or the stream's hydrology experience an imbalance (e.g., hydrologic discharge is increased) the channel undergoes a period of instability during which habitat and water quality are suboptimal and potentially limiting to certain species of fish and macroinvertebrates. In contrast, when the natural dynamic equilibrium is in balance, physical habitat and water quality is theoretically at its optimum and will support a more diverse and stable biological community (Maul et al. 2004).

Channel stability assessments

After instability is initiated, changes in the dimension, pattern, and profile of streams can be observed (Rosgen 1996) and "characteristics and conditions of the channel bed, channel banks, accumulation of debris and other causes of flow deflection, and the condition of riparian vegetation" can be used as diagnostics of channel stability/instability (Simon and Downs 1995). In addition, changes in bed material size and computations of hydraulic forces at bankfull conditions also can be used to assess transport capacity and infer channel instability (Lisle et al. 2000).

Temporal changes in channel morphology and hydraulic stability have been described (i.e., Channel Evolution Model, Schumm et al. 1984; Incised Channel Evolution Model, Simon 1989;

Channel Stability Diagram, Watson et al. 2002). However, physical indicators of channel evolution and hydrologic instability (e.g., headcut migration, scouring, coarse substrate mobility, undercut banks, intermittently receding channel banks, loss of floodplain connectivity) are largely ignored during biological assessments.

There are several assessments available to monitor channel stability using physical indicators (e.g., Stream Reach Inventory and Channel Stability Evaluation, Pfankuch 1975; Channel Instability Index, Simon and Downs 1995; Streambank Erosion Hazard Index, Near-Bank Stress, Rosgen 1996). The US Environmental Protection Agency (USEPA) and US Geological Survey (USGS) assess geomorphic condition by measuring cross-sections, longitudinal profiles, and pebble counts for national stream assessment programs (e.g., Environmental Monitoring and Assessment Program of the USEPA, Kaufmann and Robison 1998, Peck et al. 2006; National Water Quality Assessment Program of the USGS, Fitzpatrick et al. 1998).

The USEPA recently developed a standardized methodology for systematically linking sediment issues to watershed processes and to assess stream channel stability called the Watershed Assessment for River Stability and Sediment Supply (WARSSS; Rosgen 2006). While WARSSS provides an in-depth analysis of channel stability related to present and future sediment supply to rivers and streams from bank and channel erosion, this level of detail requires training in watershed hydrology and fluvial geomorphology. The entire WARSSS procedure may be considered too laborious during an initial Phase I (condition monitoring) watershed assessment since each level of a WARSSS assessment can take weeks to months to complete and validate. However, some elements of the WARSSS procedure collected during a Phase I assessment could provide information as a preliminary screening tool for planning a Phase II (TMDL stressor identification) assessment.

Stream managers should consult and consider existing habitat assessments that include more detailed assessments of channel stability (e.g., Fitzpatrick et al. 1998; Kaufmann and Robison 1998). Several components of these and other channel stability assessment techniques are discussed below. Depending on the limitation of time and resources, a few of these assessments could supplement existing water quality monitoring programs during an initial Phase I watershed assessment; the information collected could assist in determining the type and level of data collection required for a Phase II stressor identification process (USEPA 2000a). The additional time required to complete these assessments largely depends on the type and number of assessments, number of personnel, stream size, reach length, and complexity of the stream channel. Harrelson et al. (1994) describe field methods for establishing benchmarks and measuring cross-sections and longitudinal thalweg profiles; Peck et al. (2006) describe how to conduct instream measurements of channel-cross-sections, longitudinal thalweg profiles, and a modified pebble count procedure that together with measurements of woody debris can be used to assess relative bed stability (Kaufmann et al. 2008); and Rosgen (2006) outlines applications of both subjective and qualitative channel morphology assessments in Phase II stream stability analysis.

Channel cross–section

The channel cross-section provides information for calculating channel dimensions and assessing channel condition (e.g., degree of incision and/or overwidening, floodplain connectivity). Generally, bankfull width to depth ratio (W_{bf}/D_{bf}), cross-sectional area (CSA), and entrenchment ratio (ER; ratio of floodprone width to bankfull width) are used to assess channel condition, transport capacity, and stability (Rosgen 1996; Montgomery and MacDonald 2002; Watson et al. 2002).

Because the channel forming flow is presumed to correspond to the bankfull discharge (Wolman and Leopold 1957), channel width and depth are often used for interpreting and monitoring channel condition (Montgomery and McDonald 2002) and for computing ratios used for the Rosgen Stream Classification (Rosgen 1996). The height of the channel forming discharge (i.e., effective discharge; Wolman and Leopold 1957) is often difficult to identify in the field when channels are unstable (Simon et al. 2007) and bankfull indicators are not readily apparent e.g., because of bare banks due to geotechnical failure (Magner and Brooks 2007, 2008). Uncertainty in the estimation of bankfull height can be resolved by using regional hydraulic geometry curves (RHGCs; Leopold and Maddock 1953). These curves are log-log plots that compare bankfull channel cross-sectional dimensions (i.e., bankfull width, mean bankfull depth, CSA) versus drainage area (DA; NRCS 2007).

RHGCs are developed by first determining the bankfull, or channel forming flow (i.e., generally 1.2 to 1.8 recurrence interval flow) using discharge measurements from gage stations with at least ten years of consecutive data (USGS 1982). Magner and Brooks (2007) describe how separate curves should be developed for regions with similar climate, landscape terrain, land use, geology, and watershed hydrology. The National Water Management Center (NWMC) is collaborating with local, state, and federal agencies to develop RHGCs throughout the USA. See currently available RHGCs at http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/alphabetical/water/hydrology/?&cid=nrcs143_015052 (NRCS 2011c).

Once developed or obtained, RHGCs can assist in instream estimations of bankfull height using the empirically derived CSA and DA. When possible, the RHGC derived estimate of bankfull height should be validated with local observations of bank features such as a change in slope, perennial vegetation, and depositional features (Harrelson et al. 1994; Peck et al. 2006) within or just upstream or downstream of the surveyed reach. However, after debris torrents or major floods, these features may have been scoured away and will not be readily apparent (Peck et al. 2006). In this case, an undisturbed stream with the same DA, geology, and climate may be used to validate the expected CSA. A relatively accurate estimate of bankfull is required to compute sediment competence; however, if the goal of the assessment is only to infer whether or not the stream is connected to its floodplain, overwidened and aggradating, or is incised (see Figure 7-9 in Peck et al. 2006 for schematics of floodplain connected and incised streams), the RHGC derived CSA will provide a relative estimation of the expected bankfull flow height.

Longitudinal thalweg profile

A longitudinal thalweg profile measures bed and water surface elevation over a given stream length (e.g., 20 to 30 times the channel bankfull width). A longitudinal profile can also be used to record field indicators of bankfull elevation and pool sediment deposition that can provide information about channel adjustment. Observation of changes in the bed profile (i.e., increase or decrease in thalweg depth variability, changes in pool and riffle spacing) and local changes in channel slope provide information about bed stability and sediment transport. If multiple years of data are available, movement of a knickpoint (i.e., a sharp point of change in channel slope) may suggest that the channel is evolving to a new morphology. A knickpoint will migrate upstream until the upstream and downstream gradients within the reach are similar (Brooks et al. 2003) or until the knickpoint encounters a resistant substrate. Further, if the depth of unconsolidated sediment in the streambed is also recorded during the profile, the degree of pool infilling or bottom scouring can be assessed (Lisle and Hilton 1999).

A longitudinal profile also provides a localized estimation of stream gradient. As a general practice, stream gradient is estimated from topographic maps with contour lines of known elevations. In regions with relatively flat terrain, the distance between known topographic changes can fall outside the reach of interest; consequently, the gradient is estimated over a larger distance. This can result in a gradient estimation that may not accurately characterize the gradient of the localized surveyed reach. By collecting a field derived longitudinal profile, the reach-level gradient estimations may be more accurate; however, careful field surveying is necessary to get good estimates of gradient in low-relief systems. Stream gradient estimations also provide information on unit stream power and the associated boundary shear stress acting upon the bed and banks of the channel. This information can be used to assess the sediment transport competence (Kaufmann et al. 1999, 2008) and sediment transport capacity for initial departure analysis (Rosgen 2006).

Particle size distribution

In sand, gravel, or mobile-bed streams, the particle size distribution in the stream channel can be estimated by a Wolman pebble count (Wolman 1954) or sieve analysis (Lambe 1951). A pebble count is performed by random selection and measurement of the median diameter of 100 sediment particles over the study reach; particle diameters are graphically plotted to determine the portion of particles that are finer than the 50th percentile (D_{50}) and 84th percentile (D_{84}) of the sampled particles. For streams that are dominated by fine-grained sediments, a sieve analysis may be preferable. A sediment sample is collected from multiple points along the reach; after drying, the sample is sorted through a nested set of progressively finer sieves (Lambe 1951). The weights of each sediment partition are graphed as a percent of the total sample weight against diameter size (sieve opening size). The D_{50} and D_{84} are often used to evaluate channel geometry hydraulics, e.g., shear stress and associated sediment continuity. Thus, changes in particle size ranges may indicate an imbalance in sediment supply or sediment transport capacity.

In contrast to a pebble count, most commonly used habitat assessments visually characterize the dominant substrate type of the stream bed at 4 to 5 points across a transect; an estimation of percent embeddedness of coarse substrates is often also recorded. While this procedure is useful for determining the dominant substrate types available for stream biological potential and habitat quality (e.g., clean gravel for lithophilic spawners), fine sediments (silt, sand, gravel) may be underrepresented, and may not provide indication that the stream sediment transport capacity has changed. In contrast, a Wolman pebble count characterizes the full range of substrate sizes encountered, including non-dominant substrates. Changes in mean particle size of the streambed may be driven by sediment discontinuity; if a channel bed aggrades or degrades, something within the system (e.g., sediment supply or discharge) has been altered.

Hydraulic properties computed for bankfull flow

Together, the cross section, longitudinal profile, and particle size distribution can be used to compute hydraulic properties at bankfull, including boundary shear stress. Boundary shear stress provides an estimate of the forces acting on the channel bank and bed during bankfull conditions (Lisle et al. 2000). Software programs are available to compute channel dimensions and hydraulic properties (e.g., STREAM Module, http://www.dnr.state.oh.us/tabid/9188/default.aspx; RIVERMorph®, http://www.bossintl.com/html/rivermorph_overview.html). Montgomery and MacDonald (2002) described of how channel dimensions and bankfull hydraulic forces can be used to diagnose channel condition. Kaufmann et al. (2008) describe how to characterize regional expectations of relative bed stability (RBS) with which to compare and diagnose sedimentation issues related to anthropogenic disturbance. This level of detail may be more appropriate for the Phase II stressor identification investigation than for general condition monitoring; however, a record of geomorphic variables collected during condition monitoring could benefit the TMDL process (see

"Benefits of channel assessments").

Information about the entrenchment ratio (ER) can assist in identifying and validating the current state of stream channel stability by classifying the stream evolutionary stage, as an example, a stream that is considered moderately entrenched (i.e., channel confined by landform slope) when the ER is between 1.4 and 2.2 (Rosgen 1996). This stream would be considered incised and classified as Stage II in the Channel Evolution Model (Table 1-2). In such a condition, energy from higher discharges is contained and magnified within a narrower area compared to a stream that is not incised. This confinement at high flow promotes channel evolution processes of incision (i.e., downcutting and floodplain disconnection) and/or channel widening (i.e., bed is armored and downcutting is limited).

Stream reach inventory and channel stability evaluation

The Stream Reach Inventory and Channel Stability Evaluation (Pfankuch 1975), hereafter referred to as the Pfankuch Stability Index (PSI), has been used for numerous applications from stream condition assessment, international research, and stream restoration. The PSI is a tool used in the USEPA WARSSS procedure (Rosgen 2006) to assess stream channel condition and stability for watershed assessment and TMDL problem investigations. The PSI has also been used extensively in international research investigating relationships between channel stability and biota (Rounick and Winterbourn 1982; Death and Winterbourn 1994, 1995; Townsend et al. 1997b; Duncan et al. 1999; Robertson and Milner 1999; McIntosh 2000; Gislason et al. 2001; Lods-Crozet et al. 2001a, 2001b; Maiolini and Lencioni 2001; Heiber et al. 2002). The PSI has also been used to evaluate streambanks for restoration by the Izaak Walton League of America (IWLA 2006). However, this tool is not normally used for biological monitoring programs in USA (Goodrich et al. 2004). This may in part be due to the lack of familiarity of biologists with the PSI, or that the utility of this additional assessment tool for biological monitoring programs has not yet been realized.

The PSI was developed in mountainous streams in the western USA (Pfankuch 1975). Several modifications to the PSI have been suggested to extend its applicability to other stream types and to test specific research questions. Rosgen (1996) has devised a score modification procedure using his stream classification to better characterize potential and future stability of streams based on substrate character and geomorphic variables. Research assessing habitat stability (as indicated by mobility of coarse substrates) utilized PSI metrics associated only with the channel bottom (see Death and Winterbourn 1994; Death 1995; Winterbourn and Collier 1987; McIntosh 2000; Castella et al. 2001). Current research evaluating the utility of the PSI to predict fish IBI in low-gradient streams in Minnesota suggests that modifications to the original PSI should be considered for these systems (Asmus et al., *unpublished data*). Some Midwestern streams appear to be dominated by alluvial non-cohesive stream banks where groundwater discharge and internal pore pressure have destabilized non-cohesive alluvium at the toe of the bank, resulting in bank failure (Magner et al. 2004a); these conditions are not characterized by the current PSI. Modification to the current PSI could be considered to tailor this assessment tool to more accurately assess channel stability in different stream settings.

In its most basic form, the PSI can be used as a preliminary screening tool to assess channel condition and aid in determining whether a more quantitative assessment may be required. After regional calibration and validation, the PSI may offer a time-efficient and effective qualitative assessment tool that could be used in tandem with subjective habitat assessment tools such as the QHEI (Rankin 1989).

Benefits of channel stability assessments

Channel stability assessments could be beneficial to watershed assessment programs in a number of ways, including: (1) aiding in selection of reference or best attainable stream condition for developing metrics for an IBI, (2) providing a baseline for monitoring changes in present and future condition, and (3) providing a descriptive and empirical documentation of channel conditions with which to aid TMDL problem investigations of chemical and biological impairments associated with excess sediment or a reduction in sediment transport capacity.

Selection of reference streams during IBI development

Determining and defining the reference condition is a critical element in biocriteria development (Barbour et al. 2000). During IBI metric development, channel stability assessments can be used for selection of stable reference sites (Maul et al. 2004). Maul et al. (2004) found that macroinvertebrate communities in stable streams demonstrated less temporal variability than communities collected from intermediate and highly unstable channels. Characterizing streams as "stable" or "adjusting" relative to regional expectations may help explain some of the variability often found among candidate reference streams during IBI development. Explaining this variability could improve the definition of a best attainable stream condition for a particular region and stream type.

Establishing a baseline for monitoring changes

Establishing a permanent benchmark allows direct comparison of a cross section and longitudinal profile through time (Harrelson et al. 1994). Permanent benchmarks and cross-sections often are required for field assessments and validation of channel stability. These benchmarks may vary from official USGS elevation monuments on bridges to other structures such as telephone poles, building foundations, and rock outcrops in streams. Photographs taken from a consistent location and perspective can also be useful for observing changes in channel condition. Field evidence of changes in channel characteristics could signal that the flow or sediment regime has changed (Rosgen 1996) and has set in motion a period of potential channel instability that requires remedial action. Aptly targeted remediation strategies during the early stages of channel evolution may prevent system-wide degradation.

Channel stability and TMDLs

In several National Water Quality Reports to Congress, sediment has frequently been listed as one of the leading causes of water quality impairment for stream reaches assessed in the USA (USEPA 1990, 1992, 1995, 1998, 2000b, 2002, 2007). Brooks et al. (2003, p. 211) stated that excess sediment can "adversely affect water quality and aquatic habitat and is one of the primary targets of the total maximum daily load (TMDL) provisions of the Clean Water Act in the United States." Excess sediment in streams is traditionally perceived as primarily the result of land use practices causing overland or gully erosion (Waters 1995). However, excess sediment can also be the result of unstable stream channels (Brooks et al. 2003). A number of studies (NRCS 1988; Trimble 1997; Simon et al. 2006) that partitioned sediment sources between upland and channel erosion reported that contributions from unstable banks and stream beds dominated the sediment budget and that this sediment source was the main cause of declining water quality in downstream receiving waters. Specifically, Simon et al. (2006) reported that fine-grained sediment emanating from unstable stream banks was responsible for declining water quality in Lake Tahoe; Trimble (1997) reported that two-thirds of the sediment budget for San Diego Creek was from channel erosion; and a report by the Natural Resources Conservation Service (NRCS 1988) indicated that unstable stream banks in the lacustrine portion of the Nemadji River Basin contributed up to 89% of the sediment transported into Lake Superior.

Consequently, TMDL problem investigations of the causal mechanisms of excess suspended and bedload sediment (Rosgen 2006) will likely require additional data collection, including assessments of channel stability (e.g., WARSSS, Rosgen 2006). One of the issues that may confound a determination of channel stability is that often these assessments are collected one or more years after the reach was listed as an impaired waterbody. Therefore, the mechanisms originally responsible for sediment discontinuity may no longer be active (Anderson et al. 2006), as could occur when a disturbed alluvial channel has evolved to more stable channel morphology (Schumm et al. 1984; Simon 1989; Rosgen 1996; Watson et al. 2002). Consequently, an investigation may not identify the source of sediment discontinuity that existed at the time of 303(d) listing, causing investigators to target incorrect sources for remediation. In addition, assessments of channel stability are often considered incomplete until future assessments are available with which to make a comparison and validate channel instability. If channel geomorphic measurements and channel stability assessments were taken at the time of biological monitoring, these fluvial assessments could provide an historical record with which to diagnose channel instability and prescribe remediation strategies. Rehabilitation alternatives should also be assessed within the context of the spatial variability and temporal succession of channel evolution (Watson et al. 2002). Therefore, we suggest that assessments of channel morphology be included during biological monitoring to improve future TMDL investigations of impairments and for selecting aptly targeted load allocations and associated remediation strategies.

A history of turbidity and the Minnesota River

Historically, the Minnesota River has been a turbid system; the Dakota named the river *Minne sota,* or *cloudy water* (Upham 1969). In the early 1990s, high levels of TSS, nutrients, and visibly turbid waters were perceived to be the consequence of large-scale agricultural practices within the basin, inspiring the governor at the time to promote basin-wide efforts to clean up the Minnesota River within a 10-year time-frame (Feist and Niemela 2002). Government agencies and land owners collaborated to reduce surface and gully erosion by enrolling thousands of hectares in federal and state conservation easement programs and promoting best management practices, such as grass swales, riparian buffers, and conservation tillage.

A follow-up study by the Minnesota Pollution Control Agency (Feist and Niemela 2002) found that although improvements in biotic integrity were found in the headwaters of the basin, there was little change in the basin overall. The minimal change in biological condition observed was attributed primarily to increases in tile drainage, ditching, and urbanization within the basin over the intervening time period. In addition, researchers have proposed several alternate causes and mechanisms for high levels of TSS and turbidity in the Minnesota River (Magner and Steffen 2000; Hatch et al. 2001; Bauer 1998; Thoma et al. 2005). Magner and Steffen (2000) argued that extensive landscape transformation (e.g., loss of wetlands, increased tile drainage, change in vegetation) over the last century increased the occurrence of peak stream flows and initiated a period of channel adjustment. Hatch et al. (2001) suggested that streambank erosion might be a significant contributor. Thoma et al. (2005) argued that geotechnical failure from alluvial soil layering and pore pressure seeps above the waterline continually destabilize non-cohesive alluvial bluffs (Bartholomew and Gupta, unpublished data, http://a-c-s.confex.com/crops/2006am/techprogram/P23551.HTM). Bauer (1998) suggested that post-glacial knickpoint migration in the Blue Earth River is a historical but gradually decreasing supply of sediment to the Minnesota River (Mulla and Bauer, *unpublished data*, http://a-c-s.confex.com/crops/2006am/techprogram/P27313.HTM).

Clearly, identification of historical, natural, and anthropogenic mechanisms of sediment discontinuity is crucial to complete a successful TMDL. Best management practices that attempt to alleviate only one contribution of excess sediment and fail to identify the cause of hydraulic, geotechnical, or hydrologic imbalances that lead to channel instability and excess sedimentation may provide limited benefit. Unless the suite of mechanisms for sediment discontinuity is identified, costly remediation efforts may result in minor improvements (Brezonik et al. 1999)—or even make the situation worse (Watson et al. 2002).

Olentangy River Watershed TMDL

The Olentangy River Watershed TMDL (Ohio EPA 2007) is an example of an interdisciplinary framework that incorporates knowledge of biology, chemistry, fluvial geomorphology, and watershed hydrology in attempt to address biological impairments. Leading causes of impairment identified in the TMDL were habitat alteration, nutrient enrichment, flow alteration, and siltation. The TMDL suggests that remediation strategies include cattle exclusion from riparian zones, improving channel stability and water quality through two-stage ditch construction, restoring floodplain connectivity, increasing watershed storage of overbank flows, and increasing infiltration, among others. These measures are intended to benefit the biological community by attenuating nutrients and stabilizing DO, dampening peak flows and increasing base-flows, and improving habitat conditions by reducing siltation through stream bank stabilization and retention of sediment by riparian floodplains. This TMDL incorporates an understanding of processes at the scale of reach, riparian, and watershed; all scales may be necessary to successfully address TMDLs related to biological impairments.

Conclusion

Changes in hydrology, morphology, and subsequent sediment continuity can alter and impair physical habitat, water chemistry, and biota. We suggest that biotic communities in low-gradient alluvial systems would be better managed and protected if physical integrity was defined as channel stability, and that channel stability was clearly incorporated into the definition of physical habitat integrity. Physical integrity is an important foundational mechanism, or missing link in maintaining biotic integrity, and channel stability is an important dimension of physical habitat integrity that is necessary for maintaining "the chemical, physical and biological integrity of our Nation's waters" (CWA Section 101[a]). Inclusion of stability assessments during IBI development will better identify reference reaches, provide a baseline for future assessments of channel condition changes, and provide an understanding of potential fluvial processes that underlie biotic impairment during TMDL investigations. An in-depth understanding of channel stability and other aspects of fluvial geomorphology is important for bridging the knowledge gap that may often exist between biologists and geomorphologists involved in assessing waters impaired by unstable stream channels. Successful completion of TMDL problem investigations will require an understanding of processes operating at different scales within the watershed and may involve collaboration and integration of multiple disciplines, such as biology, chemistry, geomorphology, and watershed hydrology. We recommend channel stability and other fluvial geomorphic and hydrologic and hydraulic assessments occur during biological monitoring and TMDL investigations to distinguish between natural and human-induced variability in IBI scores and to meet the mandate of the Clean Water Act to protect and restore physical integrity.

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CHAPTER 2

Testing the applicability of the Pfankuch Stability Index for rating low-gradient alluvial streams in Minnesota, USA and exploring its utility for Stressor Identification of biological impairments

Introduction

The 2002 National Water Quality Report (USEPA 2002) listed eutrophication from agriculture, hydrologic modification, and habitat modification as the three leading sources of river and stream impairment in the United States. Streams determined to be impaired are listed on the Federal 303d list of impaired waterbodies requiring a Total Maximum Daily Load (TMDL) study. During a TMDL study, investigators must characterize the pollutant(s) and pollution causing or contributing to the stream impairment and suggest load and stressor reduction activities. The National Academy of Sciences (NRC 2001) has criticized the TMDL process as being flawed due to many TMDLs not identifying or targeting stream degradation factors related to flow alteration and consequent loss of physical habitat. This may be due, in part, to the difficulty in characterizing flow variability at ungaged stream sites or a lack of interdisciplinary research that connects the links between land use, hydrologic modification, channel stability, and habitat quality to biological integrity. These links need to be established so that TMDLs can correctly identify the source and mechanism of biological impairments. This will allow for watershed and reach scale implementation plans to be developed with correctly identified targets for restoration and rehabilitation.

Before the links between channel stability, habitat quality, and biological integrity can be explored, research is needed that tests how well existing channel stability assessment tools designed for certain stream types and conditions in one region may be applicable to other stream types in other regions. Where metrics or geomrphic measures are deemed to be not appropriate or applicable, attempts should be made to modify and tailor the assessment tools to the regional conditions observed. Streams that are unstable will demonstrate deviations from reference streams in their cross-section, longitudinal, and sediment profiles (Rosgen 2006). Channel condition and stability assessments have been designed (Pfankuch 1975; BEHI, Rosgen 1996; WARSSS, Rosgen 2006; Rapid Geomorphic Assessment, Simon et al. 2007). Within each of these assessments, similar indicators are rated, including bed and bank scour, bank angle of repose, degree of mass wasting, substrate mobility, deposition, and sand bar production, among others (Pfankuch 1975, Rosgen 1996, Kaufmann and Robison 1998, Simon et al. 2007). However, each of these assessment tools uses a slightly different approach in evaluating channel condition and stability, and criticisms of applying certain assessment tools and metrics to conditions observed in low-gradient, non-cohesive sediment alluvial streams have been presented (e.g., Johnson et al. 1999, Simon et al. 2007, Suppes 2009). For example, in highly sinuous, low-gradient non-cohesive sediment streams, similar indicators of instability such as bank erosion and bar formation are often observed under stable conditions as streams laterally migrate within their floodplains (Simon et al. 2007). Other indicators of channel instability may be regionally specific (e.g., groundwater induced geotechnical failure at the toe of the bank, Magner and Brooks 2008) or not well suited to a particular stream type (e.g., rating angle of repose for A stream types). Testing assessment tools within different physiographic regions and stream types is necessary in order to identify the suite of indicators most appropriate for each stream setting so that indicators of instability can be appropriately rated. After which, a gradient in channel stability can be fully explored for an association with biological integrity and habitat quality.

Research objectives

The aim of this study was two fold: a) to test the ability of channel stability metrics comprising the *Stream Reach Inventory and Channel Stability and Evaluation Index* (hereafter referred to as Pfankuch Stability Index, PSI; Pfankuch 1975) to appropriately rate channel stability indicators observed in low-gradient, alluvial streams in Minnesota; and b) explore whether a subjective channel stability assessment could aid in establishing the links among channel stability, habitat quality, and stream biological integrity. The interest in the PSI was in part due to the minimal time required to complete the assessment, current application in stream stability assessments (e.g., WARRSSS, Rosgen 2006), and literature examples demonstrating an association between PSI metrics and attributes of biological communities. The PSI has been used in many applications, from Departure Analysis and sediment rating curves (Rosgen 1994, 2006), assessing stream stability associated with bridge scour (Johnson et al. 1999), investigating the effect of grazing on stream bank stability (Meyers and Swanson 1992, Riedel et al. 2006), understanding effects of timber harvest on trout density (Eifert and Wesche 1982), to exploring associations with degree of substrate scouring and macroinvertebrate distribution and density (Rounick and Winterbourn 1982; Death and Winterbourn 1994, 1995; Townsend et al. 1997b; Duncan et al. 1999; Robertson and Milner 1999; McIntosh 2000; Gislason et al. 2001; Lods-Crozet et al. 2001a, 2001b; Maiolini and Lencioni 2001; Heiber et al. 2002). Surprisingly, the PSI has been rarely been tested as a predictor of stream health using macroinvertebrate IBIs (Magner et al. 2008) and currently no examples of research have been documented that test the PSI as a predictor of fish index of biotic integrity (FIBI).

However, researchers have criticized certain PSI metrics as not being appropriate for rating conditions of stream stability observed that are typical for certain stream types stream (Johnson et al. 1999, Meyers and Swanson 1982, Asmus et al. 2009, Suppes 2009). For example, *a priori* perceptions exist that the PSI, in its original form, has metrics that do not adequately characterize and rate conditions of channel instability such as degree of incision or where geology and typography derive low-gradient stream settings that are typically dominated by fine substrates. The PSI was developed using streams in mountainous regions in the western United States where streams typically are higher gradient and comprised of a larger percentage of fragmented rock; whereas, low-gradient alluvial streams in Minnesota are typically composed of higher percentage of glacial outwash and till. These streams can also be inherently more sensitive to disturbance. Sensitivity to disturbance is related to geology, climate, anthropogenic land use, and a stream's sediment transport capacity. Sediment transport capacity is related to stream gradient, the discharge regime, and the size and amount of sediment particles (Lane 1955). Various natural and unnatural factors can dampen sediment transport capacity (e.g., lake and wetland storage, beaver dams, check dams) or increase it (e.g., increase in impervious, increase in drain tile, loss of perennial vegetation, channel straightening, meander cutoffs). Given that different regions and stream types can vary in geology and land use in the watershed, streams may be more or less resistant to a flashier hydrologic regime. Additionally, some alluvial streams in Minnesota are largely groundwater dominated. As water moves through the non-cohesive soil to the stream, groundwater pore pressure can act on the unsupported non-cohesive soil of the bank toe and cause geotechnical failure (Magner and Brooks 2008). This condition is not assessed with the current PSI. While a scoring modification has been suggested that takes into account inherent differences in stream type (Rosgen 1994, 2006), it is my opinion that it does not correct for potential issues with the applicability of certain metrics to all low-gradient stream settings. Hence, prior to exploring associations between stream health, channel stability, and habitat quality, the PSI first needs to be field tested in different regions and steams types in order to determine whether or not certain metrics are not applicable, are problematic to score, and if metric modifications are needed to improve the utility of the assessment tool to appropriately rate indicators of channel stability observed.

This study focused on testing the PSI in low-gradient (0.5 to 2 m/km), alluvial streams (mostly potential stream types C, Rosgen 1994) which are found in river basins throughout much of Minnesota to determine which PSI metrics are not applicable or not currently rated. Potential application of a modified assessment tool could include stream assessment of physical and biological integrity, reference stream selection for IBI development, Stressor Identification for biological impairments, and characterizing channel instability for sediment related TMDLs (see Chapter 1 or Asmus et al. 2009).

Research questions and hypotheses

For this study, the following questions were identified:

Q1: *Can a subjective channel stability assessment designed using high-gradient mountain streams with coarse substrates adequately describe stream conditions and appropriately rate indicators of channel stability found in Midwestern low-gradient streams commonly dominated by fine substrates?*

My *a priori* hypothesis about the utility of the assessment tool was that certain metrics would be problematic to score in low-gradient streams dominated by glacial deposits of fine substrate. Channel stability in low-gradient alluvial streams can be diagnosed using similar indicators as mountainous streams (i.e., degree of scouring, mass wasting of stream banks, deposition). However, some metrics in the PSI (e.g., *rock angularity*, *channel capacity*, *brightness*) may not be applicable to certain stream types with glacially deposited substrates. Additionally, the PSI may not adequately describe and rate stream conditions observed in Minnesota (e.g., ground water seeps, bank composition) and perhaps much of the mid-west. The test was simply to apply the assessment tool to conditions observed across a range of stream sizes and substrate conditions and note if scoring certain metrics was problematic or if certain metrics do not seem appropriate and should be excluded from a modified assessment.

> *Ho1*: There will be no PSI metrics that are problematic to score in low-gradient streams dominated by fine substrates or with a mixture of fine and coarse substrates.
>
> *Ha1*: There will be PSI metrics that are problematic to score in certain low-gradient stream settings. Consequently, metric modifications will be recommended that more appropriately characterize and rate channel stability conditions observed in low-gradient stream settings.

Q2: Does the variation observed in FIBI, PSI, and MSHA appear to be strongly associated with inherent differences in stream size, ecoregion, subwatershed land use, water quality variables, or reach condition (i.e., channelized or natural)?

Strong associations between FIBI and stream size, ecoregion, subwatershed land use, channel condition, and physicochemical quality variables have been demonstrated elsewhere. The two watersheds selected for this study contrast markedly in geology, climate, and vegetation which are characterized by ecoregion and subwatershed land use. Some of the reaches included in the study were channelized. Consequently, these inherent regional and local differences need to be tested so that potentially confounding variables could be identified.

Ho2: Variability observed in FIBI, PSI, and MSHA for all sites combined or by watershed will not be significantly explained by regional or reach scale variables such as stream size class, ecoregion, subwatershed land use, physicochemical water quality variables, or channel condition.

Ha2: Variability observed in FIBI, PSI, and MSHA for all sites combined or by watershed can be explained by regional or reach scale variables such as stream size class, ecoregion, subwatershed land use, physicochemical water quality variables, or channel condition.

Q3: *Could a channel stability assessment tool be useful for Stressor Identification or Causal Analysis of biological impairments? In other words, will associations be found between the PSI, certain assessment zones, or individual metrics that are significantly correlated with FIBI? How do these associations compare with the strength of the associations with habitat quality? Are channel stability and habitat quality related?*

To answer these questions, an association between fish community health characterized by the FIBI and channel stability as scored with the PSI was investigated using correlation and regression analyses. Since the association between FIBI and PSI is relatively untested, I applied a two-sided test of significance. If significant ($\alpha = 0.10$) associations were found between FIBI and PSI then these channel stability assessment tools could be considered useful for Stressor Identification of biological impairments. In addition, since habitat quality has been found to be highly associated with FIBI (Rankin 1989, Sullivan et al. 2004a), I also compared the correlation results between FIBI and MSHA metrics and FIBI and PSI metrics to determine whether channel stability or habitat quality was more strongly associated with stream health and which variables were the strongest predictors. Finally, associations between PSI and MSHA metrics were also explored. If statistically significant ($\alpha = 0.10$) associations were found then these channel stability assessment tools could be considered useful for establishing causal links between channel stability, habitat quality, and fish community health for Stressor Identification of biological impairments.

Ho3.1: There will be no statistically significant correlations found between FIBI and PSI variables (two-sided test).

Ha3.1: Statistically significant correlations will be found between FIBI and PSI variables (two-sided test).

Ho3.2: There will be no statistically significant correlations between FIBI and MSHA metrics (one-sided test).

Ha3.2: Statically significant correlations will be found between FIBI and MSHA metrics (one-sided test).

Ho3.3: There will be no statistically significant correlations between select MSHA metrics and PSI variables (two-sided test).

Ha3.3: Statistically significant correlations will be found between select MSHA metrics and and PSI variables (two-sided test).

Q4: Are there other channel stability indicators or geomorphic variables that are relatively easy to collect that also explain a significant portion of the variability in stream health or channel stability? If so, should they be included in a modified channel stability assessment?

The following variables were tested for their association with FIBI, PSI, and CEM using correlation and regression analyses since they have been shown to be associated with stream health in other studies. These additional variables were considered relatively fast and easy to collect with minimal training. Results may suggest which variables warrant consideration for inclusion in a modified channel stability assessment.

<u>Channel evolution model</u>: Geomorphologists and stream hydrologists have used channel evolution models (CEM) to describe the sequence of changes observed or predicted for applications requiring an understanding of scour and sediment dynamics for bridge protection and stream restoration (Shields et al. 1994, Watson et al. 2002). However, few published studies have investigated the link between CEM stage and stream health using an index of biotic integrity (e.g., Maul et al. 2004, Magner et al. 2008). In addition, these studies tested the association between CEM stage and macroinvertebrate IBIs; whereas, no published research was located that tested an association between CEM stage and FIBI.

<u>Percent stream features as riffle, pool and run:</u> These variables are estimated and included on the MSHA form but are not scored. Research has indicated that percent pool is an important habitat component for fish communities (Gorman and Karr 1978, Schlosser 1987, Shields et al., 1998) and has been associated with FIBI (Simonson et al. 1994). When streams are incised and in the process of channel evolution, pool volume/percent may be greatly diminished (Schlosser 1982, Rosgen 2006).

Sinuosity, gradient by map, and channel slope: Stream sinuosity and gradient are typically estimated United States Geological Survey (USGS) topographic maps and aerial imagery. For streams in low-relief areas, this method may underestimate the actual gradient within the length of the sampling reach since the 10 ft contour lines can be miles apart (M. Kocian, *unpublished data*). Channel slope was measured in the field using a topographic station, stadia rod and digital laser level for a companion study. This allowed me to determine whether a more localized estimation of channel slope would be a better predictor of stream health than gradient contour maps.

Substrate characteristics: Substrate variables such as *D50, D84*, and percent substrate type (e.g., *percent sand, percent cobble & boulder, percent rock*) have been shown to be associated with channel stability (Magner et al. 2008, Rosgen 2006) and biological communities (Eifert and Wesche 1982, Magner et al. 2008, Maul et al. 2004, Sullivan et al. 2004b).

Ho4: There will be no statistically significant associations between FIBI, PSI and CEM or geomorphic variables (two-sided test).

Ha4: Statistically significant correlations will be found between FIBI, PSI and CEM or geomorphic variables (two-sided test).

Methods

Selection criteria for study watersheds and sampling stations

Watershed and site selection involved the following considerations:

- Interest in selecting watersheds that provided a contrast in subwatershed land use and sediment characteristics.
- Candidate watersheds needed to have a fish index of biotic integrity (FIBI) that could be applied to warmwater streams. Only a few river basins had an FIBI developed.
- Study reaches needed to co-locate with previously established biological monitoring stations used by the MPCA so that data collected during previous visits could be consulted during site selection.
- Sampling sites were selected in an attempt to capture gradients in FIBI, drainage area, and geomorphology (i.e., sinuosity, gradient, dominant substrate type).
- Where feasible, data from sites previously collected by the MPCA within 5 years of this study (e.g., fish, habitat, and water chemistry) were included in order to increase the number of study sites available for analysis while minimizing data collection effort; only geomorphology and channel stability assessments were collected at these sites.
- The final list of sites in each watershed contained a mixture of both natural and channelized reaches.

River basins in southwest Minnesota have very different soils and land use than river basins in northeastern Minnesota, so the first consideration was to find a watershed in each of these larger regions. At the time of this study, only a select number of river basins in Minnesota had an FIBI developed for warmwater streams. Two of the river basins with FIBI guidance documentation included the Minnesota River Basin (MRB, Bailey et al. 1993) and the St. Croix River Basin (SCRB, Niemela and Feist 2000).

In the SCRB, streams in the Snake River Watershed (hereafter SNAKE) had recently been assessed to determine if reaches were meeting water quality standards. A few reaches with low fish and invertebrate IBI scores were determined to be impaired (e.g., Snake River, Groundhouse River, Knife River), thus initiating interest in additional biological collection on these stream segments and other streams in the watershed where impairments did not occur. Additionally, surficial geology was variable in the watershed and an objective of a larger study was to characterize stream types that may have different biological expectations due to the underlying geology and resulting differences in substrate character and habitat quality.

Within the MRB, the Redwood River watershed (hereafter REDWOOD) had variable surficial geology from west to east which made it a candidate for the companion study. REDWOOD also had been revisited for a study in 2001 (Feist and Niemela 2002) and provided the potential for fish, habitat, and water chemistry data to supplement the number of sites in this study. Segments of the Redwood River had also been assessed and listed as impaired for aquatic life for fish and turbidity.

Information from previous biological sampling events by the MPCA provided additional information for site selection in these two watersheds, such as FIBI, drainage area, gradient, sinuosity, wetted width, depth variability, and dominant substrate types. In addition, the MPCA records the channel condition observed at a site as being natural or channelized and there was interest in comparing results across these two conditions.

In total, 28 stream reaches were selected: 14 reaches in SNAKE and 14 reaches in REDWOOD (Table 2-2). In terms of *channel condition*, each watershed had an equal number of reaches that were channelized (REDWOOD = 4, SNAKE = 4).

Study regions

As outlined above, these two watersheds in Minnesota were selected based on availability of fish community Index of Biotic Integrity metrics (FIBI; Bailey et al. 1993, Niemela and Feist 2000) and contrasting watershed characteristics. These watersheds differ markedly in surficial geology, mean annual precipitation, historical vegetation, and land use. These differences in watershed landscape character is largely directed by the following conditions: 1) regional differences in topography and parent soils left by a history of glacial advance and retreat; 2) a climate gradient from north to south and west to east, i.e., a precipitation gradient from west to east (Baker and Kuehnast 1978, cited in Anderson et al. 2001) and a temperature gradient from north to south along the Great Lakes expansion and contraction zone and west to east along the expansion and contraction zone of the Great Plains (USGS 1999); 4) which together gave rise to regional variation in historical vegetation, namely deep-rooted prairie grasses in the southwest, and relatively shallow-rooted forest vegetation in the northeast (Marschner 1974); 5) the result being a dramatic difference in the soils that developed over time (Anderson et al. 2001); and 6) consequently, the type of land use the soils are best suited for. Today, the flatter, low-gradient, highly fertile *udoll mollisols* in the Minnesota River Valley support intense production of row-crops, primarily corn and soybean; whereas, the relatively infertile, undulating, forested *aqualf* and *udalf alfisols* in the St. Croix River Valley are better suited to forestry (Anderson et al. 2001) and pasture. This contrast in watershed landscape character and land use allowed me to test my research hypotheses in two very different stream settings in Minnesota and to determine whether or not results were similar across and within watersheds.

Redwood River Watershed

The Redwood River watershed drains 1,826 km^2 of the MRB in Southwestern Minnesota (Waters 1977). Mean annual precipitation in MRB is 66 cm, with highest monthly mean precipitation occurring in July (DeLong 2005, pp. 364). The geology in REDWOOD varies from headwaters to mouth due to glacial history with multiple lobes advancing and retreating at various angles and extents. The headwaters of the Redwood River begin in the Prairie Coteau of the Northern Glaciated Plains Ecoregion (NGP, Figure 2.1, Omerik 1987) "characterized by flat to gently rolling landscape, composed of glacial till." The Prairie Coteau is a higher elevation plateau with poorly defined drainage and a mix of row crops and pasture (ftp://ftp.epa.gov/wed/ecoregions/us/useco_desc.doc) where lower order streams are dominated by silts and fine sands, many of which have been ditched and straightened (MPCA 2005). Mid-order streams flow northeastwardly through the Prairie Coteau Escarpment of the NGP. Here, mid- to low-gradient streams are dominated by fine sands and intermittent gravel and cobble which provide some riffle habitat. Higher order streams in REDWOOD flow through the flat till plains (Waters 1977) of the Des Moines Lobe in the Western Corn Belt Plains Ecoregion (WCBP). This region is a "combination of nearly level to gently rolling glaciated till plains and hilly loess plains" (ftp://ftp.epa.gov/wed/ecoregions/us/useco_desc.doc). The Redwood River mainstem crosses ecoregion boundaries with contrasting surficial geology; consequently, the longitudinal profile of the Redwood River is characterized by variable stream gradients which provide a diversity of sorted materials and velocities. Study reaches along the Redwood River were comprised typically of runs and pools dominated by easily mobilized sand that was interspersed with occasional boulders; whereas, riffle habitats were comprised largely of gravel and cobble.

Historical vegetation in the MRB was predominantly a mixture of tall- and short-grass prairie in the west and tall-grass prairie in the east with "high concentrations of temporary and seasonal wetlands" (ftp://ftp.epa.gov/wed/ecoregions/us/useco_desc.doc). A majority of these prairie pothole wetlands have been tile drained and converted to row-crop cultivation. A relatively recent quantification of land use in REDWOOD indicates that only a small fraction of the landscape remains as forest (2%) and wetlands (3%). Currently, 86% of land is involved in agricultural production, of which 82% of the watershed is currently tilled for corn and soybean rotation (http://www.mn.nrcs.usda.gov/technical/rwa/Assessments/reports/redwood.pdf, NRCS 2011a). Other human alterations include an extensive network of channelized streams and tiling to facilitate drainage for agricultural production (Bailey et al. 1993).

Snake River Watershed

The Snake River Watershed drains 2623 km^2 in east central Minnesota (Waters 1977) and is part of the SCRB. Mean annual precipitation for SCRB is 78 cm, with highest monthly mean precipitation occurring in June and August (Delong 2005, pp. 365). Geology in SNAKE (Table 2-2) is comprised of the Minnesota/Wisconsin Upland Till Plain of the Northern Lakes and Forests (NLF) in the north and the McGrath Till Plain and Drumlins of the Northern Central Hardwoods (NCH) in the south (Figure 2.3, http://www.epa.gov/wed/pages/ecoregions/mn_eco.htm).

Headwater streams in the NLF largely originate in groundwater dominated low-gradient wetland channels that "lack riffles and have a glide/pool type of stream morphology" (Niemela and Feist 2000). These streams are dominated by fines consisting of sand, silt, and detritus (Niemela et al. 2004) with riparian zones of scrub-shrub vegetation (Eggers and Reed 1997). In contrast, mid order streams are low- to mid-gradient streams with riffle/run/pool stream morphology (Niemela and Feist 2000) dominated largely by boulder, cobble, gravel and sand. Higher order tributaries and the mainstem of the Snake River are mid- to low-gradient streams surrounded by second growth hardwoods. These streams are dominated by riffles of gravel and cobble, runs primarily of sand, and deep pools comprised of large boulders embedded with sand.

Historical land cover in the SCRB was dominated by mature red and white pine forest (Fago and Hatch 1993) until logging and agricultural conversion largely denuded the basin (Niemela and Feist 2000). Presently, land use in SNAKE is comprised mostly of second growth woodlands and wetlands (62%). Only 32% of land acreage in the watershed is used for agricultural production of which 24% is used for hay and pasture and only 8% is tilled annually for row-crops (www.mn.nrcs.usda.gov/technical/rwa/Assessments/09020309.html, NRCS 2011b). In addition, a few low- to mid-order streams have been ditched and straightened.

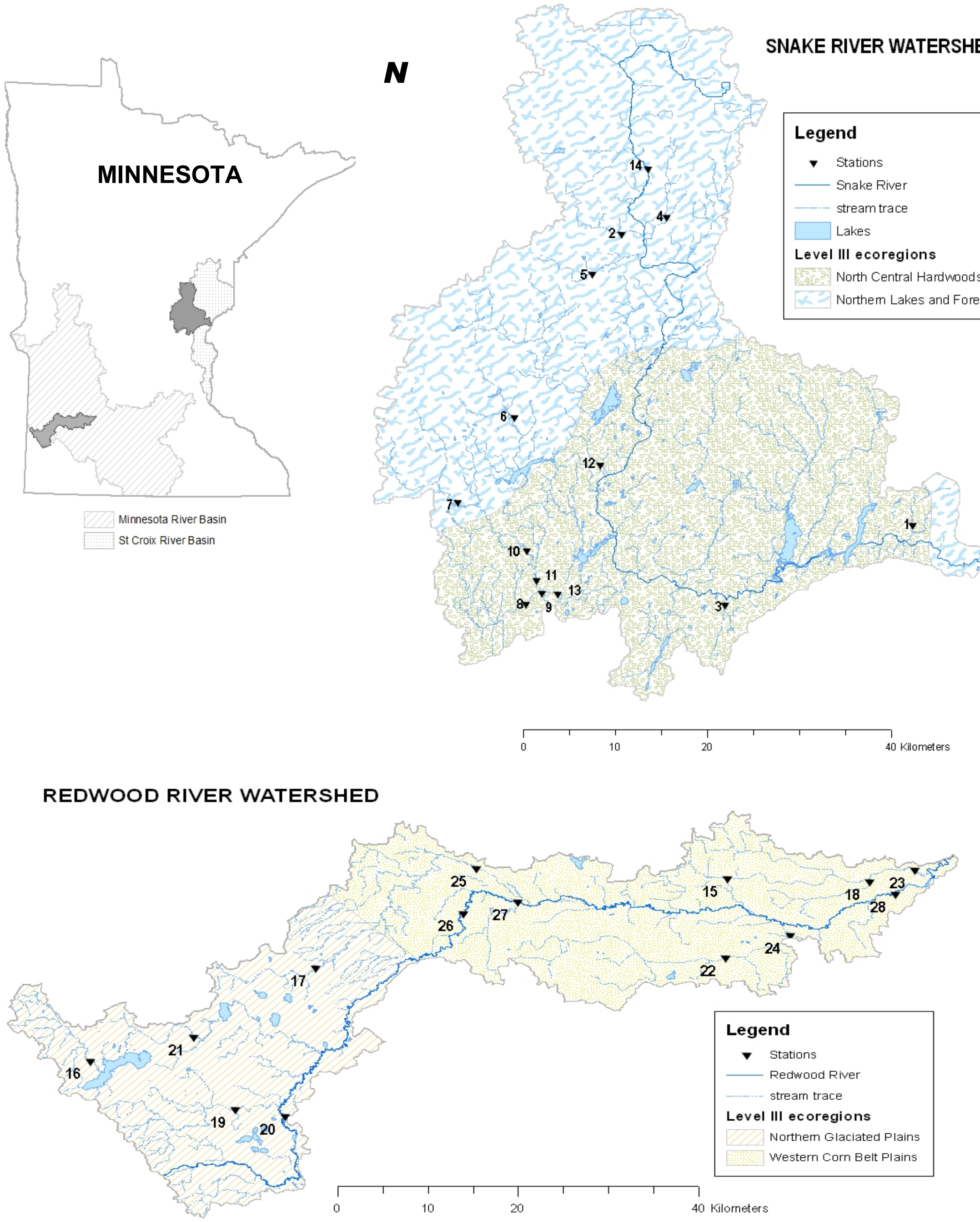


Figure 2-1: Location of study sites by watershed and level III ecoregion.

Data collection

Ecoregion, drainage area, land use statistics and channel condition

For this study, I assigned for each reach both the level III ecoregions originally proposed by Omerik (1987) and the level IV provisional ecoregion classification (USEPA, http://www.epa.gov/wed/pages/ecoregions/mn_eco.htm). Subwatershed drainage area and land use statistics were provided by MPCA. Channel condition was determined in the field and validated by consulting historical imagery. In order to test the association between channel condition and reach scale variables using correlation analyses, I assigned a numerical system to channel condition, where stream reaches that were 100% natural were designated "1", reaches that were 50% natural and 50% channelized were designated as "0.5", and streams that were 100% channelized were assigned "0".

Fish collection and IBI calculation

Fish communities were sampled using a backpack electrofisher or stream shocker following protocols employed by MPCA for their biological monitoring program (http://www.pca.state.mn.us/water/biologicalmonitoring/sf-sop-fish.pdf, see also Dolph et al. 2010 for description of fish sampling). Fish were collected during the recommended index period in order to reduce sampling variance in the community due to annual seasonal migration of certain species from lakes and larger rivers. Station lengths were established at 35 times the mean stream width (MSW) following Lyons (1992) and bounded by a minimum reach length of 150m and a maximum reach length of 500m. Fish communities were sampled by single-pass electrofishing in an upstream direction and across the full extent of the wetted width in order to sample all available habitats. Attempts were made to sample in relative proportion to the habitat types present within the reach. Depending on MSW fish were collected using one battery powered backpack with one anode operator and one netter (MSW <8m) or a gas powered electric generator on a stream barge with two anode operators and two netters (MSW >8m). However, at one site in REDWOOD, conductivity was very high (2439 μmhos) and initially we did not elicit good taxis using a backpack electrofisher. Higher conductivities (>1800 μmhos can reduce the width of the electric field and thereby reduce the success rate of fish catch (Hill and Willis 1994; Reynolds 1983). To increase the power output, we switched to a gas-powered generator tow-barge unit with AC current and fish taxis was greatly improved.

At all sites, fish captured were separated by species, enumerated, measured (smallest and largest), anomalies recorded (deformities, eroded fins, lesions, and tumors), and batch weighed. Most fish were identified to species in the field; whereas, unfamiliar species were preserved and identified later in the lab by consulting *Fishes of Wisconsin* (Becker 1983). A few representative specimens of species difficult to identify were preserved in 85% ethanol and retained as vouchers for validation of identification by trained taxononomists at the Bell Museum of Natural History, University of Minnesota. Fish too large to voucher were photographed. All remaining fish were released at the end of data recording.

Fish community data were used to calculate a fish index of biotic integrity (FIBI) using metrics developed by the MPCA separately for each study region (Bailey et al. 1993, Niemela and Feist 2000) following guidance by Karr et al. (1986). In general, metrics comprising an FIBI characterize the taxonomic and trophic composition of the fish community, measure abundance of species, and assess condition of individuals (Karr et al. 1986). Species encountered in each region are assigned to trophic and reproductive guilds, by family group, habitat preference, and by pollution tolerance. The FIBI is composed of metrics that assess stream health by using fish community attributes (Karr 1981, Karr et al. 1986) that have demonstrated a dose response to an anthropogenic disturbance gradient. The disturbance gradient developed by the MPCA (Table 2 in Dolph et al. 2011) uses a combination of GIS generated watershed statistics and aerial estimations of the extent and type of land use adjacent to the sampled reach. Candidate IBI metrics are tested against this human disturbance gradient; metrics selected for inclusion in the IBI have demonstrated a significant and predicable response to the disturbance gradient or indicate the health of individuals (e.g., DELTs). The top metric scores are associated with the reference or least impacted conditions; lower scores reflect a deviation from this reference or least impacted condition assumed to be associated with a biological stress that is a limiting condition to certain assemblages or species of the biological community.

The FIBI metrics used in this study are dependent on drainage area (DA) size classes in order to account for the inherent variability in fish community species and composition as stream sizes increase from small headwater streams to larger rivers (Tables A-2, A-3). For SNAKE, the final FIBI total score is based on a 0 to100 scale; whereas for REDWOOD, the final FIBI total score is based on a 0 to 60 scale. In order to compare FIBI scores across and between watersheds, REDWOOD scores were converted to a 0 to 100 scale to match the scale used for SNAKE. Higher FIBI scores represent better stream health.

Channel stability assessments

Two channel stability assessments were collected. The PSI was the main assessment tool tested as a predictor for fish community health and habitat quality; whereas, CEM was collected as a potential metric to include in a modified low-gradient stream assessment.

Stream reach inventory and channel stability evaluation

Channel stability was evaluated at each site using *The Stream Reach Inventory and Channel Stability Evaluation* (Pfankuch Stability Index, PSI; Pfankuch 1975). PSI metrics were individually scored in the field while consulting the detailed descriptions for each metric in the guidance manual (Pfankuch 1975). All reaches used in this study were assessed in August 2006 which corresponded to late summer base flow and low flow conditions. This allowed an assessment of the lower banks and presence of point bars that would be more difficult to assess during higher flows. Bankfull height was visually estimated in the field and validated using regional hydraulic curves developed specifically for regions in Minnesota (Magner and Brooks 2007).

The PSI is comprised of 15 metrics that characterize the degree of unstable hydrologic conditions observed (Table D-1). The PSI scores physical indicators of channel stability by rating three zones of the channel and its attendant floodplain (Table A-4). *Upper Bank* (UPPER) metrics assess the degree that vegetative vigor contributes to the capacity of the banks to resist detachment and add roughness that dampens stream power during above bank-full conditions. *Lower Bank* (LOWER) metrics rate the composition of the bank material and ability to resist detachment, presence and orientation of obstacles that may deflect flow into the bank thereby causing bank erosion, and indication of excess deposition on lateral bars. BOTTOM metrics assess the degree of substrate compaction and evidence of scouring and deposition.

During assessment of the PSI, certain metrics were challenging to rate where fine substrates dominated or turbidity was high (i.e., *brightness, rock angularity,* and *clinging aquatic vegetation)*. These metrics were marked as "not applicable" and scored by consulting other BOTTOM metrics. The PSI is rated on a scale from 38 to 152, where lower scores indicate more stable channel conditions.

Rosgen (1996) incorporates his stream classification into the final rating by adjusting the PSI score according to stream type. In order to apply the rating modification, the assessor must first determine the stream type and then categorize the current stream type as "stable" or "unstable." If the stream type is determined to be the stable stream type for the reach, the PSI numerical score is used to determine the rating (e.g., moderately unstable, stable) associated with the stream type. If the current stream type for the stream reach is considered an unstable form, the assessor must determine what the stable stream type should be (i.e., the "potential stream type", Rosgen 2006, Worksheet 7-18b, pp. 7-119). The stability rating given to the unstable reach is derived by taking the PSI numerical score and locating the rating category associated with the potential stream type--not the present stream type. While this information may be important for understanding a stream's current or potential stability, I elected to not apply the score modification proposed by Rosgen for a few reasons:

1) Most streams in this study were fairly similar in their stream type (mid-to low gradient, minor to moderately entrenched, relatively small mean particle size), so channel typing may not be as critical. However, channel typing should be considered in future studies.

2) The gradient in channel stability conditions observed would be lost when each stream is placed into a discrete category. This may impede uncovering potential associations between biotic integrity and channel stability. For example, if the PSI scores for two reaches having the stream type fell a few points on either side of a rating category division, these two reaches would be given very different stability ratings, even though the difference in scores was relatively insignificant. This difference in categorization could limit the ability of the predictor variable to explain a significant portion of the variance in the response variable. Therefore, maintaining the relative difference in scores was preferable to categorical ratings.

3) I was interested in exploring a gradient in channel stability with a gradient in biological integrity and habitat quality by applying correlation and multiple linear regression techniques since these statistical tests are considered more robust than categorical tests (e.g., Chi-square, analysis of variance between groups). Continuous scoring allowed me to apply correlation and regression analysis since both the FIBI and MSHA total scores are continuous as well.

Channel Evolution Model

Each stream reach was classified by stage(s) of stream channel evolution at the same time the PSI was collected. The *Channel Evolution Model* (herein referred to as CEM) used in this study is a framework developed by Schumm et al. 1984 and modified by Thorne et al. 1997 (Table 1-2) which describes a conceptual time/space sequence of changes in the geomorphic cross-sections of streams during periods of channel instability. CEM is a theoretical and empirically determined five-stage sequence of channel hydrogeomorphic adjustment that may occur in response to a local change in stream gradient (i.e., knickpoint migration), discharge, sediment size, or sediment load (Lane 1955) which can alter and impair habitat conditions for biota (Alexander and Hansen 1986, Shields et al. 1994, Maul et al. 2004, Sullivan et al. 2004b). This hydrogeomorphic sequence is categorized herein as follows: stable (pre-adjustment) (I), downcutting (II), widening (III), widening and aggradation (IV), and return to equilibrium (V). For statistical purposes, CEM stage was converted to a numerical gradient where CEM II = 2, CEM II and III observed in the same reach = 2.5, and CEM I = 6.

Habitat quality assessments

Two types of habitat assessments were collected: 1) the *MPCA Stream Habitat Assessment* and 2) the *Quantitative Habitat Assessment*.

MPCA Stream Habitat Assessment

The *MPCA Stream Habitat Assessment* (MSHA) was scored immediately after fish collection (http://proteus.pca.state.mn.us/publications/wq-bsm3-02.pdf). The MSHA is a visually based, qualitative assessment that is used by the MPCA for their biological monitoring program and is largely based on the Qualitative Habitat Evaluation Index (QHEI; Rankin 1989). The MSHA uses many of the same variables as the QHEI, but certain variables have been modified in an attempt to "more adequately assess important characteristics influencing Minnesota streams" (http://proteus.pca.state.mn.us/publications/wq-bsm3-02.pdf). Like the QHEI, the metrics included in the MSHA subjectively score surrounding land use, riparian quality, instream cover, substrate quality, and channel morphology (Table A-5); however, the MSHA does not assess riffle quality as a separate metric. These modifications were made in attempt to not penalize streams that are naturally devoid of riffle habitat (e.g., low-gradient streams; M. Feist, MPCA, *personal communication*); consequently, some metric score ranges have been increased (e.g., *channel stability*) to maintain a similar total point range as the QHEI. The MSHA is rated on a scale from 0 to 100 where higher scores indicate better habitat quality.

Quantitative Habitat Assessment

Quantitative measurements of habitat variables were surveyed following MPCA sampling protocols (http://proteus.pca.state.mn.us/publications/wq-bsm3-01.pdf) which are based on a transect method developed by Simonson et al. (1994). This habitat assessment method (herein referred to as *Qualitative Habitat Assessment,* QHA) was collected for a complimentary research project and to facilitate data sharing with MPCA. A full QHA habitat assessment typically requires 2 to3 people approximately 1 to 1.5 hours to complete and since the objective of this study is to identify key habitat and channel stability variables that could be collected with minimal additional field time (time allotted: approximately 15 min), for this study only certain QHA variables were consulted to reduce reduce subjective bias during scoring of MSHA metrics. Consequently, only select QHA variables that were consulted in this study are described below.

Stream feature lengths were measured and quantified as the percent of each type present per total reach length sampled for fish (e.g., *percent riffle, percent run, percent pool).* For this study, percent stream features were stream features were considered candidate geomorphic variables that could be included in a channel stability or habitat assessment.

The following QHA variables were measured across the wetted width of each transect (13 transects in total): 1) The type and percent of wetted width cover or fish such as boulder, undercut banks, woody debris, and vegetation. This information assisted in completing the MSHA metrics associated with *cover type* and *cover amount*. 2) The dominant substrate type, depth of water, and percent of vertical embededness was estimated at four equidistant points and the thalweg for a total of five points. These variables were reviewed when scoring the MSHA metrics for *substrate, embeddedness,* and *depth variability.* 3) Canopy cover was estimated at six points across the wetted width at each transect using a densiometer. These values were consulted in estimating the MSHA metric *shade*. 4) Bank erosion, riparian width and adjacent land use were recorded at each transect for the left and right bank. These variables were consulted during scoring of MSHA metrics *bank erosion* and *riparian width*.

Physicochemical measurements

Chemical and physical measures of water quality were collected prior to fish sampling following MPCA protocols (http://proteus.pca.state.mn.us/water/biomonitoring/sf-sop-fish.pdf). Infield measurements were collected using the following: a multiparameter probe for pH, water temperature, and specific conductance and a Hach winkler titration kit for dissolved oxygen. A 1-liter grab sample was collected from the water column within a section of the reach with visible flow. The grab samples were put on ice during transport to the Geochemistry lab at the University of Minnesota where the water samples were analyzed for nutrients and suspended solids: total phosphorus, total nitrogen, total ammonia nitrogen, and total suspended solids. The fraction of unionized ammonia was calculated using total ammonia and field measurements of pH and water temperature at time of collection and applying a multiplication factor (Emerson et al.1975).

Geomorphic variables

The following variables are referred to herein as geomorphic variables. Percent stream features (i.e., *pool, riffle, run*) were estimated during the quantitative habitat assessment (QHA). Sinuosity *by map* was estimated in ArcGIS using aerial imagery. Sinuosity is a ratio of the total reach length to the straight line distance between upstream and downstream ends of the sampled reach. *Gradient by map* was estimated in ArcGIS using USGS 1:24,000 topographic maps. Gradient (m/km) was estimated by locating the 10 ft contours upstream and downstream of the sampling reach and digitally measuring the stream length between the two elevation contours. Gradient was computed as the ratio of rise/run by using the known elevation difference from the topographic map (rise in feet converted to meters) and the stream distance between the two contours (run in miles converted to kilometers). *Percent Channel slope* (hereafter, *channel slope*) was estimated using a topographic station, stadia rod and digital laser level following protocols by Harrelson et al. (1994). *Channel slope* was measured in the field by measuring the surface of the water as referenced to an established benchmark for the length of the reach. The surveyed reach was the same as the reach length used for fish sampling if conditions remained uniform throughout (e.g., channelized reaches) or over two stream meander sequences (Rosgen et al. 1994) for streams demonstrating more complexity. *Channel slope* (rise/run) was then calculated as the difference between the water height at the start of the start of the sampling station and the end of the sampling station (rise) divided by the stream length (run). Substrate composition was characterized using a modified Wolman pebble count procedure (Wolman 1954) for streams with a mixture of coarse and fine substrates; whereas, for streams dominated by fines, a composite grab sample of sediment was collected in the field and sorted in the lab using a nested sieve procedure (Lambe 1951). Substrate sizes and counts (or weights from sieve analysis) were entered into STREAMS (Mecklenburg and Ward 2005) and the percent of each substrate type was computed: *percent silt/clay, percent sand, percent gravel, percent cobble, percent boulder, percent cobble & boulder*, and *percent rock. Percent rock* was computed as the combined substrate percentages of gravel, cobble, and boulder. Finally, *D50* and *D84* were computed as the cumulative percent particle size when particles were arrayed from smallest to largest.

Data analysis

Data transformations

Prior to statistical tests, variables were reviewed to determine where traditional data transformations should be applied and where histograms identified highly skewed data or extreme values. A log10 transformation was applied to drainage area (km^2) and Log10[x+1] transformations were applied to *gradient by map* and physicochemical measurements since histograms indicated that these variables were highly skewed. Log10 [x+1] transformations were also applied to geomorphic variables such as *D50* and *D84* since the distributions of these variables are based on a cumulative function which is inherently skewed. ArcSine square-root transformations were applied to percentage data, such as subwatershed land use types, stream features, and percent of each substrate type.

Statistical Analyses

First, in order to determine the degree to which basin watershed alone explained a significant portion of the variability in FIBI, PSI, and MSHA scores observed, I grouped scores by watershed and applied either analysis of variance (ANOVA) or Wilkoxin Sum Rank Statistics. Next, I explored associations between fish community health, channel stability, habitat quality, physicochemical measures and geomorphic variables using simple correlation. I also analyzed the strength and form of the association between FIBI scores and select variables using linear and polynomial regression. Finally, I developed multiple linear regression models with each subset of variables (e.g,. channel stability, habitat quality, physiochemical, geomorphic) to determine the strongest predictor variables of biological integrity between and within watershed groups.

ANOVA and Wilkoxin Sum Rank Statistics

As described earlier, the two watersheds used in this study contrast markedly in glacial history, soil, vegetation, and land use. Consequently, it was important to determine whether these underlying differences alone may explain a significant portion of the variability observed in FIBI, PSI, and MSHA between watersheds prior to testing and interpreting results of associations between fish community health, channel stability, and habitat quality. I applied Analysis of Variance tests (ANOVA) to determine whether the range and distributions in FIBI, MSHA, and PSI scores were significantly different at the scale of basin watershed (i.e., REDWOOD, SNAKE). I applied parametric t-tests when the assumption of equal variances was met and a non-parametric Wilkoxin Sum Rank Statistic for large sample sizes when the assumption of equal variances was not met. Results for considered significant at the $\alpha = 0.1$ level for a two-sided test.

Next, in order to determine whether within watershed variables were influential factors, I assessed whether distributions in FIBI, MSHA, and PSI scores grouped by *ecoregion*, *stream class* (stream size class) and c*hannel condition* (natural verses channelized) were significantly different using a Wilkoxin Sum Rank Statistic. The within watershed group sample sizes were small ($n < 10$), so for these groupings, I applied the Wilkoxin Sum Rank Statistic method for small sample sizes. Results were considered significant at the $\alpha = 0.1$ level for a two-sided test. Since the within watershed groups were quite small ($n = 3$ to 10), the confidence intervals for the Wilcoxin Sum Rank Statistic were quite large; consequently, only very large differences would generate a statistically significant result, so these tests were inherently prone to Type 2 error (statistically fail to reject Ho when Ho should be rejected). Therefore, I also reviewed scatterplots to observe whether the distribution in scores for any group was noticeably above or below the grand mean across the two watersheds. A group distribution that is noticeably above or below the grand mean could indicate that the watershed variable being tested is a potential confounding factor explaining the variance in FIBI, PSI, and MSHA but the statistical test was not robust enough to find a statistically significant difference. All statistical tests were performed using JMP® 8.0 Statistical Discovery Software (SAS Institute, Cary, IN).

Parametric and non-parametric correlation

Given the small data set used in this study, I compared the correlation results between both Pearson Product Moment Correlation (r) and Spearman Rank Order Correlation (r_s). This was done for a few reasons. 1) When testing the level of correlation between two variables a researcher must decide whether or not it is appropriate to apply parametric or non-parametric tests (and whether the test is one-tailed or two-tailed) by considering how the study was designed and whether or not the variables measured are likely to be from a population with a normal distribution. In cases of environmental data with few observations, some researchers suggest that only non-parametric tests be applied, since histograms of the data do not typically conform to the shape of a normal distribution. Other researchers have suggested that parametric tests for small data sets are acceptable if the researcher does not have sufficient evidence that suggests that the sample would be from a non-normal distribution if the sample size was large (i.e., Central Limit Theorem). 2) For exploring the strength of the association between a biotic indicator and an environmental gradient, a parametric test such as Pearson Correlation is arguably the preferred test to a non-parametric alternative such as Spearman Correlation. With a parametric test, the actual data values (or appropriately transformed data values) with their range in observations are retained; whereas, with a non-parametric alternative, data values are reduced to ranks and the range and variability between predictor variables and the response variable are lost. Parametric tests are also considered more powerful than non-parametric tests for small sample sizes (less prone to Type 2 error); however, parametric tests may be prone to Type 1 error (reject Ho and accept Ha when Ha is false).

Hence, due to the small sample sizes in this study, I applied both parametric and non-parametric correlation in order to compare the results and minimize spurious interpretation. Where large differences between correlation values occurred ($|r-r_s| > 0.10$), I reviewed bivariate scatterplots in order to determine whether extreme values were potentially overly inflating or deflating the correlation results for Pearson Correlation.

Linear and polynomial regression

Since the shape of the association between two environmental variables has often been described as being curvilinear, or wedge shaped, I reviewed scatterplots and compared the goodness of fit between linear and polynomial regression models. If competing linear and polynomial regression models were both considered significant and explained a similar portion of the variability observed between the two variables (*Adj* R^2 <0.05), I chose the simpler model (i.e., linear model). I also considered whether or not the linear and non-linear models selected could be explained with ecological concepts and therefore seemed reasonable.

Results were considered highly significant at $\alpha = 0.05$ and marginally significant at $\alpha = 0.10$. I applied two levels of significance in order to separate variables that were highly probable predictors of FIBI from variables where the association was considered significant, but not as strong, or appeared to be directed by a few outliers. Given the small sample sizes, a Type 2 error was more probable (i.e., fail to reject the null hypothesis of no association between two variables when it is false). The additional threshold of $\alpha = 0.10$ made the results less likely to present Type 2 error; although, this increased a greater likelihood of Type 1 error (i.e., reject the null hypothesis of no association and accept the alternative that there is a significant association when there was not). Bivariate scatterplots were also consulted in order to ensure that outliers were not unduly influencing the results.

Multiple linear regression

Prior to model building, correlation tables and linear regression models were reviewed; only variables that were significantly correlated (r >0.40) with the response variable and were not considered redundant with other explanatory variables (r >0.80) entered MLR analysis. Occasionally, I included redundant predictor variables if other models had identified similar predictors in order to allow MLR to chose the best set of predictor variables. I reviewed candidate models using both forward and backward multiple linear regression. All variables included in the models selected by step-wise regression were examined for significance (p <0.1). If a variable included in the model was not significant, it was removed and test statistics for a new model were generated until all predictor variables were significant. When forward and backward selections were not in agreement, I included both models in the results. I examined the *Adj* R^2 and two penalty criterion in selecting the best models. I applied both the Burnham and Anderson (2004) version (AICc) of the Akaike Information Criterion (AIC, Akaike 1974) and Mallow's Cp (1973). The best models selected had the lowest AICc (>2 AICc difference from next best model) and Cp approached the number of variables in the model.

If the *Adj* R^2 between two competing models was <4%, I chose the model with fewer variables following model selection criteria from Ulrich (2008).

Results

Applicability of PSI metrics to low-gradient alluvial streams

During the assessment of the PSI, there were a number of metrics that either did not seem applicable or where the descriptions did not include conditions observed (Table 2-4). More detailed descriptions of observations and recommendations for modifications are included in the **Discussion.**

Table 2-1: PSI metrics with descriptions of scoring issues encountered when applying to low-gradient alluvial streams.

PSI metrics	Scoring issues?	Comments
landform slope	Yes	Difficult to know where upper bank begins, variable bank angles within reach.
mass wasting or failure	No/Yes	May be improved with more quantitative descriptions within each rating category.
debris jam potential	No/Yes	Metric for sensitivity analysis but may not be suitable for current stability.
vegetative bank protection	No/Yes	May be improved with ratings that include a ratio of rooting depth to bank height.
channel capacity	Yes	Not appropriate for incised streams.
bank rock content	No/Yes	Does not include bank protection by roots or cohesive soils.
obstructions/ flow deflectors/ sediment traps	No/Yes	May be improved by separating deflectors from sediment traps and including lateral riffles.
cutting	No/Yes	May be improved by changing height of cutting in inches to ratios, adding gw seeps.
deposition	No/Yes	Sometimes difficult to characterize deposition on lower banks from bottom, especially with new vegetative growth on banks.
rock angularity	Yes	Not applicable for streams where parent material is glacial outwash, till, or loess, and not derived from fractured bedrock or sandstone.
brightness	No/Yes	Difficult to rate in streams without coarse substrates.
consolidation/ particle packing	No/Yes	Difficult to rate in sand dominated streams. May be improved with modifications that describe depth of cone penetrometer.
bottom size distribution/ percent stable materials	No/Yes	In general, metric rates sand dominated streams as unstable, appropriate for sensitivity analysis, but may not appropriately rate current conditions of stability.
scouring and deposition	No/Yes	Consider separating into two distinct metrics.
clinging aquatic vegetation	No/Yes	Challenging to rate/not applicable for highly turbid streams.

Watershed comparisons

Subwatershed and reach level statistics

At the scale of the subwatershed, drainage areas (DA) across both watersheds were mostly similar except for three larger DAs in REDWOOD (Table 2-2). For land use, subwatersheds in REDWOOD were more highly disturbed than SNAKE (Table 2-3). Subwatersheds in REDWOOD were dominated by agriculture; whereas, subwatersheds in SNAKE were largely dominated a mix of forest and wetland with only a few watersheds dominated by a mix of agriculture and range. When land use types agriculture, range, and urban were categorized together as disturbed, *percent disturbed* in REDWOOD ranged from 86 to 99% (median = 94%). In contrast, *percent disturbed* for SNAKE ranged from only 3 to 56% (median = 17%). *Percent water* and *percent urban* comprised very small percentages of each subwatershed (<5%) except for one reach in REDWOOD (R6) where water comprised 7.6%.

At the scale of the sampling reach, reach lengths ranged from 154m to 545m (median = 271m) in SNAKE and from 150m to 501m (median = 195.5m) in REDWOOD (Table 2-2). SNAKE had a larger range in gradient estimations than REDWOOD. *Gradient by map* (m/km) ranged from 0.2 to 8.84 (median = 1.54) in SNAKE and from 0.24 to 4.86 (median = 1.06) in REDWOOD. The range in *sinuosity by map* for each watershed was fairly similar; however, reaches in REDWOOD tended to be slightly more sinuous overall than SNAKE. Dominant substrate types comprising the stream bottom varied by reach (Tables 2-2) and watershed. Overall, dominant substrate types were generally comprised of larger grain sizes in SNAKE than REDWOOD. In SNAKE, many reaches contained cobble and either sand or gravel as a co-dominant substrate; sand was the most dominant substrate at only a few reaches. For REDWOOD, a majority of reaches were dominated by sand and gravel, a few reaches were dominated by silt, and only one reach (R23) was dominated by cobble. Stream feature estimations (Table 2-4) indicate that pool and riffle were typically the two most dominant stream features in SNAKE; whereas, for REDWOOD, run was typically the most dominant stream feature. Most reaches in both watersheds contained riffle habitat; however, a few reaches in each watershed did not. Notably, riffle habitat was the most dominant stream feature at only one site (S4). This reach was also an outlier in terms of gradient (channel slope 5%), D50 (110mm), and D84 (220mm).

Table 2-2: Station characteristics by reach and date sampled. Stations in with an asterisks (*) were exuded from statistical analysis due to natural background conditions.

Station ID	DA (km^2)[a]	Eco-region[b]	Dominant substrate[c]	Chan. Cond.[d]	Gradient by map (m/km)	Sinuosity by map	Sampled by[e]	Date sampled	Reach length (m)
SNAKE									
S 1	16.8	51k	sa	NA	1.88	1.08	UMN	21Jul2005	169
S 2	29.8	50b	sa, g	NA	0.90	1.15	UMN	03Aug2005	158
S 3*	30.0	51k	sa, si	OC	0.20	1.09	UMN	27Jul2005	154
S 4	31.1	50b	c, b	NA	8.84	1.11	UMN	07Jul2005	191
S 5	33.7	50b	sa, g, c	OC	1.82	1.23	UMN	19Jul2005	161
S 6	51.8	50b	c, g	NA	2.05	1.64	UMN	02Aug2005	180
S7	109.8	50b	c, sa, g	NA	2.06	2.21	UMN	26Jul2005	300
S 8	124.1	51k	c, g, sa	OC	0.45	1.06	UMN	28Jul2005	242
S 9	132.6	51k	sa, g	OC/NA	0.45	1.11	UMN	22Jun2006	355
S 10	156.2	51k	c, sa	NA	1.56	1.67	UMN	16Aug2005	367
S 11	157.7	51k	sa	NA	0.81	1.38	MPCA	30Jul2003	514
S 12	278.7	51k	c, b, g	NA	2.48	1.08	UMN	19Jul2005	335
S 13	295.3	51k	c, sa, b	NA	1.36	1.05	MPCA	31Jul2001	500
S 14	403.8	51k	c, b, sa	NA	1.51	1.24	UMN	04Aug2005	545
REDWOOD									
R 15*	20.7	47b	si	OC	0.32	1.00	UMN	22Jun2006	175
R 16	58.3	46k	si, c	NA	1.12	1.54	UMN	09Aug2005	150
R 17	71.5	46l	g, c	NA	4.86	1.88	UMN	09Aug2005	144
R 18	118.1	47b	sa, si	OC	0.38	1.05	UMN	13Jul2005	185
R 19	123.5	46k	sa, g, si	OC	0.78	1.23	UMN	03Aug2006	185
R 20	145.0	46k	sa, g, c	NA	1.00	1.38	UMN	03Aug2006	204
R 21	145.0	46k	si, g	NA	2.89	2.57	UMN	10Aug2005	172
R 22	160.3	47b	sa, g	OC	0.57	1.00	UMN	13Jul2005	179
R 23*	169.9	47b	c	NA	4.56	1.63	UMN	15Jul2005	207
R 24	215.5	47b	g, sa, c	NA	1.28	1.80	UMN	12Jul2005	233
R 25	301.5	47b	sa, si	NA	0.24	1.39	UMN	14Jul2005	207
R 26	695.7	47b	sa, g, c	NA	1.27	1.54	UMN	11Aug2005	365
R 27	797.5	47b	sa	NA	1.25	1.54	MPCA	31Jul2001	487
R 28	1635.6	47b	sa, b	NA	0.37	1.55	UMN	12Aug2005	501

[a]DA = drainage area. Sites in each watershed are arranged from smallest to largest DA.
[b]Ecoregions: 46k = Prairie Coteau and 46l = Prairie Coteau Escarpment of the Northern Glaciated Plains ecoregion (46); 47b = Des Moines Lobe of the Western Corn Belt Plains ecoregion (47); 50b = Minnesota Wisconsin Upland Till Plain of the Northern Lakes and Forests ecoregion (50); 51k = MacGrath Till Plains and Drummlins of the North Central Hardwoods ecoregion (51).
[c]Dominant substrate types collected using QHA: si = silt, sa = sand, g = gravel, c = cobble, b = boulder. Listed in order of most to least dominant and comprised at least 15% of the substrate observed.
[d]Channel condition: NA = natural, OC = old channelization, and OC/NA = half old channelization and half natural.
[e]Sampled by: UMN = University of Minnesota and MPCA = Minnesota Pollution Control Agency.

Table 2-3: Percent land use by type and overall percent disturbed** for study reaches by watershed. Percentages greater than 50% are in **bold**.

Station ID	Forest (%)	Wetland (%)	Water (%)	Ag* (%)	Range (%)	Urban (%)	Disturbed** (%)
SNAKE							
S 1	28.1	18.6	0.4	13.6	39.4	0.0	**53.0**
S 2	**60.8**	35.6	1.0	0.2	2.5	0.0	2.7
*S 3****	*12.2*	*31.5*	*0.4*	*19.1*	*34.0*	*2.4*	***55.5***
S 4	47.6	39.5	0.7	1.2	10.5	0.5	12.2
S 5	46.9	42.9	0.9	0.9	7.7	0.7	9.3
S 6	**56.1**	39.5	1.1	0.4	2.8	0.1	3.3
S 7	47.8	44.6	0.2	2.0	5.4	0.1	7.5
S 8	28.5	21.7	0.3	20.2	28.8	0.4	49.4
S 9	27.8	20.5	0.3	21.2	29.4	0.7	**51.3**
S 10	48.4	30.9	0.4	5.9	13.7	0.7	20.3
S 11	**51.9**	30.9	1.7	2.9	12.2	0.4	15.5
S 12	**50.3**	28.8	3.5	2.7	14.2	0.5	17.4
S 13	39.3	26.0	0.3	12.7	21.1	0.6	34.4
S 14	43.8	47.6	0.5	0.7	7.1	0.4	8.2
Range	27.8- **60.8**	18.6 - 47.6	0.2 - 3.5	0.2 – 21.2	2.5 – 39.4	0.0 –0.7	2.7-**53.0**
Median	47.6	30.9	0.5	2.7	12.2	0.4	15.5
REDWOOD							
*R 15****	*0.7*	*0.1*	*0.0*	***93.0***	*6.0*	*0.2*	***99.2***
R 16	1.6	2.5	0.3	**62.1**	33.2	0.3	**95.6**
R 17	1.9	2.6	4.1	**60.3**	30.9	0.1	**91.3**
R 18	1.0	0.2	0.0	**92.3**	6.3	0.1	**98.7**
R 19	2.0	5.2	2.3	**70.3**	20.0	0.3	**90.6**
R 20	2.9	3.2	7.6	**58.7**	26.6	1.0	**86.3**
R 21	1.5	6.0	0.4	**72.7**	18.6	0.9	**92.2**
R 22	1.3	1.0	0.6	**92.1**	4.5	0.5	**97.1**
*R 23****	*1.8*	*0.7*	*0.1*	***87.3***	*9.9*	*0.2*	***97.4***
R 24	1.5	1.8	0.5	**90.7**	5.1	0.4	**96.2**
R 25	3.2	1.6	0.7	**70.0**	21.0	3.5	**94.5**
R 26	2.9	4.8	2.8	**61.2**	25.8	2.4	**89.4**
R 27	2.7	4.4	2.4	**63.9**	23.6	2.9	**90.4**
R 28	2.3	3.3	1.6	**74.0**	17.2	1.6	**92.8**
Range	1.0 – 3.2	0.2 – 6.0	0.0 – 7.6	**58.7 – 92.3**	4.5 – 33.2	0.1 – 2.9	**86.3 – 98.7**
Median	2.0	2.9	1.2	**70.2**	20.5	0.7	**92.5**

*Percent agriculture (Ag) is the portion of the watershed used for growing row-crops and perennial crops.
**Percent disturbed is a combination of % agriculture (ag), % range, and % urban.
***Sites not included in the statistical analysis are excluded from the range and median values.

Table 2-4: Channel condition and geomorphic variables for stations in SNAKE and REDWOOD. Asterisks (*) indicate sites excluded from analysis.

Station	Chan Cond	%Channel Slope	%Riffle	%Pool	%Run	D50 (mm)	D84 (mm)	%Silt/Clay	%Sand	%Gravel	%Cobble	%Boulder	%Rock
SNAKE													
S1	NA	0.3107	0	60	40	0.11	0.17	57	25	14	5	0	19
S2	NA	0.0016	0	85	15	0.062	0.062	57	25	14	5	0	19
*S3**	*OC*	*0.0780*	*5*	*40*	*55*	*0.17*	*0.41*	*8*	*92*	*0*	*0*	*0*	*0*
S4	NA	5.0000	40	25	35	110	220	0	29	4	57	11	72
S5	OC	0.2800	15	50	35	0.87	95	20	38	22	17	4	43
S6	NA	0.6989	40	60	0	24	110	9	21	41	22	7	70
S7	NA	0.1051	10	35	65	17	110	0	39	35	20	6	61
S8	OC	0.0380	10	50	40	23	89	20	28	26	25	0	51
S9	OC/NA	0.0240	0	80	20	0.16	2.9	12	68	18	2	0	20
S10	NA	0.2500	10	60	30	16	75	6	36	37	20	1	58
S11	NA	0.0720	10	20	70	0.34	9.9	15	65	21	0	0	21
S12	NA	0.5500	10	50	40	54	160	1	15	40	36	8	84
S13	NA	0.1900	30	60	10	35	140	0	31	30	34	5	69
S14	NA	0.0990	10	45	45	83	420	1	27	17	27	28	72
REDWOOD													
*R1**	*OC*	*0.0130*	*0*	*85*	*15*	*0.12*	*0.57*	*44*	*56*	*0*	*0*	*0*	*0*
R16	NA	0.1100	10	70	20	0.062	0.062	52	31	10	5	2	17
R17	NA	0.4800	20	65	15	4.5	32	22	24	47	7	1	55
R18	OC	0.0320	0	35	65	0.3	0.6	6	94	0	0	0	0
R19	OC	0.0720	5	70	25	0.42	4	24	64	12	0	0	12
R20	NA	0.0745	5	55	40	1.4	5.4	29	30	41	0	0	41
R21	NA	0.0140	5	75	20	0.062	18	42	10	35	11	2	48
R22	OC	0.0890	0	50	50	0.25	0.54	5	95	0	0	0	0
*R23**	NA	*0.0200*	*25*	*40*	*35*	*23*	*100*	*24*	*15*	*25*	*34*	*3*	*62*
R24	NA	0.0500	5	45	50	18	63	28	29	28	14	2	44
R25	NA	0.0029	0	40	60	0.24	21	24	53	13	8	2	23
R26	NA	0.2600	10	20	70	2.7	39	24	42	26	8	1	35
R27	NA	0.0460	10	40	50	0.47	0.79	2	98	0	0	0	0
R28	NA	0.1875	10	40	50	1.8	22	24	26	36	10	4	50

Fish community assessments

Fish community data were collected at 28 reaches within the two watersheds: 25 stream reaches were sampled by the University of Minnesota between June and August in 2005 and 2006, and three stream reaches were sampled by the MPCA between June and August in 2001 and 2003. (Table 2-2). In total, 10, 614 individuals representing 49 species and 10 families were collected. Total individuals collected at a site ranged from 32 to 2319 in REDWOOD (median = 210) and from 37 to 535 in SNAKE (median = 197). *See Tables A-6 and A-7 for list of species and number of individuals collected by watershed.*

In terms of species diversity, I collected a greater number of native species in SNAKE (39 native) than REDWOOD (31 native). By reach, I collected a greater maximum number of native species in REDWOOD (24 species) than SNAKE (22 species). The minimum number of native species collected at a site was 5 in REDWOOD and 8 in SNAKE. Two exotic species were collected at a total of eight sites. For SNAKE, common carp (*Cyrpinus carpio*) was found at only one site; whereas, in REDWOOD, common carp were sampled at a total of 7 sites and brown trout (*Salma trutta)* was collected at one site.

In total, 12 intolerant species were collected:10 intolerant species in SNAKE and 4 intolerant species in REDWOOD. For SNAKE, intolerant species collected included: chestnut lamprey (*Ichthyomyzon castaneus*), longnose dace (*Rhynichthys cataractae*), sand shiner (*Notropus stramineus*), stonecat (*Noturs flavus*), hornyhead chub (*Nocomis biguttatus*), northern hogsucker (*Hypentelium nigricans*), rock bass (*Ambloplites rupestris*), smallmouth bass (*Micropterus dolomieui*), Iowa darter (*Etheostoma exile*), and slenderhead darter (*Percina phoxocephala*). In REDWOOD, intolerant species collected included: silver redhorse (*Moxostoma anisurum*), greater redhorse (*Moxostoma valenciennesi*), hornyhead chub (*Nocomis biguttatus*), and Iowa darter (*Etheostoma exile*). Northern hogsucker (*Hypentelium nigricans*) was also collected in REDWOOD but was not classified as intolerant for the FIBI for REDWOOD as it was for SNAKE.

FIBI metrics varied by basin and *stream class* (Tables A-8, A-9); only two FIBI metrics were common between watersheds and *stream class*. By watershed, the range in *percent simple lithophilic spawners* and *percent tolerant individuals* was surprising similar. For SNAKE, *percent simple lithophilic spawners* ranged from 2 to 73% (median = 32.5%) and from 0 to 72% (median = 31%) for REDWOOD. *Percent tolerant individuals* by reach was slightly higher in *SNAKE (*range = 2 to 96%, median = 44%) than REDWOOD (range = 1 to 63%, median = 25.5%).

Natural background conditions and sites excluded from analysis

During sampling, one reach in REDWOOD (R23) was determined to be a coldwater reach (Use Class 2A, Table 2-6). At this reach, 2-yr old brown trout (*Salma trutta*) were captured, and upon investigation it was discovered that fingerling brown trout had been stocked by the Minnesota Department of Natural Resources within the year prior to sampling. The FIBI for REDWOOD was developed for warmwater streams. Hence, I excluded this reach from additional analysis, since a warmwater FIBI would be inappropriate for rating the stream health of this coldwater reach.

Two reaches were low-gradient headwater streams (Table 2-6), one in each watershed (S3 and R15). Recent stream classification in Minnesota has determined that fish communities in low-gradient headwater streams (<0.50 m/km and <85 km^2) are distinct enough to be classed separately for FIBI development (J. Sandberg, MPCA, *unpublished data*). Compared to higher gradient streams, fish species diversity and composition in low-gradient streams tends to be naturally lower with higher percentages of tolerant individuals (Lyons 1996) due in part to the naturally low-habitat diversity associated with low-gradient headwater streams (e.g., dominance of fine sediments, slow velocity, lack of riffle habitat; Wang et al. 1998) and the influence of wetlands or groundwater that may contribute to lower dissolved oxygen conditions resulting in a naturally depauperate fish community composed principally of fish species that are capable of living in low-dissolved oxygen environments. In SNAKE, S3 had active zones of groundwater discharge and appeared to be mechanically ditched through a wetland sedge meadow. The fish community was almost entirely composed of tolerant individuals (96%) and dominated by central mud minnows (79%, *Umbra limi*) which are tolerant of low-oxygen conditions (Gee 1980). In REDWOOD, R15 had no observable flow and was dominated by silt and active zones of groundwater discharge could be felt along the banks and bottom of the channel. This reach recorded the lowest water temperature at time of fish sampling (19.5 °C) for REDWOOD. The fish community was dominated by brook stickleback (54%) which are tolerant of low-oxygen conditions and prefer coolwater habitat (<21.3°C, http://ecometrix.ca/fishdb/fish_detail.php?FID=119). Since these low-gradient reaches may have different expectations in their fish communities as a result of natural background factors and not a result of an anthropogenic stress that the FIBIs were designed to detect, I elected to remove these sites from further analysis.

In total, 25 of the 28 reaches sampled were used in statistical analysis (REDWOOD: n=12, SNAKE: n=13; Tables 2-2, 2-6).

Table 2-6: Classifications for study reaches and FIBI, PSI, CEM and MSHA scores. Asterisks (*) indicate sites that were excluded from analysis due to natural background conditions.

Station ID	Use class [a]	LG Class?[b]	Ecoregion	Size Class[c]	Channel Cond.[d]	FIBI	PSI	CEM [e]	MSHA
SNAKE									
S 1	2B	N	NLF	S-VS	NA	58	91.5	II/III (2.5)	62.0
S 2	2B	N	NCH	S-VS	NA	80	58.0	I (6)	62.0
*S 3**	*2B*	*Y*	*NLF*	*S-VS*	*OC*	*41*	*80.0*	*II/III (2.5)*	*54.0*
S 4	2B	N	NLF	S-VS	NA	78	64.0	I (6)	82.0
S 5	2B	N	NLF	S-VS	OC	68	69.0	II/III (2.5)	68.5
S 6	2B	N	NLF	S-VS	NA	76	61.0	I (6)	81.0
S 7	2B	N	NLF	S-S	NA	64	73.0	III (3)	77.0
S 8	2B	N	NCH	S-S	OC	74	68.0	III/IV (3.5)	63.5
S 9	2B	N	NCH	S-S	OC/NA	79	68.0	IV/V (4.5)	61.0
S 10	2B	N	NCH	S-M	NA	73	75.0	IV/V (4.5)	76.0
S 11	2B	N	NCH	S-M	NA	41	117.0	II/III (2.5)	54.5
S 12	2B	N	NCH	S-M	NA	76	62.0	V (5)	77.0
S 13	2B	N	NCH	S-M	NA	80	66.0	V (5)	86.5
S 14	2B	N	NLF	S-M	NA	71	82.0	III (3)	78.0
REDWOOD									
*R 15**	*2B*	*Y*	*WCBP*	*R-S*	*OC*	*29*	*97.0*	*II/III (2.5)*	*19.0*
R 16	2B	N	NGP	R-S	NA	21	101.0	II (2)	44.0
R 17	2B	N	NGP	R-S	NA	55	106.5	III, IV (3.5)	59.5
R 18	2B	N	WCBP	R-S	OC	25	74.0	IV/V (4.5)	34.0
R 19	7	N	NGP	R-S	OC	46	92.5	III/IV (3.5)	48.5
R 20	2B	N	NGP	R-S	NA	54	88.0	II/III (2.5)	65.5
R 21	2B	N	NGP	R-S	NA	15	117.0	II/III (2.5)	37.0
R 22	2B	N	WCBP	R-S	OC	46	92.0	II/III (2.5)	39.0
*R 23**	*2A*	*N*	*WCBP*	*R-S*	*NA*	*35*	*75.5*	*III (3)*	*76.5*
R 24	2B	N	WCBP	R-S	NA	60	97.0	III (3)	68.5
R 25	2B	N	WCBP	R-M	NA	25	74.0	II/III (2.5)	45.5
R 26	2B	N	WCBP	R-M	NA	42	95.0	III/IV (3.5)	59.0
R 27	2B	N	WCBP	R-M	NA	29	127.0	II/III (2.5)	52.5
R 28	2B	N	WCBP	R-M	NA	38	68.5	III/IV (3.5)	61.0

[a]Use class designation: 2B = warmwater fishery, 2A = coldwater fishery, 7 = limited resource value water.
[b]LG class?: Y = Yes, N = No. Sites considered Low Gradient class when gradient <0.50 m/km and DA <85 km^2
[c]Size class: For REDWOOD: R-S = small (<259 km^2) and R-M = midsized (259–25900 km^2). For SNAKE: S-VS = very small (<52 km^2), S-S = small (52-140 km^2), and S-M = moderate (141 – 700 km^2).
[d]Channel Condition: NA = natural, unchannelized, OC = old channelization, OC/NA = half channelized, half natural.
[e]Stages of channel evolution model: I = stable/premodified, II = downcutting, III = widening, IV = aggradation and thalweg development, V = return to quasi-equalibrium. In parentheses is the numerical designation given for analysis.

FIBI results

Fish communities were more similar to the least-disturbed condition used for developing the FIBI in SNAKE than REDWOOD (Tables 2-6, 2-7). In SNAKE, FIBI scores ranged from 80 (excellent) to 41 (poor) with a median score of 74 (very good); whereas in REDWOOD, FIBI scores ranged from 60 (very good) to 15 (very poor) with a median score of 40 (good). Box-plots (Figure 2-2) and a two-sided t-test (Table 2-7) demonstrate that the mean FIBI score was significantly higher in SNAKE than REDWOOD ($P > |t| = < 0.0001$). Watershed alone explained 63% of the variance.

Table 2-7: Results of one-way ANOVA for FIBI, MSHA and PSI scores grouped by watershed.

Basin watershed	REDWOOD (n=12)		SNAKE (n=13)		Test for unequal variances	Test for group averages different	One-way ANOVA		Hypothesis Test Result
	range	mean	range	mean	Prob>|F| two-sided F-test	Prob >|t| two-sided t-test	R^2	Prob >F	Ho: group means equal Ha: group means not equal
FIBI	15-60	38.0	41–80	70.6	0.328	<0.0001	0.63	<0.0001	reject Ho, accept Ha
PSI	127-68.5	94.4	117-58	73.4	0.766	0.0045	0.30	0.0045	reject Ho, accept Ha
MSHA	34-68.5	51.2	54.5-86.5	71.5	0.626	<0.0001	0.49	<0.0001	reject Ho, accept Ha

Channel stability assessments

Both channel stability assessments indicate that streams were more stable in the SNAKE than REDWOOD (Tables 2-6, 2-7). In SNAKE, PSI scores ranged from 58 (good) to 117 (poor), with a median score of 68 (good); whereas in REDWOOD scores ranged from 68.5 (good) to 127 (poor) with a median score of 93.75 (fair). The box-plot of PSI scores by watershed (Figure 2-2b) indicate that while there is considerable overlap in the score distributions for each watershed, the mean is significantly different between watersheds ($P > |t| = < 0.0001$); however, watershed alone explained only 30% of the variability in PSI scores. In comparison of metric zones, the range in scores between UPPER and LOWER were fairly similar between watersheds (Table A-10), although the individual UPPER metric *landform slope* was generally higher at sites in REDWOOD than SNAKE. The greatest difference in scores occurred with the zone BOTTOM; where scores were noticeably higher in REDWOOD than SNAKE. The BOTTOM metrics that had the greatest individual metric score differences between watersheds were *bottom size distribution/percent stable materials* and *scouring and deposition*. These two metrics were noticeably higher in REDWOOD than SNAKE. These results

A)

B)

C)

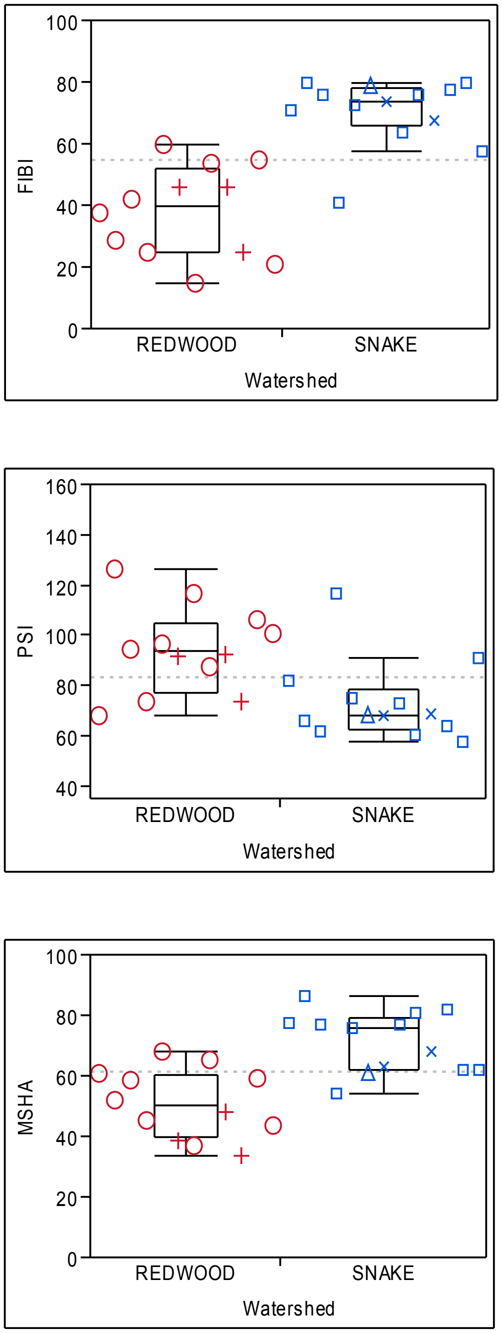


Figure 2-2: Box-plots of A) FIBI, B) PSI, and C) MSHA score distributions by watershed. REDWOOD in red: O = natural (NA) and + = channelized (OC). SNAKE in blue: ◘ = NA, + = OC, and Δ = half-natural and half-channelized (NA/OC). The dotted line is the grand mean.

suggest that substrate conditions were generally more unstable at reaches in REDWOOD than SNAKE. However, the ranges in BOTTOM scores between watersheds overlapped indicating that substrate conditions varied similarly within and between watersheds.

Stage(s) of channel evolution (CEM) assigned to each stream were variable within each watershed and reflect both “stable” (CEM stages I, IV, V) and “unstable” (CEM stages II, III) stream conditions (Table 2-6). My results indicate that in SNAKE, an equal number of reaches were considered “stable” as “unstable”; whereas for REDWOOD, only one reach was rated as "stable" (R18). This reach is channelized but has overtime reworked the banks and bottom so now there is a small terrace at the RI 1.5 flow line and the bottom profile has been reworked into point bars and a meandering thalweg (CEM IV/V). Other studies have also observed this bar formation associated with increased sinuosity and consequent development of riffle and pool features in channelized reaches that are allowed to rework their bottom configurations over time (Dietrich 1987, Figure 3 in Frothingham et al. 2002, Rhoads et al. 2003). Most reaches in REDWOOD demonstrated some degree of incision and/or overwidening (CEM II/III) or were in the process of developing point bars and thalwegs (CEM III/CEM IV) indicating that this watershed was likely undergoing system-wide channel adjustment.

Habitat quality assessments

Overall, habitat quality as as assessed with the MSHA was statistically better in SNAKE than REDWOOD (Tables 2-6, 2-7). MSHA ranged from 54.5 to 86.5 (median 76) in SNAKE; whereas in the REDWOOD, scores ranged from 34 to 68.5 (median 50.5). Watershed explained 49% of the variability in MSHA scores ($P > |t| = <0.0001$).

For most individual MSHA metrics, the scores observed overlapped well between watersheds (Table A-11). The greatest difference in metric scores observed by watershed was for *surrounding land use* and *riparian width*. REDWOOD had much lower scores for both of these metrics as compared to SNAKE, demonstrating that land use both in the subwatershed and immediate riparian zone was much more disturbed in REDWOOD. Surprisingly, the range in *substrate* scores was similar between the two watersheds (SNAKE: range = 9 to 19; REDWOOD: range = 9 to 18). However, streams in SNAKE generally scored slightly higher for *substrate* than REDWOOD (SNAKE: median = 17, REDWOOD: median = 14.5) indicating that the dominant substrate types were larger or more diverse overall in SNAKE than REDWOOD.

Physicochemical measurements

For streams in Minnesota, expected background conditions for level III ecoregions have been characterized by McCollor and Heiskary (1993). Ecoregion expectations across water quality parameters are consistently higher for ecoregions in REDWOOD than SNAKE (Tables 2-8a,b). Values above the 75th percentile of minimally impacted streams within each ecoregion may indicate a sediment or nutrient issue. For this study, there were measured values that were above these ecoregion baselines (Table 2-9). However, these measurements are from a one time grab sample and not a calculated summer-median concentration which is the statistic used by McCollor and Heiskary (1993).

Table 2-8a: Interquartile range of summer-median concentrations for total phosphorus (TP), turbidity, and total suspended sediment (TSS) for minimally impacted streams in four ecoregions in Minnesota determined from samples collected between 1970 and 1992 (from McCollor and Heiskary 1993).

Basin watershed	**Ecoregion**	**TP (mg/L) percentile**			**Turbidity (NTU) percentile**			**TSS (mg/L) percentile**		
		25	**50**	**75**	**25**	**50**	**75**	**25**	**50**	**75**
SNAKE	NLF	0.030	0.040	0.050	2	2	4	2	4	6
	NCH	0.070	0.100	0.170	5	7	10	8	10	18
REDWOOD	NGP	0.160	0.220	0.290	20	23	37	37	55	89
	WCBP	0.210	0.270	0.350	14	19	27	26	47	76

Table 2-8b: Interquartile range of summer-median concentrations for nitrogen (NO2+NO3), total ammonia (Am) and conductivity for minimally impacted streams in four ecoregions in Minnesota. determined from samples collected between 1970 and 1992 (from McCollor and Heiskary 1993).

Basin watershed	**Ecoregion**	**NO2+NO3 (mg/L) percentile**			**Am (mg/L) percentile**			**conductivity (μmhos) percentile**		
		25	**50**	**75**	**25**	**50**	**75**	**25**	**50**	**75**
SNAKE	NLF	0.01	0.01	0.03	0.20	0.10	0.06	120	230	260
	NCH	0.03	0.06	0.12	0.08	0.20	0.20	278	290	310
REDWOOD	NGP	0.01	0.07	0.43	0.12	0.20	0.20	760	840	990
	WCBP	0.89	2.60	6.50	0.11	0.20	0.20	810	645	530

Conductivity – Most notably, *conductivity* was 10 times higher in REDWOOD than SNAKE (Table 2-9, REDWOOD: range = 984 to 2439 μmhos, SNAKE: range = 115 to 385 μmhos). For SNAKE, 5 reaches had conductivities above the 75th percentile for each ecoregion and for REDWOOD 12 of 14 reaches had conductivities above the 75th percentile for each ecoregion, with some reaches 2 to 3 times greater than the 75th percentile. For REDWOOD, the extremely high values for *conductivity* in a freshwater system can be explained by underlying marine deposits that are high in minerals. These underlying layers were deposited when parts of the MRB was on the fringe of an oceanic complex during the Pleistocene period. This mineral enriched water is currently forced to the

Table 2-9: Physicochemical water quality parameters collected at time of fish sampling. In **bold** are values that were above the ecoregion baselines developed by McCollor and Heiskary (1993). Values underlined exceeded Minnesota water quality standards.

Station ID	Eco-region	Time	Temp ºC	DO mg/L	Spec Cond µmhos	pH	TP mg/L	Am mg/L	Un-Am µg/L	TN mg/L	Turb NTU	TSS mg/L
SNAKE												
S1	NCH	10:15	15.6	8.4	**347**	7.3	0.03	0.18	0.001	**0.83**	7.3	**59.6**
S2	NLF	10:45	23.7	3.3	173	6.9	0.05	**0.08**	0.33	<0.05	**4.4**	**16.7**
*S3***	*NCH*	*10:30*	*20.4*	*10.3*	***368***	*7.9*	***0.11***	*0.05*	*1.55*	*0.11*	***12.3***	*2.6*
S4	NLF	11:30	20.2	7.1	115	7.1	**0.07**	<0.05	0.20	<0.05	**5.5**	4.4
S5	NLF	10:45	20.9	4.2	179	7.3	0.05	**0.22**	1.98	<0.05	3.7	3.1
S6	NLF	11:30	23.0	5.7	**339**	7.3	0.03	**0.05**	0.41	<0.05	**4.3**	7.7
S7	NLF	10:45	19.5	8.3	158	7.4	**0.08**	**0.07**	0.66	<0.05	3.3	**12.6**
S8	NCH	11:00	17.7	7.3	**378**	7.5	0.08	0.12	1.24	**2.32**	4.8	**90.9**
S9	NCH	10:30	20.0	9.3	**385**	8.3	0.03	0.09	6.13	**2.22**	0.5	2.4
S10	NCH	10:15	15.6	10.1	282	7.9	0.03	0.05	1.11	**2.44**	2.5	5.5
S11	NCH	10.00	21.4	8.8	129	7.5	0.09	0.07	0.88	<0.05	4.6	1.3
S12	NCH	12:15	24.5	8.8	188	7.5	0.03	0.16	2.58	**0.40**	1.8	1.2
S13	NCH	12:45	23.8	6.2	131	7.4	0.08	<0.05	0.03	**0.59**	4.3	2.0
S14	NLF	10:15	23.6	6.3	131	7.3	0.04	**0.06**	0.60	0.12	**11.2**	2.2
REDWOOD												
*R15***	*WCBP*	*10:15*	*19.5*	*6.5*	***968***	*6.9*	***0.52***	***1.63***	*2.10*	*0.13*	*11.3*	*34.3*
R16	NGP	9:00	20.3	0.7	**1027**	7.3	**1.42**	**2.25**	17.70	<0.05	15.7	**734.9**
R17	NGP	14:00	23.9	6.3	**1455**	8.2	0.06	0.09	6.63	**0.47**	**34.0**	42.2
R18	WCBP	14:30	26.8	10.1	1097	8.1	**0.93**	0.05	3.68	**11.96**	2.1	7.1
R19	NGP	17:30	28.5	8.4	**1180**	7.8	**0.56**	**0.26**	11.48	0.17	15.5	30.9
R20	NGP	8:30	20.4	3.1	**1120**	7.8	0.24	**0.33**	8.75	0.17	5.7	25.3
R21	NGP	8:00	20.0	4.0	984	7.8	0.03	**0.43**	10.41	0.21	**71.0**	**170.2**
R22	WCBP	9:00	22.7	7.8	**1514**	7.9	0.15	0.12	3.96	5.67	2.4	3.7
*R23***	*WCBP*	*9:30*	*24.6*	*6.1*	***1061***	*8.1*	*0.01*	*0.11*	*6.58*	***10.37***	*7.0*	*39.6*
R24	WCBP	9:15	23.0	6.8	**1396**	8.0	0.01	0.15	6.40	**10.04**	5.8	14.9
R25	WCBP	9:30	24.8	7.2	**1604**	8.0	0.08	0.14	7.43	1.19	3.0	28.4
R26	WCBP	9:00	21.9	6.1	**2439**	8.2	**2.04**	0.10	7.43	4.32	1.8	8.9
R27	WCBP	8:30	25.2	7.2	**1338**	8.3	**0.66**	<0.05	5.49	4.00	13.1	52.0
R28	WCBP	7:30	22.5	6.0	**1338**	8.7	0.01	0.05	8.02	<0.05	15.2	3.8

Ecoregions: NCH = north central hardwoods, NLF = northern lakes and forests, WCBP = western cornbelt plains, NGP = northern glaciated plains.
Water chemistry variables: Temp = water temperature, DO = dissolved oxygen, Spec Cond = specific conductance, TP = total phosphorus, Am = Total Ammonia Nitrogen, Un-Am = unionized ammonia nitrogen, TN = total nitrogen, Turb = turbidity TSS = total suspended solids.

surface through groundwater (J. Magner, UMN, *personal communication*).

Other physicochemical parameters for which Minnesota has water quality standards (WQS) indicate that there may be potential impairments at a number of reaches (Table 2-9).

Un-ionized ammonia - Minnesota has a WQS for unionized ammonia nitrogen (Un-Am) which is 40 µg/L for 2B streams, 16 µg/L for 2A streams, and there is no Un-Am standard for Class 7 streams (MN Rule 7050.0220, https://www.revisor.mn.gov/rules/?id=7050.0220). No reaches recorded Un-Am values above this standard in either watershed.

Dissolved oxygen - The WQS for d*issolved oxygen* (DO) is 5 mg/L as a daily minimum for warmwater streams (2B, MN Rule 7050.0222, https://www.revisor.leg.state.mn.us/rules/?id=7050.0222), 7.0 mg/L for coldwater streams, and 1.0 mg/L for Class 7 (limited resource value) streams. DO measurements below the WQS for the respective use class were observed at two stations in SNAKE and four stations in REDWOOD (Table 2-9).

Turbidity - The WQS for turbidity is 25 nephelometric turbidity units (NTUs; MN Rule 7050.0222, https://www.revisor.mn.gov/rules/?id=7050.0220) for 2B streams. Two reaches in REDWOOD recorded turbidity values above the WQS (R17, R21); whereas no streams within SNAKE recorded turbidity values above the WQS. Minnesota's current WQS for turbidity has been criticized as not being based on regional background expectations that are related to surficial geology (Magner et al. 2003). A new proposed WQS will take into account background conditions. The 75th percentile values by ecoregion for turbidity in SNAKE are much lower than the current WQS and range from 4 to 10 NTUs; whereas, for ecoregions in REDWOOD, the 75th percentile values are much higher than the current WQS and range from 27 to 37 NTUs. When ecoregion based standards are applied, a greater number of exceedences occurred in SNAKE (5/14) than REDWOOD (2/14).

Associations among FIBI, PSI, and MSHA with potentially confounding watershed and reach characteristics

I tested watershed distributions in FIBI, PSI and MSHA scores with *ecoregion*, *subwatershed land use*, *channel condition*, *stream class* and *physicochemical measures* in order to determine the extent to which other sub-watershed and reach scale variables may influence the results and should be recognized as confounding variables explaining a significant portion of the variability observed in fish community health, channel stability, and habitat quality.

Ecoregion

SNAKE and REDWOOD have two level III ecoregions within each watershed (Table 2-10). Study reaches within SNAKE fell within two Level IV ecoregions, which paired exactly with the Level III ecoregions. For REDWOOD, Level IV ecoregions paired well with Level III ecoregions, except for one reach which was characterized by a unique Level IV ecoregion. Given the majority of Level IV ecoregions were similar to Level III, I chose Level III for my analysis.

My results indicate that there were no significant differences in the distribution of scores for FIBI, PSI, and MSHA when grouped by *ecoregion* (Tables 2-11a,b). Scatterplots of FIBI, PSI and MSHA score distributions between ecoregions (Figure B-1) indicate good overlap in values; however some ranges in score distributions are noticeably larger for some ecoregions. Overall, the distributions are fairly similar; therefore, I conclude that *ecoregion* was not a significant factor in this study.

Table 2-10: Distribution of study sites by Level III and Level IV ecoregions. (ftp://ftp.epa.gov/wed/ecoregions/mn/mn_eco_desc.pdf).

Watershed	Level III ecoregions	Level IV ecoregions and descriptions
REDWOOD	46 - Northern Glaciated Plains (NGP) N = 5	46k - Prairie Coteau: Higher elevation plateau with poorly defined drainage, many lakes, and mix of row crops and some pasture (n=4)
		46l - Prairie Coteau Escarpment: Slopes from plateau to river basin with perennial streams and riparian vegetation, and row crops on interfiles (n=1)
	47 - Western Corn Belt Plains (WCBP) N = 7	47b - Des Moines Lobe: Vast fertile plain of deep soils dominated by row crops (n = 7)
SNAKE	50 - Northern Lakes and Forests (NLF) N = 7	50b - Minnesota Wisconsin Upland Till Plain: Rolling landscape of woods, wetlands, pasture, and crops (n = 7)
	51 - North Central Hardwoods (NCH) N = 6	51k - MacGrath Till Plain and Drumlins: Undulating and rolling plain with drumlins and mix of woodland, row crops, and pasture (n=6

Table 2-11a: Results of Wilcoxin Sum Rank Test for FIBI, PSI, and MSHA scores grouped by *ecoregion* for REDWOOD.

REDWOOD	WCBP n=7			NGP n=5			Test for group means different	
	range	mean	median	range	mean	median	Wilkoxin statistic for small sample sizes (confidence interval)	Ho: Medians equal Ha:Medians not equal
FIBI	25-60	37.9	38	15-55	38.2	46	32.5 (22, 43)	Fail to reject Ho
PSI	68.5-127	89.6	92	88-117	101	101	40 (22, 43)	Fail to reject Ho
MSHA	34-68.5	51.4	52.5	37-65.5	50.9	48.5	32 (22, 43)	Fail to reject Ho

Table 2-11b: Results of Wilcoxin Sum Rank Test for FIBI, PSI, and MSHA grouped by *ecoregion* in SNAKE.

SNAKE	NLF n=6			NCH n=7			Test for two group means different	
	range	mean	median	range	mean	median	Wilkoxin statistic for small sample sizes (confidence interval)	Ho: Medians equal Ha: Medians not equal
FIBI	64-80	72.8	73.5	41-80	68.7	74	43 (30, 54)	Fail to reject Ho
PSI	58-82	67.8	66.5	62-117	78.2	68	35 (30, 54)	Fail to reject Ho
MSHA	62-82	74.8	77.5	54.5-86.5	68.6	63.5	51 (30, 54)	Fail to reject Ho

Ecoregion frameworks attempts to spatially group geographical areas in the conterminous United States by similarities in geology, soils, natural vegetation, land use, hydrology and physiography (USEPA, http://www.epa.gov/bioindicators/html/usecoregions.html). Upon review of the descriptions by ecoregion (Table 2-10), the characteristics in land use and glacial material are fairly similar within watersheds. Hence, the ecoregions within my study watersheds may not be distinct enough to generate a large difference in habitat types available to produce a difference in MSHA scores or elicit a difference in FIBI or PSI scores.

Subwatershed land use

While ecoregion does capture land use characteristics at a coarse level, I also tested whether more localized differences in subwatershed land use could explain differences in fish community health, habitat quality and channel stability.

FIBI and subwatershed land use - Land use types that were significantly correlated with FIBI varied by watershed grouping.

For COMBINED, FIBI was positively and significantly (p<0.05) correlated (r) with *percent forest* (0.77) and *percent wetland* (0.74), and negatively correlated with *percent agriculture* (-0.73) and *percent disturbed* (-0.76). Correlation results for *percent urban* were mixed (r = 0.42, p = 0.0387; r_s = 0.26, 0.2119). The scatterplot for FIBI with *percent urban* (Figure C-5) indicates that the range in values was very small overall (range: 0 to 2.9%) and that the correlation for COMBINED may be related more to the relative difference in FIBI scores coupled with the slightly larger range in *percent urban* for REDWOOD than SNAKE (Table 2.3). The following land use pairs were highly correlated (r >0.90): *percent agriculture* with *percent disturbed* and *percent forest* with *percent wetland*.

Within watershed associations between FIBI and land use types were not as strong. For REDWOOD, FIBI was positively and significantly correlated with only *percent water* (r = 0.57); whereas, no land use types were significantly correlated with FIBI for SNAKE.

PSI, CEM and subwatershed land use - PSI score distributions and CEM stage were tested against land use types to determine whether channel stability ratings observed in this study were associated with the type of land use in the subwatershed.

For COMBINED, streams considered more stable were associated with greater percentages of undisturbed land use. PSI scores were negatively significantly correlated (r) with *percent forest* (-0.55), *percent wetland* (-0.58), and positively associated with *percent agriculture* (0.48), and *percent disturbed* (0.52). These land use pairs were highly correlated (r >0.90)*: percent agriculture* with *percent disturbed* and *percent forest* with *percent wetland*. CEM stage was similarly associated with the same land use types as PSI; however, the degree of association (r) was not as strong: *percent forest* (0.53), *percent wetland* (0.43), *percent agriculture* (-0.46), and *percent disturbed* (-0.51).

When watersheds were analyzed separately, PSI was significantly and positively associated with only *percent wetland* (0.53) for REDWOOD. This result is somewhat surprising given that *percent wetland* ranged from only 0.2 to 6.0% in REDWOOD (Table 2-3). CEM was not associated with any land use types for REDWOOD. No land use types were significantly associated with PSI or CEM for SNAKE.

MSHA and subwatershed land use - MSHA score distributions were also tested against percent land use types to determine whether habitat quality ratings observed were strongly associated with subwatershed land use.

For COMBINED, habitat quality was lower at sites with greater disturbed land use in the subwatershed. MSHA was negatively and significantly correlated (r) with *percent agriculture* (-0.73) and *percent disturbed* (-0.74) and positively correlated with *percent forest* (0.72) and *percent wetland* (0.74). Redundant land use types (r >0.90) included: *percent agriculture* with *percent disturbed* and *percent forest* with *percent wetland*.

For REDWOOD, habitat quality was also lower at sites with greater percent disturbed land use in the subwatershed. MSHA was strongly (r >0.50) correlated with *percent forest* and *percent water* and negatively correlated with *percent agriculture*. For SNAKE, MSHA was only marginally correlated with *percent wetland* ($r = 0.43$, $p = 0.1413$, $r_s = 0.41$, $p = 0.1502$).

<u>Channel condition</u>

Channel condition refers to whether or not a reach has been mechanically channelized. Only a few reaches within each watershed were channelized (REDWOOD: 3 of 12 reaches; SNAKE: 3 of 13 reaches). Since stream channelization has been shown to negatively affect habitat quality and fish community health, I tested the association between FIBI, MSHA, and PSI for each watershed to determine if *channel condition* explained a significant portion of the variability observed.

<u>FIBI and channel condition</u> - For FIBI, the range in score distribution was larger for natural reaches than for channelized reaches. For both watersheds, the sum of ranks for channelized reaches fell within the confidence interval given for the Wilkoxin test statistic (Tables 2-12a, b). Therefore, I failed to reject the null hypothesis that the medians are equal when grouped by *channel condition*. The sample sizes were very small, so an observable difference would likely not be found to be statistically different (Type 2 error). I also reviewed the scatterplots of FIBI scores grouped by *channel condition* for each watershed (Figure B-2). FIBI scores for channelized reaches fell above and below the grand mean. This suggests that channelization alone was not a significant factor influencing fish community health for either watershed.

<u>PSI and channel condition</u> - For PSI, the range in scores was larger for natural reaches than channelized reaches. For both watersheds, the sum of PSI ranks for channelized reaches fell within the confidence interval given for the Wilkoxin test statistic (Tables 2-12a, b). Therefore, I failed to reject the null hypothesis that the medians in PSI scores are equal when grouped by *channel condition.* When the scatterplots of PSI score distributions were reviewed (Figure B-2), both watersheds exhibited overlap in the range of values observed for channelized and natural reaches; however, the PSI scores for channelized reaches all fell below the grand mean for both watersheds. These results suggest that channelized reaches in this study were comparatively as stable as a subset of natural reaches and that a portion of natural reaches were rated more unstable than channelized reaches.

Table 2-12a: Results of Wilcoxin Sum Rank Test for FIBI, PSI, and MSHA grouped by *channel condition* for REDWOOD.

REDWOOD	natural n=9			channelized n=3			Test for group medians different two-sided test (α = 0.10)	
	range	mean	median	range	mean	median	Wilkoxin statistic for small sample sizes (confidence interval)	Ho: medians equal Ha: medians not equal
FIBI	15-60	37.7	54.5	25-46	39	46	20.5 (10, 29)	Fail to reject Ho
PSI	68.5-127	97.1	97	74-92.5	86.2	92	13.5 (10, 29)	Fail to reject Ho
MSHA	37-68.5	54.7	59	34-48.5	40.5	39	10 (10, 29)	Fail to reject Ho

Table 2-12b: Results of Wilcoxin Sum Rank Test for FIBI, PSI, and MSHA grouped by *channel condition* for SNAKE.

SNAKE	natural n=10			channelized n=3			Test for group averages different, two-sided test (α = 0.10)	
	range	mean	median	range	mean	median	Wilkoxin statistic for small sample sizes (confidence interval)	Ho: medians equal Ha: medians not equal
FIBI	41-80	69.7	74.5	68-79	73.7	74	22 (11, 31)	Fail to reject Ho
PSI	58-117	75.0	69.5	68-69	68.3	68	21 (11, 31)	Fail to reject Ho
MSHA	54.5-86.5	73.6	77	61-68.5	64.3	63.5	13 (9, 33)	Fail to reject Ho

MSHA and channel condition - Scatterplots of MSHA score distributions (Figure B-2) indicate that for both watersheds, scores for channelized reaches were all below the grand mean; however, I failed to reject that MSHA median scores were significantly different when grouped by *channel condition* within either watershed (Tables 2-12a, b). These results suggest that while the medians were not statistically different, that the habitat quality was not as good at channelized streams as natural streams. However, the results also indicate that for a subset of natural streams, habitat quality was as poor as channelized streams, suggesting that other factors besides channelization may be negatively effecting habitat quality at these reaches.

Stream class

For both watersheds, FIBI metrics are variable by *stream class* which are defined by drainage area. The FIBI for REDWOOD uses two stream classes (Bailey et al. 1993) both of which were sampled in this study; whereas, the FIBI For SNAKE uses four stream classes (Niemela and Feist 2000) of which three were sampled in this study.

FIBI distributions by stream class - When FIBI scores were grouped by *stream class*, the median scores were not significantly different for either watershed (Tables 2-13a, b). However, the range in FIBI scores varied by *stream class*. For REDWOOD, the range in FIBI scores was larger for small streams than medium streams. For SNAKE, the range in FIBI scores was largest for medium streams and smallest for small streams.

PSI distributions by stream class - When FIBI and PSI scores were grouped by *stream class*, the median scores were not significantly different (Tables 2-13a, b) for either watershed. While the range in PSI scores was fairly similar by stream class in REDWOOD, the range in PSI scores by stream class was more variable in SNAKE. For SNAKE, the range in PSI scores was greatest for median streams and smallest for small streams.

MSHA distributions by stream class - For REDWOOD, median MSHA scores were not significantly different when grouped by *stream class*; whereas, for SNAKE, median MSHA scores were significantly different between small and medium streams (Tables 2-13a, b) . For SNAKE, the range in MSHA scores was also larger for medium streams and the within group median was significantly higher for small streams than medium streams. Given the overlap in score ranges observed and the size of the datasets, I did not consider *stream class* a significant factor for SNAKE.

Therefore, I concluded that *stream class* was not a significant factor explaining the variability between FIBI, PSI, or MSHA in this study.

Table 2-13a. Results of Wilkoxin Sum Rank Test for FIBI, PSI, and MSHA grouped by *stream class* for REDWOOD.

REDWOOD	**Small (n=8)**			**Medium (n=4)**			**Test for group means different**	
	range	mean	median	range	mean	median	Wilkoxin statistic for small sample sizes (confidence interval)	Ho: medians are equal Ha: medians are not equal
FIBI	15 - 60	40.25	46	25 - 42	33.5	33.5	21.5 (16, 36)	Fail to reject Ho
PSI	74 - 117	96	94.75	68.5 - 127	91.1	84.5	22.5 (16, 36)	Fail to reject Ho
MSHA	34 - 68.5	49.5	46.25	45.5 - 61	54.5	55.75	30 (16, 36)	Fail to reject Ho

Table 2-13b. Results of Wilkoxin Sum Rank Test for FIBI, MSHA, and PSI grouped by *stream class* for SNAKE.

SNAKE	**Very small (n=5)**			**Small (n=3)**			**Medium (n=5)**		
	range	mean	median	range	mean	median	range	mean	median
FIBI	58 - 80	72	76	64 -79	72.3	74	41 - 80	68.2	73
PSI	58 - 91.5	68.7	64	68 - 73	69.7	68	62 - 117	80.4	75
MSHA	62 - 82	71.1	68.5	61 - 77	67.2	63.5	54.5 - 86.5	74.4	77

Table 2-13b (cont.)

Test for Group Medians different by stream class pairs for SNAKE	**small - very small n=3, n=5**		**small - medium n=3, n=5**		**very small - medium n=5, n=5**	
	test statistic (confidence interval)	Ho: medians are equal Ha: medians are not equal	test statistic (confidence interval)	Ho: medians are equal Ha: medians are not equal	test statistic (confidence interval)	Ho: medians are equal Ha: medians are not equal
FIBI	13 (7, 20)	Fail to reject Ho	14 (7, 20)	Fail to reject Ho	29 (19, 36)	Fail to reject Ho
PSI	16 (7, 20)	Fail to reject Ho	12 (7, 20)	Fail to reject Ho	22 (19, 36)	Fail to reject Ho
MSHA	11 (7, 20)	Fail to reject Ho	10.5 (11, 20)	reject Ho, accept Ha	29 (19, 36)	Fail to reject Ho

Physicochemical measures and FIBI

For COMBINED, almost all chemical water quality variables tested were negatively and significantly (p<0.1) correlated (r) with FIBI: *conductivity* (-0.66), pH (-0.47), *total phosphorus* (-0.52), *total nitrogen* (-0.35), *ammonia nitrogen* (-0.43), *unionized ammonia nitrogen* (-0.63)*, turbidity* (-0.43), and *total suspended solids* (-0.38). *Dissolved oxygen* and *water temperature* were the only two variables not correlated with FIBI. None of the water quality variables were highly correlated with each other. Backward and forward stepwise MLR models were in disagreement as to which water quality variables to include in the best-fit model (Table 2-14). Backward step-wise regression selected *conductivity, turbidity, total phosphorus* and *unionized ammonia,* which together explained 59% of the variance observed in FIBI (P >F = 0.0002); whereas, forward step-wise regression selected *conductivity, turbidity*, and *total suspended solids* which explained 56% of the variance (P >F = <0.0001). However, *turbidity* and *total suspended solids* are conceptually redundant although they are different measures of suspended material in the water column. MLR models with *conductivity* and either *total suspended solids* or *turbidity* explained a similar portion of the variance in FIBI.

For REDWOOD, Pearson and Spearman correlation results were in disagreement as to whether or not *conductivity* was marginally (α = 0.1) associated with FIBI (r = 0.27, p = 0.3872; r_s = 0.46, p = 0.1353). The correlation threshold for metrics entering MLR was based on Pearson correlation (r >0.40); hence, no water chemistry variables entered MLR for REDWOOD.

For SNAKE, Pearson and Spearman correlation results were in disagreement as to whether or not *water temperature* was marginally associated with FIBI (r = 0.27, p = 0.2982; r_s = 0.46, p = 0.1131). The correlation threshold for metrics entering MLR was based on Pearson correlation (r > 0.40); hence, no water chemistry variables entered MLR for SNAKE.

Table 2-14: Multiple Linear Regression Models for FIBI and water quality variables for each watershed grouping. Model variables that were significant (α = 0.05) are underlined, and variables that were moderately significant (α = 0.10) are in *italics*. The best fit-models selected are in **bold**.

Watershed grouping **step-wise direction (number of predictor variables)**	**Model Variables**	***Adj R2***	**P>F**	**RMSE**	**AICc**	**Cp, p**
COMBINED (7)	conductivity, pH, total phosphorus, ammonia nitrogen, unionized ammonia nitrogen, *turbidity,* total suspended solids	0.54	0.0031	14.2	224.0	8.8
backward (5)	conductivity, total phosphorus, ammonia,total suspended solids, turbidity	0.58	0.0004	135	214.8	4.2, 6
backward (4)	**conductivity, *total phosphorus, ammonia,* turbidity**	**0.59**	**0.0002**	**13.4**	**211.9**	**2.9, 5**
backward (3)	conductivity, *ammonia,* turbidity	0.55	0.0002	14.1	212.1	3.7, 4
backward (2)	conductivity, turbidity	0.50	0.0002	14.8	212.4	4.8, 3
backward/ forward (1)	conductivity	0.41	0.0003	16.1	214.8	8.4, 2
forward (2)	**conductivity, total suspended solids**	**0.51**	**<0.0001**	**14.6**	**211.8**	**4.2, 3**
forward (3)	conductivity, *total suspended solids, turbidity*	0.56	<0.0001	13.9	211.5	3.2, 4
forward (4)	conductivity, ammonia, *total suspended solids, turbidity*	0.59	0.0002	13.5	212.1	3.0, 5
REDWOOD (0)	---	---	---	---	---	---
SNAKE (0)	---	---	---	---	---	---

Associations among indicators of channel stability and FIBI

PSI variables

Before testing with FIBI, I explored the level of correlation between PSI variables. For COMBINED, PSI total score was strongly correlated with each PSI metric zone (r >0.80) and most highly correlated with BOTTOM (r = 0.95). A number of individual metrics that describe bank stability and substrate stability were positively and strongly correlated (r >0.70) with PSI: *mass wasting or bank failure, cutting*, *brightness*, *bottom size distribution and percent stable materials,* and *scouring and deposition,* which was the most strongly correlated (0.92). The only metric negatively correlated with PSI was *channel capacity,* which was weakly correlated (-0.34). A few PSI metrics were highly correlated with each other (r > 0.70) but not considered redundant to exclude from MLR analysis.

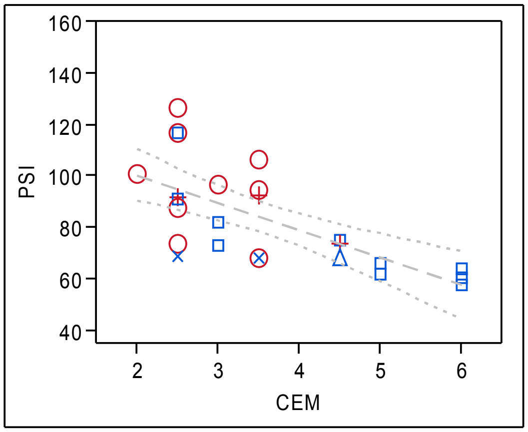
When watersheds were analyzed separately, many similar correlations emerged. For

REDWOOD and SNAKE, all three metric zones were strongly ($r > 0.70$) correlated with PSI; BOTTOM being the most strongly correlated with PSI for both watersheds. Individual metrics that were strongly correlated ($r > 0.60$) with PSI for both REDWOOD and SNAKE include many of the same metrics that were highly correlated for COMBINED: *mass wasting, cutting, brightness*, *consolidation/particle packing*, *bottom size distribution/percent stable materials*, and *scouring and deposition*. For SNAKE, many of these metrics were strongly correlated ($r > 0.60$) with each other but not redundant. Three variables were considered redundant ($r > 0.80$) in REDWOOD: *consolidation/particle packing, bottom size distribution/percent stable materials*, and *souring*.

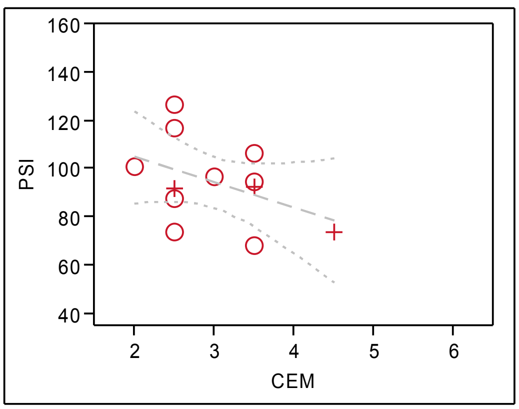
CEM and PSI variables

I explored the level of correlation between CEM stage and PSI metrics to assess the degree of concordance between these two channel stability measures.

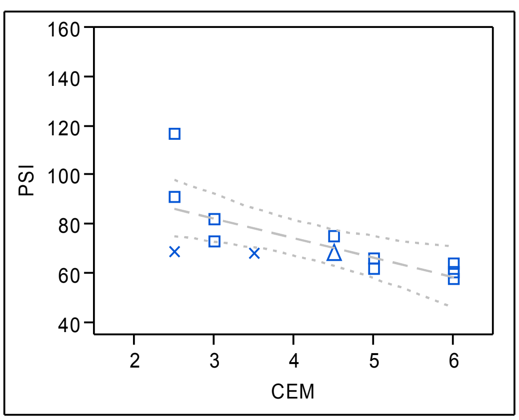
CEM was strongly correlated with PSI for COMBINED ($r = -0.68$) and SNAKE (-0.70), but not for REDWOOD (-0.43). The variability in PSI scores by CEM stage was greater in REDWOOD than SNAKE (Figure 2-3). For individual PSI zones, CEM was significantly ($p < 0.05$) or marginally ($p < 0.1$) correlated with all three PSI metric zones for SNAKE (Table 2-14); whereas, CEM was strongly correlated only with BOTTOM for COMBINED (-0.70) and REDWOOD (-0.50). The individual PSI metrics that were most strongly correlated with CEM for all three watershed groupings were *cutting* and *bottom size distribution/percent stable materials*. Additionally, for COMBINED and SNAKE, CEM was significantly correlated with *mass wasting/bank failure* and *scouring and deposition*. Two metrics that were highly correlated with CEM were unique to REDWOOD: *consolidation/particle packing* and *rock angularity.* The only PSI metric positively correlated with CEM across watershed groupings was *channel capacity*.



A) COMBINED: PSI = 121.93 - 10.68*CEM + 14.58, R^2 = 0.46, p = 0.0002.



B) REDWOOD: PSI = 125.88 - 10.50*CEM + 16.49, R^2 = 0.18, p = 0.1661.



C) SNAKE: PSI = 106.84 - 8.05*CEM + 11.85, R^2 = 0.49, p = 0.0075.

Figure 2-3: Plots and linear regression indicating significant linear associations between PSI and CEM for A) COMBINED and C) SNAKE, but no significant linear association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.

Table 2-15: Coefficients of association for both Pearson (r) and Spearman Rank Correlation (ρ) between FIBI with CEM stage, PSI total score, and individual PSI metrics for study watersheds together (COMBINED) and individually (REDWOOD and SNAKE). Results significant (p<0.05) for two sided test in **bold**, results marginally significant (p<0.1) for two-sided test in *italics*. Results <u>underlined</u> indicate where the correlation values between Pearson and Spearman were in disagreement as to whether the variable was significantly correlated with FIBI.

	COMBINED n=25		REDWOOD n=12		SNAKE n=13	
Variable	r	ρ	r	ρ	r	ρ
CEM stage	**0.63**	**0.70**	0.20	0.31	**0.74****	**0.86**
PSI	**-0.67**	**-0.74**	-0.09	-0.04	**-0.95**	**-0.84**
UPPER BANK	**-0.63**	**-0.67**	-0.10	-0.09	**-0.79****	**-0.61**
landform slope (LS)	**-0.67**	**-0.68**	-0.44	-0.38	-0.40	-0.31
mass wasting or failure (MW)	**-0.51**	**-0.52**	0.08	0.18	**-0.78****	**-0.57**
debris jam potential (DJP)	0.18	0.14	0.04	-0.20	*-0.51*	*-0.49*
vegetative bank protection (VBP)	**-0.62**	**-0.65**	-0.08	-0.12	<u>**-0.59****</u>	<u>-0.33</u>
LOWER BANK	**-0.42**	**-0.47**	0.27	0.29	**-0.71**	*-0.53*
channel capacity (CC)	**0.42†**	**0.37†**	0.28	0.28	0.32	0.10
bank rock content (BRC)	*-0.36*	*-0.36*	0.24	0.24	-0.27	0.06
obstructions/ flow deflectors/ sediment traps (OFDST)	-0.05	-0.11	*0.51†*	*0.50†*	-0.44	-0.42
cutting (C)	**-0.47**	**-0.46**	-0.20	-0.24	**-0.66**	*-0.51*
deposition (D)	-0.25	-0.31	0.29	0.29	<u>*-0.49*</u>	<u>-0.34</u>
BOTTOM	**-0.68**	**-0.71**	-0.28*	-0.11	**-0.85**	**-0.66**
rock angularity (RA)	-0.01	0.02	0.35	0.36	0.25	0.11
brightness (Br)	**-0.44**	**-0.40**	0.07*	0.25	<u>**-0.70****</u>	<u>-0.35</u>
consolidation/ particle packing (CPP)	*-0.36*	-0.29	-0.35	-0.30	-0.14	0
bottom size distribution/percent stable materials (BSD/PSM)	**-0.63**	**-0.59**	-0.33**	-0.19	**-0.65**	*-0.46*
scouring and deposition (SD)	**-0.68**	**-0.69**	-0.33	-0.18	**-0.86****	**-0.84**
clinging aquatic vegetation (CAV)	*-0.39*	**-0.41**	0.26	0.34	**-0.70**	*0.48*

† identifies metrics where the response was in the opposite direction as predicted for a one-sided test.
* variables where polynomial regression was marginally significant (p <0.1).
** variables where polynomial regression was highly significant (p <0.05). Regression equations are included in Appendix C.

Channel stability and FIBI

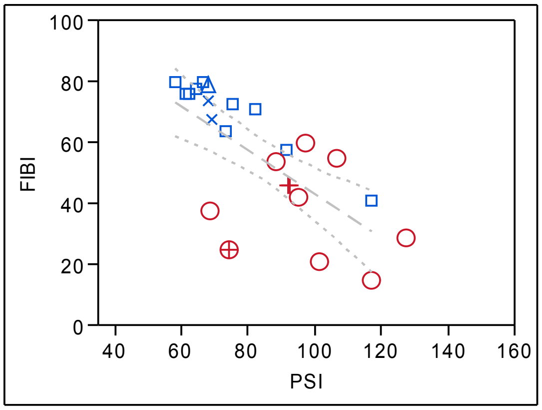
FIBI was strongly correlated with PSI and CEM for COMBINED and SNAKE; whereas, FIBI was not highly correlated with either PSI or CEM for REDWOOD (Table 2-15). The scatterplot of FIBI and PSI for REDWOOD (Figure 2-4b) indicates a potential non-linear association; however, polynomial regression was not significant (R^2 = 0.28, p = 0.2280). Linear regression results demonstrate that PSI alone explained 44% of the variability observed in FIBI for COMBINED (p = <0.0003) and 87% of the variability for SNAKE (p = <0.0001). In comparison, linear regression results (Figure 2-5) indicate that CEM explained less variability in FIBI for COMBINED (R^2 = 0.40, p = 0.0007) and SNAKE (R^2 = 0.67, p = 0.0037).

Table 2-16: Multiple Linear Regression models for FIBI and PSI metric zones for each watershed grouping. Model variables that were significant (α = 0.05) are underlined, and variables that were moderately significant (α = 0.10) are in *italics*. The best fit-models selected for each watershed grouping are in **bold**.

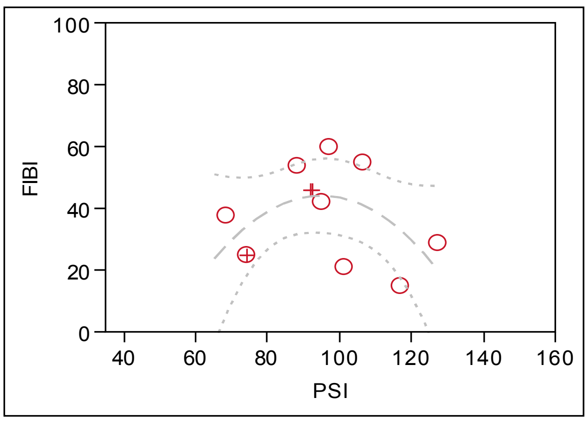
Watershed grouping (number of predictor variables)	**Model Variables**	***Adj R^2***	**P>F**	**RMSE**	**AICc**	**Cp, p**
COMBINED (3)	UPPER, LOWER, BOTTOM	0.51	0.0015	15.6	217.2	4, 4
	UPPER, BOTTOM	0.46	0.0005	15.5	214.5	2.4, 3
	BOTTOM	**0.44**	**0.0002**	**15.7**	**231.6**	**2.1, 2**
REDWOOD (1)	***[BOTTOM]^2]***	**0.24**	**0.1176**	**12.9**	**105.7**	**2, 2**
SNAKE (3)	UPPER, LOWER, BOTTOM	0.86	<0.0001	4.1	87.3	4, 4
	UPPER, BOTTOM	**0.83**	**<0.0001**	**4.6**	**86.1**	**5.1, 3**
	BOTTOM	0.70	0.0002	6.1	90.4	15.4, 2

All three PSI metric zones were significantly correlated with FIBI for COMBINED (Table 2-15); BOTTOM being the most strongly correlated with FIBI (r = -0.68). When all three zones entered MLR, only BOTTOM was retained as a significant variable (Table 2-16). Additionally, 11 of 15 PSI metrics were negatively correlated with FIBI. The best-fit MLR model selected *landform slope* and *scouring and deposition* which together explained 57% of the variance in FIBI (P >F = <0.0001).

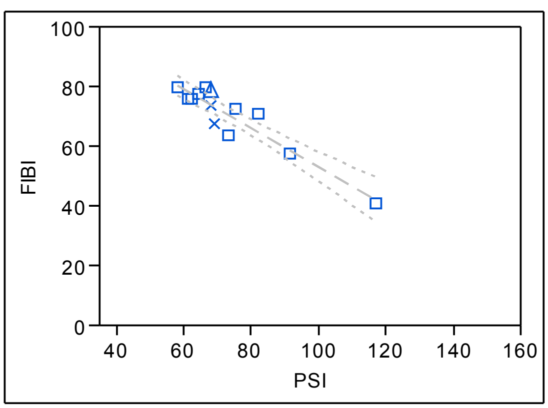
For REDWOOD, all three metric zones were weakly correlated with FIBI (r <0.30) and did not meet our correlation threshold (r >0.40) to be entered into MLR. However, the scatterplot of FIBI with BOTTOM (Figure 2-8b) indicates a potential, but weak non-linear relationship. When a polynomial term was added, BOTTOM explained 24% of the variance in FIBI, but this model was only marginally significant (P >F = 0.1176).



A) COMBINED: FIBI = 114.56 - 0.71*PSI+15.97, $R^2 = 0.44$, $p = 0.0003$.

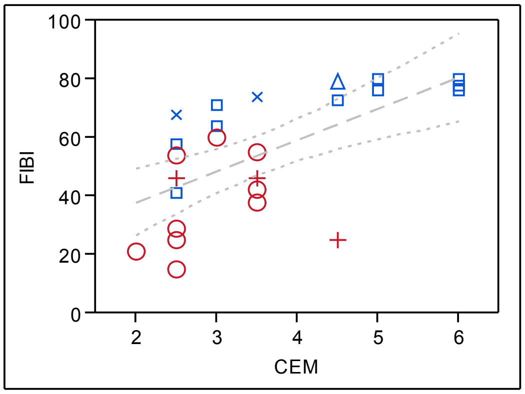


B) REDWOOD: FIBI = 42.87 + 0.02*PSI – 0.02*(PSI-94.38)^2 + 13.9, $R^2 = 0.28$, $p = 0.2280$.

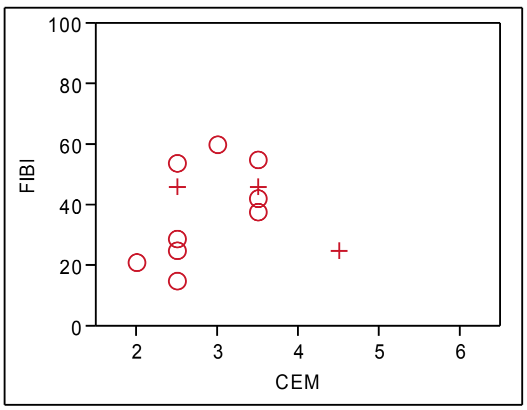


C) SNAKE: FIBI = 118.17 - 0.65*PSI+ 4.10, $R^2 = 0.87$, $p = <0.0001$.

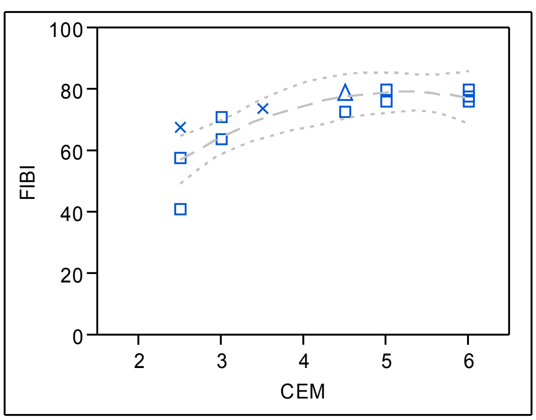
Figure 2-4: Plots and linear regression results demonstrating negative linear associations between FIBI and PSI for A) COMBINED and C) SNAKE but no significant linear or polynomial association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 16.66 + 10.64*CEM + 16.58, $R^2 = 0.40$, $p = 0.0007$.

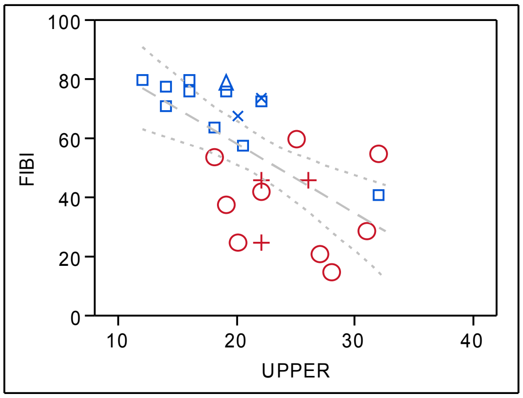


B) REDWOOD: No significant linear association.

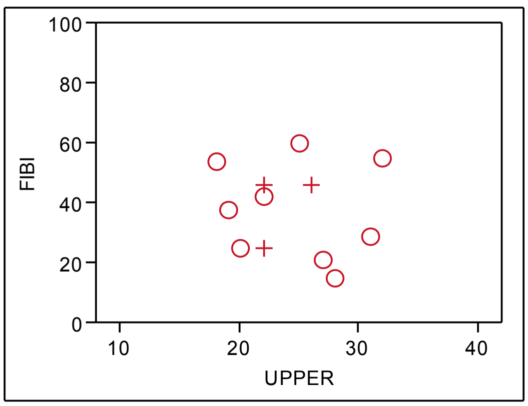


C) SNAKE: FIBI = -2.34 + 31.43*CEM - 3.02*CEM^2 + 6.91, $R^2 = 0.67$, $p = 0.0037$.

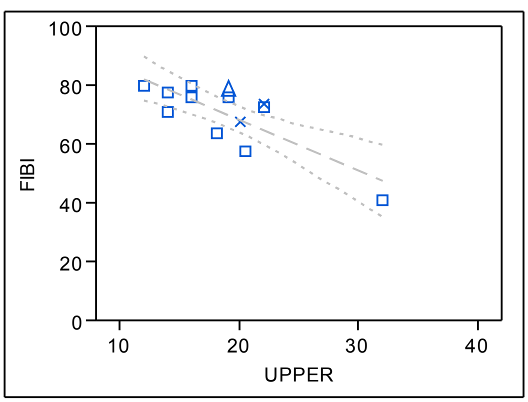
Figure 2-5: Plots and linear and polynomial regression demonstrating significant association between FIBI and CEM for A) COMBINED and C) SNAKE, but no significant association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 105.89 - 2.37*UPPER + 16.69, $R^2 = 0.39$, $p = 0.0008$.

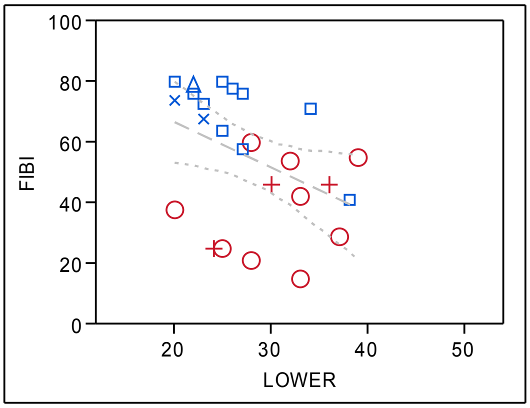


B) REDWOOD: No significant linear or polynomial association.

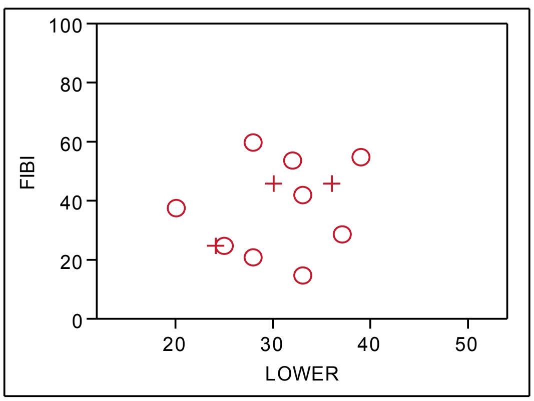


C) SNAKE: FIBI = 103.09 - 1.73*UPPER + 7.04, $R^2 = 0.63$, $p = 0.0013$.

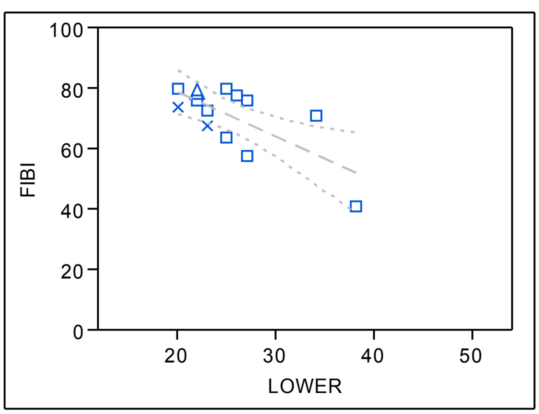
Figure 2-6: Plots and regression results demonstrating positive associations between FIBI and PSI zone UPPER for A) COMBINED and C) SNAKE and no linear or polynomial association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA = ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 96.39 - 1.49*LOWER + 19.41, $R^2 = 0.18$, $p = 0.0372$.

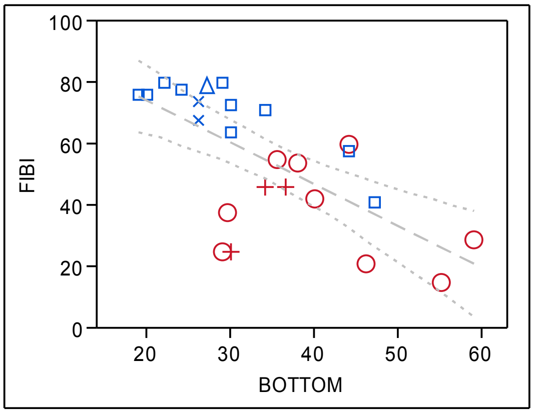


B) REDWOOD: No significant linear or polynomial association.

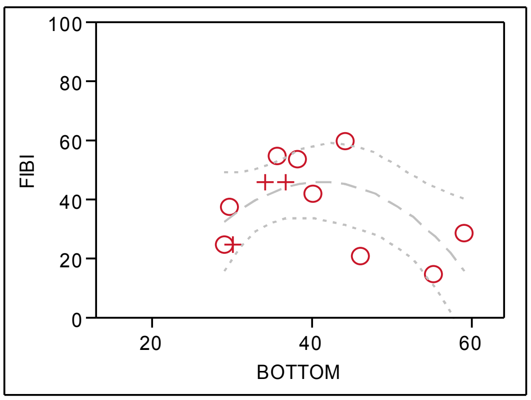


C) SNAKE: FIBI = 108.65 - 1.49*LOWER + 8,14, $R^2 = 0.50$, $p = 0.0067$.

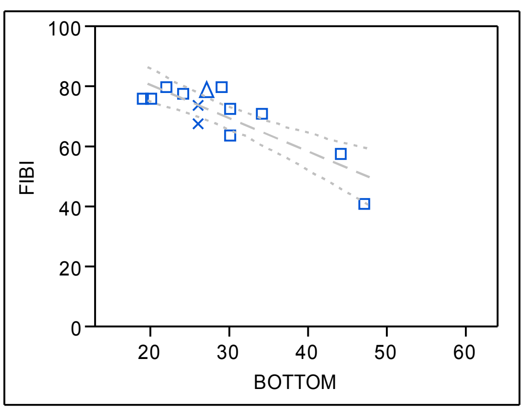
Figure 2-7: Plots and regression results demonstrating a negative linear association between FIBI and PSI zone LOWER for A) COMBINED and C) SNAKE and no linear or polynomial association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA = ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 101.70 - 1.37*BOTTOM + 15.68, $R^2 =$ 0.46, $p = 0.0002$.



B) REDWOOD: FIBI = -110.41+ 7.69*BOTTOM - 0.09*BOTTOM^2 + 12.90, $R^2 = 0.38$, $p = 0.1176$.



C) SNAKE: FIBI = 102.96 - 1.11*BOTTOM+ 6.09, $R^2 = 0.72$, $p = 0.0002$.

Figure 2-8: Plots and linear and polynomial regression demonstrating significant negative associations between FIBI and PSI zone BOTTOM for A) COMBINED and C) SNAKE, and a marginally significant association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.

For REDWOOD, *obstructions/flow deflectors/sediment traps* was the only individual PSI metric positively correlated with FIBI (r = 0.51, r_s = 0.50). Scatter plots and linear regression demonstrate that the relationship between FIBI and two additional metrics in REDWOOD may be best described using polynomial regression (i.e., *brightness,* Figure 2-18b; *bottom size distribution/percent stable materials*, Figure 2-20b). When these two variables entered MLR, only *bottom size distribution/ percent stable materials* with its polynomial term was selected (*Adj* R^2 = 0.60, P >F = 0.0034).

For SNAKE, all three PSI metric zones were significantly correlated with FIBI; BOTTOM being the most strongly correlated (Table 2-15). Scatterplots and linear regression indicate that all three associations were linear (Figures 6, 7, 8). BOTTOM alone explained 72% of the variance in FIBI; whereas, UPPER alone explained 63% of the variance. The best fit MLR model contained UPPER and BOTTOM which together explained 83% of the variation in FIBI (P >F = <0.0001). Nine of 15 PSI metrics were negatively correlated with FIBI (Table 2-15). However, in review of the results between Pearson and Spearman correlation for SNAKE, while the paired correlation results were in agreement for most metrics, for some metrics the correlation results were not (e.g., *vegetative bank protection, brightness*). Scatterplots of these two metrics (Figures 2-11c, 2-18c) revealed that only a few points were driving the Pearson Correlation and that the potential association may be best described using polynomial regression. In addition, while scatterplots demonstrate that many metric associations were linear (see Figures C-8c to C-22c), scatterplots for some metrics indicated that the pattern in the association may be best described with the inclusion of a polynomial term (e.g., *mass wasting or bank failure*, Figure C-9c; *scouring and deposition,* Figure C-21c). When significant PSI variables entered MLR, competing forward and backward selection models emerged (Table 2-17). Backward step-wise regression selected variables associated with the UPPER and LOWER zones; whereas, forward step-wise regression selected BOTTOM variables. Both of these models explained a similar amount of variance in FIBI. The best fit model selected with backward regression included a three variable model: *mass wasting or bank failure*, *debris jam potential*, and *cutting* (*Adj* R^2 = 0.89, P >F = <0.0001); whereas, forward step-wise regression selected a two variable model: *scouring and deposition* and *clinging aquatic vegetation* (*Adj* R^2 = 0.88, P >F = <0.0001). However, when polynomial terms for metrics demonstrating non-linear associations with FIBI were entered into MLR, both backward and forward step-wise regression selected the same two variable model using *mass wasting or bank failure* with its polynomial term and *brightness* without its polynomial term (*Adj* R^2 = 0.90, P >F = <0.0001).

Table 2-17: Multiple Linear Regression models for FIBI and PSI metrics by watershed grouping. Model variables that were significant (α = 0.05) are underlined, and variables that were moderately significant (α = 0.10) are in *italics*. The best fit-models selected for each watershed grouping are in **bold.**

Watershed grouping **step-wise direction (number of predictor variables)**	**Model Variables**	***Adj R²***	**P>F**	**RMSE**	**AICc**	**Cp, p**
COMBINED (11)	landform slope, *mass wasting or failure, vegetative bank protection*, channel capacity, bank rock content, cutting, brightness, consolidation particle packing, bottom size distribution/ percent stable materials, scouring and deposition, clinging aquatic	53.7	0.0171	14.2	246.5	11, 12
backward (6)	landform slope, mass wasting or failure, *vegetative bank protection,* channel capacity, scouring and deposition, *clinging aquatic vegetation*	0.63	0.0003	12.7	214.7	3.3, 7
backward/ mixed (5)	landform slope, *mass wasting or failure*, vegetative bank protection, channel capacity, scouring and deposition	0.62	0.0002	12.9	212.6	6.2, 7
backward/mixed (4)	landform slope, mass wasting or failure, *channel capacity,* scouring and deposition	0.59	0.0002	13.4	211.9	2.8, 5
backward (3)	landform slope, channel capacity, scouring and deposition	0.58	<0.0001	15.6	210.4	2.2, 4
forward/ mixed (3)	landform slope, vegetative bank protection, scouring and deposition	0.58	<0.0001	13.6	210.3	2.2, 4
forward (2)	**landform slope, scouring and deposition**	**0.57**	**<0.0001**	**13.8**	**209.0**	**1.7, 3**
forward (1)	scouring and deposition	0.44	0.0002	15.7	213.6	6.9, 2
REDWOOD (2) w/ polynomial terms	[brightness]^2, *[bottom size distribution/ percent stable materials]^2*	0.56	0.0401	9.8	111.1	5, 5
backward (2)	brightness, [*bottom size distribution/ percent stable materials]^2*	0.61	0.0144	9.3	102.7	3.2, 4
backward/forward (1)	**[bottom size distribution/ percent stable materials]^2**	**0.60**	**0.0034**	**9.4**	**98.0**	**2.3, 3**
SNAKE (9)	mass wasting or failure, debris jam potential, vegetative bank protection, cutting, deposition, brightness, bottom size distribution/percent stable material, scouring and deposition, clinging aquatic vegetation	0.87	0.0445	4.05	340.2	10, 10
backward (4)	mass wasting or failure, debris jam potential, cutting *scouring and deposition*	0.92	<0.0001	3.12	86.2	1.8, 5
backward (3)	**mass wasting or failure, debris jam potential, cutting**	**0.89**	**<0.0001**	**3.60**	**84.0**	**2.1, 4**
backward (2)	mass wasting or failure, debris jam potential	0.69	0.0012	6.18	93.9	16.3, 3
backward (1)	mass wasting or failure	0.56	0.0019	7.3	95.1	26.7, 2

forward (1)	scouring and deposition	0.71	0.0002	6.0	89.9	15.1, 2
forward (2)	**scouring and deposition, clinging aquatic vegetation**	**0.88**	**<0.0001**	**3.9**	**81.9**	**2.3, 3**
forward (3)	scouring and deposition, clinging aquatic vegetation, *deposition*	0.90	<0.0001	3.5	82.9	1.5, 4
forward/ backward (1)	[mass wasting or failure]^2	0.85	<0.0001	4.43	84.6	-1.1, 3
forward/ backward (2)	**[mass wasting or failure]^2, brightness**	**0.90**	**<0.0001**	**3.5**	**83.6**	**-1.5, 4**
forward/ backward (3)	[mass wasting or failure]^2, *deposition,* brightness	0.92	<0.0001	3.09	85.9	-0.6, 5
forward (3)	[mass wasting or failure]^2, *deposition,* [brightness]^2	0.93	<0.0001	2.94	93.3	0.9, 6

Associations among habitat quality metrics and FIBI

MSHA variables

Before testing the correlation between habitat quality and fish community health, I examined the level of correlation between MSHA, MSHA zones, and individual metrics in order to determine which subset of variables best explained the variation in MSHA scores observed and whether inherent watershed differences accounted for some of the variability. I also investigated which MSHA variables were strongly correlated with the MSHA metric *channel stability*.

For COMBINED, MSHA total score was significantly and highly correlated (r >0.80) with RIPARIAN, INSTREAM, and CHANNEL MORPH. A number of individual metrics that were significantly and positively correlated (r >0.60) with MSHA included: *riparian width, substrate*, *channel development* and *channel stability. Channel stability* was significantly and positively correlated (r) with INSTREAM (0.54) and COVER (0.69). *Channel stability* was also positively and significantly (p<0.10) correlated with the following MSHA individual metrics: *riparian width* (0.46), *bank erosion* (0.66), *substrate* (0.39), *embeddedness* (0.62), *cover type* (0.66)*, cover amount* (0.51)*,* and negatively correlated with *sinuosity* (-0.43).

For REDWOOD, 4 out of 5 MSHA metric zones were significantly (p<0.10) correlated with MSHA (LAND USE, RIPARIAN, INSTREAM, CHANNEL MORPH); only COVER was not significantly correlated. Individual metrics that were strongly and positively correlated (r) with MSHA for REDWOOD included *surrounding land use* (0.61), *riparian width* (0.58), *substrate* (0.77), *substrate type* (0.68)*, depth variability* (0.55) and *channel development* (0.87). *Channel stability* was significantly (p<0.10) and positively correlated with *bank erosion* (0.67) and *embeddedness* (0.64).

For SNAKE, 4 out of 5 MSHA metric zones were significantly (p <0.10) correlated with MSHA (RIPARIAN, INSTREAM, COVER, CHANNEL MORPH); only LAND USE was not correlated. Individual metrics positively correlated (r) with MSHA include: *bank erosion* (0.72), *substrate* (0.68), *depth variability* (0.70), *channel stability* (0.61), *pool width-to-riffle width* (0.61) and *channel development* (0.66). *Channel stability* was positively correlated with *riparian width* (0.57)*,* *bank erosion* (0.66), and *cover type* (0.65) and negatively correlated with *sinuosity* (-0.54). *Channel stability* was also marginally and positively correlated with *embeddedness* (r = 0.45, p = 0.1205).

Habitat quality and FIBI

Habitat quality as assessed with MSHA was a significant predictor of FIBI for COMBINED and REDWOOD but not for SNAKE (Table 2-18). Scatterplots and linear regression (Figure 2-9) indicate a strong linear association for COMBINED and REDWOOD where >50% of the variability observed in FIBI was explained with MSHA alone (R^2 = 0.71, p = <0.0001; R^2 = 0.55, p = 0.0029, respectively). In contrast, the association between FIBI and MSHA, while linear and significant, explained less variability for SNAKE (R^2 = 0.28, p = 0.0312).

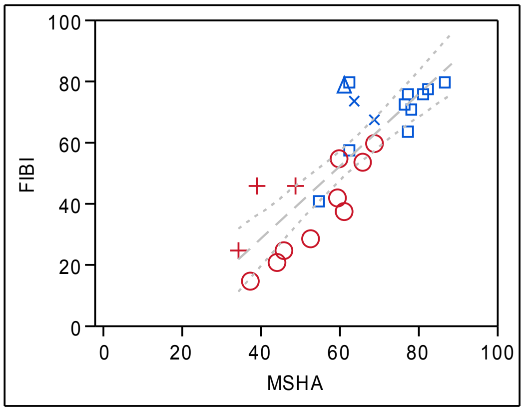
For COMBINED, all five metric zones were significantly correlated with FIBI (Table 2-18) and all associations were linear (Figures 2-10 to 2-14). RIPARIAN explained 69% of the variability in FIBI (p = <0.0001). When all five metric zones entered MLR (Table 2-18), the best-fit model explained 81% of the variance in FIBI (P >F = <0.0001) and contained RIPARIAN, INSTREAM and COVER. Ten out of 15 individual MSHA metrics were significantly correlated with FIBI (Table 2-18). For MLR, s*urrounding land use* was removed from further analysis since it was redundant with *riparian width*. Both forward and backward step-wise selection chose *riparian width* and *channel stability* for the best-fit model which explained 80% of the variance in FIBI (P >F = <0.0001).

For REDWOOD, 4 of 5 metric zones were significant predictors of FIBI; only COVER was not significantly correlated. Linear regression indicated that INSTREAM (Figure 2-12) and RIPARIAN (Figure 2-11) explained the most variability in FIBI; however, the best-fit MLR model only included INSTREAM (*Adj* R^2 = 0.53, P >F = 0.0044). Eight of 15 habitat metrics were significantly correlated with FIBI of which only one metric was negatively correlated (*pool/width-to-riffle width,* r = -0.43, r_s = -0.45). For MLR, s*urrounding land use* was removed since it was redundant with *riparian width* (r = 0.94). Forward and backward step-wise regression selected contrasting variables in the best-fit models (Table 2-19). Forward step-wise regression selected a two variable model with *substrate* and *channel stability* which explained 46% of the variance (P >F = 0.0298); whereas, backward step-wise regression selected a three variable model with *embeddedness*, *substrate types,* and *pool width-to-riffle width* which together explained 53% of the variance (P >F = 0.0249).

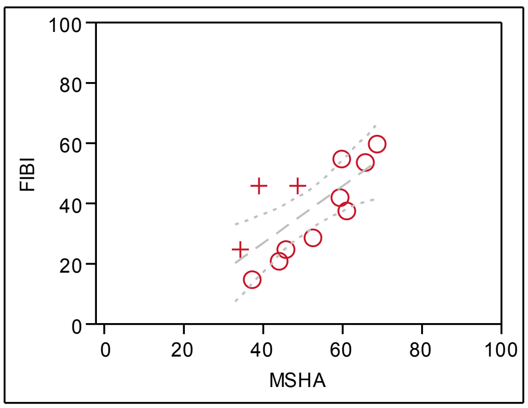
Table 2-18: Coefficients of association for Pearson (r) and Spearman Rank Correlation (ρ) between FIBI with MSHA total score and individual metrics for study watersheds together (COMBINED) and individually (REDWOOD and SNAKE). Results highly significant ($p<0.05$) for one-sided test are in **bold.** Results marginally significant for a one-sided test are in *italics*. Results underlined indicate differences in determination of significance between Pearson and Spearman results.

	COMBINED n=25		**REDWOOD n=12**		**SNAKE n=13**	
Variable	**r**	**ρ**	**r**	**ρ**	**r**	**ρ**
MSHA	**0.84**	**0.81**	**0.74**	**0.73**	**0.53**	0.34
LAND USE/ surrounding land use (SLU)	**0.65**	**0.59**	*0.41*	*0.43*	-0.02	-0.22
RIPARIAN	**0.82**	**0.79**	**0.64**	**0.53**	0.31	0.27
riparian width (RW)	**0.76**	**0.67**	**0.52**	**0.57**	<u>**0.48**</u>	<u>0.18</u>
bank erosion (BE)	**0.41**	**0.43**	0.16	0.10	**0.71****	**0.63**
shade (Sh)	**0.51**	**0.51**	0.16	0.15	-0.12	-0.02
INSTREAM	**0.66**	**0.62**	**0.76**	**0.70**	*0.46*	*0.40*
substrate (Su)	**0.54**	**0.51**	**0.63**	**0.58**	0.22	0.19
embeddedness (Em)	**0.63**	**0.65**	**0.50**	**0.51**	**0.67**	**0.75**
substrate type (ST)	0.22	0.20	**0.50**	**0.49**	0.30	0.25
COVER	**0.77**	**0.80**	0.24	0.34	**0.75**	**0.66**
cover type (CT)	**0.65**	**0.65**	0.39	0.35	**0.73****	*0.40*
cover amount (CA)	**0.61**	**0.64**	0.06	0.09	*0.43*	**0.50**
CHANNEL MORPH	**0.50**	**0.45**	*0.45*	**0.63**	0.17	0.03
depth variability (DV)	0.24	0.14	0.09	0.06	0.20	-0.17
channel stability (CS)	**0.78**	**0.88**	**0.53**	*0.48*	**0.91**	**0.70**
velocity types (VT)	-0.09	-0.12	0.31	0.29	-0.39	-0.38
sinuosity (Si)	-0.13	-0.16	0.06	0.08	**-0.59†****	*-0.48†*
pool width/riffle width (PW/RW)	-0.12	-0.13	*-0.43†*	*-0.45†*	-0.04	-0.20
channel development (CD)	**0.41**	**0.38**	**0.60**	**0.59**	-0.03	0.02

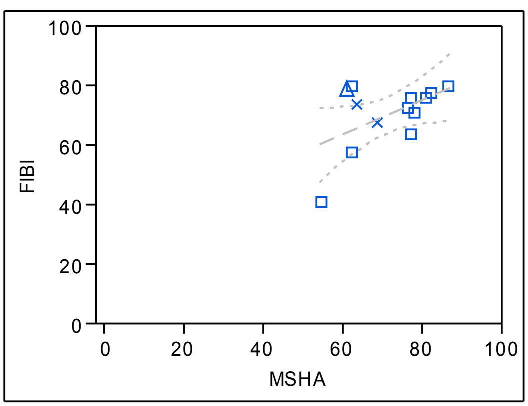
† identifies metrics where the response was in the opposite direction as predicted for a one-sided test.
* denotes variables where polynomial regression was marginally significant ($p<0.1$).
** denotes metrics that were highly significant ($p<0.05$). Regression equations are included in Appendix C.



A) COMBINED: FIBI = -18.42+ 1.19*MSHA + 11.62, $R^2 = 0.71$, $p = <0.0001$.

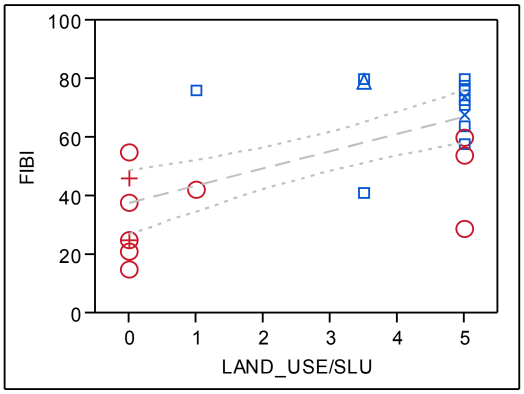


B) REDWOOD: FIBI = -10.67 + 0.95*MSHA + 10.40, $R^2 = 0.55$, $p = 0.0029$.

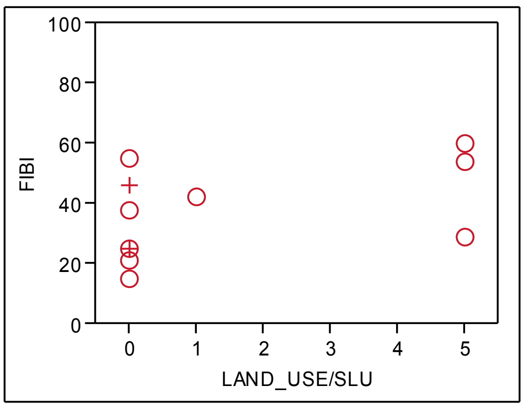


C) SNAKE: FIBI = 28.81+ 0.59*MSHA + 9.78, $R^2 = 0.28$, $p = 0.0312$.

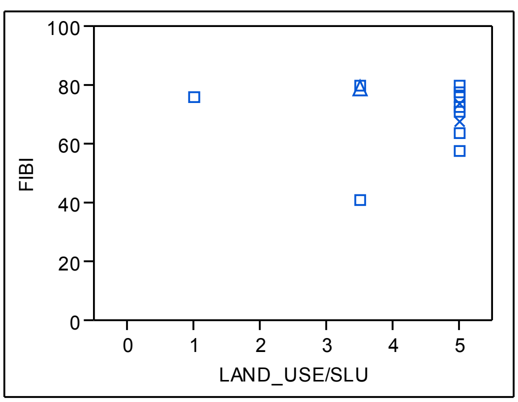
Figure 2-9: Plots and linear regression demonstrating significant positive linear associations between FIBI and MSHA for A) COMBINED, B) REDWOOD, and C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 37.84 + 5.90*LAND_USE/SLU + 16.20, $R^2 = 0.43$, $p = 0.0004$.

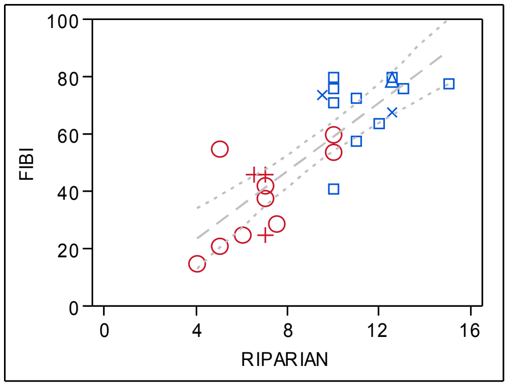


B) REDWOOD: No significant linear association.

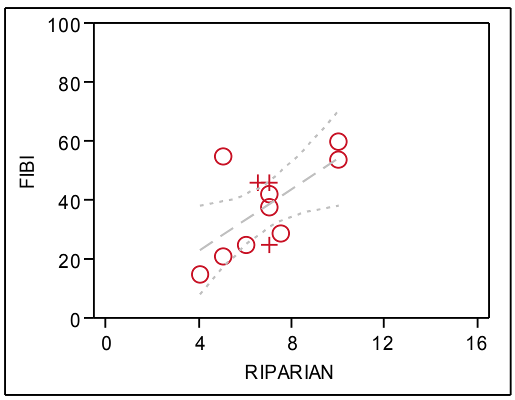


C) SNAKE: No significant linear association.

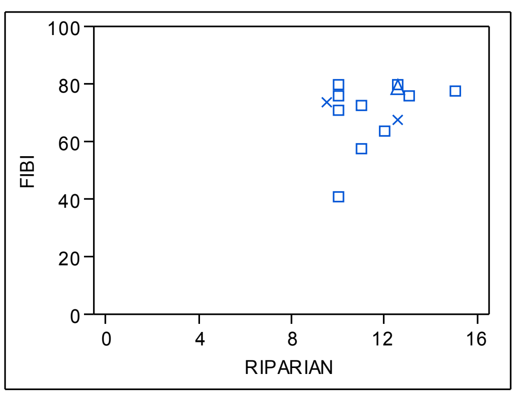
Figure 2-10: Plots and linear regression indicating a positive linear association between FIBI and MSHA metric zone/metric LAND USE/*surrounding land use* for A) COMBINED, but no significant linear association for B) REDWOOD or C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 0.03 + 5.95*RIPARIAN + 12.17, $R^2 = 0.69$, $p = <0.0001$.

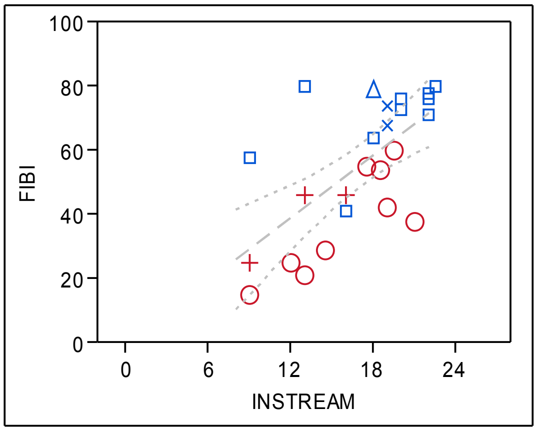


B) REDWOOD: FIBI = 2.57+ 5.18*RIPARIAN +11.99, $R^2 = 0.40$, $p = 0.0266$.

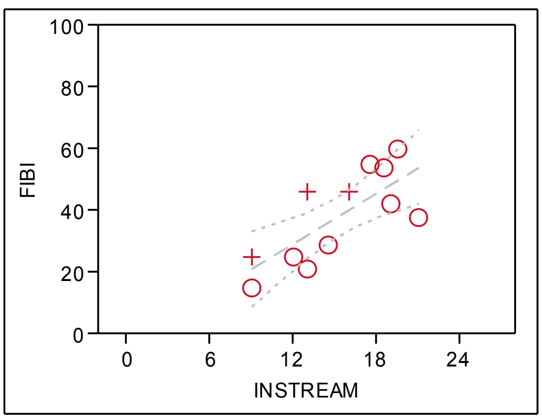


C) SNAKE: No significant association.

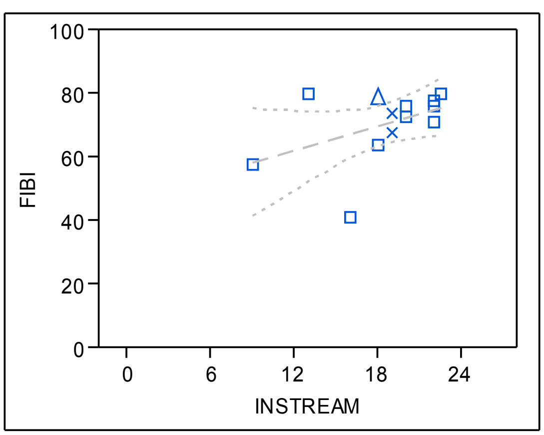
Figure 2-11: Plots and linear regression demonstrating significant, positive linear associations between FIBI and MSHA metric zone RIPARIAN for A) COMBINED and B) REDWOOD, but no significant linear association for C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 0.01 + 3.25*INSTREAM + 16.03, $R^2 = 0.44$, $p = 0.0004$.

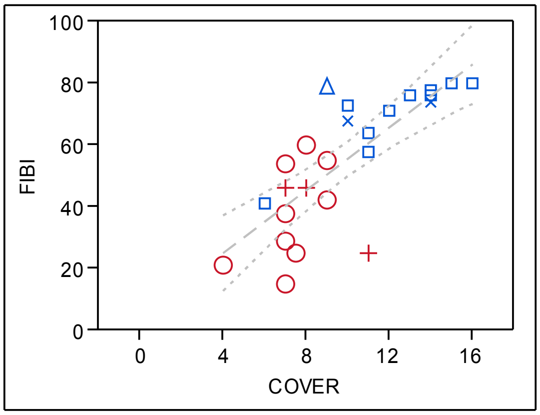


B) REDWOOD: FIBI = -3.89 + 2.76*INSTREAM + 10.16, $R^2 = 0.57$, $p = 0.0044$.

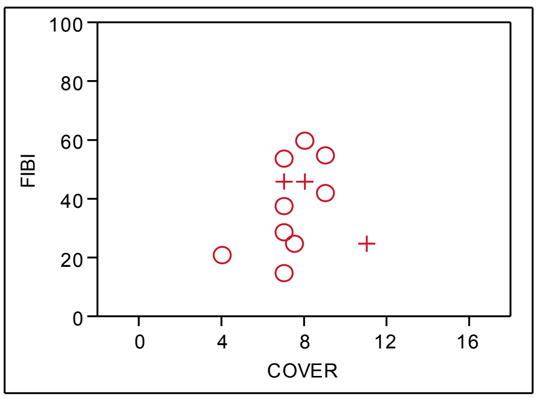


C) SNAKE: FIBI = 46.92+ 1.28*INSTREAM + 10.27, $R^2 = 0.21$, $p = 0.1177$.

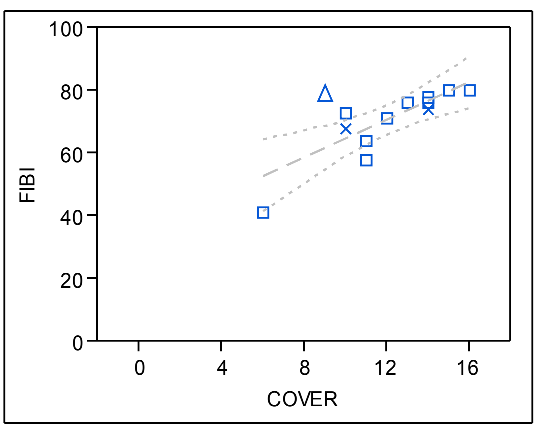
Figure 2-12: Plots and linear regression indicating positive linear associations between FIBI and MSHA zone INSTREAM for A) COMBINED and B) REDWOOD, and a weak linear association for C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 4.7902915 + 5.0882057*COVER + 13.72, $R^2 = 0.59$, $p = <0.0001$.

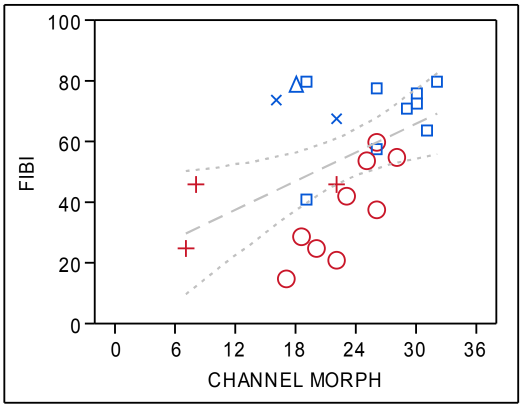


B) REDWOOD: No significant linear or polynomial association.

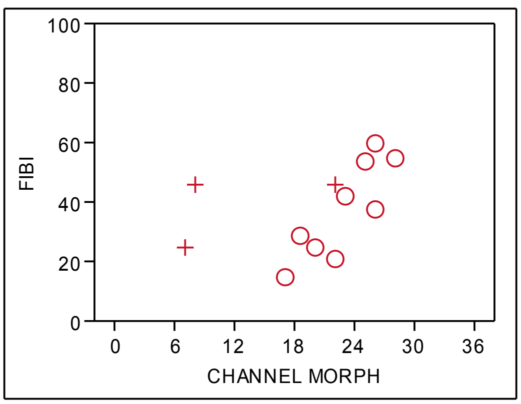


C) SNAKE: FIBI = 35.25 + 2.97*COVER + 7.66, $R^2 = 0.56$, $p = 0.0034$.

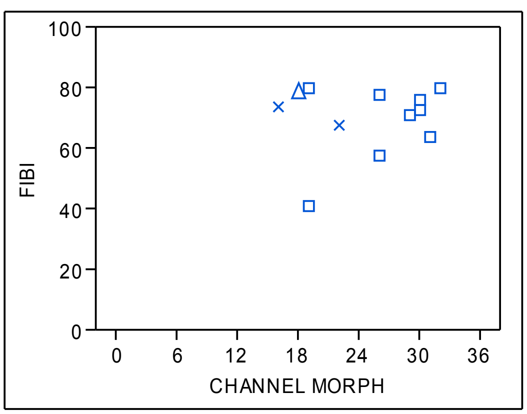
Figure 2-13: Plots and regression indicating positive linear associations between FIBI and MSHA metric zone COVER for A) COMBNED and C) SNAKE, but no significant linear or polynomial association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 19.06 + 1.57*CHANNEL MORPH + 18.56, $R^2 = 0.25$, $p = 0.0116$.



B) REDWOOD: No significant association linear or polynomial association.



C) SNAKE: No significant association.

Figure 2-14: Plots and linear regression indicating a positive linear association between FIBI and MSHA metric zone CHANNEL MORPH for A) COMBINED, but no significant linear or polynomial associations for B) REDWOOD, or SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.

For SNAKE, INSTREAM and COVER were the only zones significantly correlated with FIBI (Table 2-18). The best-fit model for SNAKE contained only COVER which explained 52% of the variance in FIBI (*P* >F = 0.0033). Seven of 15 individual MSHA metrics were significantly correlated with FIBI (Table 2-18). While most metrics were positively correlated with FIBI, *sinuosity* was negatively correlated (r = -0.59, r_s = -0.48). When individual metrics entered MLR, step-wise regression selected *embeddedness* and *channel stability* for the best fit model (*Adj* R^2 = 0.90, *P* >F = <0.0001). In comparison, a model with *channel stability* alone explained 82% of the variance in FIBI (*P* >F = <0.0001). When polynomial terms for non-linear associations were added, the best fit model selected *embeddedness* but replaced *channel stability* with metrics that described fish cover (*cover amount, cover type* with polynomial term). This model explained 95% of the variance in FIBI (*P* >F = <0.0001).

Table 2-19: Multiple Linear Regression models for FIBI and MSHA metric zones by watershed grouping. Model variables that were significant (α = 0.05) are underlined, and variables that were moderately significant (α = 0.10) are in *italics*. The best fit-models selected for each watershed grouping are in **bold.**

Watershed grouping **step-wise direction (number of predictor variables)**	**Model Variables**	***Adj R2***	**P>F**	**RMSE**	**AICc**	**Cp, p**
COMBINED (5)	LAND USE, RIPARIAN, *INSTREAM*, COVER, CHANNEL MORPH	0.80	<0.0001	9.4	196.7	6, 6
backward/ forward (3)	**RIPARIAN, INSTREAM, COVER**	**0.81**	**<0.0001**	**9.1**	**190.3**	**2.8, 4**
backward/ forward (2)	RIPARIAN, COVER	0.76	<0.0001	10.2	193.7	6.8, 3
backward/ forward (1)	RIPARIAN	0.66	<0.0001	12.2	201.0	17.5, 2
REDWOOD (3)	LAND USE, RIPARIAN, INSTREAM, CHANNEL MORPH	0.47	0.0754	10.8	113.5	4, 4
backward/ forward (2)	RIPARIAN, INSTREAM	0.56	0.0103	9.8	99.2	1.5, 3
backward/ forward (1)	**INSTREAM**	**0.53**	**0.0044**	**10.2**	**96.5**	**0.8, 2**
SNAKE (2)	INSTREAM, COVER	0.54	0.0080	7.5	98.7	3, 3
backward/ forward (1)	**COVER**	**0.52**	**0.0033**	**7.7**	**96.3**	**2.6, 2**

Table 2-20: Multiple Linear Regression models for FIBI and MSHA metrics by watershed grouping. Model variables that were significant (α = 0.05) are underlined and variables that were moderately significant (α = 0.10) are in *italics*. The best fit-models selected for each watershed grouping are in **bold.**

Watershed grouping **step-wise direction (number of predictor variables)**	**Model Variables**	***Adj R2***	**P>F**	**RMSE**	**AICc**	**Cp, p**
COMBINED (9)	riparian width, *shade*, substrate, embeddedness, substrate types, cover amount, cover type, channel stability, channel development	0.87	<0.0001	7.6	202.0	10, 10
backward/ forward (3)	riparian width, shade, channel stability	0.83	<0.0001	8.6	187.1	9.5, 4
backward/ forward (2)	**riparian width, channel stability**	**0.80**	**<0.0001**	**9.4**	**189.9**	**14.7, 3**
backward/ forward (1)	channel stability	0.60	<0.0001	13.3	205.3	50.0, 2
REDWOOD (7)	riparian width, substrate, embeddedness, substrate types, channel stability, pool width-to-riffle width, channel development	0.39	0.2624	11.6	187.6	8, 8
backward (3)	***embeddedness*, substrate types, *pool width-to-riffle width***	**0.53**	**0.0298**	**10.2**	**104.9**	**2.2, 4**
forward (3)	riparian width, substrate, *channel stability*	0.52	0.0316	10.3	105.1	2.3, 4
backward (2)	*embeddedness*, *substrate types*	0.39	0.0435	11.6	103.0	3.0, 3
forward (2)	**substrate, *channel stability***	**0.46**	**0.0249**	**10.9**	**101.6**	**1.9, 3**
backward (1)	*embeddedness*	0.18	0.0972	13.4	103.2	5.5, 2
backward (1)	*substrate types*	0.18	0.0971	13.4	103.2	5.5, 2
forward (1)	substrate	0.33	0.0296	12.1	100.7	3.0, 2
SNAKE (7)	riparian width, bank erosion embeddedness, cover type, *cover amount, channel stability, sinuosity*	0.95	0.0011	2.7	128.7	8, 8
backward/ forward (3)	embeddedness, channel stability, sinuosity	0.91	<0.0001	3.3	81.5	7.9, 4
backward/ forward (2)	**embeddedness, channel stability**	**0.90**	**<0.0001**	**3.6**	**79.7**	**10.1, 3**
backward/ forward (1)	channel stability	0.82	<0.0001	4.8	83.9	24.2, 2
SNAKE (7) with polynomial terms	riparian width, [bank erosion]^2, embeddedness, [cover type]^2, cover amount, channel stability, [sinuosity]^2	0.94	0.0410	2.5	---	11, 12
backward/ forward (4)	embeddedness, [cover type]^2, cover amount, *sinuosity*	0.96	<0.0001	2.3	86.5	4.9, 6
backward/ forward (3)	**embeddedness, [cover type]^2, cover amount**	**0.95**	**<0.0001**	**2.6**	**81.1**	**5.9, 5**
backward/ forward (2)	*embeddedness,* [*cover type*]^2	0.92	<0.0001	3.1	80.4	9.5, 4
backward/ forward (1)	[cover type]^2	0.90	<0.0001	3.8	79.6	13.9, 2

Associations among channel stability indicators and habitat quality

I computed pairwise correlations between PSI and MSHA variables in order to explore the association between channel stability and habitat quality. Prior to analysis, four metrics were removed that were not appropriate for streams in this study or where the scoring system was categorical and not continuous. From PSI, I removed *debris jam potential* and *rock angularity*. From MSHA, I removed *substrate types* and *velocity types*.

For a majority of metrics, Pearson and Spearman correlation were in close agreement (Tables 21a, b, c); however, for a considerable number of metrics, Pearson and Spearman correlation results were in disagreement although many of these were close to the threshold of significance.

In order to compare how well channel stability and habitat quality metrics were associated overall, I calculated an average number of strongly correlated pairs (r >0.40) identified by Pearson and Spearman Correlation out of a possible 306 channel stability and habitat quality metric pairs.

For COMBINED, an average of 199 highly correlated ($r > |0.40|$) pairs were identified (65%). When watersheds were analyzed separately, the number of significantly correlated pairs was much lower. For SNAKE, 163 highly correlated pairs were identified (53%); whereas, for REDWOOD, only 37 highly correlated pairs were identified (12%). Across watershed groupings, the PSI zone that was correlated with the greatest number of MSHA metrics was BOTTOM; whereas, individual PSI metrics that were correlated with the greatest number of MSHA metrics varied by watershed grouping. The MSHA metrics that were correlated with the greatest number of PSI metrics across watershed groupings were *channel stability* and *bank erosion*. The PSI metric zone and metrics that were correlated with the least number of MSHA metrics across watershed groupings were LOWER, *obstructions/flow deflectors/sediment traps* and *deposition*. The MSHA metric zones and metrics that were correlated with the least number of PSI metrics across watershed groupings were *riparian width, shade*, *depth variability*, and *channel development*.

Within each watershed grouping, results varied as to which variables that were considered significantly correlated. For COMBINED, MSHA and PSI were negatively and significantly correlated (r = -0.53, r_s = -0.60); however, the scatterplot for COMBINED indicates a potential wedge-shaped association between MSHA and PSI (Figure 2-15a). PSI metric zones UPPER and BOTTOM were significantly correlated with MSHA (Table 2-21a). In total, 8 of 11 individual PSI metrics were strongly correlated (r >50) with MSHA for COMBINED, of which, *channel capacity* was the only metric positively correlated. MSHA metric *channel stability* was strongly and negatively correlated with PSI, all three PSI metric zones, and 11 of 13 PSI metrics (Table 2-21a) of which *scouring and deposition* was the most strongly correlated.

Table 21a. Pearson (A) and Spearman (B) correlation results between select PSI, CEM and MSHA metrics for COMBINED. Only metrics where r or r_s >|0.40| displayed. Results in **bold** significant at α = 0.05. Results in *italics* significant at α = 0.1. Underlined are metrics were r and r_s were in disagreement as to whether a metric was considered a significant variable.

A)	CEM	PSI	UPPER	LOWER	BOTTOM	LS	MW	VBP	CC	BRC	OFDST	C	D	Br	CPP	BSD/PSM	SD	CAV
MSHA	**0.50**	**-0.53**	**-0.61**		**-0.50**	**-0.65**	**-0.53**	**-0.62**	**0.67**	**-0.47**				**-0.44**		**-0.48**	**-0.46**	
LAND USE						**-0.51**												
RIPARIAN	**0.52**	**-0.58**	**-0.62**	**-0.44**	**-0.52**	**-0.60**	**-0.49**	**-0.66**					**-0.40**	**-0.40**		<u>**-0.47**</u>	**-0.52**	
INSTREAM		**-0.42**	**-0.47**		**-0.47**		**-0.57**	**-0.48**	**0.74**	**-0.46**						**-0.48**	**-0.44**	
COVER	**0.75**	**-0.71**	**-0.70**	**-0.47**	**-0.68**	**-0.67**	**-0.53**	**-0.67**				**-0.48**		**-0.47**		**-0.69**	**-0.63**	**-0.44**
CH- MORPH						**-0.52**			**0.60**	**-0.44**								
RW			**-0.48**			**-0.52**		**-0.53**										
BE	**0.44**	**-0.74**	**-0.79**	**-0.63**	**-0.59**	**-0.48**	**-0.74**	**-0.59**	<u>**0.44**</u>			**-0.51**	**-0.52**	**-0.63**		**-0.46**	**-0.60**	**-0.53**
Sh	<u>**0.41**</u>	**-0.41**			**-0.44**			**-0.41**						**-0.43**		**-0.41**		
Su							**-0.50**	**-0.47**	<u>**0.75**</u>	**-0.45**								
Em	**0.68**	**-0.54**	**-0.45**		**-0.60**		**-0.52**		<u>**0.42**</u>			<u>**-0.41**</u>				**-0.52**	**-0.64**	
CT	**0.51**	**-0.53**			**-0.59**		**-0.47**		**0.43**	**-0.49**				**-0.47**		**-0.59**	**-0.51**	
CA	**0.65**	**-0.59**	**-0.65**		**-0.53**	**-0.67**	**-0.41**	**-0.61**				**-0.4**				**-0.54**	**-0.51**	
DV						**-0.44**			**0.51**									
CS	**0.60**	**-0.86**	**-0.77**	**-0.64**	**-0.84**	**-0.59**	**-0.73**	**-0.65**	**0.45**	**-0.48**		**-0.65**		**-0.77**	**-0.53**	**-0.71**	**-0.82**	**-0.57**
Si		**0.49**			**0.55**											**0.57**	**0.49**	
CD									**0.56**									

B)	CEM	PSI	UPPER	LOWER	BOTTOM	LS	MW	VBP	CC	BRC	OFDST	C	D	Br	CPP	BSD/PSM	SD	CAV
MSHA	**0.50**	**-0.60**	**-0.71**		**-0.53**	**-0.71**	**-0.56**	**-0.67**	**0.63**	**-0.51**				**-0.45**		**-0.49**	**-0.47**	<u>**-0.43**</u>
LAND USE						**-0.53**		<u>**-0.40**</u>										
RIPARIAN	**0.43**	**-0.60**	**-0.63**	**-0.42**	**-0.51**	**-0.63**	**-0.47**	**-0.67**									**-0.50**	
INSTREAM	<u>**0.49**</u>	**-0.47**	**-0.56**		**-0.47**		**-0.66**	**-0.53**	**0.76**	**-0.52**						**-0.45**	**-0.42**	
COVER	**0.71**	**-0.77**	**-0.67**	**-0.48**	**-0.73**	**-0.65**	**-0.54**	**-0.70**				**-0.53**		**-0.52**	**-0.40**	**-0.71**	**-0.64**	**-0.45**
CH-MORPH			<u>**-0.46**</u>			**-0.54**		<u>**-0.42**</u>	**0.67**	**-0.41**								
RW			**-0.48**			**-0.54**		**-0.50**										
BE	**0.45**	**-0.68**	**-0.73**	**-0.58**	**-0.56**	**-0.49**	**-0.73**	**-0.62**				**-0.47**	**-0.54**	**-0.57**		**-0.44**	**-0.57**	**-0.51**
Sh		**-0.44**			**-0.46**			**-0.42**						**-0.45**		**-0.41**		
Su		<u>**-0.40**</u>	<u>**-0.53**</u>				**-0.65**	**-0.55**		**-0.57**								
Em	**0.69**	**-0.54**	**-0.44**		**-0.56**		**-0.52**									**-0.46**	**-0.59**	
CT	**0.51**	**-0.51**			**-0.63**		**-0.48**		**0.43**	**-0.47**				**-0.46**		**-0.61**	**-0.50**	
CA	**0.62**	**-0.68**	**-0.66**	**-0.40**	**-0.57**	**-0.62**	**-0.44**	**-0.64**				**-0.43**		<u>**-0.41**</u>		**-0.55**	**-0.52**	<u>**-0.41**</u>
DV						**-0.47**			**0.59**	<u>**-0.42**</u>								
CS	**0.68**	**-0.83**	**-0.75**	**-0.62**	**-0.81**	**-0.63**	**-0.72**	**-0.72**	**0.46**	**-0.60**		**-0.56**		**-0.68**	**-0.46**	**-0.70**	**-0.78**	**-0.56**
Si		**0.44**			**0.55**		<u>**0.40**</u>				<u>**0.42**</u>			**0.44**		**0.55**	**0.50**	
CD									**0.64**									

Table 21b. Pearson (A) and Spearman (B) correlation results between select PSI, CEM and MSHA metrics for REDWOOD. Only metrics where r or r_s >|0.40| displayed. Results in **bold** significant at α = 0.05. Results in *italics* significant at α = 0.1. Underlined are metrics where r and r_s were in disagreement as to whether a metric was considered a significant variable.

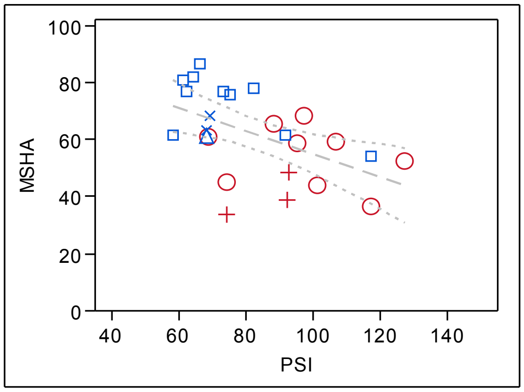
A)	CEM	PSI	UPPER	LOWER	BOTTOM	LS	MW	VBP	CC	BRC	OFDST	C	D	Br	CPP	BSD/PSM	SD	CAV
MSHA						*-0.55*			*0.52*									
LAND USE					*0.46*							*0.46*		0.42	*0.54*	0.40		
RIPARIAN			*-0.46*					*-0.50*										
INSTREAM						*-0.45*			**0.67**									
COVER	**0.79**											*-0.45*	*0.49*			**-0.59**		
CH- MORPH						*-0.55*			0.41		0.40							
RW														0.40				*0.46*
BE		**-0.84**	**-0.80**	**-0.78**	**-0.66**		**-0.83**	*-0.47*		*-0.45*	*-0.44*	**-0.62**		**-0.59**	*-0.49*	*-0.46*	**-0.71**	
Sh	**0.62**				**-0.60**						*0.46*	**-0.67**		**-0.59**	*-0.52*	*-0.54*	*-0.48*	-0.42
Su									**0.65**									
Em						*-0.48*									**-0.57**			
CT											**0.67**		*0.46*					
CA	**0.75**							*-0.47*								*-0.48*		
DV						**-0.60**			*0.44*									
CS		**-0.71**	*-0.50*		**-0.81**	-0.40	*-0.56*					**-0.61**		**-0.70**	**-0.71**	**-0.67**	**-0.83**	
Si		*0.56*			**0.65**		*0.45*					*0.44*			**0.57**	**0.66**	**0.66**	
CD									*0.44*		*0.50*							

B)	CEM	PSI	UPPER	LOWER	BOTTOM	LS	MW	VBP	CC	BRC	OFDST	C	D	Br	CPP	BSD/PSM	SD	CAV
MSHA						*-0.53*			*0.51*									
LAND USE					*0.52*										*0.51*	*0.48*		*0.45*
RIPARIAN			*-0.45*					**-0.57**										
INSTREAM									**0.64**									
COVER	**0.64**				-0.40			-0.41				-0.43	*0.50*			**-0.58**		0.41
CH-MORPH						**-0.57**			*0.51*		0.42							
RW								*-0.48*										*0.54*
BE		**-0.83**	**-0.80**	**-0.77**	*-0.56*		**-0.81**	*-0.55*		*-0.47*		*-0.55*	-0.43	**-0.58**	*-0.44*	-0.40	**-0.65**	
Sh	**0.58**				*-0.51*							**-0.62**		*-0.48*	*-0.47*	*-0.53*	-0.40	
Su									*0.54*									
Em						**-0.59**						-0.41			**-0.57**			
CT											**0.57**							
CA	**0.69**				-0.41			*-0.47*								*-0.46*	-0.40	
DV						**-0.67**			*0.53*									
CS		**-0.64**	*-0.51*	-0.41	**-0.64**	-0.43	**-0.58**					**-0.62**		**-0.63**	**-0.66**	**-0.60**	**-0.68**	
Si		**0.64**	0.43		**0.68**		*0.50*					*0.46*			*0.55*	**0.69**	**0.70**	
CD						-0.41			*0.58*									

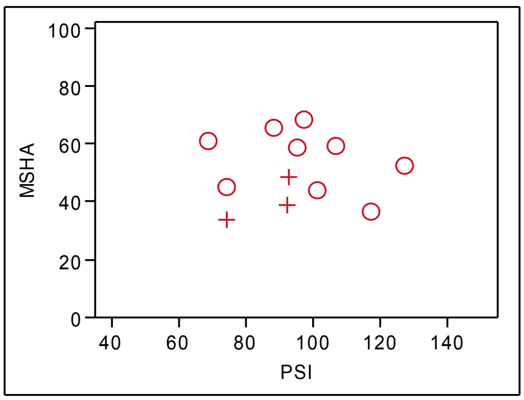
Table 21c. Pearson (A) and Spearman (B) correlation results between select PSI, CEM and MSHA metrics for SNAKE. Only metrics where r or r_s >|0.40| displayed. Results in **bold** significant at α = 0.05. Results in *italics* significant at α = 0.1. <u>Underlined</u> are metrics were r and r_s were in disagreement as to whether a metric was considered a significant variable.

A)	CEM	PSI	UPPER	LOWER	BOTTOM	LS	MW	VBP	CC	BRC	OFDST	C	D	Br	CPP	BSD/PSM	SD	CAV
MSHA	*0.45*	<u>*-0.51*</u>	**-0.71**		<u>*-0.47*</u>		**-0.73**	**-0.61**	**0.80**	*-0.46*				**-0.62**		*-0.46*		*-0.54*
LAND USE												*-0.48*						*-0.50*
RIPARIAN							<u>*-0.42*</u>						*-0.50*	<u>*-0.42*</u>				*-0.51*
INSTREAM			-0.41				**-0.71**	*-0.43*	**0.74**	**-0.55**				**-0.60**		<u>*-0.53*</u>		
COVER	**0.63**	**-0.75**	**-0.79**	<u>*-0.48*</u>	**-0.64**	**-0.62**	**-0.58**	*-0.47*			-0.42		*-0.44*	<u>*-0.53*</u>		**-0.58**	**-0.58**	**-0.66**
CH-MORPH			*-0.49*				<u>*-0.44*</u>	<u>*-0.48*</u>	**0.69**	<u>*-0.47*</u>								
RW		<u>*-0.42*</u>		<u>*-0.42*</u>								**-0.67**			<u>*-0.48*</u>			<u>*-0.51*</u>
BE	*0.53*	**-0.64**	**-0.83**		<u>*-0.46*</u>	**-0.60**	**-0.62**	**-0.68**	*0.45*				**-0.55**	**-0.62**			<u>*-0.42*</u>	**-0.77**
Sh																		
Su							**-0.61**		**0.77**	**-0.61**				*-0.54*				
Em	**0.84**	**-0.57**			**-0.65**		**-0.65**			<u>-0.41</u>						<u>*-0.47*</u>	**-0.73**	
CT	*0.46*	**-0.71**		**<u>-0.59</u>**	**-0.74**		**-0.58**		0.41	**-0.56**	**-0.60**			**-0.60**		**-0.68**	**<u>-0.56</u>**	<u>*-0.51*</u>
CA	*0.45*	*-0.44*	**-0.66**			**-0.70**												*-0.46*
DV									**0.60**	*-0.47*				*-0.54*				*-0.49*
CS	*0.52*	**-0.90**	**-0.81**	**-0.70**	**-0.78**		**-0.73**	**-0.69**				**-0.64**	*-0.49*	**-0.79**		**-0.57**	**-0.72**	**-0.72**
Si		**0.62**		**0.54**	**0.63**						**0.55**			**0.67**		**0.64**	<u>*0.45*</u>	<u>*0.48*</u>
CD									**0.61**			<u>0.41</u>						

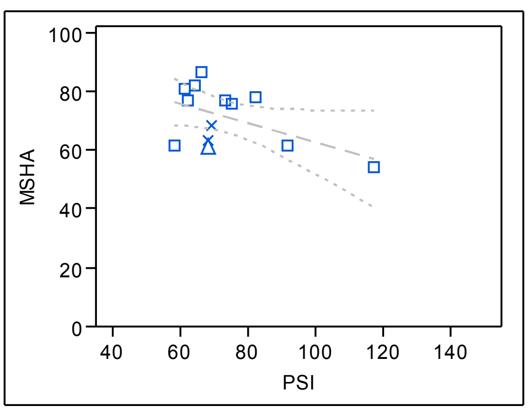
B)	CEM	PSI	UPPER	LOWER	BOTTOM	LS	MW	VBP	CC	BRC	OFDST	C	D	Br	CPP	BSD/PSM	SD	CAV
MSHA	*0.49*		**-0.70**				**-0.72**	*-0.51*	**0.81**	*-0.44*				**-0.61**		*-0.44*		**-0.58**
LAND USE												*-0.46*						-0.41
RIPARIAN																		*-0.47*
INSTREAM	<u>*0.43*</u>		**-0.59**				**-0.78**	*-0.47*	**0.82**	*-0.52*				**-0.61**				
COVER	**0.67**	**-0.71**	**-0.67**		**-0.56**	*-0.54*	*-0.45*									**-0.55**	*-0.45*	**-0.55**
CH-MORPH			*-0.46*					*-0.43*	**0.63**									
RW												**-0.58**						
BE	**0.55**	*-0.47*	**-0.72**			**-0.56**	*-0.54*	**-0.61**	*0.46*				*-0.51*	*-0.52*				**-0.72**
Sh																		
Su			**<u>-0.60</u>**				**-0.77**	**<u>-0.57</u>**	**0.94**	**-0.67**				**-0.60**				
Em	**0.81**	**-0.64**			**-0.57**		**-0.64**										**-0.71**	
CT		*-0.44*			**-0.62**		*-0.44*		0.41	**-0.59**	**-0.61**			*-0.46*		**-0.62**		
CA	*0.51*	*-0.54*	**-0.67**			**-0.68**												*-0.44*
DV									**0.62**	*-0.54*				*-0.48*	*-0.45*			*-0.43*
CS	**0.74**	**-0.62**	**-0.56**	<u>*-0.45*</u>	*-0.52*		**-0.69**	*-0.50*				*-0.49*		**-0.55**	*-0.44*	*-0.42*	**-0.64**	*-0.47*
Si		*0.42*		*0.46*	*0.51*						*0.48*		*0.44*	**0.64**		*0.51*		
CD			<u>*-0.44*</u>	**0.55**			<u>*-0.51*</u>		**0.65**				<u>*0.50*</u>					



A) COMBINED: MSHA = 95.22 - 0.40*PSI + 12.8, $R^2 = 0.25$, $p = 0.0065$.



B) REDWOOD: No significant linear or polynomial association.



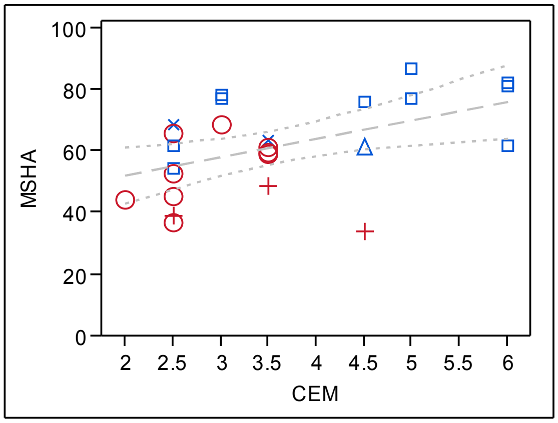
C) SNAKE: MSHA = 95.15 - 0.32*PSI + 8.97, $R^2 = 0.26$, $p = 0.0725$.

Figure 2-15: Plots and linear regression demonstrating a significant negative linear association between MSHA and PSI for A) COMBINED and C) SNAKE, but no significant linear or polynomial association for REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.

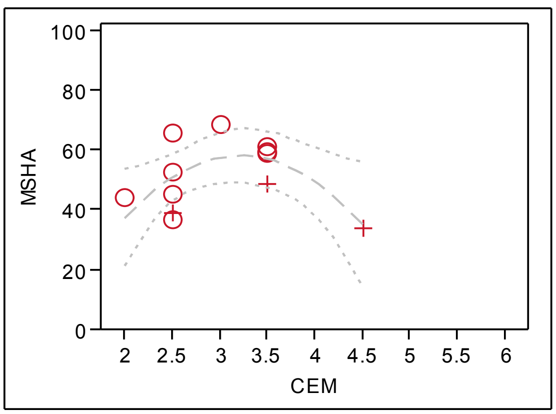
CEM was strongly correlated with MSHA, metric zones RIPARIAN and COVER, and 5 of 11 MSHA metrics, of which *embeddedness* was the most strongly correlated with CEM.

For REDWOOD, PSI and MSHA were not correlated. No PSI metric zones were correlated with MSHA. MSHA metric *bank erosion* was significantly correlated with all three PSI metric zones and PSI metric *mass wasting.* Only two individual PSI metrics were significantly correlated with MSHA: *landform slope* was negatively correlated and *channel capacity* was positively correlated; c*hannel capacity* was also positively correlated with INSTREAM, CHANNEL MORPH, *substrate*, *depth variability*, and *channel development.* MSHA metric *channel stability* was significantly correlated with PSI, PSI zones UPPER and BOTTOM, and 7 of 11 PSI metrics (Table 2-21b) of which *scouring and deposition* was the most strongly correlated. MSHA was only marginally correlated with CEM. The scatterplot (Figure 2-16b) and polynomial regression demonstrate a potential curvilinear association (R^2 = 0.43, p = 0.0832). The outlier to the general positive linear direction was a channelized reach at a higher CEM stage (CEM IV) and a lower MSHA score. COVER was the only MSHA metric zone significantly correlated with CEM.

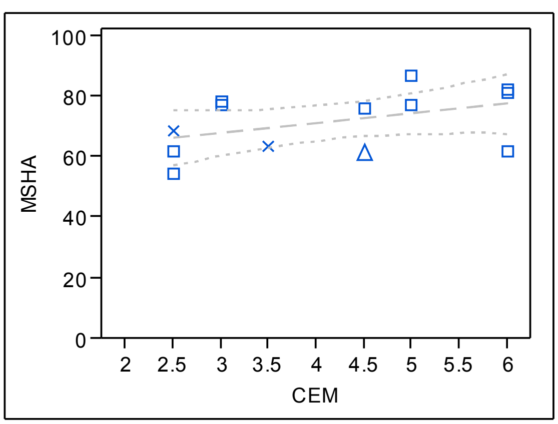
For SNAKE, the results for Pearson and Spearman correlation were in disagreement as to whether or not PSI and MSHA were significantly correlated (r = -0.51, p = 0.0725; r_s = -0.38, p = 0.2065). The bivariate scatterplot between MSHA and PSI (Figure 2-15c) indicates that many points received similar scores for PSI and MSHA and consequently cluster very near each other with a few points located further from the cluster. Hence, Pearson Correlation may be more accurately reflecting the general directional response through the cluster of points to the other outlying points than Spearman Rank Order Correlation. PSI metric zone UPPER was strongly correlated with MSHA; whereas, BOTTOM was only marginally correlated. The individual PSI metrics strongly correlated with MSHA included: *mass wasting, vegetative bank protection,* and *brightness* which were positively correlated, and *channel capacity* which was negatively correlated. PSI metric *mass wasting* was negatively correlated with a number of MSHA zones and metrics including: RIPARIAN, INSTREAM, COVER, CHANNEL MORPH, *bank erosion, substrate, embeddedness, cover types*, and *channel stability.* PSI metric *channel capacity* was positively correlated many of the same MSHA zones and metrics; however, *channel capacity* was not correlated with *cover* or *embeddedness. Channel capacity* was correlated with *depth variability;* whereas, *channel capacity* was not correlated with *mass wasting or bank failure.* MSHA metric *channel stability* was significantly correlated with PSI, all three PSI metric zones, and 8 of 13 individual metrics tested (Table 21c) of which *brightness* was the most strongly correlated. CEM was marginally correlated with MSHA. COVER was the only MSHA zone correlated with CEM. Five of 11 individual MSHA metrics tested were significantly correlated with CEM: *bank erosion, embeddedness, cover type, cover amount,* and *channel stability.*



A) COMBINED: MSHA = 40.10 + 6.01*CEM + 13.0, R^2 = 0.26, p = 0.0101.



B) REDWOOD: MSHA = -86.22 + 89.92*CEM - 14.00*CEM^2 +9.69, R^2 = 0.43, p = 0.0832.



C) SNAKE: MSHA = 58.06 + 3.23*CEM + 9.34, R^2 = 0.20, p = 0.1244.

Figure 2-16: Plots and linear regression demonstrating a significant negative linear association between MSHA and CEM for A) COMBINED and C) SNAKE, but a marginally significant polynomial association for REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.

Associations among geomorphic variables, FIBI, channel stability, and habitat quality

Geomorphic variables

For all watershed groupings, the following variables were highly correlated and considered redundant (r >0.80): *percent pool and riffle* and *percent run, gradient by map* with *channel slope,* and *D50* with *D84. Percent pool and riffle* was retained since it better represents diversity in flow habitat which has been shown to be positively correlated with attributes of biological communities. The degree of correlation between *channel slope* and *gradient by map* varied by watershed grouping. For COMBINED and SNAKE, *channel slope* and *gradient by map* were highly correlated (r = 0.88, r_s = 0.65; r = 0.98, r_s = 0.86, respectively). In contrast, *channel slope* and *gradient by map* were not as highly correlated in REDWOOD (r = 0.67, r_s = 0.26). Given the differences by watershed, both stream gradient measurements were included in correlation analyses.

Geomorphic variables and FIBI

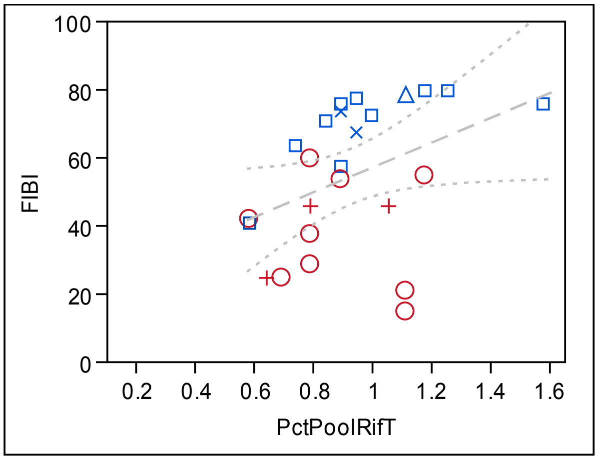
For COMBINED, FIBI was not strongly correlated with either *channel slope* (r = 0.29, r_s = 0.30) or *gradient by map* (r = 0.28 r_s = 0.31). Stream features and substrate variables that were positively and significantly ($p<0.05$) correlated with FIBI included: *percent pool and riffle* (0.40), *D50* (0.64), *D84* (0.50), *percent cobble* (0.58), *percent cobble and boulder* (0.56), and *percent rock* (0.57). Variables that were negatively and marginally (p<0.10) correlated with FIBI included: *sinuosity by map* (-0.37), *percent silt/clay* (-0.35), and *percent sand* (-0.36). Of these, the following variables were considered redundant (r >0.80): *D50* with *D84*, *percent cobble* and *percent cobble and boulder*; and *percent sand* with *percent rock.* The best fit MLR model for COMBINED (Table 2-16) explained 59% of the variance in FIBI (P >F = 0.0001) and contained three variables: *D50*, *sinuosity by map*, and *percent pool and riffle*. In comparison, a two variable model with only *D50* and *sinuosity by map* explained only 49% of the variance observed in FIBI (P >F = 0.0003).

For REDWOOD, FIBI was more strongly correlated with *channel slope* (r = 0.44, r_s = 0.46) than *gradient by map* (r = 0.18, r_s = 0.25). FIBI was significantly correlated with only one substrate variable: *D50* (r = 0.75, p = 0.0048). For MLR, *channel slope* entered with *D50*; however, only *D50* was retained as a significant variable. The single variable model with only D50 explained 52% of the variance in FIBI for REDWOOD (P >F = 0.0048).

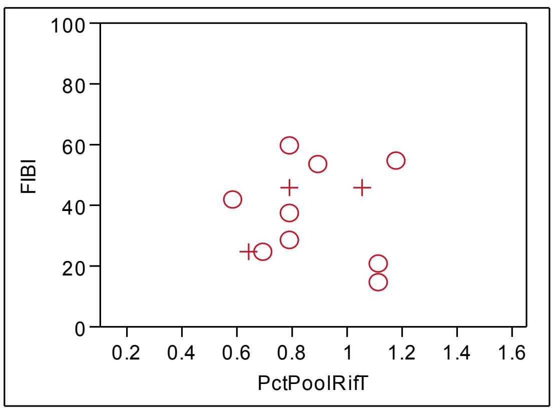
Table 2-22: Multiple Linear Regression models for FIBI and geomorphic variables by watershed grouping. Model variables that were significant (α = 0.05) are underlined and variables that were moderately significant (α = 0.10) are in *italics*. The best fit-models selected for each watershed grouping are in **bold**.

Watershed grouping **step-wise direction (number of predictor variables)**	**Model Variables**	***Adj R2***	**P>F**	**RMSE**	**AICc**	**Cp, p**
COMBINED (3)	**D50, sinuosity by map, percent pool and riffle**	**0.59**	**<0.0001**	**13.4**	**209.5**	**4, 4**
forward (2)	D50, sinuosity by map	0.49	0.0003	15.0	231.2	8.6, 3
forward (1)	D50	0.39	0.0006	16.4	215.9	13.5, 2
REDWOOD (2)	D50, channel slope	0.49	0.0189	10.5	100.8	3. 3
backward/ forward (1)	**D50**	**0.52**	**0.0048**	**10.2**	**96.7**	**1.5, 2**
SNAKE (3)	D50, percent pool, *[percent pool and riffle]^2*	0.87	0.0002	3.9	92.1	5, 5
backward/forward (2)	**D50, [percent pool and riffle]^2**	**0.87**	**<0.0001**	**4.0**	**86.4**	**4.2, 4**
backward/forward (1)	[percent pool and riffle]^2	0.75	0.0004	5.6	91.1	13.1, 3

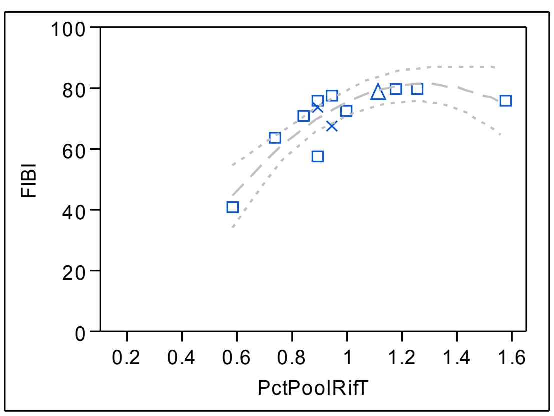
For SNAKE, FIBI was not strongly correlated with either *channel slope* (r = 0.22, r_s = -0.10) or *gradient by map* (r = 0.14, r_s = -0.12). FIBI was positively and significantly (p<0.05) correlated (r) with *percent pool* (0.58), *percent pool and riffle* (0.67), and *percent cobble* (0.57). Other variables that met the correlation threshold for MLR included: *D50* (0.41), *percent rock* (0.42), and *percent sand* (-0.43). While *D50* was redundant (r >0.80) with *percent cobble* and *percent rock,* I elected to bring both *D50* and *percent cobble* into MLR. This allowed the model to choose the predictor with the best correspondence with other candidate model predictors. During MLR examination of the variable response with FIBI, diagnostics revealed that *percent pool and riffle* demonstrated a curvilinear relationship with FIBI which was best described with the addition of a polynomial term (Figure 2-15). When the polynomial term was added to the set of predictors, the best fit model selected *D50* and *percent pool and riffle* with its polynomial term. (*Adj* R^2 = 0.87, P >F = <0.0001). In comparison, a model with only *percent pool and riffle* with its polynomial term predicted 74% of the variance in FIBI (P >F = 0.0004).



A) COMBINED: FIBI = 27.47 + 0.44*%PoolRif + 19.6; R^2 = 0.16, p = 0.0456.



B) REDWOOD: No significant linear or polynomial association.



C) SNAKE: FIBI = -41.74+ 193.11*PctPoolRifT -75.67*PctPoolRifT^2 + 5.56; R^2 = 0.79, p = 0.0004.

Figure 2-17: Plots and regression demonstrating significant positive associations between FIBI and geomorphic variable *percent pool and riffle* for A) COMBINED and C) SNAKE, but no linear or polynomial association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.

Geomorphic variables and channel stability

I explored which geomorphic variables explained a significant portion of the variability in PSI and PSI zone BOTTOM since this zone was the most strongly correlated with PSI for each watershed grouping. In addition, I also tested the association between CEM and geomorphic variables since CEM was a candidate metric for a modified channel stability assessment.

For COMBINED, PSI and BOTTOM were positively correlated with *sinuosity by map,* but were not correlated with either *gradient by map* or *channel slope*. PSI was negatively and at least marginally (p<0.1) correlated (r) with the following substrate variables: *D50* (-0.43), *percent cobble* (-0.54), *percent cobble and boulder* (-0.52)*, percent rock* (-0.43). BOTTOM was almost as strongly correlated with the same substrate variables as PSI: *percent cobble* (-0.50), *percent cobble and boulder* (-0.48), and *percent rock* (-0.43), but was not correlated with *D50.* CEM was also correlated with *percent pool and riffle* (0.49)*, D50* (0.48)*, percent cobble* (0.48)*,* and *percent cobble and boulder* (0.43). CEM was also positively and significantly correlated with c*hannel slope* (0.46, p = 0.0196), but not significantly correlated with *gradient by map* (0.28, p = 0.1786). Unlike PSI and BOTTOM, CEM and was not correlated with *sinuosity by map.*

For REDWOOD, PSI was significantly correlated with *sinuosity by map* (0.55). PSI was strongly correlated with *gradient by map* (0.71), but not *channel slope* (0.09). For stream features, PSI was positively correlated with *percent riffle* (0.49) and *percent pool and riffle* (0.47). *Percent riffle* and *percent pool and riffle* were significantly correlated but not redundant (r = 0.73, p = 0.0072). BOTTOM was correlated with *gradient by map* (0.48) and *sinuosity by map* (0.58). CEM was only correlated with *percent gravel* (r = 0.64).

For SNAKE, PSI and BOTTOM were not correlated with either *gradient by map, channel slope,* or *sinuosity by map.* PSI was negatively correlated with *percent pool* (-0.51) and *percent pool and riffle* (-0.65) and BOTTOM was only negatively correlated with *percent pool and riffle* (-0.59). *Percent pool* and *percent pool and riffle* were strongly correlated (0.63) but not redundant. PSI and BOTTOM were negatively correlated with *percent cobble* and positively correlated with *percent sand.* Additionally*,* BOTTOM was also correlated with *percent cobble and boulder* (-0.49) and *percent rock* (-0.50). These two substrate variables were highly correlated (r >0.90). CEM was only strongly and positively correlated with *percent pool and riffle* (0.70).

Geomorphic variables and habitat quality

I applied correlation tests to investigate to what degree geomorphic variables were significantly associated with habitat quality and the degree of correspondence between substrate variables collected via a pebble count and the MSHA metric *substrate*. The *substrate* metric scores the presence and size of the two most dominant substrate types by stream feature; whereas, a pebble count characterizes all the substrate types present in their relative proportion.

For COMBINED, MSHA was significantly correlated with *gradient by map* (r = 0.44, r_s = 0.52); whereas, correlation results were mixed for *channel slope* (r = 0.37, r_s = 0.55). For stream features, MSHA was correlated with only *percent riffle* (0.63). Habitat quality was positively correlated with an increase in the relative quantity and size of substrates. MSHA was positively correlated with *D50* (0.81), *percent rock* (0.79), *D84* (0.73), *percent cobble* (0.75), *percent boulder* (0.59), and negatively correlated with *percent sand* (-0.52), and *percent silt/clay* (-0.47). The only substrate variable not correlated with MSHA was *percent gravel*. MSHA metric *substrate* was most strongly correlated with *D50* (0.77), followed by *D84* (0.74), and *percent rock* (0.64).

For REDWOOD, habitat quality was positively correlated with gradient by map (r = 0.41, r_s = 0.43), but not *channel slope* (r = 0.20, r_s = 0.26). For stream features, MSHA was positively correlated with only *percent riffle* (0.58). MSHA was strongly and positively correlated with *D50* (0.80), followed by *D84* (0.60) and *percent rock* (0.60), and negatively correlated with *percent sand* (-0.42). MSHA was not correlated with *percent gravel,* and in contrast to COMBINED and SNAKE, MSHA was not correlated with *percent cobble* or *percent boulder*. MSHA metric *substrate* was most strongly correlated with *D50* (0.63), and unlike COMBINED and SNAKE, *substrate* was not correlated with either *D84* or *percent rock.*

For SNAKE, MSHA was correlated with *gradient by map* (r = 0.60, r_s = 0.58); whereas, correlation results were mixed for *channel slope* (r = 0.39, r_s = 0.60). For stream features, MSHA was strongly correlated with *percent riffle* (0.73) and correlation results were mixed for *percent pool and riffle* (r = 0.40, r_s = 0.29). Substrate variables that were strongly (r >0.50) and positively correlated with MSHA included: *D50* (0.83)*, D84* (0.76), *percent cobble* (0.85), *percent boulder* (0.87)*,* and *percent rock* (0.88); whereas, *percent silt/clay* (-0.75), and *percent sand* (-0.63) were negatively correlated. The only substrate variable not correlated with MSHA was *percent gravel.* MSHA metric *substrate* was positively correlated with variables representing larger substrate sizes: *D84* (0.93), followed by *percent rock* (0.84), and *D50* (0.81).

Discussion

Applicability of PSI metrics to low-gradient alluvial streams

My *a priori* hypothesis about the utility of the assessment tool was that certain metrics would be problematic to score in low-gradient streams dominated by glacial deposits of fine substrate (e.g., *rock angularity*, *channel capacity*, *brightness*) or might not adequately describe and rate alluvial stream indicators observed (e.g., ground water seeps, bank composition). The test was simply to apply the assessment tool in reaches covering a range of stream sizes and substrate conditions and note if scoring certain metrics was problematic or metrics did not seem appropriate for characterizing channel stability indicators observed. My experience with the assessment tool indicates that some of the metrics are applicable for low-gradient, alluvial streams whereas others are not (Table 2-1). The original PSI could still be considered applicable in certain physiographic regions in Minnesota where higher gradient, moderately entrenched streams (B or F stream types, Rosgen 1994) occur in bedrock and sandstone controlled valley types (e.g., parts of the Lake Superior River Basin in north-eastern Minnesota, parts of the Driftless Area in southeastern Minnesota, parts of the Cedar River Basin in Southern Minnesota). The original PSI should be tested using these stream types in future studies. However, changes to the original PSI, in my opinion, are needed in order to enhance the ability of the assessment tool to more appropriately rate channel stability indicators observed in low-gradient alluvial streams in Minnesota and regions with similar physiography across much of the Midwest.

Suggested metric modifications for a modified, low-gradient stream assessment

The original PSI has been tested by different stream assessors in various river basins in Minnesota. These assessors identified metrics that were difficult to score in low-gradient stream settings and have offered suggestions for a modified assessment tool (J. Genet & H. Wiegner, MPCA; B. Suppes & C. Anderson, UMN; *personal communications*). The modifications include: substituting certain metrics with metrics used in other channel stability assessments, tailoring metric descriptions to low-gradient conditions observed, changing the number of rating categories, and including metrics that are considered biologically or ecologically meaningful. Many of these suggested modifications have been incorporated into a modified assessment tool, the *Channel Condition and Stability Index* included in Chapter 3. The CCSI should be tested in future studies to validate that the metrics improve the assessment tool for rating channel stability indicators low-gradient alluvial streams as well as are shown to be associated with biological integrity and/or habitat quality.

UPPER BANKS

The UPPER BANK is considered the area that is at and above the bankfull flow (1.4 to 1.7 RI flow). Assessors often found it difficult to identify bankfull height, especially in streams that were incised or grazed. Knowing the relative height of bank-full is crucial, since all the UPPER BANK and LOWER BANK metrics are assessed based on what is determined to be height of bankfull flow. A regional hydraulic geometry curve (RHGC) developed in the region of interest should be consulted to assist in locating the bankfull height while in the field and validating with bankfull indicators (Harrelson et al. 1984, Magner and Brooks 2007).

landform slope: This metric attempts to rate the likelihood of high flows to detach material from the banks above the bank-full flow line. Steeper banks are considered more likely to experience detachment due to the combination of erosion and gravity (Pfankuch 1975). While the PSI metric for *landform slope* may be appropriate for mountain streams with close valley walls (e.g., stream type A and B, Rosgen 1996), it may not be best suited as a method to rate the stability of stream types typical of broad alluvial valleys (e.g., stream type C, Rosgen 1994). MPCA assessors also found this metric difficult to characterize since in incised streams with abandoned terraces, the upper bank zone was not always immediately adjacent to the stream channel, and therefore, depending on the distance from the channel the forces of flow acting on the upper banks would be related to both the distance from the bankfull channel as well as the degree of incision. Another criticism of this metric is that the bank angle of repose was extremely variable along the reach length due to areas where bank failure had already occurred, or due to cattle trampling. An assessment tool used in low-gradient streams, should take into account the degree of floodprone extent as well as the degree of channel incision. Suggested alternatives to *landform slope* are two new candidate metrics: *degree on incision* and *intermediate floodprone width*. Used together, these two metrics should more appropriately characterize the degree of stream connectivity with the floodplain and consequently, the ability of low-gradient alluvial streams to overbank, attenuate nutrients, and deposit sediment to maintain a suitable substrate environment for biological communities.

degree of incision: This is a new metric proposed which would utilize the low bank height ratio (LBR) by Rosgen (2006, pp. 5-47) where the low-bank height (LBH) is compared to the bankfull height (BfH) as a ratio (LBH/BfH). When the ratio is 1.0 the channel is not incised; whereas, when the ratio is <1.0 the channel is incised. When a channel is incised the normal high water flow (~1.5 yr RI) is no longer able to overbank and dissipate flow energy as water spills out onto the floodplain; consequently, when greater flow is contained in the cross-section, more flow energy is available to erode banks and bottom substrates. Excess scouring due to channel incision has been demonstrated to adversely affect biological communities (Rowe et al. 2000). *Intermediate floodprone width* is an intermediate width between bankfull width and floodprone width used in calculating the Entrenchment Ratio (ER, 2x the bankfull max depth) for stream classification (Rosgen 1996). Mecklenburg and Fey (2011) apply the intermediate floodprone width (at 1.5x the bankfull max depth) as a method to assess whether a low-gradient stream (<2%) has an ecologically functioning floodplain. A well-connected floodplain acts as a refuge for aquatic species during high flows and provides ecological functions such as sediment removal, nutrient attenuation through vegetative update and microbial processes (e.g, denitrification), and provides allochthonous material and woody debris habitat when branches and trees enter the stream channel. These benefits are limited when the floodplains are disconnected from their channels. Surprisingly, this lateral component of floodplain connectivity (Ward 1989) is not assessed by many commonly applied stream habitat assessments (e.g., QHEI, Rankin 1989; Rapid Bioassessment Protocol, Barbour et al. 1999; Sorenson et al. 1994) even though this lateral component has been documented to be ecologically important for the life history success of many fish species (see Muhar and Jungwirth 1998, Opperman et al. 2010). What generally is assessed by these habitat assessments is the riparian width and width of the floodplain while the connectedness of the floodplain is not assessed. For stream stability and departure analysis, Rosgen (2006) uses degree of incision coupled with degree of entrenchment to assess the degree of floodplain confinement by the valley walls, presence of abandoned terraces, and degree of downcutting in the current bankfull cross-section. Entrenched and/or incised streams concentrate flood-flows within the confined channel and increase the magnitude of hydraulic forces acting on the channel bottom (Walters et al. 2003), thereby increasing the potential for greater bed mobility which can negatively impact biological communities. Consequently unstable conditions observed in the upper bank can be associated with unstable conditions on the channel bottom, which is a critical habitat zone for aquatic communities. Hence a metric that assesses floodplain connectivity and/or degree of incision is a missing habitat component that should be added to existing habitat assessments or supplemental channel stability assessments should be collected along with habitat assessments.

<u>*intermediate floodprone width*</u> - I suggest incorporating the *intermediate floodprone width ratio* presented by Mecklenburg and Fey (2011) which is a height and width that is halfway between *bankfull flow* and the *entrenchment ratio* (ER). In this study, I found that most streams that were rated with the PSI as being unstable, were not yet considered entrenched, even though flood flows at the 1.5 RI bankfull were being confined and significantly magnifying the flow energy on the bottom of the channel. Therefore, instead of 2 times the bankfull width (which corresponds typically to the 50 RI

flood flow) as suggested by Rosgen (1996) for the *entrenchment ratio,* I suggest applying the *intermediate floodprone width ratio* presented by Mecklenburg and Fey (2011) which is the 1.5 times bankfull flow (approximately the 10 to 25 year RI flood flow). This intermediate floodprone width has been proposed as an indicator of an ecologically functioning stream channel where a stream with a low-inner berm or terrace with vegetation has the ability to dissipate flow energy from high flow events as well as attenuate a portion of the nutrients and sediment load (Mecklenburg and Fey 2011). This metric should also provide w way to distinguish channelized streams that are evolving to include a vegetated low-bank within the trapezoidal cross-section from other channelized streams where evolution is not occurring or where channels are repeatedly dredged. These channelized streams that have over time evolved and developed an inner low-bank have demonstrated that this zone can provide ecological benefits (Mecklenburg and Fey 2011) and habitat quality as some degree of sinuosity associated with alternate berm development creates depth and flow variability—even riffles and pools--as that can support high biological integrity (*personal observation*).

<u>mass wasting or failure</u>: This metric rates evidence of both recent mass wasting/bank failure events as well as the potential for future events. While this metric is intended for large bank slumping events that can block channels and constrict water flow (Pfankuch 1975), smaller events should also be recorded and rated since a number of these smaller events can add up to a considerable amount of excess sediment as bank slough material that enters the stream channel and is either deposited within the reach or is transported and contributing to water quality issues downstream. A modification suggested here for low-gradient streams is to rename the metric to *mass wasting or bank failure* and change the metric descriptions to count quantify and characterize both large and smaller episodes of bank collapse.

<u>vegetative bank protection</u>: This metric seemed to be quite applicable to the different streams settings encountered in this study, since it considers the rooting depth as well as the extent of cover on the upper banks. Even areas dominated by deep rooted grasses can score well. In contrast, assessment tools such as the *Rapid Geomorphic Assessment* (Simon and Downes 1995) rate grasses poorly in comparison to trees and shrubs, since the authors surmise that grasses die during the winter and therefore, do not provide bank protection during this time. Most of the grassy banks in this study were composed of Reed Canary Grass (*Phalaris arundinacea*) which has a very deep, fibrous root system, which in my opinion still provides excellent bank protection--even during winter. A slight modification to this metric is suggested, which is to incorporate a relative rooting depth (rooting depth to bank height) to better characterize the difference between deep to moderately rooted vegetation as well as the degree to which banks are protected along the lower zones of the bank (Rosgen 2006).

debris jam potential (floatable objects): This metric attempts to predict unstable channels due to future contributions of dead fall being carried into streams by over bank flows and consequently causing flow deflection and bank collapse. If the goal of the stream assessment is to test the present condition against a fish or invert IBI, this is not a useful metric. Therefore, this metric is excluded in the modified assessment presented in Chapter 3.

LOWER BANKS

The lower banks are defined as the vertical zone of the banks the high water line (1.5 RI flow) and the low water line (baseflow). During high flows, the velocity of water will act to erode the materials on the channel banks. The ability of the channel banks to resist erosion is related to the composition of the bank materials (substrate size, highly erodable fines, cohesive materials, bank protection from roots), the direction of flow (e.g., parallel to banks or directed into banks by flow deflectors), and the cross-sectional profile of the channel (1.5 RI flows able to access floodplain, or confined in incised channel). The original metrics associated with this zone are described below and suggestions for modifications are included.

channel capacity: This metric intends to assess whether or not the current cross-section is able to contain bankfull flow or if bankfull flow is not contained and expressions of higher volume flows are found as debris in tree limbs above the cross-section. These conditions may indicate that the current capacity of the channel is exceeded by higher volume flows or excess sedimentation aggrading on the channel bottom. The Pfankuch (1975) metric includes channel width-to-depth dimensions in the ratings. For a majority of streams in my study, the channels were in the process of downcutting or had downcut and were in the process of widening. These streams experienced bed-level lowering that now allows more water to be contained in the channel during high flows, lessening the likelihood for overbank flooding. The width-to-depth ratios of these streams are consequently low, and would receive a rating of *excellen*t with the current PSI metric version. While this metric may function appropriately in streams experiencing a high sediment load, as would likely be the case in mountain streams with forest harvest practices, it does not appear applicable for low-gradient streams that are hydrologically unstable where excess stream power is able to scour away bottom substrates thereby lowering the base-level and *increasing* channel capacity. Incising streams in the process of channel evolution where base-level lowering is not confined by bedrock or armoring would fit this example. Similar criticisms of applying the *channel capacity* metric to incising streams have been noted by Johnson et al. (1999) and Suppes (2009). A channel evolution model describes the morphological changes associated with the entire channel cross-section (upper banks, lower bank, and bottom) and not just the lower banks. Therefore, I suggest removing the *channel capacity* metric from the LOWER bank metrics and instead incorporate a *Stage of channel evolution* that is a stand alone metric apart from the metrics associated with the UPPER, LOWER, or BOTTOM zones.

<u>bank rock content</u>*:* This metric is intended to rate the strength of the bank material to resist erosion by scouring flows (Pfankuch 1975). The scoring system rates only the size of rock and the composition of rock sizes comprising the lower bank without any consideration of cohesive fine-grained bank materials that are highly resistant to detachment. This metric also does not take into account deep rooted grasses and root wads from trees that also armour and protect banks from erosion. In REDWOOD, *bank rock content* had a narrow range in scores observed, since most of the banks were composed of sand and silt. However, some banks also had good protection from deep and dense roots of reed canary grass (*P. arundinacea)* which was the predominant species along the banks of both natural and channelized streams. Consequently, for REDWOOD, a majority of reaches (86%) were rated "poor" for *bank rock content* even though some degree of bank protection from roots was present. A modified channel stability assessment should include descriptions of root density as well the cohesive properties of the soil matrix comprising the lower banks. An assessment tool developed by Johnson et al. (1999) to rate channel stability near bridges incorporates a metric named *bank soil texture and coherence* which scores bank material composed of cohesive clay and silty clay as "excellent" and bank material composed of uncohesive sands, gravel mixtures, or presence of lenses as "poor". An additional consideration is whether or not the cohesive nature of the soil particles are variable when dry verses when inundated with high flow or lose matric suction by ground water seeps (Simon and Collison 2001). Therefore, a suggested modification for this metric is to include additional descriptions that incorporate cohesive soil matrices and bank composition elements including roots, as well as descriptions of the cohesive nature under wet and dry soil conditions.

<u>*obstuctions/flow deflectors/sediment traps*</u>: This metric rates to what degree the presence of large rock and logs either change the direction of flow so that the flow is being deflected into banks and contributing to bank failure or are blocking or slowing flow so that particles fall out and cause depositional areas (Pfankuch 1975). Logs can affect habitat in both positive and negative ways. Logs can either obstruct flow along margins and create slack water and deep pools which are considered a positive habitat feature (Pfankuch 1975) or logs can be oriented in such a way that flow forces are directed against exposed banks causing bank collapse and infilling of pools and run features, or logs can block flow to such a degree that the sediment transport capacity is reduced and pools are more apt to fill with sediment thereby reducing depth. A suggested modification to this metric is to divide the

metric into two: *flow deflectors* and *obstructions to flow/sediment traps* where both are rated relative to the negative consequences to habitat. Separating these two metrics helps to better identify what type of habitat condition is being affected and by what manner (flow deflection or reduced channel transport capacity) by a Stressor Identification investigator. Another suggested modification for flow deflectors is the inclusion of lateral riffles and check-boxes noting the type(s) of flow deflectors observed. This also aids in understanding whether watershed or local factors may be acting on the channel (e.g., large scale watershed hydrologic and hydraulic adjustments causing changes in riffle orientation, local storm-related tree fall).

<u>*cutting*</u>: This metric refers to the degree to which flow forces are acting on or contributing to exposed, unprotected surfaces of the lower bank (Pfankuch 1975). In general, as flow increases against the bank, the zone under the protected banks will erode and carve away until the root mass protecting the upper portion of the lower bank falls away. This can result in a straight bank face that is susceptible to additional erosion through cutting and geotechnical failure. Modifications to this metric are suggested, including relative height of bank ratios and descriptions for scouring at the toe of the bank and ground water seeps. The original PSI includes descriptions that refer to the height of cutting in inches. Since these descriptions can indicate different degrees of severity that are dependent on stream size, a modification presented here is to make the description a unitless ratio where the severity of the condition is rated based on the relative height of cutting as compared to the total height of bank that may include areas of bank protection by roots. Souring at the base of the bank under roots that did not necessarily lead to a flat vertical face was also observed. MPCA staff have suggested that this be referred to as scouring and not cutting, therefore, both are included in the name for a modified metric. Ground water seeps contribute to bank collapse by reverse hydrostatic pressure on the lower bank during low flow conditions. These features were prominent in both the SNAKE and REDWOOD watersheds and appeared to be actively undermining the toe of the channel bank during low flow conditions. This condition should be acknowledged as a factor which could theoretically lead or contribute to bank collapse. The new modified metric name is *cutting/scouring/or ground water seepage.*

<u>*deposition*</u>: In the original PSI, this metric is associated with LOWER BANK; this metric rates the degree to which point bars and mid-channel bars are building due to excess deposits of sediment (Pfankuch 1975). The build-up of lateral bars is typically associated with sand and gravel-bed rivers (i.e., Rosgen stream type C, 1996). Most streams in Minnesota are either C or E type streams. E types generally do not have the build-up of depositional bars but may experience instream aggradation on the bottom. It was also confusing in C type streams to try to separate the build-up of

lateral bars in the LOWER BANKS from the aggradation of sediment on the BOTTOM since excess deposition can often be observed as the build-up of mid-channel and lateral bars within the low-flow channel. Therefore, I suggest removing *deposition* from this zone and incorporating it as one of the indicators for a modified metric associated with the BOTTOM: *evidence of deposition/ excess aggradation*.

BOTTOM

All metrics in the zone BOTTOM are indicators associated either with resistance to bed mobility, demonstration of bed mobility or a lack thereof. With these concepts in mind, I reviewed the original PSI metrics to determine whether they were appropriately characterizing conditions observed in streams in this study and where modifications could be considered.

rock angularity: This metric is intended to assess the degree to which forces of scour act on the rock matrix of the channel bottom and tumble metamorphic and igneous rock fragments (Pfankuch 1975) which may result in smoothing and rounding of rock fragments over time. For many streams in this study, there were a number of sites that were devoid of coarse substrates and were dominated by sands or silts, rendering this metric not applicable. In addition, there were sites with occasional cobble and boulders that were well-rounded, but are likely glacial relics that were smoothed by the shifting and grinding under the pressure of glaciers and deposited by glacial meltwater and not by present day present fluvial forces as this metric intends to rate. The application of this metric to other stream types that are alluvial or colluvial in origin has also been questioned by other researchers (e.g., Meyers and Swanson 1992, Johnson et al. 1999, Suppes 2009). It has been suggested that two or more assessment tools be developed and tailored to each unique setting in Minnesota where certain metrics would be used based on the parent material of the region (J. Magner, UMN, *personal communication*). If this was done, than *rock angularity* could still be applicable in areas where the fracturing of parent material supplies the substrate to the stream bottom, such as in areas of basalt near Lake Superior or in the driftless area of south-eastern Minnesota, as well as other areas with sedimentary rock, like sandstone. However, even in regions where the parent material is glacial deposited material such as outwash, till, and loess, variability still remains. Given that this metric would not be applicable to a majority of stream reaches in Minnesota, it might be preferable to exclude this metric for a Minnesota specific channel stability assessment tool, or alternatively, use rock angularity as one of a variety of indicators for degree of scouring, when it is applicable. In the CCSI form included in Chapter 3, *rock angularity* was not included, since this assessment tool has been developed primarily low-gradient streams that were alluvial or colluvial in origin.

brightness: This metric intends to assess the degree to which the bottom substrates have been mobilized during recent high flow events (Pfankuch 1975). Rocks that are stationary over time will likely have algae, diatoms, and moss growing on their surface thereby making their original color appear dull or stained. The term "brightness" is used to describe the exposure of the undersides of rocks that is not stained and generally brighter in appearance. The undersides of these rocks are newly exposed through recent mobilization and tumbling during high flow events. Theoretically, the more rock that appear bright, the greater the degree of scouring or tumbling is inferred to have occurred. As was the situation with *rock angularity*, this metric did not appear applicable to streams that were devoid of coarse substrates. However, there were some streams that had some gravel or small cobbles that were concentrated in small riffles or on the fringes of runs where these materials may have been carried or rolled during bankfull conditions within the spring of the year or during summer high flow conditions. In this case, where there was presence of gravel or smaller cobble, this metric did appear to be functional in characterizing evidence of bedload movement. The PSI guidance manual (Pfankuch 1975) does suggest to "Look first for changes in sands and gravel" (pp. 19). In some streams, a greener chroma could be observed in the sands along on the fringe of the stream channel, which would indicate that this area was not moved by recent high flow events, or warm temperature and high nutrients have allowed for algal blooms by late summer. Most often evidence of scouring would likely occur within the thalweg of these channels, which often were too deep to see the bottom. In other situations, high turbidity precluded visibility of the bottom. In addition, some streams had different sizes of coarse substrates, from gravel to cobble--even occasional boulder--in small to large streams. Consequently, it did not seem appropriate to rate the transport capacity of a large stream in the same context as a small stream. For example, in some larger steams it would seem typical for high flows to mobilize small cobble; whereas, it would not be likely that small, low-gradient streams would generate the transport capacity necessary to mobilize the same size cobbles. This observation was also noted by Johnson et al. (1999). Since the ability to apply this metric was not seemingly applicable or equal to rate for all stream settings, I suggest using it as a secondary indicator for assessing the degree of scouring instead of a primary one. In the CCSI form, I have included rock *brightness* as one of the indicators for consideration for assessing a modified metric called *evidence of degradation/excess scouring*.

consolidation or particle packing: This metric assesses the degree to which rock and fine material are overlapping and imbricated and consequently, resistant to movement. A stable stream bottom would allow for the packing of sands around the interstices of rock and make them less likely for water to pass around the rock and dislodge it from its location; whereas, an unstable stream bottom would demonstrate less compaction and be easily dislodged by flow. The shape of the substrates can be a factor in the ability of the substrates to overlap. Round substrates would be more easily moved and rolled by flow than flat rocks. This metric was for apparent reasons difficult to rate in streams without coarse substrates. A modification suggested by J. Magner (*personal communication)*, is to use a cone penetrometer to assess the degree of compaction of the sand and other substrate materials. The penetrometer designed by J. Magner is made of inexpensive copper tubing with a copper tip soldered on the end. The hollow tubing also provides acoustic interpretation as to the substrate size of the sub-pavement. A layer of fine material over a more coarse layer of substrates may indicate severe embeddedness and a change in either the amount of fines entering the system or a reduction in sediment transport capacity. The CCSI metric includes descriptions of probe depth in the rating.

bottom size distribution and percent stable materials: This metric intends to rate the character of the substrate observed compared to what would be expected as well as the relative percent of the bottom that is composed of substrates that are “stable” or unlikely to move during high flow conditions. Pfankuch (1975) does note that the substrate sizes referenced in the rating descriptions are to be used “only to guide thought” since substrates such as small cobbles could be considered stable in small streams; whereas, the same size class could be highly mobilizeable in larger streams. My experience, as well as the experience by other assessors, found the metric *bottom size distribution* difficult to rate unless you were personally familiar with the streams overtime to be able to notice a shift in substrate size. Most often, assessors are visiting a stream for the first time, and so this knowledge by experience is not possible. The second part of this metric, *Percent stable materials* was also somewhat problematic in streams that were 100% sand and gravel and therefore, often 80 to 100% mobilizeable. Most stream in REDWOOD were rated the same for this metric. A suggestion proposed by J. Magner (*personal communication*) was to offset the high score for sand with a metric that pairs the ability of the stream to transport and mobilize sand, such as *water gradient/sediment transport capacity*. After testing this modification in the Cedar River watershed (Asmus, *unpublished*), it was apparent that the *bottom size distribution and percent stable materials* metric should be removed. Streams that were largely sand dominated and relatively stable were being consistently rated as moderately stable. While this rating may be appropriate for stream sensitivity analysis, it may not be appropriate for understanding the current condition of stream stability. Therefore, this metric water omitted in the CCSI.

scouring and deposition: The PSI guidance manual (Pfankuch 1975) suggests that when rating this metric, the assessor should take into account other stability indicators associated with other BOTTOM metrics (e.g., *rock angularity, brightness, consolidation/particle packing*). The rating descriptions for *scouring and deposition* include degree and location of cutting coupled with depth and extent of pool deposition. Both scour and deposition may be occurring within the same reach, but for channels that are dominated by one process or the other, as could be either channels in the process of incision and degradation or widening and aggradation, the PSI rating would be the same, regardless of which process was dominating. Meyers and Swanson (1992) also suggest that these processes be separated, since in their experience, "A stream rarely scours and deposits in the same short reach." Hence, a suggested modification is to separate these two indicators and make them individual metrics (e.g, *evidence of degradation/excess scouring* and *evidence of deposition/ excess aggradation).* Information collected in this manner would help to infer which process is out of balance with channel equilibrium for a given stream type and location in the watershed (e.g., zone of scouring, transfer, deposition). For biological studies, separating these two processes would allow for exploring the association with each channel process independently with a response in biological community attributes and IBI scores.

<u>*clinging aquatic vegetation*</u>: This metric was useful for assessing the degree to which plants may have been uprooted and scoured away during bankfull flow events, but only appeared to be applicable in streams that had good water clarity, as was the case mostly in SNAKE. In contrast, in REDWOOD, there were a fair number of streams that were turbid at the time of sampling and have relatively poor water clarity consistently during the summer. These conditions, if sustained for long periods of time, can be light limiting and suppress the growth of certain plants. Therefore, this metric may not be a good indicator for streams experiencing chronic high sediment loads. My recommendation is to remove *clinging aquatic vegetation* from being a primary indicator, but allow it to be considered as a secondary indicator for rating degree of scour in the newly proposed metric *evidence of degradation/excess souring.*

<u>*stage of channel evolution*</u>: This metric is not included in the original PSI but is being proposed here for a modified assessment. CEM was correlated with many PSI metrics indicating that to some degree, the stage of channel evolution was associated with the conditions of instability observed, as would be expected. However, the PSI metrics in their current form, do not provide indication of a systemic mechanism that is causing or contributing to channel instability. Conversely, CEM as a stand alone metric does not provide an indication of whether or not stream is downcutting only a small degree or in the process of rapidly downcuttring. As an example, a stream with cobble and boulder substrates may be slightly disconnected from the floodplain due to a slight degree of downcutting and as a consequence of armoring by cobble and boulder is not able to further downcut and so has transitioned to a slow process of widening in part of the reach. During this slow

transformation of the channel, the habitat may remain of high quality. This stream would have a CEM stage of II/III. Likewise, a sand-bed stream with a localized knickpoint may be rapidly downcutting and overwidening as it laterally adjusts and consequently, habitat quality could be greatly compromised. This situation would also be rated a CEM II/III. Therefore, I recommend that a CEM be included as a metric in a channel stability assessment tool tailored to alluvial streams in Minnesota, but where the rating system for the metric also incorporates the degree of severity of conditions observed associated with processes of downcutting and/or widening.

Modifications to number of rating categories descriptions, and metric scoring

Suppes (2009) suggested changing the number of rating categories from four to five in order to create a "median" category. This would allow the assessor to more comfortably categorize indicators that are in the middle of the continuum of stability to not have to be forced to rate the indicator as leaning toward stable (good) or unstable (fair) but instead something inbetween (B. Suppes, UMN, *personal communication*). Pfankuch (1975) suggests that an assessor should consider using inbetween scores by crossing off the original score and writing in the new score that better represents the condition. Perhaps Suppes (2009) may have overlooked this mention in the manual (see Pfankuch 1975, pp. 9). A similar criticism was presented by Meyers and Swanson (1992). However, in this case the authors were aware of the rating modification proposed by Pfankuch (1975) but reported that it was rarely used by the assessors and suggested that "observers should be encouraged to rate streams more flexibly by scoring between the values on the form." A remedy for this may be for project managers to make special note of this rating modification during training with their field crews who will be implementing the assessment.

I agree with Suppes (2009) suggestion of providing a "moderate" instability category and changing the rating system to five categories for each indicator. This will allow for more detailed and definitive descriptions on the worksheet to aid assessors in more accurately and uniformly rating the severity of conditions observed. A five category rating scheme is also comparable to the rating scheme used for the IBI where communities are rated as *excellent, good, fair, poor*, and *very poor.* The threshold for the IBI is generally set somewhere within the center category of "fair." A PSI rating scheme that is comparable to the IBI would also present less confusion during communication with water quality managers that are already familiar with IBI rating categories.

In addition, in my opinion the scoring weight assigned to each individual metric should also be tailored to the intention of the assessment tool (e.g., for understanding a stream's sediment competence as compared to a reference stream, degree of substrate mobility that may negatively impact biological communities). Pfankuch (1975) designed his rating scheme to give more weight to certain indicators based on his experience assessing channel response to timber harvesting activities. Since stream types have inherently and intrinsically different sensitivities to disturbance (see Table 8-1 in Rosgen 1996 or Table 2-4 in Rosgen 2006), the rating scheme for individual metrics should be tested and tailored to different stream settings, such as the low-gradient alluvial stream settings tested herein. While Rosgen does suggest adjusting the final PSI score to account for inherent differences in channel stability by stream type (Rosgen 1996, pp. 6-16), it may be more instructional for an assessment tool to have score weightings designed for each individual metric in different stream settings and stream types (e.g., is the severity of *cutting* a stronger indicator of scouring than substrate mobility in sand dominated streams?). Some metrics on the original PSI may be more appropriate for B stream types (e.g, *channel capacity*) and so modifications to individual metrics may be required so that deviations in individual metrics scores can be observed more readily.

<u>*substrate composition*</u>: The PSI, in its original form, does include characterizing the substrate using the Wolman (1954) pebble count method. For this study, substrate was characterized by applying both a pebble count for coarse substrates and through sieve analysis (Lambe 1951) where fine substrates dominated since this level of detail was important for calculating hydraulic properties for a different study. This level of detail and effort may not be necessary for characterizing substrate composition available for habitat for fish and macroinvertebrates; however, characterizing the relative composition of substrate sizes either through visual observation or via a pebble count procedure is recommended. *D50* was strongly associated with FIBI in this study and others (D'Ambrosio at al. 2009) and has also been associated with macroinvertebrate IBIs in other studies (Lammert and Allan 1999). Additionally, *D50* is useful for comparing the substrate composition from different years in order to determine if the stream's sediment competence is out of balance or is in equilibrium (Rosgen 1996). Kaufmann and Robison (1998) classify gravel using two different size classes: fine gravel (2 to 16 mm) and coarse gravel (16 to 64 mm).

If field time allows, I suggest to at least record the percent of different substrate types observed in an assessment of channel stability and habitat quality and to include additional size classes following Kaufmann and Robison (1998). The Ohio EPA (2009) prefers that assessors use a visual estimation of all substrate types that "provide usable habitat" (i.e., of sufficient quantity and density to be utilized by aquatic organisms) over conducting a pebble count since "pebble count analyses often miss one or more substrate types that are visually observed and which are available to aquatic organisms" and that "it has been observed that pebble count analyses tend to under-estimate the percent composition of large substrates.” However, for new assessors it may be instructional to initially conduct a few pebble counts to develop an eye for estimating substrate types available to aquatic organisms (Ohio EPA 2006).

Associations among indicators of channel stability, habitat quality, and biological integrity

To investigate whether a subjective channel stability assessment tool could be useful for causal analysis of biological impairments, an ecological response to a gradient in channel stability must be first tested and realized. My hypotheses were that channel stability would be correlated with biological integrity and that a channel stability would be correlated with habitat quality. However, the full range in indicators was not observed in this study so for some metrics, a response may not have been found. These results should be considered exploratory and tested with a larger dataset that attempts to increase the gradient in the explanatory variables and the response variable. Within this study, I applied correlation analyses to investigated the strength of the association between channel stability variables in order to identify which channel zones and individual metrics were most strongly directing the gradient in channel stability indicators observed as well as the level of correlation between indicators. Secondly, I employed correlation and regression analyses to explore the association between indicators of channel stability and biological integrity using the combined dataset from both watersheds and then testing watersheds individually. This was done in order to identify potential similarities and differences between watersheds that contrasted in geology and land use. Next, I explored which habitat quality metrics were highly correlated and the association with biological integrity in order to compare results with channel stability. Finally, I tested the degree of association between channel stability indicators and habitat quality to explore whether these two assessments of stream condition are interrelated and could be useful for establishing causal links between channel stability, habitat quality, and biological integrity.

Associations among PSI variables

A large number of PSI zones and metrics were significantly correlated with PSI for COMBINED as well within each individual watershed, indicating that all three zones had some variability in conditions observed and that each assessment zone contributed to the range in PSI scores. However, reaches in this study captured only 61% of the possible range in PSI scores for COMBINED, while for REDWOOD and SNAKE only 51% of the potential range in PSI scores (Table A-10) was captured in this study. What is missing in the range observed for both watersheds were reaches that were rated at the extreme ends of the channel stability gradient (PSI scores between

38 to 57, and between 128 to 152). Additionally, for SNAKE, most reaches were rated as "good" to "fair", while only one reach was rated as "poor" (S11); whereas, reaches in REDWOOD had scores that were more evenly distributed across the range in scores observed. Consequently, this lack of range may have limited the ability of the current dataset to detect important associations between channel stability, biological integrity, and habitat quality.

Metrics within one PSI zone were also strongly correlated with metrics in a different PSI zones indicating that there was an association between indicators of channel instability in different regions of the stream cross-section. For example, *mass wasting* from UPPER and *brightness* from BOTTOM were strongly correlated with each other, indicating that the degree of bank instability was positively associated the the degree of substrate mobility. This association is logical in the context of channel evolution, where a channel that is in the process of downcutting will have steeper banks that will likely result in *mass wasting*, while the lower base level results in the deeper profile that contains larger flow events, thereby increasing sediment transport capacity and the percentage of the bottom substrates that are mobilized, which would be indicated by the degree of *brightness*. Consequently, reaches that are undergoing incision or are at different stages of channel evolution will more likely demonstrate a concordant degree of instability in the UPPER, LOWER, and BOTTOM zones.

Some metrics associated with the BOTTOM zone were highly correlated and considered redundant in REDWOOD; whereas the same metrics were highly correlated but not redundant in SNAKE. This difference in the degree of association for BOTTOM metrics within watersheds may in part due to the difference in substrate characteristics found in SNAKE and REDWOOD. For REDWOOD, most streams had a majority of fine-grained sediments (e g., sand, gravel) which are highly mobilizable (Figure 7 in Reice 1994). Consequently, since sands tend to be scoured away and redeposited annually with high flows, most streams that were sand dominated would rate similarly for *bottom size distribution/percent stable materials, consolidation/particle packing* and *scouring and deposition*). In contrast, reaches in SNAKE had more variable substrate conditions, where a higher number of reaches had some percentage of cobble and boulder substrates mixed with sand and gravel. Hence, depending on substrate characteristics and flow-regime, the percentage of stable, well packed particles and degree of scouring could inherently be more variable between reaches in SNAKE than REDWOOD.

<u>Associations among CEM and PSI variables</u>

A modified channel evolution model (CEM, modified from Schumm et al. 1984 and Thorne et al. 1997) was included to explore whether categorizing a reach by its CEM stage could provide insight into the mechanisms of channel stability in play locally as well as watershed-wide to aid in identifying the cause or mechanisms of channel instability during Stressor Identification or for sediment related TMDLs. CEM describes a conceptual time and space sequence of changes in the geomorphic cross-sections of streams during a period of channel instability. Knowledge of whether or not a stream is in the process of channel adjustment, especially which stage of channel evolution, could provide the reason for good or poor channel stability ratings using the PSI.

CEM was strongly associated with the degree of channel stability observed as measured with the PSI for SNAKE, but not for REDWOOD. The scatterplot of CEM with PSI for REDWOOD (Figure 2-3) indicates that most reaches were in the process of downcutting and/or widening (CEM II to CEM III) and that there was more variability in PSI scores associated with each CEM stage; whereas, for SNAKE, the PSI scores were more variable for CEM stages II and III (CEM 2.5) as for stable CEM stages. The lack of a strong association between CEM and PSI for REDWOOD may be due to a few reasons: 1) the range in CEM and PSI was not sufficient to detect a significant association, 2) channel instability at some sites was associated with other mechanisms of instability and not channel evolution processes (e.g., woody debris deflectors, cattle grazing, mechanical channelization, or 3) CEM stage by itself doe not consider the severity of conditions observed that are related to channel adjustment. A method that incorporates the degree of downcutting and widening could be added to the CEM stage so that this difference in severity is recorded as well.

For all watershed groupings, CEM was strongly associated with metrics comprising the BOTTOM zone. These results are not surprising, given that CEM describes processes that can dramatically affect the degree of substrate stability (e.g., degree of scouring, deposition, compaction). However, it is surprising that for REDWOOD UPPER metrics such as *mass wasting/bank failure* and *vegetative bank protection* were not as strongly correlated with CEM as they were for SNAKE. This may be due in part to mechanisms of instability that are not related to channel adjustment. In REDWOOD, some reaches were experiencing a moderate degree of bank failure due to downed trees, scouring near the bank from from flow coming out of draintiles, cattle trampling, where land was plowed close to the top of bank (<3m) and planted in shallow rooted annual row-crops (e.g., corn, soybean). Consequently, the degree of *mass wasting/bank failure* in REDWOOD may have been related to mechanisms other than CEM. In contrast, the adjacent land use in SNAKE was mostly woodland or meadow where banks were well vegetated and protected by deep roots. Consequently, bank failure observed in SNAKE would more likely be related to CEM. As for *vegetative bank protection,* the range in scores in REDWOOD was narrow since most banks were composed of grasses (Table A-10); and hence similarly rated lending to a lack of range. LOWER was also not strongly correlated with CEM in REDWOOD; whereas LOWER was strongly correlated with CEM for SNAKE. However, the individual LOWER metric *cutting* was strongly correlated with CEM in

REDWOOD (*r* = -0.78), indicating that the combined set of scores for LOWER masked this association.

One of the most notable results was that CEM was negatively correlated with all PSI metrics except *channel capacity*, which *w*as positively correlated. The *channel capacity* metric intends to rate the capacity of the channel cross-section to contain bankfull flow and the frequency at which flows are likely to exceed the volume that can be contained by the cross-section (Pfankuch 1975). In mountain streams where timber harvesting is occurring, there may be a greater potential for these streams to receive overland runoff from the watershed and consequently experience instream aggradation. Excess aggradation could reduce *channel capacity* and thereby increase the number of out of bank flow events. However, in alluvial streams where a change in the hydrologic regime or stream gradient is more likely to occur due to changes in land use, bridgework, and channel modification, a channel will likely respond by down-cutting where the incised channel cross-section will result in an *increase* in channel capacity and a lower width-to-depth ratio. In this study, most of my streams in REDWOOD and many in SNAKE were in the process of downcutting and/or widening; as a result, the frequency of out-of-bank flows would be less likely. Consequently, these incised reaches were rated rated "excellent" or "good" for *channel capacity* but in fact should be rated "fair" to "poor" as a condition that represents channel instability. This observation has also been documented in other studies (Johnson et al. 1999, Suppes 2009).

Associations between biological integrity and channel stability

My results demonstrate that there were many channel stability metrics that were strongly associated with biological integrity (Table 2-18); however, results varied by watershed grouping. FIBI was highly correlated with PSI and CEM for COMBINED and SNAKE; whereas, for REDWOOD, FIBI was not highly correlated with either PSI or CEM.

Within each watershed model, metrics associated with substrate mobility were retained demonstrating that indicators of substrate stability were important predictors of stream health across watersheds and substrate conditions. Across watershed comparisons, BOTTOM was strongly correlated with FIBI, although the strength and form of the association varied by watershed grouping. For SNAKE, the association was strongly linear, whereas, for REDWOOD the association appeared to be curvilinear. REDWOOD is a highly disturbed watershed, so it is feasible that the potential curvilinear patterns are a spurious response to site specific conditions related to high nutrient loads and other impacts related to agricultural land use. However, another theoretical explanation for the arch shaped pattern observed is the Intermediate Disturbance Hypothesis (IDH, Odum 1963, Grime 1973, Horn 1975, Connell 1978). IDH theorizes that species diversity is at its maxima when there is an intermediate level of disturbance in severity and occurrence. This intermediate level of disturbance creates and maintains the greatest diversity in habitat while also keeps the pressure of competitive exclusion in balance. Together, these conditions allow and support the co-existence of the greatest number of species. BOTTOM is comprised of metrics that assess the degree of bed mobility or lack thereof. Bed mobility is a function of particle size and bankfull tractive force, which are greatly influenced by channel slope, degree of entrenchment (Walters et al. 2003), and degree of channel incision (Rowe et al. 2009). Bed mobility has been demonstrated to be associated with fish community composition and FIBI in other studies. Walters et al. (2003) tested the association between geomorphic and hydraulic variables and fish community composition in high and low-gradient streams in Georgia. The authors found that bed mobility and tractive force associated with flood flows were key predictors of fish community composition. Rowe et al. (2009) reported that for wadeable streams in Iowa, streams with higher FIBI scores were associated with greater substrate stability. Differences in fish community composition along the continua of disturbance could be captured within FIBI metrics, and hence, could translate into differences in FIBI observed in this study. What is not understood, is where along the continua of disturbance is being represented within each of these watersheds. For example, if reaches in SNAKE are already experiencing an intermediate level of disturbance annually, a greater degree of disturbance would translate into lower FIBI scores. Hence a linear association would be observed. In contrast, for REDWOOD, if some reaches experienced less bed mobility than expected (e.g., overwidened streams with lower sediment transport capacity), these reaches would also score lower for degree of substrate compaction due to minimal annual scouring (lower BOTTOM scores). This could be a reason for lower FIBI scores on the left side of the scatterplot; whereas, for reaches exhibiting an intermediate degree of annual bed movement and scouring (intermediate BOTTOM scores), FIBI scores would be the highest, and finally, in reaches where the degree of scouring became excessive (higher BOTTOM scores), the FIBI scores could again be lower, due to excessive souring of bottom substrates being a stress to the fish community. This potential pattern should be tested with a larger data set to confer that this is a valid response in this region.

The shape of the associations between FIBI and individual channel stability metrics were also variable by watershed grouping. For COMBINED, regression indicated significant linear associations between PSI metrics and FIBI; however, the shape of the response could also often be described as wedge-shaped for many (e.g., Figures 2-8a, C-11a, C-20a, C-21a). For SNAKE, the pattern in the response could often be best described as linear to slightly curvilinear (e.g., Figures C-19c, C-11c, C-18c, C-21c); whereas, the shape of the response for REDWOOD could be best described as being potentially arch shaped (e.g., Figures 2-8b, C-18b, C-20b) or not clearly defined (Figures C-15b, C-

19b, C-21b).

Other research has indicated that it is quite common for ecological studies to demonstrate hederostadastic or non-linear associations between biotic response variables to a gradient in environmental conditions. Often these associations demonstrate a dose-response curve or wedge-shaped response (e.g., Figure 2 in Wang et al. 1998, Figure 8 in Karr and Chu 2000, Figure 8 in Cormier et al. 2008). Ecological dose-response patterns that are curvilinear can represent situations where an initially unimpacted biological variable is not negatively affected by the initial change in the environmental variable, but when a certain threshold is breached, the response in the biological community becomes more pronounced (Fahrig 2001). For SNAKE, some scatterplots indicate a potential threshold where the FIBI score begins to drop off precipitously near an intermediate PSI metric score (e.g., Figures C-9c, C-21c). Therefore, it is possible that the curvilinear responses observed for SNAKE indicate an inflection point at which conditions of channel stability are severe enough to elicit a negative response in the biological community. Change-point analysis could be employed to identify these potential thresholds in future studies.

Ecological dose-response patterns that are wedge-shaped may indicate a myriad of environmental conditions that are present to various degrees within the watersheds and proximity to the stream channel at the low end of the disturbance gradient. At some point along the gradient of exposure, the variable of interest that was measured can become the dominant stressor or limiting variable (Cade and Noon 2003). For wedge-shaped responses, other statistical analyses such as quantile regression regression may be more appropriate (Terrell et al. 1996, Cade et al. 1999). The wedge shaped associations for COMBINED could indicate the influence of unmeasured stressors which are present and negatively impacting FIBI scores to various degrees (Karr and Chu 2000, Cade and Noon 2003) along with the target variables measured and being tested (e.g., channel stability). Or, another reason for the wedge-shaped response for COMBINED, could be that since the underlying shape of the associations between the two watersheds was different (e.g., polynomial and linear) resulting in what resembles a wedge-shaped response when the watersheds were combined.

For some metrics, the direction in the response differed by watershed. For example, *obstructions/flow deflectors/sediment traps* was positively correlated with FIBI for REDWOOD; whereas, it was negatively correlated for SNAKE. This difference in part could be due to the range in values observed as well as a few outliers that are influencing the degree of correlation. The scatterplots (Figures C-14 b, c) demonstrate that for SNAKE, two values are directing the negative correlation; whereas, in REDWOOD, one value is largely directing the positive correlation. However, theoretically, it is feasible that flow deflection by woody debris could have positive or negative consequences to habitat quality depending on local or regional factors. For example, in streams where riffles and large substrates are not as common, flow deflection by woody debris and other instream structures such as boulders can enhance habitat quality. Some streams in REDWOOD were dominated by fine substrate. At these reaches, the presence of woody debris provided localized areas of flow deflection and scour. Localized scour associated with woody debris can increase pool depth and provide variability in flow velocity (Abbe and Montgomery 1996). These conditions provide suitable habitat for certain habitat specialists thereby affording greater opportunity for a more diverse fish community (Schwartz et al. 2011), as well as for larger fish and older age classes (Gorman and Karr 1978, Schlosser 1987, Shields et al. 1998). In addition to enhancing pool depth and volume (Mutz 2000), instream structures such as large woody debris and boulders can act as sediment traps and create shallow habitat with slower velocities on the wake of the structure (Buffington and Montgomery 1999), thus creating localized zones of variable velocities and substrate size classes (Yarnell et al. 2006). Hence the presence of instream woody debris can increase geomophic complexity thereby increasing habitat diversity (Yarnell et al. 2006). Woody debris and faster velocity also provides suitable habitat for invertebrate colonization, thereby enhancing food diversity for invertivores. Together, the presence of woody debris coupled with some degree of flow deflection may support a more diverse fish community which may translate into higher IBI scores for certain streams in REDWOOD as compared to similar streams without woody debris enhanced flow deflection. For SNAKE, the negative association observed at a few sites, while not statistically significant, could be hypothetically related to the fact that most streams in SNAKE had presence of other suitable structures such as large cobble that provide riffle habitat and variable flow velocity that supports colonization by benthic invertebrates and riffle-inhabitants. Under these conditions, flow deflection by woody debris may not necessarily enhance existing habitat, or the presence of armored cobble under woody debris could impede further pool depth via scouring. For some streams in SNAKE where flow deflection was observed, the woody debris was oriented in such a manner than excess scouring and bank erosion were likely occurring at the beginning of the year with spring snow-melt, but when flows receded, sediment had settled out and reduced pool volume. This condition would reduce habitat quality that could limit the presence of certain fish species, resulting in a lower FIBI score (e.g., S11).

The only metric that was not significantly correlated with FIBI for any watershed grouping was *rock angularity*. This is due to the lack of rock at many sites as well as the inappropriate application of this metric to glacially derived material. *Rock angularity* is appropriate for streams where fractured clasts of sandstone or bedrock is rolled and tumbled by flow so that the roundness of the rock can be used to infer the degree of substrate mobility. However, for streams composed of glacial material observed in this study, where rocky substrates occurred, these rocks were often round from the grinding action under the weight and movement of glacial ice over 8,000 years ago. Consequently, round glacial rocks are not reflective of current stream hydraulics. Hence, this metric was removed from the modified assessment presented in Chapter 3.

Associations among MSHA variables

Some of the differences in variables that were significantly associated with MSHA between watershed groupings can be partly attributed to a lack of overall range in MSHA observed in this study compounded with a lack of range in individual metric scores within each watershed (Table A-11). For example, the range in MSHA scores observed across watersheds was only 51% of the total possible range; for REDWOOD, the range observed was only 41% while for SNAKE the range observed was only 31%. Therefore, it is somewhat surprising that strong associations were observed even for variables with very narrow ranges in scores observed.

For both REDWOOD and SNAKE, greater *channel stability* was associated with less *bank erosion* and *embeddedness.* This is not surprising, given that the metric rates the degree of bank and bottom instability together in the rating. *Channel stability* was negatively correlated with *sinuosity* in SNAKE. A high degree of sinuosity, while typically associated with favorable habitat conditions, may also be related to a change in pattern (Rosgen 2006) as a response to exacerbated flow conditions or where the outside bends are eroding as flow is directed into banks by downed trees or point bar deflection which are unstable stream conditions. These conditions co-occurred at certain reaches with higher sinuosity.

Associations among habitat quality variables and biological integrity

Habitat quality was strongly associated with better biological condition (i.e., biological integrity) in both watersheds; although habitat quality was more strongly associated with FIBI in REDWOOD than SNAKE. MSHA is largely based on metrics used in the QHEI (Rankin 1989). The high correlations observed between FIBI and QHEI have been well documented in other studies (e.g., Rankin 1989, Dyer et al. 2000, Lau et al. 2006). Surprisingly, MSHA was not strongly correlated with FIBI for SNAKE. The scatterplot (Figure 2-9c) indicates that for SNAKE, the general association appears to be linear, but that two points are outside the confidence interval which may be deflating the level of association for Spearman correlation. These two reaches had high FIBI scores with only moderate MSHA scores. Most notably, both of these reaches scored poorly for *depth variability* and *channel morphology.* At time of sampling, these two reaches were comparatively deep with slow velocities throughout the reach which may be the result of an instream shallow rock dam or beaver dam downstream. The dams did not appear to be barriers to fish migration during high flow; however, the dams still could be acting as barriers to fish migration during low flow which consequently could influence FIBI scores at these two reaches.

MSHA metric zones associated with riparian quality and substrate quality were the most strongly correlated with FIBI across watershed groupings. The INSTREAM zone has also been found to be significantly correlated with FIBI in other studies (e.g., Lau et al. 2006). INSTREAM is comprised of the metrics describing substrate type and quality. Coarser substrates (e.g., boulder, cobble, gravel) receive higher scores than fine substrates (e.g., sand, silt, clay) and the degree of embeddedness is also rated. For REDWOOD, RIPARIAN zone and *riparian width* were significantly correlated with FIBI. Water quality managers suggest or require a minimally disturbed zone of perennial vegetation next to all streams and ditches in order to trap overland runoff from entering waterbodies. Riparian buffers trap sediment (Cooper et al. 1987), attenuate nutrients (Groffman et al. 1992), shade streams, introduce allochthanus material (Hynes 1963), assist the infiltration rate of surface water into shallow groundwater, protect banks from erosion, and provide a vegetative buffer that protects aquatic organisms from pesticides and herbicides being sprayed on lands near streams (see Naiman and Decamps 1997).

Riparian width was a significant variable for COMBINED, but not for either watershed alone. One reason for this statistical difference is that the range in scores for *riparian width* was wide across watersheds, but narrow within watersheds (Table A-11). For REDWOOD, a majority of sites had narrow riparian as most streams were bound by row-crop agriculture; whereas in SNAKE, the width of the riparian was generally wide, since a majority of streams ran through woodlands. Therefore, for REDWOOD, it is possible that the lack of wide riparian width may be one of the factors that is biologically limiting in this watershed, as indicated by the low overall FIBI scores, even though a statistical association was not identified here in this study. Wichert and Rapport (1998) suggest that if riparian zone vegetation is re-established, biological condition would also improve. Riparian zones help prevent overland sediments, nutrients, and pesticides from entering streams. Nutrients are a major concern within many watersheds of the MNRB where nitrate concentrations were found to be higher than the drinking water standard (http://mrbdc.mnsu.edu/mnbasin/wq/nitrates). Perhaps if sufficient buffers were re-established—at least to, if not more than the riparian width required by Minnesota Statutes (Sect.103E.021)--some degree of nutrient attenuation could be achieved. However, benefits may not be as great in channelized reaches that are repeatedly dredged thereby preventing the establishment of a low-flow channel with a vegetated floodplain that can attenuate nutrients and sediments. Landowners need to be informed of the nutrient reduction opportunities, ecological benefits—and substantial reduced cost in ditch maintenance—that can be gained when channelized ditches are left alone and allowed to partially recover over time. The federal attention and pressure to reduce nutrient loading to the gulf of Mexico may provide the attention that is required to make this a beneficial alternative to costly ditch maintenance activities. In tandem should also be enforcement of riparian buffer widths as required by states and counties. These are cost-effective solutions to begin addressing the issue of nutrient loading to the Gulf of Mexico while also addressing local water quality issues caused to downstream receiving waterbodies within the state.

Better biological condition was also strongly related to substrate size and condition (e.g., degree of embeddedness of coarse substrates). Across watershed groupings, greater degree of embeddedness was related to reduced biological integrity (Table 2-24). This result demonstrates that *embeddedness* may negatively impact FIBI scores across regions that inherently differ in geology and degree of disturbed land use in the subwatershed. Embeddedness of coarse substrates has been shown to severely impact habitat quality and biota (Rabeni and Smale 1995, Waters 1977). Rabeni and Smale (1995) demonstrated that lower FIBI scores were correlated with a reduction in habitat quality caused by embeddedness of riffle habitat. Conditions leading to embeddedness can interfere with life history requirements of certain fish species by decreasing availability of suitable substrates required for reproduction (e.g., lithophilous spawners, nest builders) and feeding (Waters 1977).

The MSHA zone COVER was strongly related to biological integrity in SNAKE,but not in REDWOOD. The scatterplot for SNAKE indicates that many reaches scored well for this metric and that the range in scores was fairly wide; whereas for REDWOOD, the range in scores observed was narrow (Figure 2-13). This zone is comprised of two metrics that score both the presence of different cover types (e.g., woody debris, deep pools, overhanging vegetation, instream vegetation, root wads, undercut banks, boulders) as well as relative proportion of the stream providing suitable cover habitat for fish. The scatterplots for *cover type* and *cover amount* (Figures C-29, C-30) indicate that for REDWOOD, while the diversity in cover types present was high, the relative proportion of stream area with good cover was low. For SNAKE, the diversity is cover types was high while the relative proportion of stream cover was also high. For SNAKE, COVER explained 54% of the variability in FIBI and the MSHA metric *cover types* alone explained over 91% of the variability in FIBI. For streams in Ohio, D'Ambiosio et al. (2008) also reported the highest correlation between FIBI and cover quality as compared to other QHEI metrics. For SNAKE, the most common cover types encountered were overhanging vegetation, deep pools and boulder. For REDWOOD, the most common cover types encountered were deep pools, woody debris and overhanging vegetation; in contrast to SNAKE, boulder was not a common cover type for REDWOOD. The greatest difference between watersheds was the amount of cover. My results suggest that the combination of cover diversity as well as the overall spatial extent of good cover is important for maintaining biological integrity. Therefore, an understanding of what can cause a loss in habitat diversity, quality, and quantity is important for identifying the cause of a loss of species and biological impairment. Interestingly, *cover type* was positively associated with *channel stability* for SNAKE; but not for REDWOOD. FIBI scores in REDWOOD were more variable across cover types and cover amount than SNAKE. This may in part be due to the amount of instream vegetation observed in some reaches in REDWOOD which may indicate an excess nutrient issue that may magnify the diel oxygen or ammonia nitrogen concentrations at other times of the day or year which could be an unmeasured stress in this study. The one stream that scored poorest for cover was choked with vegetation. In this case, the score given was -1 due to the extreme density of aquatic macrophytes that may impede or slow fish passage. However, other streams that were 50% to 75% full of dense vegetation received a high score, even though the dense macrophytes may not be as good of a cover type as deep pools or woody debris.

The MSHA metric *channel stability* was a strong predictor of biological integrity across watershed groupings (Table 2-24) and one of the strongest predictors retained in regression models for COMBINED and REDWOOD. These results support the hypothesis that better biological condition would be associated with more stable stream channels. For wadeable streams in Iowa, Rowe et al. (2009) reported positive associations between higher FIBI scores and mean residual pool depth, substrate stability, percent of coarse substrate, and a negative association with height of channel incision. These are all indicators associated with stable stream channels. For REDWOOD, *channel stability* was also strongly correlated with degree of *embeddedness.* Degree of *embeddedness* could be related to an increase in sediment supply or loss of sediment transport capacity. Both of these scenarios can lead to aggradation (i.e. excess embeddedness) when the ability of the available stream power to move the annual load of sediment is surpassed. Therefore it was not surprising that *embeddedness* and *channel instability* (i.e., aggradation) were correlated.

Two MSHA metrics were highly correlated with FIBI but the direction of the response was opposite of what would be expected. In REDWOOD, *pool/width-to-riffle width* was negatively and weakly correlated with FIBI. In SNAKE, *sinuosity* was negatively and moderately correlated in FIBI. The scatterplot of FIBI and *sinuosity* for SNAKE (Figure C-34) indicates a curvilinear response, which, *w*hen the association was described using polynomial regression the association became highly significant ($R^2 = 0.80$, $p = 0.0003$). Except for the slight upward curve at the beginning of the plot where two channelized reaches had a *sinuosity* score of "0", most of the remaining sites fall within a relatively straight line as the *sinuosity* score increases and then noticeably drops off toward the two sites that scored highest for *sinuosity*. This could be a spurious result or could be explained by the observed channel evolution occurring at these two sites (S1 and S11). S1 was in the process of downcutting and widening (CEM II/III) and S11 was in the process of widening and returning to equilibrium (CEM IIII/IV). These two streams also received the two highest PSI scores in SNAKE (91.5 and 117, respectively). In REDWOOD, the scatterplot (Figure C-34) indicates that there was greater variability in FIBI scores with increased sinuosity. In this case, it is possible that some streams had better habitat quality due to stable meander bends with associated depth variability; whereas, for other streams greater sinuosity was related to poorer habitat conditions such as bank erosion and embeddedness related to unstable stream channels. Streams that are in the process of channel evolution are likely adjusting to an imbalance in the watershed (e.g., sediment supply or hydrology). When a stream loses equilibrium due to an increase in discharge or gradient, the channel will morphologically adjust through an increase in the meander wavelength (i.e., sinuosity). Likewise, when a stream has aggraded and a new thalweg is being developed, a period of instability along the outside bends caused by flow deflection from point bar and/or center bar buildup will cause additional bank erosion and a consequent increase in sinuosity. Therefore, in the context of channel evolution, the negative correlation between FIBI and *sinuosity* observed in this study may be associated with channel instability, which in the examples described above, would be associated with less than optimum habitat conditions as would typically be expected for highly sinuous reaches.

<u>Exploring the association between channel stability and habitat quality</u>

I explored the level of association between channel stability indicators and habitat quality variables in order to identify highly correlated pairs that may either describe the same stream features from different perspectives (e.g., biologists view of woody debris as cover and co-factor with deep pools or fluvial geomorphologists view of woody debris as flow-deflector and associated with localized scour) or where channel stability indicators were associated with a gradient in habitat quality that could support the link between channel stability and habitat quality for stressor identification of biological impairments.

In this study, the strength of the association between PSI and MSHA was weak. For COMBINED, the scatterplot of PSI and MSHA (Figure 2-15a) suggests a potential wedge-shaped association. For REDWOOD, the scatterplot indicates that there was no visible direction of correlation between PSI and MSHA; whereas, for SNAKE, correlation results were weak and mixed. Upon closer examination of the scatterplots, it appeared that the channelized reaches may be masking a potentially stronger associations between PSI and MSHA. For REDWOOD, if the channelized reaches were excluded, a curvilinear relationship would be more pronounced, but still not significant. The natural streams with the highest MSHA scores were rated "good" for habitat quality (R20 = 65.5; R24 =

68.5), but "fair" for channel stability (PSI: R20 = 88, R24 = 97). The resulting scatterplot suggests that intermediate channel stability scores were associated with streams demonstrating the best habitat quality. These same streams also had the highest FIBI scores. Other studies using the PSI to predict biological community attributes with habitat quality reported that intermediate PSI scores were associated with optimal habitat conditions and the best biological condition. Eifert and Wesche (1982) found that intermediate PSI scores between 65 and 91 were associated with the best habitat conditions for trout in Wyoming streams. For streams around Mt. Shaska, California, Brouha and Renoud (1981) reported that intermediate PSI scores between 77 and 83 were related to the highest trout standing stock and suitable habitat conditions were associated with scores between 58 and 100.

For SNAKE, Pearson and Spearman correlation were in disagreement as to whether or not PSI and MSHA were significantly correlated. The scatterplot (Figure 2-15c) indicates that most of the streams in SNAKE rated similarly for MSHA and PSI and consequently, the points cluster very close together; only a few points are forming the direction and strength of the association with Pearson correlation. On the other hand, Spearman Rank Correlation was not able to identify the potential negative linear association due to the larger number of points that scored similarly. When the values were reduced to ranks, the relative difference between MSHA and PSI scores for the one outlying point (S11) was reduced. This reach on the South Fork of the Groundhouse River (S11) scored the lowest for habitat quality (54.5, fair) and had the highest score for channel stability (PSI = 117, poor). The conditions at this site indicate that the channel had downcut and was in the process of widening (CEM II/III). At the time of assessment (2006) the reach demonstrated conditions of severe aggradation and flow deflection as sediment bars were in the process of building up on the inside bends and directing flows toward the outside bends. This reach was listed as impaired for biota related to excess fine sediment (<2 mm). The TMDL identified a lack of clean, gravel substrate as the habitat limiting factor to gravel spawning species (MPCA 2009a). Unstable stream banks associated with unrestricted cattle access immediately upstream and consequent flow deflection exacerbating bank instability within and downstream of the pasture were identified as the main cause and source of the excess fine sediment. Remediation strategies suggested by the TMDL Implementation Plan (MPCA 2009b) included cattle exclusion, restricted cattle access, and stream bank restoration, among others. A few years after the initial visit in 2006, this site was revisited again in 2009. The channel stability score was lower (PSI = 95, fair) indicating a moderately unstable channel. Habitat quality had also improved since 2006, primarily due to increased pool depth and riffle habitat comprised of clean, unembedded gravel (*personal observation*). This site appeared to be entering a CEM IV, where point bars were building up along the outside bends and becoming vegetated with willow and grasses, consequently reducing the channel width thereby increasing the velocity to remove fines. Since the

TMDL listing for this stream, an upstream landowner voluntarily removed his cattle from the pasture, and since then the banks have re-vegetated and re-stabilized (J. Magner, MPCA, *personal communication*), resulting in a slightly narrower channel width. The combination of bank stability and narrow widening has likely resulted in a reduction of sediment delivery and an increase in sediment transport capacity, thereby removing the aggraded fine sediment and uncovering and resorting gravel materials that have formed suitable riffle habitat for gravel spawning species. Given the increased depth variability, presence of clean, coarse gravel, and flow variability, the habitat score was also improved (MSHA = 74, good). This is one example of how conditions of channel stability and habitat quality may be related (cause and effect). Additional examples of this type of time series sampling events along the trajectory of channel evolution would be invaluable to documenting links between channel stability, habitat quality, and biological integrity.

A few associations were found, where, technically, the same component of the stream channel was assessed but they were called by different names for different purposes. For example, across watershed groupings, PSI metric *mass wasting or bank failure* was strongly correlated with MSHA metric *bank erosion* and *cutting.* The degree of cutting was more severe in REDWOOD than SNAKE. This may be related in part to the different soils and vegetation in REDWOOD than SNAKE. A majority of banks in REDWOOD were comprised of silts and sand which were highly erodible, and coupled with a higher degree of incision, were more often getting cut below the protection of the rootline. In contrast, stream banks in SNAKE were composed of highly erodible sand or a mixture of rock with tree roots where the streams were not as incised, and so the roots were still protecting the banks during high flows.

An interesting collection of channel stability and habitat quality variables that describe cross-sectional and longitudinal channel morphology were identified that were strongly and consistently correlated across watershed groupings. The MSHA metric zone CHANNEL MORPH and metrics *depth variability* and *channel development* were all positively correlated with PSI metric *landform slope* and negatively correlated with *channel capacity.* Together, these variables stable channel morphology. Streams that are stable are more likely to develop more variable patterns in depth, and hence, stream feature variability (e.g., pool and riffle complexes). Unstable steam channels that are overwidened in their cross-section typically accrue sediment on the bottom due to a loss of transport capacity. As sediments fill in pools, residual pool depth diminishes, and hence the channel has less *depth variability*, and rates lower for *channel development* (rates stability of riffles and pools), and channel morphology. *Channel capacity* was also strongly correlated with this suite of variables as well as many other habitat variables (Tables 21a,b,c); however, the direction of correlation was opposite of what would be expected. While most other associations between channel stability indicators and habitat quality metrics were negative, all associations between habitat quality metrics and *channel capacity* were positively correlated. CEM was the only other channel stability indicator that was positively correlated with all other habitat quality metrics.

The *channel capacity* metric was intended to rate mountainous streams where timber harvesting practices would be likely to increase sediment supply and aggrade the channel to the point where overbank flows would be more likely (i.e., reduced cross-sectional area). While aggradation is an indicator of an unstable stream channel, degree of incision/downcutting is as well (i.e., increased cross-sectional area). In this case, channel capacity is *increased* so that out of bank flows are more likely. *Channel capacity* then, in essence, is the same as CEM. CEM also describes an increase and subsequent decrease in cross-sectional area due to degradation and then aggradation. However, CEM was not associated with as many habitat quality metrics as *channel capacity.* This difference may be attributed to the the scoring system for CEM in this study only where I only assigned a numerical value to each CEM stage, without regard for the severity of aggradation or degradation as *channel capacity* did. *Sinuosity* was the only other MSHA metric where the direction of correlation was opposite of what would be expected with channel stability indicators. As noted earlier, an increase in *sinuosity* through bank erosion on the outside bends can be also described as a change in meander wavelength (Rosgen 1994), which is also an indication of channel instability. Another noteworthy observation is that channelized reaches that lacked *sinuosity* had fairly stable banks due to the lack of outside bend erosion. However, the bottom substrates were very unstable, supported by the positive correlation between *sinuosity* scores (higher scores for greater degree of sinuosity) being positively correlated with BOTTOM scores (higher scores for higher degree of substrate mobilization).

Interestingly, MSHA zone COVER was the only habitat zone significantly correlated with CEM for both REDWOOD and SNAKE. COVER was also related to MSHA metrics *bank erosion* and *channel stability* in SNAKE. Streams in the process of downcutting and widening typically have cut banks and evidence of bank erosion on both sides of the channels. A high degree of cutting and bank erosion can reduce the amount of overhanging vegetation. Overhanging vegetation can be the most prevalent cover type available in stable prairie streams. Dense overhanging vegetation not only provides cover from predators, but also provides shade that maintains cooler water temperature and provides a suitable substrate for macroinvertebrates that are a quality food source for certain fish species. Additionally, when a stream is in the process of over widening (CEM III) a loss of residual pool depth can occur due to a loss of sediment transport capacity and consequent aggradation in pools (Rosgen 2006). Therefore, unstable stream channels can also cause a loss of quantity, quality, and extent of good fish cover which can also affect biological communities.

The MSHA metric *channel stability* was significantly correlated with a number of PSI metrics across watershed comparisons (Tables 21a,b,c). Not surprisingly, the MSHA metric *channel stability*, which rates bank stability and bottom stability was strongly correlated with channel stability indicators that rate the severity of bank erosion (*mass wasting*) and degree of substrate instability (i.e., *brightness, scouring and depositio*n). However, the scatterplots (Figures C-32b,c) show that most of the points in both REDWOOD and SNAKE scored the same and only a few points scored differently and were directing the association. MSHA metrics such as channel stability as rated on a categorical scale with no opportunity to provide a score between the two ratings. The PSI allows the assessor to cross-off a value and provide a score the assessor thinks is more accurate for the conditions observed.

My results also indicate that indicate that the association between channel stability and habitat quality is complex, given the different scenarios that could occur along the multiple trajectories of channel adjustment. For example, for channelized streams that lack depth variability, conditions of channel instability can cause bank erosion and an increase in sinuosity as the channel reworks the channel bottom and develops a thalweg over time. This can result in a more complex network of pools and riffles and an increase in habitat complexity which could be rated as good, and in some cases, even excellent habitat (*personal observation*). Likewise, for unchannelized alluvial, low-gradient streams, as a channel downcuts and widens, a loss of channel complexity can occur as the stream aggrades sediment and infills pools which would be rated as pool habitat quality; however, as the channel remains unstable and enters stage CEM IV, the bottom sediments are reworked and instream meandering occurs which increases pool depth and quality of gravel-riffle complexes, resulting in a rating of good habitat quality. In another scenario, a stream in the process of widening can destabilize trees, which upon entry into the stream channel can cause flow deflection, scouring, bank erosion and a poor rating of channel stability, while at the same time the presence of woody debris, flow deflection, and scouring increases cover, sinuosity, pool formation, and depth and flow variability (Abbe and Montgomery 1996, Bilby and Bisson 1998, Yarnell et al. 2006) which would be rated as good habitat quality. For some channelized streams in low-gradient areas between lakes that dampen peak flows and where the sediment transport capacity is limited, a rating for channel stability would be rated as good to excellent when the habitat quality would be rated poor due to the lack of depth variability, coarse substrates, sinuosity, and variable channel morphology. Hence, the relationship between channel stability and habitat quality is complex given the different scenarios described.

Suggested modifications to the MSHA

While the MSHA was related to fish community health, in my opinion, this habitat quality assessment could be improved to better assess present conditions and note where deviations in expected conditions for certain stream types occur. One criticism of the MSHA is that it was modified from the QHEI in order to not unfairly score low-gradient streams that typically comprised of fine substrates and lack riffles. Modifications included the removal of the riffle and pool quality metrics that are a part of the QHEI (Rankin 1989). While these modifications allow low-gradient streams to not be unfairly rated due to the natural absence of riffle features, the removal of the riffle and pool quality metrics, however, limits the ability to assess habitat quality related to two of the most important habitat zones for certain sensitive fish and macroinvertebrates. A suggestion is for the development of two MSHA worksheets with metrics designed to rate low-gradient streams typically devoid of riffle habitat separate from mid-to high gradient streams that typically have some riffle habitat.

Another criticism of the MSHA is that the INSTREAM metric *embeddedness* rates the average degree of embeddedness across the entire length of the reach. At a future time, an assessor does not have information on whether or not suitable coarse substrates were present and in an unembedded condition in the riffles or whether there is a degree of infilling of pools. As an example, a stream that has a riffle that is 0% embedded, a run that is 25% embedded, and two pools that are 75% embedded, would be rated as overall 50% embedded. Another issue is that the rating is based on quartiles, hence, the assessor must decide if the overall substrate degree of embeddedness is 25 to 50% (fair) or 50 to 75% (good). Unless the level of embeddedness is consistently low or high across the reach, critical information on whether or not the stream has quality unembedded habitat zones cannot be inferred from this metric. Certain sensitive fish and invertebrate species require clean coarse substrates for reproduction, feeding and protection (e.g., lithophilic spawners) and larger fish tend to prefer deep pool habitat (Schlosser 1987). As stated by the Ohio EPA (2009), "Next to temperature and an adequate supply of water, the composition of the substrate found in the stream channel is the most important feature that predicts biological potential." The MPCA has recently incorporated a companion field form to supplement the MSHA scoring sheet called the *Stream Condition and Stressor Identification* (SCSI) worksheet. One of the stream condition areas that are recorded is the presence of "*substrate suitable for lithophilic spawners*" as well as observations of excess deposition in riffles, pools, and runs. These additional observations are intended to provide more information on small zones of substrate that may be important to certain fish species, but that may not be inadvertently documented on the MSHA since it tends to limit scoring to dominant substrate and habitat types.

The MSHA zone RIPARIAN rates riparian quality as *riparian width*, *shade*, and degree of *bank erosion* which primarily characterize the condition of the banks during summer base-flow. What is not assessed with these metrics is the degree to which the attendant floodplain is connected to the stream channel. Neither the QHEI (Rankin 1989) or MSHA rate the degree of floodplain connectivity, even though the attendant floodplain is considered by stream ecologists as part of the lateral dimension of the stream corridor which includes the stream channel, adjacent riparian and floodplain zones (Petts 2000, Junk et al. 1989, Ward et al. 1989). Connected floodplains dissipate flow energy during bankfull flows, provide flow refugia for fish (Junk et al. 1989) and lotic invertebrates (Hayden and Clifford 1974), reduce sediment and nutrient loading to adjacent and waterbodies (Cooper et al. 1987, Groffman et al. 1992, Forshay and Stanley 2005), and reintroduce allochthonous materials such as large woody debris that provide cover and increase hydraulic complexity (Abbe and Montgomery 1996). Addition of a floodplain connectivity metric to the MSHA or SCSI worksheet should be considered, otherwise, a channel stability assessment that rates the degree of floodplain connectivity should be paired with a habitat quality assessment. This could be rated as degree of incision and floodprone extent. Incised channels have been described as being "extremely harsh" conditions for stream biota (Shields et al.1998) due to the flashier hydrograph and magnified shear stress associated with these deeper profiles that contain greater volumes of water during high flow conditions. According to Karr (1981), morphological channel adjustments related to channel incision may be more detrimental to biological integrity than point or non-point source pollution. The flow refugia associated with a stream channel's floodplain may be disconnected and unavailable to fish when streams are deeply incised (Shields et al.1988). These conditions associated with high flows are generally not observed during mid-summer habitat assessments when flow velocities have slowed. Features such as pool depth, velocity refugia, presence of off channel areas that could become inundated during high flows (e.g., abandoned meanders), and well connected floodplains are critical elements of habitat that are inundated only during certain times of the year and which are not currently assessed with most habitat assessments. A habitat assessment, then, may not assess the most critical habitat conditions required for survival (e.g., presence of back-water or overbank flow refugia during high flows, stable substrates for spawning and rearing). Habitat availability associated with lateral connectivity and during different seasons and flow conditions have been referenced by Ward (1989) as one of the four-dimensions of streams: horizontal (flow direction), vertical (groundwater, hyporeic zone), lateral (floodplain connectivity) and time (how streams change over the course of seasons and years). In my view, it is just as important--or more important--to assess habitat availability during extremes of high-flow and low-flow conditions, as during typical base-flow conditions. Examples of ways to assess floodplain connectivity and degree of incision are presented by Ohio EPA (2007, 2009), VANR (2007), and included in the CCSI in Chapter 3. In order to rate floodplain connectivity and degree of incision, biologists conducting habitat assessments will need training in the basics of fluvial morphology and stream classification (e.g., Rosgen 1994) so that they can imagine flow conditions and habitat availability during bankfull stage.

It has been observed that biologists, with minimal training in the concepts of fluvial geomorphology, have difficulty in scoring the MSHA metric *channel stability* and other MSHA metrics associated with channel morphology (e.g., pool and riffle development, depth variability, *personal observation*). Training in fluvial geomorphology may be necessary for biologists to imagine bankfull flow conditions related to flow velocity, substrate mobilization, channel evolution, and the degree to which a stream has lateral connectedness and near-stream and in-stream flow refugia. Additionally, training that develops an understanding of the baseline of habitat conditions that are expected for a given stream type (e.g., mid-to high gradient verses low-gradient, substrate dominated sand verses a mixture of substrate types) is necessary before conditions associated with channel instability can be interpreted as negatively impacting habitat quality. This will aid in more effective characterization of streams for not only Stressor Identification, but also in selecting reference or best attainable habitat conditions for IBI development (Maul et al. 2004) and Tiered Aquatic Life Use (TALU) expectations. The PSI assessment tool or modified version may provide an instructive method for educating biologists on how to observe and interpret physical indicators of channel stability and note when conditions may be negatively influencing habitat quality.

One final criticism is that the metric *channel stability*, while it was strongly correlated with biological integrity in both watersheds, does not indicate from the rating whether the issues observed were related to bank instability (e.g., bank erosion) or bottom instability (aggradation or degradation). Bottom instability by itself is undoubtedly more detrimental to the health of biological communities that bank instability alone, since streams may demonstrate high levels of bank erosion, but unless coupled with degradation (incision/widening) or aggradation (embeddeness), bank erosion is not detrimental to biological communities within the reach being sampled. A suggestion is to add check-boxes so that the assessor can note one or both conditions as being unstable, or supplement the habitat quality assessment with a channel stability assessment that rates both the condition of the banks and bottom separately.

Investigating potentially confounding watershed and reach scale characteristics

In order to determine whether and to what degree watershed and reach scale characteristics could could be confounding variables associated with stream conditions observed, I applied ANOVA and a Wilkoxin Sum Rank test to compare distribution*s* of *FIBI, PSI, and MSHA* scores when grouped by *watershed, ecoregion, stream class*, and *channel condition.* I also tested the level of correlation between subwatershed land use and physicochemical quality variables with FIBI.

My results indicate that biological integrity, channel stability, and habitat quality were significantly better in SNAKE than REDWOOD. These two watershed contrasted markedly in geology and land use which could be a reason for the significant differences in fish community health observed. Water chemistry variables such as nutrients and suspended sediment measures contrasted markedly between watersheds and ecoregions. Much of these differences could be attributed to different background expectations.

While significant differences were observed between watersheds, the within watershed variability in FIBI, MSHA, and PSI could not be significantly explained by *ecoregion, stream class*, or *channel condition.* However, significant correlations were found between FIBI, PSI, and MSHA and certain subwatershed land use types as described below. In addition, some measures in dissolved oxygen and turbidity were in violation of water quality standards and could be influencing the FIBI scores at a few reaches within each watershed.

Biological integrity and subwatershed land use

While a strong association between land use and stream health was found for COMBINED, no association was found when watersheds were analyzed separately. The lack of strong associations between subwatershed land use and FIBI for REDWOOD and SNAKE may be due to the lack of a sufficient gradient in percent land use types within each watershed. For COMBINED, scatterplots demonstrate that points associated with each watershed are clustered closely at opposite corners of the plots (Figures C-1, 2, 6, 7) due to both the significant difference in the within watershed distributions in FIBI scores coupled with the small range in *percent land use types* observed within watersheds. These clusters by watershed could be considered a spurious result; however, the high correlations observed between FIBI and land use types for COMBINED are inline with findings reported in other studies (Wang et al. 1997, Fitzpatrick et al. 2001, Diamond et al. 2002). For streams in Wisconsin, Wang et al. (1997) found a positive relationship between FIBI and *percent forest* in the watershed and a negative relationship between FIBI and *percent agriculture*. For streams in Wisconsin, Fitzpatrick et al. (2001) reported a positive relationship between FIBI and *percent forest* and a negative relationship with *percent agriculture*. For streams in Virginia, Diamond et al. (2002) reported positive associations between FIBI and *percent forest* and negative associations between FIBI and *percent urban* and *percent agriculture.* The two FIBIs used in this study were developed using reference or least impacted conditions found in each region. For SNAKE, a majority of sites had fish communities that deviated minimally from the least impacted conditions observed in the SCRB; whereas, in contrast, many FIBI scores were low in REDWOOD which reflects a moderate to severe deviation from least impacted conditions found in MRB at the time of FIBI development. Therefore, it is likely that land use was a significant factor in explaining the variation in FIBI observed between watersheds.

Channel stability and subwatershed land use

For COMBINED, greater disturbance in the watershed was associated with decreased channel stability and land use types associated with less disturbance with greater channel stability. Similar results have been documented in other studies. For example, Diana et al. (2008) found that *percent agriculture* was associated with decreased flow stability and positively correlated with increased bank erosion. Other studies have documented better habitat conditions with greater *percent wetland* in the watershed (e.g., Diana et al. 2008, Roth et al. 1996) which was related to greater flow stability, i.e., channel stability. Wetlands and lakes act as water interception and locations of water storage during high flow events, consequently dampening potential stream flow energy. Hence, a loss of wetlands can result in an increase in stream flow energy since water is no longer intercepted and held back during snow-melt or stormwater events. This water is now directed more quickly to the stream channel thereby decreasing flow stability and exacerbating bank erosion. This can result in unstable stream channels that deliver excess sediment to waterbodies downstream. Recent research (Engstrom et al. 2009) has indicated that the dramatic increase in tile drainage in the Minnesota River Basin and significant loss of perennial vegetation has altered the hydrologic regime of the basin. The authors demonstrated through sediment core dating, that ditching, tiling, and loss of wetlands and perennial crops in much of the MRB during the 1930s to 1960s is correlated with a two-fold increase in stream flows and consequent increases in tractive force along bluffs and stream banks. The result is channel instability and extensive bank and bluff erosion in the MRB which carries excess sediment via the Minnesota River to the Mississippi River and Lake Pepin. These two rivers are listed for excess turbidity. The TMDL calls for best management practices that provide more water storage in the MRB in order to reduce the peak stream flows that have been determined to be the main cause exacerbating bank erosion along much of the Minnesota River and tributaries (MPCA 2011). Many of my study reaches in REDWOOD were in the process of channel adjustment. When comparing the stream trace from a contour map with the current stream trace from aerial photographs, reach R27 on the Redwood River had noticeably increased in sinuosity over time, which could be a response to an increase in the discharge regime (e.g., change in pattern, Rosgen 2006).

Habitat quality and subwatershed land use

For both watersheds, better habitat quality was associated with subwatersheds with greater percent undisturbed land. While the specific type of land use that was significantly correlated with

MSHA varied by watershed grouping; across watershed groupings, MSHA was positively correlated with undisturbed land use types and negatively correlated with percent disturbed land use types. The associations between subwatershed land use and habitat quality observed in this study are similar to results reported in other regions. For streams in Wisconsin, Wang et al. (1997) reported that *percent forest* in the subwatershed was positively associated with habitat quality; whereas, *percent agriculture* was negatively correlated, but only after *percent agriculture* exceeded 50%. For streams in Michigan, Diana et al. (2008) found positive correlations between habitat quality and land use types that were characterized as undisturbed land (e.g., *percent forest, percent wetland*); whereas, habitat quality was negatively correlated with land use types that were categorized as disturbed land (e.g., *percent agriculture*, *percent urban)*.

Biological integrity and physicochemical variables

Nutrient and sediment variables were highly associated with FIBI for COMBINED, but were weakly associated with FIBI when watersheds were analyzed separately. The significant associations between FIBI and water chemistry variables for COMBINED are partially related to the large difference in ecoregion background expectations between watersheds. However, at a number of stations in each watershed, nutrient and sediment measures were above ecoregion expectations. In addition, DO measurements were below the WQS of 5 mg/L at reaches in both watersheds. Many of these low DO values were from early morning readings when DO is likely to be lowest (before 9:00 a.m.); however, other measurements were from mid-morning readings (after 10:00 a.m.) when DO is likely to be slightly higher due to the onset of photosynthetic activity. Consequently, it is possible that other reaches may also experience low DO below the WQS during the nighttime which was not captured during the time of fish sampling in this study. Low DO may indicate the influence of naturally low DO water influx to the stream from wetlands or groundwater or may indicate excess nutrient enrichment that is enhancing higher aquatic plant productivity and greater plant respiration during the nighttime or increased microbial decomposition, among others. Low DO can be a limiting factor to certain fish species and could potentially be an influence on the FIBI scores in this study. Hence, while some of the variability observed between watersheds could be attributed to different background expectations, some of the variability observed could also indicate the presence of a biological stress related to land use practices or other local conditions. Agriculture is the dominant land use in REDWOOD and consequently, nutrient enrichment associated with agricultural land use could be contributing to the lower overall FIBI scores in REDWOOD as compared to SNAKE. Hence, it is feasible that water quality was a biologically limiting factor n REDWOOD. It is also feasible that habitat quality or channel stability were also biologically limiting factors in this watershed.

Turbidity values were also measured above the current WQS of 25 NTUs in REDWOOD, but not in SNAKE. When the new proposed ecoregion WQS were applied, more reaches reported violations in SNAKE than REDWOOD. It appears that Minnesota's current turbidity standards are potentially under protective of streams in SNAKE and overprotective of streams in REDWOOD. However, a one-time measurement is not sufficient to determine if turbidity is a limiting factor at these reaches; although, high values may indicate a potential for biological stress since the presence of suspended fine particles can reduce light penetration and inhibit plant growth, irritate gill tissues of sensitive fish and make them more susceptible to disease, and increase solar radiation that can increase stream temperature and reduced dissolved oxygen, among others. It is also assumed that high turbidity values can also be related to a loss in habitat quality as suspended sediment eventually settles on the bottom and consequently smother fish eggs of lithophilic spawners and fill in interstitial spaces thereby limiting habitat for benthic fish and macroinvertebrates. A new proposed WQS will no longer be based on turbidity, but total suspended solids (TSS). TSS is often collected as a measure of mobilizable sediment carried by the rising limb of high flows and deposited along the bottom during the falling limb of the hydrograph. An additional consideration is that TSS and turbidity are both related to the amount of inorganic particles in suspension as well as the amount of organic material (Waters 1995, Lenhart et al. 2010) such as humic acids and algae. A method is available that can easily determine the fraction of TSS that is inorganic sediment verses organic material (Lenhart et al. 2010). While TSS was collected and weighed in this study, the organic fraction was not derived; however, visual evidence at some sites (e.g., R16) suggest that decomposing plant material and/or algae may be a cause for high turbidity observed. Suspended organic material may indicate a different type of stress to the biological community than suspended sediment. Decomposing plant material can increase biological oxygen demand and lower dissolved oxygen conditions below a supporting level for sensitive fish and aquatic macroinvertebrate species. High levels of suspended organic material can also be comprised of sestonic algae which flourish with excess nutrients (Lenhart 2008). Eutrophic conditions that support the growth of excess algae may also increase the likelihood of extreme diel oxygen swings in streams which can be significant stress to the biological community.

Alternatively, high levels of TSS may indicate that overland erosion or unstable stream banks are actively eroding and contributing sediment to the stream during higher flows (Lenhart et al. 2010). The excess sediment can settle during low flows and embed coarse substrates thereby reducing the availability of important habitat areas required by certain fish and other organisms for feeding, reproduction, and protection. However, collections of TSS alone are not sufficient for the calculation of the bedload movement of fine sands (< 2mm). The bedload material comprised of fine and coarse sand can become suspended and carried in the water column with the rising limb of the hydrograph, during which a TSS grab sample could be collected. During the recessing limb of the hydrograp, suspended sediment drops out of suspension and covers bottom substrates. Bedload sediment can also be composed of coarse sand and gravels that are rolled downstream by high velocity flows but are not suspended and carried into the water column. A method that assesses the movement of bedload sediment is needed to better characterize conditions that may impact habitat quality and biological communities. Currently, habitat metrics that characterize the degree of embeddedness and depth of fine particles within each stream feature (e.g., riffles, runs, pools) and/or channel stability metrics that characterize the degree of uncompacted sediment, evidence of aggradation, and degree of pool infilling may be more instructive in determining the degree to which excess bedload sediment or loss in sediment transport capacity are negatively impacting habitat quality and biological communities than TSS or turbidity.

Biological integrity and channel condition

Interestingly, c*hannel condition* was not a significant factor that explained a significant portion of the variability in FIBI scores observed in either watershed. These channelized reaches performed as well or better than many natural reaches sampled in this study. Channelized reaches in both REDWOOD and SNAKE were fairly low-gradient; however, some of these low-gradient channelized reaches also contained riffle habitat and coarse substrates that may be more strongly associated with some of the better biological conditions observed within each watershed. Natural streams in REDWOOD were more often associated with greater *percent riffle*; however, some channelized streams also possessed riffle habitat. *Percent riffle* was correlated with *channel slope,* which indicates that for REDWOOD a number of natural and channelized streams with some degree of gradient were able to sort and rework coarse materials such as gravel to form riffle habitat or at least provide coarse substrate in shallow runs. In Tyler Creek (R19) which is a channelized reach, gravel was observed forming riffle habitat associated with resorted of bottom materials such as sand and gravel, thereby creating a meandering thalweg within the trapezoidal channel banks and consequently develop some degree of channel morphology as riffle and pools. The stream features of this reach were characterized as 5% riffle, 25% run and 70% pool. This channelized reach also performed biologically as well or better than many natural streams in REDWOOD (FIBI = 46), even though the *percent disturbed* land use in the subwatershed was 97%. Another channelized reach, Clear Creek (R22), did not contain riffle habitat (50% run, 50% pool), but the slight degree of a meandering thalweg being formed inside the trapezoidal channel was creating an observable degree of depth variability, so the runs were relatively shallow and the gravel was clean and well sorted. This reach contained hornyhead chub (*Nocomis biguttatus*) which require clean coarse substrates to build nests, perennial flow, and are considered intolerant to poor water quality (Bailey et al. 1993). Surprisingly, this channelized reach also performed as well as or better than most of the natural reaches in REDWOOD (FIBI = 46). For SNAKE, two of the channelized reaches (S8 and S9) on the South Fork of the Groundhouse River were both relatively low-gradient (0.5 m/km) and were dominated by pool habitat (S8 = 50%, S9 = 80%). S8 also had 10% riffle habitat and 40% run, while S9 had 20% run and no riffle habitat within the reach, but riffle habitat was observed immediately downstream of the reach. This half-channelized reach (S9) was characterized as fine grained (percent fines = 80%, *D50* = 0.16mm), while the other reach (S8), was a mixture of fine and coarse substrates (percent fines = 48%, *D50* = 23mm). These two reaches (S8 and S9) were both rated as fairly stable (PSI = 68, CEM III/IV and IV/V respectively) and both had fish communities that scored on par with the two best performing natural reaches in SNAKE (FIBI = 74 and 79, respectively), even though these two channelized reaches also had the highest *percent disturbed* land use in the subwatershed (49% and 51%, respectively) in SNAKE.

Other researchers in the Midwest have also documented relatively good biological integrity in channelized streams that was comparable to natural streams. In Illinois, Rhoads et al. (2003) found that biological integrity in a channelized stream that had not been reworked for at least 60 years had a FIBI score that was significantly higher than another channelized streams that had been more recently dredged. In addition, the stream that had not been reworked for at least 60 years received an FIBI score that was slightly higher than two other natural streams sampled during the study. The authors noted that the main difference observed between the two channelized streams was that the more recently dredged reach had a flat, uniform bottom without evidence of bar formation; whereas, the channelized reach that not been reworked in 60 years had developed a meandering inset stream and a low-flow floodplain within its trapezoidal form. The authors suggested that the meandering pattern was created by vertical accretion and bar formation along the bottom of the channel resulting in variation in bed elevation results in pool habitat but not riffle habitat. The authors attributed the enhanced biological integrity found in this channelized stream as well as the natural streams to variation in hydraulic variability associated with morphological variability, point bar deflection, woody debris, and overhanging vegetation that created physical habitat conditions that were capable of supporting a more diverse fish community. Rhoads et al. (2003) suggest that the flow variability associated with different areas of point bars and pools provide niche habitats to support the feeding and foraging habitats of a more diverse fish community both in terms of species as well as size and age classes.

In Minnesota, other researchers have also observed that channelized streams can perform biologically as well or better than many natural streams (J. Magner, MPCA and E. Rankin, Ohio

University, *personal communications*). The results in this study also support this claim. It has been hypothesized that these biologically well performing reaches appear to be associated with channelized streams that have perennial flow with constant groundwater support that may keep them thermally stable during summer and winter months. Reaches have not been dredged for a long period of time may develop point bars with overhanging vegetation that shades and provides cover. These reaches are also moderate gradient (0.5 to 2.0 m/km) that provides sediment transport capacity sufficient to rework gravel and sand substrates into meandering sequences of riffles and pools or at least shallow runs and deep pools that provide a diversity in habitat for different size species and age classes (*personal observation*). Channelized reaches that are allowed to re-meander inside the trapezoidal confines of the high banks can also develop low-flow channels with small, adjacent vegetated floodplains that can store sediments and attenuate nutrients, thereby improving water quality—as well as habitat quality. More importantly, these channelized reaches are capable of supporting good quality habitat that can support a diverse, healthy biological community which may prevent these reaches from being listed as biologically impaired.

Associations among geomorphic variables, biological integrity, channel stability, and habitat quality

Geomophic variables were also tested to determine if additional information collected during stream sampling events in either a channel stability or habitat quality assessment could better characterize background conditions for understanding a stream's biological potential and for observing a loss of habitat potential. Geomomorphic variables tested included two different stream gradient estimations, proportion of stream features within the sampling reach (e.g., percent pool, percent riffle), and a substrate characterization procedure (pebble count or visual estimation).

<u>Differences in degree of correspondence between two stream gradient measures</u>

In this study, two different methods were applied to estimate stream gradient. *Channel slope* was collected using a laser level and measuring the water level physically within the sampling reach. *Gradient by map* used topographic contour maps in ArcGIS where the 10ft elevation contours either changed within the reach sampled or were located a considerable distance upstream or downstream of the sampled reach. The correlation between *channel slope* and *gradient by map* was much stronger in SNAKE (r = 0.98, r_s = 0.86) than for REDWOOD (r = 0.67, r_s = 0.26). The topography in SNAKE was more variable than REDWOOD, which was relatively flat with only certain segments near the mouth of the REDWOOD that had more rolling character. Consequently, the distance between elevation contours for REDWOOD was generally farther than between elevation contours for SNAKE. Consequently, for SNAKE, a localized change in gradient was more likely be captured and using both measures; whereas, for REDWOOD, a slight change in instream elevation due to a riffle or head-cut was less likely to be captured as a significant change in elevation within the sampling reach. Consequently, the difference between the strength of the correlation between *channel slope* and *gradient by map* observed in this study may be due in part to the difference in watershed topography between REDWOOD and SNAKE. However, the ability to detect small changes in gradient within a reach using a topographic station is debatable, given the likelihood for user error and could also be a factor in this study. Researchers have investigated and attempted to quantify the variability associated with different methods of stream gradient estimations, by comparing infield measurements using a laser level and stadia rod, remotely using contour maps and digital imagry in GIS, and Digital Elevation Model (DEM) mapping applications (M. Kocian, UMN, *unpublished data*). In addition, new GPS technology has more advanced precision field based capability and is currently being tested by the MPCA for Stressor Identification projects (D. Pemble, MPCA, *personal communication*). These new advancements may allow for both more time efficient and more accurate GIS and field based estimations of stream gradient which could be important for understanding flow derived and maintained habitat quality and sediment transport capacity at both the reach gradient, valley slope, and watershed elevation changes. All of these scales may be important for understanding differences in fish community expectations based on stream potential to create and support quality habitat that is related to watershed geology, climate, topography (e.g., available stream power to sort and move sediment i.e., stream gradient), and changes in watershed land use that alter the hydrologic regime (Poff et al (2006).

Geomorphic variables and channel stability

Geomorphic substrate variables were consistently correlated with PSI, however, the best fit models selected different substrate variables for COMBINED and SNAKE, and no substrate variables for REDWOOD. For SNAKE, lower PSI scores (relatively more stable) were associated with larger substrates. Larger substrates such as cobble and boulder are inherently more resistant to scour and mobilization that smaller substrates such as gravel and sand. Consequently, reaches with a greater percent of larger substrates may be expected to withstand increases in discharge and downcutting more readily that reaches with sand and gravel. While the range in larger substrate types was narrower in REDWOOD, the range for other substrate types such as *percent gravel* and *percent rock* was fairly wide (0 to 47% and 0 to 55%, respectively). Many of the reaches in both watersheds contained a mix of substrate types (Table 2-3). Streams with a mix of substrate sizes may downcut slightly as the fines are removed leaving the larger substrate clasts behind that subsequently armour the bottom from further downcutting. In these situations, if the reaches are slightly incised, the additional flow energy contained in the cross-section can still erode away the banks and overwiden the stream cross-section leading to aggradation. The rate at which the stream widens is largely dependent on the bank material and degree of protection by rooting vegetation. Where a stream has not downcut past the rooting line, the process of widening may be very slow. In contrast, where a stream has incised to such a degree that roots are no longer providing protection to the bank during higher flows, the banks will undercut and undermine the banks above resulting in more rapid widening. Some reaches in SNAKE were downcut only slightly and the bottom appeared to be fairly well armored as was also the case for some reaches in REDWOOD. However, for some reaches, the flows were eroding the unprotected toe of the banks, leading to tree fall and bank slumping. The PSI, in its present form, was not able to rate whether the stream had incised to a point at which the flows are undermining the protection afforded to the banks by the rooting depth or the degree to which the stream had overwidened. This should be considered in a modified version.

In terms of stream features, streams that were rated more stable in SNAKE had higher percentages of larger substrates and higher *percent pool*; whereas, for REDWOOD, streams that were rated as more stable were associated with higher *percent riffle and pool*. These results indicate that for SNAKE, streams with larger substrates were associated with more stable conditions as rated by the PSI, and larger, more stable substrates were associated more often with streams that had well-developed pools. Walters et al. (2003) also found a strong association between coarser substrates and well developed riffles and pools; whereas, in contrast, streams with fine substrates tended to lack well developed riffles and pools. The authors attributed this difference to fine substrates such as sand being more highly mobilizable and therefore, less able to form well developed riffles, and pools would tend to fill in with sand (Walters et al. 2003). While the PSI does rate the degree of substrate mobilization and aggradation (i.e., *scouring and deposition*), it does not rate the degree of pool infilling. This should be considered for a modified version of the PSI. Rating the degree of pool infilling will assist in linking conditions of channel instability with less than optimal habitat conditions for Stressor Identification.

For REDWOOD, streams that were rated as more unstable (higher PSI scores) were more often associated with streams with higher gradient and sinuosity. These results are not surprising, given the processes that are associated with channel evolution. Reaches in REDWOOD that were the most sinuous were also incised and in the process of widening and lateral migration as the inside bends were building point bars and deflecting flows along the outside bends causing exacerbated erosion. Hence, these reaches also scored poorly for *mass wasting or bank failure* and *cutting* as well as *scouring and deposition* and *consolidation and particle packing*. The flow energy required to transport sediment and cause scouring is related to gradient. Very low-gradient streams often lack the flow energy required to cause excess scouring and severe bank erosion. Sinuous streams with sufficient gradient to transport sand and gravel (e.g., C stream type) are also more likely to become unstable with a change in discharge regime. However, low-gradient streams can also become unstable when they become incised and when flow-variability becomes more extreme.

Geomorphic variables and biological integrity

Except for *channel slope* in REDWOOD, neither stream gradient estimation (i.e., *channel slope* or *gradient by map*) was significantly correlated with FIBI for COMBINED or SNAKE. This may be due to a narrow range in gradient observed within both watersheds, except for one outlier in SNAKE (S4) where *channel slope* was 5%, while all other reaches in both watersheds were below 1%. Due to the higher gradient, S4 could be classified as a B3 stream type in an alluvial valley; however, this reach had a well-connected floodplain and was not entrenched and so could also be classified as a C3 stream type with cobble and sand. Other reaches in SNAKE also had higher percentages of cobble, boulder and sand. Hence, I determined that gradient was not considered a significant factor to consider to exclude this site from analysis. While stream gradient was not strongly correlated with stream health in this study, stream gradient has been found to be correlated with FIBI in other studies (D'Ambrosio et al. 2009). However, stream gradient and FIBI in that study may also be associated with other confounding variables, such as land use, geology, and substrate size that are often correlated with stream gradient. FIBI metrics should be tested against stream gradient and other natural gradients (e.g., drainage area, elevation) to identify and reduce the inflation in metric values due to fish community differences that are related to gradient (e.g., substrate size, velocity).

The stream feature combination *percent pool and riffle* was significantly correlated with FIBI for COMBINED and SNAKE. In contrast, no stream features were significantly correlated with FIBI for REDWOOD. For SNAKE, a non-linear association between FIBI and *percent pool and riffle* was found. The scatterplot of FIBI regressed against percent *pool and riffle* (Figure 2-17c) demonstrates that initially, as the *percent pool and riffle* increased, so did FIBI until around 80 to 90 *percent pool and riffle* at which point the slope of the regression line flattened. The three highest scoring sites for SNAKE had between 0 to 30 *percent riffle*, 60 to 90 *percent pool,* and only 0 to 15 *percent run*. From these results, streams with variability in stream features performed better than streams dominated by run and in SNAKE here was a threshold at which point an increase in *percent riffle* did not improve biological integrity. Other studies have linked FIBI with presence of stream features such as *percent pool* (Simonson et al. 1994) or depth diversity (Gorman and Karr 1978) which is somewhat related to the depth variability that would be associated with well developed pool and riffle complexes. Pool depth is an important habitat component for fish communities in that deep pools provide protection from predators, high flow refugia or resting cover, low-flow refugia (Rankin 1989), summer thermal refugia, and winter refugia (Toth et al. 1982). Other researchers have found that habitat volume (e.g., greater percent pool) verses aerial extent of habitat was associated with greater species diversity and density (Angermeier and Schlosser 1989). Lack of deep pool habitat may be associated with unstable, incising channels (Schlosser 1987) that may shift the community from a mix of age classes toward a dominance by short lived species (Schlosser 1982).This shift in community composition may translate into lower FIBI scores if metrics are included that rate the age structure of the community.

For REDWOOD, streams with higher *percent pool and riffle* were more variable in how well they performed biologically (Figure 2-17c). The three streams with the highest FIBI scores had between 5 to 20 *percent riffle*, 45 to 65 *percent pool*, and 15 to 50 *percent run.* However, streams with some of the lowest FIBI scores also had similar *percent riffle and pool*. These reaches with the lowest FIBI scores (R16, R21) were both natural streams with very long and large deep pools within the reach that were heavily embedded with silt. In contrast, streams with higher FIBI scores were dominated by sand and gravel substrates and had much lower percent silt (Table 2-3). A study by Heitke et al. (2006) also found a negative association between FIBI score and percent silt for streams in Iowa. The authors attributed the higher percentage of silt at some streams to prairie soils that are composed of fine material but where agricultural land use practices had resulted in unvegetated banks, channel incision, and excessive bank erosion. The two lowest performing streams in this study were both in moderately grazed pastures with trampled banks; however, it was also evident from the channel cross-section that these streams had also downcut and the now higher contained flows were exacerbating bank erosion. A landowner adjacent to Coon Creek (R21) surmised that the excessive bank erosion observed coincided with an increase in tile drainage in the watershed over the last decade (*personal communication*). The stream was deeply incised, but had not yet become entrenched. During a sampling visit in June 2006 when the stream flow was higher, the stream substrate was comprised of clean, gravel substrate and the stream features present included well developed riffles and deep pools that were also free of silt. In contrast, during a repeat sample visit in August of the same year when flows were lower, the bottom substrates were embedded with 8 to 10 inches of silt. Except for a small area of faster flow at the upstream end of the reach where a hydraulic jump occurred in association with a log jam, the rest of the reach was uniform in depth due to the deep over-layer of silt. Hence, the habitat quality had changed dramatically between the two visits both in substrate quality and depth variability. The heavy siltation at these two reaches could also explain the very low FIBI scores. Silt can settle on the bottom and fill in pools, riffles, and interstitial spaces so that the quality and availability of cover and niche habitats (Frothingham 2002) is greatly reduced. Excess siltation can cover coarse gravels and negatively affect certain fish species that rely on gravel for feeding and reproduction (Berkman and Rabeni 1987). These conditions can translate into lower FIBI scores. Consequently, observation of seasonal variability in flow, substrate, and habitat quality, may be required to identify stressors that are a cause of biological impairment, especially in watersheds with exacerbated flow variability and where soils are composed of silt, as is typical for prairie regions in the Midwest.

In terms of substrate variables, *D50* was a significant predictor of FIBI across watershed groupings. My results are similar to results reported for streams in Ohio (D'Ambrosio et al. 2009). It is interesting that while *D50* was a significant predictor in SNAKE, the MSHA metric *substrate* was not. However, *substrate* was a significant predictor for COMBINED and REDWOOD. It is possible that *D50* and *substrate* characterize substrate habitat differently and for different purposes (e.g., habitat quality or sediment transport competence). *D50* works best for a unimodal distribution of size classes (US ACE 1994). For a bimodal distribution, *D50* may not be an appropriate measure for either estimating sediment transport competence or for rating habitat quality. In this case, the MSHA metric *substrate* may provide the important habitat information needed. However, the MSHA metric *substrate* may still be inadequate when coarse substrates are present but are <80% of a given stream type. As an example, the presence of gravel in a run may not be recorded if sand dominates. Gravel is an important habitat component that allows for the successful reproduction of spawning fish that utilize this substrate type, especially in low-gradient streams where riffles are absent. Therefore, a habitat assessment should indicate when gravel is present—even if it is only present in a small area.

Rabeni (2000) suggests that it is important to sample and note the presence of all available habitats found in the stream, even if the habitat amount is minor compared to other dominant habitat types. The author suggests analyzing these minor habitats separately and to treat them as if they were equal in abundance to the dominant habitat types in order to increase their significance and ability to explain differences in fish communities between streams. Therefore, I recommend that habitat quality assessments should record the relative percent of substrate types present in the reach as a supplement to the MSHA, similar to the methods outlined by Ohio EPA (2009) for their Primary Headwater Habitat Evaluation. This would allow smaller substrate habitat units to be recorded. Percent substrate types should only be included if their presence and density is "ecologically meaningful" (Rabeni 2000). In other words, of sufficient size and density to be utilized by aquatic organisms (e.g., gravel only noted if it is concentrated over an adequate area for fish to utilize for spawning).

Geomorphic variables and habitat quality

For all three watershed groupings, substrate variables were strongly associated with habitat quality. The substrate variables that were the most strongly associated with MSHA varied by watershed grouping; however, all substrate variables were comprised of larger substrates (e.g., *percent cobble, percent boulder, percent rock*). This result was not surprising given that the MSHA substrate metric comprises up to 20% of the total point score for MSHA where the metric assigns higher score values to the larger substrate types present within each stream feature. *D50* and the percent of the different substrate sizes that are collected during a pebble count or visual estimation (Ohio EPA 2009) may provide important information in characterizing substrates available for habitat development (e.g., channel morphology, riffle and pools) as well as provide a method for observing changes in substrate composition over time. A pebble count or an accounting of the percent of different size substrates observed should be included in a habitat assessment or a channel stability assessment.

Summary of research findings

The objectives of this study were a) to determine whether or not an existing channel stability assessment tool was applicable to low-gradient stream in Minnesota, b) whether a subjective channel stability assessment tool could be a time-efficient approach to gaining a better understanding of the geomorphic condition and hydrologic stability of the stream channel, and c) whether this information can be informative to the SI process through exploring the associations between channel stability, stream health and habitat quality.

I found that the PSI, in its original form, has some utility in characterizing channel conditions observed in streams found in Minnesota and requires minimal field time to collect. However, some metrics did not seem applicable to certain low-gradient conditions observed, especially where substrates were dominated by sands or where glacial relicts were present. I also found that certain metrics were not effectively characterizing conditions related to hydrologic instability (e.g., *channel capacity* in incised streams, bank failure caused by groundwater seeps) requiring modification to the PSI to more accurately describe conditions found in Minnesota. Additional metrics should also be considered (e.g., f*loodplain extent, degree of incision, stage of channel evolution*) to better link the conditions of channel instability observed in alluvial systems with biological stressors.

The results of this study suggest that channel stability is important for understanding the difference in biological communities and stream health between streams and that channel stability may be related to habitat quality. The significant correlations between FIBI and PSI for SNAKE and COMBINED demonstrate that channel stability is potentially an important driver of fish community health and could be an causal link for Stressor Identification; however, the results for REDWOOD were more difficult to interpret. For SNAKE, stable channels were more often associated with larger substrates and better habitat quality as indicated by higher MSHA scores, greater percent pool and riffle habitat, greater diversity and amount of fish cover, and less embeddedness; whereas, unstable channels were more often associated with increased bank erosion, unstable or embedded substrates, less fish cover, and less variable channel morphology. This gradient in stream conditions was associated with biological integrity. For REDWOOD, the association between biological integrity and a gradient channel stability and habitat quality was more variable in part due to heavy siltation at some reaches and potential curvilinear associations with channel stability indicators where an intermediate degree of scouring and flow-deflection by woody debris may have created optimum habitat conditions related to residual pool volume, flow variability, and fish cover. The lack of a strong association between channel stability and stream health in REDWOOD could potentially be related to a flashy hydrologic regime associated with agricultural land use practices or water quality issues not captured by one-time grab samples.

Streams used in this study also demonstrated that channelized streams have the capacity to support healthy fish communities and habitat quality that were similar to natural streams found in both watersheds. Additional research is needed that demonstrates the financial and ecological benefits of sizing ditch systems appropriately to not only remove water quickly from fields but to also allow channels to rework meander sequences and develop within channel vegetated floodplains that can ameliorate nutrient loading to streams and support quality habitat for fish and invertebrate communities within attendant watersheds as well as downstream receiving water bodies.

Potential predictors of fish community health

One of the objectives of this study was to identify potential predictors of fish community health from channel stability indicators (Table 2-23), habitat quality metrics (Table 2-24), and select geomorphic variables (Table 2-25). This information will aid in developing assessments that are tailored to identify indicators of channel stability that may directly or indirectly affect stream fish community composition and stream health. I also explored whether other geomorphic variables could also be predictors of fish community health that should be collected with either a channel stability assessment or habitat quality assessment.

Table 2-23: Summary of significant channel stability predictors of FIBI for COMBINED, REDWOOD, and SNAKE. Asterisks denote the percent (%) of variance explained (R^2 for single predictors or *Adj* R^2 for polynomial models where * = >16%, ** = >36%, *** = >64%, and *** = >81%). In parentheses is the direction and shape of the regression line: (+) = positive, linear; (-) = negative, linear; and (^) = curvilinear. MLR denotes the variable or group of predictor variables selected with multiple linear regression.

Channel Stability Metrics	**COMBINED**	**REDWOOD**	**SNAKE**
CEM	**(+)		***(+) /***(^)
PSI	**(-)		**(-)
UPPER	**(-)		**(-)
LS	*(-)	*(-)	**(^)
MW	*(-)		**(-) / ****(^)
DJP			*(-)
VBP	**(-)		**(-) / **(^)
LOWER	*(-)		**(-)
CC	*(+)		
BRC		**(^)	***(^)
OFDST		*(+)	*(-)
C	*(-)		**(-)
D			*(-)
BOTTOM	**(-) MLR	**(^) MLR	***(-)
RA			
Br	*(-)	**(^)	**(-)
CPP			
BSD/PSM	**(-)	***(^) MLR	**(-)
SD	**(-)		***(-)
CAV	*(-)		**(-)
[UPPER+BOTTOM]			****[MLR]
[SD+CAV]			****[MLR]
[LS+SD]	**[MLR]		
[MW^2+Br]			****[MLR]
[MW+DJP+C]			****[MLR]
Total channel stability predictors	**15**	**6**	**21**

Table 2-24: Summary of significant habitat quality predictors of FIBI for COMBINED, REDWOOD, and SNAKE. Asterisks denote the percent (%) of variance explained (R^2 for single predictors or *Adj* R^2 for polynomial models where * = >16%, ** = >36%, *** = >64%, and *** = >81%). In parentheses is the direction and shape of the regression line: (+) = positive, linear; (-) = negative, linear; and (^) = curvilinear. MLR denotes the variable or group of predictor variables selected with multiple linear regression.

Habitat Quality Metrics	COMBINED	REDWOOD	SNAKE
MSHA	***(+)	**(+)	*(+)
SLU	**(+)	*(+)	
RIPARIAN	***(+)	**(+)	
RW	**(+)	*(+)	*(+)
BE	*(+)		**(+) / ***(^)
Sh	*(+)		
INSTREAM	**(+)	**(+) MLR	*(+)
Su	*(+)	**(+)	
Em	**(+)	*(+)	**(+)
ST		*(+)	
COVER	**(+)		**(+) MLR
CT	**(+)		**(+) / ****(^)
CA	**(+)		*(+)
CHANNEL MORPH	*(+)	*(+)	
DV			
CS	**(+)	*(+)	***(+)
VT			
Si			*(-) / ***(^)
PW/RW		*(+)	
CD	*(+)	**(+)	
[RIPARIAN+INSTREAM+COVER]	****[MLR]		
[RW+CS]	****[MLR]		
[Em+ST+PW/RW]		**[MLR]	
[Su+CS]		**[MLR]	
Total habitat quality predictors	**17**	**14**	**10**

Table 2-25: Summary of significant geomorphic variable predictors of FIBI for COMBINED, REDWOOD, and SNAKE. Asterisks denote the percent (%) of variance explained (R^2 for single predictors or *Adj* R^2 for polynomial models where * = >16%, ** = >36%, *** = >64%, and *** = >81%). In parentheses is the direction and shape of the regression line: (+) = positive, linear; (-) = negative, linear; and (^) = curvilinear. MLR denotes the variable or group of predictor variables selected with multiple linear regression.

Geomorphic Variables	COMBINED	REDWOOD	SNAKE
%pool			*(+)
%riffle			
%pool&riffle	*(+)		**(^)
channel slope		*(+)	
gradient by map			
sinuosity by map			
D50	**(+)	**(+) MLR	*(+)
D84	*(+)		
%silt/clay			
%sand			*(-)
%gravel			
%cobble	*(+)		*(+)
%boulder			
%cobble&boulder	*(+)		
%rock	*(+)		*(+)
[D50+sinuosity+%pool]	**[MLR]		
[D50+%pool&riffle]			***[MLR]
Total geomorphic predictors	**7**	**2**	**7**

My results indicate that there were variables that were significant predictors of FIBI across watershed groupings. Channel stability predictors of biological integrity generally described the angle and condition of banks and stability of bottom substrates. Habitat quality predictors described the extent of the riparian, the condition of the instream zone, degree of embeddedness, and channel stability. Mean substrate size (*D50*) was the only geomorphic variable that was the best predictor across watershed groupings.

For SNAKE, fish community health was best predicted by channel stability indicators more often than habitat quality metrics or geomorphic variables. The strongest channel stability predictors included variables that described channel evolution, bank stability, and stability of bottom substrates. The best habitat predictors included variables and described diversity and amount of fish cover, degree of bank erosion and sinuosity, and channel stability.

For REDWOOD, fish community health was best predicted by habitat quality metrics more often than channel stability indicators. The strongest FIBI predictors were habitat metrics associated with the riparian extent, condition of the instream zone (e.g., substrate type, embeddedness, diversity in channel morphology) and overall channel stability. The PSI metrics that were the strongest potential predictors of FIBI in REDWOOD were metrics associated with the angle of banks, presence of woody debris flow deflectors, and substrate stability, although the shape of the association was non-linear and should be explored in future studies.

The strongest predictors selected with MLR also varied by watershed grouping. For COMBINED, MSHA variable combinations RIPARIAN+INSTREAM+COVER and *riparian width +channel stability* explained >80% of the variance (*Adj* R^2). For REDWOOD, MSHA zone INSTREAM explained 53% of the variance (R^2). In contrast, for SNAKE, multiple predictor variables and metrics explained >80% of the variance (*Adj* R^2): three with PSI variables, one with MSHA zone COVER, and one geomorphic combination. The best predictor model was *mass wasting* and *brightness* which explained 90% of the variance in FIBI.

Recommendations for future studies

More research is needed that incorporates diverse disciplines such as biology, chemistry, ecology, and geomorphology in order to characterize optimum habitat conditions related to the flow regime, thermal regime, water quality, and suitable substrate conditions required for optimum habitat and biological potential in different stream types. Following this, habitat quality and channel stability assessment tools should be field tested and modified to ensure that these tools are appropriately rating local conditions so that deviations that are a likely cause of impairment can be identified. However, before the benefits of a regionally tailored channel stability assessment can be realized, stream biologists and geomorphologists need to define a baseline of what constitutes the best biological potential for different stream types as it relates to both optimum habitat quality and stable stream conditions. Following this, more research is needed that relates biological condition to changes in habitat quality associated with changes in channel stability in different regions, stream size, and stream types. During a Stressor Identification, it may be important to compare habitat and channel stability conditions between streams where the biological condition is impaired with one where it is not. If streams occur in two different areas of the watershed, the stream setting may be different relative to inherent differences in substrate type due to geology, gradient and associated transport capacity--as well as position in the watershed (e.g., zone of sediment supply, transfer, or deposition). These inherent differences could result in different expectations for optimal habitat quality and channel stability. A more appropriate comparison would be one where the streams are relatively similar in geology and location in the watershed and the only measured difference is related to channel stability and/or habitat quality. It may also be important to characterize the type of disturbance (Lake 2000) and where the biological communities being compared are currently located along the disturbance response gradient (e.g, at lower end of ramp disturbance) and in relation to adjacent water-bodies with better biological condition and species pools. This is necessary in order to understand community differences that may exist between streams being compared s well as the opportunities for recovery (e.g., loss in number of sensitive individuals or complete loss in sensitive species). Additionally, improvements in biological condition as a response to improvements in channel stability and habitat quality may only be possible in settings where poor water quality is not the limiting factor —although certain restoration practices can also mitigate stress associated with high nutrient and sediment loads (e.g., reconnecting floodplains).

Different components of biological communities (e.g., fish and insects) are responsive to different types of stressors (Plafkin et al. 1989, Lammert and Allan 1999, Norton et al. 2000). A future study should test the association between channel stability and habitat quality using both fish and macroinvertebrate assessments. Comparing the response in both communities may be more instructive for determining which components of aquatic communities are more sensitive to various types of stress--including channel stability. Understanding how different taxa and trophic groups of invertebrates and fish may respond to a gradient in channel stability and habitat quality is necessary since both fish and macroinvertebrates are used in biological assessments for streams in Minnesota. Since fish are highly mobile, they may reflect the conditions encompassing a larger portion of the stream network within a given region or watershed; whereas, macroinvertebrates may be more reflective of local conditions in habitat (Plafkin et al. 1989). Potentially, given these differences, macroinvertebrates may be more sensitive to a gradient in channel stability and associated habitat quality, at least where unstable channel conditions are localized and not system-wide. Where channel instability is localized, fish that require clean, coarse substrates for spawning may find them intermittently within a moderately unstable stream reach or other adjacent tributaries within the watershed; whereas; during other times of the year, fish may migrate within unstable reaches for feeding and seeking out thermal refugia. Hence, macroinvertebrates may be a more direct measure of localized conditions of channel stability than fish. This hypothesis should be tested in future studies.

Management implications: biological assessment, Stressor Identification and TMDLs

Since the Clean Water Act of 1972, many of the Nation's streams are now cleaner due to the regulation of point-source pollution (EPA 2000); however, many of our Nation's streams are still not meeting one or more designated uses due to the increasing magnitude of unregulated non-point source pollution.

Karr and Yoder (2004) provide the following definitions for *pollutants* and *pollution* as referenced in the Clean Water Act [Sections 502(6) and 502(19)]:

> "*Pollutants* are substances added to waters by human activity"; whereas, " *pollution* [is] human-induced alteration of waters caused by pollutants as well as non-pollutant agents, such as *flow alteration, loss of riparian zone, physical habitat alteration*, and introduction of alien taxa." (Italics added by author for emphasis)

Bioassessment is an effective screening tool for identifying non-point source pollution since biological communities (e.g., fish, invertebrates, algae) are sensitive to environmental stressors such excess nutrients, habitat alteration, flow alteration, and excess sedimentation as a consequence of anthropogenic activities within the watershed (Karr 1981). The composition of aquatic communities possessing biological integrity will remain relatively constant when exposed to slight changes in water quality and habitat conditions, such as a slight increase in diel oxygen flux due to increases in primary productivity as a consequence of excess nutrient loading, or variations in stream flow due to episodic flood conditions (pulse disturbance, Lake 2000). Ohio EPA (2006) states that an impairment occurs when the stream's . . . "capacity to handle stressors is exceeded. This occurs when the external inputs to the stream become excessive, or when the stream characteristics are altered so that it can no longer assimilate these stresses without harm to the aquatic life". When relatively unimpaired biological systems are under sustained and magnified stress (press disturbance, Lake 2000), the composition of the community will change to a degree that is considered a significant deviation from an expected, natural biological composition. Index of Biotic Integrity metrics, if well chosen, can detect these changes.

Although bioassessments are useful for identifying biological impairments, they do not often identify the source, mechanism, or pathways of the impairment (USEPA 2000a, Norton et al. 2003, D'Ambrosio et al. 2009). Rabeni (2000) likens knowledge of a biological impairment without identifying the underlying causes to a doctor diagnosing that a patient has a high fever but not identifying the cause of the fever, which is obviously required for prescribing the correct remedy.

Recent TMDLs have identified changes in the natural flow regime as a stressor and cause of biological impairment [e.g., Big Darby Creek Watershed TMDL (Ohio EPA 2006), Olentangy Creek Watershed TMDL (Ohio EPA 2007)]. An anthropogenically altered flow regime can be considered a disturbance (Resh et al. 1998, Lake 2000). Resh et al. (1998) characterize disturbance as an event where the frequency and intensity are outside of normal variation, since biological communities are adapted to a range of conditions that are anticipated and expected (e.g., annual high flow). Life history requirements for many species are timed to minimize the negative effects of these expected disturbances, and for some species, these events are necessary for successful spawning and reduced competition for resources. However, when watershed land use activities gradually increase and alter the timing and magnitude of flow conditions to such a degree that the resistive and assimilative capacity of the stream is breached, this press disturbance can result in moderate to severe habitat degradation or water quality impairments, results in a loss of sensitive species. These types of disturbance may elicit a ramp or press response in the biological community (Lake 2000) where there is no opportunity for recovery. Examples of a ramp or press with a lack of biological recovery include the "urban stream syndrome" (Meyer et al. 2005, Walsh et al. 2005). Agriculturally intensive watersheds can experience similar effects as described by the urban stream syndrome where row-crops are the dominant land use and extensive networks of drain-tile have significantly altered the natural flow path. Both of these examples can increase the magnitude and intensity of flow conditions related to rain events by circumventing natural hydrologic pathways with shallow subsurface stormwater conduits (i.e, stormwater pipes and draintiles). The consequence of these altered flow paths may be a loss of hydrological--and ecological--stability. Hydrologically, watersheds with human altered flow-paths may experience more frequent and flashier hydrographs as stormflows are routed through pipes or draintile thereby circumventing contact time with the soil profile. The intensified magnitude in flow energy can lead to channel instability, altered channel morphology (Blann et al. 2009), and decreased summer base flows (Roy et al. 2005). Ecologically, stormflow that quickly enters pipes and bypasses contact with the soil profile may limit the ability for microbes and plants to mediate nutrient delivery to streams (e.g., nitrates, Blann et al. 2009, Logan et al. 2004). Excess nitrates can fuel nuisance algal blooms, plant growth, result in periods of oxygen deficiency (Rabalais 2002), and affect drinking water. These aforementioned conditions can reduce habitat, food, and water quality required to support a diverse aquatic community. Ultimately, the biological stress associated with these magnified conditions can lead to dominance of tolerant species (Meyer et al. 2005, Walsh et al. 2005). Changes to the aquatic community can translate into lower Index of Biotic Integrity Scores (IBI, Karr et al. 1986) and lead to 303(d) listing of streams for biological impairments. Disturbances of this magnitude and type can have long lasting effects on the composition of the biological community unless the stress is alleviated and/or rehabilitation measures are implemented.

Changes in hydrologic regime and consequent reduction in stream community health for urban watersheds have been documented (Goetz and Fiske 2008, Meyer et al. 2005, Nilsson et al. 2003, Roy et al. 2005); however, little research has been conducted on the consequence of a change in hydrologic regime on stream community health in highly disturbed agricultural dominated watersheds. Perhaps this is partly due to the issue of attempting to decouple multiple stressors acting simultaneously at various scales (i.e., riparian encroachment, local nutrient and fertilizer applications, change in flow regime as a consequence of extensive networks of draintile, loss of perennial vegetation). The difficulty in elucidating strong associations may also be dependent on a combination of regional factors (e.g., surficial geology and substrate type) and strong underlying land use factors (Wang et al. 1997). More research is needed that attempts to decouple and explore the biological response to a change in flow regime related to agricultural land use practices.

In order to develop the causal links between land use activities and a loss of biological integrity, attempts should be made during biological sampling activities to record evidence of mechanisms or pathways of potential biological stressors, especially indicators of flow alteration and mechanisms resulting in a loss of habitat quality. Items could include calculation of percent impervious in the watershed, percent disturbed land use in close proximity to the stream channel (e.g., row-crop cultivation in riparian zone, landscaping to stream edge), estimation of the density of drain tile in the subwatershed (where county records exist) and evidence of changes in sediment transport capacity or the stream's hydrologic regime (e.g, channel instability). Data collection strategies have been suggested (Fitzpatrick et al. 1998, Kaufmann and Robison 1998, Asmus et al. 2009, Rowe et al. 2009) that inventory the quality of habitat and fluvial geomorphic condition of the stream channel, including evidence of channel instability. These assessments can vary considerably in their approach and time investment in the field. While more detailed data collection can enhance knowledge of a stream's condition, the level of detail needed for Stressor Identification is still being explored and debated. Research investigating to what degree stream geomorphic condition, and channel stability influence habitat quality and biotic communities exist (Shields et al. 1994, Maul et al. 2004, Sullivan et al. 2004, Yarnell et al. 2006, Rowe et al. 2009); however, the association between channel stability, habitat quality, and biological communities remains poorly understood (Imhof et al. 1996, Petts 2000, Sullivan et al, 2004, Yarnell et al. 2006). This study also demonstrated that the shape of the association may also vary between linear to curvilinear to wedge-shaped requiring careful consideration of statistical approaches that appropriately describe these potential relationships.

During Stressor Identification, habitat quality is often listed as a candidate cause of a loss of biological integrity. However, a Stressor Identification investigation must consider whether the lack of habitat quality is a natural condition (e.g., a low-gradient, sand or silt dominated prairie stream) or is a negative consequence of anthropogenic activities (e.g., channelization, loss of riparian, change in flow regime due to land use activities). In order to distinguish between natural conditions of low-habitat quality that is a result of instream, near-stream, and watershed impacts, additional information is needed, such as descriptions of channel condition (e.g., channelized or natural) and potential causes of bank erosion and excess sedimentation (e.g., animal trampling, extreme flow events, geomorphically unstable stream channels). At present, some state biological monitoring programs (e.g., Minnesota) are reviewing their existing biological monitoring approach to determine whether to integrate some type of qualitative channel stability assessment along with collection of qualitative habitat assessments. Implementing a subjective channel stability assessment at time of biological assessment could assist in determining reference or least impacted condition for IBI development, during assessment (e.g., when attempting to elucidate whether temporal differences in IBI scores are related solely to inherent variability in the biological community or are related to anthropogenic changes adjacent to the stream channel or within the watershed), as a screening tool for characterizing differences between biologically impaired and unimpaired reaches for Stressor Identification, and indicating which reaches and watersheds may require more intensive study (e.g., WARSSS, Rosgen 2006). Streams with impaired biota should be also viewed during different seasons and at different flow stages to determine what are potentially the strongest limiting factors at play in these streams (e.g., water temperature, water chemistry, flow refugia, substrate mobility, embeddedness).

It is also necessary for researchers to identify the hydrologic and geomorphic conditions that are required to maintain or develop optimum habitat potential. Results of this study indicate that habitat potential may be strongly related to substrate condition, diversity and quantity of cover, and late summer residual pool volume and that the quality of these habitats may be inextricably linked to channel stability. Additional research is needed that empirically identifies the causal links and thresholds of stress that negatively affect specific components of the biological community.

Conclusion

Streams are a product of their environment (Platts 1974, 1979). Stream biotic potential may be directly linked to instream as well as near-stream habitat, which is dependent on geology, hydrology (Ziemer 1973), watershed vegetation, and land use. Changes in stream discharge regime or gradient can cause a cascade of channel geomorphic changes (Lane et al. 1955, Schumm et al. 1984, Rosgen 1994, Simon 1989) that can cause a loss in habitat quality and ecological benefits of the attendant floodplain (Oppermann et al. 2010). Changes in channel stability and consequent changes in habitat quality may cause an imbalance in the biological community that could translate into lower IBIs scores and stream impairments. Integration of seemingly disparate disciplines (e.g., biology, hydrology, geomoporphology) is necessary for biological stressors related to channel morphology and habitat quality to be correctly identified so that causal links can be developed. This will result in aptly targeted TMDL implementation plans.

The ability of a stream to resist morphological adjustments is related to geology, substrate, vegetation and hydrology. Alluvial streams composed of fine substrates associated with glacial till, outwash, and loess are more sensitive to slight changes in hydrology and vegetative bank protection. With a slight increase in hydrologic regime or gradient, alluvial streams may downcut and disconnect from floodplains which can exacerbate bank erosion, substrate mobility, widening, a loss of transport capacity, and aggradation or embeddedness. A subjective assessment tool that adequately rates these channel stability indicators often observed in low-gradient streams with fine substrates is needed for many regions in Minnesota as well as much of the Midwest. While more detailed geomorphic assessments are necessary for restoration objectives, the time requirements for collecting more detailed geomophic measurements may be too time consuming for most state biological programs to implement at every site where biological communities are sampled. A time efficient channel stability assessment tool affords the opportunity for biologists and water quality managers with some degree of training to characterize basic indicators of floodplain connectivity, degree of incision, bank and bottom resistance to erosion, and evidence of degradation and aggradation. This elementary information may be useful for selecting reference streams for IBI development, biological assessment, Stressor Identification of biological impairments, and guiding where more advanced geomorphic surveys are needed. It is my hope that The *Channel Condition and Stability Index* included in Chapter 3 will aid this effort.

Although this study was exploratory in nature, my results suggest that characterization of the hydrologic and geomorphic stability of the stream channel may be one important aspect for identifying the causal links between land degradation, sedimentation, habitat loss and biological stress contributing to or resulting in a biological impairment. Strong correlations were found between channel stability, habitat quality, and biological integrity. These results support the pairing of channel stability assessments with habitat quality assessments. For streams in SNAKE the relationship between channel stability, habitat quality and biological integrity was linearly associated; however, for REDWOOD, a potential curvilinear response was found. It is possible that an intermediate degree of scouring, flow deflection by woody debris, and deposition may provide optimal habitat conditions that support the best biotic potential in low-gradient alluvial streams dominated by fine substrates. More research is needed that identifies and characterizes the degree and type of instability that is biologically beneficial and sustainable (does not lead to excess degradation and aggradation).

The intermediate links between watershed land use, channel stability, habitat quality and biological integrity need to be identified and further explored. This information would support the hierarchical theory that geomorphology and hydrology interact within a natural cycle of variation (i.e., channel stability) that creates and maintains diverse habitat components (i.e., habitat quality) that, in turn, support biological integrity (e.g., Poff et al. 2006, Asmus et al. 2009). Land use or other influences in the watershed that alter the hydrologic and sediment regime can initiate a cascade of channel geomophic changes that can result in a change in channel stability and habitat quality (Burcher et al. 2007). Results of this study indicate that these changes can either improve or be detrimental to biological integrity depending on the situation and consequence of instability (e.g., unstable channelized reach developing habitat complexity through bank erosion and point bar formation, woody debris flow deflectors increasing localized scour and residual pool depth).

Results of these studies will better inform the TMDL process for improved understanding as to the cause(s) and mechanisms of biological impairments related to non-point pollution stressors involving changes in the hydrologic regime, sediment delivery, and habitat quality. Establishing these causal links should result in more cost- effective remediation strategies, improved biological condition, and the de-listing of streams--as well as increased protection for presently unimpaired or minimally degraded reaches. The ultimate goal of these efforts being improved water quality, protection of high value resource waters, and a more balanced, integrated--and sustainable--watershed approach.

A thing is right when it tends to preserves the stability,
integrity, and beauty of the biological community;
it is wrong when it tends otherwise.

~ Aldo Leopold (1949)

CHAPTER 3

Channel Condition and Stability Index (CCSI):

A modified channel stability assessment for low-gradient alluvial streams

This chapter is the result of a collaborative project with the Minnesota Pollution Control Agency (MPCA) and was undertaken while I was both a student of the UMN and a staff member of the MPCA. The assessment tool outlined here was a collaborative effort with Dr. Joe Magner and other UMN and MPCA staff that were seeking modifications to the original PSI to more appropriately describe field conditions in low-gradient streams in Minnesota.

Guidance Manual for the Channel Condition and Stability Index

The Channel Condition and Stream Stability Index (CCSI) presented here is designed to be a fast and cost-effective qualitative screening level tool that will be informative to staff involved in water quality assessment and Stressor Identification (EPA 2002) of biological and chemical impairments. This protocol was developed through consulting other existing channel stability assessments (Pfankuch 1975; Simon and Downes 1995; Rosgen 2006; VANR 2007; Magner et al. 2010) and includes modifications that attempt to better characterize physical indicators of channel condition and stability observed in low- to mid-gradient streams in Minnesota. The guidance manual provides a background in channel stability concepts and provides detailed descriptions of each metric included on the CCSI field assessment sheet.

Regional application

The CCSI was developed specifically for low-gradient (< 2% channel slope) alluvial streams in geologic regions in Minnesota that are carved into deposits of loess, glacial outwash, and glacial till, which are generally comprised of finer materials such as silt, clay, sand, gravel with occasional cobble and boulder. The focus of this assessment tool is for "C" stream types (Rosgen 1994). These low-gradient, alluvial streams continue to rework the bottom sediment as they meander back and forth within their belt width over time and build low-flow channels and inner berms. The metrics are designed to detect local and watershed alterations that lead to aggradation or degradation. Due to the nature of fine, easily eroded and transported sediment that typically comprise the bed and banks, these low-gradient alluvial streams are generally more sensitive to changes in watershed hydrology and adjacent riparian vegetation than streams cutting through sedimentary limestone, carbonaceous rock, or bedrock. For these higher gradient streams (generally A or B stream types), the original *Pfankuch Stability Index* (PSI, Pfankuch 1975) could be applied. Regions for the PSI could include high-gradient streams within the Driftless Area of the Lower Mississippi River Basin in Minnesota, Iowa, Illinois, and Wisconsin and streams in the basalt region in the Lake Superior River Basin in north-east Minnesota. Some regions will have considerable variation in stream types and consequently, both the CCSI and PSI may be applied within the same watershed. Each reach should be rated using the appropriate tool according to stream type. The CCSI does not apply to low-gradient stream types that typically do not have upper banks to rate and flow-through wetlands (stream type "E"). For these streams, note the stream type and provide general comments on the riparian condition on the *Stream Condition & Stressor Identification (SSCI)* form.

Training in Field Methods and Regional Context

The ability to distinguish between natural stream conditions and indicators of channel instability or disequilibrium (excess aggradation or degradation) requires more than one training event to develop. The trainings should involve readings and presentations on the basic principles of fluvial geomorphology and infield training with an experienced geomorphologist. The streams selected for training should include a range of stream sizes and types that an trainee will likely assess during that sampling year. Visiting multiple locations with a trained geomorphologist will assist the assessor in developing a perspective on what constitutes a stable verses an unstable channel under different geologic settings, climate regime, stream manipulation practices (i.e., channelization or damming) and scale (i.e. small or large rivers).

<u>Equipment list</u>: Verify that a guidance manual, forms, clipboard, pencils, wooden measuring dowel or metal probe, measuring tape, camera, and GPS are present before commencement of this procedure. If a Regional Hydraulic Geometry Curve is available for the region of interest, a list of field numbers with corresponding drainage areas (DA in mi^2) of the reaches being sampled and the RHGC will also need to be acquired before heading into the field.

<u>Length of assessment reach an index of collection</u>: The location and length of the sampling reach is determined during site reconnaissance (see SOP—**Reconnaissance Procedures for Initial visit to Stream Monitoring Sites**). The MPCA will be evaluating channel condition and stability during the sampling index period for macroinvertebrates (August to September). Unless otherwise instructed, observations of physical channel condition should be limited to the sampling reach (35 times the mean wetted width, 150m up to 500m). The CCSI should be completed when streams are at or near base flow immediately after macroinvertebrate sampling. Physical stream characteristics are scored using a qualitative and semi-quantitative observation based method (modified from Pfankuch 1975, Simon and Downes 1995, VANR 2007, Rosgen 2006, Magner et al. 2010).

Measuring mechanical shear strength using a probing rod: To learn how to interpret the probe data you will need to spend some time in the field observing and learning from a geomorphologist the art and science of fluvial sediment dynamics, observations, and interpretations.

<u>Worksheet</u>: Observations are recorded on the ***Channel Condition and Stability Index*** (CCSI) field form. A copy of the form is attached (Table D-2) and guidelines for filling out the worksheet are described in this document.

In addition to the CCSI metrics, a few additional observations will be recorded on the backside of the form to aid in Rosgen channel typing: *substrate composition* and measurements of a cross-section. This information can be used by a Phase II assessor to characterize the stream using the Rosgen Stream Classification (1994).

Estimation of bankfull flow – A relatively close estimation of the bankfull flow line (1.5 RI flow) is needed in order to properly assess the CCSI metrics for Upper Banks verses Lower Banks and for determining the CEM stages observed. A RHGC developed for the region of interest, if available, will greatly assist in locating the height of bankfull. Before heading to the field, see if an RHGC has been developed for the region in which biological surveys are being conducted. Note: If a RHGC is available, it will also be necessary to have the DA (units in mi^2) of the surveyed reaches prior to heading into the field.

When in the field, use the DA of the reach to find the expected cross-sectional area (CSA) on the RHGC. After the CSA is determined, locate a riffle within or just upstream of the survey reach or, if there is no riffle, find the straightest, narrowest, and shallowest area of the reach. In low gradient sinuous streams, this type of morphology is generally found between two meander bends and is referred to here as a "cross-over" where the thalweg shifts location from one bank to another (VANR 2007). At the riffle or cross-over, see if you can first see any indicators of the bank-full flow line. Indicators of annual high flow may include debris caught in branches, lateral banks with new deposition, the root line of willow, alder, or other riparian vegetation (Harrelson et al. 1994). To locate these bankfull indicators when tall grasses are dense, walk the bank and note the location of bank inflection which may indicate an active terrace or an abandoned floodplain terrace. Besides cobble and boulder, riffles can also be comprised of gravel and larger sand particles. In sand and gravel bed streams, a shallow area with slightly faster flow can produce areas of clean gravel substrate. Look for and note these locations as you are sampling for macroinvertebrates or conducting a pebble count.

Channel cross-section – After bankfull indicators have been located, estimate the bankfull width (BfW)and bankfull mean depth (MeanBfD). Compute the cross-sectional area (CSA) and then compare the field estimated CSA to the CSA on the RHGC. If the two CSAs are in agreement, record the cross-sectional dimensions on the backside of the worksheet and illustrate the cross-section with terraces and floodplain. Draw a line for the height of bankfull. and record the version of the curve that was used. If the instream bankfull indicators and bankfull flow line determined by using the RHGC are not in agreement, adjust the bankfull height using the width until the infield CSA matches the expected CSA from the RHGC. Be mindful that the stream may be incised or is under the influence of upstream or downstream wetland and lake storage that may cause the infield CSA to not perfectly match the CSA from the RHGC.

Substrate composition (%) - Conduct a pebble count or visually characterize the percent of substrate types observed in the spaces provided. Both mineral and organic fractions of the substrate are estimated. This information can be used to understand inherent differences in biological communities or habitat quality given the availability of coarse substrates and size classes or limitations to habitat potential due to high prevalence of silt. The substrate composition can also be used to characterize the stream using the Rosgen Stream Classification. Woody debris and muck are included here for Stressor Identification, since a large percentage of these organic materials can influence the concentration of dissolved oxygen through decomposition.

For reference, the substrate types are included below using the size descriptions from VANR (2007). The traditional pebble count sizes are modified here for a basic level generalization of substrate size for stream classification (Rosgen 1996) and habitat quality assessment (Kaufmann and Robison 1998):

<u>Bedrock</u>: larger than a car (Volkwagen Bug)

<u>Boulder</u>: >256mm (basketball to Volkswagen Bug)

<u>Cobble</u>: 64 – 256 mm (tennis ball to basketball)

<u>Coarse Gravel</u>: 16-64 mm (marble to tennis ball)

<u>Fine Gravel</u>: 2 to 16 mm (peppercorn to marble)

<u>Sand</u>: <2 mm (smaller than a peppercorn)

<u>Silt</u>: fine inorganic material that is dark brown and slightly gritty and greasy to the touch (smaller than sand). Will not hold its shape when compacted into a ball.

<u>Clay</u>: fine inorganic material that can form a ball and will hold its shape when pressed into a ball or band.

<u>WD/Detritus</u>: organic matter that forms a sizeable layer on the bottom to be considered part of the substrate composition (e.g., wetland with decomposing vegetation or stream with high volume of woody debris).

<u>Muck</u>: black, organic matter that is in the final stages of decomposition. Visual particles of muck will disintegrate when rubbed between fingers. Muck is often found in channels within or downstream of wetlands.

Tape Down Distance (TDD) - Take the TDD measurement and record the location information and measurement (in 1/100ft) on the backside of the CCSI worksheet in the space provided. The TDD measurement recorded at time of sampling can be compared during future sampling events to infer whether flow conditions are comparable or different.

General Comments – Describe stream observations on the general condition of the channel and riparian areas. Record if there were photos taken of conditions observed.

Initial Field Observations Prior to Rating the Assessment

A Channel Evolution Model (CEM) has also been included as part of the assessment process. Understanding the concepts and controls of the CEM will aid the assessor in determining whether conditions are considered part of the natural process of stream migration or are considered indicators of instability. Before starting the assessment, an assessor should first walk the stream and observe indicators of aggradation or degradation or whether the sediment supply is in equilibrium with the sediment transport capacity Next, as part of the assessment scoring process, the main indicators and mechanisms of aggradation or degradation should be rated (scored) in relation to the degree that they contribute to the current conditions of stability or instability observed.

The Channel Evolution Model (CEM)

Disequilibrium and channel instability occurs when watershed disturbances are collectively magnified in the hydrologic regime and expressed in the channel and sometimes the valley health (e.g., conditions alter riparian vegetation). The disequilibrium often results in a change in stream gradient and/or sediment transport capacity (see Figure 3.1; Lane's Balance).

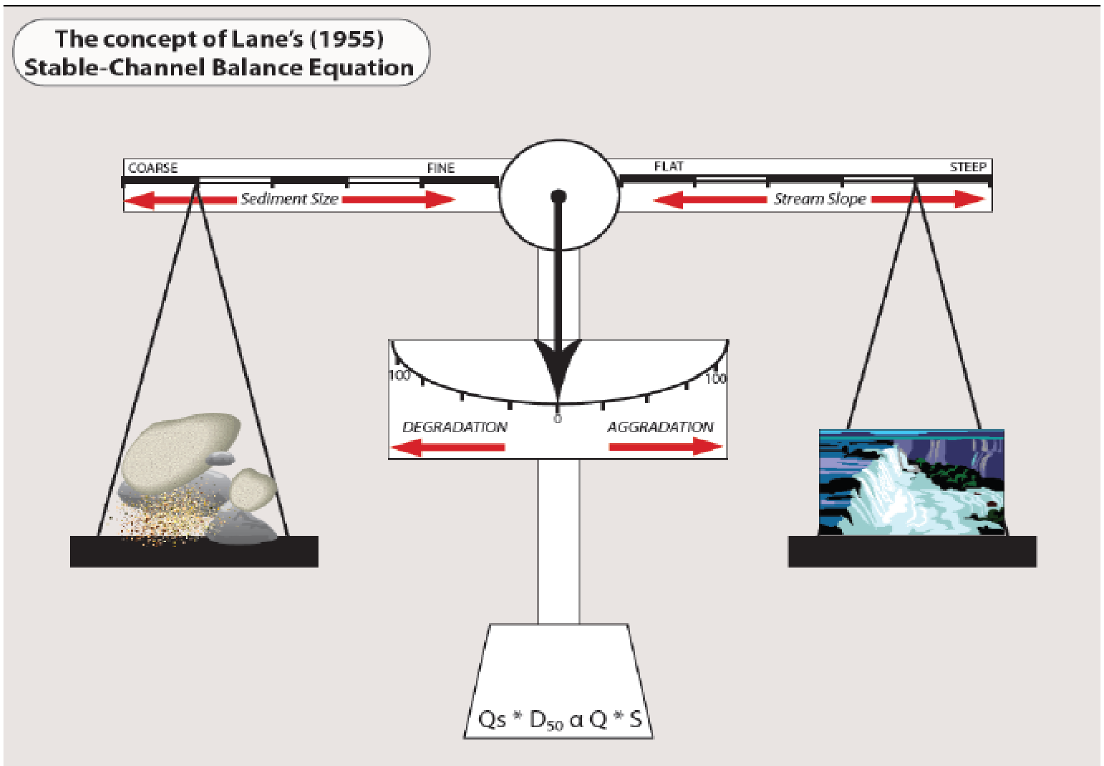
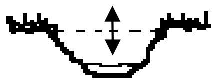
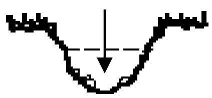
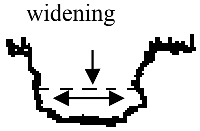
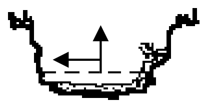
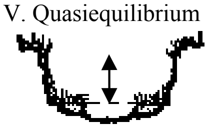


Figure 3.1: Lane's Balance (1955) demonstrating that a stream is considered in equilibrium when either the stream slope or flow volume are in balance with either the sediment supply or particle size. Figure adapted from Rosgen (2006) and recreated by B. Suppes. Permission granted by B. Suppes.

When the stream's ability to resist morphological changes is pushed past a natural background threshold, a stream may adjust its pattern (e.g., sinuosity), dimension (cross-section width to depth dimensions), and profile (gradient, and longitudinal sequence of pool, riffle, run and relative depth) in order to accommodate the new regime being imposed (Rosgen 1996). In Minnesota, the new regime is often an increase in discharge (Q) from changes in land use, land cover, or climate change. Morphological changes in the stream's hydraulic geometry have been observed and described in channel evolution models (e.g., Schumm et al. 1984, Simon 1989, Rosgen 1996). These morphological changes may be observed in a longitudinal succession as knickpoints migrate upstream, or when a disturbance (channelization) alters the local stream gradient and sediment transport capacity.

Table 3-1: Channel Evolution Model (CEM) stages. Modified from Schumm et al. (1984) and Thorne (1999).

I. Sinuous, premodified 	**I. Pre-adjustment** – Channel is in regime (processes of degradation balanced with aggradation). Channel exhibits little evidence of excessive bank erosion and cutting. For sinuous alluvial streams, the outside bends demonstrate some bank erosion and the inside bends some deposition. However, the degree of bank erosion and deposition is in balance and is characteristic of the natural hydrologic regime of alluvial streams.
II. Degradation 	**II. Degradation/Widening** – An increase in channel slope, discharge or decrease in sediment supply has tipped the scale toward degradation. The channel cross-section is deepening due to excess scouring. Channel has disconnected from the floodplain. Bank erosion and cutting is excessive along both the inside and outside bends. Lower bank angles are starting to steepen. Trees may be seen leaning into the stream from one or both sides of the channel. Note: Degradation may not be observed when coarse substrates are armoring the channel bottom. In this case, channel widening will be the dominant process. Cutting along both banks may be observed.
III. Degradation and widening 	**III. Widening and Aggradation** – Banks have steepened to the point where the banks are destabilized and are collapsing. Cutting may be observed along one or both banks. New tree fall or areas of mass wasting/bank failure may also be observed. At this stage, the channel cross-section is overwidened and consequently, sediment transport capacity is reduced leading to excess aggradation in pools and runs.
IV. Aggradation and widening 	**IV. Thalweg Channel Adjustment** – During this stage, the stream may be introducing meanders that allow sediment to settle out along the inside bends thereby concentrating flow along the outside bends. Consequently, thalwegs are beginning to form along the outside bends; some degree of cutting and bank collapse may still be observed (Thorne 1999).
V. Quasiequilibrium 	**V. New Dynamic Equilibrium** – Thalweg reformed, banks stable, and sand bars revegetated. Smaller floodplain within active channel. Old terraces may be visible. Processes of natural degradation and aggradation are in equilibrium. Seasonal periods of degradation and aggradation are occurring; however, no net degradation or aggradation observed.

Note: The morphological adjustments observed (Table 3.1) may alternate back and forth between CEM stages within a given reach. For example, where coarse substrates are available and concentrated intermittently along the channel bottom, the stream may not have the ability to down-cut but will widen instead (CEM III). Where coarse substrates are not available, the stream may downcut considerably (CEM II) before breaching a critical bank repose angle at which point bank collapse could occur.

Channel Condition and Stability Assessment (CCSI) Metrics

The CCSI metrics rate channel stability indicators as they relate to channel form, function, and sediment continuity. The design of the worksheet and manual follows the Pfankuch guidance manual (Pfankuch 1975). Metrics from other channel stability assessments were consulted and incorporated into this assessment (Simon and Downes 1995, VANR 2007, Rosgen 2006, Ohio EPA 2007, Magner et al. 2010). Modifications to the original metrics and the scoring process have been introduced to broadly characterize stream conditions observed in Minnesota. Further research is needed to define the reference condition for various stream types so that calibration of scores and stability ratings will more accurately reflect deviations from the regional expectation. For some stream types in certain regions, the reference condition in the absence of hydrologic change due to changes in the rate of watershed evapotranspiration (e.g., perennial to annual crops) and/or hydrologic manipulation (e.g., drain tiling, storm drains, increase in impervious) may not be readily available, so a general interpretation on the conditions of stability will need to be matched with more detailed geomorphic surveys when feasible.

The CCSI rates channel conditions as they relate to channel form, function, and sediment continuity. Similarly to the PSI, The CCSI evaluates three regions of the channel and attendant floodplain: Upper banks, Lower Banks, and Bottom. Make sure you are assessing the correct area of the channel for each metric. There are 14 metrics. Each metric has 5 rating categories (excellent, good, fair, poor, very poor). The scoring strategy is intended to separate good sites from poor sites while allowing for sites that are inbetween to be classified as moderately unstable (not good, not poor). Please note: The ratings provided were developed to rate 2nd to 4th order stream reaches. When scoring a 5th or 6th order stream, the metric scoring strategy may need to be rescaled using best professional judgment.

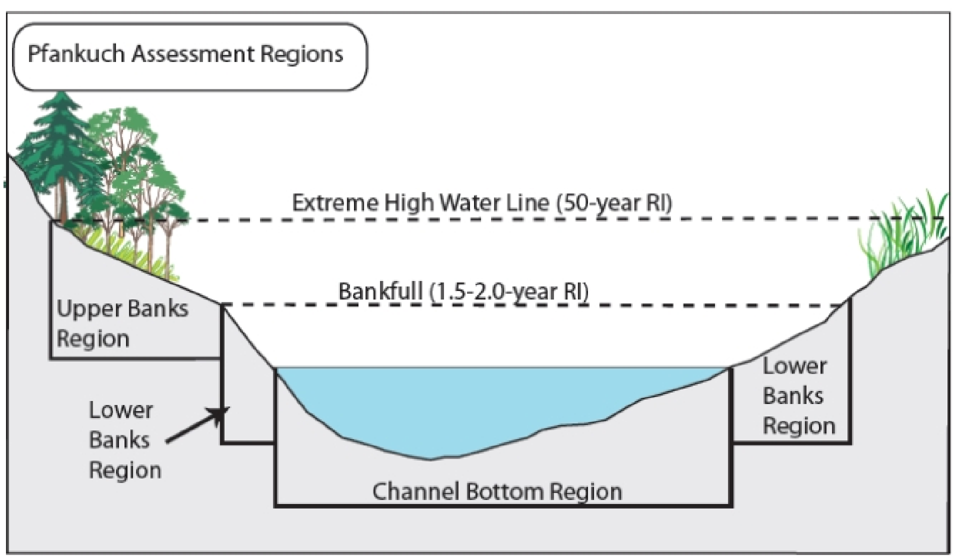


Figure 3.2: The three PSI and CCSI assessment regions. Illustration modified from Pfankuch (1975) by B. Suppes. Permission granted by B. Suppes.

The three assessment zones are broadly characterized as follows:

<u>Upper banks</u> – The region above what is estimated as the bankfull flow (1.5-yr RI) (normal high water line to extreme high water line). In non-incised streams, this zone is the attendant floodplain that extends back to the valley wall, if present. In incised streams, this zone is above the bankfull flow line as indicated by high flow indicators (e.g., debris in tree limbs, inflection point on banks, height of depositional features) and verified with a regional hydraulic geometry curve.

<u>Lower banks</u> – The region between the base-flow (indicated by water or at what is considered normal summer flow) and the bankfull flow line (1.5 to 2 yr RI flow, or high water line). This region is regularly submerged during annual high flow and generally becomes visible when flows reduce to seasonal base-flow. The objective of the metrics in this zone is to assess the ability of the banks to withstand the erosive force of high flows (i.e., the shear strength of the bank material to resist erosion). Additionally, the depositional metrics for this zone are used to infer whether the channel does not currently have the transport capacity to carry away the annual sediment load (e.g., when a stream cross-section is overwidened) or if the sediment load to the stream is overburdening the current transport capacity (e.g., when overland erosion has increased do to land use practices or from unstable stream banks upstream).

<u>Bottom</u> - The bottom or bed of the channel. This is the portion of the channel that encompasses the wetted width during base-flow (channel bottom to base-flow flow line indicated by water in the figure above). The objective of the metrics in this zone is to assess the degree to which the bottom substrates are resistant to movement by scouring flow, evidence of recent mobilization during annual high flow events, evidence of excess sediment in pools, and whether lateral riffles or tree limbs are positioned such that flow is directed into the banks causing erosion. Lateral riffles are also a sign that the erosive force of the annual high flow has increased in recent times and is therefore an indicator of instability (i.e., excess degradation).

Associated with each assessment region are individual metrics that score the ability of the stream channel to dissipate flow, resist detachment of bed and bank materials, and transport its annual sediment load. The magnitude of hydraulic forces that are at work during stream flows (< 2-yr RI) and the capacity of the stream to move sediment, will determine if the channel is stable or unstable. Extreme events (100-yr RI) can cause irreversible channel damage (e.g., Root River).

The three assessment zones and their corresponding metrics are described as follows:

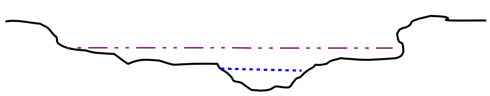
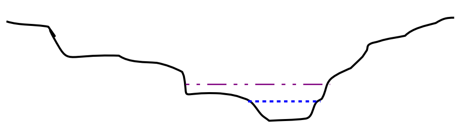
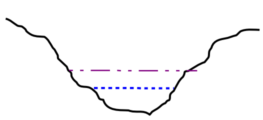
UPPER BANKS

This region is immediately adjacent to the channel and tends to be primarily a terrestrial environment. However, during high flows (1.5-yr RI or greater), this area can be inundated with water during which the stream flow interacts with trees, downed limbs, and upper bank vegetation. This zone is scored by assessing the degree to which energy from higher than annual flows has the opportunity to dissipate over the adjacent floodplain as well as the type and condition of vegetation available to protect banks and capture excess sediment and nutrients.

Intermediate Floodprone Width

The original Pfankuch (1975) metric assesses the degree of *landform slope* adjacent to the stream channel. This metric has been modified herein to rate the degree of floodplain connectivity for low-gradient streams (<2% channel slope). Floodplain connectivity is the interaction between the stream channel and the attendant floodplain (Kondolf et al. 2006). The *intermediate floodprone width* is defined as the ability of high flows to access attendant floodplains and dissipate erosive energy of relatively frequent high flow events (approximately 1.5 year RI to 10 year RI flows) and utilize the ecological benefits of healthy riparian vegetation to attenuate nutrients and sediment; or the degree that similar flood-flow would be constrained within the bankfull cross-section and valley walls by relict terraces, modified bank heights (levies, retaining walls), or mechanical dredging and channelization. Ohio EPA (2009) characterize floodprone width targets for low gradient streams by analyzing floodprone width at three different flow heights in order to "reveal floodplain characteristics at low stages that have a strong influence on ecological services and riparian quality (Figure 1.5, Mecklenburg and Fey 2011)". Mecklenburg and Fey (2011) measure the high-flow stage using Rosgen's ER ($2xBfD_{max}$), the intermediate stage is measured at 1.5x bankfull max depth ($1.5xBfD_{max}$), and the low-flow stage is the bankfull flow ($1.0xBfD_{max}$). While the ER and bankfull flow are typically measured for geomorphic surveys, the intermediate flow is not. Mecklenburg and Fey (2011) consider the intermediate flow as being ecologically beneficial in that this is a more frequent flow (~5 to 10 yr RI) that can provide nutrient and sediment attenuation when this zone is inundated by high flows. A lack of a well-connected floodplain at this height may be identified as a cause of biological stress related to water quality and habitat issues related to excess nutrients and sediment as well as unstable habitat zones (e.g., mobilized rocks). Hence, this intermediate flood stage has been incorporated into the CCSI assessment (see Table 3.2).

Table 3.2: Diagrams of cross-sections with the bankfull flow line (blue dotted line), the *intermediate floodprone width*, (purple dashed line) and descriptions of the metric ratings.

	**Excellent:** The ratio of the *intermediate floodprone width* (IntFpW) at 1.5 times the bankfull max depth (1.5xBfD_{max}) to the bankfull width (BfW) is greater than 10 [IntFpW >10.0 x BfW]. For these streams, the floodplain is connected at bankfull flow and the energy from overbank flows (2-10 yrs) is largely dissipated. During extreme flood events the channel is likely to maintain existing channel dimensions with little sign of channel instability post-flooding.
	**Good:** These are fairly stable streams where the floodplain is connected at bankfull flow and the energy from overbank flows (2-10 yrs) is largely dissipated; however, high flows are now slightly confined during very high flow events . A stream that is in the process of downcutting may still have a relatively high intermediate floodprone width ratio; however, when terraces are present, the small degree of confinement that now occurs may concentrate higher flows within a smaller area thereby increasing sediment transport capacity and an increase in excess scouring of bottom substrates.
	**Fair:** The ratio of the intermediate floodplain width at 1.5 times the bankfull max depth and the bankfull width is 3.0 to 5.0. This could apply where streams are beginning to downcut and adjust or where channels have downcut and adjusted but are still confined by relict terraces. Overbank flows at this stage may cause some minor channel adjustments.
	**Poor:** The ratio of the intermediate floodprone width at 1.5 times the bankfull max depth and the bankfull width is 1.5 to 3.0. This could occur where channelized streams have adjusted to include a small connected floodplain within the trapezoidal cross-section or in a deeply incised stream that is confined by relict terraces. However with this small floodplain there is some limited benefit of sediment and nutrient attenuation by vegetation during overbank flows.
	**Very Poor:** The ratio of intermediate floodprone width at 1.5 x bankfull max depth and bankfull width is <1.5. This would largely apply to channelized streams where the channel has not adjusted or is just beginning to introduce a low-floodplain within the trapezoidal cross-section or a very incised stream. There is little opportunity for floodplain attenuation of nutrients or sediments.

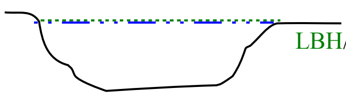
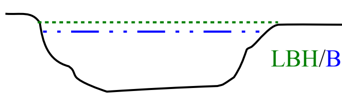
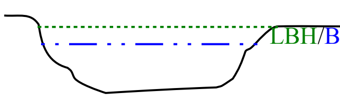
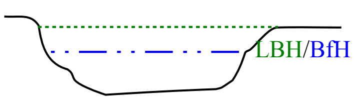
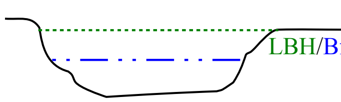
Degree of Incision

This metric is not in the original Pfankuch (1975) but is added herein to the modified version. This metric assesses the degree to which higher than 1.5 RI flows are contained and magnified within a channel with a lower base-level due to downcutting (due to mechanical or hydrologic processes).

Incised streams that have down-cut to a lower base elevation will have contained flow that now erodes material below the observed top-of-bank. Evidence of this occurrence may be slumps of grass within the stream (greater than 1 meter by 1 meter), trees that have fallen into the stream from flows scouring below roots and undermining banks, and exposed soil surfaces between areas that still have vegetation overhanging banks.

In some instances, the degree of incision may not be uniform throughout the length of the reach. If this occurs, score one area of the reach and then score the other area. Afterward, average the scores and take note of this condition in the comments.

Table 3.3: Diagrams of channel cross sections indicating the low bank height (LBH, green dotted line) and the bankfull height (blue dashed line) and descriptions of the ratings for *degree of incision.*

 LBH/BfH = 1-1.05	**Excellent:** Channel has access to floodplain regularly at bankfull flow (1.5 RI). Flow energy largely diminished during high flows. Low Bank Height (LBH) to Bankfull Height (BfH) ratio = 1 to 1.05
 LBH/BfH = 1.05 – 1.2	**Good:** Channel has access to floodplain in larger than 1.5 RI flows, but may no longer during annual or bi-annual flows. LBH/BfH = 1.05 to 1.2
 LBH/BfH = 1.2 – 1.3	**Moderate:** Channel is incised. Annual flows and some larger no longer accessing floodplain. Flows concentrated and downcutting likely. LBH/BfH = 1.2 to 1.3
 LBH/BfH = 1.3 – 1.4	**Poor:** Channel is severely incised. Cutting along both banks obvious. Critical height of bank surpassed, mass wasting /bank failure observed or likely. LBH/BfH = 1.3 to 1.4
 LBH/BfH = 1.4 – 1.5	**Very Poor:** Channel is deeply incised. Higher flows frequently contained and likely cause severe cutting on both banks and excess scouring on bottom. LBH/BfH > 1.5

Vegetative Bank Protection

Upper bank vegetation is considered anything above bankfull flow that is likely to support and maintain the integrity of the channel form. Consider bank vegetation from the bankfull flow line to at least 20 feet from the flow line, as a general rule. This metric assesses the degree that plant or tree roots are stabilizing banks and holding soil in place. Trees and shrubs generally have deeper roots than grasses and forbs. However, prairie grasses and the invasive Reed Canary Grass have very deep root systems (>12 inches) that can contribute greatly to the level of bank protection. Therefore, this metric has been slightly altered from the original Pfankuch (1975) in order to better characterize conditions found in low-gradient streams in Minnesota that often have banks that are protected by deep rooted grasses or shrubs.

Activities within the riparian zone can introduce less protective, shallow-rooted vegetation (animal grazing, lawn care, golf-courses) or clear the banks of protective vegetation (dense grazing, row-crop cultivation) that can destabilize banks and lead to bank collapse. Consider the underling root depth, density, and amount of exposed soil within the riparian zone adjacent to the stream channel (within 10m) when scoring this metric. When scoring this metric, consider only the outside bends or banks that would likely experience erosive flow (not inside, depositional areas).

In addition to bank protection and stabilization, vegetation can also benefit the stream channel by dampening erosive overbank flows and reducing the velocity. The greater the density of stable trees and grasses along the banks, the greater the resistance to flow. Another factor to consider when scoring this metric is the variety and vigor of the vegetation being assessed. Vegetative variety and vigor (mixture of trees, shrubs, and grasses) afford greater bank protection than old decaying trees and sparse grass stands.

<u>Excellent</u> – Trees, shrubs, grasses and forbs together cover more than 90% of the ground. Openings in this cover exposing bare soil are rarely found or are small and evenly dispersed. A variety of species and age classes suggest a dense and vigorous soil binding root mass.

<u>Good</u> – Trees, shrubs, grasses and forbs cover 70 to 90 % of the ground. Shrub species and shallower grasses may be more prevalent than trees and deep rooted grasses. Openings in the ground cover are occasional but of fair size to be easily observed.

<u>Fair</u> – Plant cover ranges from 50 to 70%. Occasional deep rooted vegetation present, but most vegetation is shallow rooted and/or large bare spots are visible. There may be a lack of cover due to extensive shading by trees, dead vegetation or activities within the riparian zone (e.g., grazing, landscaping, row crops, etc).

<u>Poor</u> – 25-50% of the ground is covered with vegetation. Deep rooted vegetation is essentially absent or exists in scattered, discontinuous clumps. Shallow rooted vegetation is pulled loose from soil easily. Overall, vegetation provides little soil binding bank protection. Riparian land use will play a large role in the vegetative management.

<u>Very Poor</u> – <25% of the ground is covered with vegetation. Majority of ground bare or comprised of shallow-rooted perennials. Little or no bank protection from vegetation.

Mass Wasting or Bank Failure (recent)

The original Pfankuch (1975) assesses the existing and future potential of soil detachment and evidence of large landslide events. We have modified this metric here to account for only relatively recent events that may have occurred within the same year or previous year prior to the assessment and modified the characterization to account for smaller but still significant bank failures that may contribute excess sediment to stream channels.

In assessing this metric, consider the height of bankfull flow and the likelihood for sediment from nearby unstable banks to be carried into the stream channel during baseflow as well as high flow conditions. In meandering streams, focus the assessment to the outside bends that are likely to show signs of mass wasting and bank failure due to their exposure to the most erosive energy of higher flows. Where riparian is disturbed (e.g., grazing), evidence of mass wasting/bank failure may also be observed along the inside bends. Rate the occurrence and magnitude of areas of mass wasting/bank failure as follows:

Excellent - There is little or no evidence of mass wasting/bank failure that has occurred recently.

Good - There is evidence of infrequent (1 to 2 medium) and/or very small slumps (3 to 4). Occasionally, small areas of banks appear “raw” with exposed, unprotected soil. Where evidence of relatively recent slumps have occurred (same year or likely previous year), areas are re-vegetated and relatively stable.

Fair - Evidence of mass wasting/bank failure is more frequent (3 to 4 moderate occurrences, 1 or 2 large areas). Normal high waterline erodes soil at toe of steep banks, thereby causing banks above toe slope to become undermined and slump into channel periodically during the year.

Poor - Mass wasting/bank failure frequency and size is contributing large volumes of sediment to the stream channel yearlong (5 or more small occurrences, 2 to 3 large occurrences, or 1 severe). Normal high water line frequently erodes away toe slope and undermines steep banks above. Geotechnical instability also likely as wetted banks dry when high flows recede.

Very Poor – Mass wasting/bank failure is almost continuous along the outside bends of the channel and some on the inside bends of very incised streams. High volume of excess sediment from banks likely.

Comments Upper Banks

Include any pertinent descriptions of conditions of the *Upper Banks*. Also include any information related to whether or not the assessor experienced any confusion on bankfull indicators or any of the *upper bank* metrics. These comments will be reviewed prior to quality control CCSI revisits as well as to improve and target future training opportunities.

LOWER BANKS

This channel zone is located between the normal high water line (1.5-yr RI flow line) and base-flow; the lower banks define the extent of the base-flow stream wetted width. Some plants may be able to grow on this region of the banks between high and low flows; however, plants may be relatively sparse depending on the energy regime.

For low-gradient streams under stable hydrologic conditions, the stream channel may migrate slowly side to side within the floodplain zone over time. Consequently, the outer bank of meander bends may show signs of bank erosion while the inside bends form point bars and accrue sediment. Unstable conditions can be observed when the outside bends show excessive cutting and mass wasting/bank failure, as the stream tries to increase sinuosity or when the channel is incised and widening. Evidence of incision and widening may include cutting along both the inside and outside banks of the stream channel and deposition along the inside bend or along both sides of the channel that is excessive compared with other streams in the region of similar geologic character.

Bank Materials/ Shear Strength

The composition of the bank material is related to the geologic history of the region (bedrock, glacial till, glacial outwash) as well as the history of the stream itself (alluvial deposition, lacustrine silts and clay), and protection afforded by vegetative growth (e.g., tree and grass roots) and human alterations (e.g., riprap).

This metric assesses both the composition of the bank materials and local conditions that will provide resistance to detachment by high, scouring flows as well as the ability of the stream banks to resist detachment and collapse under low flow conditions (e.g., silt banks and gw seepage). To assess this metric, focus on the exposed lateral surface of the bank on the outside bend of meandering streams that would be most affected by the scouring forces of high flows or would be most likely to collapse due to gw seepage during low flows.

Excellent – Rock, root, or cohesive materials makes up to 90% or more of the volume of the banks. Or, bank made of cemented clay and other cohesive materials that do not crumble when touched and would easily resist scouring during high flows.

Good – Banks are composed of 65 to 75% rock or mixture of roots or cohesive fine materials such as clay with gravel or sand that can resist detachment during high flows; however, slight crumbling to the touch when dry. Bank mostly stable during high flow conditions and when dry. No stratification observed.

Fair – 40 to 65% of the bank volume is rock, roots, or cohesive material. Bank is somewhat resistant to crumbling when touched. Bank would remain relatively stable during most flow conditions, however, fluvial action could slowly erode bank, stratification observed, or cracks could form when dry, leading to bank collapse.

Poor – 20 to 40% of the bank is composed of rock, roots, or cohesive material. Soil matrix crumbles easily when touched, or stratification of soil and/or silt/clay lenses present. “Pop-outs” or bank erosion during high flows or when dry likely or evident.

Very poor - <20% of the bank composed of rock fragments, roots, or cohesive material. Banks mostly sand or silt that crumbles easily to the tough when dry or easily dislodged by flows or groundwater seeps.

Flow Deflectors

Objects in the stream, both naturally occurring and human related, may locally change the natural longitudinal course of flow and lead to bank instability depending on their angle of flow deflection and associated velocity. The presence of numerous flow deflectors can greatly destabilize the channel reach. The flow deflection may occur only during high flow; therefore this metric requires the assessor to imagine the flow conditions at the bankfull elevation and higher.

Large woody debris (LWD)/ boulders - A large tree or branches may fall from one bank and stretch across only ¾ of the stream cross-section or boulders may be oriented in such a manner as to channel flow toward the banks. In this case, LWD or boulders may channel and “deflect” flow toward the opposite bank thereby causing localized bank erosion and bank collapse.

Lateral riffles - Lateral riffles form when previously horizontal riffles have been dislodged due to higher velocities or where local knickpoints are migrating upstream (this phenomena suggests bed instability that can adversely affect the lower banks). In unstable streams, lateral riffles comprised of gravel or small cobble can form and deflect flow into stream banks and cause localized bank instability, as well as indicate an imbalance in the flow regime.

Center bars – In overwidened cross-sections, aggradation in the center of the stream may cause a mid-channel build-up of sediments that will begin to divert and concentrate flow to the outside banks. When this occurs, the center bar is acting as a flow deflector as well as is an indicator of channel instability related to excess deposition or a loss of sediment transport capacity due to an overwidened cross-section.

Point bars – Point bars, or lateral bars are natural features in stable, sinuous, low-gradient streams. However, in unstable channels, point bars or lateral bars can form on the inside bend and aggrade sediment in an overwidened cross-section as the thalweg begins to form on the outside bend. When this occurs, the point bar may act as a flow deflector and destabilize the outside bend and further destabilize the banks until the stream achieves an appropriate degree of sinuosity and slope for the new flow and sediment regime imposed upon the channel.

Excellent – Logs and other flow deflectors cause minimal bank erosion, if present. Riffles are stable and perpendicular to flow.

Good – Some minor flow deflectors present (1 to 2). These flow deflectors cause some cross-currents and minor bank instability, but very localized.

Fair – Moderately frequent flow deflectors (3 to 4 small or 1 large) likely to cause bank erosion during high flow. Lateral riffles may be observed which direct flow into banks.

Poor –Flow deflectors fairly frequent (5 to 6 small, 2 large). Cross-current pattern strong, deflecting into banks and creating extreme bank erosion, cutting back banks, adding sinuosity to the channel or creating avulsion.

Very poor – Frequent flow deflectors (6 or more small, 2 or more large) cause highly erosive cross-currents and severe bank erosion over a fairly extensive portion of reach (greater than 40% of reach length).

Obstructions to Flow/ Sediment Traps

Objects that block flow and locally slow the velocity of water tend to have a buildup of fine sediment behind them. Where this occurs, these objects are considered "sediment traps." For example, downed trees and branches may build up perpendicularly across the channel (log jams or beaver dams) and obstruct flow. This may cause a slowing down of water velocity as water backs up behind the jam. The sediment carried by higher velocity flows drops out and aggrades behind the dam at the start of the pool and "traps" sediment that would have otherwise been carried downstream. When a large volume of sediment is trapped, channel capacity can be reduced to the point where normal high flows now overtop the banks, thereby causing floods.

If water appears impounded but no large beaver dams or obstructions are observed within the reach being sampled, consider walking downstream of the reach a reasonable distance to see if obstructions are observed. If not, or time is limited, write in comments that the reach appears impounded and score according to the degree the reach appears to be impacted by very large impoundment from observation of velocity and sediment accumulation.

Excellent – No obstructions to flow observed. Normal sediment accumulation associated with boulders, woody debris, and instream vegetation.

Good – Some minor obstructions and sediment traps present (1 to 2 occurrences observed). Minor accumulation of sediment; sediment transport capacity minimally impacted.

Fair – Sediment traps moderately frequent (3 or 4 occurrences). Presence of obstructions contributing to measurable degree of pool infilling (1/4 to 1/3 of total depth), or noticeable slowing of water velocity behind obstructions causes some accumulation of sediment above what would be expected for natural conditions.

Poor – Sediment traps more frequent, cause infilling of pools and/or high degree of aggradation in runs. Sediment transport capacity moderately reduced from what would be expected of normal conditions.

Very poor – Numerous or large obstructions or sediment traps. Sediment transport capacity greatly diminished resulting in severe aggradation within pools and/or runs.

Cutting or Ground Water (GW) Seepage

Cutting is the degree the banks have steepened as a result of scouring flows and episodes of bank collapse. This may be due to channel base-level lowering during a stage of degradation where the scouring flows now erode under the rooting depth of vegetation, or when the channel is attempting to increase sinuosity by scouring into the outside bends. Some degree of cutting is likely to be observed under natural stream conditions. This may be observed along the outside bend of sinuous streams or along bottom of deep rooted vegetation during lower than baseflow conditions. Cutting that is Unless the channel encounters a resistant surface (bedrock, armoring of the channel bottom with coarse substrates), the channel will continue to degrade until the banks become nearly vertical and begin to collapse due to gravity (geotechnical failure).

Incised channels contain additional flow volume due to a now deeper planform and consequently, flow energy that previously overtopped the banks and dissipated is now held and magnified within the channel walls. The result is increased discharge and stronger erosive forces that will actively erode composite bank materials below the root-line, causing undermined banks eventually leading to bank collapse, even when the tops of the banks are well vegetated. Additionally, as the channel down-cuts, the profile may encounter stronger ground water discharge. Hydrostatic pressure being relieved during base-flow can create groundwater pore pressure seeps that push sediment out at the toe of the bank; thereby causing a "pop-out failure" and additional bank collapse (Cancienne et al. 2008).

Excellent – Very little or no cutting is evident. Raw, eroding banks are infrequent (1 to 2 small, localized occurrences), short and generally less than 6" high or less than ¼ of bank height. If GW seepage is present, seepage affects less than 5% of reach.

Good – Few locations of cutting evident (3 to 4 localized occurrences). Cutting occurs along the outside meander bend of sinuous channels and at areas of constriction. Raw, eroded areas are equivalent in length to one channel width or less. Vertical cuts are generally less than 12" high or between ¼ to 1/3 of bank height. Groundwater seeps may be observed causing localized "pop-outs" but less than 5 to 10% of reach.

Fair – Bank cutting occurs frequently along the reach along one or both sides (5 to 6 occurrences if small and localized). Root mat overhangs and sloughing evident. Trees may lean in toward stream or collapse as roots are undermined by scouring flows or from groundwater driven failure. Raw vertical banks 12 to 24" or 1/3 to ½ of bank height. Ground water driven bank failure apparent but fairly localized (10 to 20% of reach).

Poor – Significant (5-6) cuts. Cuts up to ½ to ¾ of bank height. Root matts may be overhanging with unstable cut banks underneath, with bank sloughing evident, or GW driven bank instability and failure occurring over 20 to 40% of outer banks.

Very poor - Bank cutting is nearly continuous along the outside bends of entire reach. Some cuts are over 24" high or greater than half of bank height. Undercutting of the vegetative root line, root overhangs, and vertical bank failures may also be frequent (greater than 50% of reach) or GW driven bank failure extensive (>25% of reach). New tree fall may also be evident.

Comments on Lower Banks

Include any pertinent descriptions of conditions of the *Lower Banks*. Also include any questions related to how the assessor viewed or scored the metric, and if the assessor experienced any confusion on how to score the metrics comprising this assessment zone; these comments will be reviewed prior to quality control assessment revisits as well as to improve and target future training opportunities.

BOTTOM

The bottom of the stream is largely an aquatic environment year round. The biological community of plants, fish, and macroinvertebrates are largely supported by the character of the substrate and the degree of movement during high flows. Large immobilizable substrates support the growth of diatoms, algae, moss and plants that provide food and protection for many species of fish and macroinvertebrates. Smaller, mobilizable substrates (sand, silt, gravels) may move often during high flows and do not afford opportunity for growth of vegetation and diatoms. If the sediment transport capacity is in regime, substrates may remain stationary during high flows. In some streams, sands may be firm and green with periphyton. When substrates are mobilized, the substrate may be easily mobilized by kicking, sands and substrates may feel spongy underfoot or easily penetrated with the copper rod, and gravel or sand may appear “brighter” as the substrates have rolled during high flows and the unstained sides are now visible. Hence, the degree of scour may be inferred from looking at the condition of diatoms on rocks and rooted plants, as well as the degree to which substrates are packed or “bright.”

The following metrics consist of rock and plant indicators that provide evidence that substrates have been moved during high flow conditions. When possible, assessments within this zone should take place during base-flow conditions when the water is clear and not turbid.

Consolidation or Particle Packing (vertical)

For streams dominated by sand and fines, the probing rod will provide an estimate of bed material density if the rod is driven into the bed by applying a constant downward force. The depth of penetration may be influenced by ground water pore pressure; however, the end result will still point to the likelihood of mobility with an increase in stream power associated with a rise in water stage. Generally, cohesive till will be dense and if this high density sediment covers >80% of the channel bed the risk of bed mobility will be very low. Mixtures of sediment will likely occur in most streams, your challenge is to define the relative density as measured by mechanical shear and determine the spatial variability over the study reach. This will require you to interpret probe contact with sediment and probe response to downward pressure.

<u>Excellent</u> – Probe depth minimal if any due to very firmly packed sediment. 0 to 1 inch or 0 to 2.5 cm.

<u>Good</u> – Probe depth 1 to 3 inches (2.5 to 8 cm) before encounters densely packed material or

resistant surface.

Fair – Probe depth 3 to 5 inches (8 to 13 cm). Some evidence of underlain resistant material; however, overlain sediment relatively loose and likely to be easily transported with a small increase in water velocity. 3 to 5 inches or 8 to 13 cm.

Poor – Probe depth 5 to 8 inches (13 to 20 cm). Very loose bed sediment in many places but not all.

Very Poor - Probe depth > 8" or >20 cm. Sediment relatively unconsolidated; indicates that this is an actively mobile bed during high flows.

Evidence of Degradation/Excess Scouring & Evidence of Aggradation/Excess Deposition

The processes of scouring and deposition are scored together as one metric for the Pfankuch (1975) channel stability assessment as they are considered as two interrelated processes as conditions of incision and channel instability (scour and bank collapse) upstream may translate into excess deposition downstream. However, it is unlikely that these two related processes may be observed together within the reach length being assessed (150 to 500 m). For example, while conditions of scouring related to an incising stream channel are observed within the reach, the water velocity may be sufficient to carry the sediment downstream and outside the reach where aggradation will likely occur. Equally possible, conditions of deposition observed within the reach are the result of channel instability (scour and bank collapse) upstream of the reach and consequently may be outside of the area where observations are being scored. While both conditions (excess degradation or aggradation) are symptoms of channel instability, fish and macroinvertebrates may be effected by these two conditions differently directly or indirectly through alteration to habitat quality (e.g., scouring and mobilization of substrates verses excess sedimentation and embeddedness of coarse substrates). It may be important then, to characterize observations of excess degradation or aggradation independent of each other. In response, we will assess these two conditions separately here.

Evidence of Degradation/ Excess Scouring

Stream conditions related to excess scouring may be detrimental to biological communities. High velocities and associated shear stress may dislodge and mobilize organisms and the substrates that they are clinging to or using as protection. Events related to scouring may also dislodge recently spawned fish eggs, instream vegetation, and immature insect larvae. Rocks with periphyton that are scraped and consumed by algophytes may be tumbled so that the side with periphyton is turned upside down and unavailable to grazers. Metrics in the original PSI that score these conditions include: *rock angularity*, *brightness* and *clinging aquatic vegetation*, among others. The PSI guidance manual (Pfankuch 1975) suggests that these metrics be used to infer the degree of scouring observed when scoring the metric *scouring and/or deposition.* Since not all alluvial streams have coarse substrate to rate *rock angularity* and *brightness,* these metrics have been excluded in this modified assessment. However, these indicators can still be used to infer the degree of scouring observed where coarse substrates are available. Other observations such as the presence of a knickpoint/knickzone and bar substrate material may be instructive for determining the degree of scouring. These conditions are described below as indicators that may assist in rating the CCSI metric *evidence of degradation/excess scouring*.

Knickpoint or knickzone observed- Knickpoints are more localized than knickzones. A point or zone where degradation and incision begins is likely to be found along the longitudinal profile of an incising stream. Upstream of the knickpoint the conditions may be stable, and downstream the channel conditions will likely demonstrate conditions related to excess degradation, before aggradation. Therefore, the presence of a knickpoint or knickzone is associated with degradation/excess scouring and channel instability.

Rock brightness - When stationary, rocks become stained with diatoms and algae. Rocks that are rolled by a recent high flow event, will be tumbled in such a manner that the unstained undersides of a percentage of rocks is now exposed, which appears lighter, or brighter than rocks that are darkened by periphyton. Since not all zones within a stream channel may be scoured during high flows (e.g., shallow-edge habitat), focus your attention on areas of the stream that would be likely to be scoured during high velocity flow events. In streams without large substrates, focus attention on sands and gravels. Then step-back and put the stream in context with its surrounding and stream size. Is the degree of brightness observed indicating normal annual bed movement or excess mobilization and therefore, excess scouring?

Bar substrate coarser on top than within - Streams that have recently experienced greater than normal velocity will likely demonstrate a substrate size difference in the vertical profile of deposited sediment on point and center bars. Locate a point or center bar and remove the overlaying 1 to 2 inches of sediment. Is the substrate composition on top of the bar coarser than what was buried? If so, this may indicate flow conditions that are of higher velocities that the streams annual discharge regime.

Excellent – Little evidence of abnormal scouring observed (<5% of reach). Vegetation is well rooted, where water clarity allows for the growth of deep rooted plants and moss in areas that would characteristically experience swifter flows during periods of higher flow. Rocks, where present, are darkened from periphyton with few areas of bright substrates. Some fines are observed surrounding coarse sediments are would be expected for a stable stream in the region, for the stream type, and gradient of the reach.

Good – Some localized scour at constrictions, like under bridges or around downed trees (5-15% affected) or where grades steepen. Where water clarity allows, vegetation present in slower waters such as in shallower depths along the wetted edge or in slow velocity pools, as well some areas experiencing swifter velocity. Rocks and gravel, where present, are mostly dark with some light spots visible (<15% of reach). Some fines observed, but may be slightly less than would be observed for stable streams in the region, stream type and gradient.

Moderate – Evidence of areas experiencing scour noticeable or moderately frequent (15-25% of bottom affected). Examples of areas that might have evidence of scour would include zones of construction, such as downstream of undersized culverts and bridge passageways, where tree roots armour banks and the stream appears wider upstream and downstream of the zone of constriction, and bends. Where visibility allows for plants to anchor and grow, vegetation is less than would be expected and rocks and gravel may be mixed with dark and bright (<25%). Where applicable, there is less sand and fines surrounding coarse substrates than may be expected. Substrate size on bars somewhat coarser than within.

<u>Poor</u> – Noticeable scour pools at bridges, constrictions, and where knickpoints occur (25-40% of bottom affected). Cutting along both sides of the stream channel may also indicate that the channel is experiencing downcutting as the bottom is scoured away. Where water clarity allows, vegetation is spotty or found only in backwater areas. Where present, rocks may be relatively free of fine sediment or tops of bars coarser than within.

<u>Very poor</u>- More than 40% of bottom substrates moved due to excess scouring. Deep scour pools associated with bridges and constrictions. Dramatic knickpoint may be observed within reach or upstream of reach. Where stream is incised, severe cutting along both banks. Where applicable, rock and gravel may appear bright (>40%) and coarse substrate is abnormally clean of fines. Vegetation may be scarce and tops of bars much coarser than within.

Evidence of Aggradation/ Excess Deposition

Depending on the stream type, evidence of excess aggradation may be observed in the riffles, runs, and/or pools constriction where the banks are armored with riprap or tree roots, around obstructions such as downed trees, and along outside bends of sinuous streams. Where water clarity allows, vegetation observed is less than would be expected due to relatively recent scouring events (within year). Where applicable, less sand between coarse substrates than would be expected for this stream type or where there are lateral and center bars, the deposited material on top of bars is coarser than within.

Embeddedness in riffles/runs- The degree to which fine substrates surround and bury coarse substrates is embeddedness. Coarse substrates in pools tend to be embedded due to the slower flow velocities associated with these stream features. However, when embeddedness is observed in runs and riffles, excess sediment sources or loss of sediment competence is occurring within the reach. Embedded substrates may be the result of upstream pasture grazing, overland run off, mass wasting/bank failure in upstream reaches, and overwidened stream channels, among others. Regardless of the mechanism, embeddedness is a sign of excess deposition and is an indicator of channel instability.

Pool depth diminished- Streams that are experiencing an increase in sediment loading to the stream or a loss of sediment transport capacity as could occur with in overwidened stream channels.

Lateral bar or center bar build-up- Lateral and center bars that demonstrate excess new sediment deposition such as sand or gravel indicate that either the sediment load has increased or the sediment transport capacity has been decreased from the natural channel equilibrium (sediment in/stored > sediment out/mobilized). Where streams have access to their floodplains during high flows or have within channel bars, some sediment will be naturally deposited during the receding limb of the hydrograph; hence, a thin layer of new deposition is natural/expected. However, depending on the size of the stream, when the volume of new sediment is a few inches to a few feet, and appears larger than the normal amount of annual sediment deposition, excess aggradation is occurring. Center bars may also indicate an overwidened cross-section due to channel evolution. Sediment transported from upstream by higher velocity flows now enters the overwidened cross-section which creates a zone of slower velocity (diminished sediment transport capacity); consequently, suspended sediment settles out on the bottom of the channel and builds up on top of center or lateral bars, as well as embeds coarse substrates on the stream bottom and within pools.

Excellent – Excess deposition is minimal or non-existent. Where pools are present, pool depth/size not diminished by infilling of materials (<1/8 of total depth affected). Where rock present, cobble and gravel minimally embedded (<10% in runs).

Good – Slight embeddedness observed (cobble 10-15%, gravel 10-25% in runs). Where present, pool depth/size slightly diminished due to infilling (1/8-1/4 of total expected depth) but only in some localized areas of the reach (5-15% of total).

Moderate - Excess deposition is observed in patches along the reach (15-25% of reach affected). Deposition at obstructions and moderate embeddedness observed in runs (cobble 15-25%, gravel 50-75%). Where present, pool depth/size noticeably diminished (1/4-1/3of total) or some new material on bars. Some habitat conditions negatively affected but some pools with decent depths and good quality. Riffle quality also moderately affected, but still provides functional habitat.

Poor- Excess deposition is apparent (25 to 40% of the reach) and is negatively affecting habitat quality. Extensive embeddedness observed where coarse substrates are present (>25% for cobble, >75% for gravel). Where pools are observed, pool depth/size greatly diminished (1/3 to 1/2 of total) or bar build-up noticeable 25-40% Extensive deposition at obstructions, on bars, and along bottom observed.

Very poor - Excess deposition is extensive (>40% of the reach). Pool depth almost non-existent or severely diminished, greatly limiting pool availability for fish. Some localized areas of scouring associated with woody debris or large boulders may be present, but large pools are greatly filled in with sediment (>1/2 of total depth). Where visible, lateral and center bars indicate substantial accumulation of new sediment.

Stage(s) of Channel Evolution

Indicators observed while walking the stream should provide indication of which CEM stage(s) appear to be active and prominent. To rate this metric, refer to the Channel Evolution Model (CEM) Figures (I-V) on the backside of the worksheet and ratings for previous metrics. Make a determination as to the degree to which channel adjustment is currently affecting the condition of the channel or is the dominant process of channel instability. Are the channel processes of aggradation and degradation in equilibrium (Stage I or V), are the processes of channel adjustment minor at this stage (just being initiated -

Stage II, III) or in process of returning to equilibrium (Stage IV), or does the channel appear to be actively and noticeably downcutting (Stage II) or widening (Stage III), and are either degradation or aggradation the dominant process of instability (cause of mass wasting/bank failure, cutting, scouring, aggradation)? Use your interpretation of the erosional forces at work that are acting on the channel during bankfull conditions. Record the stream stages observed in the location provided and circle the severity rating.

Excellent – Channel appears relatively stable (stage I or V); however, there may be small, localized instances where some bank erosion is observed. The nature of the bank erosion is from from natural flow deflectors or natural meandering. Overall, little evidence of channel instability is observed.

Good – Channel appears relatively stable, but some minor evidence of instability observed indicating that the channel has slightly downcut or is attempting to widen; or the channel is at the last stage of channel adjustment (stage IV to stage V) with some minimal erosion along outside bends due to lateral bar deflection. Lateral bars may now be well-vegetated.

Moderate – Channel appears to be in the process of evolving toward a more stable cross-section (stage III to stage IV). A thalweg is starting to form along the outside bend and sediment is being stored along the inside bend. Some grasses or vegetation starting to grow on the point bar.

Poor – Channel is actively downcutting and/or widening. Some lower bank and bottom metrics scouring in at least the moderate to poor range.

Very poor – Channel is actively in the process of rapidly downcutting or widening to such a degree that channel evolution is the dominant process of instability. Many banks demonstrating severe cutting or mass wasting/bank failure. Where applicable, new tree fall is evident as the channel is attempting to widen. The substrate is very uncompacted due to recent scouring events Some lower bank and bottom metrics also scouring in the poor to very poor range.

Scoring and interpretation

Total score: The total score range is 15-165 where lower scores reflect stable conditions and high scores reflect unstable channel conditions. Channel condition is categorized as follows:

Excellent: 15 – 26. Good: 27-43. Moderate: 44-79. Poor: 80-115. Very Poor: 116-156

Please note: Since this assessment tool and scoring strategy has not been fully tested in all stream settings, some score adjustments may be required.

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APPENDIX A

Tables of study locations, stream assessments, and data collected

Table A-1: Study site locations for SNAKE and REDWOOD watersheds.

Station ID	Stream Name	County	Latitude	Longitude
	SNAKE			
S 1	Bear Creek	Pine	45.8595	-92.8694
S 2	Bergman Brook	Kanabec	46.1565	-93.2784
S 3	Hay Creek - 1	Pine	45.7787	-93.1324
S 4	Cowan's Brook	Aitkin	46.1741	-93.2158
S 5	Hay Creek - 2	Kanabec	46.1153	-93.3201
S 6	Little Ann River	Kanabec	45.9686	-93.4288
S7	Ground House River - 1	Kanabec	45.8816	-93.5067
S 8	South Fork Ground House River - 1	Kanabec	45.7786	-93.4112
S 9	South Fork Ground House River - 2	Kanabec	45.7899	-93.3887
S 10	Ground House River - 2	Kanabec	45.8028	-93.3963
S 11	Ground House River - 3	Kanabec	45.8328	-93.4098
S 12	Knife River	Kanabec	45.9204	-93.3082
S 13	Ground House River - 4	Kanabec	45.7887	-93.3663
S 14	Snake River	Aitkin	46.2228	-93.2419
	REDWOOD			
R 15	Judicial Ditch #33	Redwood	44.5373	-95.4067
R 16	Norwegian Creek	Lincoln	44.2994	-96.2820
R 17	Three Mile Creek - 1	Lyon	44.4176	-95.9755
R 18	Ramsey Creek - 1	Redwood	44.5399	-95.2073
R 19	Tyler Creek	Lyon	44.2472	-96.0783
R 20	Redwood River - 1	Lyon	44.2403	-96.0090
R 21	Coon Creek	Lincoln	44.3308	-96.1404
R 22	Clear Creek - 1	Redwood	44.4433	-95.4056
R 23	Ramsey Creek - 2	Redwood	44.5527	-95.1458
R 24	Clear Creek - 2	Redwood	44.4727	-95.3178
R 25	Three Mile Creek - 2	Lyon	44.5411	-95.7572
R 26	Redwood River - 2	Lyon	44.4873	-95.7752
R 27	Redwood River - 3	Lyon	44.5021	-95.6979
R 28	Redwood River - 4	Lyon	44.5249	-95.1694

Table A-2: Fish index of biotic integrity (FIBI) metrics for SNAKE. Metrics used are dependent on by stream class (table modified from Niemela and Feist 2000).

	Stream Classes for SNAKE		
	Very small ($< 52\ km^2$)	**Small ($52\text{-}140\ km^2$)**	**Moderate ($141\text{-}700\ km^2$)**
Species richness and composition			
Total number of species	X	X	X
Number of headwater species	X		
Number of minnow species	X	X	
Number of darter species			X
Number of intolerant species		X	X
Percent tolerant species	X	X	X
Percent dominant two species	X	X	
Trophic and reproductive function			
Number of invertivore species	X		
Number of benthic invertivore species		X	X
Number of omnivore species			X
Number of piscivore species			X
Percent simple lithophils	X	X	X
Fish abundance and condition			
Number of fish per 100 meters	X	X	X
Percent DELT anomalies	X	X	X
Total Number of Metrics	**9****	**9****	**10**

*Metrics scored on a scale of 0 to 10; IBI total score is based on a scale from 0 to 100.
** The cumulative metric score for very small and small streams is multiplied by 1.11 to normalize the final IBI score to a 0 to 100 scale.

Table A-3: Fish index of biological integrity (FIBI) metrics* for REDWOOD. Table modified from Bailey et al. 1993).

	Stream Size Classes for REDWOOD	
	Small (<259 km^2)	**Midsized (259-25900 km^2)**
Species richness and composition		
Total number of native fish species	X	X
Number of darter species	X	X
Number of sunfish species		X
Number of sucker species (excluding white sucker)		X
Number of minnow species (excluding common carp, creek chub, fathead minnow)	X	
Number of intolerant species	X	X
Proportion of individuals that are tolerant	X	X
Trophic and reproductive function		
Proportion of individuals that are simple lithophils	X	X
Proportion of individuals that are omnivores	X	X
Proportion of individuals that are specialized insectivores	X	X
Proportion of individuals that are top carnivores		X
Fish abundance and condition		
Catch per unit effort (Time) by gear type	X	X
Proportion of individuals with deformities, eroded fins, lesions, and tumors (DELT)	X	X
Total number of metrics	**10****	**12**

*Metrics scored on a scale of 0 to 5; IBI total score is based on a scale from 0 to 60.
**The cumulative metric score for small streams is multiplied by 1.2 in order to normalize the score using 10 metrics with a score using 12 metrics.

Table A-4: Metrics and scoring ranges comprising the Pfankuch Stability Index (PSI) with metric abbreviations in parentheses (Pfankuch 1975).

Channel region	Metric	Scoring range
Upper Banks	**Upper bank zone (UPPER)**	**40 to 10**
	landform slope (LS)	8 to 2
	mass wasting or failure (MW)	12 to 3
	debris jam potential (DJP)	8 to 2
	vegetative bank protection (VBP)	12 to 3
Lower Banks	**Lower bank zone (LOWER)**	**52 to 13**
	channel capacity (CC)	4 to 1
	bank rock content (BRC)	8 to 2
	obstructions/flow deflectors/sediment traps (OFST)	8 to 2
	cutting (C)	16 to 4
	deposition (D)	16 to 4
Bottom	**Bottom zone (BOTTOM)**	**60 to 15**
	rock angularity (RA)	4 to 1
	brightness (Br)	4 to 1
	consolidation or particle packing (CPP)	8 to 2
	bottom size distribution and percent stable materials (BSD/PSM)	16 to 4
	scouring and deposition (SD)	24 to 6
	clinging aquatic vegetation (CAV)	4 to 1
PSI total score (PSI)		**152 to 38***

* Lower scores reflect better channel stability and condition.

Table A-5: Metrics and scoring ranges comprising Minnesota's Stream Habitat Assessment (MSHA) with metric abbreviations in parentheses.

Metric regions / types	Metric	Scoring range
Land Use (within 2 miles upstream)	**Surrounding land use (LAND USE)**	**0 to 5**
Riparian	**Riparian zone (RIPARIAN)**	**0 to 15**
	riparian width (RW)	0 to 5
	bank erosion (BE)	0 to 5
	shade (Sh)	0 to 5
Instream - Substrate	**Instream zone (INSTREAM)**	**-1 to 27**
	substrate type per stream feature (Su)	0 to 20
	embeddedness (Em)	-1 to 5
	number of substrate types (ST)	0 to 2
Instream - Cover	**Cover (COVER)**	**-1 to 17**
	cover types present (CV)	0 to 7
	cover amount (CA)	-1 to 10
Channel Morphology	**Channel Morphology (CHAN-MORPH)**	**-2 to 37**
	depth variability (DV)	0 to 6
	channel stability (CS)	0 to 9
	velocity types (VT)	-2 to 4
	sinuosity (Si)	0 to 6
	pool width/riffle width (PW/RW)	0 to 3
	channel development (CD)	0 to 9
MSHA Total Score (MSHA)		**-2 to 102***

*Higher MSHA scores reflect better habitat quality.

Table A-6: Taxa list, FIBI metric classification**, and number of fish collected at study sites (n=14) in SNAKE.

Scientific Name	**Common Name**	**IBI Classification***		**S 1**	**S 2**	**S 3**	**S 4**	**S 5**	**S 6**	**S 7**	**S 8**	**S 9**	**S 10**	**S 11**	**S 12**	**S 13**	**S 14**
Petromyzontidae	**Lamprey**																
Ichthyomyzon castaneus	chestnut lamprey	I	Pi													1	
Esocidae	**Pike**																
Esox lucius	Northern pike		Pi								2				1		9
Umbra limi	central mudminnow	T	In		194	400	1	14	30	12	336	20	45	46	4		10
Cyprinidae	**Minnows**																
Cyprinus carpio	common carp	E, T	Om			10											
Hybognathus hankinsoni	brassy minnow	Mi						8	3	21	2	8	1				
Notemigonus crysoleucas	golden shiner	T										1					
Semolitus atromaculatus	creek chub	T		10	89	1	49	11	146	26	14	80	145	46			5
Rhinichthys atratulus	blacknose dace	T	SL				18	1	109	49	33	12	54	2		15	
Rhynichthys cataractae	longnose dace	I, Mi	BI, SL										255	5	72		9
Nocomis biguttatus	hornyhead chub	I, Mi	In						6	1	48	10	16	4	11	15	
Notropus stramineus	sand shiner	I, Mi	In	2													
Campostoma anomalum	central stoneroller	Mi											18			1	
Pimephales notatus	bluntnose minnow	T									3	11	4	1			
Pimephales promelas	fathead minnow	T	Om	4						2		1				2	
Phoxinus eos	northern redbelly dace	He Mi	In	3	49		15	8	18	45		2	2				
Proxinus neogaeus	finescale dace	He Mi	In		6												
Phoxinus eos	common shiner	Mi	SL		71		28	6	94		180	250		7		130	1
Margariscus margarita	pearl dace	He Mi	In	257			47		6	49							
Catostomidae	**Suckers**																
Catostomus commersoni	white sucker	T	Om	4		66	12	5	9	12	11	176	79	5	1	141	3
Moxostoma macrolepidotum	shorthead redhorse		BI, SL														
Moxostoma erythrurum	golden redhorse		BI, SL						2			1	1				
Hypentelium nigricans	northern hogsucker	I	BI, SL								1		15		1	2	
Moxostoma sp.	redhorse yoy								5				4				

*Tolerance and trophic assignments from Niemela and Feist (2000): **I** = intolerant, **T** = tolerant, **E** = exotic, non-native, **M**i = minnow, **He Mi** = headwater minnow, **Da** = darter, **Om** = omnivore, **In** = Insectivore, **BI** = benthic insectivore, **Pi** = piscivore, **SL** = simple lithophilic spawner.

Table A-6 (cont,):

Scientific Name	Common Name	IBI Classification*		S 1	S 2	S 3	S 4	S 5	S 6	S 7	S 8	S 9	S 10	S 11	S 12	S 13	S 14
Ictaluridae	**Catfishes**																
Noturus gyrinus	tadpole madtom		BI								2				5	6	
Noturus flavus	stonecat	I	BI												11	1	
Ameiurus melas	black bullhead	T	Om												1	1	
Ameiurus natalis	yellow bullhead		Om			2											
Gadidae	**Freshwater Cod**																
Lota lota	burbot		Pi, SL	3	1	11	3			4	10	1	90	4	53	148	30
Gasterostidae	**Sticklebacks**																
Culaea inconstans	brook stickleback	T	In	37	66	12	2	7	20	32	23	3	5	32		2	
Centrarchidae	**Sunfishes**																
Ambloplites rupestris	rock bass	I	Pi								8	5	3	2	8		2
Lepomis macrochirus	bluegill		In												2		
Micropterus dolomieui	smallmouth bass	I	Pi							7			22	2	18	30	13
Micropterus salmoides	largemouth bass		Pi			2									7		4
Percidae	**Perches**																
Etheostoma nigrum	johnny darter	Da	BI		19	2	32	11	70	16	24	42	166	29	2	61	3
Etheostoma exile	Iowa darter	I, Da	BI	4					3		13						
Perca flavecens	yellow perch		In			1											
Percina caprodes	logperch	Da	BI, SL						4				3		71	5	2
Percina maculata	blackside darter	Da	BI, SL								5	11	28				
Percina phoxocephala	slenderhead darter	I	BI, SL													5	1
Sander vitreus	walleye		Pi, SL												2		

*Tolerance and trophic assignments from Niemela and Feist (2000): **I** = intolerant, **T** = tolerant, **E** = exotic, non-native, **M**i = minnow, **He Mi** = headwater minnow, **Da** = darter, **Om** = omnivore, **In** = Insectivore, **BI** = benthic insectivore, **Pi** = piscivore, **SL** = simple lithophilic spawner.

Table A-7: Taxa list, FIBI metric classification*, and number of fish collected at study sites (n=14) in REDWOOD.

Scientific Name	**Common Name**	**IBI Classification***		**R 15**	**R 16**	**R 17**	**R 18**	**R 19**	**R20**	**21R**	**R 22**	**R 23**	**R 24**	**R 25**	**R 26**	**R 27**	**R 28**
Esocidae	**Pike**																
Esox lucius	northern pike		TC													2	
Salmonidae	**Trouts**																
Salmo trutta	brown trout	E	TC>300 mm										6				
Cyprinidae	**Minnows**																
Cyprinus carpio	common carp	E	Om		50				8	211					1	17	55
Hybognathus hankinsoni	brassy minnow	Mi	Om	18	122			1		673	3		2		6	73	3
Semolitus atromaculatus	creek chub	T		9	3	39	6	5	29	68	12	2	102		53	25	27
Rhinichthys atratulus	blacknose dace	Mi	SL	5		62	36			5	17	10	222		201	1	
Nocomis biguttatus	hornyhead chub	I, Mi				3				8	5	2		1	9	1	
Notropus stramineus	sand shiner	Mi	Om				5				26			13	90	96	357
Notropis blennius	river shiner	Mi	BI, SL														1
Hybopsis dorsalis	bigmouth shiner	Mi	Om	4		2		1		23	52	2	5	12	83	11	
Campostoma anomalum	central stoneroller							4		737		5		1	111	41	3
Pimephales notatus	bluntnose minnow	Mi	Om					4		31	11	11		32	223	60	300
Pimephales promelas	fathead minnow	T	Om	24	166		12	5	70	34			18		11	110	45
Cyprinella spiloptera	spotfin shiner	Mi									4	1		5	15	65	136
Phoxinus eos	common shiner	Mi	Om, SL			5		10		152	35	72		32	286	78	161
Catastomidae	**Suckers**																
Catostomus commersoni	white sucker	T	SL	1	62	1	1	2	12	45		1	6	1	15	6	2
Moxostoma anisurum	silver redhorse	I, Ca	BI, SL													2	1
Moxostoma erythrurum	golden redhorse	Ca	BI, SL									8		1	4	16	8
Moxostoma valenciennesi	greater redhorse	I, Ca	BI, SL														1
Hypentelium nigricans	northern hogsucker	Ca										5			4	3	36
Moxostoma ssp.	redhorse yy																7

*Tolerance and trophic assignments from Bailey et al. (1993): **I** = intolerant, **T** = tolerant, **E** = exotic, non-native, **M**i = minnow, **Da** = darter, **Ca** = Sucker, **S** = sunfish, **Om** = omnivore, **BI** = benthic insectivore, **SL** = simple lithophilic spawner; **TC** = top carnivore.

Table A-7 (cont.):

Scientific Name	Common Name	IBI Classification*		R 15	R 16	R 17	R 18	R 19	R 20	R 21	R 22	R 23	R 24	R 25	R 26	R 27	R 28
Ictaluridae	**Catfishes**																
Ictualurus punctatus	channel catfish		TC>300mm									6				1	28
Noturus gyrinus	tadpole madtom									7	5						7
Ameiurus melas	black bullhead	T			44				91	4		6				2	
Gaterostidae	**Sticklebacks**																
Culaea inconstans	brook stickleback			73	98	3				7					9	1	
Centrarchidae	**Sunfishes**																
Lepomis cyanellus	green sunfish	S	BI							9						2	
Lepomis macrochirus	bluegill	S	BI													4	3
Lepomis humilis	orangespotted sunfish	S	BI						1								12
Percidae	**Perches**																
Etheostoma nigrum	johnny darter	Da				16				129	2	4		8	8	19	15
Etheostoma exile	Iowa darter	I, Da			78					161							
Perca flavecens	yellow perch								36						1	3	
Ethoeostoma flabellare	fantail darter	Da	BI			9				15					2		
Percina maculata	blackside darter	Da	BI, SL									3			6	10	12
Sander vitreus	walleye		TC, SL						1								

*Tolerance and trophic assignments from Bailey et al. (1993): **I** = intolerant, **T** = tolerant, **E** = exotic, non-native, **M**i = minnow, **Da** = darter, **Ca** = Sucker, **S** = sunfish, **Om** = omnivore, **BI** = benthic insectivore, **SL** = simple lithophilic spawner; **TC** = top carnivore.

Table A-8: Index of Biotic Integrity metric values and corresponding metric scores (in parentheses) for each reach by drainage area size class* for SNAKE (Niemela and Feist 2000). The individual metric scoring range for SNAKE is 0 to 10. In **bold** are FIBI scores and individual metric scores that represent a considerable deviation from least impacted expectation (scores <5).

	S1 S-VS	S2 S-VS	S3 S-VS	S4 S-VS	S5 S-VS	S6 S-S	S7 S-S	S8 S-S	S9 S-S	S10 S-M	S11 S-M	S12 S-M	S13 S-M	S14 S-M
FIBI**	58	80	**41**	78	68	76	**64**	74	79	73	**41**	76	80	71
Total number of species	9(7)	10(10)	10(10)	10(10)	9(7)	14(7)	13(7)	17(10)	18(10)	22(7)	**14(2)**	18(5)	25(10)	**14(2)**
Number of headwater species (excluding tolerant)	2 (5)	3(10)	**0(0)**	2(5)	1(5)	---	---	---	---	---	---	---	---	---
Number of minnow species (excluding tolerant)	3(5)	4(7)	**0(0)**	3(5)	3(5)	5(7)	4(5)	3(5)	4(5)	---	---	---	---	---
Number of darter species	---	---	---	---	---	---	---	---	---	3(5)	**1(0)**	**2(2)**	4(7)	3(5)
Number of intolerant species	---	---	---	---	---	2(5)	2(5)	4(10)	3(7)	6(5)	5(5)	7(7)	7(7)	4(5)
Percent of individuals that are tolerant species	17(7)	75(5)	**96(0)**	40(10)	54(10)	60(5)	48(7)	59(5)	48(7)	29(7)	28(7)	2(10)	28(7)	19(10)
Percent of the dominant two species	**91(0)**	51(10)	**92(0)**	46(10)	35(10)	49(7)	35(10)	**72(2)**	68(5)	---	---	---	---	---
Number of invertivore species (excluding tolerant)	3(5)	3(5)	2(5)	2(5)	**1(2)**	---	---	---	---	---	---	---	---	---
Number of benthic invertivore species	---	---	---	---	---	4(10)	**1(2)**	5(10)	3(7)	7(7)	**2(0)**	6(5)	8(7)	**4(2)**
Number of omnivore species	---	---	---	---	---	---	---	---	---	1(10)	1(10)	2(7)	3(5)	1(10)
Percent individuals that are piscivores	---	---	---	---	---	---	---	---	---	**10(2)**	**4(0)**	33(10)	20(7)	62(10)
Percent of individuals that are simple lithophilic spawners	**2(0)**	31(5)	**15(2)**	30(5)	**17(2)**	43(7)	**24(2)**	34(5)	71(10)	61(10)	**17(2)**	73(10)	71(10)	50(7)
Total number of fish per meter (excluding tolerant)	1.6 (10)	1.0 (10)	0.1 (10)	0.7 (10)	0.2 (10)	1.3 (10)	0.4 (10)	1.3 (10)	0.9 (10)	2.2 (10)	0.3 (10)	0.8 (10)	1.3 (10)	0.1 (10)
Percent of the individuals with Deformities, Eroded fins, Lesions, or Tumors (DELT)	0 (10)	0.2 (10)	0 (10)	1.0 (10)	0 (10)	0.6 (10)	0.4 (10)	0.6 (10)	0 (10)	0.3 (10)	0 (10)	0 (10)	0.1 (10)	0 (10)

*S-VS = very small (<52 km^2), S-S = small (52-140 km^2), and S-M = moderate (141 – 700 km^2). [c]

FIBI scores in **bold indicate reaches below the impairment threshold for SNAKE (Niemela and Feist 2000).

Table A-9: Index of Biotic Integrity metric values and corresponding metric scores (in parentheses) for REDWOOD (Bailey et al. 1993). In **bold** are metrics score in **bold** are considered a considerable deviation from least impacted expectation (scores <3).

	R15 S	R16 S	R17 S	R18 S	R19 S	R20 S	R21 S	R22 S	R23 S	R24 S	R25 M	R26 M	R27 M	R28 M
FIBI (12 to 60)	26.4	21.6	38.4	**24.0**	36.0	33.6	22.8	33.6	32.8	40.8	24	30	32	30
FIBI converted to 0 to 100 scale*	29	21	55	**25**	46	54	15	46	35	60	25	42	29	38
Total number of native fish species	7(3)	7(3)	9(3)	**5(1)**	12(5)	17(5)	6(3)	11(3)	6(3)	15(5)	10(3)	9(3)	24(5)	20(5)
Number of darter species	**0(1)**	1(3)	2(5)	**0(1)**	1(3)	**1(1)**	**1(1)**	**1(1)**	**0(1)**	2(3)	**1(1)**	3(5)	2(3)	2(3)
Number of sunfish species	---	---	---	---	---	---	---	---	---	---	**0(1)**	**0(1)**	2(3)	2(3)
Number of sucker species (excluding white sucker)	---	---	---	---	---	---	---	---	---	---	**1(1)**	2(3)	3(3)	4(3)
Number of minnow species (excluding common carp, creek chub, fathead minnow)	3(5)	**1(1)**	4(3)	**2(3)**	6(5)	7(5)	**0(1)**	8(5)	3(3)	7(5)	---	---	---	---
Number of intolerant species	**0(1)**	1(3)	1(3)	**0(1)**	1(3)	2(3)	**0(1)**	**1(1)**	**0(1)**	2(3)	**1(1)**	2(3)	2(3)	2(3)
Percent of individuals that are tolerant species	26(3)	**52(1)**	29(3)	**32(1)**	**45(1)**	16(3)	**63(1)**	7(5)	**35(1)**	6(5)	1(5)	7(5)	25(3)	11(3)
Percent of individuals that are simple lithophils	**2(1)**	**10(1)**	49(3)	62(5)	**24(1)**	**9(1)**	**0(1)**	30(3)	63(5)	72(5)	32(3)	45(3)	64(5)	19(1)
Percent of individuals that are omnivores**	35(3)	**54(1)**	5(5)	**28(1)**	20(5)	**49(1)**	25(3)	**74(1)**	7(5)	**62(1)**	**84(1)**	**62(1)**	**69(1)**	**76(1)**
Percent of individuals that are specialized insectivores	**0(1)**	**0(1)**	**6(1)**	**0(1)**	**3(1)**	**1(1)**	**2(1)**	**0(1)**	**0(1)**	11(3)	1(1)	**1(1)**	**0(1)**	**6(1)**
Percent of individuals that are top carnivores	---	---	---	---	---	---	---	---	---	---	**0(1)**	**0(1)**	**0.5(1)**	**2.3(1)**
Catch per unit effort (number of individuals per minute) (excluding tolerant)	**1.5(1)**	**5.7(1)**	**1.6(1)**	**2.6(1)**	**2.0(1)**	36.7(5)	**0.6(1)**	11.2(3)	**6.2(1)**	**3.3(1)**	**2.3(1)**	**8.8(1)**	**6.9(1)**	**6.1(1)**
Percent of individuals with deformities, eroded fins, lesions, and tumors (DELT)	0.8(3)	0.3(3)	0(5)	0(5)	0(5)	0.04(3)	**4.2(1)**	0(5)	0.3(3)	0.7(3)	0(5)	0.2(3)	0.3(3)	0(5)

*The FIBI total score for REDWOOD is converted to a 0 to 100 scale for comparison with FIBI scores for SNAKE.

Table A-10: PSI and CEM results by reach. Statistics for percent (%) of score range observed for COMBINED, REDWOOD and SNAKE. Metrics with ≤ 60% of total metric score range observed are in **bold**. Metric abbreviations found in Table A-5.

	LS	MW	DJP	VBP	UPPER	CC	BRC	OFDST	C	D	LOWER
Possible score range	2-8	3-12	2-8	3-12	10-40	1-4	2-8	2-8	4-16	4-16	13-52
S1	2	7.5	6	5	20.5	2	8	5	8	4	27
S2	2	6	2	6	16	2	8	2	4	4	20
*S3**	*4*	*4*	*4*	*6*	*18*	*2*	*8*	*2*	*6*	*4*	*22*
S4	4	3	4	3	14	4	6	4	8	4	26
S5	4	6	4	6	20	3	6	2	8	4	23
S6	4	3	6	6	19	3	6	4	4	5	22
S7	5	6	4	3	18	3	6	4	8	4	25
S8	6	6	4	6	22	2	7	2	5	4	20
S9	6	4	6	3	19	2	7	4	5	4	22
S10	6	6	4	6	22	3	4	2	6	8	23
S11	8	9	6	9	32	2	8	4	12	12	38
S12	6	3	4	3	16	4	3	2	10	8	27
S13	2	4	3	3	12	3	8	2	8	4	25
S14	4	3	4	3	14	4	6	4	8	12	34
Score range observed for SNAKE	2-8	3-7.5	2-6	3-9	12-32	2-4	3-8	2-5	4-12	4-12	20-38
% of possible range	100	**50**	67	67	67	75	83	**50**	67	67	**47**
*R15**	*8*	*3*	*2*	*6*	*19*	*2*	*8*	*2*	*6*	*4*	*22*
R16	8	6	4	9	27	2	8	4	10	4	28
R17	6	9	8	9	32	3	8	8	8	12	39
R18	8	6	2	6	22	2	8	2	4	8	24
R19	8	9	2	9	26	2	8	4	8	8	30
R20	6	6	2	6	18	2	8	4	10	8	32
R21	8	9	4	7	28	1	8	4	12	8	33
R22	8	6	2	6	22	2	8	4	10	12	36
*R23**	*8*	*9*	*3*	*6*	*24*	*2.5*	*8*	*4*	*8*	*4*	*26.5*
R24	8	9	2	6	25	2	8	4	10	4	28
R25	8	6	2	6	20	2	5	2	12	4	25
R26	6	6	4	6	22	3	8	4	6	12	33
R27	8	11	4	8	31	3	8	2	16	8	37
R28	8	3	4	6	19	4	6	2	4	4	20
Score range observed for REDWOOD	4-8	3-11	2-8	6-9	18-32	1-4	5-8	2-8	4-16	4-12	20-39
% of possible range	67	89	100	**33**	**47**	100	**50**	100	100	67	**49**
Score range observed for COMBINED	2-8	3-11	2-8	3-9	12-32	1-4	3-8	2-8	4-16	4-12	20-42
% of possible range	100	89	100	67	67	100	83	100	100	67	**56**

* Sites that were not included in the statistical analysis were excluded from the summary of score range.

Table A-10 (cont.):

	RA	Br	CPP	BSD/ PSM	SD	CAV	<u>BOTTOM</u>	PSI	CEM **
Possible score range	1-4	1-4	2-8	4-16	6-24	1-4	15-60	38-152	2-6
S1	3	2	5	14	18	2	44	91.5	2.5
S2	3	2	5	4	6	2	22	58	6
*S3**	*3*	*3*	*6*	*14*	*12*	*2*	*40*	*80*	*2.5*
S4	2	1	4	4	12	1	24	64	6
S5	1	1	6	4	12	2	26	60	2.5
S6	3	1	3	4	8	1	20	61	6
S7	3	1	4	8	12	2	30	73	3
S8	3	1	3	6	12	1	26	68	3.5
S9	2	1	6	10	6	2	27	68	4.5
S10	2	2	4	8	12	2	30	75	4.5
S11	2	3	4	12	20	4	47	117	2.5
S12	2	1	3	4	6	3	19	67	5
S13	3	1	8	8	12	1	29	66	5
S14	3	1	5	8	20	2	34	82	3
Score range observed for SNAKE	1-3	1-3	3-8	4-14	6-20	1-4	19-47	58-117	2.5-6
% of possible range	67	67	83	83	**62**	100	**62**	**51**	88
*R15**	*2*	*3*	*8*	*16*	*24*	*3*	*56*	*97*	*2.5*
R16	3	1	7	16	18	1	46	101	2
R17	3	2	4	8	16	2.5	35.5	106.5	3.5
R18	2	1	5	8	12	2	30	74	4.5
R19	2	2	4	10	16	2.5	36.5	92.5	3.5
R20	3	2	7	12	12	2	38	88	2.5
R21	2	3	8	16	24	2	55	117	2.5
R22	3	3	5	8	12	3	34	92	2.5
*R23**	*3*	*1.5*	*2.5*	*6*	*10*	*2*	*25*	*75.5*	*3*
R24	3	2	6	12	18	3	44	97	3
R25	3	1	4	6	12	3	29	74	2.5
R26	3	2	5	10	16	4	40	95	3.5
R27	3	4	8	16	24	4	59	127	2.5
R28	2	1.5	4	8	12	2	29.5	68.5	3.5
Score range observed for REDWOOD	2-3	1-4	4-8	6-16	12-24	1-4	29-59	68.5-127	2-4.5
% of possible range	**33**	100	67	83	67	100	67	**51**	**50**
Score range observed for COMBINED	1-3	1-4	3-8	4-16	6-24	1-4	19-59	58-127	2.5-6
% of possible range	67	100	83	83	100	100	89	**61**	88

* Sites that were not included in the statistical analysis were excluded from the summary of score range.

**For CEM, where two stages observed, average stage number used (e.g., CEM stages II and III = 2+3/2 = 2.5).

Table A-11: MSHA metric scores, composite zone scores (underlined), and total score observed for each study site. Statistics for percent (%) of score range observed for each metric grouping for COMBNED, REDWOOD, and SNAKE. Metrics with < 67 % of total metric score range observed are in **bold**. See Table A-5 for full metric names for abbreviations listed here.

	SLU	RW	BE	Sh	RIPARIAN	Su	Em	ST	INSTREAM
Possible score range	0-5	0-5	0-5	0-5	0-15	0-20	-1-4	0-2	-1-26
S1	5	5	4	2	11	9	0	0	9
S2	5	5	4	1	10	9	2	2	13
*S3**	*5*	*3.5*	*4*	*1*	*8.5*	*9.5*	*1*	*0*	*10.5*
S4	5	5	5	5	15	19	3	0	22
S5	5	4	4	4.5	12.5	16	1	2	19
S6	5	5	4	4	13	17	3	0	20
S7	5	4	4	4	12	17	1	0	18
S8	5	4.5	4	1	9.5	16	1	2	19
S9	3.5	4.5	4	4	12.5	15	3	0	18
S10	5	5	4	2	11	17	3	0	20
S11	3.5	3	3	4	10	15	1	0	16
S12	1	4	4	2	10	19	3	0	22
S13	3.5	3.5	5	4	12.5	17.5	3	2	22.5
S14	5	5	4	1	10	19	1	2	22
Score range SNAKE	1-5	3-5	3-5	1-5	8-15	9-19	1-3	0-2	9-22.5
% of possible score range	80	**40**	**40**	80	**47**	**50**	**40**	100	**50**
*R15**	*0*	*2*	*5*	*1*	*8*	*2*	*0*	*0*	*2*
R16	0	0	4	1	5	12	1	0	13
R17	0	0	3	2	5	14.5	1	2	17.5
R18	0	1	4	2	7	9	0	0	9
R19	0	1.5	4	1	6.5	10	3	0	13
R20	5	5	4	1	10	15.5	1	2	18.5
R21	0	0	3	1	4	10	-1	0	9
R22	0	2	4	1	7	15	1	0	16
*R23**	*3.5*	*3.5*	*4*	*2*	*9.5*	*17*	*2*	*2*	*21*
R24	5	5	4	1	10	16.5	1	2	19.5
R25	0	1	4	1	6	9	1	2	12
R26	1	2	4	1	7	16	3	0	19
R27	5	4.5	3	0	7.5	14.5	0	0	14.5
R28	0	1	5	1	7	18	1	2	21
score range REDWOOD	0-5	0-5	3-5	0-2	5-10	9-18	-1-3	0-2	9-21
% of possible score range	100	100	**40**	**40**	**33**	80	80	100	**41**
score range COMBINED	0-5	0-5	3-5	0-5	5-15	9-19	-1-3	0-2	9-22.5
% of possible score range	100	100	**40**	100	67	50	80	100	**50**

* Sites that were not included in the statistical analysis were excluded from the summary of score range.

Table A-11 (cont.):

	CT	CA	COVER	DV	CS	VT	Si	PW/ RW	CD	CHAN-MORPH	MSHA
Possible score range	0-7	-1-10	-1-17	0-6	0-9	-1-4	0-6	0-2	0-9	0-37	-2-100
S1	4	7	11	6	6	2	6	0	6	26	62
S2	5	10	15	3	9	1	3	0	3	19	62
*S3**	*4*	*7*	*11*	*6*	*6*	*2*	*0*	*2*	*3*	*19*	*54*
S4	7	7	14	6	9	2	2	1	6	26	82
S5	7	3	10	6	7.5	2	0	2	4.5	22	68.5
S6	6	7	13	6	9	0	4	2	9	30	81
S7	4	7	11	6	9	4	4	2	6	31	77
S8	7	7	14	6	9	1	0	0	0	16	63.5
S9	6	3	9	3	9	1	2	0	3	18	61
S10	7	3	10	6	9	3	4	2	6	30	76
S11	3	3	6	3	0	3	6	1	6	19	54.5
S12	7	7	14	6	9	3	3	0	9	30	77
S13	6	10	16	6	9	3	3	2	9	32	86.5
S14	5	7	12	6	9	2	3	2	7	29	78
Score range SNAKE	3-7	3-10	6-16	3-6	0-9	0-3	0-6	0-2	0-9	16-31	54.5-86.5
% of possible score range	**57**	70	**56**	**50**	100	**60**	100	100	100	**41**	**31**
*R15**	*3*	*-1*	*2*	*0*	*6*	*1*	*0*	*0*	*0*	*7*	*19*
R16	5	-1	4	6	6	1	4	2	3	22	44
R17	6	3	9	6	6	3	4	0	9	28	59.5
R18	4	7	11	0	6	1	0	0	0	7	34
R19	4	3	7	6	6	3	2	2	3	22	48.5
R20	4	3	7	6	6	2	4	2	5	25	65.5
R21	4	3	7	3	0	3	6	2	3	17	37
R22	5	3	8	0	6	2	0	0	0	8	39
*R23**	*5.5*	*7*	*12.5*	*6*	*8*	*4*	*4*	*2*	*6*	*30*	*76.5*
R24	5	3	8	3	6	2	6	0	9	26	68.5
R25	4.5	3	7.5	6	6	1	2	2	3	20	45.5
R26	6	3	9	6	6	3	2	0	6	23	59
R27	4	3	7	6	1.5	2	4	1	4	18.5	52.5
R28	4	3	7	6	6	4	3	1	6	26	61
Score range REDWOOD	3-6	-1-7	4-11	0-6	0-6	1-4	0-6	0-2	0-9	7-28	34-76.5
% of possible score range	**43**	73	**39**	100	67	**60**	100	100	100	**57**	**42**
Score range COMBINED	3-7	-1-10	4-16	0-6	0-9	0-4	0-6	0-2	0-9	7-31	34-86.5
% of possible score range	**57**	100	67	100	100	80	100	100	100	**65**	**51**

* Sites that were not included in the statistical analysis were excluded from the summary of score range.

APPENDIX B

FIBI, PSI and MSHA scores grouped by ecoregion, stream class, and channel condition

Results of Analysis of Variance (ANOVA) and Wilkoxin Sum Rank Test for small sample sizes are included in Tables 2-6, 2-8, and 2-9).

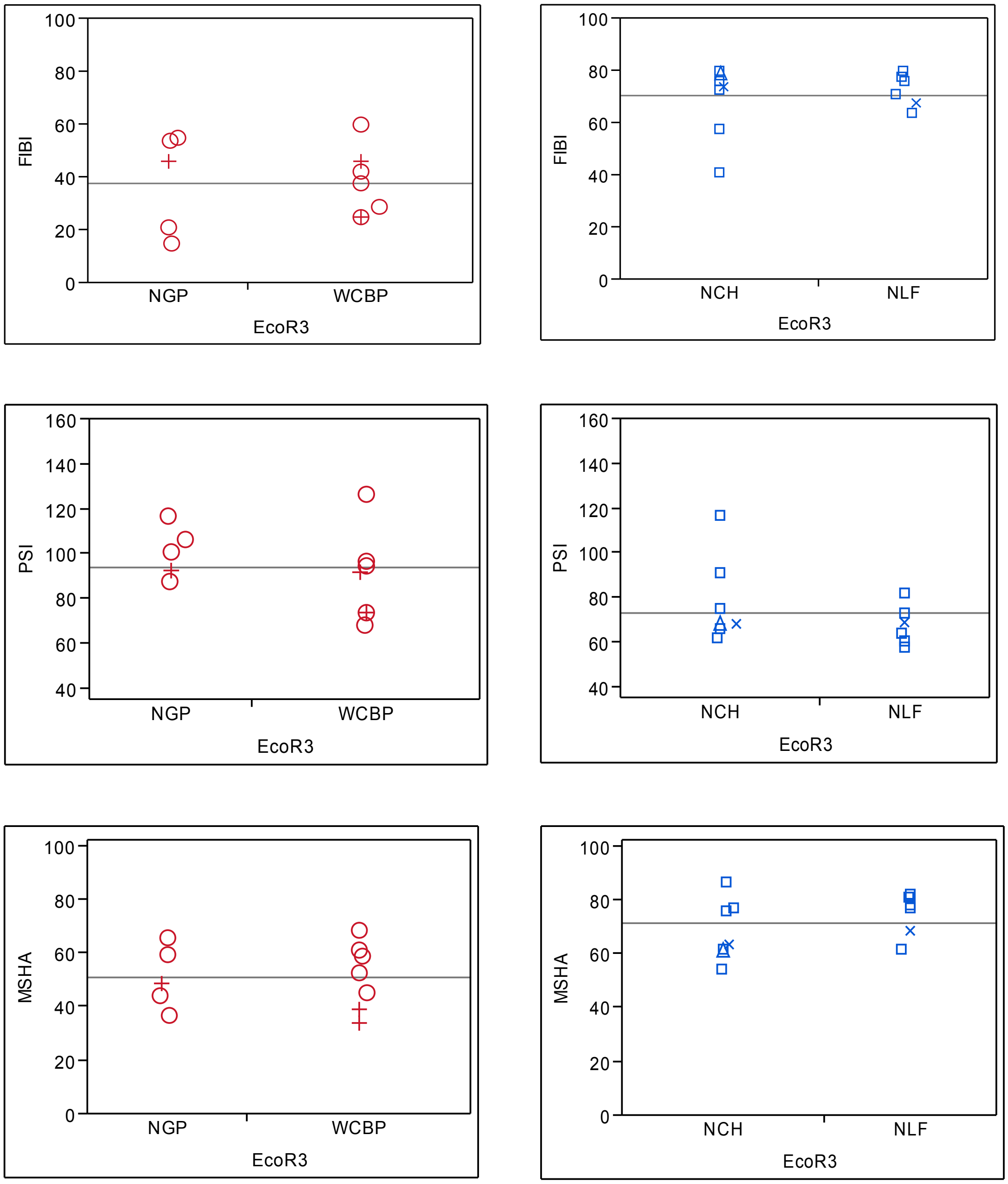


Figure B-1. Distributions in FIBI, PSI, and MSHA scores by Level III *ecoregion* in REDWOOD and SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA = ◘, OC= x, and OC/NA= Δ. The solid line is the grand mean.

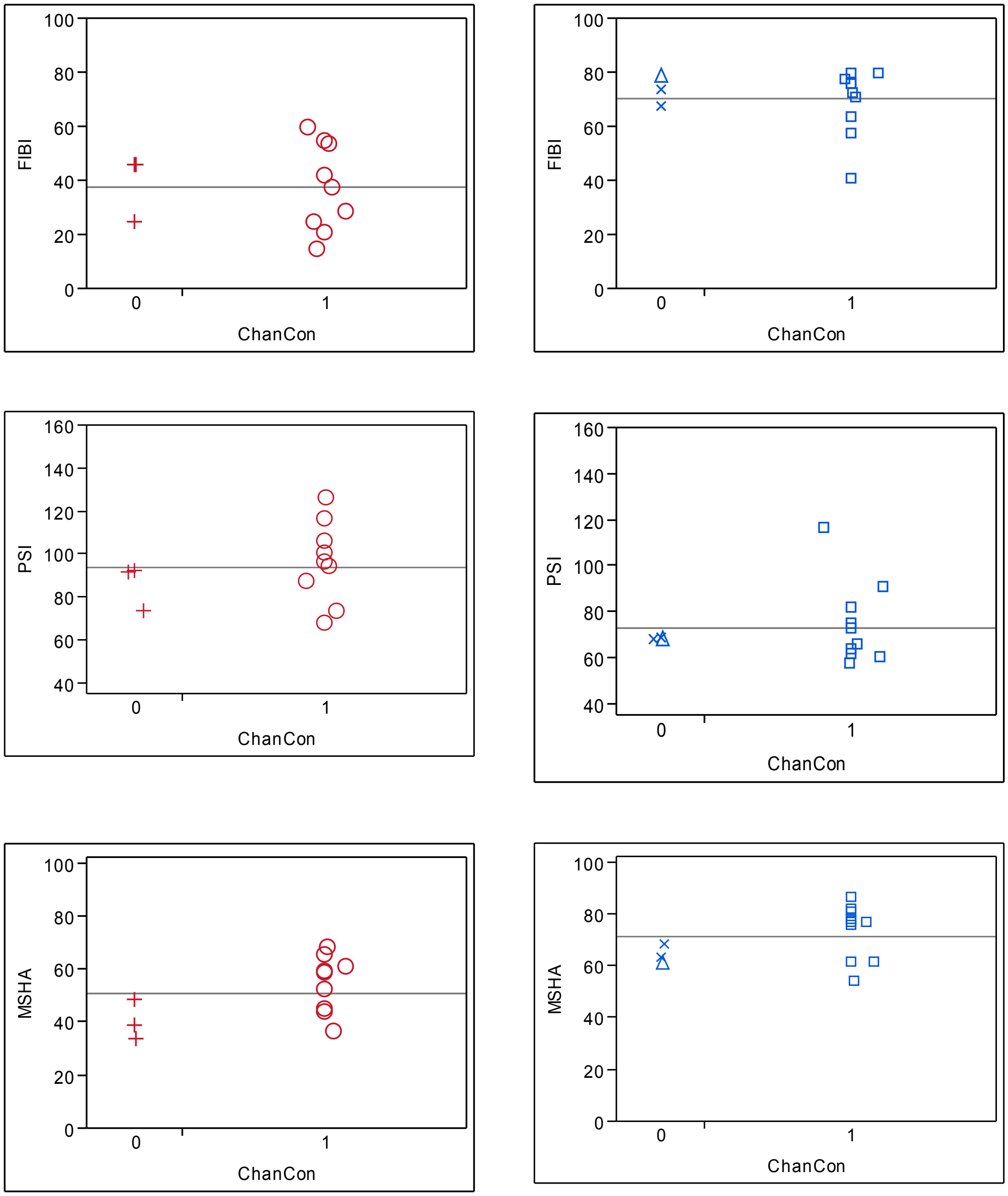


Figure B-2: Distributions in FIBI, PSI, and MSHA by *channel condition* for REDWOOD and SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA = ◘, OC= x, and OC/NA= Δ. The solid line is the grand mean.

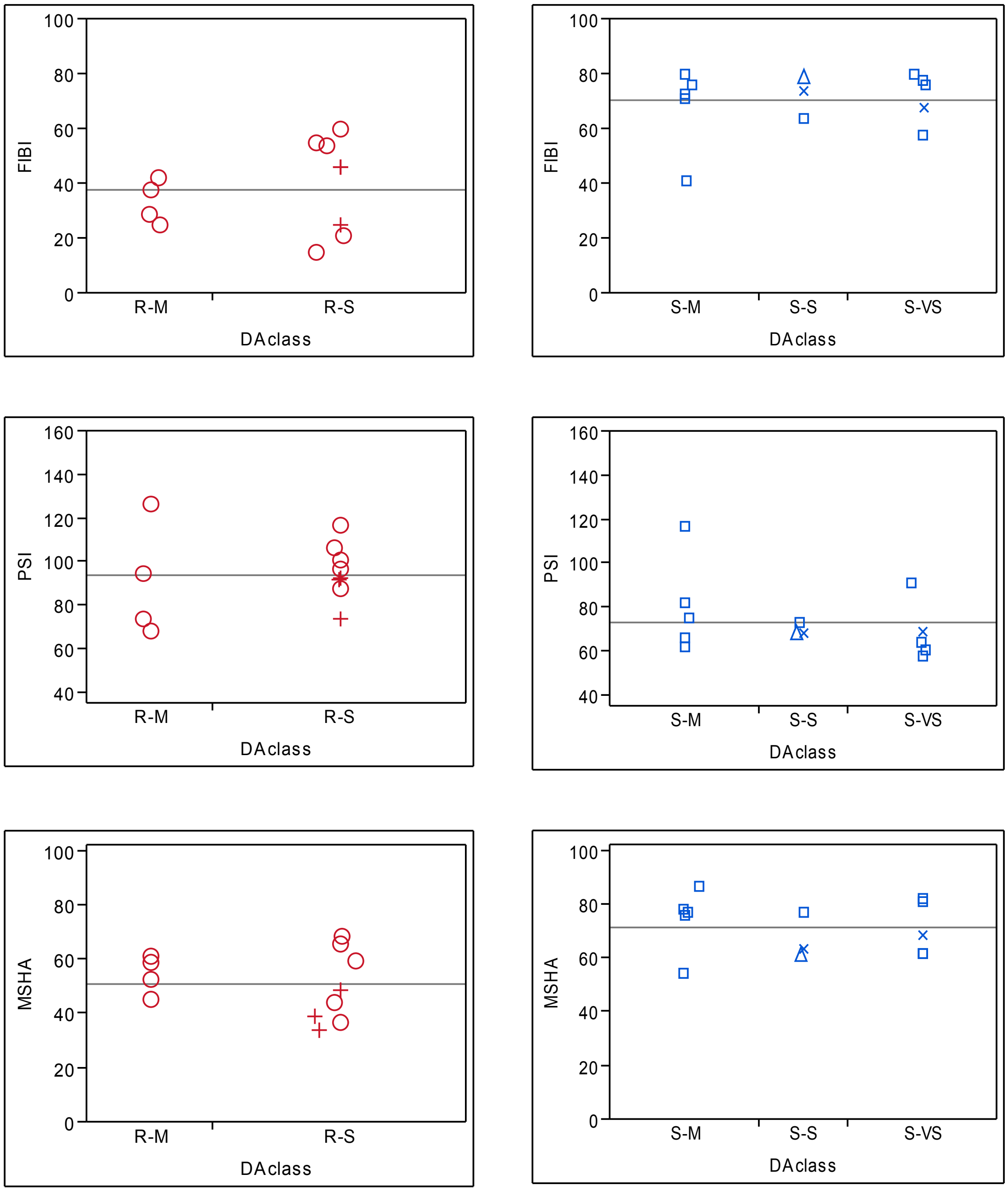


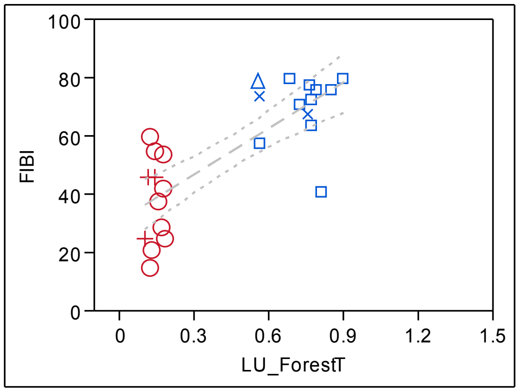
Figure B-3: Distribution in FIBI, PSI, and MSHA by drainage area *stream class* for REDWOOD and SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ. The solid line is the grand mean.

APPENDIX C

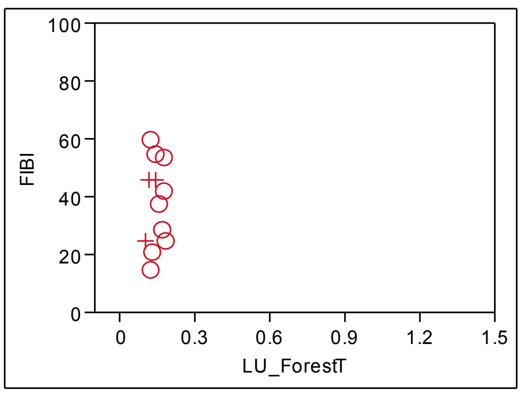
Bivariate scatterplots and linear and polynomial regression results for individual PSI and MSHA metrics

The variable name will indicate whether or not a transformation was applied (e.g., logDA, logGradient(x+1), pctCobbleT). For variables ending in “T”an ArcSine Square Root transformation was applied.

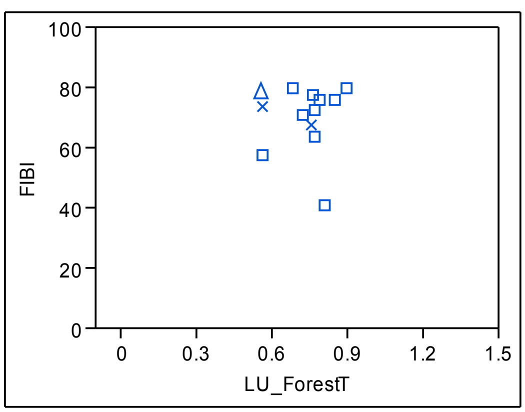
Graphs and statistical tests generated from JMP© 8.0 Discovery Software (SASS Institute).



A) COMBINED: FIBI = 31.65 + 52.19*LU_ForestT + 13.63, $R^2 = 0.59$, p = <0.0001.

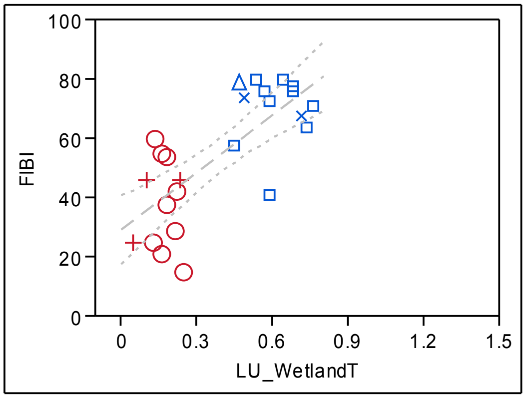


B) REDWOOD: No significant association.

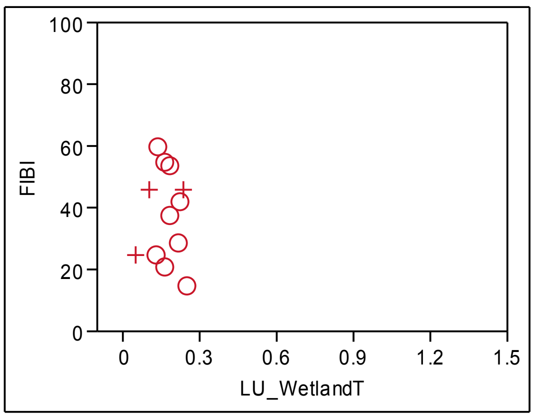


C) SNAKE: No significant association.

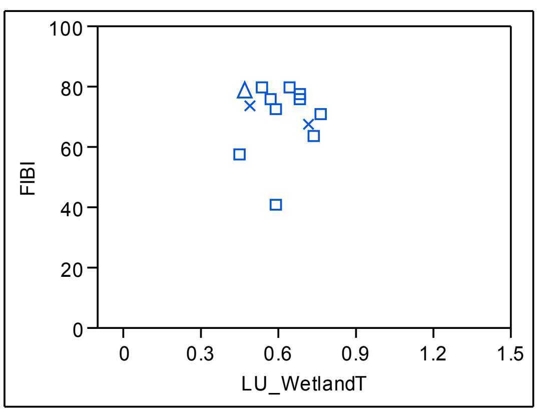
Figure C-1: Plots and linear regression demonstrating a significant association between FIBI and *percent forestT* for A) COMBINED, but no association for B) REDWOOD or C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 29.27 + 64.98*LU_WetlandT + 14.30, $R^2 = 0.55$, $p = <0.0001$.

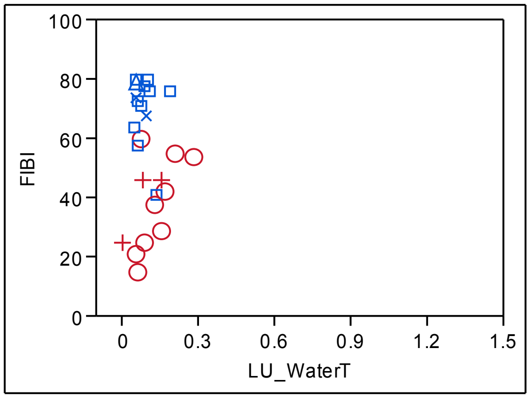


B) REDWOOD: No significant association.

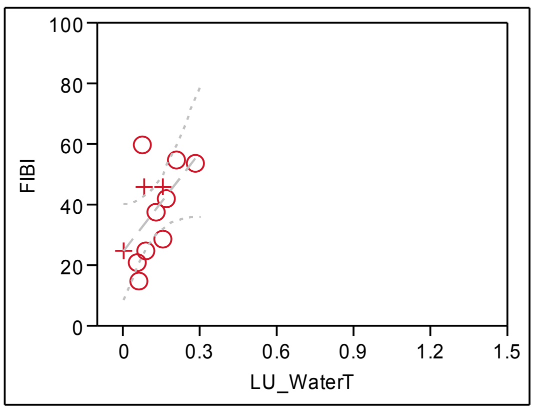


C) SNAKE: No significant association.

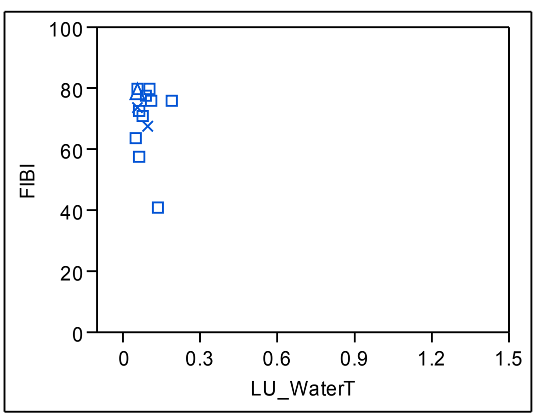
Figure C-2: Plots and linear regression demonstrating a significant association between FIBI and *percent wetlandT* for A) COMBINED, but no association for B) REDWOOD or C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: No significant association.

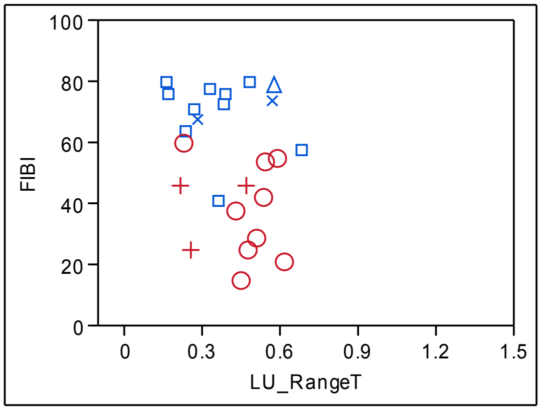


B) REDWOOD: FIBI = 24.77 + 110.51*LU_WaterT + 12.74, $R^2 = 0.33$, $p = 0.0522$.

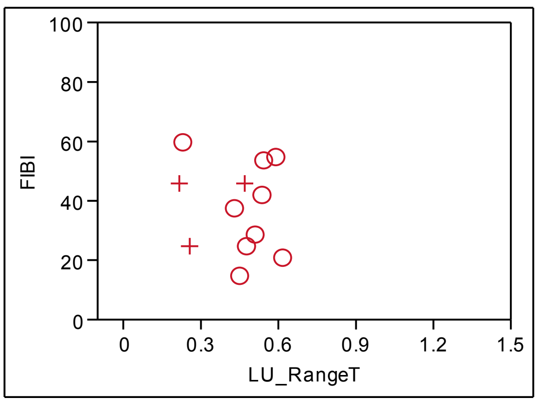


C) SNAKE: No significant association.

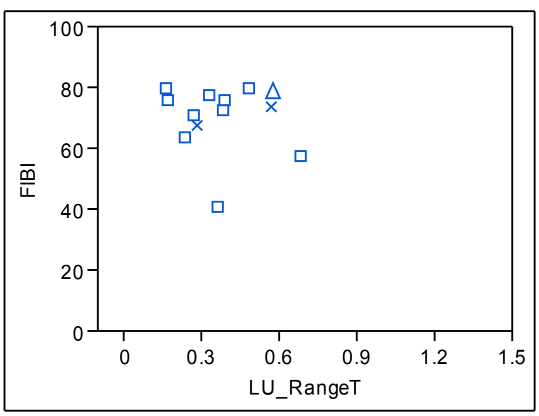
Figure C-3: Plots and linear regression demonstrating a significant association between FIBI and *percent waterT* for B) REDWOOD, but no significant association for A) COMBINED or C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: No significant association.

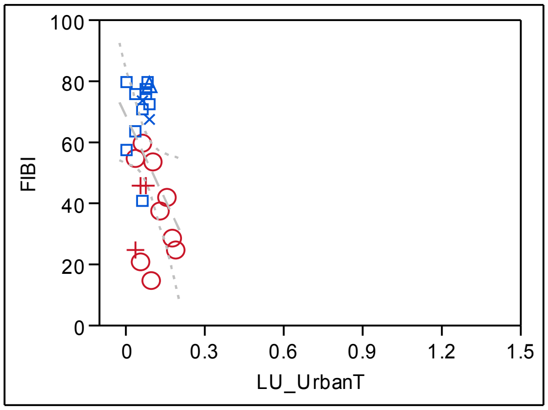


B) REDWOOD: No significant association.

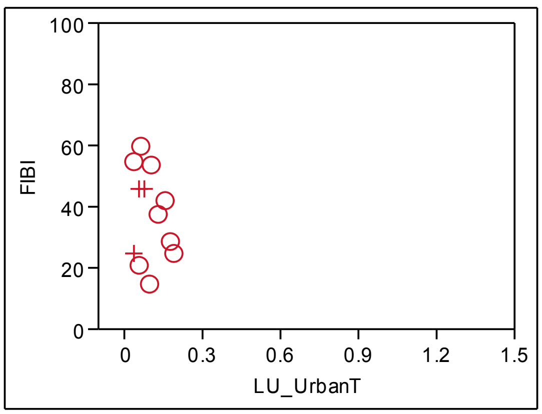


C) SNAKE: No significant association.

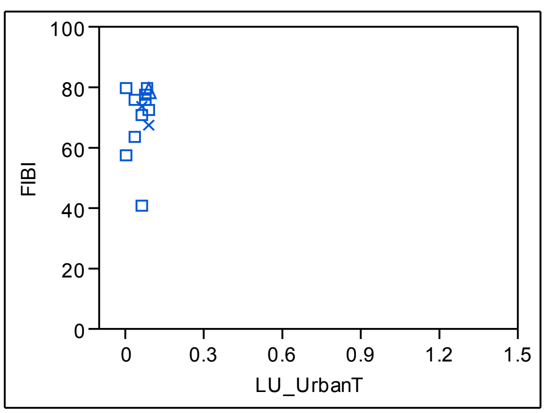
Figure C-4: Plots demonstrating no significant associations between FIBI and *percent rangeT* for any watershed grouping. A) COMBINED, B) REDWOOD, C) SNAKE). REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 68.84 - 185.77*LU_UrbanT + 19.44, R^2 = 0.17, p = 0.0387.

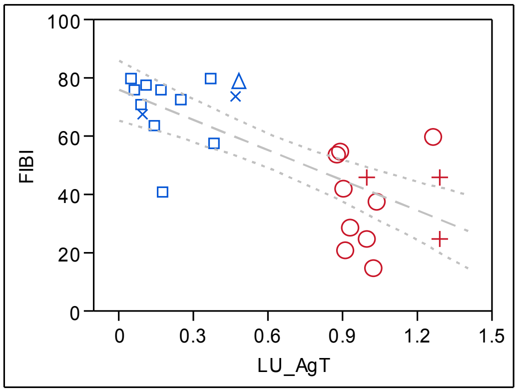


B) REDWOOD: No significant association.

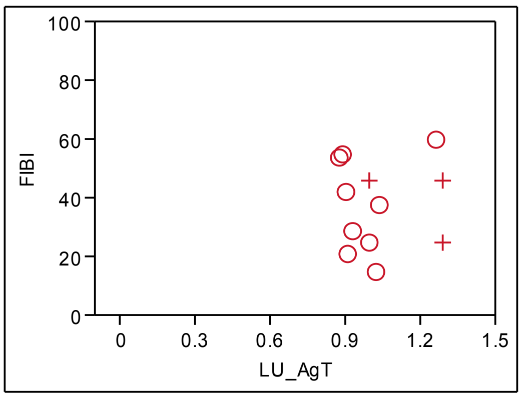


C) SNAKE: No significant association.

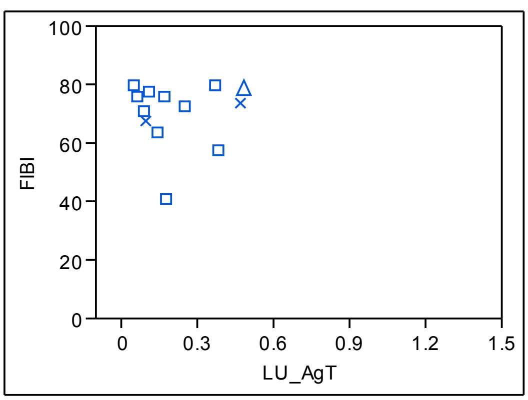
Figure C-5: Plots demonstrating a significant association between FIBI and *percent urbanT* for A) COMBINED, but no significant association for B) REDWOOD or C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 75.98- 34.63*LU_AgT + 14.54, R^2 = 0.54, p = <0.0001.

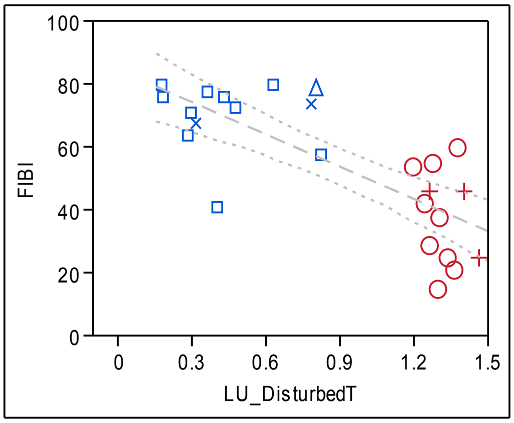


B) REDWOOD: No significant association.

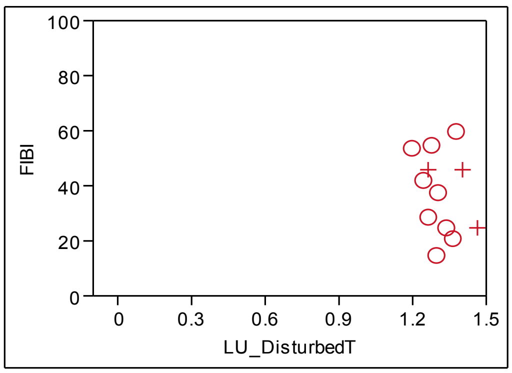


C) SNAKE: No significant association.

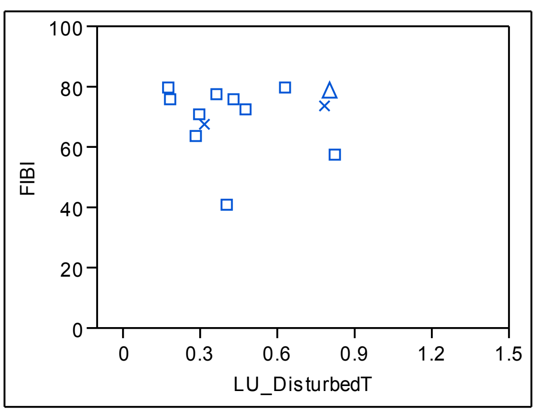
Figure C-6: Plots demonstrating a significant association between FIBI and *percent agricultureT* for A) COMBINED, but no significant association for B) REDWOOD or C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 84.28 - 33.86*LU_DisturbedT + 13.95, R^2 = 0.57, p = <0.0001.

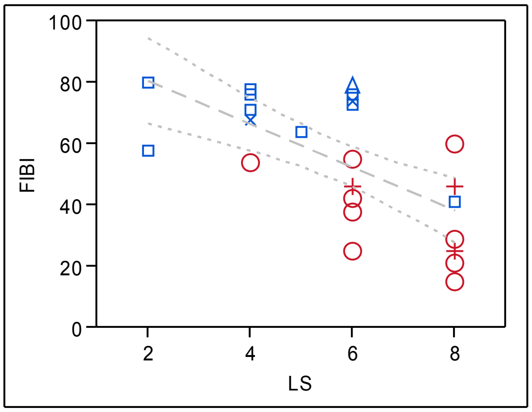


B) REDWOOD: No significant association.

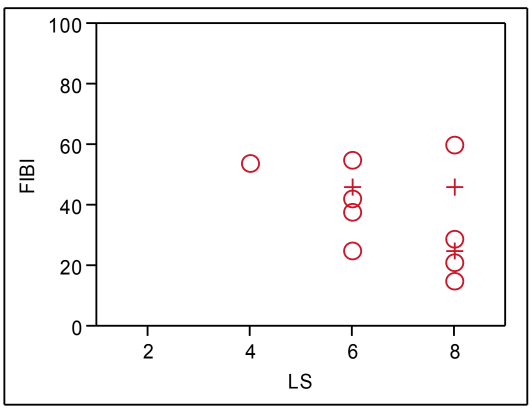


C) SNAKE: No significant association.

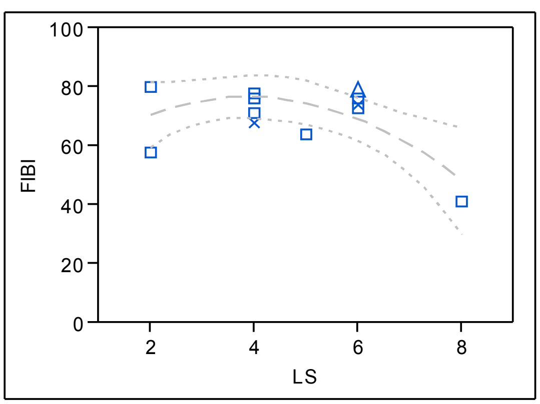
Figure C-7: Plots demonstrating a significant association between FIBI and *percent disturbedT* for A) COMBINED, but no significant association for B) REDWOOD or C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 94.74 - 7.05*LS + 15.94, $R^2 = 0.44$, $p = 0.0003$.

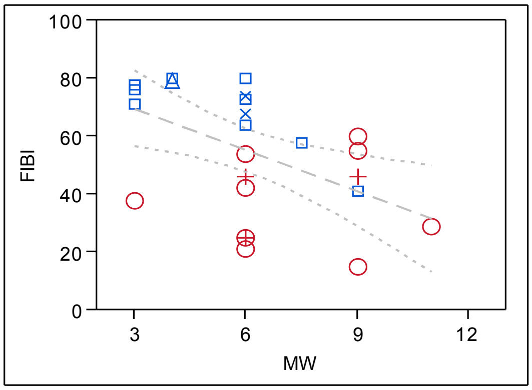


B) REDWOOD: No significant linear or polynomial association

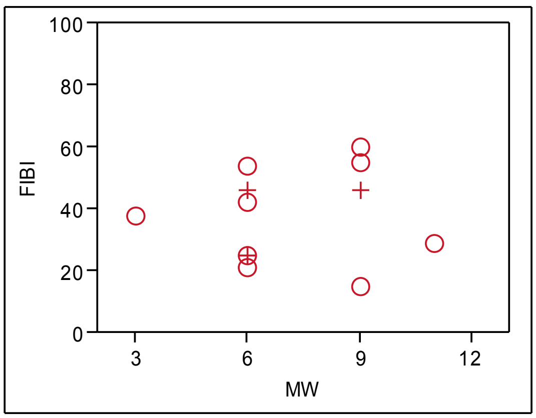


C) SNAKE: FIBI = 85.96 - 2.21*LS - 1.68*LS^2, $R^2 = 0.46$, $p = 0.0457$.

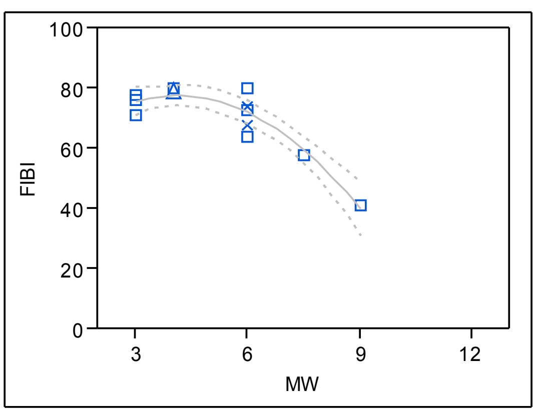
Figure C-8: Plots and linear and polynomial regression demonstrating a significant negative association between FIBI and PSI metric *landform slope* for C) COMBINED and C) SNAKE but no significant linear or polynomial association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 83.72 - 4.73*MW + 18.34, R^2 = 0.26, p = 0.0085.

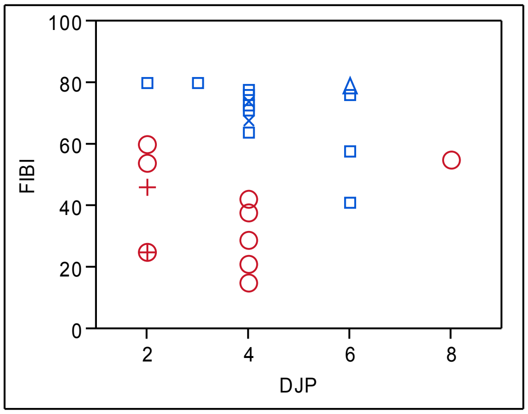


B) REDWOOD: No significant linear or polynomial association.

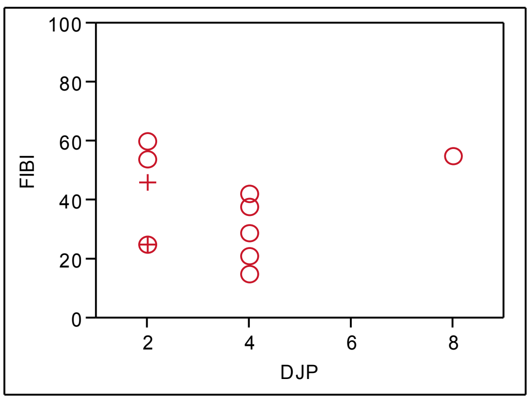


C) SNAKE: FIBI = 51.50 + 12.79*MW - 1.56*MW^2 + 4.33, R^2 = 0.87, p = <0.0001.

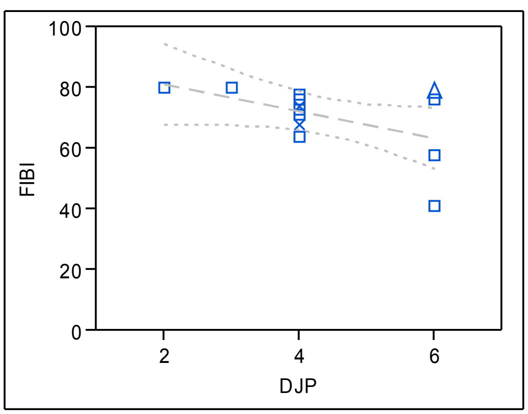
Figure C-9: Plots and linear and polynomial regression demonstrating negative association between FIBI and PSI metric *mass wasting or failure* for A) COMBINED and C) SNAKE, but no significant linear or polynomial association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: No significant association.

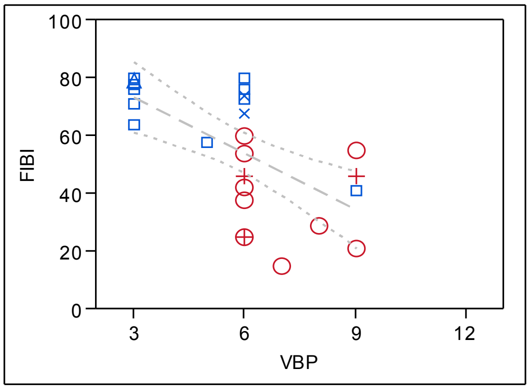


B) REDWOOD: No significant linear or polynomial association.

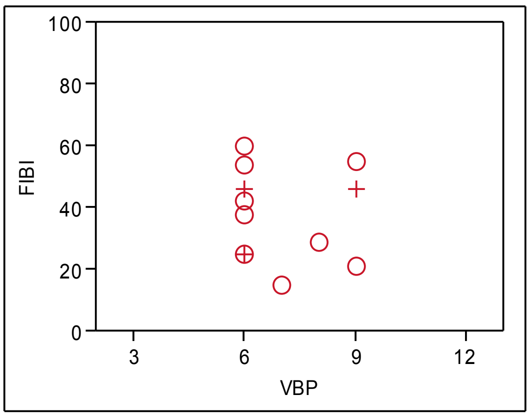


C) SNAKE: FIBI = 90.17 - 4.46*DJP + 9.93, $R^2 = 0.26$, $p = 0.0755$.

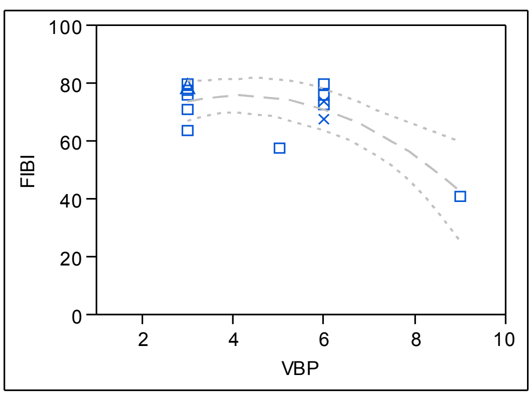
Figure C-10: Plots demonstrating a significant linear association between FIBI and PSI metric *debris jam potential* for C) SNAKE and no linear or polynomial association for A) COMBINED or B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 92.94 - 6.50*VBP + 16.78, R^2 = 0.38, p = 0.0010.

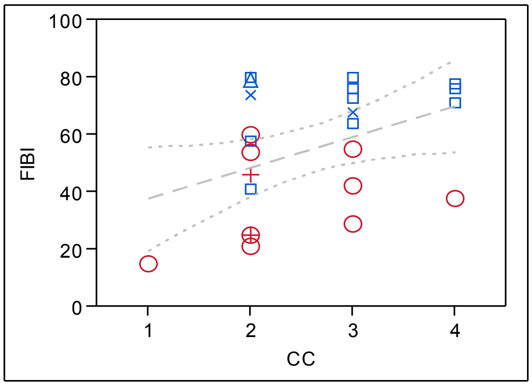


B) REDWOOD: No significant linear or polynomial association.

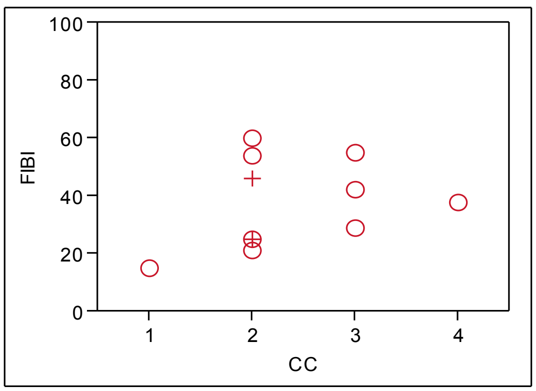


C) SNAKE: FIBI = 51.45+ 11.77*VBP - 1.41*VBP^2 +7.78, R^2 = 0.59, p = 0.0351.

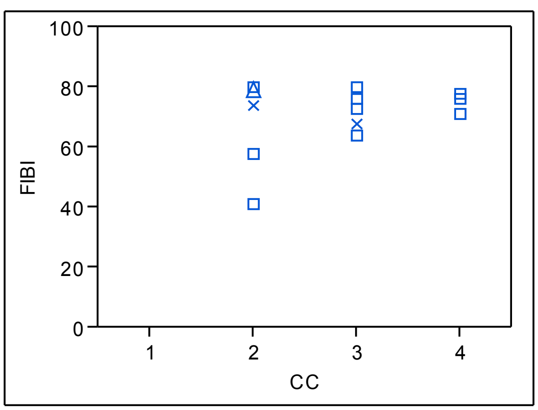
Figure C-11: Plots and linear and polynomial regression demonstrating a significant negative association between FIBI and PSI metric *vegetative bank protection* for A) COMBINED and C) SNAKE. but no linear or polynomial association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



COMBINED: FIBI = 26.75 + 10.85*CC + 19.37, R^2 = 0.18, p = 0.0358.

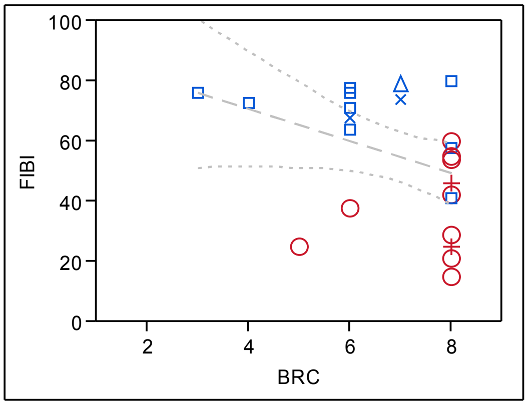


REDWOOD: No significant association.

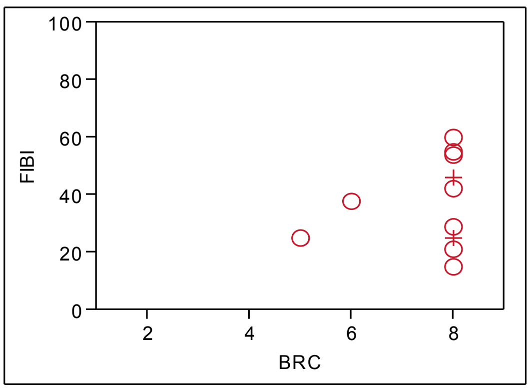


SNAKE: No significant linear or polynomial association.

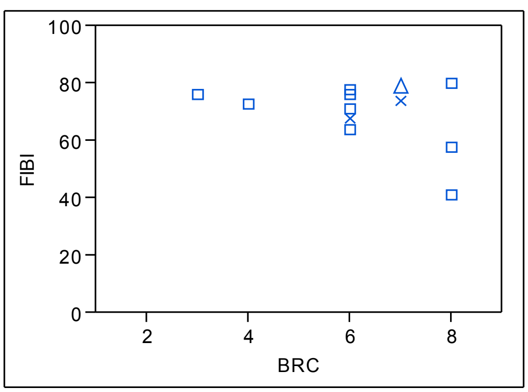
Figure C-12: Plots and regression demonstrating a positive linear association between FIBI and PSI metric *channel capacity* for A) COMBINED, but no significant linear or polynomial association for B) REDWOOD or C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 92.07- 5.33*BRC + 19.91, R^2 =0.13, p = 0.0738.

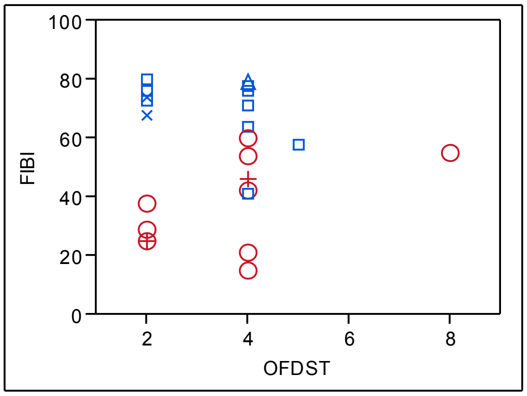


B) REDWOOD: No significant linear or polynomial association.

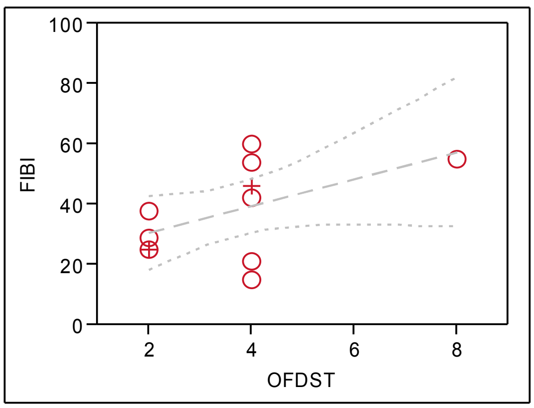


C) SNAKE: No significant linear or polynomial association.

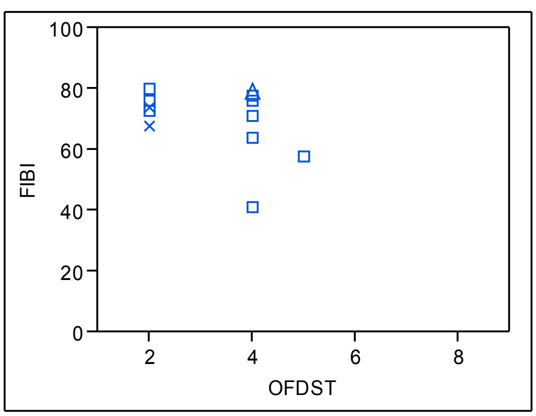
Figure C-13: Plots demonstrating a potential weak association between FIBI and PSI metric *bank rock content* for A) COMBINED, but no significant linear or polynomial associations for B) REDWOOD and C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: No significant linear or polynomial association.

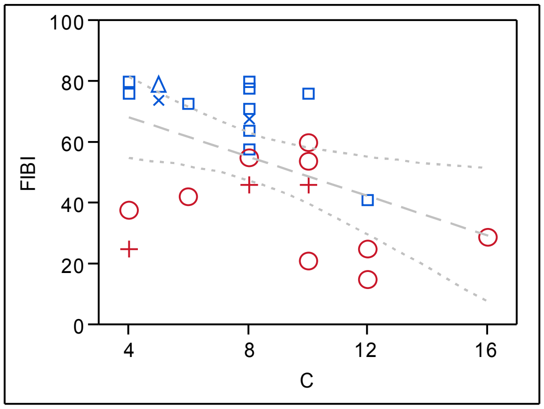


B) REDWOOD: FIBI = 21.50 + 4.50*OFDST + 13.38, $R^2 = 0.26$, $p = 0.0920$.

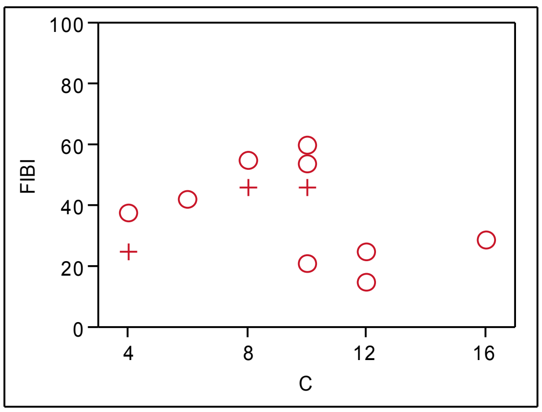


C) SNAKE: No significant linear or polynomial association.

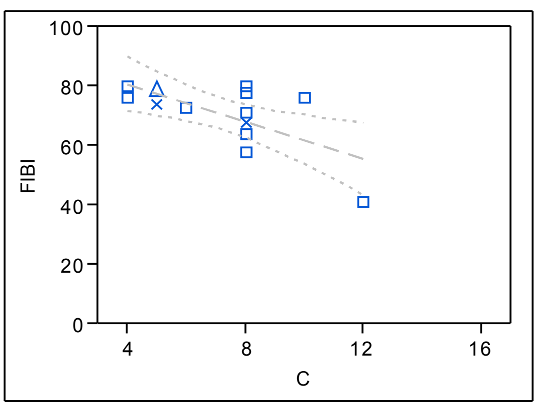
Figure C-14: Plots demonstrating a potential association between FIBI and PSI metric *obstructions/flow deflectors/sediment traps* for B) REDWOOD, but no significant linear or polynomial associations for A) COMBINED or C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 81.31 - 3.23*C + 18.89, R^2 = 0.22, p = 0.0181.

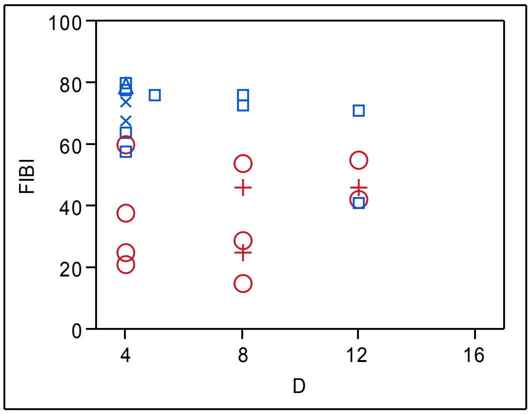


B) REDWOOD: No significant linear or polynomial association.

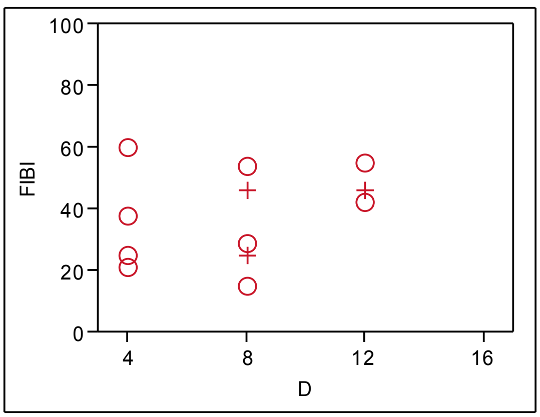


C) SNAKE: FIBI = 93.17- 3.12*C + 8.62, R^2 = 0.44, p = 0.0133.

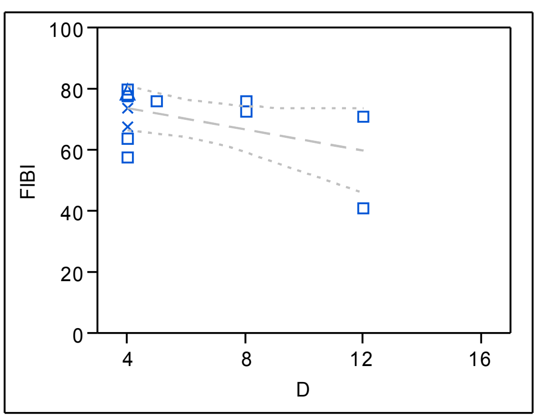
Figure C-15: Plots and linear regression demonstrating significant negative relationship between FIBI and PSI metric *cutting* for A) COMBINED and C) SNAKE, but no significant linear or polynomial association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: No significant linear or polynomial association.

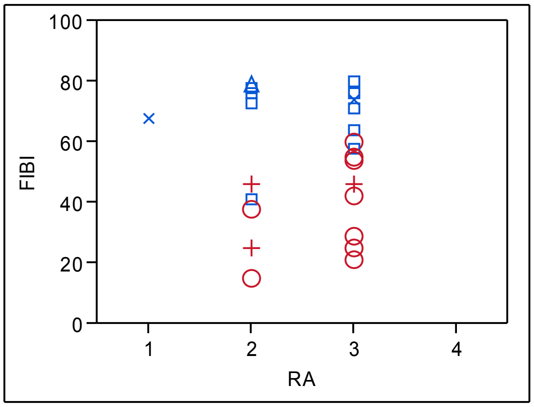


B) REDWOOD: No significant linear or polynomial association.

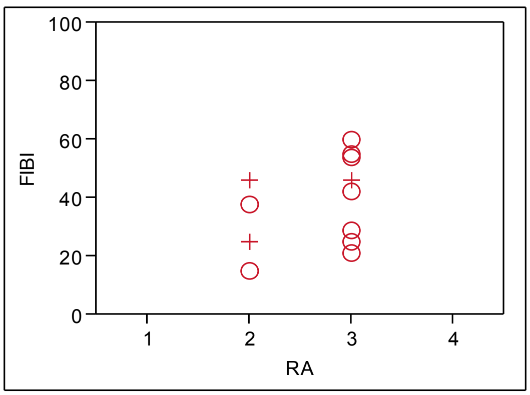


C) SNAKE: FIBI = 80.97 - 1.75*D + 10.08, $R^2 = 0.24$, $p = 0.0925$.

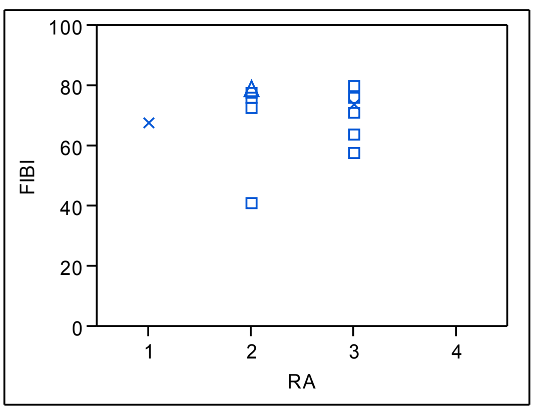
Figure C-16: Plots and regression indicating a potential negative association between FIBI and PSI metric *deposition* for C) SNAKE, but no significant linear or polynomial association for A) COMBINED or B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: No significant association.

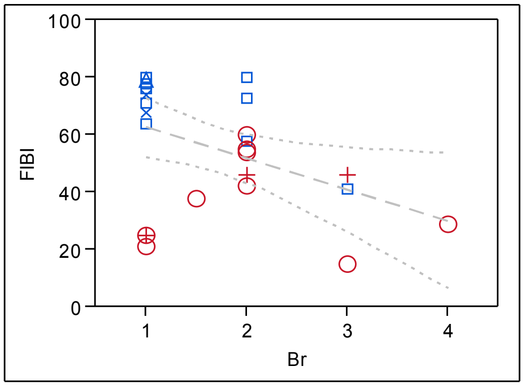


B) REDWOOD: No significant association.

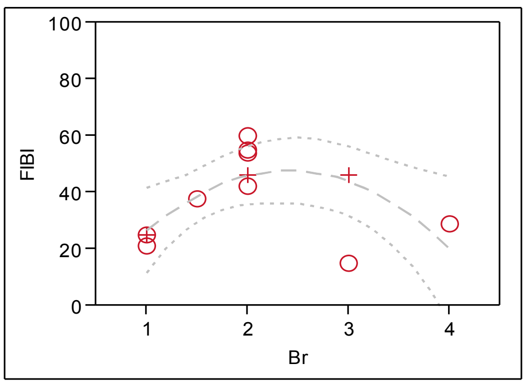


C) SNAKE: No significant association.

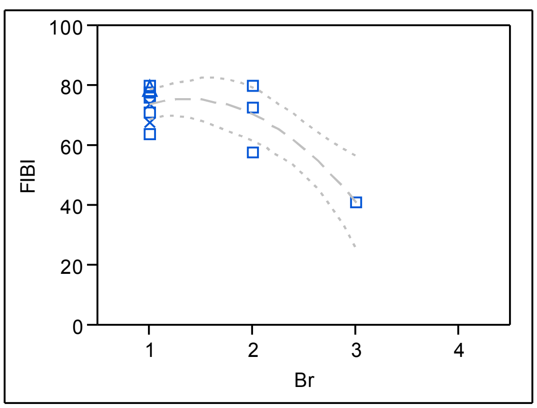
Figure C-17: Plots and correlation results indicating no linear or polynomial association between FIBI and PSI metric *rock angularity* for A) COMBINED, B) REDWOOD, or C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 73.34 - 10.81*Br + 19.25, R^2 = 0.19, p = 0.0298.

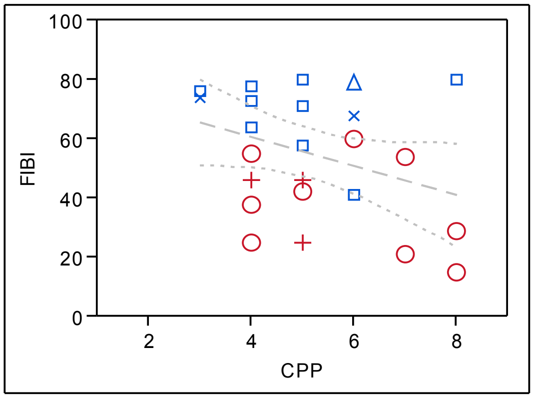


B) REDWOOD: FIBI = -14.52+ 51.80*Br - 10.78*Br^2 + 12.06, R^2 = 0.46, p = 0.0643.

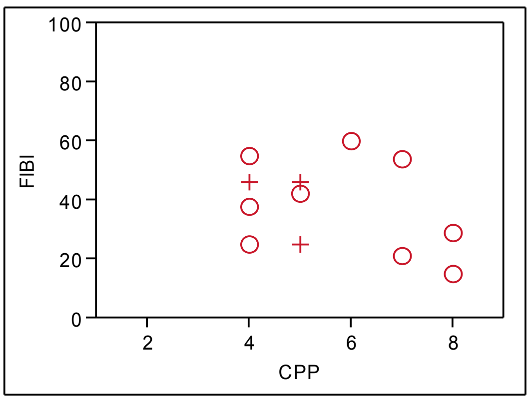


C) SNAKE: FIBI = 52 + 34.83*Br - 12.83*Br^2 + 6.95, R^2 = 0.67, p = 0.0039.

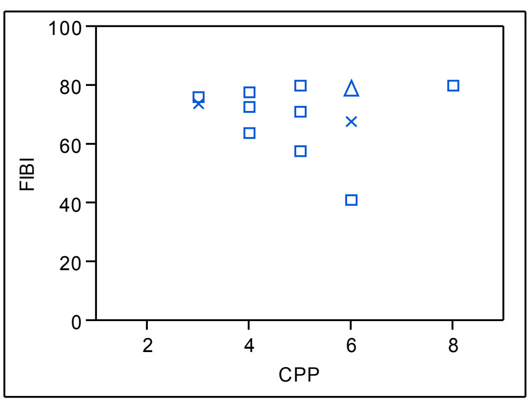
Figure C-18: Plots and linear and polynomial regression demonstrating significant negative associations between FIBI and PSI metric *brightness* for A) COMBINED and C) SNAKE, and a potential curvilinear association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 80.22- 4.90*CPP + 19.93, $R^2 = 0.13$, $p = 0.0756$.

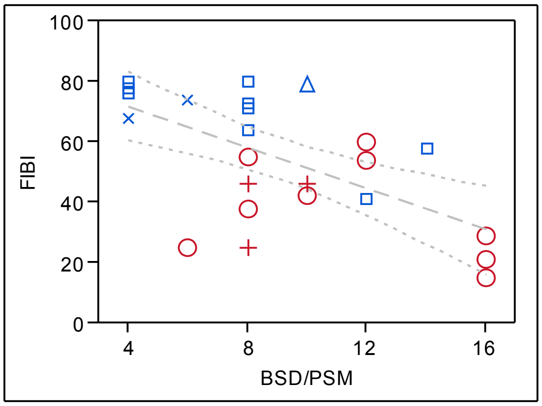


B) REDWOOD: no significant linear or polynomial association.

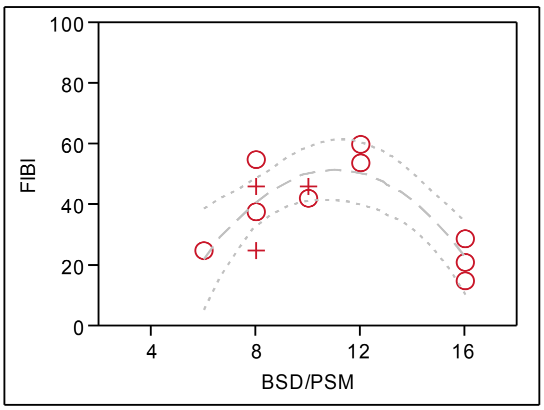


C) SNAKE: no significant linear or polynomial association.

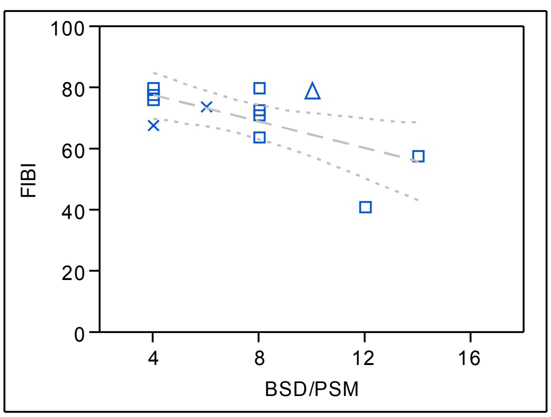
Figure C-19: Plots and linear regression demonstrating a weak potential association between FIBI and PSI metric *consolidation/particle packing* for A) COMBINED, but no significant linear or polynomial association for B) REDWOOD or C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 85.60- 3.42*BSD/PSM+ 16.66, R^2 = 0.39, p = 0.0008.

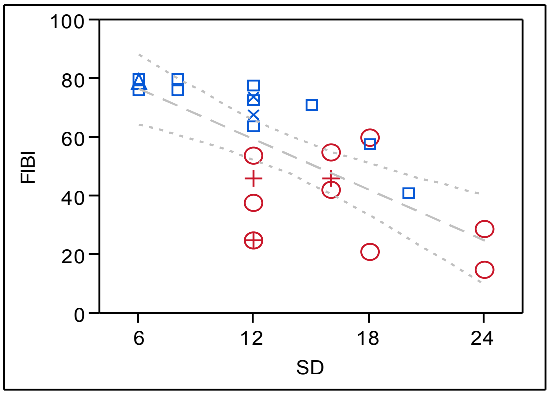


B) REDWOOD: FIBI = -89.98+ 25.73*BSD/PSM - 1.17*BSD/PSM^2 + 9.36, R^2 = 0.67, p = 0.0065.

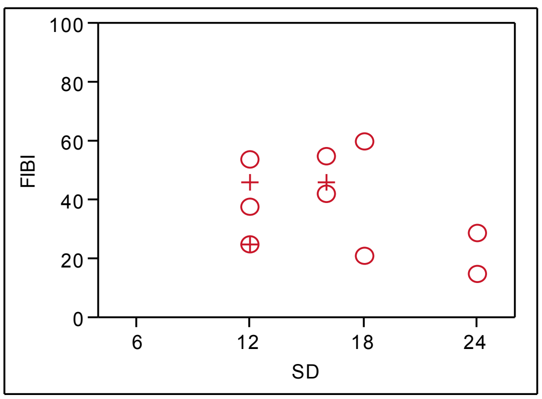


C) SNAKE: FIBI = 86.13 - 2.15*BSD/PSM + 8.81, R^2 = 0.42, p = 0.0173.

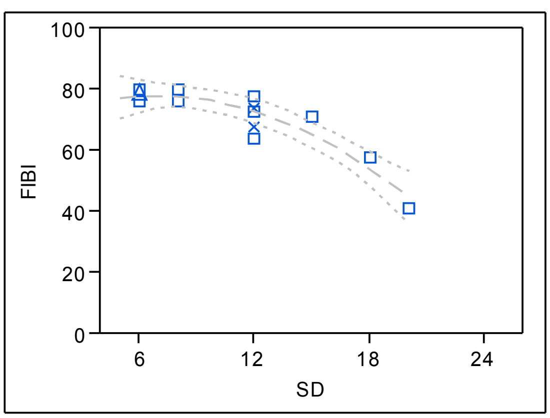
Figure C-20: Plots and regression demonstrating significant negative associations between FIBI and PSI metric *bottom size distribution/percent stable materials* for A) COMBINED and C) SNAKE, and a significant curvilinear association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 93.68 - 2.86*SD + 16.57, $R^2 = 0.46$, $p = 0.0002$.

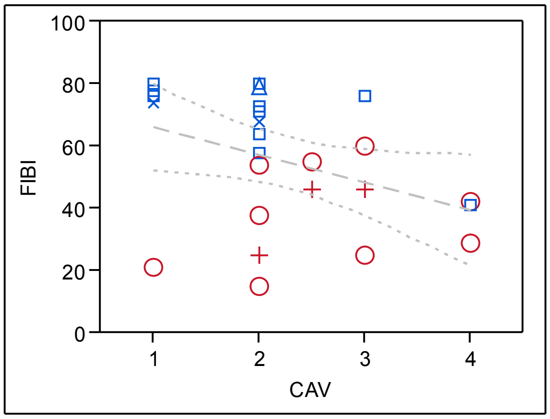


B) REDWOOD: No significant linear or polynomial association.

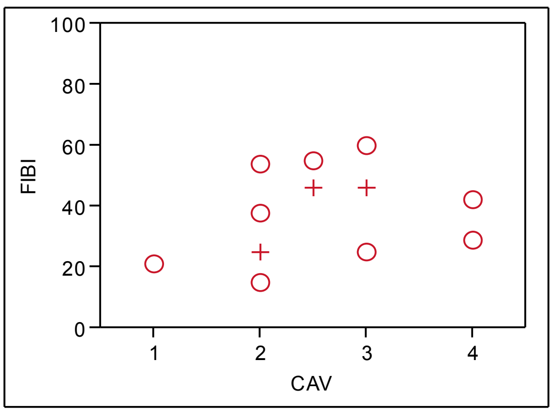


C) SNAKE: FIBI = 69.11 + 2.61*SD - 0.19*SD^2+ 4.59, $R^2 = 0.86$, $p = <0.0001$.

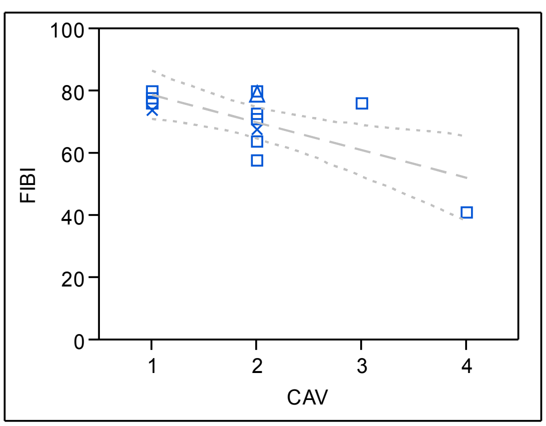
Figure C-21: Plots and regression demonstrating a potential negative association between FIBI and PSI metric *scouring and deposition* for A) COMBINED and C) SNAKE, but no significant linear or polynomial association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 74.75 - 8.84*CAV + 19.72, R^2 = 0.15, p = 0.0567.

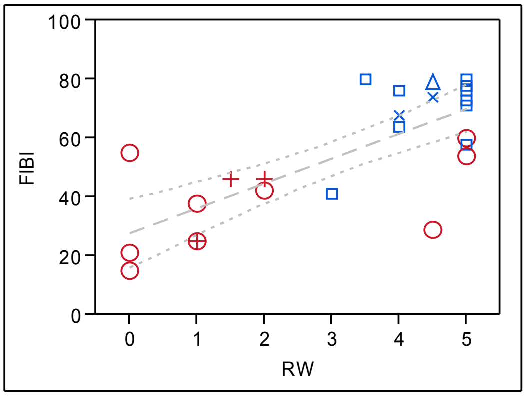


B) REDWOOD: No significant linear or polynomial association.

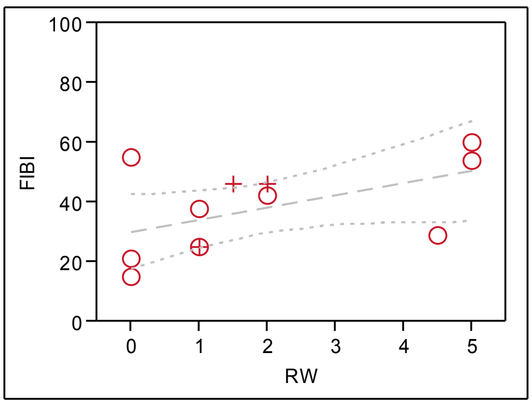


C) SNAKE: FIBI = 87.72- 8.907*CAV+ 8.30, R^2 = 0.48, p = 0.0084.

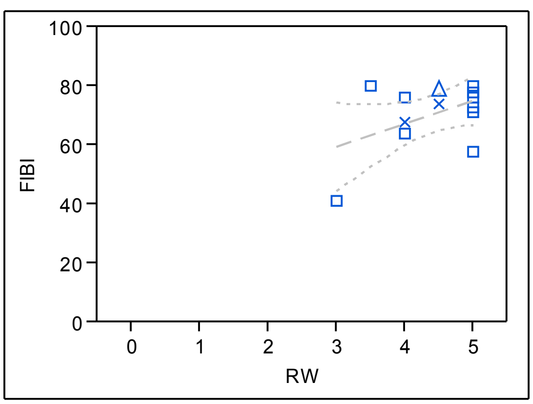
Figure C-22: Plots and linear regression indicating a potential negative association between PSI metric *clinging aquatic vegetation* for A) COMBINED and C) SNAKE, but no significant linear or polynomial association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 27.65 + 8.48*RW + 13.94, R^2 = 0.58, p = <0.0001.

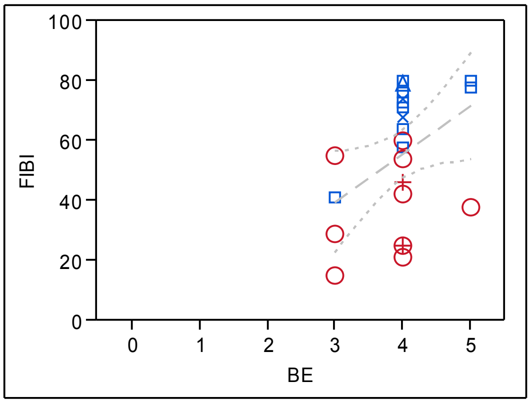


B) REDWOOD: FIBI = 30.24 + 4.05*RW + 13.28, R^2 = 0.27, p = 0.0850.

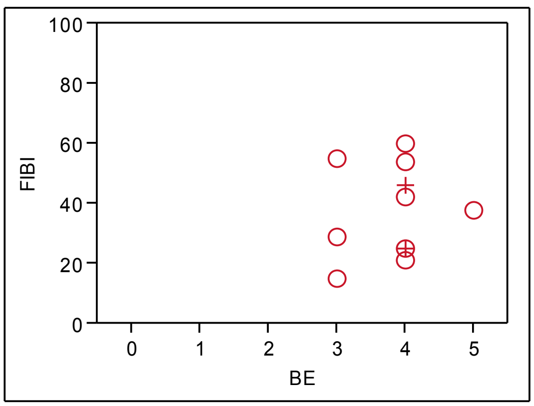


C) SNAKE: FIBI = 35.45 + 7.95*RW + 10.09, R^2 = 0.23, p = 0.0937.

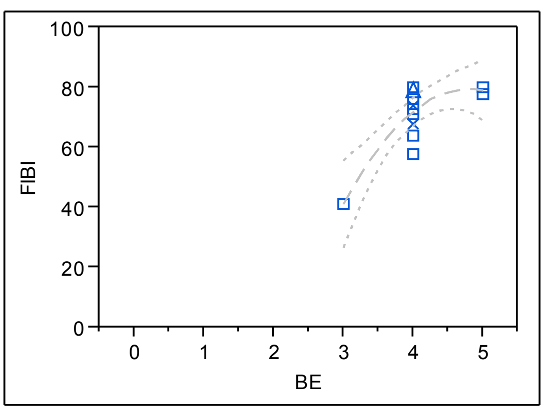
Figure C-23: Plots and linear regression demonstrating a strong positive linear association between FIBI and MSHA metric *riparian width* for A) COMBINED, but weak associations for B) REDWOOD and C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = -8.17+ 15.94*BE + 19.50, $R^2 = 0.17$, $p = 0.0418$.

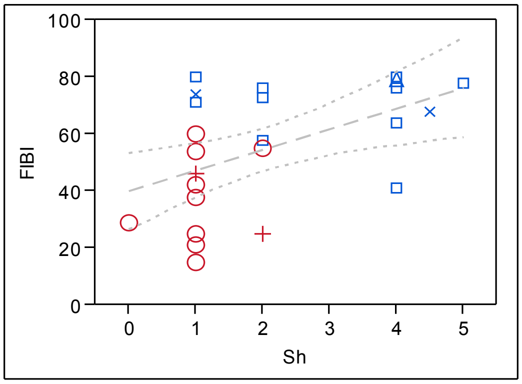


B) REDWOOD: No significant linear or polynomial association.

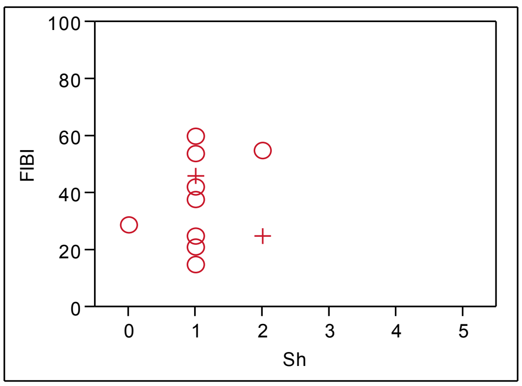


C) SNAKE: FIBI = -194.50 + 114.20*BE - 11.90*BE^2 + 6.55, $R^2 = 0.71$, $p = 0.0022$.

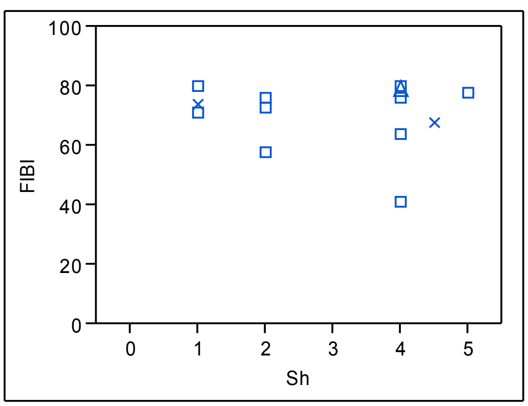
Figure C-24: Plots and regression indicating a positive association between FIBI and MSHA metric *bank erosion* for A) COMBINED and C) SNAKE, but no linear or polynomial association for C) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 40.00 + 7.26*Sh + 18.43, $R^2 = 0.26$, $p = 0.0098$.

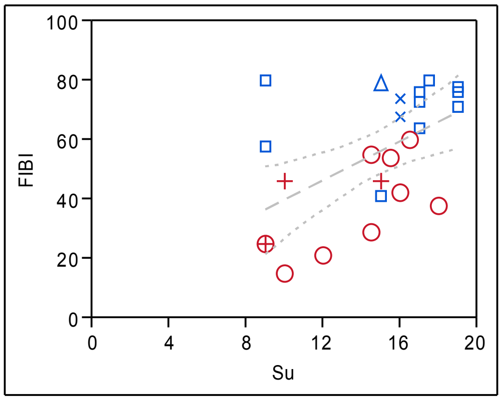


B) REDWOOD: No significant linear or polynomial association.

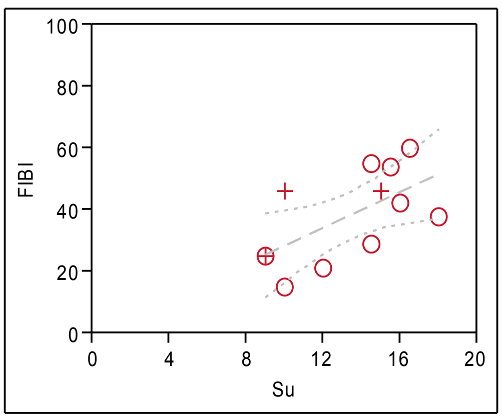


C) SNAKE: No significant linear or polynomial association.

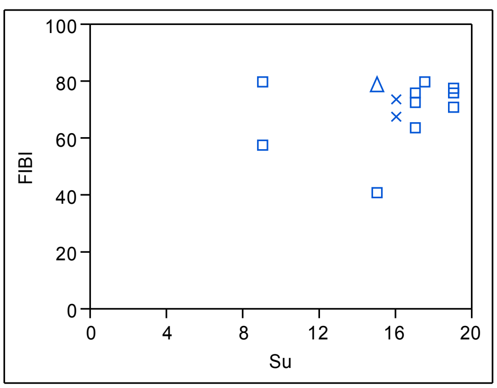
Figure C-25: Plots and linear regression indicating a weak positive association between FIBI and MSHA metric *shade* for A) COMBINED, but no significant linear or polynomial association for B) REDWOOD or C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 6.77+ 3.30*Su + 18.01, R^2 = 0.29, p = 0.0056.

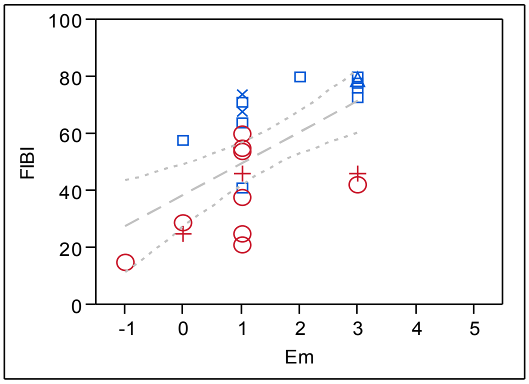


B) REDWOOD: FIBI = -0.92 + 2.92*Su + 12.11, R^2 = 0.39, p = 0.0296.

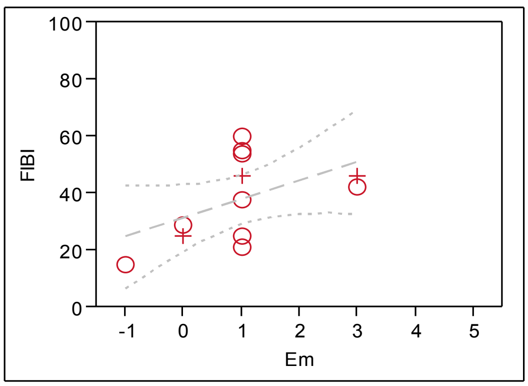


C) SNAKE: No significant linear or polynomial association.

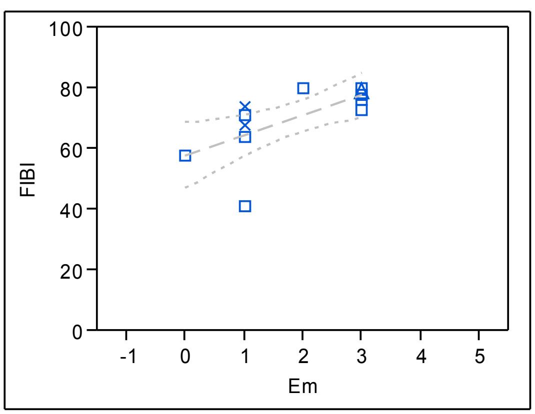
Figure C-26: Plots and linear regression indicating a positive association between FIBI and MSHA metric *substrate* for A) COMBINED and B) REDWOOD, but no significant linear or polynomial association for C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 38.60 + 11.05*Em + 16.59, R^2 =0.40, p = 0.0008.

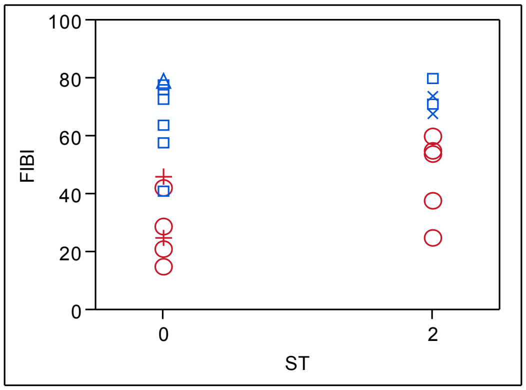


B) REDWOOD: FIBI = 31.43 + 6.57*Em + 13.44, R^2 = 0.25, p = 0.0972.

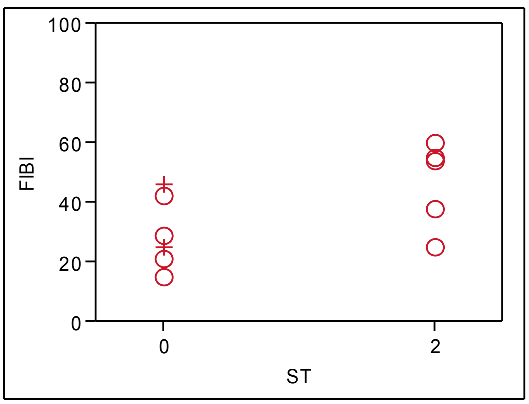


C) SNAKE: FIBI = 57.91 + 6.61*Em + 8.59, R^2 = 0.45, p = 0.0127.

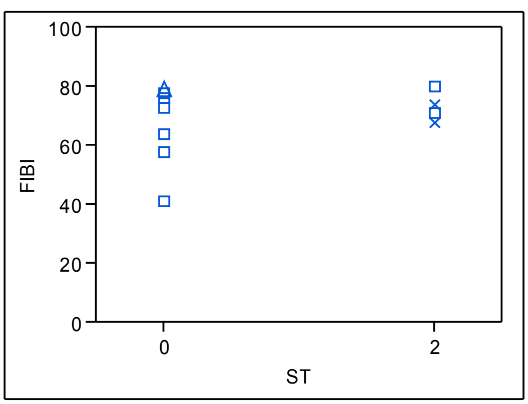
Figure C-27: Plots and linear regression indicating positive linear associations between FIBI and MSHA metric *embeddedness* for A) COMBINED, B) REDWOOD, and C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: ANOVA, t-test p>t = 0.1447.

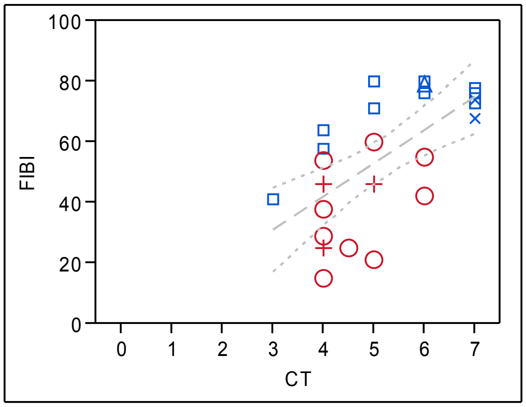


B) REDWOOD: ANOVA, t-test p>t = 0.0486.

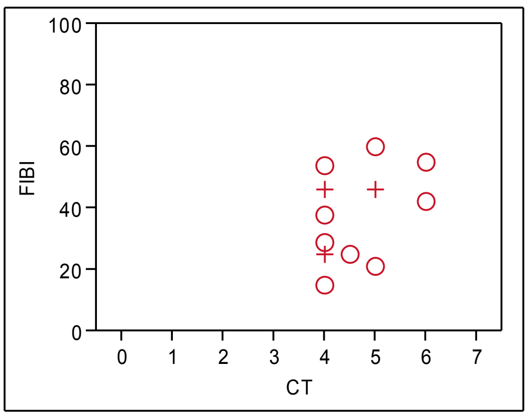


C) SNAKE: ANOVA, t-test p>t = 0.1623.

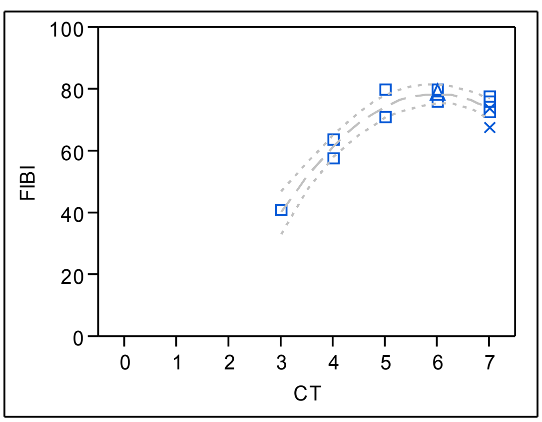
Figure C-28: Plots and ANOVA indicating a significance difference between FIBI and MSHA metric *substrate type* for B) REDWOOD, but no significant difference for A) COMBINED and B) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = -1.78 + 10.95*CT + 16.34, $R^2 = 0.42$, $p = 0.0005$.

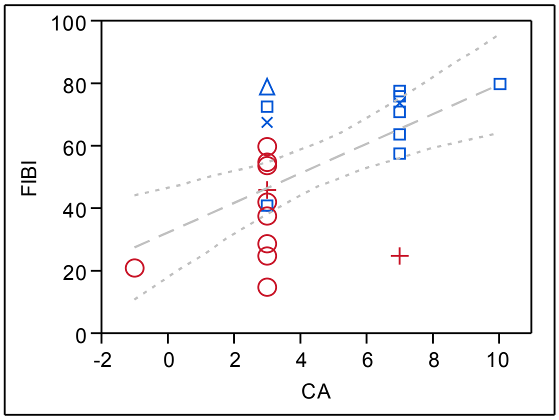


B) REDWOOD: No significant linear or polynomial association.

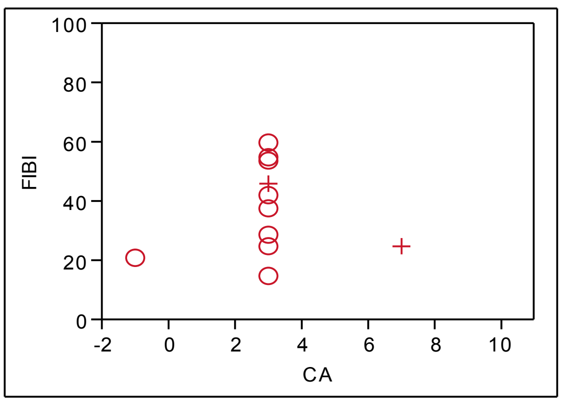


C) SNAKE: FIBI = -76.36 + 52.04*CT - 4.37*CT^2 + 3.57, $R^2 = 0.91$, $p = <0.0001$.

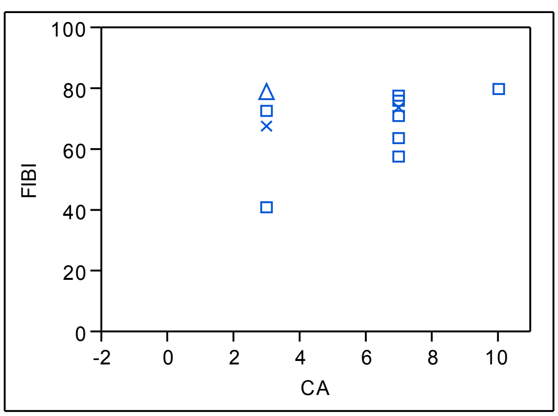
Figure C-29: Plots and linear and polynomial regression indicating a positive association between FIBI and MSHA metric *cover type* for A) COMBINED and C) SNAKE, but no significant linear or polynomial association for B) REDWOOD. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 32.69 + 4.76*CA + 16.98, $R^2 = 0.37$, $p = 0.0014$.

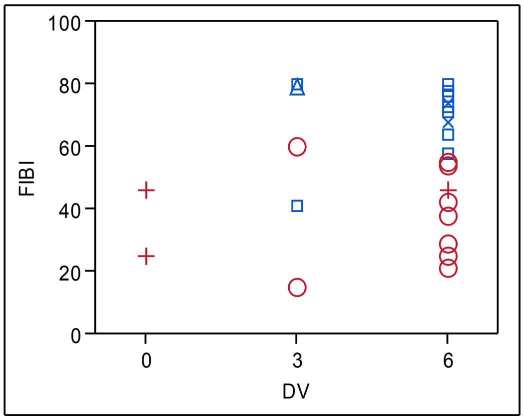


B) REDWOOD: No significant linear or polynomial association.

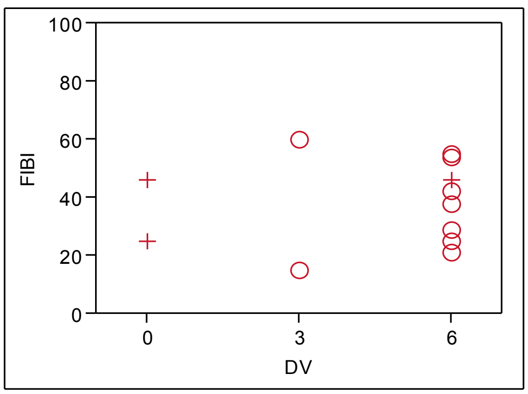


C) SNAKE: No significant linear or polynomial association.

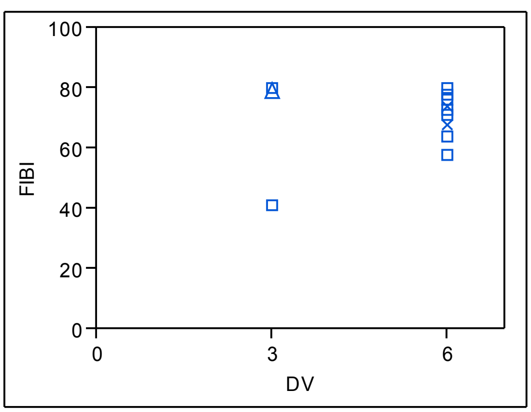
Figure C-30: Plots and linear regression indicating a positive linear association between FIBI and MSHA metric *cover amount* for A) COMBINED, but no significant linear or polynomial associations for B) REDWOOD or C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: No significant linear or polynomial association.

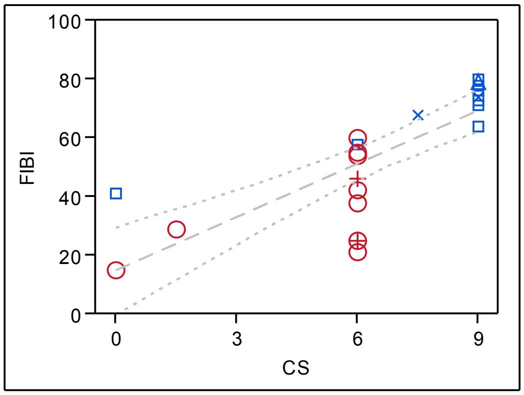


B) REDWOOD: No significant linear or polynomial association

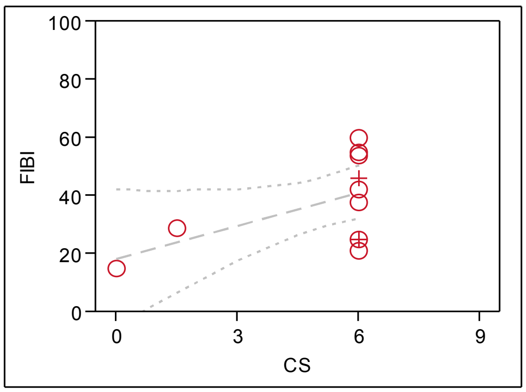


C) SNAKE: No significant linear or polynomial association.

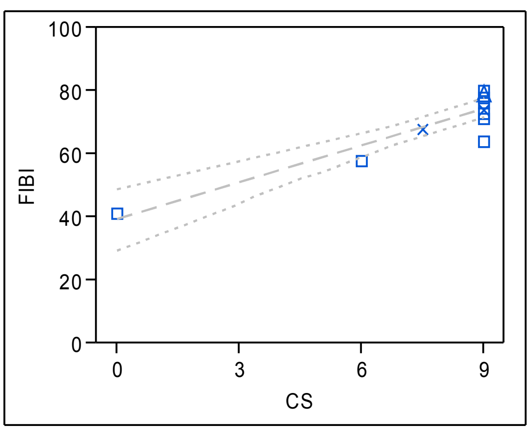
Figure C-31: Plots indicating no significant linear or polynomial association between FIBI and MSHA metric *depth variability* for A) COMBINED, B) REDWOOD, and C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



COMBINED: FIBI = 14.94 + 6.06*CS + 13.29, $R^2 = 0.61$, p = <0.0001.

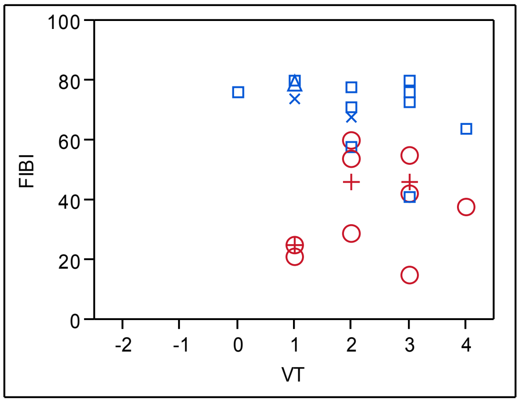


REDWOOD: FIBI = 18.56 + 3.79*CS + 13.16, $R^2 = 0.28$, $p = 0.0764$.

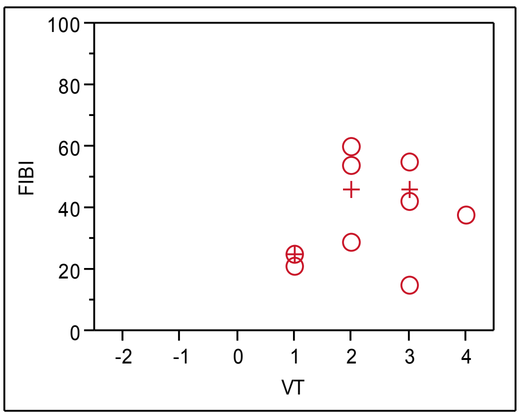


SNAKE: FIBI = 39.24+ 3.94*CS + 4.75, $R^2 = 0.83$, p = <0.0001.

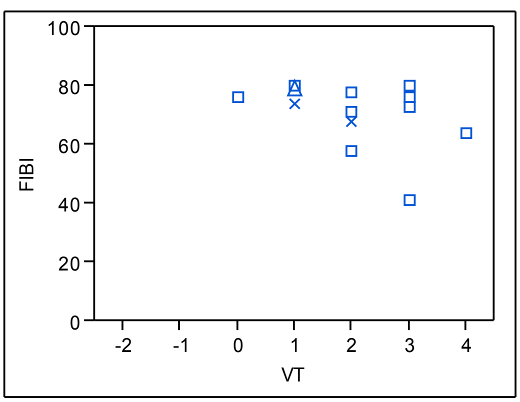
Figure C-32: Plots and linear regression demonstrating positive linear associations between FIBI and MSHA metric *channel stability* for A) COMBINED, B) REDWOOD, and C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: No significant association.

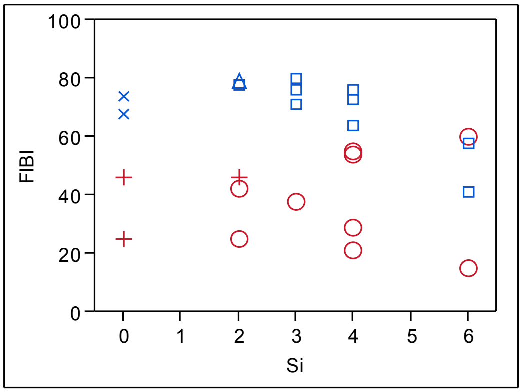


B) REDWOOD: No significant association.

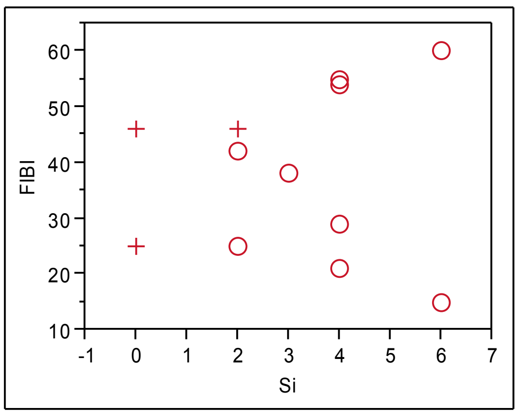


C) SNAKE: No significant association.

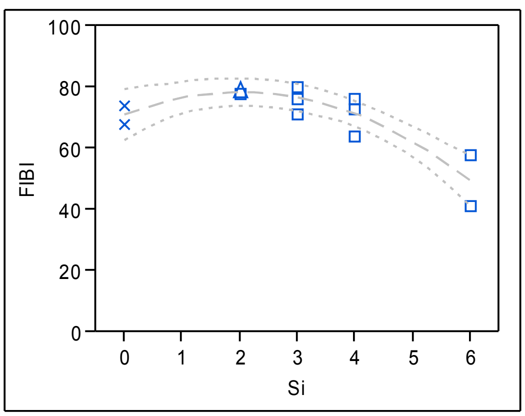
Figure C-33: Plots indicating no significant associations between FIBI and *velocity types* for any watershed grouping. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: No significant association.

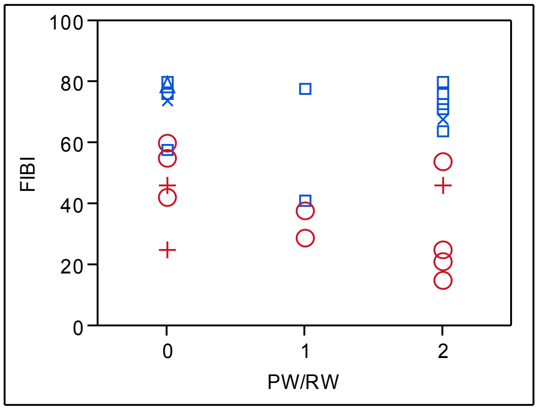


B) REDWOOD: No significant association.

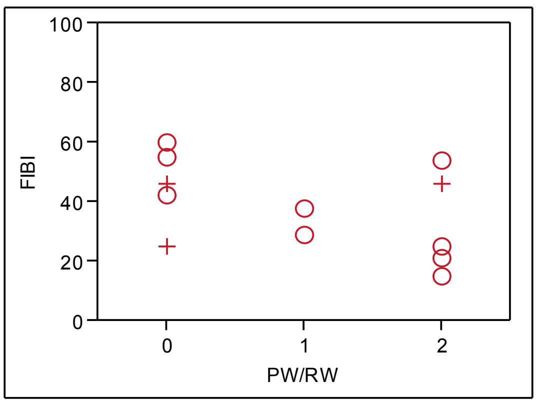


C) SNAKE: FIBI = 71.05 + 7.33*Si - 1.82*Si^2 + 5.44, R^2 = 0.80, p = 0.0003.

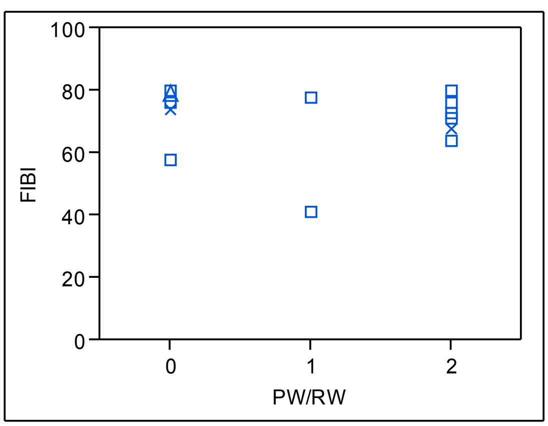
Figure C-34: Plots and regression demonstrating no association between FIBI and *sinuosity* for A) COMBINED and B) REDWOOD, and a negative curvilinear relationship for C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: No significant association.

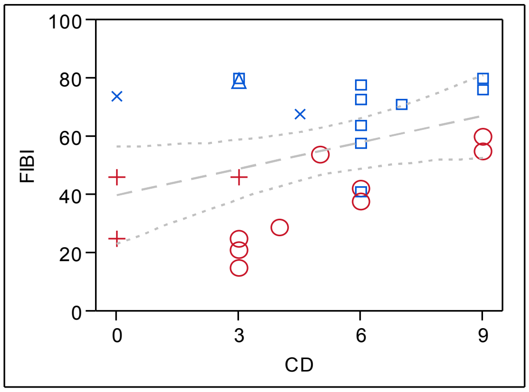


B) REDWOOD: No significant association.

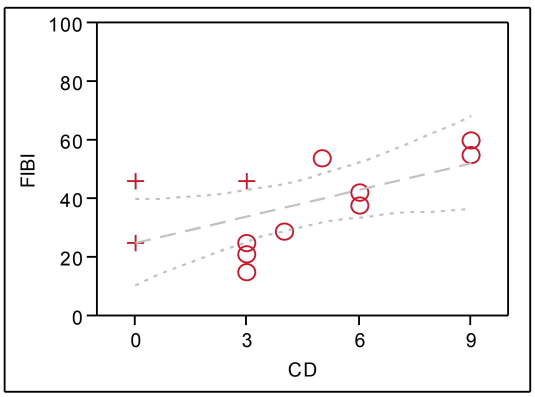


C) SNAKE: No significant association.

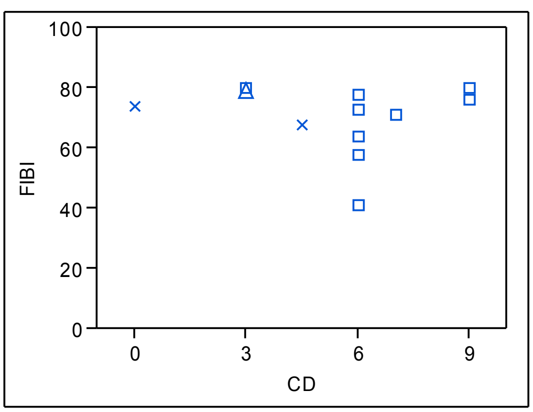
Figure C-35: Plots indicating no significant associations between FIBI and *pool width-to-riffle width* for any watershed grouping. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.



A) COMBINED: FIBI = 39.83 + 3.02*CD + 19.53, $R^2 = 0.17$, $p = 0.0437$.



B) REDWOOD: FIBI = 25.193634 + 3.0132626*CD + 12.47, $R^2 = 0.36$, $p = 0.0409$.



C) SNAKE: No significant association.

Figure C-38: Plots and linear regression demonstrating significant positive associations between FIBI and *channel development* for A) COMBINED and B) REDWOOD, but no association for C) SNAKE. REDWOOD in red: NA= o, OC= +; SNAKE in blue: NA= ◘, OC= x, and OC/NA= Δ.

APPENDIX D

Field datasheets for PSI and CCSI

Table D-1. Stream Reach Inventory and Channel Stability Evaluation. Modified from Pfankuch (1975).

		Excellent		Good		Fair		Poor	
UPPER BANKS	**landform slope**	Bank slope gradient <30%	2	Bank slope gradient 30-40%.	4	Bank slope gradient 40-60%.	6	Bank slope gradient 60% +.	8
	mass wasting or failure (existing or potential)	No evidence of past or any potential for future mass wasting into channel	3	Infrequent and/or very small. Mostly healed over. Low future potential.	6	Moderate frequency and size, with some raw spots eroded by water during high flows.	9	Frequent or large, causing sediment nealry yearlong OR immenent danger of same.	12
	debris jam potential (floatable objects)	Essentially absent from immediate channel area	2	Present but mostly small twigs and limbs.	4	Present, volume and size are both increasing.	6	Moderate to heavy amounts, predominantly larger sizes.	8
	vegetative bank protection	90%+ plant density. Vigor and variety suggests a deep, dense, soil binding, root mass	3	70-90% density. Fewer plant species or lower vigor suggests a less dense or deep root mass.	6	50-70% density. Lower vigor and still fewer species form a somewhat shallow and discontinuous root mass.	9	<50% density plus fewer species and less vigor indicate poor, discontinuous, and shallow root mass.	12
LOWER BANKS	**channel capacity**	Ample for present plus some increases. Peak flows contained. Width to depth (W/D) ratio < 7.	1	Adequate. Overbank flows are rare. W/D ratio 8-15.	2	Barely contains present peaks. Occasional overbank floods. W/D ratio 15-25.	3	Inadequate. Overbank flows common. W/D ratio >25.	4
	bank rock content	65%+ with large, angular boulders 12"+ numerous.	2	40-65%, mostly small boulders to cobbles 6-12".	4	20-40%, with most in the 3-6" diameter class.	6	<20% rock fragments of gravel sizes, 1-3" or less.	8
	obstructions/ flow deflectors/ sediment traps	Rocks and old logs firmly embedded. Flow pattern without cutting or deposition. Pools and riffles stable.	2	Come present, causing erosive cross currents and minor pool filling. Obstructions and deflectors newer and less firm.	4	Moderately frequent, moderately unstable obstructions and deflectors move with high water causing bank cutting and filling of pools.	6	Frequent obstructions and deflectors cause bank erosion yearlong. Sediment traps full, channel migration occurring.	8
	cutting	Little or none evident. Infrequent raw banks less than 6" high generally.	4	Some, intermittently at outcurves and constrictions. Raw banks may be up to 12".	8	Significant. Cuts 12-24" high. Root mat overhangs and sloughing evident.	12	Almost continuous cuts, come over 24" high. Failure of overhangs frequent.	16
	deposition	Little or no enlargement of channel or point bars.	4	Some new increase in bar formation, mostly from coarse gravels.	8	Moderate deposition of new gravel and coarse sand on old and some new bars.	12	Extensive deposits of predominantly fine particles. Accelerated bar development.	16

BOTTOM	**rock angularity**	Sharp edges and corners, plane surfaces roughened.	1	Founded corners and edges, surfaces smooth and flat.	2	Corners and edges well rounded in two dimensions.	3	Well rounded in all dimensions, surfaces smooth.	4
	brightness	Surfaces dull, darkened, or stained, generally not "bright".	1	Mostly dull, but may have up to 35% bright surfaces.	2	Mixture, 50/50 dull and bright, +/- 15% (35-65%).	3	Predominantly bright, 65%+, exposed or scoured surfaces.	4
	consolidation or particle packing	Assorted sizes tightly packed and/or overlapping.	2	Moderately packed with some overlapping.	4	Mostly a loose assortment with no apparent overlap.	6	No packing evident. Loose assortment, easily moved.	8
	bottom size distribution and percent stable materials	No change in sizes evident. Stable materials 80-100%	4	Distribution shift slight. Stable materials 5-80%.	8	Moderate change in sizes. Stable materials 20-50%.	12	Marked distribution change. Stable materials 0-20%.	16
	scouring and deposition	Less than 5% of the bottom affected by scouring and deposition.	6	5-30% affected. Scour at constrictions and where grades steepen. Some deposition in pools.	12	30-50% affected. Deposits and scour at obstructions, constrictions, and bends. Some infilling of pools.	18	More than 50% of the bottom is in a state of flux or change nearly yearlong.	24
	clinging aquatic vegetation (moss and algae)	Abundant. Growth largely moss-like, dark green, perennial. In swift water, too.	1	Common. Algal forms in low velocity and pool areas. Moss here too and swifter waters.	2	Present but spotty, mostly in backwater areas. Seasonal blooms make rocks slick.	3	Perennial types scarce or absent. Yellow-green, short-term bloom may be present.	4

Table D-2: Channel Condition & Stream Stability Index (CCSI)

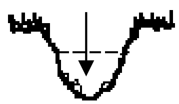
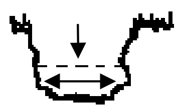
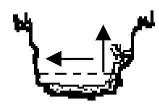
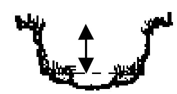
Field Number:_________________ _ Stream:______________________________ Date: ______________ Staff: _________________ Total Score: ____________

		Excellent (15-26)	Good (27-43)	Moderate (44-79)	Poor (80-115)	Very poor (116-156)
1. Upper Banks For a. and b. Assess at riffle , shallow cross-over. or shallow, narrow run. Estimate bankfull using indicators and RGHC For c. and d. assess the outside bends or banks likely to receive erosive flows.	a. **Intermediate floodprone width** (1.5x BfD_{max}) BfW ____ FpW _____	Floodplain extensive. High flow energy (2-10yr RI) largely dissipated. IntFpW >10.0 x BfW 1	Floodplain moderately extensive. IntFpW 5-10 x BfW 3	Floodplain wide, but limited. FpW 3-5 x BfW 5	Floodplain narrow, minimal energy dissipation with high flows. FpW 1.5-3 x BfW 7	Floodplain almost non-existent, high flows contained. FpW <1.5 x BfW 10
	b. **Degree of incision** LBH ____ BfH ___	Channel not or minimally incised in some places. LBH/BfH = 1.0-1.05 (0-5%) 1	Channel is marginally incised LBH/MaxBfD = 1.05-1.15 (5-15%) 3	Channel is slightly incised LBH/MaxBfD = 1.15-1.25 (15-25%) 6	Channel is moderately incised LBH/MaxBfD = 1.25-1.5 (25-40%) 9	Channel is deeply incised LBH/MaxBfD = >1.5 (>40%) 12
	c. **Vegetative bank protection** □ trees □ shrubs □ grasses □ perennials	90%+ plant density. Trees or thick grasses dominate; deep roots cover most of upper banks. Roots >10” deep, generally 1	70-90% density. Fewer trees and deep rooted grasses; roots 5-10” deep, generally 3	50-70% density; roots shallow (1.5 – 5”) or discontinuous; bare spots may be visible 5	<25-50% density, plants or grasses with very shallow roots (0.5-1.5”), or bare ground between plants common 7	Very little root protection (<25%), majority of ground bare, vegetation with very shallow roots (<0.5”) 10
	d. **Mass wasting or bank failure**	No or little evidence mass wasting or bank failure 1	Infrequent (1-2 medium) and/or very small (3-4). or mostly healed over. 2	Moderate frequency (3-4 medium) and size (1-2 large), some raw spots eroded by water during high flows (5-6) 4	Frequent (5 or more) or large (2-3 large, or 1 severe), banks contributes fair amount of sediment during high flows 7	Almost continuous mass wasting along channel, severe condition 11
	Comments on Upper Banks:					

2. Lower Banks Assess outside bends or areas that are likely to be scoured by flow.	e. **Bank materials/ shear strength**: □ rock □ sand □ silt □ riprap □ cohesive soil □ roots	Bank is largely comprised of rocks, roots or cohesive materials (>90%), or <5% of reach is moderately erodable	1	65-75% rock or mixture of roots or cohesive fine materials, some crumbling to the touch, minimally eroded by flow or GW (<10% of reach)	3	40-65% rock, roots or cohesive material. Some slightly friable locations present <25% can allow for some eroded spots	5	20-40% rock fragments, roots, or cohesive material. Moderately to somewhat friable mixture (25-50%), Erosion likely during high flows or when soil dries (geotechnical failure) or GW seeps	7	<20% rock fragments, roots, or cohesive material. Banks mostly sand or silt that crumbles easily to the touch when dry or easily dislodged by GW seeps	9
	f. **Flow deflectors**: □LWD □ boulders □ lateral riffles □ center bars □ point bars	Flow pattern without cutting or very minor. Pools and riffles stable	1	Some present (1-2 small), causing erosive cross currents and minor bank instability, very localized	3	Moderately frequent (3-4 small, or 1 large), cause erosive cross-currents and moderate bank instability (10 to 20% of reach)	5	Fairly frequent flow deflectors (5 to 6, 2 large), cause major instability in 20 to 40% of reach.	7	Frequent flow deflectors (>6 small, >2 large) cause highly erosive cross-currents and severe bank erosion (>40% of reach)	9
	g. **Obstructions to flow/ sediment traps**: □ WD □ boulder □ beaver dams □ check dams	No obstructions to flow observed; very minimal retention by sediment traps	1	Some minor obstructions and sediment traps present (1-2). Sediment transport capacity minimally impacted	3	Sediment traps moderately frequent (3-4), may cause some pool infilling (1/4 to 1/3 of total depth) or slowing of water velocity	6	Sediment traps entrain sediment and fill in pools (1/3 to ½ of pools depth). Sediment transport capacity moderately diminished	10	Obstructions large (block 2/3 to entire stream width) or sediment traps frequent (>4), severe loss in pool depth (>50%). Sediment transport capacity greatly diminished	14
	h. **Cutting/ scouring or gw seepage**	Infrequent (1-2) raw banks. Little evidence of undercutting (<1/8 of bank height) or seepage (<5% of reach)	2	Some (3-4), raw banks at outcurves and constrictions (1/8 to ¼ of bank height). Some toe slope erosion or seepage (5-10% of reach)	4	Moderate frequency (4-6), raw banks 1/3 to 1/2 of bank height. Toe slope erosion or seepage apparent (10-20% of reach)	6	Significant (5-6). Cuts 1/2 to 3/4 of bank height). Root mat overhangs and sloughing evident, or GW driven failure (20-40% of reach)	10	Almost continuous raw bank (>3/4 of bank height). Toe slope erosion fairly continuous (>40% of outside bend) or GW failure extensive (>25% of reach)	14
	Comments on Lower Banks:											

3. Bottom	k. **Consolidation or particle packing (vertical)**	Bed firmly packed. Probe depth 0-1” (0-2.5 cm) in runs 1	Bed fairly well packed. Riffles and pools stable. Probe depth 1-3” (2.5-8 cm) in runs 3	Bed moderately packed (3-5” or 8-13 cm) in runs. 6	Loose bed sediment. Probe depth 5-8” (13-20 cm) in runs. 10	Unconsolidated actively mobile bed. Probe depth >8” (>20cm) in runs 14
	l. **Evidence of degradation /excess scouring** □ knickpoint observed □ rock brightness □ bar substrate coarser on top than within	< 5% of the bottom affected by scouring. Where water clarity allows, vegetation abundant, algae clinging to materials, rooted plants visible in swifter waters 1	5-15% affected. Scour at constrictions and where grades steepen. Where water clarity allows, vegetation present in slower waters, algal forms in swift velocity and pool areas 3	15-25% affected. Scour at obstructions, constrictions, and bends. Vegetation less than would be expected due to local areas of scour. Where applicable, less sand between coarse materials or slightly larger materials on top of bars than within 5	25 to 40% affected. Scour pools at bridges, constrictions, and where knickpoints occur or cutting along both sides of channel in places. Where water clarity allows, perennial vegetation and algae spotty or mostly in backwater areas. Where present, rocks may be relatively free of fine sediment or tops of bars coarser than within 7	> 40% of bottom substrates moved annually. Extremely deep scour pools associated with bridges and constrictions or dramatic knickpoint within reach or cutting severe along both sides of channel. Where applicable, vegetation scarce, rocks clean of fines or tops of bars much coarser than within 9
	m. **Evidence of aggradation/ excess deposition:** □ embeddedness in riffles/runs □ pool depth diminished □ lateral or center bar build-up	<5% of the bottom affected by excess deposition (cobble and gravel minimally embedded, <10% in runs). Where present, pool depth/size not diminished (<1/8 of total) 1	5-15% affected. Slight embeddedness observed (cobble 10-15%, gravel 10-25% in runs). Where present, pool depth/size slightly diminished (1/8-1/4 of total) 3	15-25% affected. Deposition at obstructions and embeddedness (cobble 15-25%, gravel 50-75%) observed in runs. Where present, pool depth/size noticeably diminished (1/4-1/3 of total) or some new bar build-up 6	25-40% affected. Extensive deposition at obstructions, on bars, and along bottom. Extensive embeddedness (>25% for cobble, >75% for gravel) observed. Where present, pool depth/size greatly diminished (1/3 to 1/2 of total) or bar build-up noticeable 10	>40% of bottom demonstrating excess deposition. Pool depth severely diminished (>1/2 of total) or lateral/ center bars with substantial accumulation of new sediment 14
	Comments on Bottom:					

4. Stage of channel evolution: Stages observed: ___&____ &___&___	Channel appears to be relatively stable (stage I or V); □ however, some bank erosion observed, but mostly from deflectors or natural meandering 1	Channel adjustment appears to be: □ minor; slight downcutting or widening, not severe □ evolving from stage IV to V; thalwegs are fairly well established, little deposition in pools 3	Channel appears to be evolving towards a more stable cross-section (III to IV); thalweg beginning to form on outside bend sediment newly deposited along inside bend. □ some instability related to lateral bar build-up 5	Channel appears to be: □ downcutting (II) and/or □ widening (III) noticeable to severe fluvial bank erosion or cutting observed, trees may be leaning inward from one or both banks 7	Channel experiencing severe downcutting and or widening, which is the dominant process of instability. Many areas with highly eroded banks. New tree fall and mass wasting may be present 11
Comments CEM stage:					

CEM Stages	**I. Pre-adjustment**	**II. Degradation**	**III. Degradation and Widening**	**IV. Aggradation and Widening**	**V. New Dynamic Equilibrium**	**Cross section↓**
						

Substrate composition □ pebble count □ observation _____%bedrock _____%boulder _____%cobble _____%coarse gravel ____%fine gravel ____%sand _____%silt _____%clay ____%WD/detr. ____%muck	**Cross-section (at riffle, crossover, or straight: & narrow section):** BfW ______ BfD_____ BfW/D ______ CSA ______ ER______ Validated w/ RHGC? Yes ____ No _____ Version: □ Mid-Central MN □ East-Central MN □ NW-Central MN □ SE MN Till □ SE MN Karst
General Comments:	