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Local and Systemic Controls on Fish and Fish Habitat in South Dakota Rivers and Streams: Implications for Management

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Local and Systemic Controls on Fish and Fish Habitat in South Dakota Rivers and Streams: Implications for Management

By

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This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy degree and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this dissertation does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Dr. Charles R. Berry Date

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Abstract

Local and Systemic Controls on Fish and Fish Habitat
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Craig L. Milewski

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Assessments of the health of rivers and streams in prairie environments would improve if the role of systemic patterns and processes among geologic-climatic settings in controlling physical habitat and fish communities were better defined. My research approach was based on a premise that assessments of the health of rivers and streams in prairie environments would benefit from studies that 1) examine the moderating effects of systemic patterns and processes by comparing physical habitat continua and fish communities among geologic-climatic settings, 2) determine the relative influence of locally interacting variables (e.g., channel shape and riparian vegetation) and systemic processes in structuring physical habitat and fish communities among a range of streams sizes, and 3) test the effects of biotic and abiotic controls on habitat partitioning by fish during critical periods of low flows common in prairie streams. My research had three complementary parts: two field studies and a laboratory study. The first field study tested the hypothesis that systemic processes moderate physical riverine environments, and thus biological communities, in distinct ways between a semi-arid region and a subhumid region. The second field study tested the hypothesis that in a subhumid region the

interactions of local variables have greater influence on physical habitat and fish communities in small streams than in rivers. The laboratory study tested the influence of predators, large woody debris, and turbidity on habitat use by common minnow species under simulated low flow conditions.

In the first study, longitudinal trends in channel morphometry, bankfull dimensions, stream bank and riparian traits, substrate, and fish community attributes were compared between the Bad River in a semi-arid region of western South Dakota and the Big Sioux River in the sub-humid region in eastern South Dakota. Findings suggest that along the Big Sioux River, the longitudinal changes in physical characteristics are gradual and continuous. Bankfull dimensions, channel bottom width, sand substrate, and streambank as deposition increased longitudinally while silt substrate, and percent of bank with vegetation decreased. In contrast, in the Bad River, longitudinal changes in these physical characteristics showed either a random pattern or a pattern of no change. In the Bad River, vertical channel dimensions (i.e., bank length and bank height) did increase with watershed size but not uniformly as they did in the Big Sioux River. Relationships of fish community attributes with watershed size were similar to the physical patterns. For example, in the Big Sioux River, most fish community attributes showed a continuous pattern of change either upward or downward with watershed size. In contrast, in the Bad River, most attributes show no discrete changes with watershed. My findings show that while prairie streams in sub-humid regions exhibit a truncation of the river continuum concept (RCC), physically and biologically, in semiarid regions, further truncation of the upper part of the RCC occurs. While both rivers had similarities in pioneering species in the upper parts of each river, only the Big Sioux River had a headwater component in the upper part. Also, a general randomness or lack of pattern in the physical and biological structure in the Bad River can be conceptualized as a longitudinal stretching of a reach of river into a longer segment of river. This would account for the seemingly lack of pattern in fishes.

In the second study, findings indicate that variation in channel morphometry, physical habitat, and riparian-related habitat decreases with watershed size in a sub-humid prairie stream. Variation in channel morphometry, physical habitat, and riparian related habitat in tributaries could not be explained by local riparian conditions or adjacent land use. In fact, land use was or had been pasture, which limited comparison with other adjacent land use types (e.g., cropland). Furthermore, within pastures the level of animal vegetation use could not account for variation in riparian-related cover types among tributary sites. In this study the range of physical conditions among tributaries was coupled with a range of biological attributes. However, very few significant correlations were found between the biological and physical attributes. This suggests that the systemic controls even among small watersheds do have an influence on site-specific physical habitat and biological attributes. Several phenomena are probably responsible for this variation: hydrologic alterations caused by upland conversion to agriculture, cumulative loss of riparian buffering capacity, subtle differences in sub-watershed hydrology and geology, and flow fluctuations.

In the laboratory study, low flow conditions were simulated in three experimental streams. Two suites of trials were performed: low and high turbidity trials.

Temperature, flow and lighting were kept relatively constant among trials. For a trial, each stream was stocked with one of seven fish community types (a combination of one or more red shiner, sand shiner, and black bullhead) and configured with one of four random stream layouts (all layouts contained shallow and deep habitats with and without woody debris). Trials were run for 2 days, gates dropped between habitats, and fish counted within each habitat (response variable). ANOVA tested for interactions among habitats, community types, and turbidity. Under simulated low flows, I found that a predatory fish (black bullhead) used deeper pockets of water with woody debris more than other habitats. Two small minnow species (red and sand shiners) used the deeper pockets of water more than the shallow areas. High turbidity reduced physical habitat selection by both minnow species and the predator. Finally, my findings suggest that predation is more important than competition in partitioning habitat use by minnow species, and that woody debris may play a critical role as fish habitat during droughts.

In semi-arid regions, watershed assessments will require more broad comparisons among rivers to differentiate the effects of natural and altered systemic-level processes on physical patterns and biological attributes. In sub-humid rivers, the watershed level processes that govern tributary dynamics need to be evaluated, because local variables appear to have minimal influence on physical habitat and fish communities. Finally, habitat partitioning in fish communities at low flows as regulated by habitat complexity, predation, and turbidity suggests that efforts that protect and restore systemic processes that create channel heterogeneity will ensure that prairie fishes will persist.

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List of Abbreviations

ANOVA..analysis of variance

ANCOVA..analysis of covariance

CPUE...catch per unit effort

°C... degrees celcius

ENSO..el Nino southern oscillation

g..gram

km...kilometer

L..liter

LWD...large woody debris

m...meter

NTU...nephelometric turbidity units

PC...principal component

PCA..principal component analysis

RCC..river continuum concept

WD...woody debris

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CHAPTER 1

INTRODUCTION

Introduction

In alluvial rivers, systemic level patterns in sediment transport and flow regime moderate local interactions among channel shape and slope, bed and bank materials, and riparian conditions. The outcome of systemic and local interactions is a continuum of physical habitat conditions. Theoretically, a response to this continuum of physical habitat conditions is a continuum of fish community structure and function. In prairie streams in subhumid and semiarid regions, this proposed continuum of change on physical habitat and fish communities is less understood than in more stable, forested environments.

In eastern South Dakota, research of river ecology provides collective evidence that among basins fish population and community dynamics are first moderated systemically by temporal variation in water quality (Sinning 1968; Berry et al. 1994; Dieterman 1994) and streamflow (Fisher 1995; Kirby 2001; Arterburn 2001; Shearer 2001), by slope differences among basins (Wall et al. 2001), and then locally by physical complexity among basins (Sinning 1968; Tol 1976; Kubeny 1992; Walsh 1992; Bratten 1993; Berry et al. 1994; Fisher 1995). Findings indicate that fish community relationships with site-specific habitat were often weak, or were influenced by climatic conditions (wet vs dry) during the period of a study. These findings do not suggest that the relationships are non-existent, but within the hierarchy of spatial and temporal interactions systemic processes must be considered before fish and physical habitat assessments can form a sound basis for management decisions. Otherwise, assessing the health of a river or stream based on fish samples and local habitat conditions could provide either erroneous or inconclusive results. For more conclusive assessments of rivers and streams in semi-arid or sub-humid regions, research is needed that establishes the hierarchical relationships between systemic processes and local interactions.

Literature Review

Stream Concepts

Advancements in stream ecology and management increase when research integrates biological systems with physical systems. For example, the River Continuum Concept (RCC) was proposed as a biological analog of the energy equilibrium theory of the physical system of geomorphologists and provided a framework for integrating biology with the physical-geomorphic environment (Vannote et al. 1980). In theory, community structure and function along river gradients conform to the mean state of the physical system. The theory predicts that as the physical-geomorphic state changes along river gradients, biological communities will make functional and structural adjustments. The RCC was generally applicable for streams in forested watersheds with cold, autotrophic headwater streams having a forest canopy cover and 1 or 2 coldwater adapted fish species. However, the basic geomorphic premise of the RCC is useful for modeling streams in other environments. For example, the conterminous United States was divided into 7 broad regions based on the effect that lithology, runoff, and relief had on longitudinal patterns in channel form (Brussock et al. 1985). These effects on longitudinal patterns formed the basis for concordance with the RCC or departure from the RCC. The very eastern fringe of South Dakota is in a region (Glaciated Interior Region) where streams do not possess the structure in headwaters as described in the RCC. In essence, the proposed river continuum is truncated and many of the biological traits in the headwaters assume an upstream shift of the warm water, heterotrophic environment (Wiley et al. 1990) and higher species richness typical of the middle of the RCC. The remaining portion of South Dakota is in a large region making up most of the mid-continental (Ephemeral) defined by Brussock et al. (1985) as having streams that should potentially be considered biologically unique and therefore might not conform to the RCC. However, rather than being biologically unique, this characterization of a large mid-continental region is probably a gross characterization that reflected a lack of knowledge of relations between biological communities and the physical environment.

The use of smaller, more discrete land units, such as ecoregions (Omernik 1987), to study and characterize physical patterns and biological communities would increase our knowledge of rivers that do not conform to the RCC. Ecoregions are based on landform, landuse, potential natural vegetation, and soils (Omernik 1987). The premise is that within ecoregions, geomorphic processes and physical characteristics are more similar, than in streams among different ecoregions. Thus, biological communities should be more similar within than among ecoregions. Understanding how landscape patterns influence geomorphic processes can help predict ecosystem behavior (Frissell et al. 1986; Swanson et al. 1988) within and among ecoregions. Predicting ecosystem behavior by testing for biological analogs to geomorphic processes within and among ecoregions can yield knowledge useful for assessing the health of rivers and streams. Current biomonitoring protocol recommend using ecoregions to classify streams prior to developing biological monitoring tools (Barbour et al. 1999).

Geomorphic processes, resulting physical conditions, and the biological responses can be defined and tested as a general integration of interacting variables along four dimensions (Ward 1988): 1) a longitudinal dimension that integrates upstream-downstream linkages; 2) a lateral dimension where exchanges of materials and energy occur between the channel and riparian-floodplain areas; 3) a vertical dimension where interactions between the channel and groundwater occur; and 4) time, which imposes a temporal hierarchy on the three spatial dimensions. The strength of interacting variables along one dimension may vary as a function of their position along another dimension. For example, the strength of lateral interactions among riparian vegetation, channel morphometry, and channel substrates may change as a function of longitudinal position as patterns and processes in sediment and water transport change upstream. A useful concept for understanding longitudinal shifts in sediment and water transport is the threshold of critical power. The threshold of critical power is where stream power is equal to critical power (Bull 1979). Stream power is the power available to transport sediment load and critical power is the power needed to transport sediment. The threshold of critical power separates the modes of net deposition (stream power < critical power) and net erosion (stream power > critical power) in fluvial systems. Conceptually, in tributaries, stream power exceeds critical power and down-cutting is the dominant process; in mid-reaches, stream power equals critical power and lateral migration is the dominant process; and in large rivers critical power exceeds stream power and alluviation is the dominant process. Understanding how thresholds broadly change along a river system would provide insight into differences in habitat forming processes in upper, middle and lower reaches.

Beyond a broad understanding of how thresholds change, geomorphologists and fishery biologists are not currently able to predict threshold values (Heede and Rinne 1990). As an alternative, dynamic equilibrium can be used to visualize quasi-balance situations and disequilibrium can be used to characterize situations undergoing erosion and drastic changes (Heede and Rinne 1990). A stream that is in dynamic equilibrium can make relatively fast changes from one physical state to another following natural disturbance (e.g., flood event). In contrast, a stream that is in disequilibrium is often making long term adjustments to man-made changes in hydrology or sediment yield (via agriculture, deforestation, and urbanization). In the event of large-scale, cumulative landscape or channel alterations, instream and near stream changes may result from system level factors that produce slow changes not noticeable until some threshold is reached, which is followed by dramatic changes in local conditions without an apparent disturbance event (Heede and Rinne 1990). Developing habitat assessment approaches that identify differences between dynamic equilibrium and disequilibrium in streams would define management approaches that either protect the equilibrium state or restore fluvial processes (i.e. hydrology and sediment yield).

In brief, geology and climate, variation in geomorphic processes, and natural and human-induced changes in channel equilibrium are physical phenomena that define similarities or differences in habitat qualities along rivers and their biological analogs. These physical and biological phenomena need to be considered in regional and watershed level contexts when habitat restoration projects are planned (Frissell and Nawa 1992). By doing so, habitat features at a site can be diagnosed as healthy, changing, or degraded. Then, managers can decide if changing or degraded sites have problems that are locally based (e.g., high cattle use) and easily remedied; or if instability is caused by reach or system perturbations (e.g., channel and watershed alterations). Thus, research that defines the hierarchical relationships of systemic and local interactions on habitat conditions would help promote management designed to solve problems rather than treat symptoms.

Stream Classifications

Stream classifications can hierarchically organize the structural attributes and functional processes associated with systemic and local variables (Frissell et al. 1986) as discussed in the previous section. These variables include geology and climate, geomorphic processes, riparian interactions, stream dimensions, and specific habitat components (e.g., large woody debris) that can be spatially and temporally classified to aid stream managers. By hierarchically classifying stream systems, complex aspects of system behavior caused by physical phenomena on different spatial and temporal scales can be ordered, analyzed, and predicted (Frissell and Nawa 1992). Thus, managers can avoid faulty interpretations that can occur at the ecosystem level when extrapolating findings from a smaller spatial scale to a larger spatial scale (e.g., from a single reach to an entire river) (Minshall 1988). Also, managers can make knowledgeable landuse decisions, increase the capability of predicting benefits and eliminating stresses, properly extrapolate research results, and transfer fish management experiences from one area to another (Lotspeich and Platts 1981). Related benefits realized by categorizing rivers based on channel morphology include 1) predicting a river's behavior from its appearance, 2) developing specific hydraulic and sediment relations based on morphological channel type and state, 3) allowing extrapolation of site-specific data collected on a given stream reach to those of similar character, and 4) providing a frame of reference of communication for those working with rivers in many professional disciplines (Rosgen 1994).

The hypothesis that streams can be based on geologic and climatic causes can be tested in the field under a broad range of geomorphic, climatic, and riverine features (Lotspeich and Platts 1981). Testing should incorporate specific questions about prairie stream classification (Matthew 1988). One major question was, "Can hydraulic parameters, geomorphology, and physicochemical measurements be incorporated into a useful hierarchy of prairie stream classification that includes variables like slope, channel morphology, stream density, etc., to facilitate broad comparisons within and among regions?" Prairie stream research of large-scale contexts should attempt to answer this question by making broad comparisons between and among regions. Additionally, the premise is that physical interactions at several dimensions will cause an analogous biological response also useful for broad comparisons within and among regions. By making these comparisons, patterns will emerge that improve the use of physical and biological data in watershed-level assessments despite high natural variation typical of prairie streams.

Fish Community Structure in Prairie Streams

A framework of streamflow patterns based on flow variability, flood regime patterns, and extent of intermittency (Poff and Ward 1989) describe a continuum of benign to harsh stream environments. In harsh stream environments, fish communities are dominated by generalists, trophic structure is simple, and species richness is lower compared to fish communities in benign environments which have more specialists, trophic structure is more complex, and species richness is higher. Many rivers in the semi-arid region of western South Dakota classify as 'intermittent' and rivers in eastern South Dakota would classify as 'perennial runoff' with high flow variability. Theoretically, fish communities in these systems (reviewed by Poff and Ward) are controlled by abiotic factors, except at low flows when biotic interactions become temporarily important. Habitat partitioning in unstable environments may be less important in structuring fish communities than in stable environments except at low flows.

Studies of streams in eastern South Dakota provided similar evidence that fish community dynamics and fish habitat are dictated primarily by flow regime but that woody debris or habitat complexity may be important during low flows. For example, in the Vermillion River, Bratten (1993) found that in July, when flow and velocity were moderate, no species or size classes were specifically associated with one habitat. In August during low discharge, the fish community used a narrower range of depth, velocity, substrate, and woody debris. No specific fish populations or size classes were associated with pools or woody habitat. However, in the extremely low gradient James River, large woody debris complexes were important to fish at low base flows during a drought year and during higher base flow conditions the previous year (Walsh 1992). Thus, the availability of physical habitat, which depend on systemic processes, coupled with low flows define potentially critical periods for fish communities.

Although fish communities in prairie streams are commonly composed of habitat generalists and specific habitat assemblages may be uncommon, biotic interactions may invoke segregation following low flow, or intermittent conditions. Restated as a question, Matthews (1988) asked, "How do effects of spates or droughts compare or interact with biotic interactions to decide the ultimate community structure or dynamics of community structure of prairie streams?" During critical drought periods, defining the role of physical habitat to fish community structure and dynamics would justify habitat protection and restoration despite long-term generality in physical habitat-use patterns. Direct observation of these mechanisms under controlled and easily manipulated laboratory conditions will provide insight into how and why fish select typical cover types.

Research Approach

My research approach was based on a premise that assessments of the health of rivers and streams in prairie environments would benefit from studies that 1) examine the role of systemic processes in moderating physical habitat and fish community attributes among geologic-climatic settings, 2) establish links between systemic processes and local interactions on fish attributes and physical habitat within a geologic and climatic setting, and 3) test the role of biotic and abiotic interactions on habitat partitioning by fish under critical flow scenarios common in prairie streams.

My research has three complementary parts: two field studies and a laboratory experiment. The first field study tested the hypothesis that systemic processes moderate physical riverine environments in distinct ways between a semi-arid region and a sub-humid region and that fish community attributes provide biologically equivalent parallels to the physical environment. The second field study tested the hypothesis that in a sub-humid region the interactions of local variables have greater influence on fish communities and physical habitat in smaller streams than in larger rivers. The laboratory experiment tested the influence of predators and competitors, large woody debris, and turbidity on habitat use by common minnow species under simulated low flow conditions.

Findings from this research meet the two goals of providing managers and researchers with 1) a framework to assess the influence of local and systemic processes on fish and fish cover, and 2) basic insight into fish use of cover as influenced by habitat and biotic interactions at low flow. This knowledge will prove useful to habitat protection and restoration efforts, and define new research needs.

CHAPTER 2

A COMPARISON OF INFLUENCE OF SYSTEM LEVEL DYNAMICS ON FISH AND FISH HABITAT BETWEEN TWO GEOLOGICALLY-CLIMATICALLY DISTINCT RIVERS IN SOUTH DAKOTA

Introduction

The ability to interpret survey data from rivers in prairie environments will improve when research integrates and tests the many concepts and theories that have formed the basis of past studies. Frequently tested and used models are a river continuum concept (RCC) (Vannote et al. 1980), a hierarchy of streamflow patterns (Poff and Ward 1989), and hierarchical classifications based on geomorphology (Frissell et al. 1986). Testing the application of these models to the physical environment and fish communities in prairie streams would define a management framework that would guide selection of realistic protection and restoration approaches, and identify new research needs aimed at solving problems basic to managing dynamic environments not encountered in more stable stream environments.

One of the most cited models in stream ecology is the RCC, which was proposed as a framework for integrating biology with the physical-geomorphic environment (Vannote et al. 1980). In theory, community structure and function along river gradients conform to the mean state of the physical system. One prediction is that as the physical-geomorphic state changes along river gradients, biological communities will make structural and functional adjustments. Although the RCC was generally applicable for streams originating in forested watersheds with cold, autotrophic headwaters and 1 or 2 coldwater adapted fish species, the authors suggested that the basic geomorphic premise of the RCC may be used for understanding streams in other environments. In fact, the effects of lithology, runoff, and relief on longitudinal patterns in river channels formed the basis for dividing the conterminous United States into 7 regions (Brussock et al. 1985). In South Dakota, the very eastern fringe fell within a region (Glaciated Interior Region) where rivers did not possess the physical conditions in headwaters as described in the RCC. In this region, the physical and biological traits of headwaters mimic a warm water, heterotrophic environment and higher species richness typical of the middle reaches of the RCC. The remaining portion of South Dakota fell within a region (Ephemeral) defined as having streams that should potentially be considered biologically unique and distinct from the RCC, because of the special adaptations of organisms to widely fluctuating conditions. However, such a broad generalization of a large mid-continental region probably reflected a lack of knowledge of relations of biological communities with streamflow patterns.

A framework of streamflow patterns based on flow variability, flood regime patterns, and extent of intermittency (Poff and Ward 1989), within the conterminous United States, describes a general continuum of "benign" to "harsh" stream environments. In hydrologically benign environments, specialists are more common, trophic structure is more complex, and species richness is higher compared to harsh environments where generalists dominate fish communities, trophic structure is simple, and species richness is lower. In South Dakota, streams in the sub-humid region in the eastern part of the state are more benign than streams in the western semi-arid region of the state. Theoretically, based only on streamflow patterns, the rivers in the sub-humid region should have a community structure that has more trophic complexity, higher species richness, and more specialists than in the semi-arid region. However, streamflow patterns alone do not account for all the environmental variables that moderate biological communities. Thus, studying the effects of a longitudinal continuum of physical change on biological communities remains valid.

A longitudinal continuum of physical change reflects dominant geomorphic processes, which depend on discharge and sediment transport patterns (Leopold et al. 1964; Knox 1976; Wolman and Gerson 1978; Bull 1979; Brussock et al. 1985; Brinson 1993; Heede and Rinne 1990). Dominant fluvial geomorphic processes at the systemic level typically follow a sequence of downcutting in the headwater reaches, lateral migration in the midreaches, and alluviation in the downstream reaches. Longitudinal shifts from one dominant geomorphic process to another should be reflected as changes in channel morphometry. However, channel morphometry is moderated locally by interactions with riparian vegetation, and bed and bank materials (Keller and Swanson 1979; Grissinger and Bowie 1984; Platts and Nelson 1985; Beschta and Platts 1986; Clifton 1989; Trotter 1990; Johnson and Ryba 1992). These systemic and local interactions within a watershed can be hierarchically classified in terms of fluvial geomorphic processes (Frissell et al. 1986), but such a classification must be couched within its geologic and climatic region.

Theoretically, among geologic and climatic settings, unique sets of system level dynamics moderate local interactions, which ultimately register as a unique continuum of physical habitat and fish communities. The application of this theory to prairie streams in the Northern Great Plains needs further testing. Therefore, I tested the hypothesis that in prairie streams of South Dakota, systemic processes moderate the physical environment in the semi-arid region differently than in the sub-humid region and that fish community attributes provide biologically equivalent parallels to the physical environment. Testing the application of river continuum theory and streamflow theory to prairie streams will provide river and watershed managers with a more reliable hierarchical framework useful for interpreting habitat and biological assessment information for rivers in South Dakota.

Study Sites

The Big Sioux River in eastern South Dakota and the Bad River in western South Dakota (Figure 2-1) were selected for study. The Big Sioux River lies mostly in the Northern Glaciated Plains ecoregion and partially in the Western Corn Belt Plains ecoregion. The parent geology is composed of mostly glacial till and the climate is sub-humid. Mean annual rainfall is 51-64 cm. Land use is mostly row crops on the uplands and flood plain, and mostly pasture along river and tributary corridors. The Bad River is in the Northwestern Great Plains ecoregion. The parent geology is Pierre shale and the climate is semiarid. Mean annual rainfall is 41-46 cm. Land use is a mix of rangeland and small grains in the uplands, hay land on the flood plains, and rangeland in the breaks and corridors of the river and tributaries.

Hydrologically, the Big Sioux River has a higher mean annual discharge, higher flow exceedence values, and fewer periods of intermittency when compared to a similar sized watershed area of the Bad River (Table 2-1). Overall, mean monthly runoff for the Big Sioux River is higher than the Bad River (Figure 2-2). Mean annual runoff for the Big Sioux and Bad rivers show typical effects of wet-dry phases (Figure 2-3) as moderated by the El Nino Southern Oscillation (ENSO). This effect is also notable for the month of August in both rivers (Figure 2-4).

Fish and habitat were sampled at 20 sites along the Bad River and 17 sites along the Big Sioux River (Figure 2-5). On the Bad River, fish and habitat were sampled in the summer of 1996; and on the Big Sioux River, fish and habitat were sampled in 1997 and 1998. Mean annual runoff for all three years and both rivers were above average.

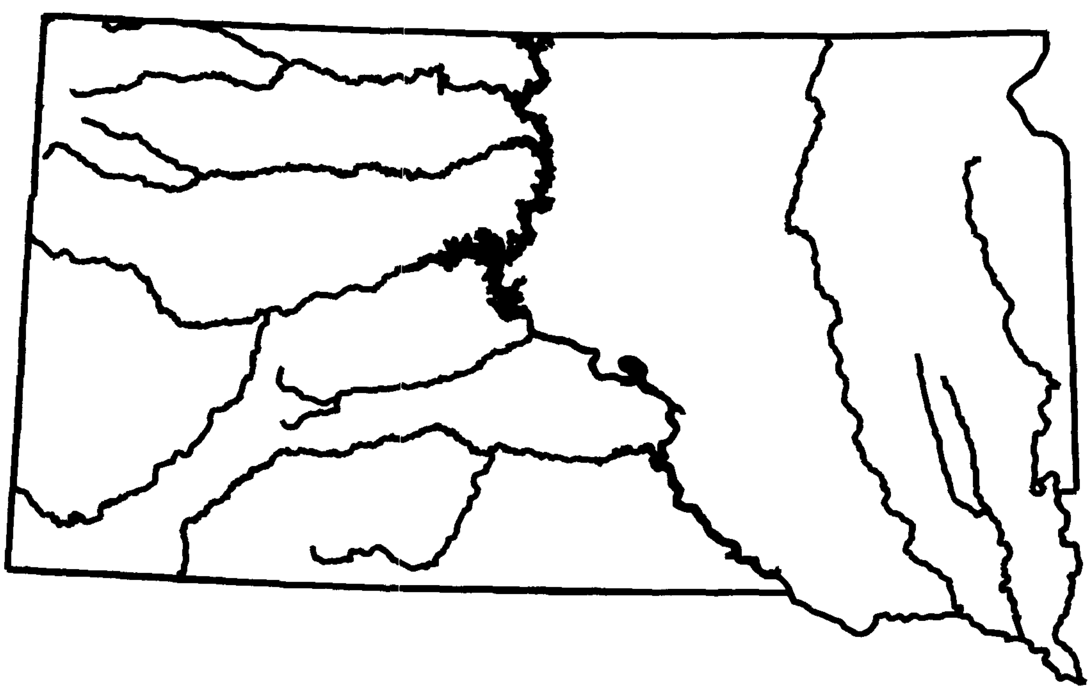


Figure 2-1. Map of South Dakota showing locations of the Big Sioux River and Bad River watersheds.

Table 2-1. Flow traits for a similar sized watershed area in the Bad and Big Sioux Rivers in western and eastern South Dakota. Bad River data are from a USGS gauging station near Ft. Pierre, SD (years 1929-2000) and Big Sioux River data are from a gauging station near Dell Rapids, SD (years 1949-2000).

Statistic	Bad River	Big Sioux River
Watershed area (contributing)	8044 km^2	7777 km^2
Annual runoff (m^3)	155,788,524	380,281,884
Annual mean (m^3/s)	4.924	12.056
Highest annual mean (m^3/s)	34.045	46.808
Lowest annual mean (m^3/s)	0.172	0.654
10 percent exceedence (m^3/s)	6.735	29.715
50 percent exceedence (m^3/s)	0.025	2.830
90 percent exceedence (m^3/s)	0.000	0.311

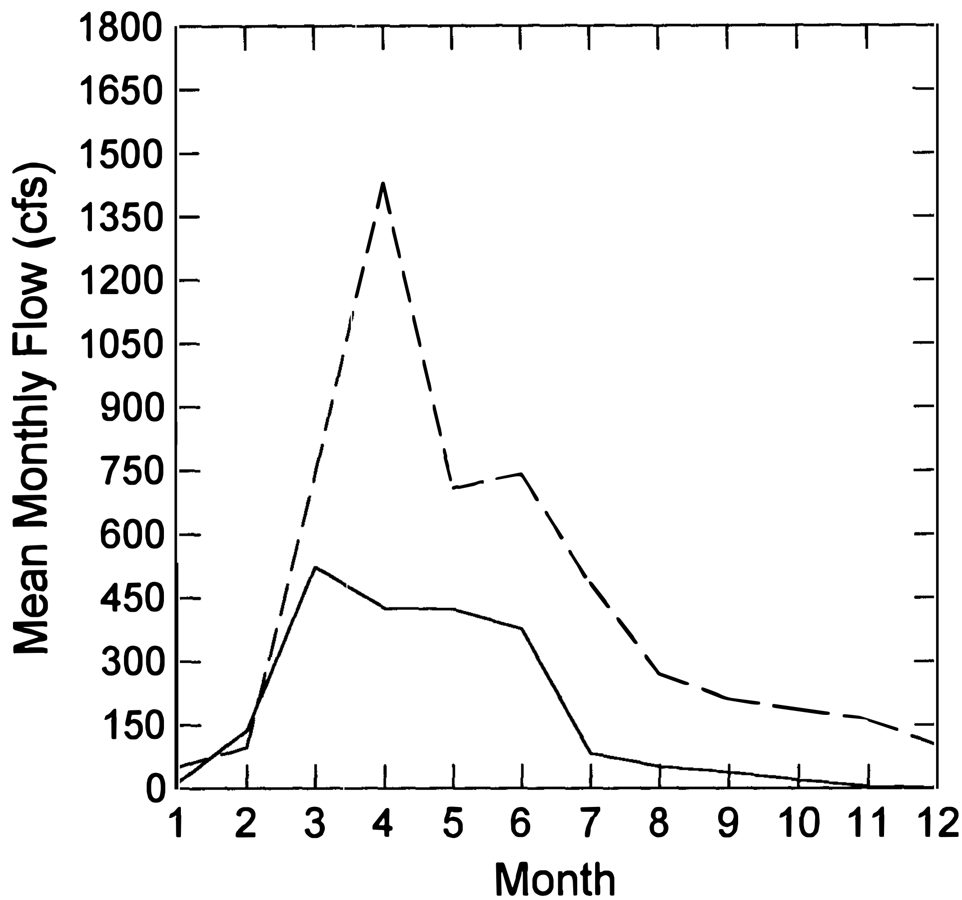


Figure 2-2. Mean monthly discharge for the Bad River (solid line), years 1929-2000, and Big Sioux River (dashed line), years 1949-2000, in South Dakota.

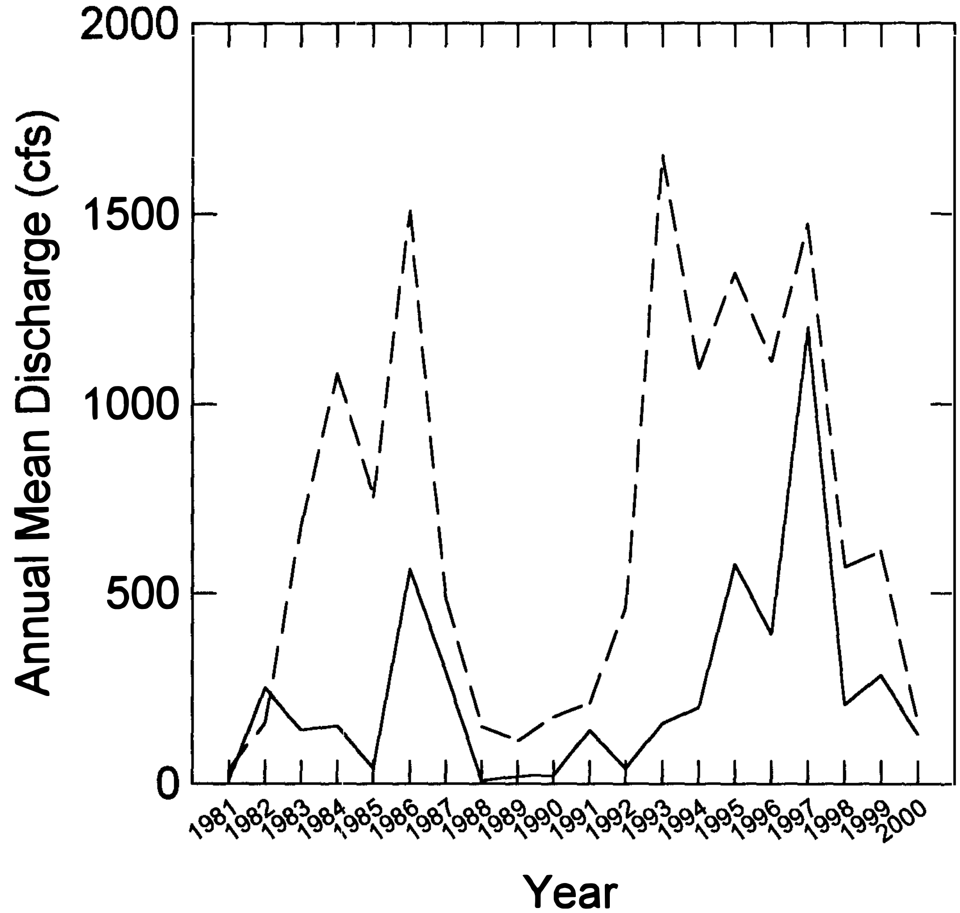


Figure 2-3. Annual mean discharge for the Bad River (solid line), years 1929-2000, and Big Sioux River (dashed line), years 1949-2000, in South Dakota.

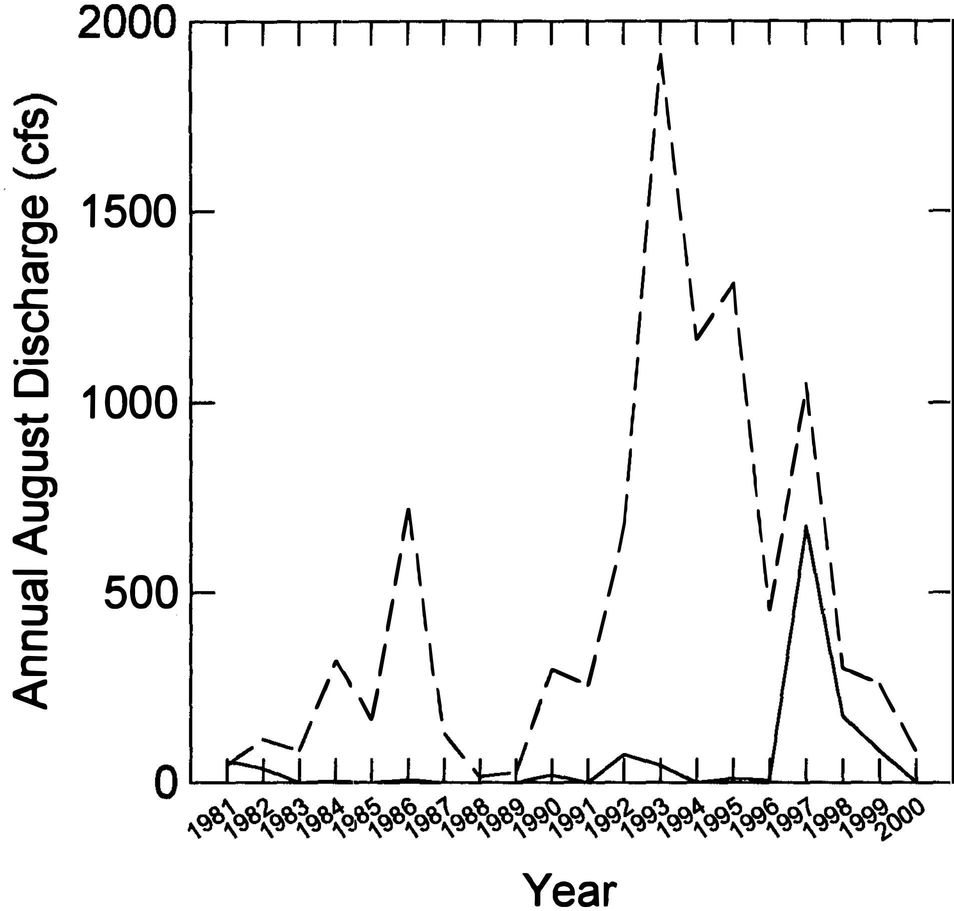


Figure 2-4. Mean annual August discharge for the Bad River (solid line), years 1929-2000, and Big Sioux River (dashed line), years 1949-2000 in South Dakota.

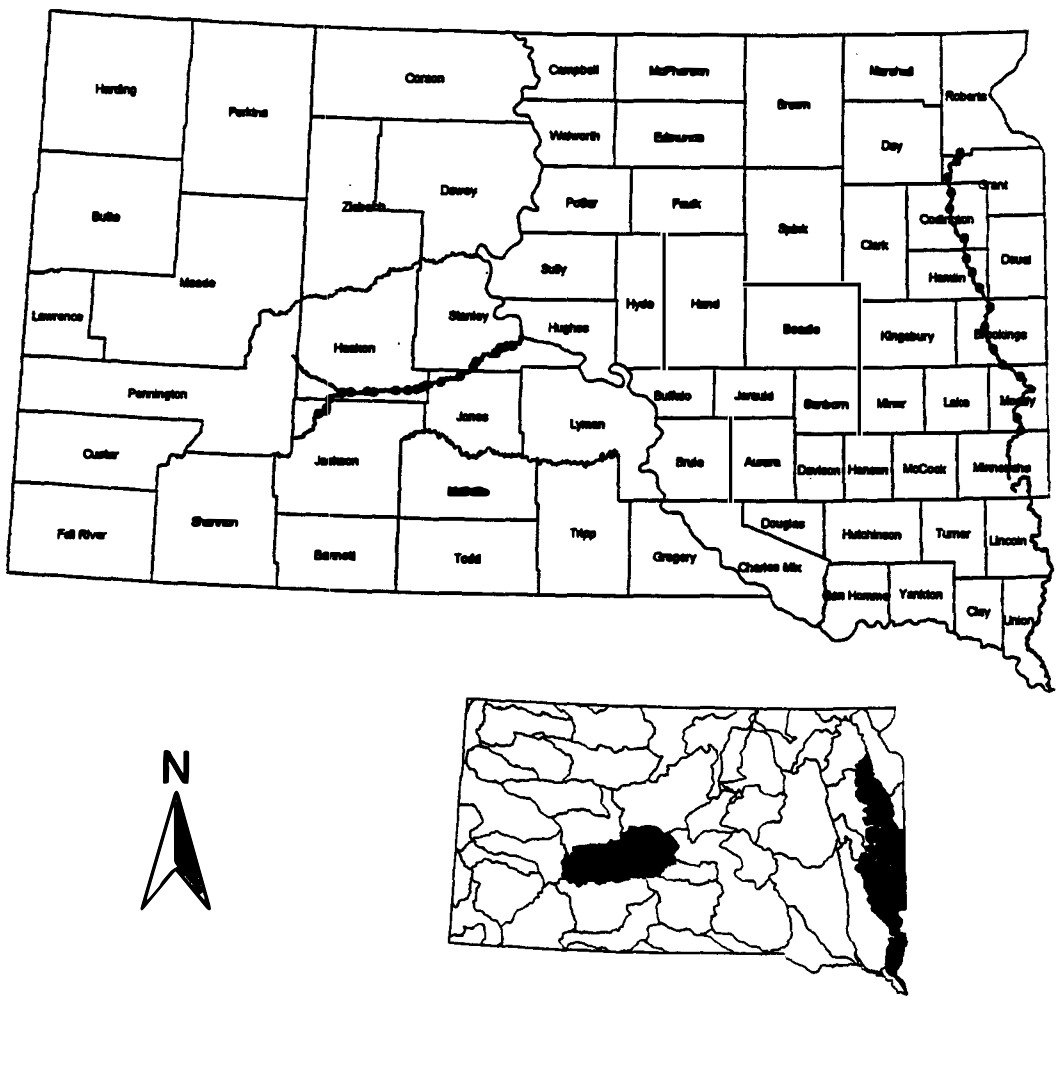


Figure 2-5. Fish and habitat sampling sites in the Bad and Big Sioux River watersheds.

Methods

Environmental Attributes

Field measurements of physical characteristics using a transect method were adapted from Simonson et al. (1994) and Platts et al. (1983). Terms and definitions are provided in Appendix A. Reaches were selected within one type of riparian land use in most cases, and where bridges and dams appeared to have minimal impacts. Once a reach was selected, a preliminary mean stream width (PMSW) was obtained and used to determine transect spacing (Simonson et al. 1994). When low flows restricted stream width to a small portion of the streambed, streambed width was used to determine transect spacing. Within each reach 9 to 13 transects were placed 3 PMSWs apart (Figure 2-6). In most cases, streams greater than 10 m wide were homogenous (e.g., uniform in channel morphometry and depth), and transects spaced 3 PMSWs were judge to be adequate. On the lower 4 reaches of the Big Sioux River, transects were spaced 2 PMSW apart (check). Transects were marked with flags, then data collection began on the upstream end of the reach and proceeded downstream.

Transect data collection were divided into 3 practical components based on tools used. The first suite of data was collected according to visual estimates and counts. On either end of a transect the riparian land use, dominant vegetation type, animal vegetation use, dominant bank substrate, and bank slumping (presence/absence) were recorded. Where a transect crossed the stream, dominant macrohabitat type was designated as pool, riffle, or run. Bed substrate data was collected using the Wolman "pebble count" by visually dividing the transect into eight "cells". Within each cell, substrate size was measured and the class size recorded. This method objectively classified substrates in clear streams and was a necessity in turbid streams where visual estimates were not possible.

A second suite of data focused on stream bank and riparian features and was measured with a graduated pole and angle finder. After identifying the break point between the channel bank and channel bottom, measurements related to stream bank length, bank angle, and bank height were taken (Figure 2-6). Along the stream bank length, the length of bank that was vegetated, eroded, and depositional was measured. Vegetated portions were that length of bank where root structure contributed to bank stability, eroded portions were that length with no root structure support, and depositional portions were that length where recent deposition dominated the bank surface. Riparian-related cover types were measured at the end of each transect as the horizontal length of overhanging vegetation (OHV) and undercut bank (UCB) extending over the streambed.

A third suite of data focused on horizontal and vertical point measurements which were used to calculate stream width, depth and velocity; channel bottom and top width; and bankfull width, depth, and width:depth ratio. At most sites, point data were obtained by staking a tape measure from left top bank to the right top bank. In some cases, the tape measure was staked at left bankfull and right bankfull. Moving from left to right, key channel features (i.e., location codes) were identified and the distance from the left stake was recorded. Vertical measurements were bankfull depth, water depth, and water velocity. Bankfull depths were measured at the waters edge and at three points within the stream. Water depth and velocity were measured at the three points within the stream

(1/4, 1/2, and 3/4 of the distance across the stream surface).

At each site, data were also collected on large woody debris (LWD), discharge, water surface slope, and water quality. The number of LWD was tallied for the entire reach. Length and diameter measurements of all LWD were measured and used to calculate the volume of LWD within the reach. Discharge data were collected at a single transect or other stream cross-sections where flow was uniform. The velocity-area method described in Gordon et al. (1992) was used. Water surface slope (%) was calculated by dividing the drop in water surface from transect one to transect 13 by the longitudinal stream distance using a surveying level.

Water quality data measured were water temperature, air temperature, turbidity, dissolved oxygen, and conductivity. These measurements were made once at each reach.

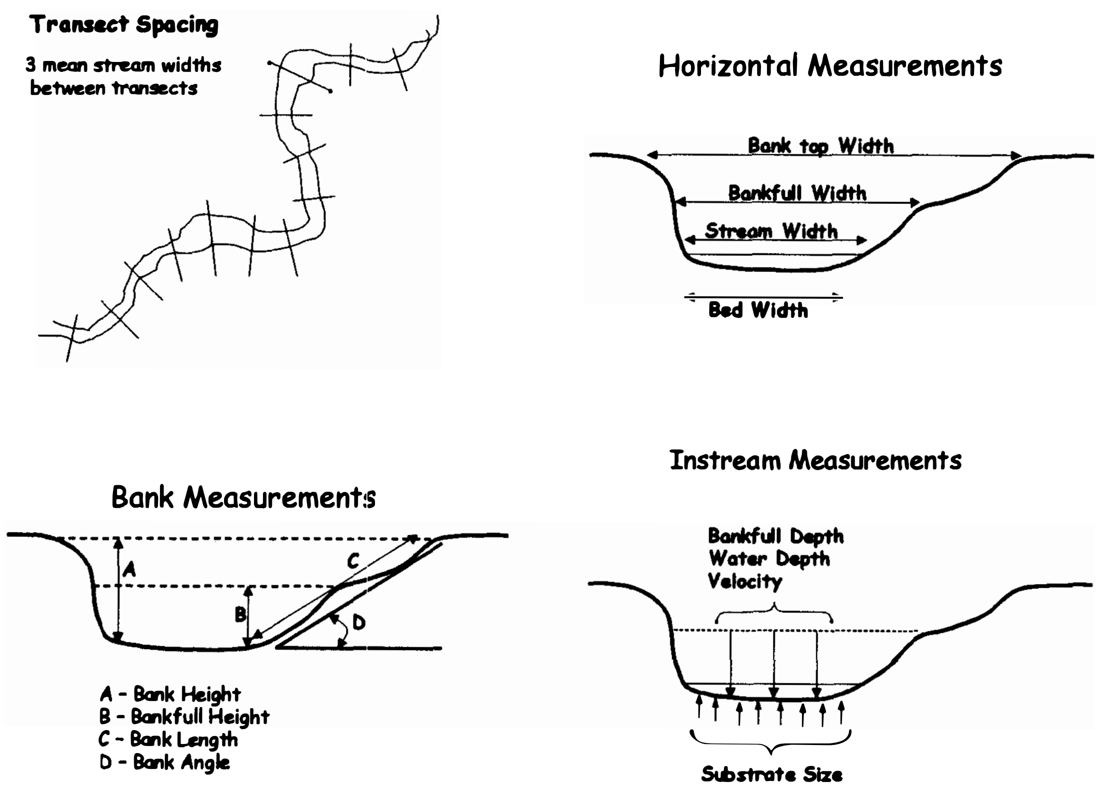


Figure 2-6. Diagrams of transect spacing, and horizontal, bank, and instream measurements.

Fish Sampling

Fish were collected in all reaches with bag seines having 8mm mesh size. Pools and runs were seined usually in a downstream direction with a seine that reached from bank to bank. A block net having 8 mm mesh was placed across the stream to prevent fish from escaping. Riffles were usually sampled by kicking through the substrate in a down stream direction toward a bag seine place across the stream at the bottom of the riffle. Blocknets were used in all reaches except for the lowest 12 sites on the Big Sioux River. In the Big Sioux River, high velocities (>0.3 m/s) in the lowest 12 sites prevented effective sampling of all habitats; however, representative sampling of the reach was attempted to obtain data for characterizing community attributes. In the Bad River, low streamflows permitted seining of almost all pools, runs and riffles. Fish sampled were identified, counted, and weighed.

Fish Community Attributes

Quantification of fish community attributes facilitated comparisons of fish ecology between basins. First, attributes that were applicable to South Dakota stream fishes were selected and modified following several sources (Karr et al. 1986; Niemela et al. 1998; EPA 1999). Community attributes represented several aspects of species richness and composition, tolerance, trophic structure, and reproduction (Table 2-2). Second, designation of life-history attributes for each species was based on a review of several resources (Cross 1967; Scott and Crossman 1973; Trautman 1981; Pflieger 1997; Barbour et al. 1999). Following these designations, a value for each community attribute was calculated for each site (e.g, % of individuals as omnivores). Calculations used relative abundance data from the Big Sioux River and catch rate data from the Bad River.

Statistical Analyses

Physical Environment.--Two statistical analyses were used to test my research hypothesis that in prairie streams of South Dakota, systemic processes moderate the physical environment in distinct ways between a semi-arid region and sub-humid region. First, an exploratory approach using principal components analysis (PCA) of select physical characteristics were used to discern prominent longitudinal patterns unique to each basin. My statistical hypothesis states: if longitudinal patterns are not different between basins, then longitudinal patterns unique to each basin should not be observed on plots of PC's. Physical variables used in the analyses were restricted to those not subject to large seasonal or annual changes caused by fluctuations in streamflow. Examples of variables eliminated from the analysis are water depth and velocity, stream width, and macrohabitats (e.g., pools, runs, and riffles).

The second statistical analysis was directed at testing the hypothesis that between the two geologic and climatic settings, streamflow patterns and sediment transport patterns create systemic level patterns that are unique and thus, register as a unique continuum of physical characteristics. Longitudinal differences in physical characteristics between watersheds were tested with analyses of covariance (ANCOVA). Watershed membership served as the categorical variable separating the geologic-climatic setting and watershed area (km^2) served as a covariate that represented the longitudinal continuum. Four groups of dependent physical variables were tested: channel dimensions, bankfull dimensions, streambank conditions, and streambed substrate. My statistical hypothesis states: if a physical variable is not on a unique continuum, then the relationship of that variable with watershed size should be the same between the Big Sioux River and Bad River watersheds. As above, physical variables used in the analyses were restricted to those not subject to large seasonal or annual changes caused by fluctuations in streamflow.

Fish Community Attributes.—ANCOVA was used to test two hypotheses under the theory that systemic processes moderate the fish communities in distinct ways between a semi-arid region and sub-humid region. In the ANCOVA, watershed membership served as the categorical variable and as a surrogate that distinguished systemic level differences, and watershed area served as a covariate that represented the longitudinal continuum. Four groups of dependent fish community attributes were tested: species richness, headwater/pioneering species, intolerant/tolerant species (includes sensitive species), trophic guilds, and lithophilic species.

My first hypothesis was that fish community attributes between a semi-arid region and a sub-humid region should reflect the natural streamflow fluctuations of each region. My statistical hypothesis states: if streamflow fluctuations do not influence fish community attributes, then those traits typically identified as being influenced by the streamflow patterns should not be different between basins.

My second hypothesis was that longitudinal patterns in fish community attributes should be biologically analogous to longitudinal patterns in the physical environment between basins. My statistical hypothesis states: if fish community attributes are not influenced by longitudinal physical trends inherent to each watershed, then the watershed with the most discrete continua of physical attributes will not have the most discrete continua of fish community attributes.

Table 2-2. Life-history designations used to quantify fish community attributes in the Big Sioux River and Bad River.

Common Name	Scientific name	Trophic[1]	Tolerance[2]	Sensitive (S)	Habitat Guild[3]	Headwater (H)	Pioneer (P)	Simple Lithophil (SL)
Mooneyes	**Hiodontidae**							
Goldeye	Hiodon alosoides		I	S	WC			
Carps and Minnows	**Cyprinidae**							
Central stoneroller	*Campostoma anomalum*	H	M		B	H	p	
Red shiner	*Cyprinella lutrensis*	I	T		G			
Common carp	*Cyprinus carpio*	O	T		B			
Brassy minnow	*Hybognathus hankinsoni*	H	M		G			
Plains minnow	*Hybognathus placitus*	H	M		G			
Common shiner	Luxilus cornutus	I	M		WC			SL
Golden shiner	*Notemigonus crysoleucas*	I	T		WC			
Emerald shiner	*Notropis atherinoides*	I	M		WC			SL
Bigmouth shiner	*Notropis dorsalis*	I	M		B			
Spottail shiner	*Notropis hudsonius*	I	I	S	WC			
Sand shiner	*Notropis ludibundis*	I	M		WC			
Topeka shiner	*Notropis topeka*	I	I	S	WC			
Bluntnose minnow	*Pimephales notatus*	O	T		G		P	
Fathead minnow	*Pimephales promelas*	O	T		G		P	
Flathead chub	*Platygobio gracilis*	I	M		WC			
Blacknose dace	*Rhinichthys atratulus*	I	M		B	H		SL
Rudd	*Scardinius erythrophthalmus*	O	T					
Creek chub	*Semotilus atromaculatus*	I	T		WC		P	
Suckers	***Catostomidae***							
River carpsucker	*Carpiodes carpio*	O	M		B			
White sucker	*Catostomus commersoni*	O	T		B			SL
Blue sucker	Cycleptus elongatus	I	I	S	B			SL
Bigmouth buffalo	*Ictiobus cyprinellus*	I	M		G			
Shorthead redhorse	*Moxostoma macrolepidotum*	I	M	S	B			SL
Bullhead/Catfishes	***Ictaluridae***							
Black bullhead	*Ameiurusmelas*	I	T		B		P	
Yellow bullhead	*Ameiurus natali*	I	M		B			
Brown bullhead	*Ameiurus nebulosus*	I	T		B			
Blue catfish	*Ictalurus furcatus*	P	M		B			
Channel catfish	*Ictalurus punctatus*	I	M		B			
Stonecat	*Noturus flavus*	I	I	S	B			
Tadpole madtom	*Noturus gyrinus*	I	M	S	B			
Flathead catfish	*Pylodictis olivaris*	P	M		B			
Pikes	***Esocidae***							
Northern pike	*Esox lucius*	P	M		WC			
Trout-perches	***Percopsidae***							
Trout-perch	*Percopsis omiscomaycu*	I	M	S	B			
Sticklebacks	***Gasterosteiae***							
Brook stickleback	*Culaea inonstans*	I	M	S	WC	H		
Temperate Basses	***Percichthyidae***							
White bass	*Morone chrysops*	P	M		WC			

Sunfishes	***Centrarchidae***							
Green sunfish	*Lepomis cyanellus*	I	T		WC		P	
Orangespotted sunfish	*Lepomis humilis*	I	M		WC			
Bluegill	*Lepomis macrochirus*	I	M		WC			
Smallmouth bass	*Micropterus dolomieu*	P	M		WC			
Largemouth bass	*Micropterus salmoides*	P	M		WC			
Black crappie	*Pomoxis nigromaculatus*	P	M		WC			
Perches	***Percidae***							
Iowa darter	*Etheostoma exile*	I	I	S	B	H		
Johnny darter	*Etheostoma nigrum*	I	M		B	H	P	
Yellow perch	*Perca flavescens*	I	M		WC			
Logperch	*Percina caprodes*	I	M		B			SL
Blackside darter	*Percina maculata*	I	M		B			SL
Walleye	*Stizostedion vitreum*	P	M		B			SL

1 I=insectivore, O=omnivore, H=herbivore, P=predator.
2 I=intolerant, M=moderately tolerant, T=tolerant.
3 B=benthic, WC=water column, G=generalist.

Results

Descriptive Information and Summary Statistics for the Big Sioux and Bad Rivers

Riparian Land Use and Animal Vegetation Use.—Riparian land use and animal vegetation use tended to reflect the differences in landscape-level management between the two basins. Riparian land use in the Bad River was a mix of rangeland, woodland, and prairie (Table 2-3). Cattle were not confined to the riparian corridor along the Bad River and animal vegetation use was classed as low at all sites (Table 2-3). Although some of the land use was classed as woodland or prairie this does not suggest that animal use does not occur, and in fact, cattle are often wintered in these areas. Riparian land use along the Big Sioux River was mostly pastureland (Table 2-3), which was distinguished from rangeland in that cattle were often confined to the riparian corridor. Likewise, animal vegetation use was more commonly classed as moderate or high (Table 2-3).

Riparian Vegetation Types.—Riparian vegetation was more heterogeneous along the Bad River than along the Big Sioux River. Along the Bad River, most reaches had a mix of grasses, sedges, willows, shrubs, and trees (Figure 2-7). The most obvious pattern observed was a tendency toward more willow-covered banks in the downstream direction with the exception of two sites where grasses and sedges became dominant. Along the Big Sioux River, grasses and sedges were dominant at all sites (Figure 2-8). Willows were present sporadically along the river and green ash in the lower sites, but both normally comprised less than 5% of vegetation that contributed to bank stability.

Table 2-3. Riparian land use and animal vegetation use (Platts et al. 1983) at 20 sites in the Bad River and 17 sites along the Big Sioux River in South Dakota.

	Bad River		Big Sioux River	
Site	Riparian Land Use	Animal Vegetation Use	Riparian Land Use	Animal Vegetation Use
1	Rangeland	Low	Pasture	Low
2	Rangeland	Low	Pasture	Moderate
3	Rangeland	Low	Pasture	Low
4	Woodland	Low	Pasture	High
5	Woodland	Low	Pasture	Moderate
6	Woodland	Low	Pasture	High
7	Woodland	Low	Cropland	Low
8	Woodland	Low	Cropland	Low
9	Woodland	Low	Prairie	Low
10	Prairie	Low	Pasture	Low
11	Prairie	Low	Pasture	Low
12	Prairie	Low	Open woodlands	Low
13	Hayland	Low	Pasture	Moderate
14	Rangeland	Low	Pasture	High
15	Rangeland	Low	Woodland	Low
16	Rangeland	Low	Pasture	High
17	Woodland	Low	Open woodlands	Low
18	Woodland	Low		
19	Rangeland	Low		
20	Rangeland	Low		

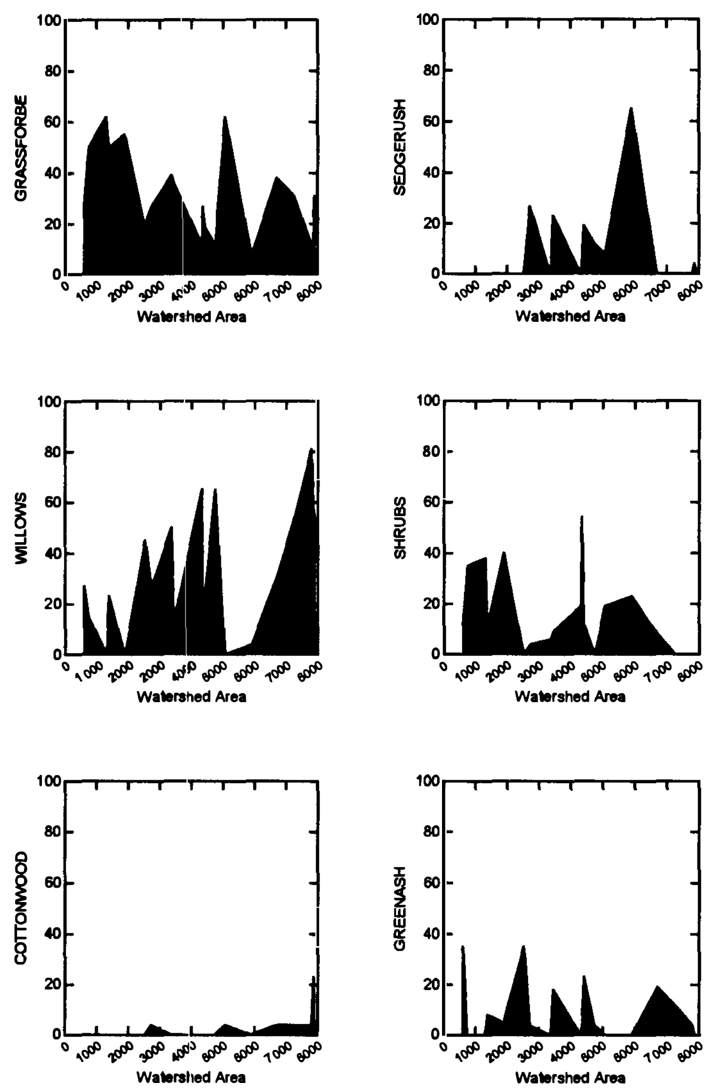


Figure 2-7. Longitudinal profiles of riparian vegetation types (%) for the Bad River.

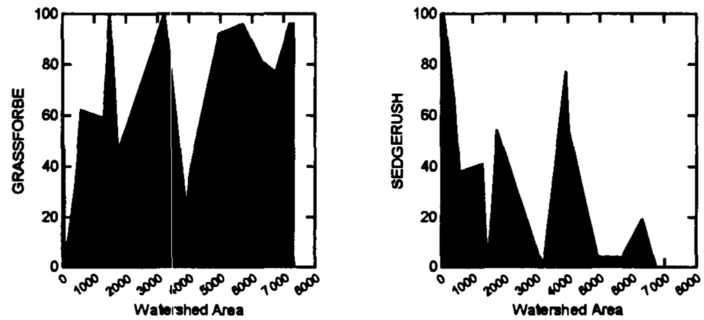


Figure 2-8. Longitudinal profile of riparian vegetation types (%) for the Big Sioux River.

Riparian-related Cover Types.—Longitudinal trends in riparian-related cover types were generally different between rivers. In the Bad River, overhanging vegetation was rare or absent and showed no distinct relationship with watershed size; while in the Big Sioux River, the most substantial amounts of overhanging vegetation occurred at some sites with smaller watersheds and became rare in streams with the largest watershed sizes (Figure 2-9). In both rivers, measurable amounts of undercut banks were less than 0.1 m (Figure 2-9). LWD only became a consistent component in the both rivers (Table 2-3) when riparian landuse along the continuum began supporting woodland or open woods (Table 2-10).

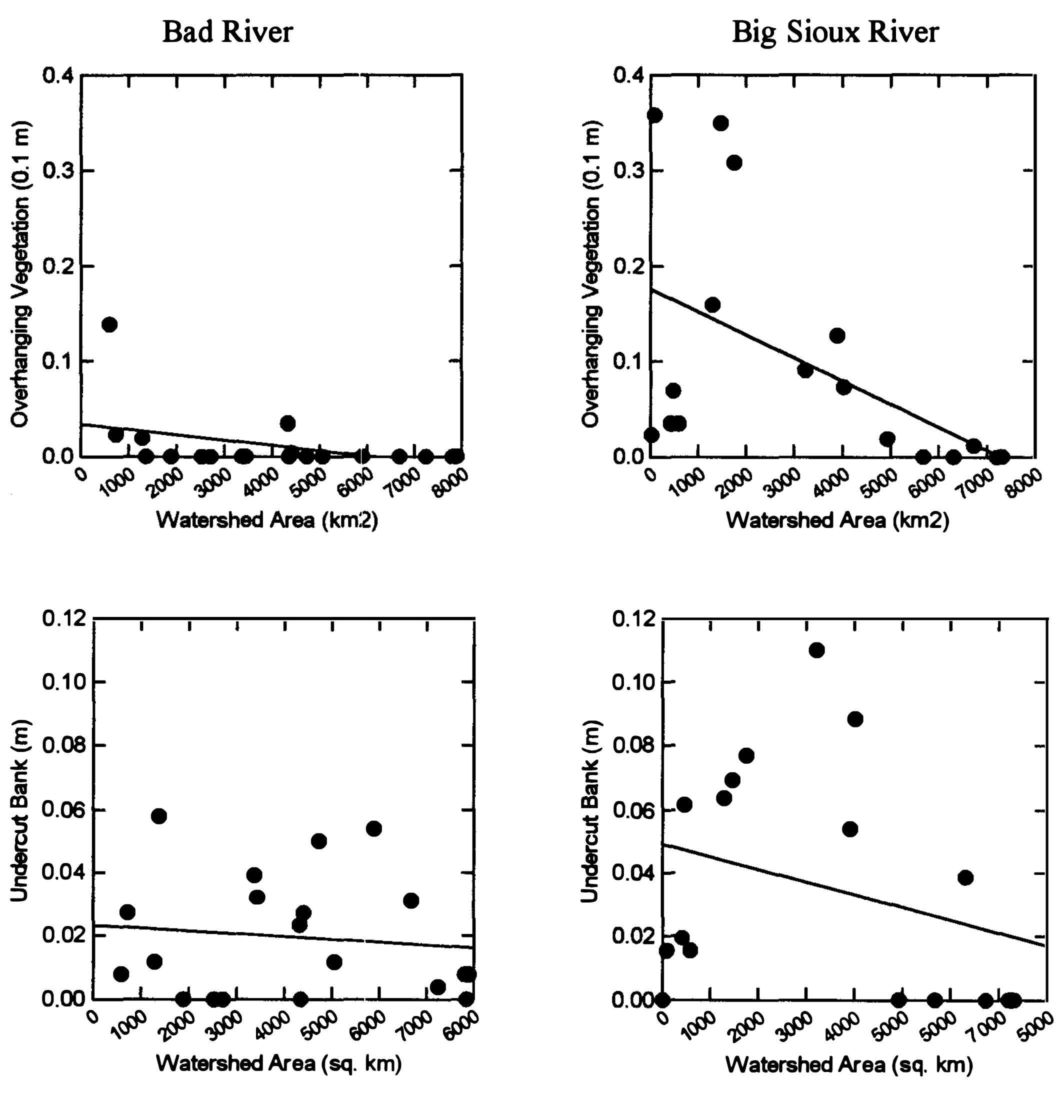


Figure 2-9. Mean horizontal distances of overhanging vegetation and undercut bank for the Bad River and Big Sioux River.

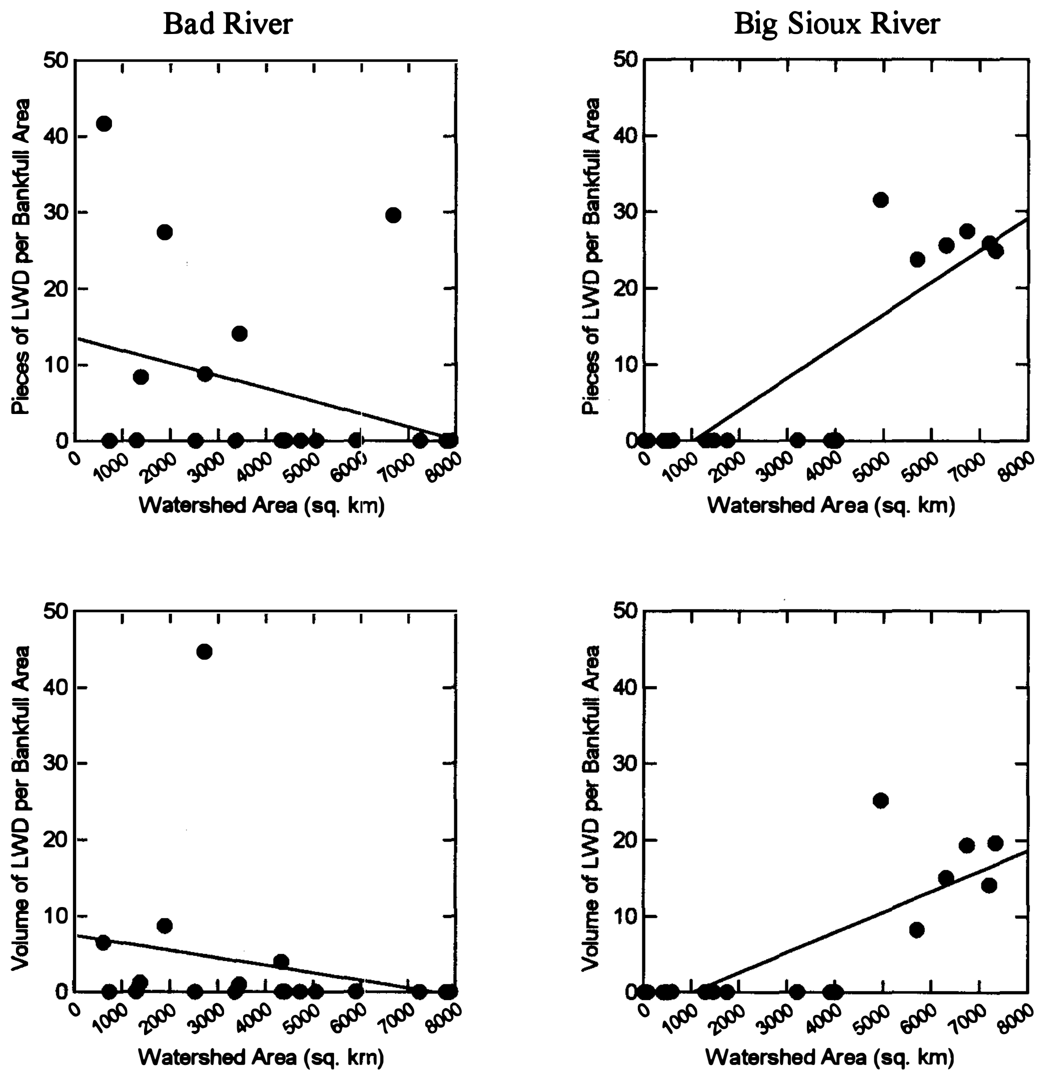


Figure 2-10. Pieces and volume of large woody debris (LWD) per bankfull area for the Bad River and Big Sioux River.

Streamflow.—Streamflows in the Bad River was lower than those in the Big Sioux River (Figure 2-11). The upper five sites in the Big Sioux River had the lowest flows during fish and habitat sampling. The fact that streamflows at the remaining sites tended to decline with watershed size reflect high runoff and my attempt to sample sites in a downstream direction as flows receded. The Bad River normally becomes intermittent during the summer months, but during this study streamflows never ceased.

Water Quality.-- Water temperature and dissolved oxygen in both rivers showed no trends peculiar to each basin except that water temperatures on the lower sites on the Bad River were generally higher than in the Big Sioux River (Figure 2-12). These sites were sampled in mid-summer and the lower volumes of water were notably susceptible to warming by ambient air temperatures. Conductivity was almost 3 times higher in the Bad River compared to the Big Sioux River with the exception of the three most upstream sites (Figure 2-12). Turbidity in the Bad River was consistently below 50 NTU's, while in the Big Sioux River turbidity showed no clear trend and was most often above 50 NTU's (Figure 2-12).

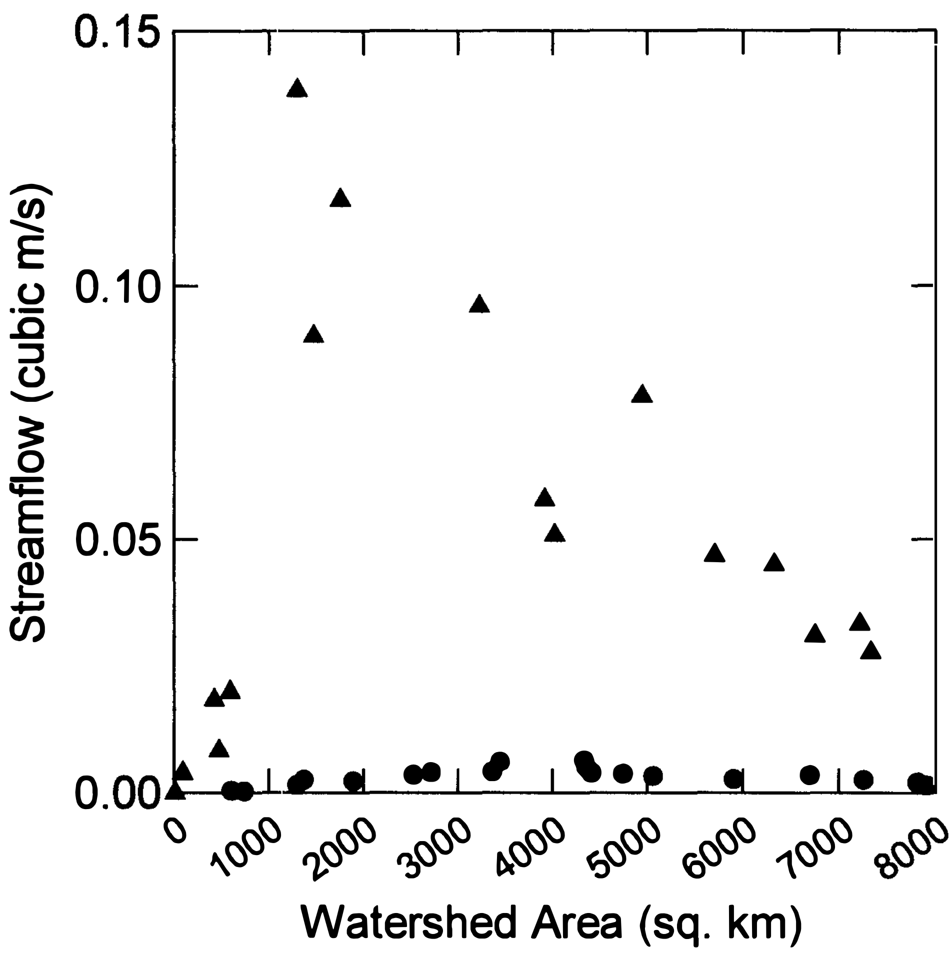


Figure 2-11. Plots of streamflows measured at the time fish and habitat were sampled for the Bad River (●) and Big Sioux River (▲). The Bad River was sampled entirely in the summer of 1996. The upper 8 sites in the Big Sioux River were sampled in 1997 and the lower 9 sites were sampled in 1998.

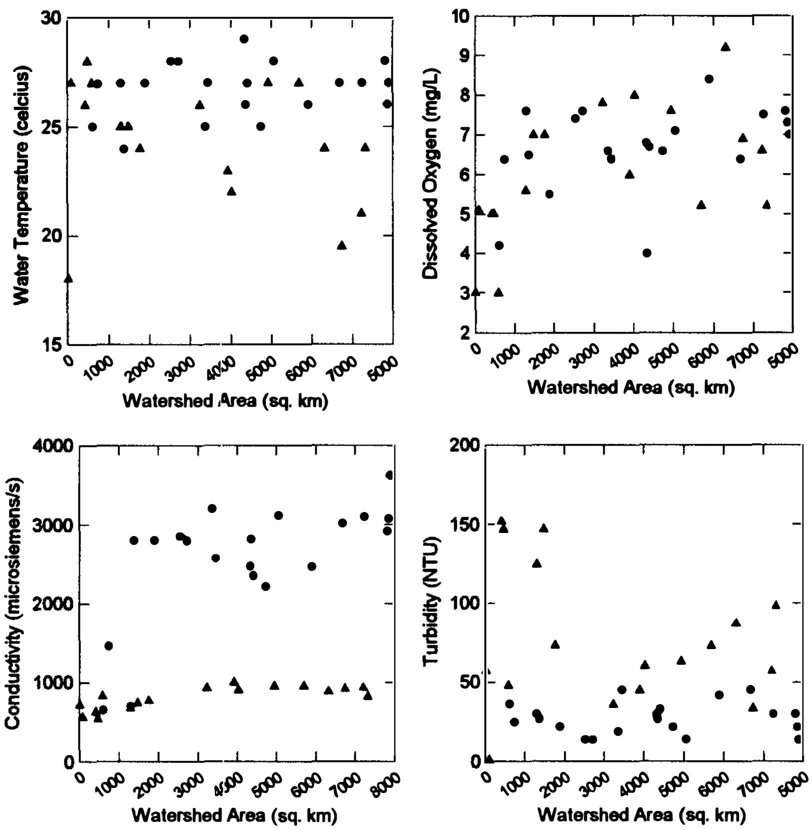


Figure 2-12. Plot of water quality parameters at sampling sites during time of study for the Bad River (●) and Big Sioux River (▲).

Physical traits.--Physical data from the Big Sioux River were collected from sites having watershed sizes ranging from 18 km^2 to 7329 km^2 (Table 2-4) and from the Bad River ranging from 611 km^2 to 7907 km^2 (Table 2-5). Summary statistics show a wide range in physical conditions in both rivers. Streambed substrate in the Big Sioux River showed a shift from silt and sand substrate in the upper sites to sand and gravel in the lower sites (Table 2-6). Streambed substrate in the Bad River revealed no discernable trends (Table 2-7). In general, all sizes of gravel were present and gravel usually dominated, followed by fines (sand and silt). Cobble was found at most reaches, sometimes making up about 10% of the substrate.

Table 2-4. Summary statistics (mean (standard error)) for select physical traits at 17 sites on the Big Sioux River.

	Site									
Trait	1	2	3	4	5	6	7	8	9	10
Watershed area (km^2)	18	93	476	420	591	1300	1476	1759	3230	4027
Bank height (m)	0.75 (0.03)	0.98 (0.07)	1.01 (0.04)	0.97 (0.06)	1.05 (0.07)	1.37 (0.06)	1.51 (0.07)	1.34 (005)	1.73 (0.09)	1.73 (0.07)
Bank angle	172	137	132	145	161	151	151	150	152	158
Bank length (m)	4.41 (0.33)	1.82 (0.26)	2.02 (0.28)	4.48 (0.81)	5.06 (0.58)	3.56 (0.36)	3.90 (0.67)	2.58 (0.17)	3.85 (0.24)	6.72 (1.19)
Bank vegetated (m)	4.31 (0.36)	0.85 (0.13)	1.22 (0.27)	2.43 (0.63)	1.51 (0.26)	1.88 (0.22)	1.67 (0.46)	0.77 (0.08)	1.18 (0.17)	1.52 (0.38)
Bank eroded (m)	0.00 (0.00)	0.35 (0.12)	0.47 (0.09)	0.64 (0.17)	1.81 (0.53)	1.58 (0.25)	1.83 (0.18)	1.70 (0.13)	0.71 (0.27)	0.87 (0.24)
Bank depositional (m)	0.08 (0.08)	0.63 (0.20)	0.33 (0.11)	1.41 (0.39)	1.74 (0.49)	0.10 (0.10)	0.39 (0.39)	0.10 (0.07)	1.99 (0.34)	4.43 (1.17)
Channel top width (m)	8.67 (1.68)	13.90 (4.66)	10.27 (2.16)	17.63 (1.79)	21.63 (2.28)	24.20 (0.74)	17.73 (1.10)	19.37 (1.26)	22.37 (0.61)	32.06 (0.46)
Channel bottom width (m)	1.15 (0.22)	4.54 (0.37)	3.45 (0.16)	5.85 (0.72)	10.85 (1.27)	17.18 (0.41)	12.32 (0.75)	14.21 (0.66)	15.44 (0.56)	22.08 (1.37)
Bankfull width (m)	5.63 (0.52)	6.95 (0.46)	5.71 (0.26)	12.99 (1.13)	18.3 (1.40)	22.32 (0.94)	18.46 (1.34)	17.85 (0.50)	20.99 (0.52)	33.37 (1.70)
Bankfull depth (m)	0.34 (0.01)	0.69 (0.05)	0.65 (0.02)	0.77 (0.74)	0.70 (0.03)	0.90 (0.01)	0.86 (.03)	0.89 (0.02)	15.3 (0.06)	1.20 (0.08)
Stream width (m)	2.73 (0.42)	5.98 (0.38)	4.46 (0.10)	8.49 (0.61)	14.93 (1.46)	20.75 (0.67)	15.88 (0.58)	17.32 (0.50)	17.86 (0.30)	26.56 (1.08)
Stream depth (cm)	15	44	31	19	44	75	57	63	55	43
Water velocity (m/s)	<0.00	0.12	0.33	0.31	0.20	0.45	0.48	0.48	0.39	0.42

Table 2-4 continued. Summary statistics (mean (standard error)) for select physical traits at 17 sites on the Big Sioux River.

	Site						
Trait	11	12	13	14	15	16	17
Watershed area (km)	3919	4941	5701	6324	6744	7213	7329
Bank height (m)	1.66 (0.09)	2.01 (0.08)	2.11 (0.12)	2.50 (0.10)	2.77 (0.13)	2.54 (0.09)	2.70 (0.16)
Bank angle	154	147	150	149	149	151	154
Bank length (m)	4.72 (0.41)	4.71 (0.53)	5.27 (0.31)	8.26 (1.41)	6.54 (0.66)	7.90 (0.63)	7.62 (0.68)
Bank vegetated (m)	1.55 (0.24)	1.75 (0.34)	1.00 (0.15)	1.48 (0.34)	3.07 (0.53)	1.63 (0.21)	2.85 (0.55)
Bank eroded (m)	0.75 (0.23)	0.95 (0.22)	1.18 (0.29)	1.45 (0.35)	0.84 (0.25)	1.38 (0.29)	0.62 (0.18)
Bank depositional (m)	2.38 (0.44)	2.00 (0.42)	3.09 (0.42)	5.33 (1.51)	2.63 (0.34)	4.88 (0.63)	4.15 (0.43)
Channel top width (m)	33.70 (2.55)	29.77 (1.85)	29.23 (2.00)	49.87 (8.37)	41.67 (1.33)	43.10 (0.66)	37.43 (1.24)
Channel bottom width (m)	21.45 (0.80)	15.45 (0.81)	17.16 (0.86)	17.68 (2.10)	24.80 (1.61)	25.08 (1.74)	23.05 (2.26)
Bankfull width (m)	28.98 (1.05)	27.01 (1.41)	28.77 (0.77)	38.12 (2.70)	41.85 (1.10)	42.25 (1.82)	40.25 (1.81)
Bankfull depth (m)	1.16 (0.05)	1.66 (0.07)	1.58 (0.05)	2.11 (0.10)	2.39 (0.15)	2.16 (0.10)	2.38 (0.20)
Stream width (m)	24.68 (0.74)	20.40 (0.74)	22.35 (0.89)	27.10 (1.42)	31.65 (1.47)	34.34 (1.65)	30.88 (1.71)
Stream depth (m)	43	47	53	46	44	49	32
Water velocity (m)	0.47	0.47	0.38	0.37	0.24	0.234	0.29

Table 2-5. Summary statistics (mean (standard error)) for select physical traits at 20 sites on the Bad River.

	Site									
Trait	1	2	3	4	5	6	7	8	9	10
Watershed area (km)	611	743	1302	1378	1893	2536	2720	3372	3450	4333
Bank height (m)	2.96 (0.06)	3.32 (0.45)	3.40 (0.40)	2.96 (0.27)	5.80 (0.30)	4.81 (0.22)	2.93 (0.21)	4.23 (0.70)	4.05 (0.30)	5.85 (0.50)
Bank angle	130 (3)	130 (4)	136 (3)	141 (3)	139 (3)	131 (4)	135 (5)	128 (3)	143 (3)	136 (3)
Bank length (m)	4.33 (0.22)	4.79 (0.46)	6.80 (0.64)	4.87 (0.39)	10.18 (1.00)	10.62 (0.95)	6.13 (0.99)	7.69 (1.32)	10.86 (1.55)	14.34 (1.67)
Bank vegetated (m)	1.69 (0.29)	2.06 (0.40)	3.71 (0.69)	2.03 (0.43)	6.03 (1.20)	6.73 (1.04)	0.85 (0.25)	4.24 (1.08)	5.62 (1.19)	8.80 (1.18)
Bank eroded (m)	1.85 (0.23)	2.50 (0.45)	2.12 (0.49)	2.17 (0.35)	2.75 (0.55)	3.22 (0.36)	2.82 (0.51)	2.87 (0.81)	2.85 (0.46)	2.40 (0.44)
Bank depositional (m)	0.79 (0.20)	0.29 (0.10)	0.96 (0.38)	0.67 (0.22)	1.46 (0.41)	0.68 (0.22)	2.46 (1.15)	0.58 (0.21)	2.39 (0.79)	3.03 (0.95)
Channel top width (m)	9.07 (0.73)	12.83 (017)	15.63 (1.24)	16.17 (3.66)	24.97 (4.44)	29.77 (0.93)	15.17 (1.27)	17.43 (2.47)	29.60 (6.70)	43.27 (2.39)
Channel bottom width (m)	1.96 (0.28)	6.38 (0.54)	5.00 (0.44)	6.29 (0.62)	5.81 (0.63)	4.55 (0.54)	0.76 (0.05)	7.91 (1.21)	6.46 (1.00)	11.30 (1.17)
Bankfull width (m)	4.53 (0.24)	9.88 (0.50)	8.95 (0.35)	10.25 (0.56)	9.76 (0.78)	10.31 (0.82)	13.91 (1.02)	12.62 (0.73)	12.72 (0.63)	21.34 (1.24)
Bankfull depth (m)	0.94 (0.03)	1.15 (0.16)	0.89 (0.07)	1.11 (0.16)	1.36 (0.13)	1.25 (0.06)	1.01 (1.21)	1.29 (0.11)	1.07 (0.14)	1.36 (0.07)
Stream width (m)	3.91 (0.25)	7.75 (0.77)	6.79 (0.36)	7.98 (0.61)	6.93 (0.71)	5.97 (0.52)	7.65 (0.71)	10.20 (0.90)	9.66 (0.86)	14.10 (1.29)
Stream depth (m)	62	59	33	53	47	33	22	45	44	55
Water velocity (m)	0.02	0.01	0.13	0.19	0.08	0.13	0.24	0.25	0.14	0.21

Table 2-5 continued. Summary statistics (mean (standard error)) for select physical traits at 20 sites on the Bad River.

	Site									
Trait	11	12	13	14	15	16	17	18	19	20
Watershed area (km)	4359	4416	4740	5066	5903	6698	7257	7811	7860	7907
Bank height (m)	5.26 (0.83)	4.93 (0.33)	2.61 (0.22)	4.44 (0.58)	3.83 (0.57)	2.90 (0.23)	3.57 (0.27)	3.92 (0.31)	4.91 (0.43)	8.33 (1.64)
Bank angle	146 (4)	126 (2)	143 (3)	152 (4)	140 (5)	131 (4)	138 (3)	138 (3)	133 (3)	130 (3)
Bank length (m)	17.48 (2.57)	7.47 (0.43)	5.34 (0.45)	20.85 (3.10)	9.73 (1.14)	5.56 (0.62)	7.33 (0.67)	8.10 (0.69)	8.42 (0.68)	13.66 (2.25)
Bank vegetated (m)	8.89 (1.38)	4.43 (0.48)	1.68 (0.31)	5.78 (1.77)	5.78 (0.77)	2.72 (0.42)	2.78 (0.56)	5.58 (0.66)	4.68 (0.77)	2.95 (0.95)
Bank eroded (m)	2.15 (0.83)	2.02 (0.31)	1.85 (0.38)	4.78 (1.20)	0.71 (0.16)	1.98 (0.50)	2.76 (0.58)	1.47 (0.33)	2.93 (0.73)	8.29 (2.17)
Bank depositional (m)	6.20 (1.38)	1.02 (0.34)	1.85 (0.45)	10.29 (2.43)	3.19 (1.05)	1.15 (0.47)	1.80 (0.45)	1.05 (0.41)	0.80 (0.26)	2.42 (1.06)
Channel top width (m)	42.77 (10.12)	23.77 (3.28)	23.4 (1.19)	59.1 (8.07)	28.67 (2.80)	24.43 (0.30)	20.67 (0.95)	26.90 (2.19)	29.90 (4.24)	43.33 (8.34)
Channel bottom width (m)	6.88 (0.77)	8.89 (0.85)	5.20 (0.59)	6.78 (1.24)	7.79 (0.97)	8.66 (0.81)	6.58 (0.61)	7.25 (0.97)	6.61 (0.84)	5.95 (0.54)
Bankfull width (m)	14.59 (0.73)	12.75 (0.76)	14.02 (0.90)	26.69 (3.57)	15.92 (0.70)	13.55 (0.57)	14.85 (0.88)	14.45 (1.24)	17.32 (1.56)	16.21 (1.40)
Bankfull depth (m)	0.92 (0.06)	1.26 (0.11)	1.14 (0.04)	0.86 (0.04)	0.89 (0.04)	1.07 (0.05)	1.21 (0.09)	1.16 (0.07)	0.95 (0.07)	1.02 (0.05)
Stream width (m)	8.47 (0.70)	10.95 (0.77)	8.00 (0.46)	9.73 (1.07)	9.40 (0.82)	10.23 (0.73)	8.15 (0.75)	9.23 (0.89)	8.78 (0.86)	8.29 (0.71)
Stream depth (m)	23	57	31	24	21	31	35	28	20	19
Water velocity (m)	0.31	0.07	0.12	0.18	0.16	0.14	0.22	0.18	1.14	0.11

Table 2-6. Streambed substrate (%) for 17 sites on the Big Sioux River.

Substrate	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Detritus	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Clay	0	2	8	4	0	6	2	3	10	5	5	8	14	9	4	1	5
Silt	55	27	34	6	33	12	2	1	9	1	6	1	6	0	0	0	0
Sand	4	37	35	31	23	25	22	27	39	56	62	75	34	51	29	57	50
Very fine gravel	2	11	22	31	14	14	8	20	2	14	0	5	0	0	2	5	3
Fine gravel	0	17	3	20	26	16	33	22	10	6	2	10	18	18	35	10	21
Medium gravel	0	5	1	9	2	3	21	12	10	15	15	5	20	14	16	11	5
Coarse gravel	0	3	1	2	5	5	14	19	0	3	20	0	5	12	0	0	2
Very coarse gravel	0	2	0	1	1	2	1	0	0	4	0	0	7	0	10	3	7
Cobble	0	0	0	0	0	6	1	0	0	0	0	0	0	0	8	12	9
Large Cobble	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1
Boulder	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Large boulder	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1

Table 2-7. Streambed substrate (%) for 20 sites on the Bad River.

Substrate	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Detritus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Clay	104	26	17	12	25	3	2	14	21	14	7	19	25	0	13	2	4	26	0	33
Silt	0	27	15	45	14	1	4	12	3	45	5	26	12	14	12	30	37	3	31	3
Sand	0	9	6	3	3	13	27	15	15	3	18	30	35	26	15	12	26	4	25	3
Very fine gravel	0	1	10	4	0	8	0	4	3	0	14	3	1	5	7	6	11	4	5	0
Fine gravel	0	5	14	9	0	6	4	4	10	4	6	5	11	25	5	6	7	4	3	5
Medium gravel	0	5	19	6	11	21	15	9	10	21	19	3	5	16	17	14	9	22	14	22
Coarse gravel	0	5	10	7	14	10	25	5	6	9	16	3	7	14	10	5	9	21	17	23
Very coarse gravel	0	11	9	6	6	12	22	0	10	6	13	5	8	10	13	11	0	8	9	0
Cobble	0	11	3	11	3	7	5	2	7	1	4	9	0	4	8	10	0	12	0	7
Large Cobble	0	3	1	2	0	0	0	2	2	0	1	2	0	0	2	6	0	0	0	8
Boulder	0	2	0	0	0	0	0	3	0	0	0	0	0	0	1	3	0	0	0	0
Large boulder	0	0	0	0	0	0	0	2	1	1	0	0	0	0	0	0	0	0	0	0

Fish Collections.—In the Big Sioux River, 31 species representing 9 families were collected (Table 2-8). Three of these species were non-indigenous: common carp, white bass, and European rudd. No federally endangered species were sampled. Minnows were the most abundant fishes captured. In the Bad River, 20 species representing 7 families were sampled (Table 2-9). Eight of these species were non-indigenous with several likely introductions: common carp, golden shiner, northern pike, green sunfish, orange-spotted sunfish, bluegill, largemouth bass, and yellow perch. A few hybrid sunfish (green sunfish x bluegill) were collected at six sites. Minnows were the most abundant fish captured.

Table 2-8. Fishes collected and numbers sampled from 17 sites along the Big Sioux River.

Common Name	1	2	3	4	5	6	7	8	9
Minnows									
Central stoneroller	0	2	5	214	3	0	0	0	0
Red shiner	0	0	0	0	0	0	2	0	0
Common carp	0	0	3	2	5	2	4	2	3
Brassy minnow	0	0	0	0	0	0	0	0	0
Common shiner	0	25	40	323	95	5	19	2	0
Emerald shiner	0	0	0	0	1	4	12	16	22
Bigmouth shiner	0	30	41	605	1	0	0	0	0
Spottail shiner	0	0	0	0	0	0	0	0	0
Sand shiner	0	18	33	737	83	41	56	6	49
Bluntnose minnow	0	0	0	0	0	0	0	0	0
Fathead minnow	20	445	195	171	4	1	1	23	9
Blacknose dace	1	10	0	6	0	0	0	0	0
Rudd	0	0	0	0	0	1	0	0	0
Creek chub	18	70	69	283	24	0	4	0	0
Suckers									
White sucker	71	906	68	1352	58	19	6	5	15
Bigmouth buffalo	0	0	0	0	0	0	0	0	0
Shorthead redhorse	0	0	0	27	14	1	1	1	12
Bullhead/Catfishes									
Black bullhead	0	0	11	14	12	11	1	2	0
Channel catfish	0	0	0	0	0	0	0	0	11
Stonecat	0	0	0	0	0	0	3	0	1
Tadpole madtom	0	0	0	0	3	0	0	0	0
Pikes									
Northern pike	0	43	11	0	2	2	4	0	2
Trout-perches									
Trout-perch	0	0	0	0	0	0	0	0	0
Sticklebacks									
Brook stickleback	4	0	0	0	0	0	0	0	0
Temperate Basses									
White bass	0	0	0	0	0	0	0	0	19
Sunfishes									
Green sunfish	0	0	0	0	0	0	0	0	0
Orangespotted sunfish	0	1	0	0	0	0	0	0	0
Perches									
Iowa darter	1	2	2	0	0	0	0	0	0
Johnny darter	1	6	27	476	96	0	0	0	0
Yellow perch	0	43	0	2	7	5	2	5	1
Walleye	0	0	0	0	23	13	3	8	35

Table 2-8 continued Fishes collected and numbers sampled from 17 sites along the Big Sioux River.

Common Name	10	11	12	13	14	15	16	17
Minnows								
Central stoneroller	1	6	4	2	0	0	0	0
Red shiner	4	3	8	12	157	17	43	84
Common carp	5	14	3	5	2	0	0	0
Brassy minnow	0	9	0	0	0	0	0	0
Common shiner	146	104	99	24	3	11	5	6
Emerald shiner	292	93	159	367	89	25	21	57
Bigmouth shiner	55	18	165	5	3	8	0	0
Spottail shiner	0	0	0	3	0	0	0	0
Sand shiner	503	228	249	56	226	67	169	60
Bluntnose minnow	0	0	0	0	1	0	0	0
Fathead minnow	533	58	56	54	29	2	19	34
Blacknose dace	0	6	0	0	0	0	0	0
Rudd	0	0	0	0	0	0	0	0
Creek chub	1	5	12	16	4	0	4	5
Suckers								
White sucker	68	101	5	10	13	1	2	7
Bigmouth buffalo	0	0	0		1			
Shorthead redhorse	19	11	1	15	4	5	7	9
Bullhead/Catfishes								
Black bullhead	0	0	0	0	0	0	0	0
Channel catfish	36	3	9	28	190	294	204	94
Stonecat	0	0	0	0	0	0	0	0
Tadpole madtom	1	0	0	0	0	0	0	0
Pikes								
Northern pike	1	2	1	1	0	0	0	0
Trout-perches								
Trout-perch	0	0	0	0	0	1	0	0
Sticklebacks								
Brook stickleback	0	0	0	0	0	0	0	0
Temperate Basses								
White bass	10	12	11	3	4	4	6	5
Sunfishes								
Green sunfish	0	1	0	0	0	1	0	0
Orangespotted sunfish	0	1	0	2	8	1	0	0
Perches								
Iowa darter	0	0	0	0	0	0	0	0
Johnny darter	1	0	1	0	6	0	0	1
Yellow perch	1	2	0	5	0	0	0	0
Walleye	23	22	4	9	1	0	3	5

Table 2-9. Fishes collected and numbers sampled from 20 sites along the Bad River.

Common Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Mooneyes																				
Goldeye	0	0	0	0	0	1	0	3	0	0	0	2	0	0	0	0	0	0	0	0
Carp and Minnows																				
Red shiner	0	53	172	194	401	780	823	208	1050	265	880	729	654	1661	1259	833	316	248	228	113
Common carp	0	2	2	0	1	1	0	0	4	2	3	1	0	4	1	2	3	1	48	35
Plains minnow	4	103	234	7	1	121	58	81	70	29	227	0	14	65	153	23	16	355	195	117
Golden shiner	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Emerald shiner	0	28	0	0	0	3	2	0	1	1	0	0	0	0	0	0	0	0	0	0
Sand shiner	1	96	166	56	87	93	228	19	67	67	189	24	85	401	71	257	60	117	134	7
Fathead minnow	12	73	68	26	20	79	86	22	5	0	1	0	0	3	5	0	0	0	13	0
Flathead chub	0	0	52	1	0	3	8	0	0	2	0	0	12	127	7	33	107	153	270	196
Suckers																				
River carpsucker	0	0	3	3	5	0	0	3	1	0	2	2	10	42	4	5	32	16	331	22
White sucker	0	2	39	4	3	11	3	9	13	15	6	1	5	9	16	2	0	1	9	4
Shorthead redhorse	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	3	0	0	1	0
Bullhead/Catfishes																				
Black bullhead	5	19	42	5	3	2	0	2	3	0	1	0	6	1	0	2	0	2	1	0
Channel catfish	0	0	41	2	23	15	8	35	29	51	26	35	172	220	49	178	377	485	1143	160
Pikes																				
Northern pike	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Sunfishes																				
Green sunfish	6	119	21	5	1	1	7	0	3	1	10	2	6	2	2	0	1	2	2	0
Orangespotted sunfish	4	28	29	12	65	3	1	19	36	7	4	5	3	0	0	0	0	0	0	0
Bluegill	0	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hybrid	0	0	0	2	1	2	0	0	0	1	1	3	0	0	0	0	0	0	0	0
Largemouth bass	0	0	0	3	0	0	0	0	0	0	0	1	1	0	0	3	0	0	0	0
Perches																				
Yellow perch	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Exploration of Physical Patterns Between Rivers

Using principal components analysis, a longitudinal pattern of physical traits was found in the Big Sioux River that was not found in the Bad River. In the analysis, 20 variables were reduced to 5 principal components (PC), which explained 80% of the variation in the data set (Table 2-10). The most distinguishing pattern was revealed on a plot of PC 2 versus PC 1 (Figure 2-13). The Big Sioux River sites followed a general sequence of physical change that corresponded with watershed size. In the Big Sioux River, channel bottom width, bankfull dimensions, streambank as deposition and sand substrate increased while percent of bank with vegetation and silt substrate decreased. In the Bad River, this pattern did not occur. In contrast to the Big Sioux River, the Bad River sites encompassed a greater range in vertical channel dimensions (i.e., bank length and bank height), and channel top width, but with no distinct correspondence with watershed size.

Comparison of Longitudinal Patterns Between Rivers

Results from ANCOVA indicate that several physical differences exist between rivers that were independent of watershed, and that most variables did not show similar trends with watershed size (Table 2-11). Nine variables had means that were significantly different between rivers (Table 2-12). In the Bad River, bank height, bank length, percent bank erosion, percent clay, percent cobble, and slope were higher. In the Big Sioux River, bank angle, bankfull width:depth ratio, and percent sand were higher. Although the means were different between rivers, 4 of these 9 variables, bank height, bank length, bankfull width:depth ratio, and percent sand increased significantly with watershed size in both rivers (Table 2-13). Two additional variables had means that were not significantly different between rivers, but changed significantly with watershed size: channel top width increased and percent bank slumping decreased (Table 2-13). Percent gravel substrate was the only variable with means that were not different between rivers and showed no relationship with watershed (Table 2-11).

Seven variables had statistically significant interactions between basin and watershed area (Table 2-11), which indicate that a physical trait was similar for some watershed sizes but not all. Bankfull height in the Big Sioux River increased consistently with watershed size, while it remained relatively constant in the Bad River (Figure 2-14). Bankfull depth followed the same pattern (Figure 2-15). Bankfull widths were similar between basin in the smallest watershed sizes but increased at a greater rate in the Big Sioux River than in the Bad River (Figure 2-15). Channel bottom width also increased in both rivers but the Big Sioux River at a greater rate than in the Bad River (Figure 2-14). Percent bank erosion did not show a trend with watershed size and was about the same in both rivers (Figure 2-16). Percent bank as depositional in the Bad River did not show a trend with watershed size but in the Big Sioux River increased with watershed size (Figure 2-16). In both rivers, percent silt substrate was similar in smaller watersheds, showed no trend in the Bad River, and decreased with watershed size in the Big Sioux River (Figure 2-17).

These findings indicate that each river had a unique gradient of physical traits. These gradients can be given descriptions that portray the general differences between the Big Sioux River and Bad Rivers. Three prominent distinctions can summarize the results in terms of systemic-level differences between the Big Sioux and Bad Rivers. First, the Bad River had traits of an incised channel, while the Big Sioux River does not. In the Bad River, banks were higher and steeper, and percent of bank eroded was slightly higher. Second, relative rates of change were generally higher and more consistent for a greater number of physical variables in the Big Sioux River than in the Bad River. Comparatively, as watershed size increases in the Big Sioux River, the channel bottom widens, bankfull width and depth increase, sand substrates and bank deposition became more prominent, and silt substrates declined. In the Bad River, the most consistent change was an increase in channel top width. Other variables like bank height and bank length increased, but were quite variable. The final systemic-level difference between the Bad and Big Sioux River was higher overall slope of the Bad River (Figure 2-18).

Table 2-10. Principal components (PC) and variable loadings for 20 Bad River sites and 17 Big Sioux River sites. Total variance explained in data was 80% (PC1=28.8, PC2=15.2, PC3=12.2, PC4=12.8, PC5=10.7).

Variable	PC1	PC2	PC3	PC4	PC5
Bankfull Depth	**0.92616**	0.13466	0.06866	-0.12396	0.15492
Bankfull height	**0.91541**	0.15968	0.06003	-0.14812	0.17409
Bankfull width	**0.86963**	0.17688	0.05516	0.35448	-0.19463
Channel Bottom Width	**0.85158**	-0.06777	-0.00425	0.34459	-0.17577
Bank as Depositional (%)	**0.78778**	0.02529	0.21464	0.12916	-0.27261
Sand substrate (percent)	**0.69025**	-0.32850	0.11963	0.24346	-0.31747
Bank vegetated (%)	**-0.62761**	0.05029	0.51966	-0.10863	0.09505
Watershed area	**0.55375**	0.59081	0.10499	0.03005	0.10873
Silt substrate (%)	**-0.53586**	-0.18956	0.52287	-0.04275	0.25497
Channel Top Width	0.50681	**0.75455**	0.05388	0.28884	-0.08475
Bank Length	-0.04906	**0.94042**	0.07125	0.09845	0.06739
Bank Height	-0.10012	**0.82562**	-0.10455	-0.29430	0.33787
Eroded Bank (%)	-0.20912	-0.09835	**-0.85803**	-0.03658	0.21888
Bank Slumping (%)	-0.10496	-0.05911	**-0.83452**	-0.20708	-0.00882
Clay substrate (%)	-0.10797	0.14502	-0.30468	**-0.82885**	-0.19428
Bankfull width:depth	0.22948	0.17222	-0.00301	**0.75727**	-0.43686
Gravel substrate(%)	-0.06142	0.28899	-0.45620	**0.61997**	0.14254
Bank angle	0.20931	-0.17988	0.25955	**0.56109**	-0.48756
Slope (%)	-0.20315	0.01997	-0.02237	0.04439	**0.79295**
Cobble substrate (%)	0.14999	0.38031	-0.02430	-0.06484	**0.68683**

Table 2-11. Analysis of covariance test results for physical attributes in the Bad and Big Sioux rivers. Basin membership was the categorical variable and watershed area was the co-variable. If a test did not have a significant interaction between basin and watershed area, then the test was performed a second time without the interaction term.

Variable	Sources of Variation	F-ratio	P
	Channel dimensions		
Bank height	Basin	52.23	0.0000
	WA	11.26	0.0019
Bankfull height	Basin	46.74	0.0000
	WA	112.48	0.0000
	Basin*WA	130.30	0.0000
Bank angle	Basin	30.46	0.0000
	WA	0.15	0.6961
Bank length	Basin	12.11	0.0013
	WA	6.62	0.0146
Channel top width	Basin	0.91	0.3467
	WA	30.15	0.0000
Channel bottom width	Basin	0.65	0.4253
	WA	45.60	0.0000
	Basin*WA	28.06	0.0000
	Bankfull dimensions		
Bankfull width	Basin	0.20	0.6565
	WA	106.35	0.0000
	Basin*WA	35.61	0.0000
Bankfull depth	Basin	34.78	0.0000
	WA	101.63	0.0000
	Basin*WA	114.96	0.0000
Bankfull width:depth	Basin	12.85	0.0010
	WA	4.44	0.0424
	Streambank conditions		
Bank vegetated (%)	Basin	1.78	0.1907
	WA	3.17	0.0839
	Basin*WA	7.94	0.0081
Bank eroded (%)	Basin	4.16	0.0491
	WA	2.99	0.0927
Bank as depositional (%)	Basin	0.14	0.7155
	WA	18.63	0.0001
	Basin*WA	13.23	0.0009

Table 2-11. Analysis of covariance test results for physical attributes in the Bad and Big Sioux rivers. Basin membership was the categorical variable and watershed area was the co-variable. If a test did not have a significant interaction between basin and watershed area, then the test was performed a second time without the interaction term.

Variable	Sources of Variation	F-ratio	P
Bank slumping (%)	Basin	0.82	0.3708
	WA	4.44	0.0424
	Streambank Substrate		
Clay substrate (%)	Basin	7.39	0.0102
	WA	2.05	0.1611
Silt substrate (%)	Basin	1.14	0.2925
	WA	4.30	0.0457
	Basin*WA	6.11	0.0187
Sand substrate (%)	Basin	38.89	0.0000
	WA	9.14	0.0047
Gravel substrate (%)	Basin	0.01	0.8995
	WA	0.57	0.4544
Cobble substrate (%)	Basin	6.29	0.0170
	WA	3.18	0.0833
	Water Surface Slope		
Water surface slope (%)	Basin	10.93	0.0022
	WA	2.10	0.1559

Table 2-12. Physical attributes that were significantly different (P<0.05) between the Bad and Big Sioux Rivers.

Variable	BAD Mean (SE)	BSR Mean (SE)
Bank height	4.3 (0.3)	1.7 (0.16)
Bank length	9.2 (0.99)	4.9 (0.48)
Bank angle	136.2 (1.5)	150.6 (2.2)
Bankfull width:depth ratio	13.7 (1.2)	19.4 (1.3)
Bank eroded (%)	35.6 (2.5)	28.0 (3.8)
Clay (%)	18.4 (4.9)	5.1 (0.96)
Sand (%)	14.5 (2.3)	38.2 (4.1)
Cobble (%)	6.8 (1.1)	2.4 (1.1)
Water surface slope (%)	0.14 (0.02)	0.06 (0.01)

Table 2-13. A list of physical attributes that change significantly (P<0.05) with watershed area in the Bad and Big Sioux Rivers.

Variable	Direction of change
Bank height	+
Bank length	+
Channel top width	+
Bankfull width:depth ratio	+
Bank slumping (%)	-
Sand (%)	+

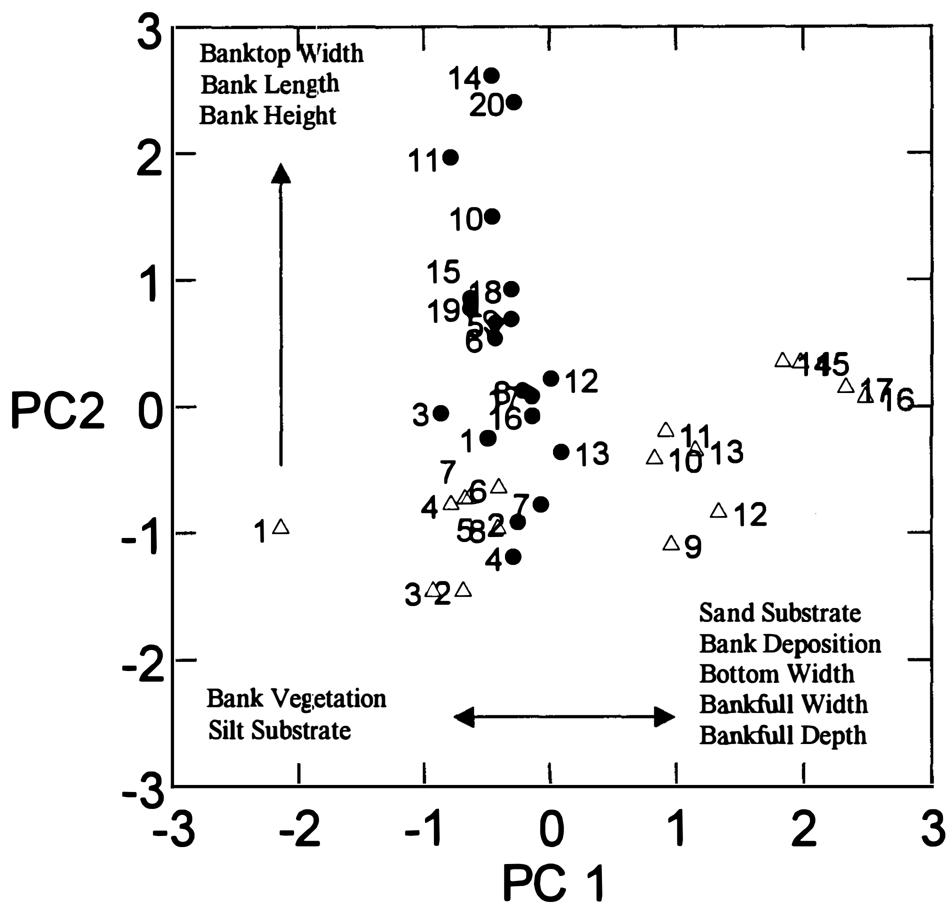


Figure 2-13. A plot of principal component 2 (PC2) against principal component 1 (PC1) showing physical separation between the Bad River (filled circles) and the Big Sioux River (open triangles). Points are labeled with rankings of watershed size within each basin with 1 being the smallest.

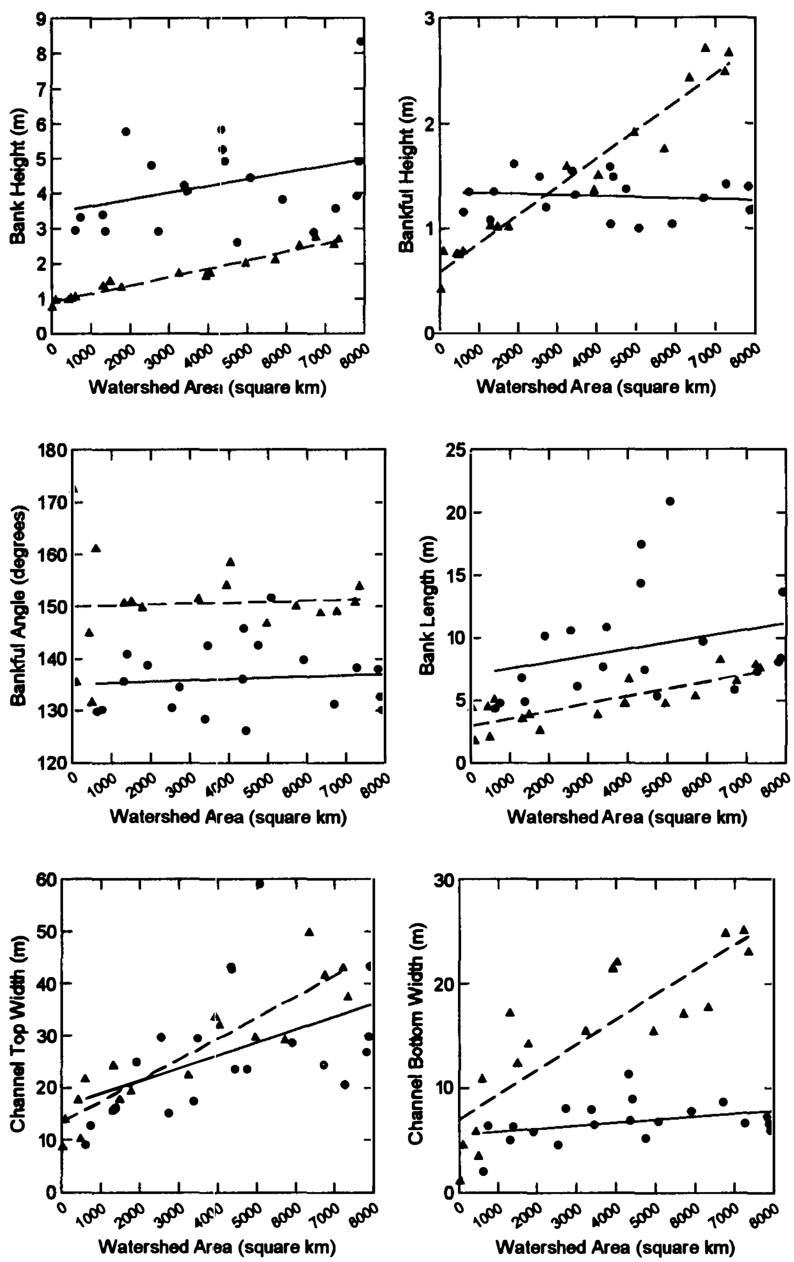


Figure 2-14. Plots of analysis of covariance test data related to channel morphometry from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line and triangles).

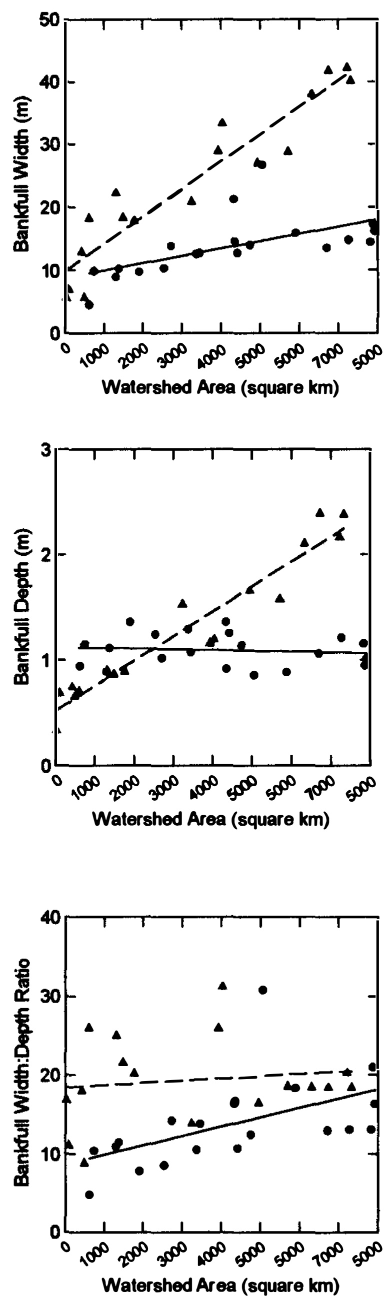


Figure 2-15. Plots of analysis of covariance test data related to bankfull dimensions from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line and triangles).

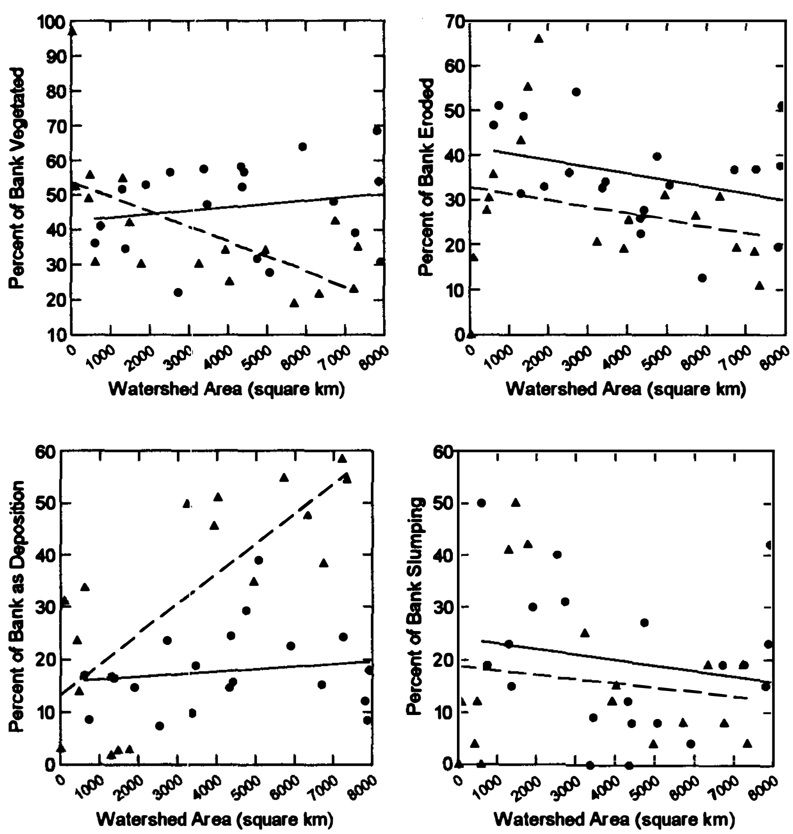


Figure 2-16. Plots of analysis of covariance test data related to bank stability from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line and triangles).

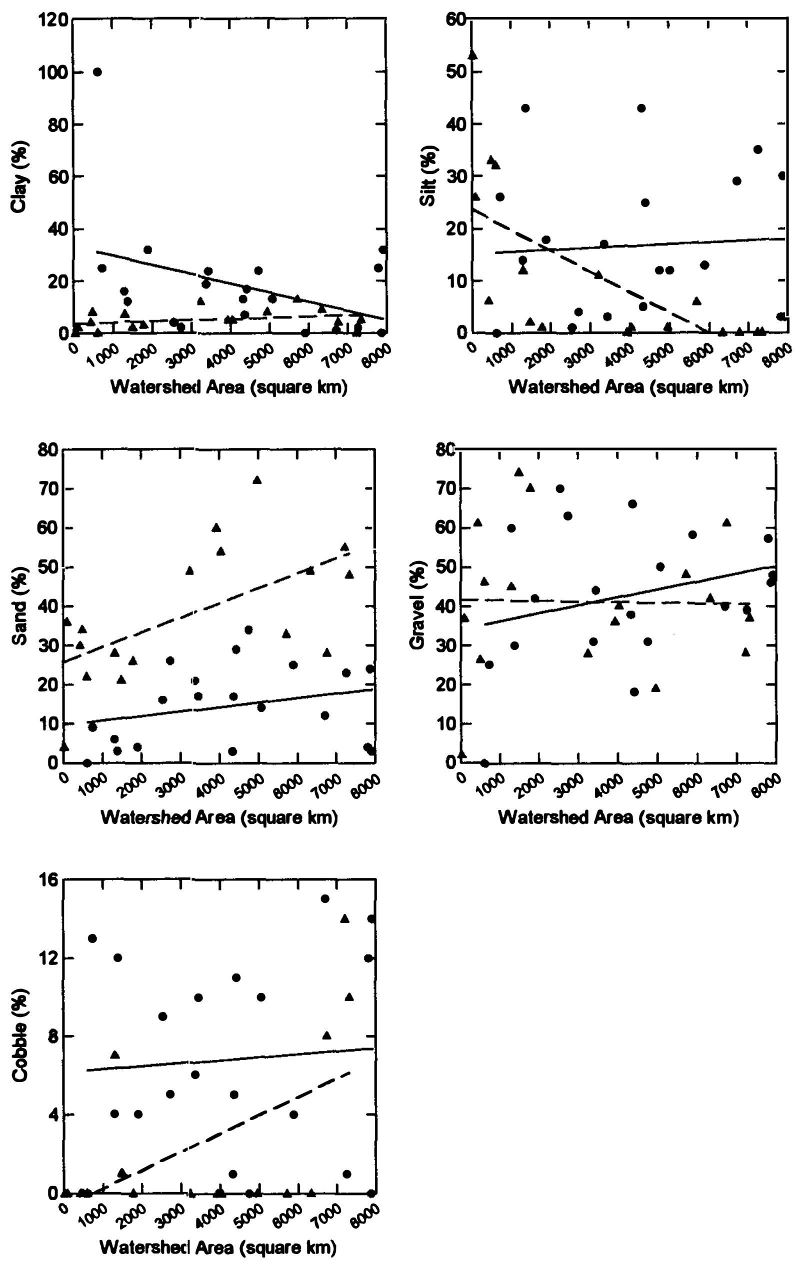


Figure 2-17. Plots of analysis of covariance test data related to substrate from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line and triangles).

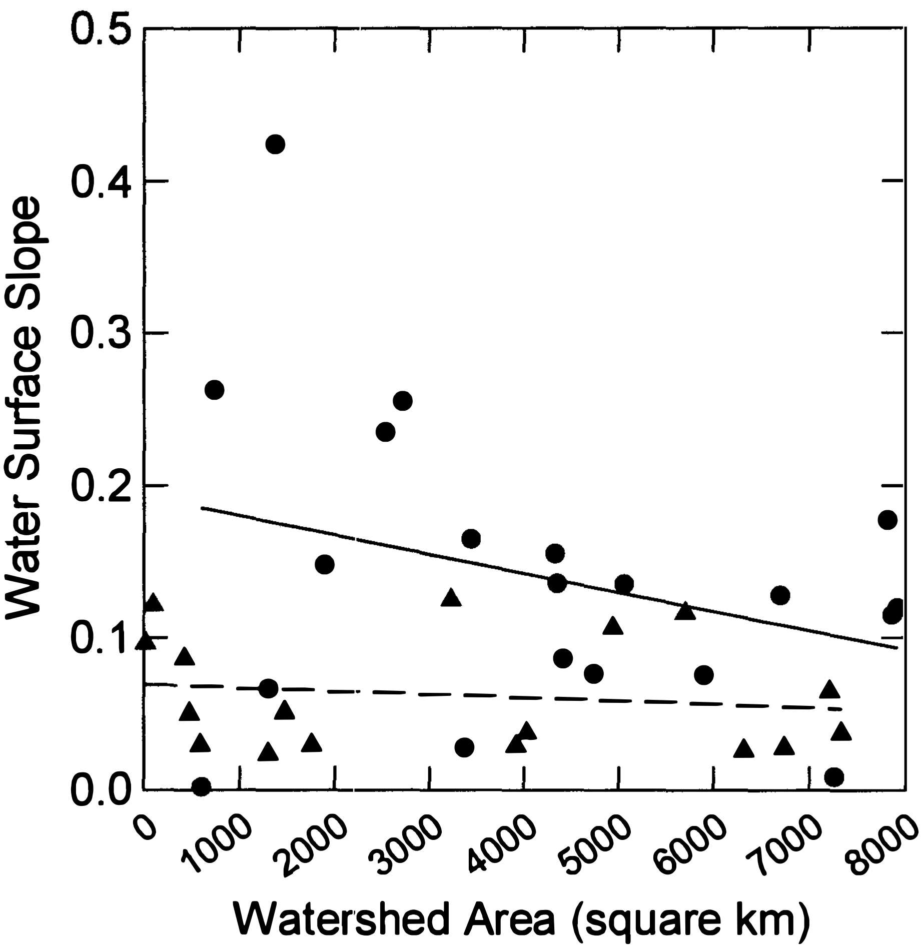


Figure 2-18. Plots of analysis of covariance test data for water surface slope from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line

Comparison of Fish Communities between Rivers

Results from ANCOVA found that several fish community attributes were significantly different between rivers, that some attributes shared similar relationships with watershed size, and that some attributes had different relationships with watershed size between basins (Table 2-14). These differences are described below by groups of fish community attributes.

Species richness.--Five of six species richness attributes were significantly higher in the Big Sioux River than in the Bad River (Table 2-15). The number of benthic species in the Big Sioux River was higher in smaller watershed sizes but decreased and approached the lower numbers found in the Bad River (Figure 2-19).

Headwater/pioneering species.--In the headwater/pioneering group of attributes, distinct differences and similarities between rivers were found (Table 2-14). In the Bad River, headwater species were non-existent, and in the Big Sioux River they were high in small watersheds and declined to one or no species as watershed size increased (Figure 2-20). In the Big Sioux River, the relative proportions of individuals and biomass as headwater species were clearly highest in watersheds less than 600 km^2. In both rivers, the proportions of individuals and biomass of pioneer species were similarly higher in smaller watersheds and declined with watershed size (Figure 2-21).

Intolerant/tolerant species.--In the intolerant/tolerant group, attributes related to intolerant species were not significantly different between basins (Table 2-14). The number of sensitive species and proportion of individuals as sensitive species were higher in the Big Sioux River (Figure 2-22). In both rivers, the proportion of biomass as sensitive species were low in small watershed, remained low in the Bad River and increased with watershed size in the Big Sioux River. In both rivers, the proportion of biomass as tolerant species was high and decreased with watershed size (Figure 2-23). The proportion of individuals as tolerant was also high in both rivers and decreased with watershed size (Figure 2-23), but on average the proportion of individuals as tolerant was higher in the Bad River (Table 2-15). Although green sunfish numbers and biomass were high at two upper sites in the Bad River, both rivers otherwise had very low numbers (Figure 2-23).

Trophic guilds.--In the trophic groups, the proportion of biomass for each trophic guild revealed more clear relationships than the proportion of individuals for each guild. In the Big Sioux River, the average biomass of predators and omnivores were significantly higher than in the Bad River (Table 2-15). In contrast, in the Bad River, the average biomass of insectivores and herbivores was higher than in the Big Sioux River (Table 2-15). In both rivers, inverse trends in insectivore and ominvore biomasses were found (Table 2-16). In both rivers, the proportion of biomass as insectivores increased with watershed size (Figure 2-24), while the proportion of biomass as omnivores decreased (Figures 2-25). No trends in herbivores was shown for either river (Figure 2-26)

Lithophilic species.—In the Big Sioux River, the proportion of biomass as lithophilic species was much higher than in the Bad River (Table 2-15). In the Big Sioux River, there was a trend for proportion of individuals as lithophilic species to decline with watershed area (Figure 2-27).

Table 2-14. Analysis of covariance test results for fish community attributes in the Bad and Big Sioux rivers. Basin membership was the categorical variable and watershed area (WA) was the co-variable. If a test did not have a significant interaction between basin and WA, then the test was performed a second time without the interaction term.

Variable	Sources of Variation	F-ratio	P
	Species Richness and Composition		
Total species richness	Basin	9.47	0.0041
	WA	0.51	0.4766
Native species richness	Basin	36.69	0.0000
	WA	1.76	0.1922
Native minnow richness	Basin	15.09	0.0004
	WA	1.10	0.3013
Water column species richness	Basin	1.10	0.3000
	WA	0.20	0.6522
	Basin*WA	6.61	0.0148
Benthic species richness	Basin	14.25	0.0006
	WA	0.36	0.5489
	Basin*WA	5.61	0.0238
Benthic insectivore richness	Basin	34.39	0.0000
	WA	0.00	0.9702
	Headwater and Pioneer Community Attributes		
Number of headwater species	Basin	22.33	0.0000
	WA	6.24	0.0176
	Basin*WA	6.24	0.0176
Proportion of individuals as headwater species	Basin	9.85	0.0035
	WA	5.63	0.0235
	Basin*WA	5.63	0.0235
Proportion of biomass as headwater species	Basin	10.92	0.0022
	WA	6.82	0.0134
	Basin*WA	6.82	0.0134
Proportion of individuals as pioneer species	Basin	2.52	0.1214
	WA	24.11	0.0000
Proportion of biomass as pioneer species	Basin	1.21	0.2789
	WA	22.48	0.0000
	Intolerant/Tolerant Attributes		
Number of intolerant species	Basin	1.26	0.2683
	WA	3.01	0.0916

Table 2-14. Analysis of covariance test results for fish community attributes in the Bad and Big Sioux rivers. Basin membership was the categorical variable and watershed area (WA) was the co-variable. If a test did not have a significant interaction between basin and WA, then the test was performed a second time without the interaction term.

Variable	Sources of Variation	F-ratio	P
Proportion of individuals as intolerant species	Basin	1.84	0.1831
	WA	1.56	0.2187
Proportion of biomass as intolerant species	Basin	2.46	0.1259
	WA	0.24	0.6263
Number of sensitive species	Basin	40.45	0.0000
	WA	0.18	0.6684
Proportion of individuals as sensitive species	Basin	18.85	0.0001
	WA	0.12	0.7269
Proportion of biomass as sensitive species	Basin	0.39	0.5334
	WA	5.00	0.0321
	Basin*WA	6.42	0.0161
Proportion of individuals as green sunfish	Basin	12.25	0.0013
	WA	6.97	0.0125
	Basin*WA	7.13	0.0116
Proportion of biomass as green sunfish	Basin	10.59	0.0026
	WA	5.22	0.0287
	Basin*WA	6.00	0.0197
Proportion of individuals as tolerant	Basin	19.71	0.0000
	WA	18.10	0.0001
Proportion of biomass as tolerant	Basin	0.58	0.4481
	WA	27.26	0.0000
	Trophic Guilds		
Proportion of individuals insectivorous minnows	Basin	2.61	0.1148
	WA	1.74	0.1956
Proportion of biomass as insectivorous minnows	Basin	2.16	0.1509
	WA	3.26	0.0799
	Basin*WA	9.98	0.0033
Proportion of individuals as insectivores	Basin	12.51	0.0012
	WA	20.64	0.0001
	Basin*WA	7.51	0.0098
Proportion of biomass as insectivores	Basin	13.34	0.0009
	WA	4.17	0.0490

Table 2-14. Analysis of covariance test results for fish community attributes in the Bad and Big Sioux rivers. Basin membership was the categorical variable and watershed area (WA) was the co-variable. If a test did not have a significant interaction between basin and WA, then the test was performed a second time without the interaction term.

Variable	Sources of Variation	F-ratio	P
Proportion of individuals as predators	Basin	8.15	0.0072
	WA	0.42	0.5167
Proportion of biomass as predators	Basin	10.27	0.0029
	WA	0.04	0.8252
Proportion of individuals as omnivores	Basin	18.16	0.0001
	WA	20.58	0.0000
	Basin*WA	8.01	0.0078
Proportion of biomass as omnivores	Basin	12.72	0.0011
	WA	8.18	0.0071
Proportion of individuals herbivores	Basin	18.66	0.0001
	WA	0.18	0.6679
Proportion of biomass as herbivores	Basin	17.57	0.0001
	WA	0.69	0.4102
	Simple Lithophils		
Proportion of individuals as simple lithophils	Basin	54.06	0.0000
	WA	7.61	0.0093
	Basin*WA	5.41	0.0263
Proportion of biomass as simple lithophils	Basin	61.18	0.0000
	WA	0.05	0.8181

Table 2-15. A list of fish community attributes that were significantly different (P<0.05) between the Bad and Big Sioux rivers.

Metric	BAD Mean (SE)	BSR Mean (SE)
Number of species	11.2 (0.4)	13.8 (0.8)
Number of native species	8.2 (0.3)	12.5 (0.7)
Number of native minnows	4.5 (0.2)	6.4 (0.5)
Number of benthic insectivores	1.8 (0.2)	3.5 (0.2)
Proportion of biomass as insectivores	62.4 (4.4)	35.2 (5.4)
Proportion of biomass as omnivores	25.0 (3.7)	48.4 (5.0)
Proportion of individuals as predators	0.08 (0.05)	5.4 (1.9)
Proportion of biomass as predators	3.9 (2.0)	16.3 (3.4)
Proportion of individuals as herbivores	9.8 (1.9)	0.6 (0.3)
Proportion of biomass as herbivores	8.7 (1.8)	0.1 (0.09)
Proportion of individuals as intolerant	0.05 (0.04)	0.3 (0.2)
Number of sensitive species	0.4 (0.1)	1.4 (0.1)
Proportion of individuals as sensitives	0.09 (0.04)	2.0 (0.5)
Proportion of biomass as lithophils	8.6 (2.4)	49.3 (4.7)

Table 2-16. A list of fish community attributes that were similarly and significantly related to watershed area in the Big Sioux and the Bad Rivers.

Metric	Direction
Proportion of individuals as pioneers	-
Proportion of biomass as pioneers	-
Proportion of biomass as insectivores	+
Proportion of biomass as omnivores	-
Proportion of individuals as tolerant	-
Proportion of biomass as tolerant	-

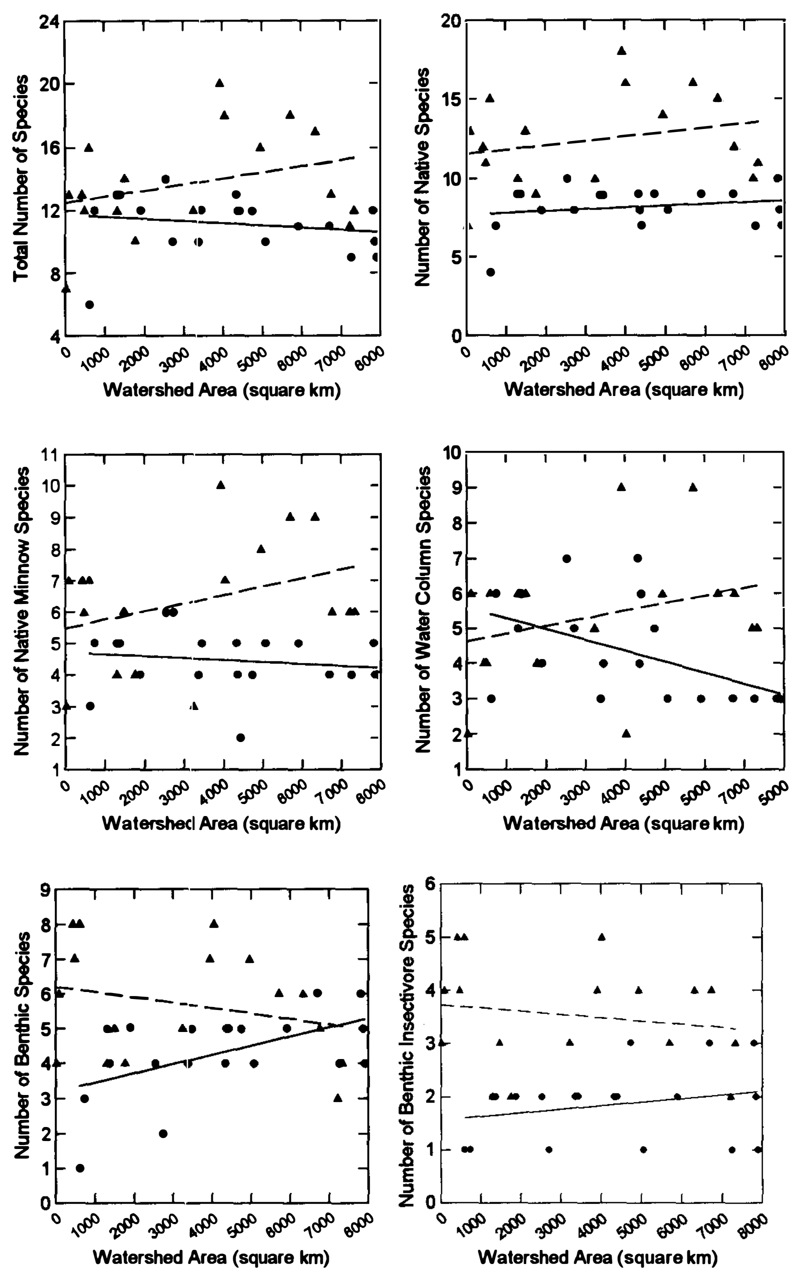
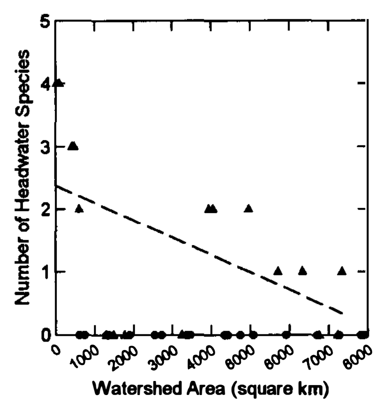


Figure 2-19. Plots of analysis of covariance test data for species richness attributes from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line and triangles).



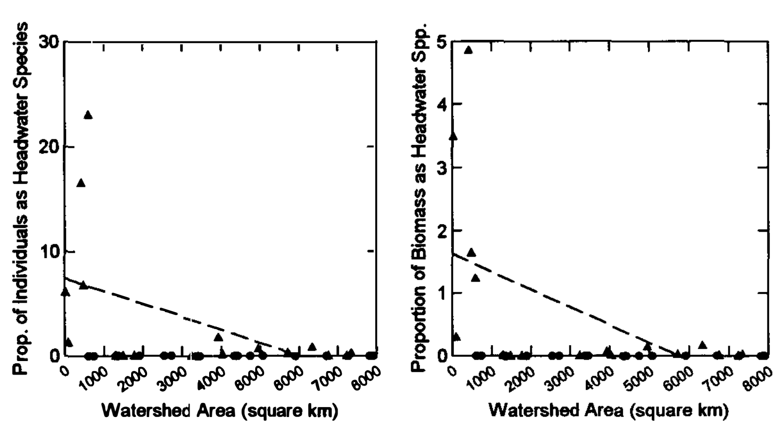
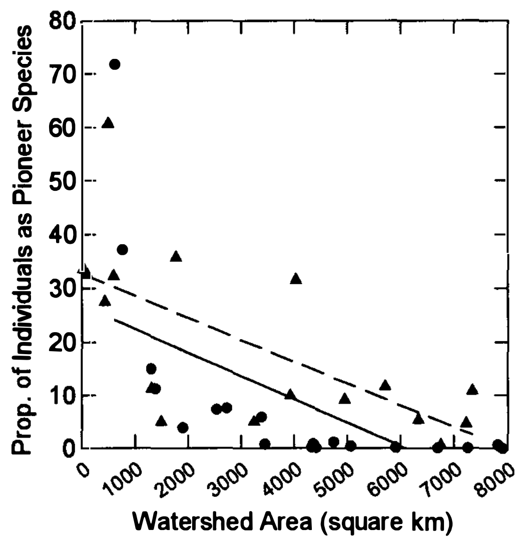


Figure 2-20. Plots of analysis of covariance test data for attributes of headwater species from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line and triangles).



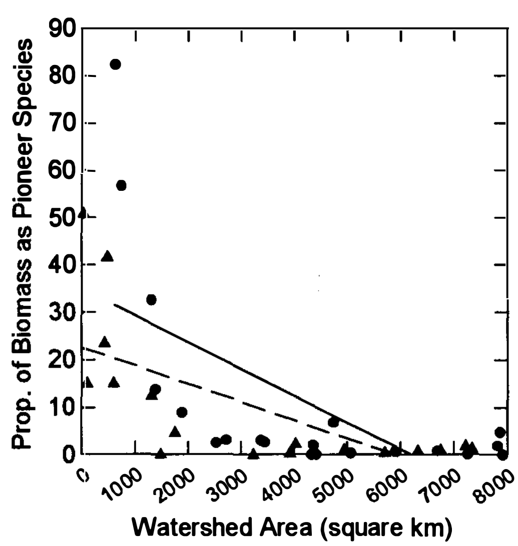


Figure 2-21. Plots of analysis of covariance test data for attributes of pioneering species from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line and triangles).

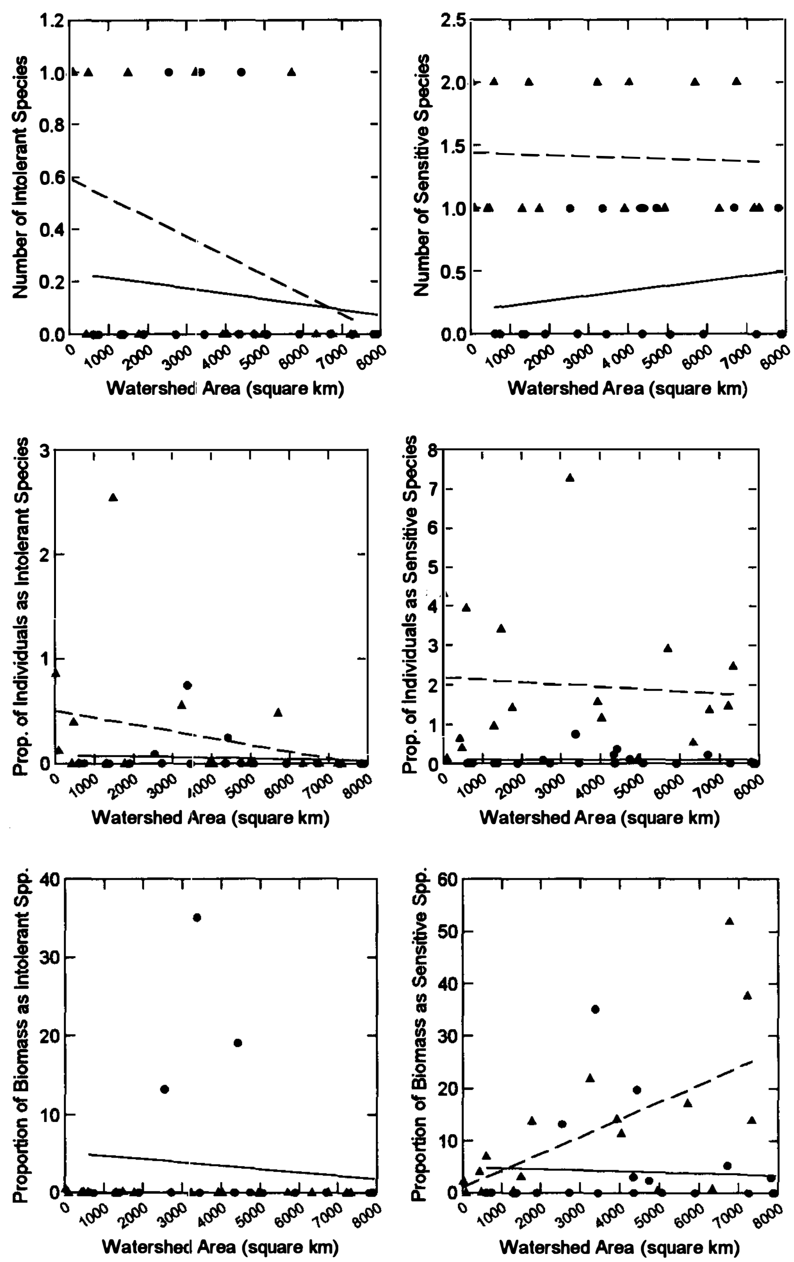


Figure 2-22. Plots of analysis of covariance test data for attributes of intolerant and sensitive species from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line and triangles).

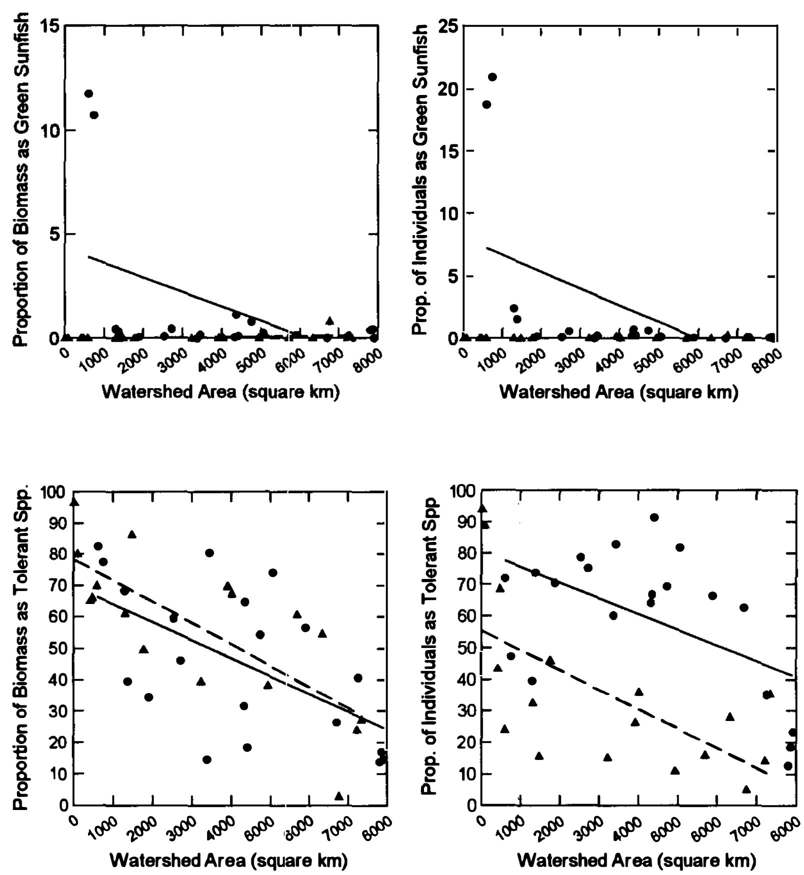


Figure 2-23. Plots of analysis of covariance test data for green sunfish and tolerant species from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line and triangles).

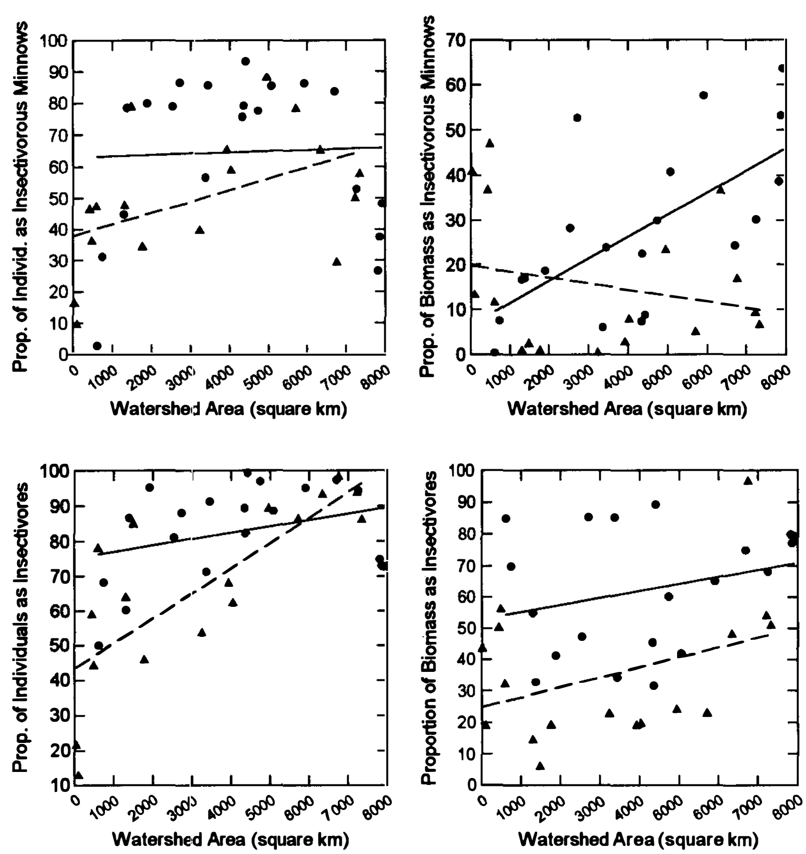


Figure 2-24. Plots of analysis of covariance test data for insectivorous guilds from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line and triangles).

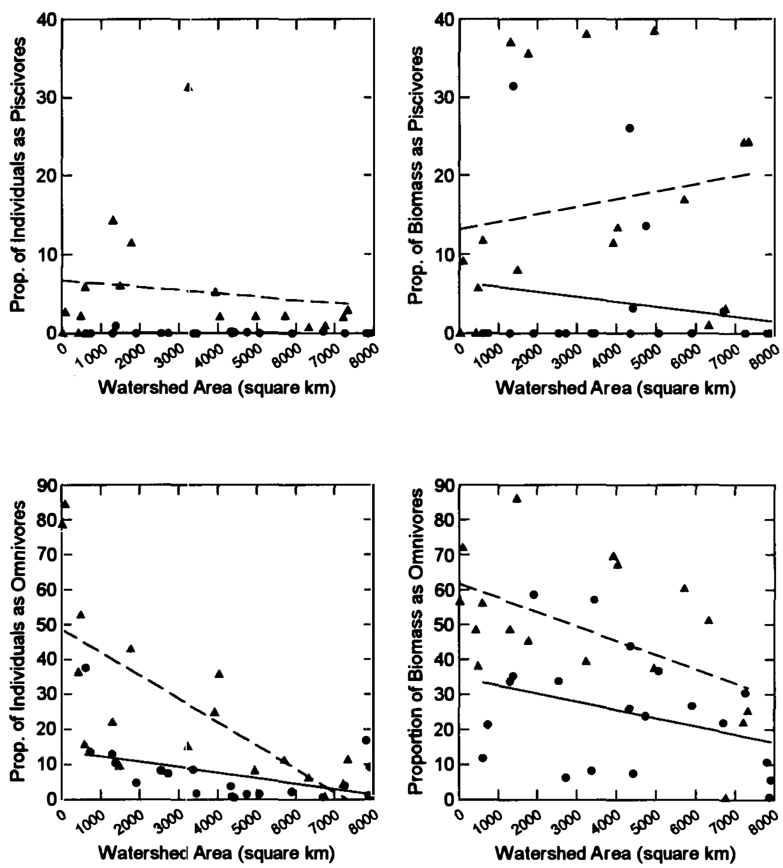


Figure 2-25. Plots of analysis of covariance test data for omnivorous and piscivorous guilds from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line and triangles).

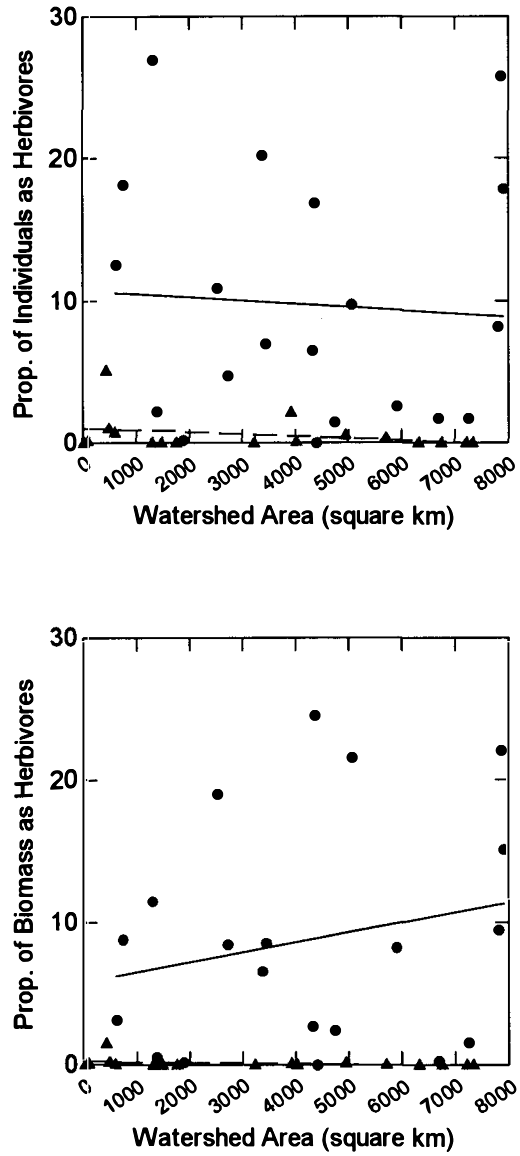
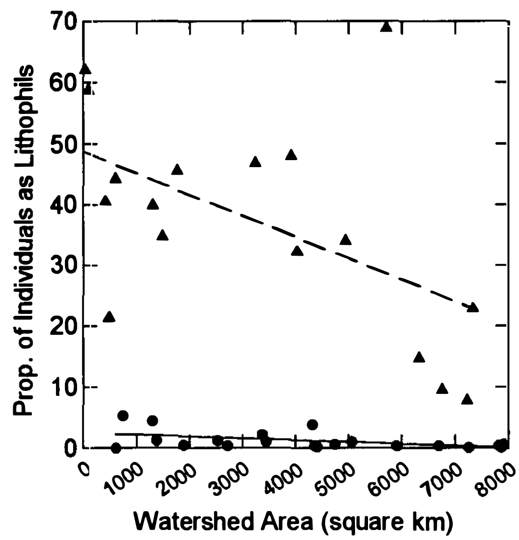


Figure 2-26. Plots of analysis of covariance test data for herbivorous guilds from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line and triangles).



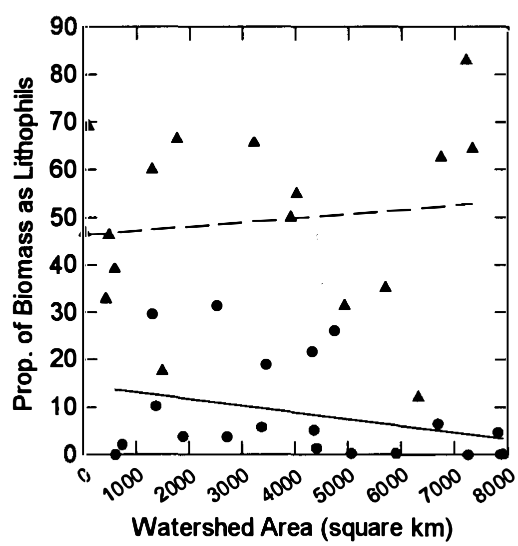


Figure 2-27. Plots of analysis of covariance test data for lithophil species from 20 sites in the Bad River (solid line and circles) and 17 sites in the Big Sioux River (dashed line and triangles).

Discussion

The RCC is strongly based on the principles of fluvial geomorphology, whereby the structure and function of the biological communities conform to physical patterns and processes (Vanotte et al. 1980). In the Great Plains region, the environment has been described as one where the RCC does not fit very well (Brussock et al . 1985), and that "harsh" conditions limit specializations to the physical environment (Poff and Ward 1989). The ability of fish to persist suggests generalized adaptations and tolerances that preclude the need for specific habitat conditions (Matthews and Hill 1980; Ross et al. 1985; Bart 1989; Fausch and Bramblett 1991; Walsh 1992; Bratten 1983). Although specific habitat conditions may not be required for most fishes, the ability of fish structure and function to conform to generalized habitat conditions along a river continuum cannot be dismissed. My findings suggest that rather than dismiss the RCC as a useful model for Great Plains rivers, comparisons of the physical system and biological communities of Great Plains rivers provide insight into the scale at which physical patterns and processes require closer scrutiny by managers and researchers.

I identified systemic-level patterns at three broad scales that influenced differences in physical structure and fish community traits between the semi-arid Bad River and the sub-humid Big Sioux River. The first is related to geology at a large-spatial scale that necessarily sets the physical template for observed gradients. The second is related to regional climate controls on streamflow patterns and variability, which directly influence fish community structure and function. The third is related to in-channel sediment and water transport processes that directly define structural traits of observed continua.

Physical Background

Within each river system parent geology governs watershed-level patterns. For example, in the Bad River, the parent material of Pierre shale results in the higher percentage of clay found in the bed and banks. Also, the higher slope in the Bad River accounts for the higher percentage of cobble. In contrast, in the Big Sioux River, the glacial till parent material and lower slope account for the higher percentage of sand. Cobble can be an important substrate for periphyton and macroinvertebrate diversity and production while shifting sand can actually impede diversity and production (Allan 1995). Thus, these substrate differences may partially explain why insectivores comprise a significantly higher proportion of fishes in the Bad River and omnivores comprise a significantly higher proportion of fishes in the Big Sioux River. Insectivores generally rely on a stable invertebrate food base, and omnivores usually become dominant when the food base becomes unstable (Karr et al. 1986).

Streamflow Effects

Although physical structure at the systemic level can influence biological communities, in the Great Plains region, climatic conditions subject biological communities to dramatically fluctuating environments (Fausch et al. 1991; Stanley and Fisher 1992). A conceptual model for streamflow patterns and variability (Poff and Ward 1989) provides a larger context within which to understand biological communities in fluctuating environments. Supported by much research, it illustrates how biological communities in highly fluctuating flow environments with extended periods of intermittency are trophically simple, have lower species richness, and fewer specialists compared to more stable flow environments with more perennial flows.

Similarly, I identified a set of fish community attributes in the semi-arid Bad River that were typical of the harsher flow conditions while those in the Big Sioux River were typical of more benign conditions. In essence, the Bad River has a fish community that is a subset of that in the Big Sioux River. For example, in the upper reaches of the Big Sioux River, headwater species and pioneering species were found, but in the upper reaches of the Bad River only pioneering species were found. This indicates that streamflows in the headwaters of the Bad River cannot support a permanent although sometimes isolated headwater guild of fishes. However, stream flows in the mid reaches and perhaps habitat refugia allow for the persistence of pioneering species and upstream colonization of headwater reaches. In a very similar way, intolerant and sensitive species exist in the Big Sioux River, but in the Bad River intolerant species are absent and only sensitive species are present. The absence of intolerant species in the Bad River portrays the greater extremes in environmental conditions than that found in the Big Sioux River, but the presence of sensitive species indicates that some community resistance to these extremes is present. Finally, trophic complexity in the Big Sioux River was higher as exemplified by the more diverse predatory component of the fish community. In the Big Sioux River, walleye, channel catfish, and northern pike are common, but in the Bad River only the channel catfish is common.

Some of the findings in this study do not match that expected in the conceptual model linking fish community specialization to flow patterns (Poff and Ward 1989). One expectation is that specialization would be higher in a river with more stable, perennial flows. Given the harsher flow conditions in the Bad River compared to the Big Sioux River, the level of omnivory in the fish community might be expected to be higher and the level of herbivory lower. However, in the Bad River, the level of omnivory was lower and the level of herbivory was higher.

At least two explanations may account for the disparity from the conceptual model. First, the model does not account for physical habitat differences, either natural or altered, that could influence the food chain. As I describe above, the shifting sand in the Big Sioux River may create an unstable food base, which would induce omnivory, and the coarse substrate in the Bad River may influence periphyton production and thus induce herbivory. Second, the model does not account for water quality differences, again either natural or altered, that could influence the food chain. Although the Bad River does discharge large amounts of sediment during high flows, most of the sediment comes from the lower part of the watershed (USDA 1998). Furthermore, I found that during base flows the turbidity of the water was less throughout its length when compared to the Big Sioux River, which has been identified as being impaired by total suspended solids (DENR 1996). Lower turbidity at base flows may allow for light penetration, which would provide the primary productivity directly necessary for herbivory and indirectly for insectivory.

In the discussion above, I describe how the geologic-climatic setting has an effect on the background traits of physical habitat and fish communities of a semi-arid prairie stream in western South Dakota and a sub-humid prairie stream in eastern South Dakota.

Gaining an understanding of these background traits by comparing rivers allows researchers to begin to isolate the physical imprint of sediment and water transport processes unique to each system, and to assess how human impacts have altered these unique processes.

In-channel Patterns

Physical channel structure at any point along the longitudinal axis of any river can be defined as the outcome of dominant channel-forming processes of sediment and water transport at that point (Leopold 1964). I found that the physical channel structure of both rivers reflected unique systemic level differences in the transport of sediment and water. In a sub-humid river, the longitudinal changes in physical characteristics reflect an increase in lateral migration and a decrease in down-cutting, which is characterized by a decrease in stream power relative to increases in critical power (Bull 1979). With this shift, a wider channel, increases in net deposition along the bank, and a sand bedload, as I found, are typical. Compared to the Big Sioux River, the Bad River showed patterns of little longitudinal change in physical traits, which suggest sediment and water transport are similar longitudinally. In fact, channel bottom width and bankfull width were quite consistent along the river, which suggests not only a lack of lateral migration, but only slight increases in bankfull discharges. Furthermore, the seemingly random appearances in some physical channel dimensions could be the effects of disrupted transport processes caused by channel incision and the upstream movement of nick-points that have occurred in the past (USDA 1998). Also, the banks of the Bad River were dominated by hard clay, which is resistant to erosion, and could slow the rate of lateral migration that typically occurs after down cutting is complete (Schumm et al. 1984). In terms of dominant channel forming processes, the Big Sioux River structure reflects one dominated by down cutting in the upper reaches to one dominated by lateral migration in the lower reaches of the study area. In contrast, the Bad River structure reflects one that has been dominated by down cutting.

Because biological communities in the Big Sioux River were subjected to more greater longitudinal changes in stream size, habitat volume, and substrate than in the Bad River, community structure and function were expected to show more prominent changes than in the Bad River. However, the results are not as clear as the effects of streamflow on community structure. For example, with the substantial increase in stream size and habitat volume with watershed size in the Big Sioux River, overall increases in species richness, number of minnow species, and number of water column species should increase with watershed size (Fausch et al.1984; Karr et al. 1986). Although my study did not show the expected increase, an earlier study of the Big Sioux River that included more of the lower watershed showed a distinct increase in total species richness and number of minnow species with watershed size (Milewski et al. In press). In this study, the number of native species sampled in the lower three Big Sioux River sites declined noticeably below that of the previous sites, which may have obscured typical relationships. Because no large changes in physical habitat conditions were obvious, I can only presume that sampling became inefficient or that other unexplained changes in the environment (e.g.; water quality) caused this decline.

Conclusion

By integrating streamflow theory into river continuum theory, knowledge of the systemic controls on the physical habitat and on flow regime can be translated to a biological analog as suggested by the RCC. My findings suggest that a biological analog to the physical system in these prairie streams has utility in defining fish community structure and function as long as flow regime is considered part of the physical system. In many ecological respects, the entire Bad River continuum is analogous to an abbreviated portion of the middle Big Sioux River continuum. For example, fish community attributes present in the upper and lower reaches of the Big Sioux River are absent from the upper and lower reaches of the Bad River. While prairie streams in more humid Midwest regions lack the forested, cold water element of the RCC as pointed out by Wiley et al. (1990), prairie streams in subhumid regions exhibit a further truncation of the RCC when comparing the physical and biological structure. As the environment becomes semiarid, further truncation of the upper part of the RCC occurs; but an additional response also can be defined. In semi-arid environments, what at first appears to be a general randomness or lack of uniform, longitudinal change in the physical and biological structure can be conceptualized as a system that has fewer but longer river segments that also show little uniform changes. This would take into account the seemingly lack of diversity or lack of pattern in fishes. That is, rivers that exhibit a uniform continuum of measurable change also have greater heterogeneity of subunits, i.e., segments, than one that does not show clear and obvious changes on the longitudinal axis.

Management and Research Needs

My study compared one semi-arid river gradient with one sub-humid river gradient and found that a "snap-shot" of the semi-arid river was comparatively "simple" or homogeneous compared to the sub-humid river. The relatively simple community in the Bad River does not mean that it is less healthy than the Big Sioux River, and in fact the opposite could be true. However, my study was not designed to elucidate landscape level differences in land use that may affect the physical or biological integrity among rivers within similar geologic and climatic settings. Rather, my findings suggest that at the system level, semi-arid rivers may lack the sensitivity to land use effects because the inherently low physical and biological complexity, and low biological specialization typically used in assessments is simply not present. However, comparing the physical and biological attributes of the Bad River to others in the same geologic and climatic setting or ecoregion may provide greater insight into the ways biological attributes can be used to assess the health of rivers in this region.

Although flow fluctuations limit species richness and composition, physical habitat conditions influence community structure and function during low or intermittent flows (Bramblett and Fausch 1991; Capone and Kushlan; Walsh 1992). In intermittent streams, physical habitat conditions and water quality in isolated pools and the persistence of pools during extended dry periods must be incorporated into models of patch structure to adequately understand the community structure and function over time (Stanley et al. 1997). Patch structure in semi-arid rivers is likely to be influenced by natural systemic processes, but could potentially be threatened by the cumulative effects of landscape level activities that alter flow or sediment regime. Furthermore, pools that predictably offer refuge during extended drought periods and provide a source of biological organisms for recolonization following resumption of flow may need protection from local disturbances during drought. Semi-arid watersheds, and to a lesser extent sub-humid watersheds, may need habitat assessment techniques that evaluate pool characteristics (i.e., patch structure) during extended drought periods to determine the importance of these as refugia and subsequently as sources of fish following the resumption of flows (Schlosser 1991; Stanley et al. 1997).

CHAPTER 3

THE RELATIONSHIP OF LOCAL AND SYSTEMIC VARIABLES TO FISH AND FISH HABITAT IN THE BIG SIOUX RIVER IN EASTERN SOUTH DAKOTA

Introduction

Protection and restoration of riparian areas and other natural channel conditions of rivers and streams in Midwestern agricultural landscapes have a large potential to benefit fisheries resources. Particularly, low order streams, which comprise 70-80% of drainage network in watersheds, have the greatest impact because of their potential to provide high productivity and habitat for spawning and nursery areas for fish that later migrate to downstream reaches. Also, many species are found primarily in tributaries and serve as sensitive indicators of physical habitat degradation. Within any given reach, physical habitat is directly related to the local interactions of channel morphometry with bed and bank materials and riparian vegetation (Keller and Swanson 1979; Grissinger and Bowie 1984; Platts and Nelson 1985; Beschta and Platts 1986; Clifton 1989; Trotter 1990; Johnson and Ryba 1992). However, in alluvial, riverine environments, these local interactions are constrained by the dominant geomorphic process (e.g., downcutting, lateral migration, and alluviation) at the systemic level, which depend on stream power, sediment load, and flow regime.

Managers might presume that protection and restoration of local conditions in small streams would have the greatest benefits because systemic dynamics would be least influential on local improvements to riparian areas. For example, prohibition of grazing can improve riparian vegetation, streambanks, and channel conditions, but these improvements can be countered by upstream factors (Platts and Nelson 1985). For example, loss of stable riparian vegetation may be caused by increased meandering in parts of the watershed due to changes in sediment and flow (Minshall 1988). Under these conditions, loss of riparian vegetation and bank stability can occur when bank height and angles exceed critical values (Little et al. 1982; Grissinger and Bowie 1984). Hence, natural or structural management of local conditions, such as riparian ecosystems, requires the real causes of degradation to be identified and the potential for rehabilitation determined (DeBano and Heede 1987; Manci 1989). Meeting these requirements must begin by first understanding how local and systemic variables control physical habitat variation at several spatial scales. With this understanding, assessing the source of physical habitat degradation and defining realistic protection and restoration efforts will improve.

In addition, understanding the effects of local and systemic controls on physical habitat, as well as fish communities, will solve some of the difficulties with interpreting fish community surveys. In eastern South Dakota, research in riverine environments has begun to show how fish and fish habitat are controlled locally and systemically by factors (e.g., physical complexity, water quality, and discharge) that vary over several spatial and temporal dimensions (Tol 1976; Kubeny 1992; Walsh 1992; Bratten 1993; Berry et al. 1994). Due to environmental variation, drawing conclusions about the health or integrity of a river based on fish samples alone could prove erroneous or inconclusive. A research approach that pursues an understanding of the theoretical hierarchy of local and systemic controls on the physical habitat would be appropriate. For managers, riparian and watershed management decisions would improve with the ability to measure site-specific habitat, which are less prone to temporal variation, and to link measured parameters to local and systemic controls. Therefore, I tested the hypothesis that local interactions have greater influence on physical habitat and fish communities in streams than in larger streams.

Study Sites

The Big Sioux River watershed in eastern South Dakota (Figure 3-1) was selected for study. In the Big Sioux River watershed, the parent geology is mostly glacial till and the climate is sub-humid. Hydrologically, the Big Sioux River mainstem sites rarely become intermittent; however, wet-dry cycles have prominent effects on annual discharge (Figure 3-2). Tributaries become intermittent during dry phases. The Big Sioux River lies within two ecoregions: the Northern Glaciated Plains (NGP) and the Western Corn Belt Plains (WCBP). Throughout the watershed, land use is mostly row crops on the uplands and floodplain, and mostly pasture along river and tributary corridors.

Methods

Environmental Attributes

The methods for measuring environmental attributes are described in chapter 2.

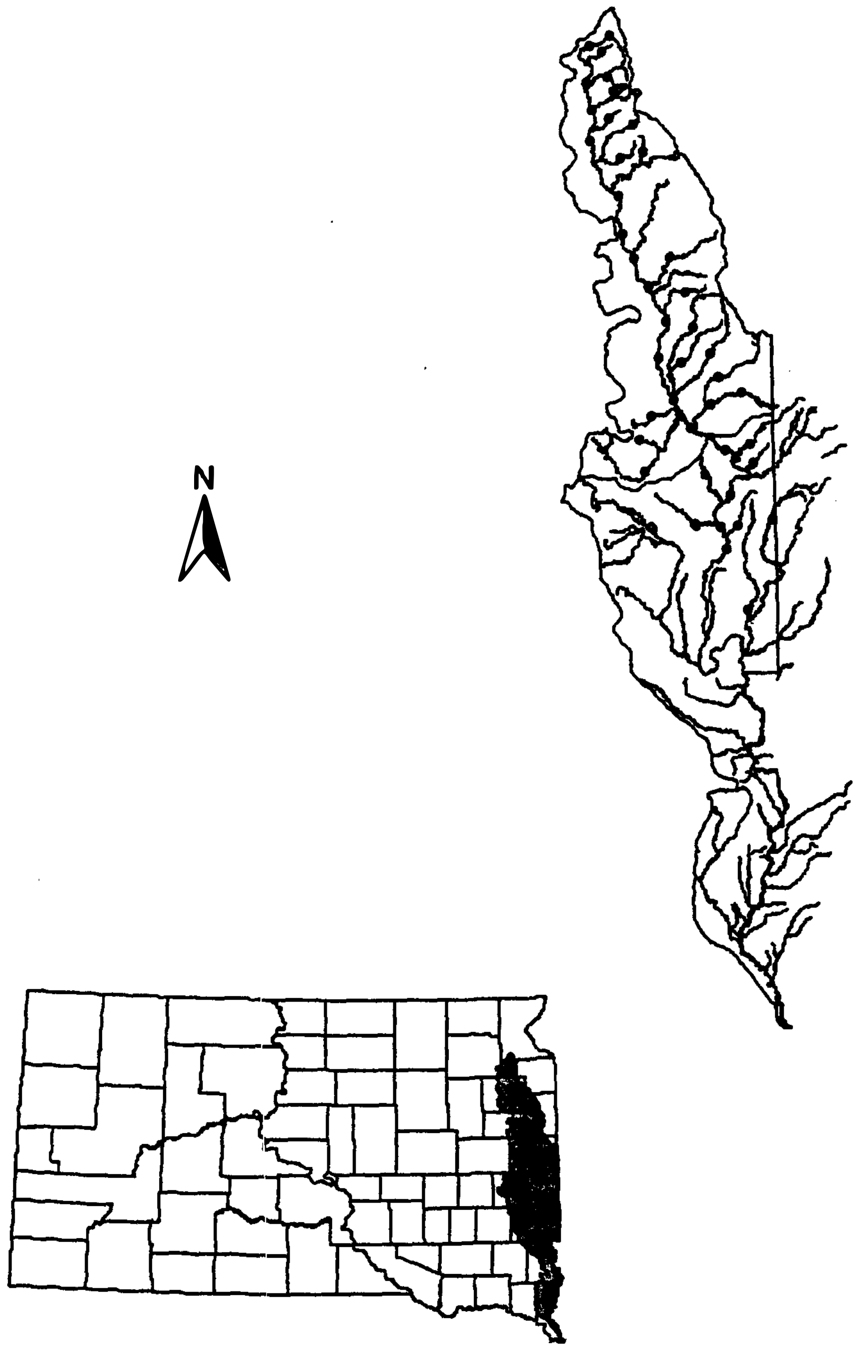


Figure 3-1. The Big Sioux River in eastern South Dakota with location of study sites.

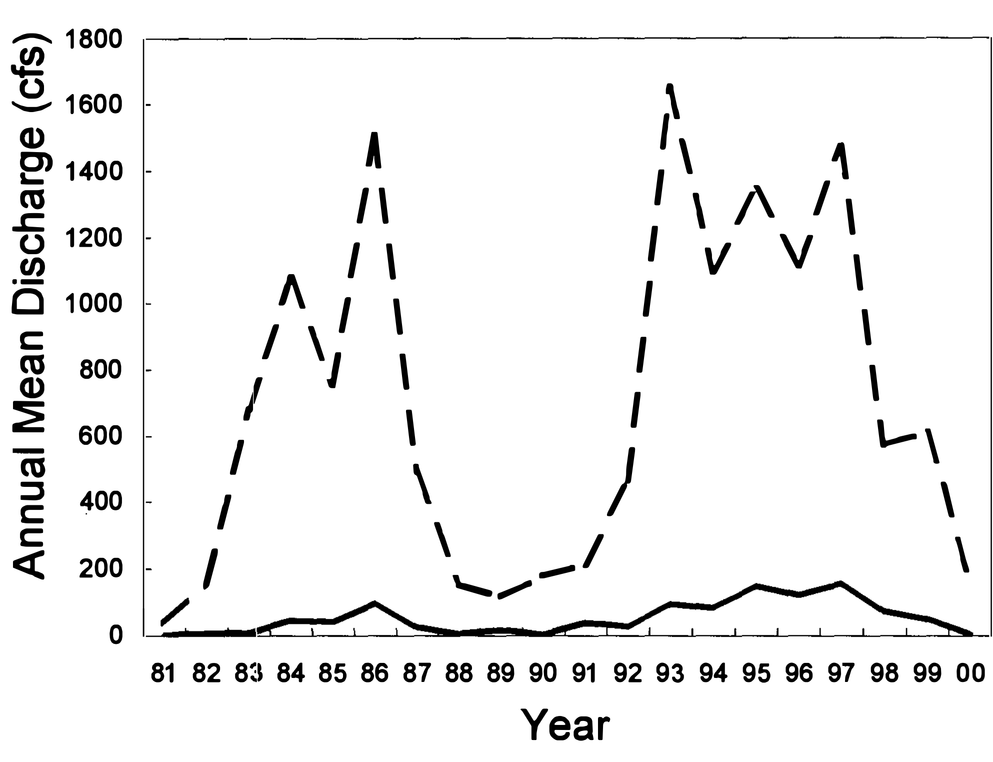


Figure 3-2. Annual mean discharge for USGS gauging sites near the City of Watertown (solid line) and near the City of Dell Rapids (dashed line) for the Big Sioux River showing prominent effects of wet and dry phases.

Fish Sampling

Fish were sampled in all reaches with bag seines having 8 mm mesh size. Pools and runs were seined usually in a downstream direction with a seine that reached from bank to bank. A block net having 8 mm mesh was placed across the stream to prevent fish from escaping. Riffles were usually sampled by kicking through the substrate in a down stream direction toward a bag seine placed across the stream at the bottom of the riffle. Blocknets were used in all reaches except for the lowest 12 sites on the Big Sioux River. At these 12 sites, high streamflows prevented effective sampling of all habitats; however, representative sampling of the reach was attempted to obtain data for characterizing community attributes. In the tributaries of the Big Sioux River, depletion of the fishes in the reach was performed by seining the entire reach with 3 to 6 passes. In hydrologically diverse reaches, discrete habitats were depleted. Blocknets were placed in the upper and lower end of the reach or habitat being sampled to prevent movement in and out of the reach or habitat. Fishes sampled in each pass were placed in separate holding crates and processed independently. Fish sampled from all reaches were identified, counted, and weighed. For each fish species sampled from Big Sioux River tributaries, population estimates (No./100 m^2 and g/100 m^2) using the Leslie depletion method on all pass data were calculated.

Fish Community Attributes

The methods used to select and calculate fish community attributes are described in chapter 2. Attributes represented aspects of species richness and composition, tolerance, trophic structure, and reproduction (Table 3-1). A value for a community attribute was calculated for each site. Calculations used population estimate data from tributaries of the Big Sioux River, and relative abundance data from the Big Sioux River.

Statistical Analyses

The hypothesis that local variables have greater influence on physical habitat and fish communities in smaller than in larger streams was examined several ways. First, prominent patterns in physical traits unique to watershed size were explored using principal components analysis (PCA) of select physical characteristics and plots of principal components (PC's). Second, to assess local and systemic controls on riparian-related cover types, the amounts of undercut banks and overhanging vegetation were plotted against watershed size and physical traits for grazing practices rated as low, moderate, and high. Third, plots of fish community attributes against watershed size were constructed. Fourth, Spearman Rank correlation analysis was used to explore relationships of fish community attributes (Table 3-1) in tributaries to physical habitat and select water quality parameters (Table 3-2).

Table 3-1. Fish community attributes used in analysis of Big Sioux River study.

Grouping	Attribute
Species richness and composition	Total species richness
	Native species richness
	Native minnow species richness
	Water column species richness
	Benthic species richness
	Benthic insectivore richness
Headwater/pioneering attributes	Number of headwater species
	Proportion of individuals as headwater species
	Proportion of biomass as headwater species
	Proportion of individuals as pioneering species
	Proportion of biomass as pioneering species
Intolerant/tolerant attributes	Number of intolerant species
	Proportion of individuals as intolerant species
	Proportion of biomass as intolerant species
	Number of sensitive species
	Proportion of individuals as sensitive species
	Proportion of biomass as sensitive species
	Proportion of individuals as green sunfish
	Proportion of biomass as green sunfish
	Proportion of individuals as tolerant species
	Proportion of biomass as tolerant species
Trophic guilds	Proportion of individuals as insectivorous minnows
	Proportion of biomass as insectivorous minnows
	Proportion of individuals as insectivores
	Proportion of biomass as insectivores
	Proportion of individuals as predators
	Proportion of biomass as predators
	Proportion of individuals as omnivores
	Proportion of biomass as omnivores
	Proportion of individuals as herbivores
	Proportion of biomass as herbivores
Reproduction	Proportion of individuals as simple lithophils
	Proportion of biomass as simple lithophils

Table 3-2. Physical attributes and select water quality parameters used in Spearman rank correlation analysis in the Big Sioux River tributaries.

Grouping	Attribute
Watershed attribute	Watershed size
Channel morphometry	Bank height
	Bankfull height
	Bank length
	Bank angle
	Channel bottom width
	Channel top width
Bankfull attributes	Bankfull width
	Bankfull depth
	Bankfull width:depth ratio
Stream bank attributes	Percent of bank vegetated
	Percent of bank eroded
	Percent of bank as deposition
	Percent of bank slumping
Physical habitat attributes	Percent clay
	Percent silt
	Percent sand
	Percent gravel
	Percent cobble
	Percent boulder
	Flow (m^3/sec)
	Mean water surface width (m)
	Percent pool
	Percent riffle
	Percent run
	Percent slope
	Mean depth (cm)
	Depth coefficient of variation
	Mean velocity (m/sec)
	Velocity coefficient of variation
	Overhanging vegetation (percent of surface area)
	Undercut bank (percent of surface area)
Water quality	Water temperature (°C)
	Dissolved oxygen (mg/L)
	Turbidity (NTU)
	Conductivity (µSiemens/cm)

Results

Physical Environments of the Big Sioux River and its Tributaries

Descriptive Statistics.—Descriptive statistics for physical attributes and select water quality parameters are given in Table 3-3. Sites had watershed sizes from 4 to 396 km^2 and a well distributed range of physical traits.

Physical Traits.--An exploration of data using principal components analysis reduced 20 variables to 5 principal components which explained 86% of the variation in the data set (Table 3-4). The most revealing of principal component (PC) plots was PC 2 versus PC 1 (Figure 3-3) and PC 3 versus PC 1 (Figure 3-4). Two patterns are apparent on the first plot. First, sites having the largest watershed sizes separate from the remaining sites and exhibit increases in channel and bankfull dimensions, percent sand substrates, and percent of banks as depositional. No strong pattern with percent eroded banks, percent bank slumping and percent gravel exist. Second, the remaining sites show no distinct pattern with watershed size, but do show a range in percent bank erosion, percent bank slumping, and percent gravel. In the second plot, a group of sites separate from the smaller watershed group based on higher slope and higher percent of cobble.

An examination of scatterplots reveal that, although most physical traits associated with the Big Sioux River mainstem reaches exhibit either an upward or downward trend with watershed size, physical traits among the tributaries or small streams that have watershed sizes less than 500 km^2 exhibit a greater range of conditions. Measurements related to channel morphometry (Figure 3-5) show a distinct increase in all measurements except bank angle, which was consistent around 150°. Bankfull width

Table 3-3. Descriptive statistics for physical attributes and select water quality parameters in the Big Sioux River tributaries (N=26).

Attribute	Minimum	Maximum	Mean	Standard error
Watershed size (km^2)	4	396	114	22
Bank height	0.57	1.76	0.99	0.06
Bankfull height	0.18	1.07	0.51	0.03
Bank length	0.85	3.83	2.09	0.17
Bank angle	99	157	134	3
Channel bottom width	0.46	6.70	2.29	0.29
Channel top width	1.60	14.07	5.78	0.66
Bankfull width	1.11	10.62	4.30	0.50
Bankfull depth	0.15	0.89	0.43	0.03
Bankfull width:depth ratio	4.58	22.47	10.28	0.93
Percent of bank vegetated	23	81	60	3
Percent of bank eroded	2	53	29	3
Percent of bank as deposition	0	46	11	2
Percent of bank slumping	0	62	11	3
Percent clay	0	65	4	3
Percent silt	3	100	40	6
Percent sand	0	62	15	3
Percent gravel	0	76	34	5
Percent cobble	0	22	5	1
Percent boulder	0	14	2	1
Flow (m^3/sec)	<0.00001	0.0060	0.0014	0.0003
Mean water surface width (m)	1.01	7.87	3.34	0.34
Percent pool	0	100	48	6
Percent riffle	0	23	6	1
Percent run	0	100	46	7
Percent slope	0.0100	0.5972	0.2013	0.0398
Mean depth (cm)	7	35	19	1
Mean velocity (m/sec)	0	0.29	0.14	0.02
Overhanging vegetation (percent of surface area)	0	100	30	7
Undercut bank (percent of surface area)	0	18	6	1
Water temperature (°C)	22.0	31.0	25.7	0.5
Dissolved oxygen (mg/L)	2.5	10.0	6.6	0.3
Turbidity (NTU)	11	233	68	10
Conductivity (μSiemens/cm)	156	1890	816	63

and depth showed a distinct increase with watershed size while bankfull width:depth ratio showed no distinct pattern with watershed size (Figure 3-6). A large range in percentage of bank that was vegetated, eroded, and depositional characterized bank conditions among tributaries and smaller stream reaches of the Big Sioux River (Figure 3-7). However, in watersheds greater than 3000 km^2, a smaller range was observed and percent of the bank as depositional materials was consistently higher, while percent of bank that was eroded and slumping was consistently lower (Figure 3-7). In tributaries, the percentage of substrate that was silt or gravel had very wide ranges compared to the other substrates (Figure 3-8). In the Big Sioux River, sand and gravel composed most of the substrate with generally higher percentages of sand than in tributaries and silt below 10% in most river sites (Figure 3-8).

Variables associated with flow conditions during the period of study were also distinct between tributary sites and Big Sioux River mainstem sites. In the tributaries, a greater diversity in macrohabitat conditions occurred than in the river sites (Figure 3-9). Pools, riffles, and runs were identified in tributaries, which also had a higher range in water surface slopes. Runs were almost exclusively identified in the river sites, which may have partially related to the higher than average river discharge conditions. Concurrent with these results, mean depth and velocities in the Big Sioux River mainstem sites were higher than in the tributaries, but variation for depth and velocity were generally higher in the tributaries (Figure 3-10).

Riparian-related Cover Types.--Overhanging vegetation and undercut banks exhibited a large range of values in the tributaries (Figure 3-11) similar to other physical traits. Both decreased with watershed size (Figure 3-11). Generally, higher lateral measurements of overhanging vegetation (>0.5 m) were found in the smallest of tributaries that had bankfull heights < 0.5 m (Figure 3-12), channel top widths < 5 m (Figure 3-12), bankfull width:depth ratios < 10 (Figure 3-13), and banks that were at least 60% vegetated (Figure 3-14). Higher lateral measurements of undercut bank (>0.1 m) were found in the tributaries that had bankfull heights < 1.0 m (Figure 3-15), channel top widths < 10 m (Figure 3-15), bankfull width:depth ratios < 15 m (Figure 3-16), and banks that averaged less than 30% depositional material (Figure 3-17). All tributaries were either in pastures or fenced off areas that had a recent history of grazing. And because the history of grazing regimes among sites is unknown, but most likely continuous during the growing season, no comparisons could be made that might discern the long-term effects of grazing on physical traits. Furthermore, land use data and riparian data for stream courses above each site were not collected for this analysis.

The volume of LWD and pieces of LWD were absent in reaches where riparian landuse was anything other than wooded or open woods (Figure 3-11). LWD was first found in measurable amounts in the segment of the Big Sioux River mainstem that had riparian land use described as wooded or scattered woods (Figure 3-11).

Table 3-4. Principal components (PC) and variable loadings for 43 Big Sioux River sites. Total variance explained in data was 86% (PC1=47.2, PC2=12.9, PC3=9.3, PC4=10.8, PC5=6.0).

Variable	PC1	PC2	PC3	PC4	PC5
Bankfull height	**0.97309**	0.00563	-0.01274	0.10694	0.02352
Bankfull depth	**0.97029**	0.00437	-0.01026	0.10121	0.02907
Watershed area	**0.95678**	0.03729	0.06976	0.13041	0.03974
Bankfull width	**0.93462**	-0.08701	0.03361	0.30732	0.00634
Channel top width	**0.92056**	-0.09406	-0.02102	0.31862	0.00278
Bank height	**0.89820**	-0.09559	0.04282	0.22467	-0.04503
Channel bottom width	**0.89615**	-0.14921	0.04796	0.31714	0.00319
Bank as depositional (%)	**0.84624**	0.19141	-0.23186	0.16082	0.02160
Bank length	**0.83016**	0.04601	0.07216	0.46371	0.02658
Sand substrate (%)	**0.78221**	-0.08913	-0.25094	-0.02106	0.16589
Bank vegetated (%)	**-0.70431**	0.45919	0.30374	-0.04916	-0.11806
Silt substrate (%)	**-0.55354**	0.47514	-0.42405	-0.05521	-0.40279
Bank eroded (%)	-0.16000	**-0.87911**	-0.10763	-0.14917	0.13340
Bank slumping (%)	0.07645	**-0.80079**	-0.15026	0.23138	-0.11716
Gravel substrate (%)	0.12614	**-0.68597**	0.55799	-0.04293	-0.04710
Cobble substrate (%)	-0.01607	0.09649	**0.84824**	-0.01329	-0.10533
Water surface slope (%)	-0.30618	0.11421	**0.55888**	-0.42609	-0.12479
Angle	0.31765	0.15985	-0.18969	**0.85538**	0.14843
Bankfull width:depth	0.48719	-0.33071	0.03656	**0.73250**	-0.03657
Clay substrate (%)	0.02427	0.00438	-0.17632	0.09644	**0.94852**

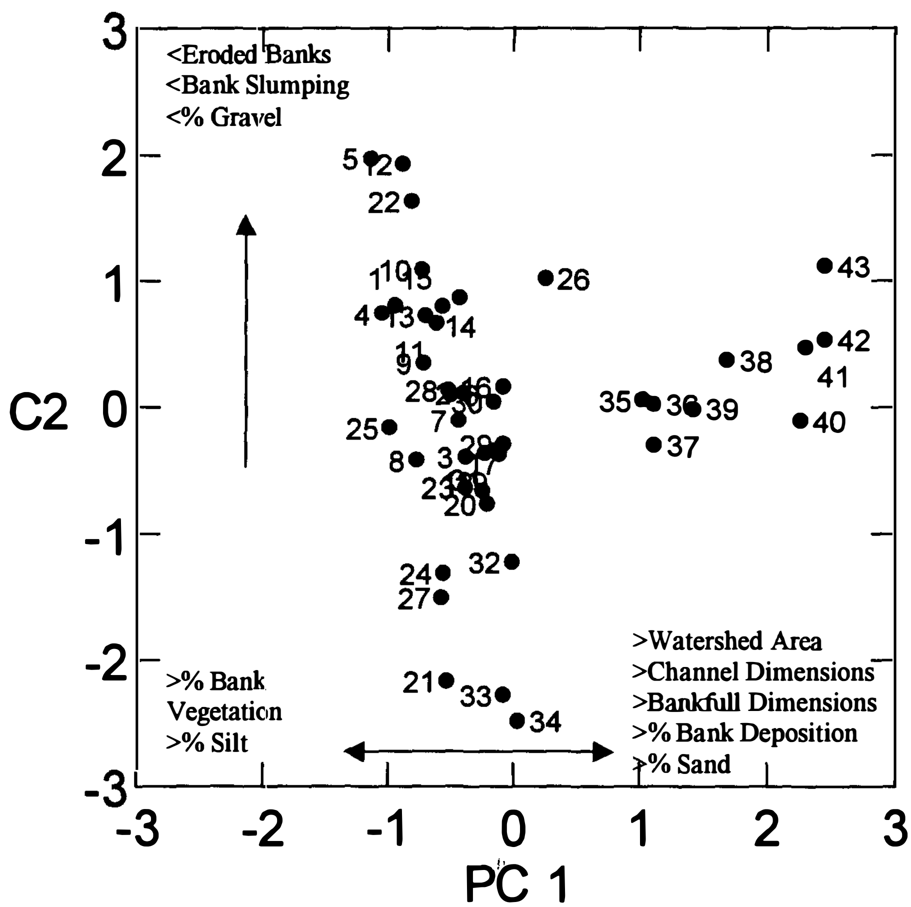


Figure 3-3. A plot of principal component 2 against principal component 1 showing physical differences between streams with small and large watershed sizes in the Big Sioux River. Points are labeled with rankings of watershed sizes with 1 being the smallest.

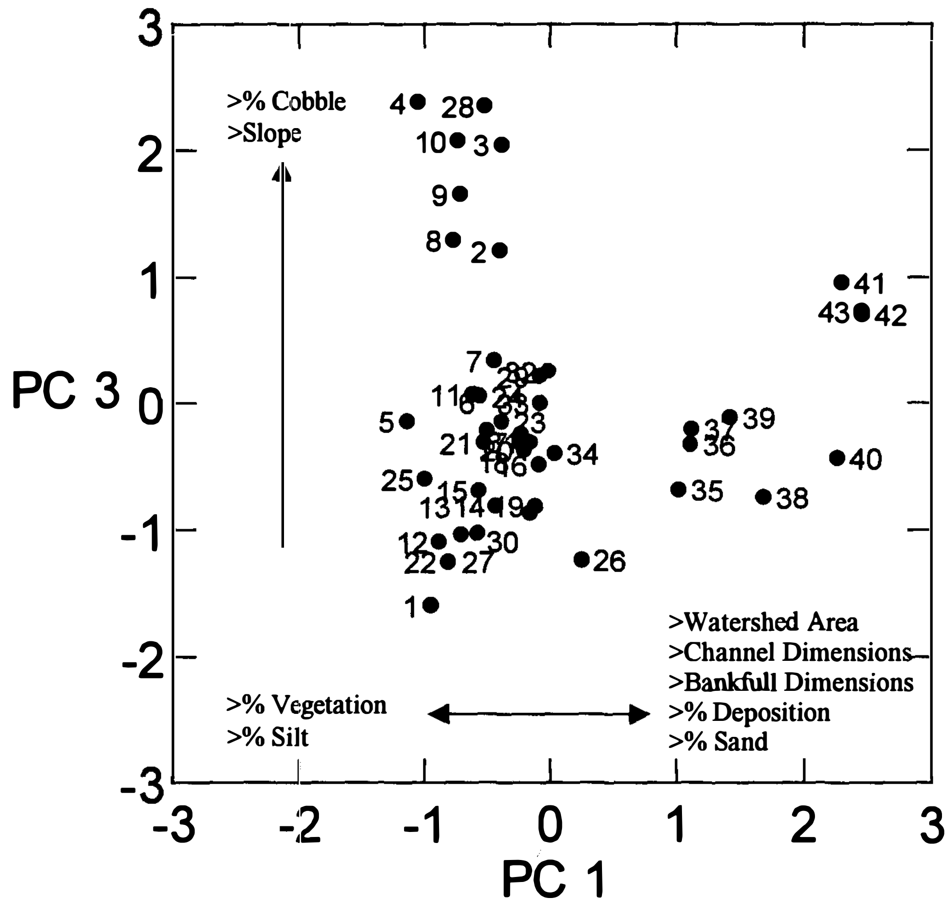


Figure 3-4. A plot of principal component 3 against principal component 1 showing physical differences between streams with small and large watershed sizes in the Big Sioux River. Points are labeled with rankings of watershed sizes with 1 being the smallest.

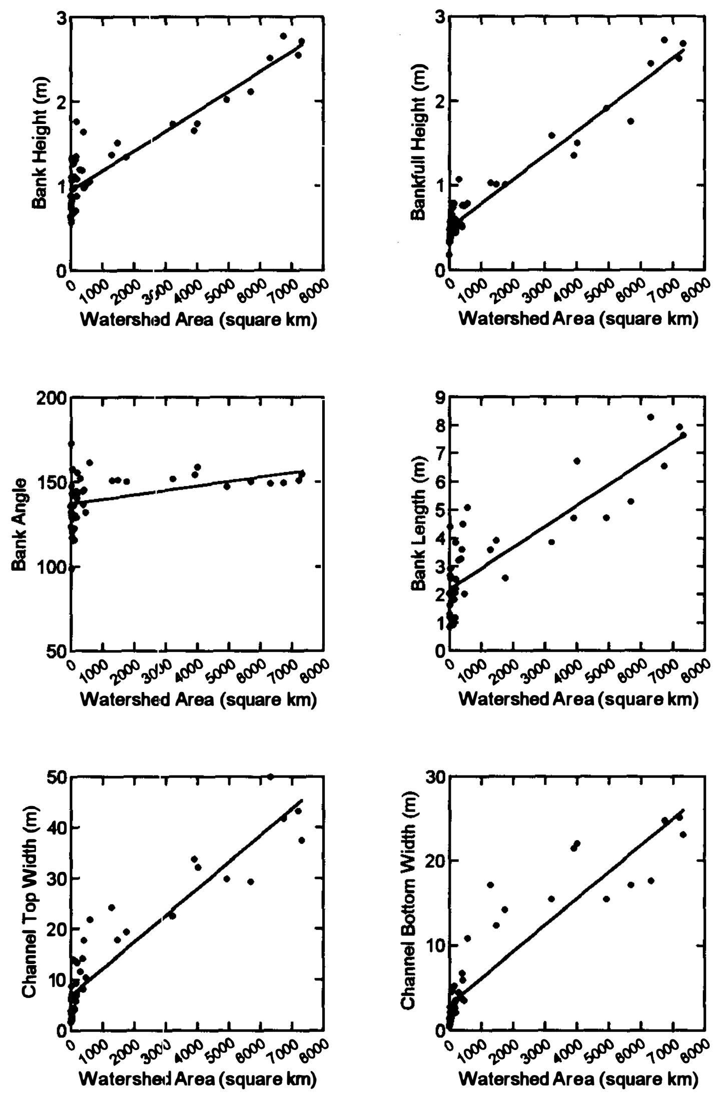


Figure 3-5. Scatterplots of channel morphometry against watershed area at 43 sites in the Big Sioux River watershed.

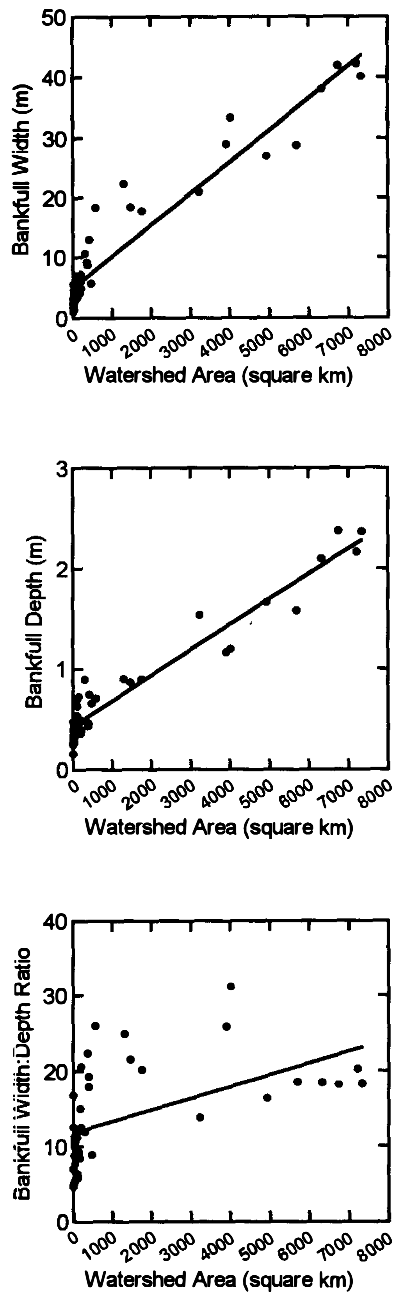


Figure 3-6. Scatterplots of bankfull dimensions against watershed area at 43 sites in the Big Sioux River watershed.

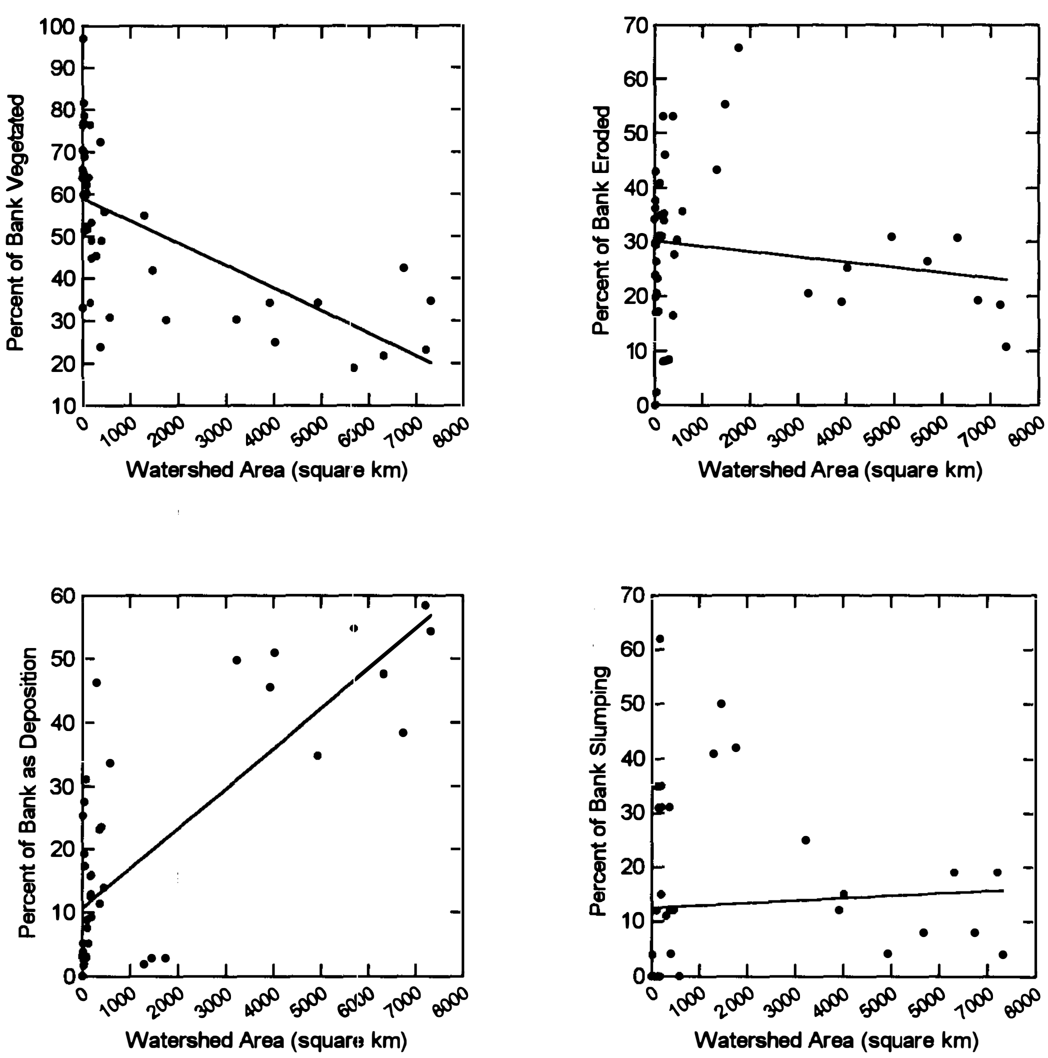


Figure 3-7. Scatterplots of bank erosion, deposition, vegetation, and bank slumping against watershed area at 43 sites in the Big Sioux River watershed.

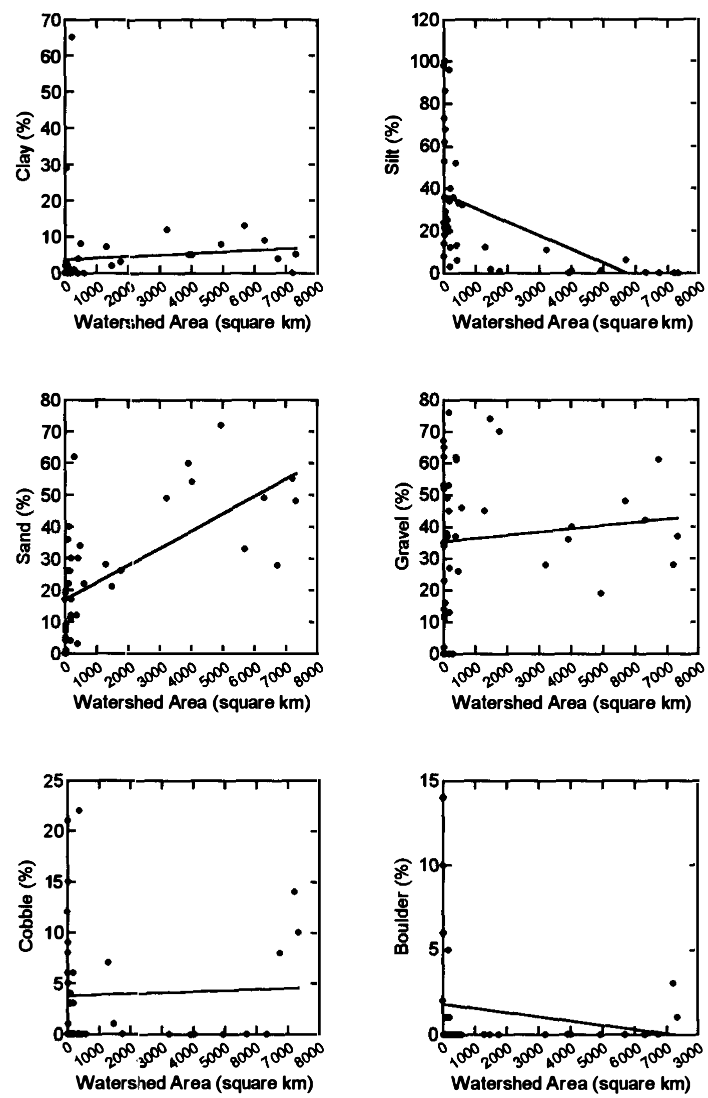


Figure 3-8. Scatterplots of substrate against watershed area at 43 sites in the Big Sioux River watershed.

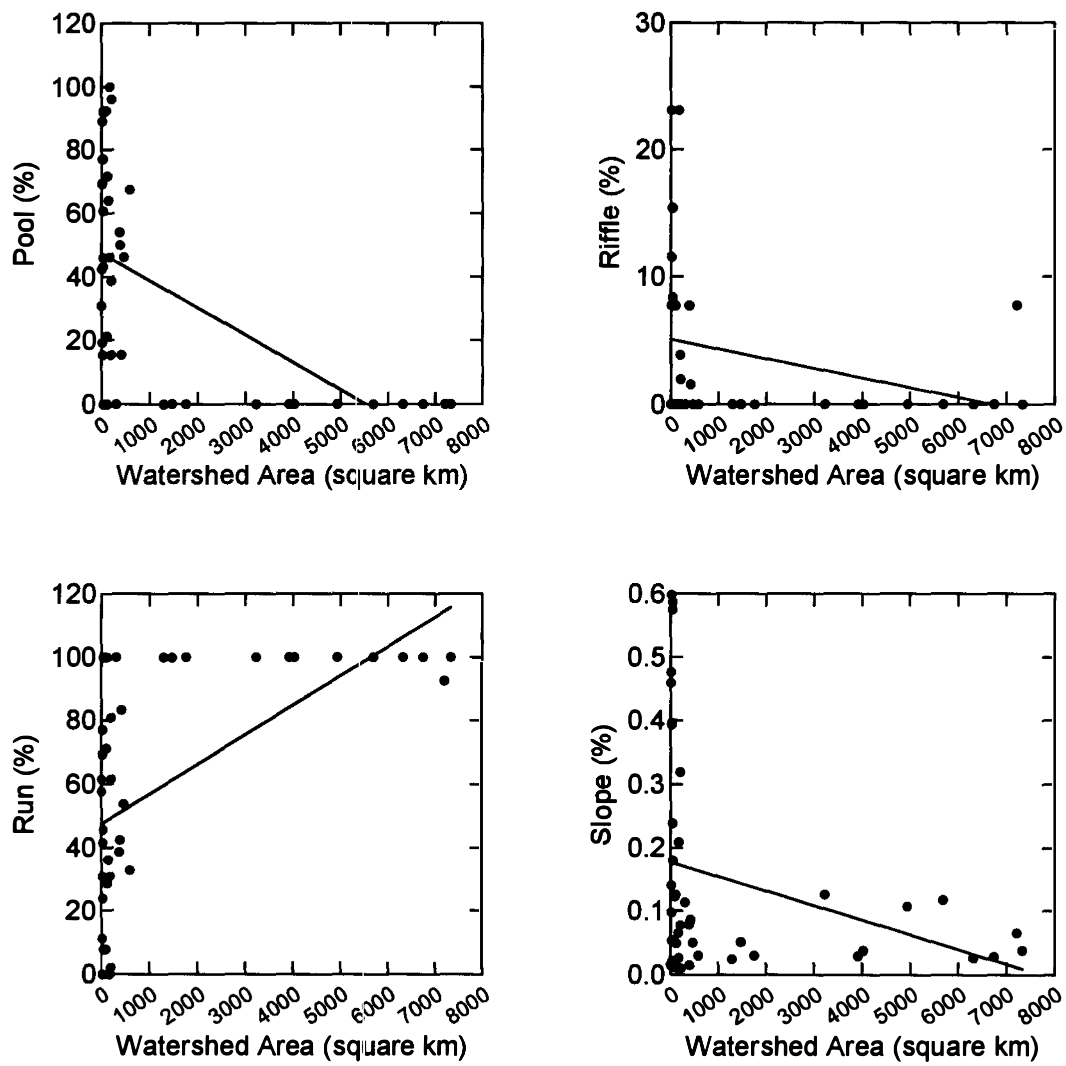


Figure 3-9. Scatterplots of macrohabitats and water surface slope against watershed area at 43 sites in the Big Sioux River watershed.

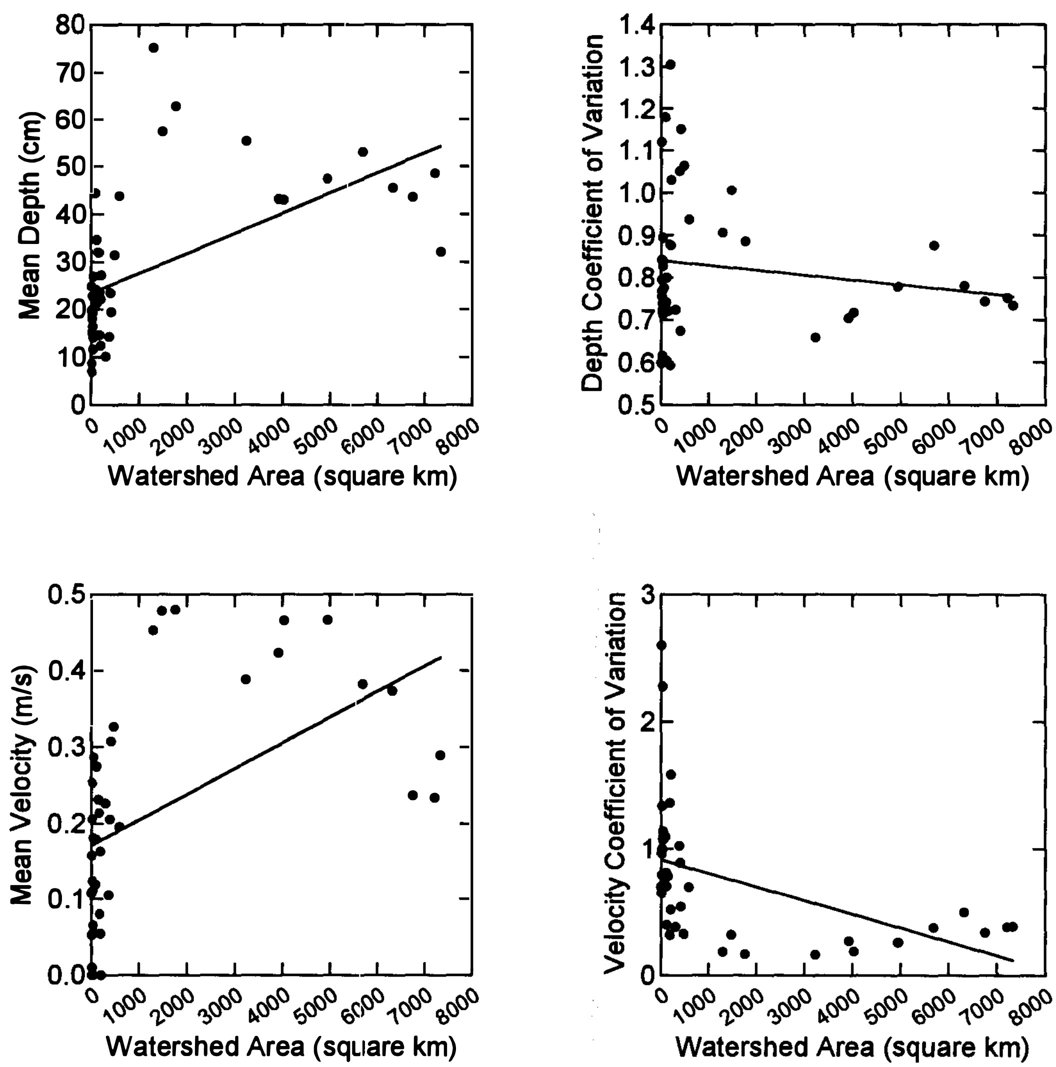


Figure 3-10. Scatterplots of means and coefficients of variations for depth and velocity against watershed area at 43 sites in the Big Sioux River watershed.

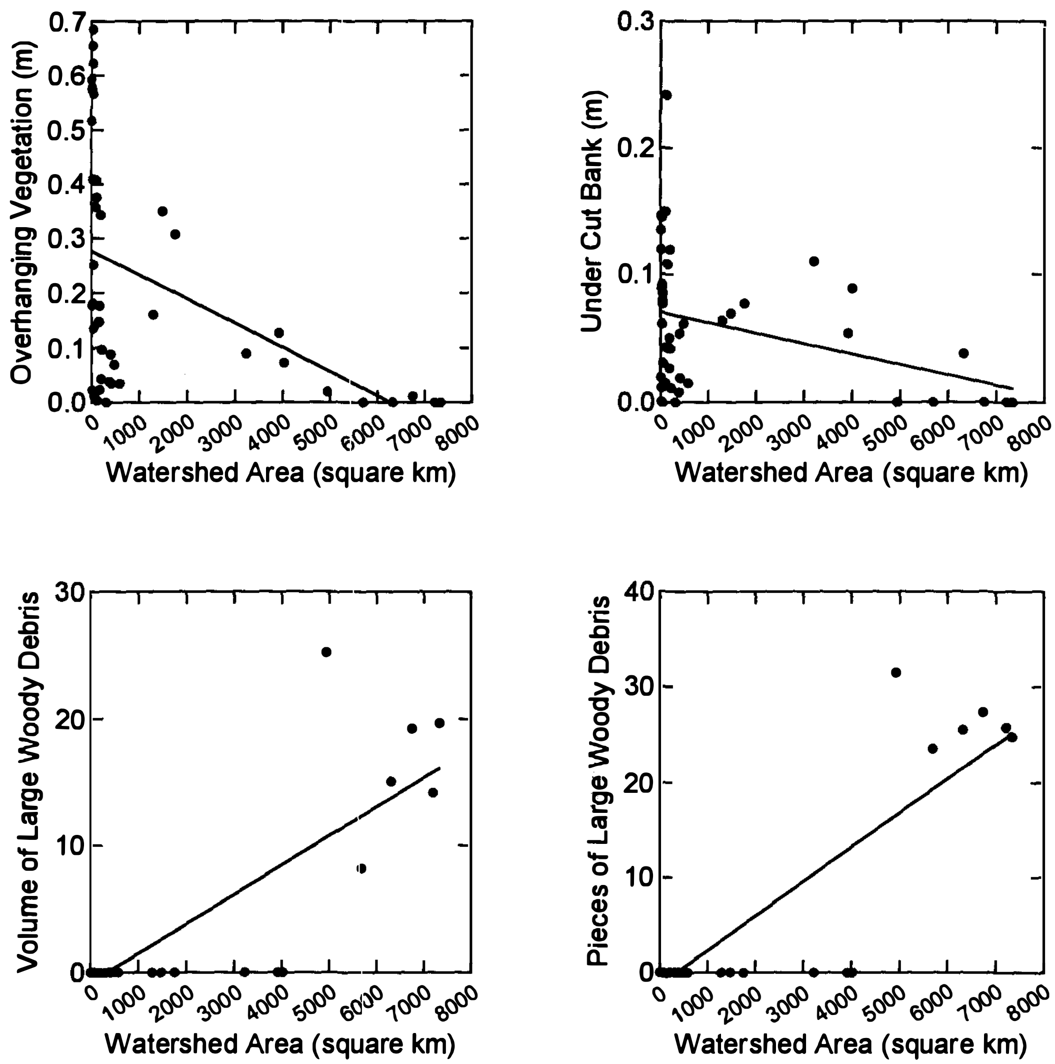


Figure 3-11. Scatterplots of overhanging vegetation, undercut banks, volume of large woody debris (LWD), and pieces of LWD with watershed areas for 43 sites in the Big Sioux River watershed.

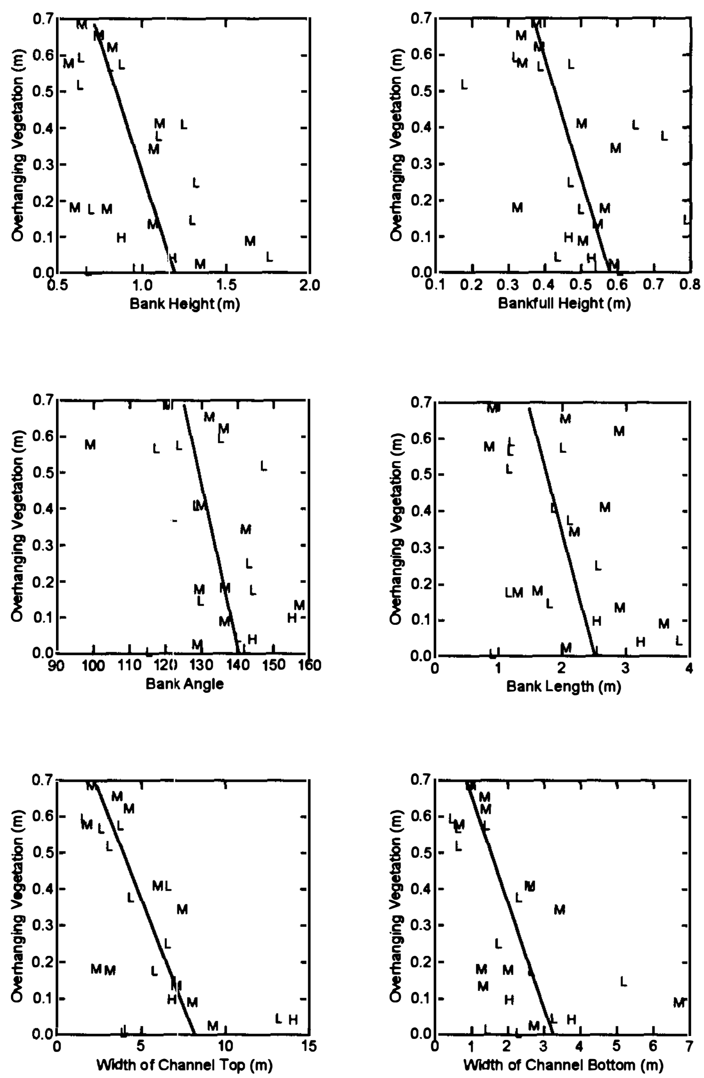


Figure 3-12. Scatterplots of overhanging vegetation with channel morphometry in tributaries of the Big Sioux River. Animal vegetation use is symbolized with L = low, M = moderate, and H = high.

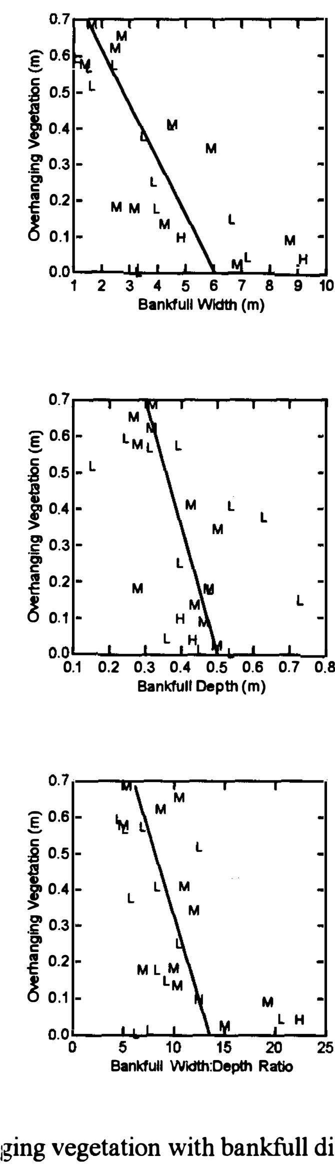


Figure 3-13. Scatterplots of overhanging vegetation with bankfull dimensions in tributaries of the Big Sioux River. Animal vegetation use is symbolized with L = low, M = moderate, and H = high.

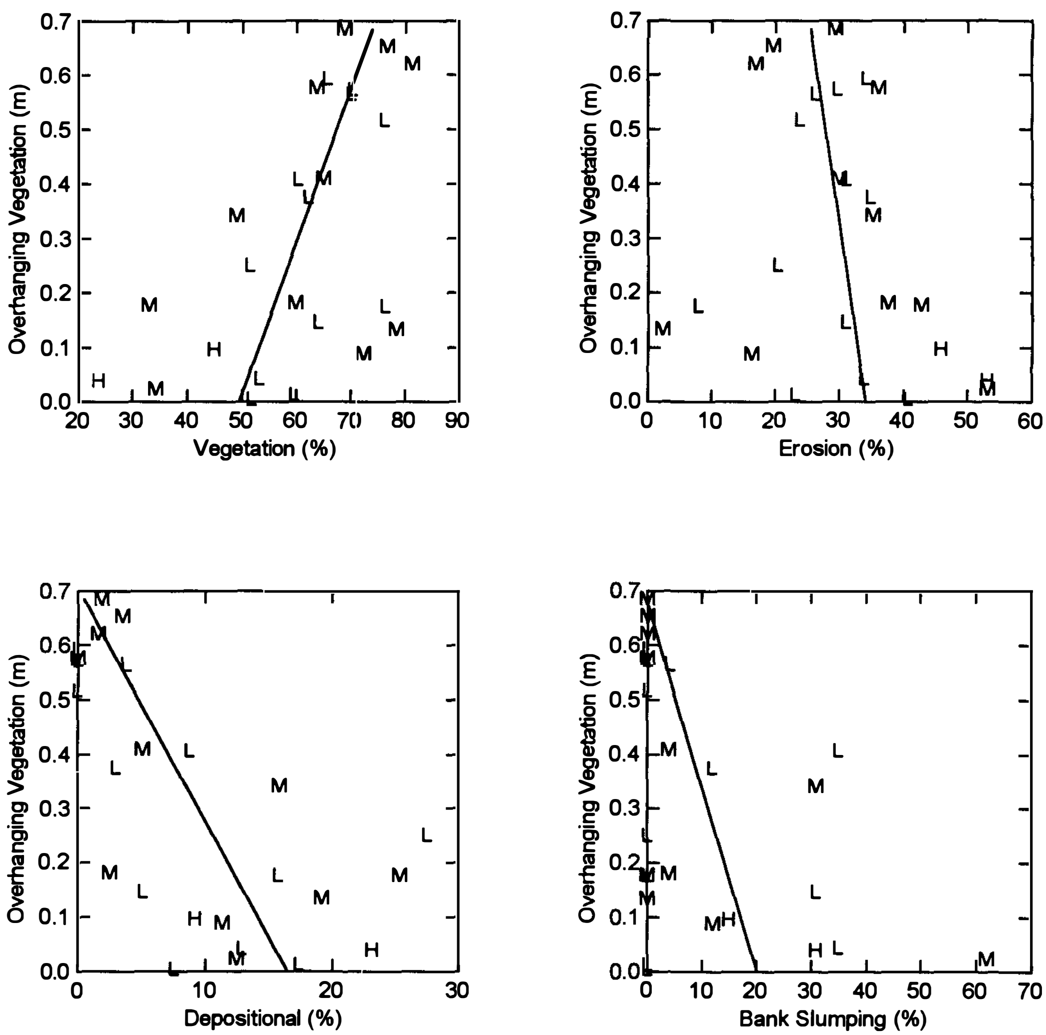


Figure 3-14. Scatterplots of overhanging vegetation with percentage of that is vegetated, eroded, depositional, and slumping in tributaries of the Big Sioux River. Animal vegetation use is symbolized with L = low, M = moderate, and H = high.

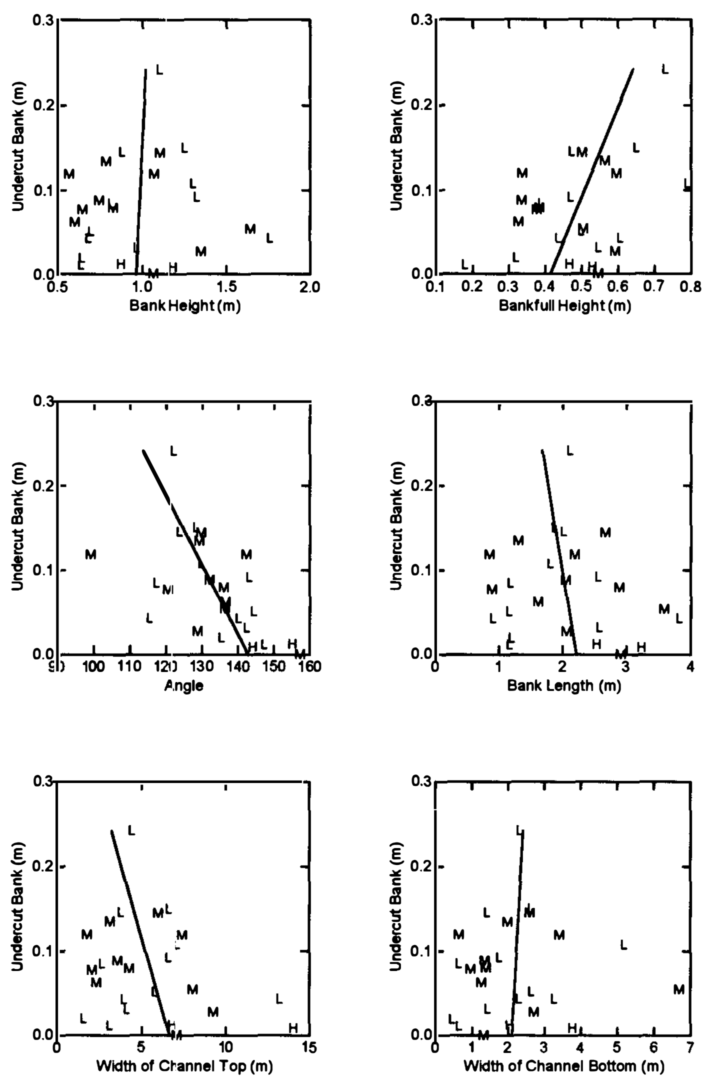


Figure 3-15. Scatterplots of undercut bank with channel morphometry in tributaries of the Big Sioux River. Animal vegetation use is symbolized with L = low, M = moderate, and H = high.

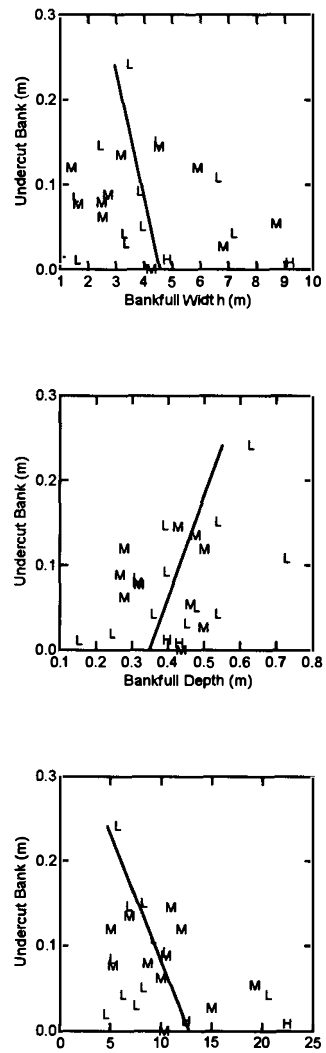


Figure 3-16. Scatterplots of undercut bank with bankfull dimensions in tributaries of the Big Sioux River. Animal vegetation use is symbolized with L = low, M = moderate, and H = high.

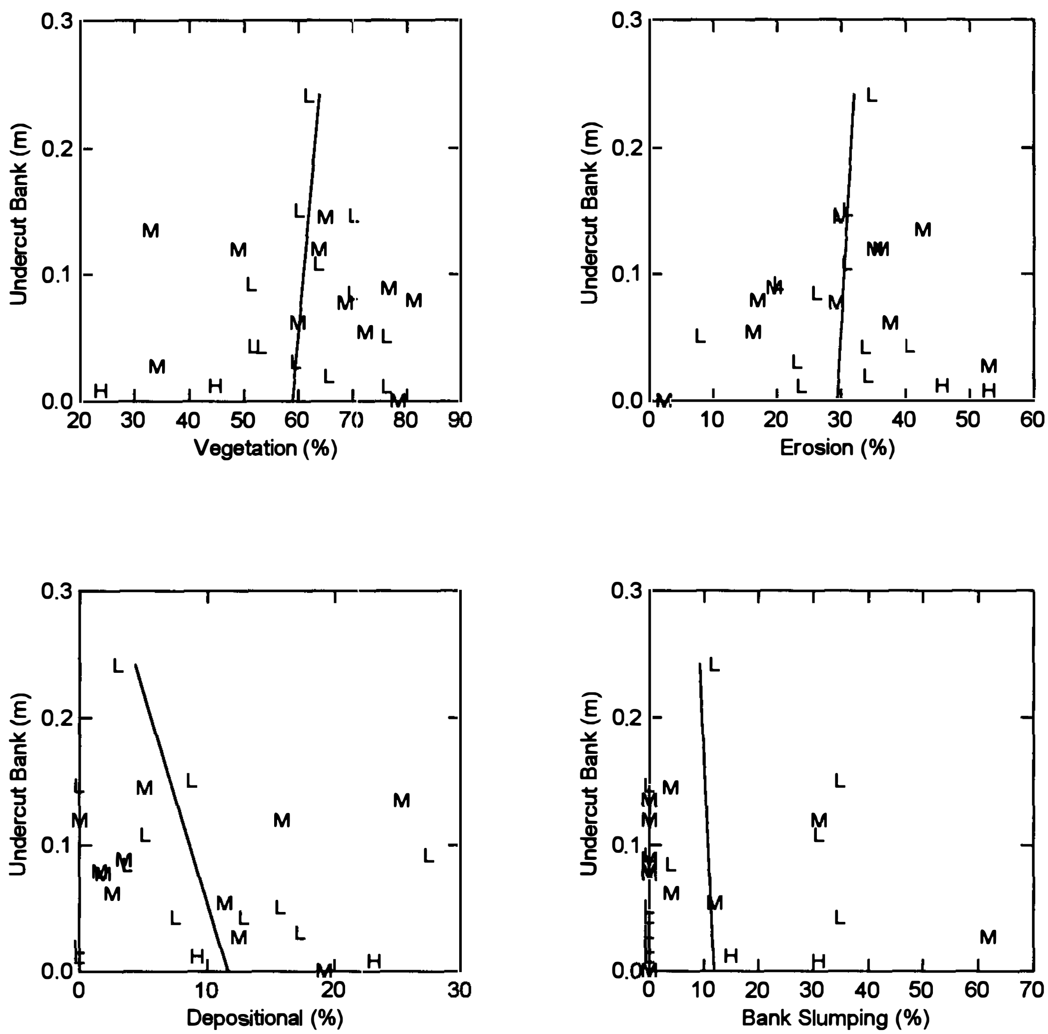


Figure 3-17. Scatterplots of undercut bank with percentage of bank that is vegetated, eroded, depositional, and slumping in tributaries of the Big Sioux River. Animal vegetation use is symbolized with L = low, M = moderate, and H = high.

Fish Communities in the Big Sioux River Watershed

Descriptive Statistics.--In the tributaries, a wide range in values was found within all groups of attributes (Table 3-5).

Scatterplots.--Scatterplots of fish community attributes from 43 sites in the Big Sioux River watershed show that several attributes vary widely among sites <500 km^2 compared to sites with larger watershed sizes (Figures 3-18 to 3-27). As a precaution to defining a linear or non-linear relationship with watershed size, erroneous conclusions could be drawn. For example, many headwater and pioneering species are common in tributary sites and may weight the value of the other attributes in a manner not possible in mainstem sites.

Correlations with Habitat Variables.—Thirty three fish community attributes were correlated with 34 habitat variables. Only 19 correlations were significant at the P=0.001 level (Table 3-6). The most prominent finding was that many of the richness and composition attributes were positively correlated with variables related to watershed or stream size. The only correlation with water quality was the number of benthic species positively correlated with dissolved oxygen. The proportion of individuals as simple lithophils was the only attribute significantly correlated (positively) with flow or water velocity.

Table 3-5. Descriptive statistics for fish community attributes in the Big Sioux River tributaries (N=26).

Attribute	Minimum	Maximum	Mean	Standard error
Total species richness	3	18	9.6	0.8
Native species richness	2	17	9.2	0.8
Native minnow species richness	0	10	4.2	0.5
Water column species richness	1	7	3.8	0.4
Benthic species richness	1	12	4.4	0.4
Benthic insectivore richness	0	8	3	0.3
Number of headwater species	0	5	2.1	0.3
Proportion of individuals as headwater species	0	80	14.1	3.7
Proportion of biomass as headwater species	0	88	6.8	3.4
Proportion of individuals as pioneering species	0	97	57.8	5.8
Proportion of biomass as pioneering species	0	97	48.3	5.9
Number of intolerant species	0	2	0.7	0.1
Proportion of individuals as intolerant species	0	73	7.1	3.4
Proportion of biomass as intolerant species	0	84	4.5	3.2
Number of sensitive species	0	3	1.6	0.2
Proportion of individuals as sensitive species	0	80	9.2	3.6
Proportion of biomass as sensitive species	0	88	6.2	3.4
Proportion of individuals as green sunfish	0	8	0.8	0.4
Proportion of biomass as green sunfish	0	4.7	0.5	0.2
Proportion of individuals as tolerant species	17	99	62.8	5.3
Proportion of biomass as tolerant species	12	99	72.3	4.9
Proportion of individuals as insectivorous minnows	0	88	34.3	6.2
Proportion of biomass as insectivorous minnows	0	88	30.3	5.6
Proportion of individuals as insectivores	0	98	69.6	4.9
Proportion of biomass as insectivores	0	89	59.6	4.9
Proportion of individuals as predators	0	55	2.7	2.1
Proportion of biomass as predators	0	70.8	7.1	3.1
Proportion of individuals as omnivores	0	87	27.1	4.1
Proportion of biomass as omnivores	0	83	32.6	4.0
Proportion of individuals as herbivores	0	13	0.7	0.5
Proportion of biomass as herbivores	0	11.6	0.6	0.5
Proportion of individuals as simple lithophils	0	71	16.5	3.4
Proportion of biomass as simple lithophils	0	90	30.8	4.6

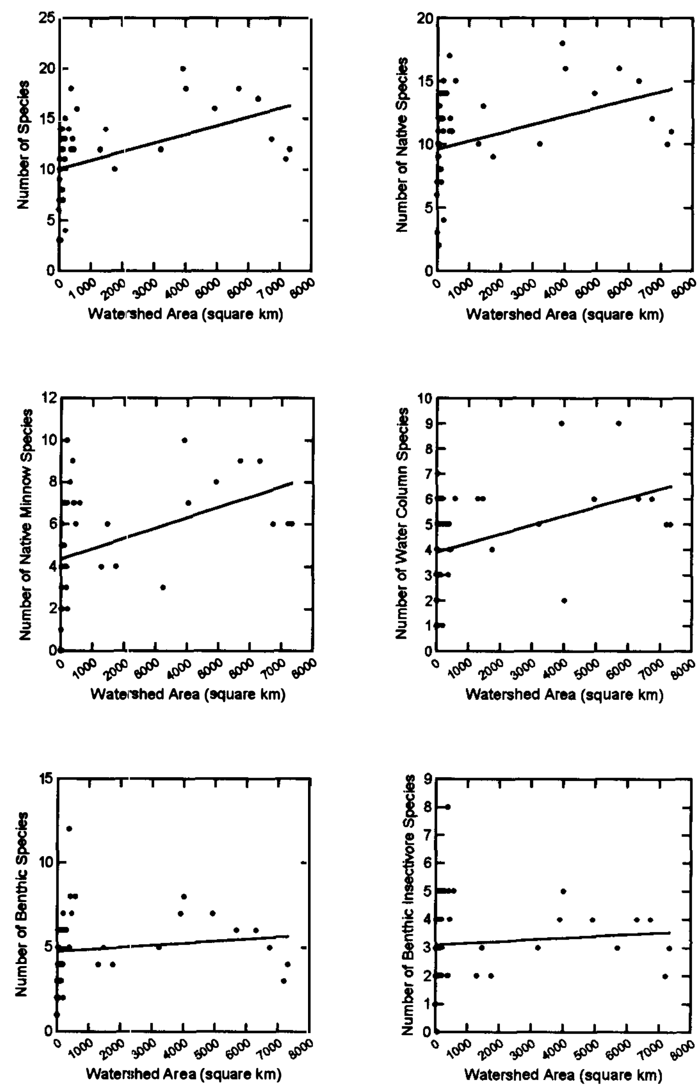


Figure 3-18. Scatterplots of species richness attributes for 43 sites in the Big Sioux River watershed.

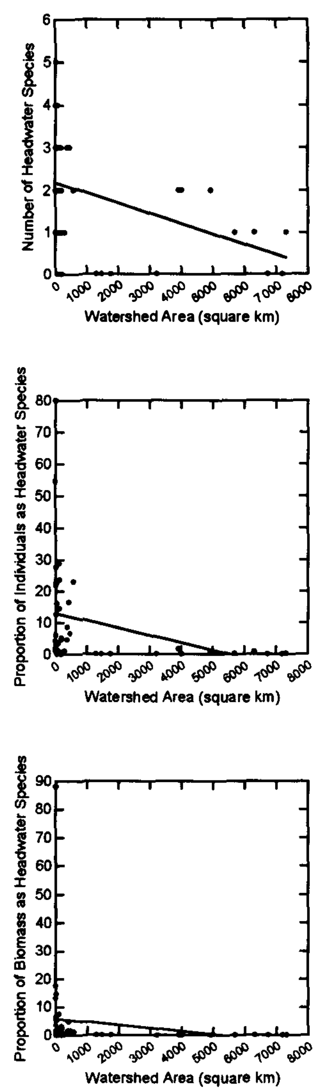


Figure 3-19. Scatterplots of headwater attributes for 43 sites in the Big Sioux River watershed.

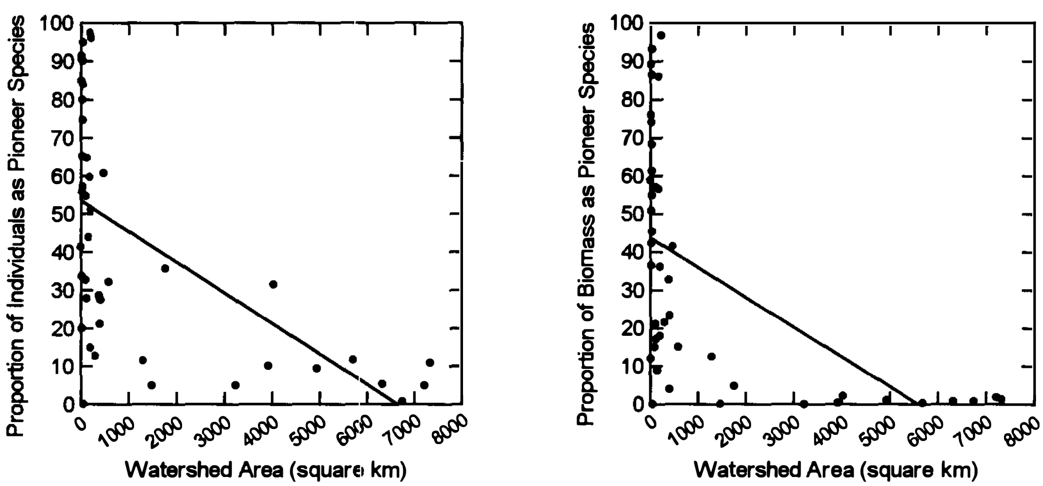


Figure 3-20. Scatterplots of pioneer species attributes for 43 sites in the Big Sioux River watershed.

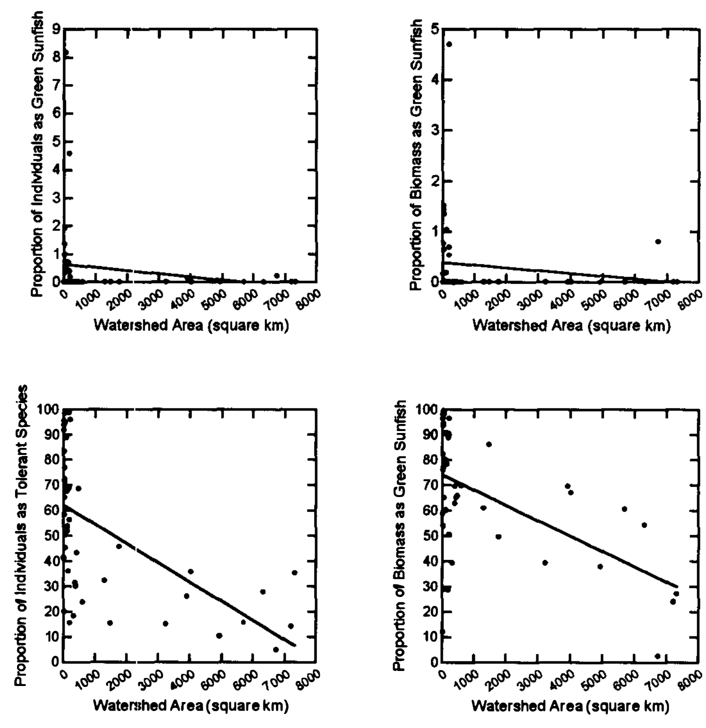


Figure 3-21. Scatterplots of green sunfish and tolerant species attributes for 43 sites in the Big Sioux River watershed.

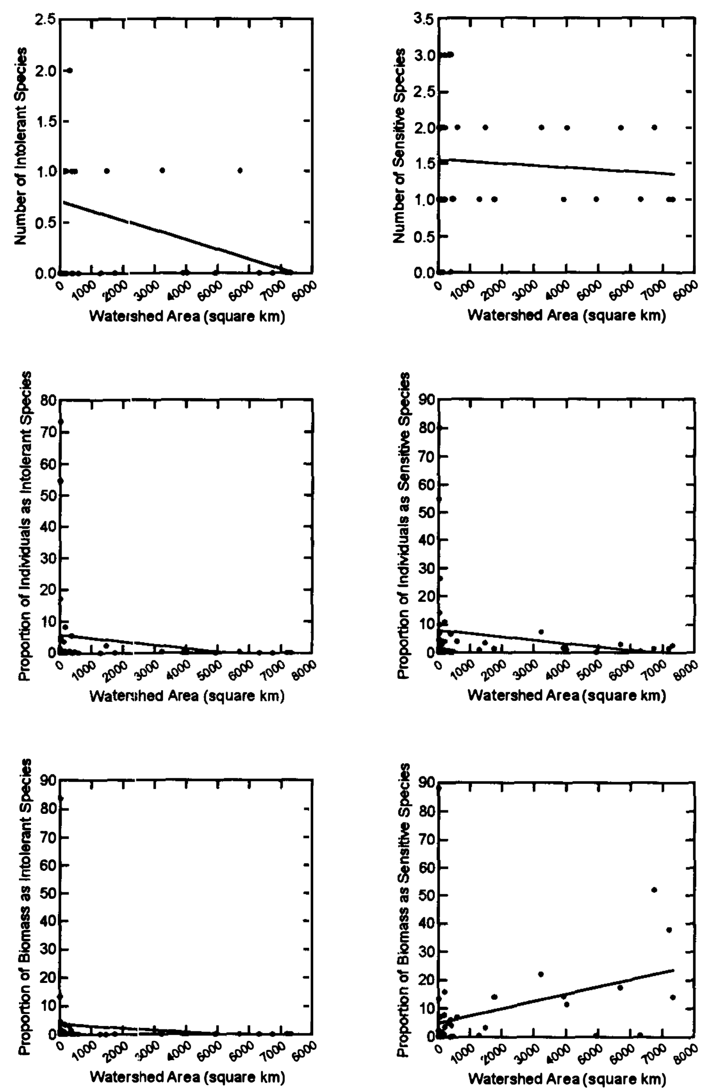


Figure 3-22. Scatterplots of intolerant and sensitive species attributes for 43 sites in the Big Sioux River watershed.

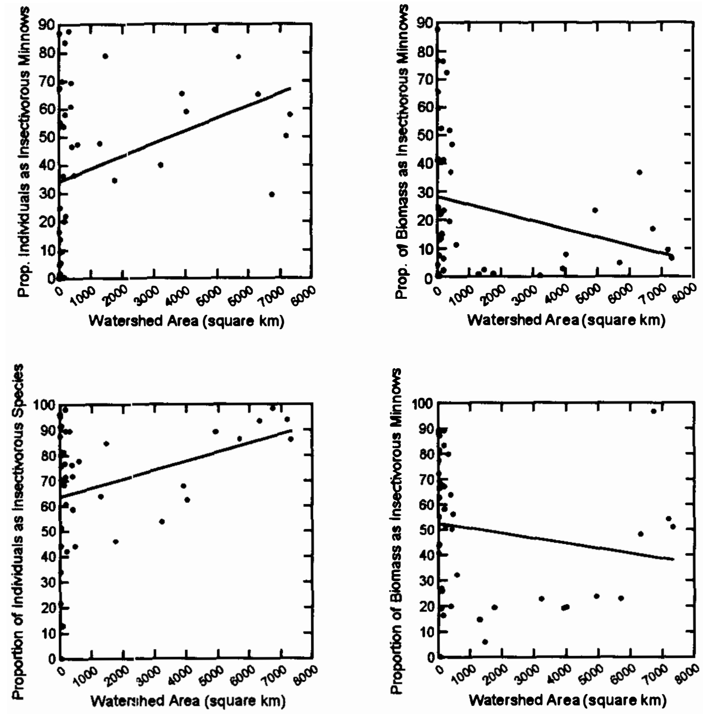


Figure 3-23. Scatterplots of minnow species attributes for 43 sites in the Big Sioux River watershed.

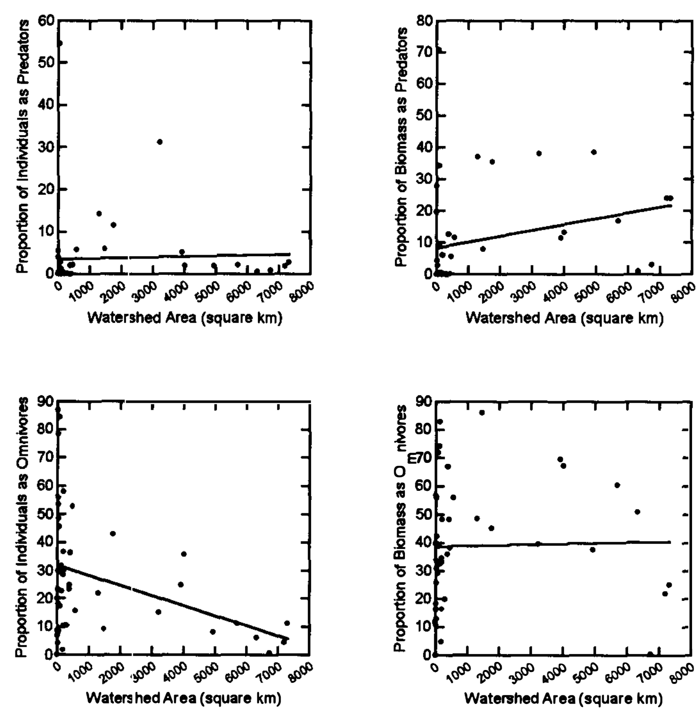


Figure 3-24. Scatterplots of predator and omnivore attributes for 43 sites in the Big Sioux River watershed.

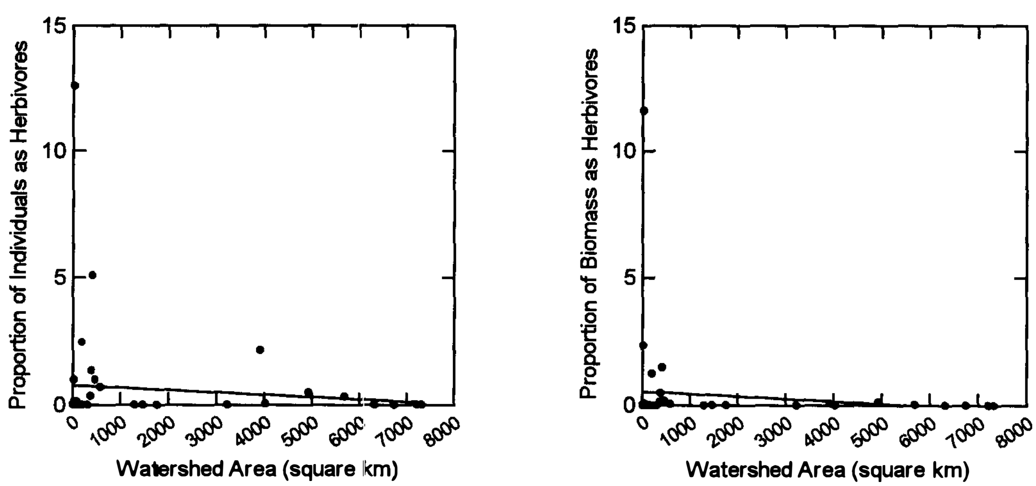


Figure 3-25. Scatterplots of herbivore species attributes for 43 sites in the Big Sioux River watershed.

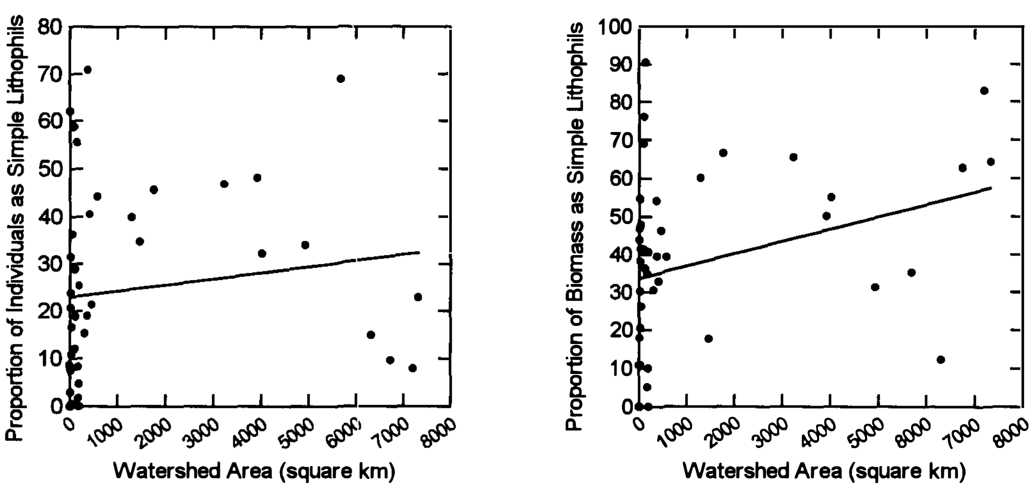


Figure 3-26. Scatterplots of simple lithophil attributes for 43 sites in the Big Sioux River watershed.

Table 3-6. Fish community attributes and their significant correlations with habitat variables. Spearman rank correlation (r_s) was used and because of the large number of variables in the analysis, a P-value of 0.001 was selected as the level of significance.

Fish community attribute	Habitat variable	r_s
Number of species	Watershed area	0.6207
	Channel top width	0.6660
	Channel bottom width	0.6668
	Bankfull width	0.6902
	Percent bank as depositional	0.6719
	Water surface width	0.6635
Number of native species	Channel top width	0.6384
	Channel bottom width	0.6668
	Bankfull width	0.6647
	Water surface width	0.6381
Number of native minnows	Watershed area	0.6500
	Channel top width	0.6700
	Channel bottom width	0.7106
	Bankfull width	0.7175
	Water surface width	0.7314
Number of benthic species	Dissolved oxygen	0.6334
Number of intolerant species	Mean depth	-0.7454
Proportion of individuals as simple lithophils	Flow	0.7693
	Mean velocity	0.7226

Discussion

Theoretically, in any given geologic-climatic region, the outcome of locally interacting variables and systemic changes in the downstream transport of sediment and water is a broad pattern of site-specific physical habitat conditions (Vannote et al. 1980; Burssock et al 1985; Ward 1988; Brinson 1993). In some regions, the larger systemic patterns and local interaction have been organized into a hierarchical framework (classification) that have been used to predict potential physical states given changes in landuse, to assess the success and failures in local habitat improvements, and to define realistic approaches to stream protection and restoration (Frissell et al. 1986; Frissell and Nawa 1992). With these same uses intended, my findings suggest that within the sub-humid, glacial landscape of the upper and central Big Sioux River watershed, a hierarchal level of systemic controls can be defined that begin to accommodate the broader longitudinal patterns in physical habitat. Nested within this hierarchical level at a lower spatial scale are riparian-related controls on physical habitat.

Local vs Systemic Controls in Small Watersheds

In the Big Sioux River, the greatest influence on site-specific physical habitat was longitudinal patterns in channel conditions and substrate, which are broadly related to the systemic-level dynamics of sediment and water. However, it was quite apparent that in the smaller watersheds, which include all tributaries and the 5 upper reaches of the Big Sioux River, a wide range of physical conditions existed. Most noticeable is that these sites with smaller watershed do not separate into distinct groupings with respect to channel and bankfull dimensions; and furthermore, the continuum of "less erosion and slumping" to "more erosion and slumping" fail to show any relationship with rankings of watershed size (Figure 3-3). The question then is "are local controls or systemic controls responsible for this range of condition in small watersheds?" The answer is that probably both influence channel and bank conditions, as well as riparian-related cover types.

More specifically, my findings suggest that it is the streams with watershed sizes of less than 150 km^2 where local riparian conditions substantially interact with sediment and water transport processes to influence site-specific habitat conditions. The most substantial evidence was that the greatest amount of overhanging vegetation occurred along streams with the smallest bankfull widths (<3 m) and bankfull depths (<0.4 m). The banks of these streams were covered with 60% vegetation or more, depositional banks were rare, and bank slumping was virtually absent. Landuse was pasture, but the current level of animal vegetation use could not account for variation among tributary sites. Many studies have demonstrated the positive effects that herbaceous vegetation has on stream dynamics usually in response to removal of grazing pressure in small, low gradient streams (Beschta and Platts 1986; Clifton 1989). However, beyond a certain bank height and angle, and bank substrate, a critical bank height threshold is reached where bank failure occurs (Little et al. 1982; Grissinger and Bowie 1984). Then, local riparian conditions, which consist wholly of herbaceous vegetation, do not have the structural capacity to have a significant influence on bank stability, and thus, site-specific habitat conditions.

Beyond a threshold of herbaceous vegetation to have an effect on site-specific habitat, physical habitat in small streams become systemically more of a product of sediment and water transport. My findings show that among tributaries, the wide range in physical habitat indicates a range in sediment and water transport balances. Several phenomena are probably responsible for this variation: hydrologic alterations caused by upland conversion of prairie to agriculture, cumulative loss of riparian buffering capacity, subtle differences in subwatershed hydrology and geology, and flow fluctuations. These concerns need to be further addressed, because these kinds of phenomenon influence ecological indicators useful for assessing watershed health.

Local vs Systemic Controls in the Big Sioux River

In watersheds greater than 1000 km^2, which are entirely in the Big Sioux River, two distinct patterns emerge that are related to systemic processes. First, most channel and bankfull dimensions increase consistently with watershed size, which would indicate consistent downstream increases in bankfull discharge (Leopold et al. 1964). Second, 3 sites with watershed sizes between 1000 and 2000 km^2 have very little bank deposition, higher bank erosion and slumping, and lower percentages of sand bed substrate compared to 9 sites downstream. This is consistent with sediment transport processes in rivers where upper reaches are generally suppliers of sediment and downstream reaches are receivers of sediment (Chang et al. 1982; Brinson 1993). Historically, it is unknown how the rates of sediment and transport processes have been altered, but during this study, similarities in the relative channel dimensions, bank conditions and bed substrates suggest that sediment and water transport in the upper 3 reaches were in similar equilibrium and that in the lower nine reaches were in similar equilibrium. My findings suggest the 3 sites had downcutting as a dominant process and the lower 9 sites had lateral migration as a dominant process.

Upon this template of systemic dynamics and dominant processes, local controls on site-specific habitat can be assessed. My findings show that overhanging vegetation and undercut banks decline with watershed size to very low lateral distances. As with the tributaries, these low distances probably correspond to increased bank heights, bank slumping, and banks as depositional features. In contrast, LWD became a prominent feature within the stream channel as soon as woody vegetation was present in the riparian areas. I should note, however, that woody vegetation was infrequently the dominant vegetation providing bank support in the reaches that I sampled. Woody vegetation was found as isolated patches of trees within the floodplain connected by scatterings of trees near the banks. In fact grasses, particularly reed canary grass, was the dominant vegetation that contributed root structure to the immediate stream banks. It was doubtful that this restricted lateral migration of the stream banks, which was responsible for periodic toppling of trees into the stream channel.

Although trees can influence channel morphometry (Beschta and Platts 1984; Trottor 1990; Flebbe and Doloff 1991), provide habitat for prairie stream organisms (Walsh 1992; Shumacher 1995), and serve as a major substrate and refuge for invertebrates in sand-dominated streams (Wallace and Benke 1984; Hax and Golladay 1998), my findings are limited in scope and are inconclusive on this aspect. However, what they do show is the ability of a limited woody environment in the riparian zones of lower river reaches to contribute significantly to stream habitat. One important observation was that the length of reach sampled in these lower river sites often spanned more than one landuse type, which often showed evidence of different intensities of long-term animal vegetation use not measurable by simple herbaceous standards. This would partially account for the patchiness of diverse woodland vegetation connected by a scattering of mature trees. The importance of woody vegetation to the ecology of the Big Sioux River needs closer scrutiny, much like that proposed to analyze the effects of large indigenous animals (e.g., beaver, moose) on habitat patch dynamics in river corridors (Naiman and Regers 1997).

Fish Community Attributes

Theoretically, fish communities in tributaries in prairie environments would be expected to have few strong relationships to the physical environment alone (Stauffer and Goldstein 1997), and that fish community attributes would be subject to the effects of flow fluctuations (seasonal and annual) (Ross et al. 1985; Bart 1989; Fausch and Bramblett 1991; Schlosser 1992), and concomitant water quality extremes (Smale and Rabeni 1995). Nevertheless, in one obvious respect my findings showed that fish community attributes generally exhibited a wider range in values in small streams than in the river, which was also the case for the physical traits. In fact, I suspected that the wide range in values of physical habitat variables might explain the wide range in values of fish community attributes. However, from the large number of possible correlations, only a small percentage was significant. Although a larger sample size and more sophisticated multivariate analysis may elucidate complex relations with physical habitat, the few significant correlations of fish community attributes to physical variables clearly indicate that systemic processes at the sub-watershed level need to be understood.

One significant regional consideration should be given to temporal shifts in wet and dry phases that have pronounced ecological consequences in prairie ecosystems. Prior to and during this study, a series of wet years caused sufficient runoff to maintain perennial flows in tributaries, which should have allowed for upstream migrations and recolonization of habitat space within tributary reaches. Clearly, attributes related to headwater species and pioneering species were most pronounced in smaller watersheds; yet within these small watersheds the range in their values suggest physical habitat or other variables were influential during a wet phase. However, the lack of significant correlations with the range of physical conditions suggests that other variables are important to resident headwater fishes and that recolonization is not necessarily dependent upon local conditions.

My findings are not to be totally unexpected since others have found that the fish communities in prairie streams do not correlate well with local physical conditions (Stauffer and Goldstein 1997). In eastern South Dakota, the reasons probably reflect natural limitations as well as landuses. As I alluded to above, where natural flow conditions fluctuate dramatically fish populations are usually persistent, but abundances are not usually as stable as they are in environments that fluctuate less (Ross et al. 1985; Poff and Ward 1989). Fish in these environments are usually subject to low oxygen and high temperatures associated with low flows, which can extirpate local fish populations. In addition to these natural limitations, the landscape has been converted to intense agricultural uses, which are known to alter sediment and flow regimes, stream buffering capacity, and water quality (National Research Council 1992), and in turn, have greater effects on the biological health or integrity of streams than local conditions (Roth et al. 1996; Wang et al 1997). Thus, the range in cumulative effects among tributaries probably confounds findings. Incorporating stream level variability into analysis of site-level fish and habitat relationships may elucidate more conclusive effects of site-level habitat effects on fishes (Dunham and Vinyard 1997).

Management and Research Needs

Although a hierarchy of local and systemic controls can be defined for the broader Big Sioux River watershed that begin to explain the formation of site-specific physical habitat, more research needs to be given to the tributaries. I suggest three major areas of knowledge are needed. First, cumulative effects, which encompass the interactions of natural processes with land use activities, needs to be analyzed at appropriate scales (Sidle and Hornbeck 1991). In the Big Sioux River, the most appropriate scale would be at the subwatershed or tributary scale. In fact, study of the cumulative effects on stream fish communities and habitat at the subwatershed level is an absolute necessity in eastern South Dakota given the intense agricultural land uses. An approach that identifies and compares least-impacted subwatersheds with hydrologically altered subwatersheds would provide the understanding needed to determine when cumulative effects have altered the hydrology to the point that local streamside vegetation no longer contributes to structural stability to tributaries. Loss of structural stability through cumulative hydrological alterations in tributaries eventually can lead to reduced physical stability of the receiving river. In eastern South Dakota, most likely the hydrology has been altered as a result of changes to the landscape (Miller and Nudds 1996). However, the level of alteration and its effects on stream ecology are probably not as extreme as rivers and streams in adjacent Midwest agricultural regions where wetlands and subsurface drainage is prevalent.

Second, knowledge on the subsurface hydrology and its relationship to fish persistence in tributaries, especially during low flows or intermittency, is absolutely necessary to the long-term preservation of ecological communities in eastern South Dakota. The ability of a stream to provide critical low flow habitat in the form of suitable "pool patches" may be critical for recolonization of tributaries following resumption of flows (Watzin and McIntosh 1999). Tributaries with abundant "patches" compared to tributaries with few "patches" would theoretically be more resilient. Recent research has shown the importance of subsurface hydrology to Topeka shiner populations in eastern South Dakota tributaries (Wall et al. 2001), and this same approach holds promise for other fishes or community attributes.

Third, a database that is standardized with field protocol and compatible with geographical information systems (GIS) at SDSU, Wildlife and Fisheries Sciences is critical. I developed a relational database that is compatible with field protocol and GIS. Currently, it is being tested by a local government agency in watershed assessments of the Big Sioux River and has proven user friendly by technicians. Further improvements will prove beneficial to assessment and monitoring activities designed to develop management plans for protection and restoration efforts.

CHAPTER 4

AN EXPERIMENTAL TEST OF THE EFFECTS OF BIOTIC INTERACTIONS, WOODY DEBRIS, AND TURBIDITY

movement by spawning fish, recolonization, reproduction and recruitment, and habitat use) have been shown to vary substantially among years and seasons due to variation in flow regime (Walsh 1992; Bratten 1993; Dieterman 1995; Fisher 1995). Despite variation in flow regime and its effects on fish community dynamics, fish species have persisted over time (Bratten 1993; Dieterman 1995). Persistence of aquatic organisms in prairie streams affected by wet-dry cycles depends to a large degree on the ability to exhibit resilience (recolonization) following periods of low flow (Stanley and Fisher 1992) when survival in a shrinking environment can depend on habitat complexity and biotic interactions (Capone and Kushlan 1991; Fausch and Bramblett 1991; Pusey et al. 1993). During low flows as habitat volume shrinks, biotic interactions may occur or intensify and thus produce physical habitat limitations.

If physical habitat coupled with low flows define critical periods for fish communities, then establishing the role of physical habitat to fish communities during these critical periods would justify habitat protection and restoration despite long-term generality in physical habitat-use patterns. The availability and use of physical habitat is partly dependent on local and systemic controls. In the mainstem reaches, local control includes the inputs of large woody debris, which provide cover for fishes (Walsh 1992). However, prairie streams in agricultural landscapes are often systemically subject to higher than natural turbidity (Karr et al. 1985; USEPA 1990), which has been shown in studies to affect the behavior of fishes (Newcombe and MacDonald 1991). Both large woody debris and turbidity have been the focus of studies and assessments with implications for management of rivers in eastern South Dakota. In situ studies or assessments should try to account for the influence of turbidity on use of specific habitat components by fish, which may confound findings used in making management decisions. My laboratory experiment examined the effects of habitat complexity and turbidity on fish behavior.

Direct observation of these mechanisms under controlled and easily manipulated laboratory conditions will provide insight into use of fish habitat that may be moderated by local and systemic controls. My goal was to examine the potential role of fish cover to common, native fish species during critical periods of low streamflows that may be useful for protection and restoration efforts. I tested the effect of large woody debris, competition, and predation on habitat partitioning by common minnow species under simulated low turbidity and high turbidity drought conditions. I proposed two research hypotheses: 1) habitat use by minnow species commonly tolerant of low flow conditions will be generalized in the absence of competitors or predators, but will be partitioned in the presence of competitors or predators, and 2) turbidity will reduce habitat partitioning because visual perception among species will be impeded.

Methods

Experimental Streams

Experimental streams were designed to simulate typical low flow conditions in prairie streams in eastern South Dakota. Three experimental streams were designed with drop-gates and removable cover to facilitate counting of fish at the end of each trial run. Each stream was made of fiberglass construction with dimensions of 0.7 m wide by 9.75 m long (9.1 m usable) (Figure 4-1). The bottom consisted of washed sand and was adjusted to simulate an alternating series of shallow (7-10 cm) and deep areas (36-40 cm). These areas were equal in surface area (1.6 m^2). Removable woody debris cover units (WDCU) were constructed with aerial dimensions approximating 0.5 m wide by 1.0 m long that would fit within a shallow or deep area. The structure of each WDCU consisted of three parallel pieces of American elm (each one about 20–45 cm diameter) spaced 5-10 cm apart and were held together by nailing smaller pieces of wood across their top surface. Discharge circulation was adjusted so that water levels were held constant and stream velocities were about 1 cm/sec in shallow habitats. Water temperatures approximated that normally found during mid-summer in natural streams (28-33 °C). Dissolved oxygen was never less than 6 mg/L. Ambient light:dark ratio was held constant at 14:10 using fluorescent lights and automated switches. Low turbidity trials were performed during the first half of experimentation with municipal water that had no added suspended solids. High turbidity trials followed and suspended solids were added in the form of clayey muck from a nearby tributary. When water was being pumped (recirculated) from the experimental streams' receiving tank to the elevated

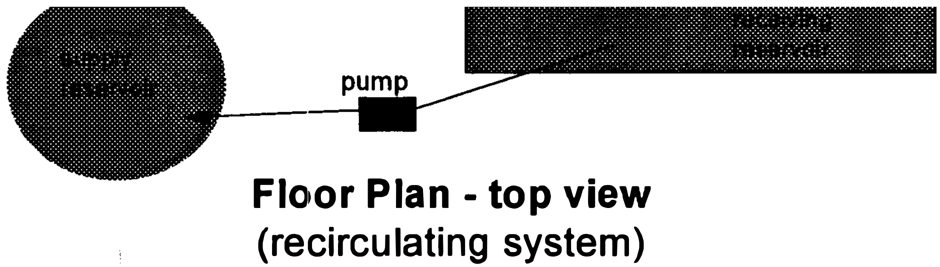


Figure 4-1. Floor plan diagram of three experimental streams.

source tank, muck was gradually added into the turbulence of the source tank. Water turbidity during low turbidity trials less than 5 NTUs, and during high turbidity trials was around 200 NTUs.

Experimental Design

A suite of low turbidity trials was performed and then a suite of high turbidity trials was performed. For a trial, one of 28 possible combinations of four woody debris (WD) configurations (Figure 4-2) and seven "community" types (Table 4-1) was randomly selected for each experimental stream so that each had a different WD

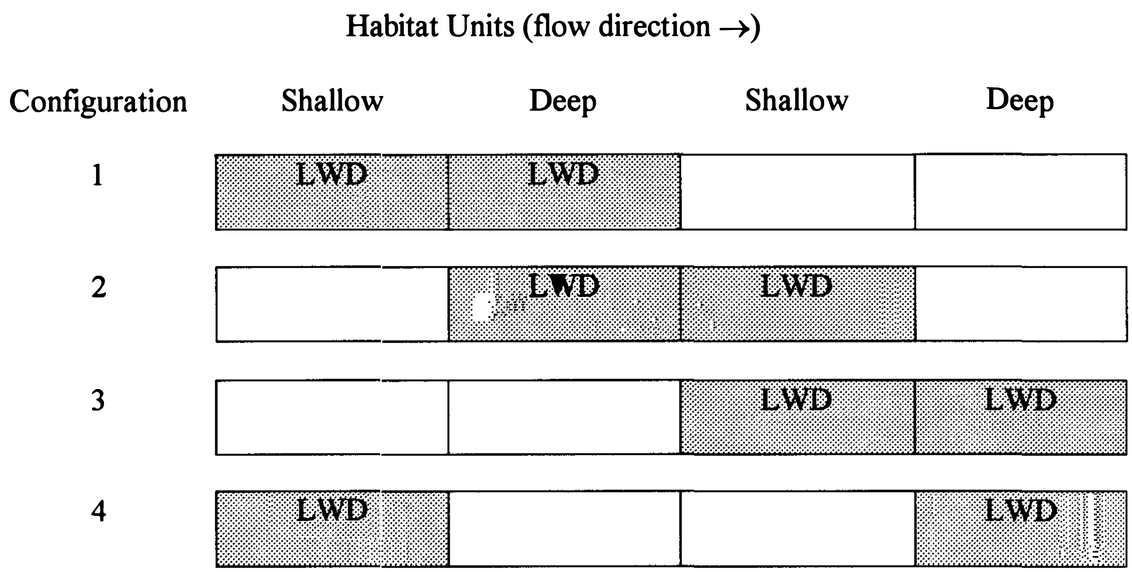


Figure 4-2. Four possible configurations for woody structure in both a shallow and deep area (shaded boxes with LWD).

Table 4-1. Seven "community" types used in the laboratory trials.

1. Sand shiners
2. Red shiners
3. Black bullheads
4. Sand shiners and Red shiners
5. Sand shiners and Black bullheads
6. Red shiners and Black bullheads
7. Sand shiners, Red shiners, and Black bullheads

configuration, and a different "community" type for each trial. At the end of all trials, each combination had been tested once per experimental stream, thus providing 3 replicates per combination or 12 per habitat type. Because each combination was selected at random per stream, spatial interspersion encapsulated variation associated with habitat configuration, unknown disparities among streams, and laboratory apparatus; and temporal interspersion encapsulated variation associated with fish size and health, and laboratory ambiance. These trials were performed again, but under high turbidities following the same protocol. Thus, variation associated with turbidity was interspersed. For my experiment, I selected red shiners and sand shiners as prey species and as potential competitors. I selected black bullheads as a predator species. I selected these species for two reasons: they are common in prairie streams and readily obtainable in large numbers from local streams. All species were collected using bag seines and kept in separate holding tanks before use. For each trial, a fresh batch of red shiners (25 individuals), sand shiners (25 individuals), and black bullhead (5 individuals) were used when needed. Minnow densities were within the range of those found during my field studies.

Statistical Analyses

Data were combined into a three-way ANOVA to simultaneously test the research hypotheses that 1) common minnow species will be generalized in cover use in the absence of competitors and predators, and under different levels of turbidity, and 2) minnow species will become selective in cover use in the presence of competitors or predators, but less so at higher turbidity levels. Multiple pair-wise comparisons were made when tested effects were significant.

Results

Minnow Habitat Use, Community Composition, and Turbidity

Red Shiners.--ANOVA test results for red shiners found a significant two-way interaction between habitat and community, and between habitat and turbidity (Table 4-2). Generally, red shiner numbers were greater in deep areas than in shallow areas (Figure 4-3). However, in communities that had predators (i.e., RB, and RSB), red shiner numbers were greater in deep areas without WD than in deep areas with WD (Figure 4-3). Although red shiner numbers were greater in deep areas with and without WD compared to shallow areas with and without cover (Figure 4-4), their numbers were found in greater numbers in shallow areas when turbidity was high (Figure 4-4). In sum, red shiners were not generalized in habitat use, but selected the deeper areas. Red shiners shifted their selection of deep areas to that without WD when a predator selected deep areas with WD. Red shiners increased their selection of shallow areas when turbidity was high.

Sand Shiners.—In the ANOVA test, a significant three-way interaction (Table 4-3) confound straight-forward interpretation but patterns do emerge (Figure 4-5). Most obvious was that sand shiner numbers were generally greater in deep areas with and without WD than in shallow areas with and without woody debris (Figure 4-5). However, sand shiner numbers were higher in shallow areas when turbidity was high (Figure 4-5). Finally, sand shiner numbers were higher in deep areas without WD than in deep areas with cover in 3 of 4 scenarios when in the presence of predators (Figure 4-5). In sum, sand shiners were not generalized in habitat use but selected deeper habitat types. When turbidity was high selection of habitats were rather similar. Sand shiners shifted their selection of deep areas to that without WD when a predator selected deep areas with WD. However, when turbidity was high and in the presence of a predator, sand shiners continued to select deep areas over shallow areas.

Predator Habitat Use and Prey Consumption

Two *A posteriori* tests were performed for black bullhead habitat use and prey consumption. ANOVA test results show a significant interaction between habitat and turbidity (Table 4-4). When turbidity was low, black bullheads were found almost exclusively in deep areas with WD (Figure 4-6). When turbidity was high, black bullhead numbers were greater in deep areas without WD than when turbidity was low (Figure 4-6).

ANOVA results show a significant interaction between the number of prey consumed and turbidity (Table 4-5). When only a single prey species was present, the number of prey consumed was not significantly different between levels of turbidity (Figure 4-7). When both prey species were present, the number of prey consumed was significantly higher at low turbidity than at high turbidity (Figure 4-8).

Table 4-2. Analysis of variance results for the log_{10}(number of red shiners +1) among 4 habitat types, 4 community types, and 2 levels of turbidity.

Source of Variation	df	MS	F	Significance
Habitat	3	10.41	90.69	P<0.01
Community	3	0.54	4.68	P<0.01
Turbidity	1	1.95	17.00	P<0.01
Habitat x Community	9	0.44	3.80	P<0.01
Habitat x Turbidity	3	0.57	5.00	P=0.01
Community x Turbidity	3	0.16	1.36	P=0.25
Habitat x Community x Turbidity	9	0.09	0.80	P=0.62
Error	52	0.11		

Table 4-3. Analysis of variance results for the log_{10}(number of sand shiners +1) among 4 habitat types, 4 community types, and 2 levels of turbidity.

Source of Variation	Df	MS	F	Significance
Habitat	3	8.80	49.80	P<0.01
Community	3	0.64	3.62	P=0.01
Turbidity	1	2.16	12.24	P<0.01
Habitat x Community	9	0.90	5.10	P<0.01
Habitat x Turbidity	3	0.54	3.06	P=0.03
Community x Turbidity	3	0.33	1.84	P=0.14
Habitat x Community x Turbidity	9	0.37	2.11	P=0.03
Error	52	0.18		

Table 4-4. Analysis of variance results for the log_{10}(number of black bullhead +1) among 4 habitat types and turbidity.

Source of Variation	df	MS	F	Significance
Habitat	3	7.6284	256.4433	P<0.0001
Turbidity	1	0.0607	2.0412	P=0.0001
Habitat x Turbidity	3	0.3824	12.8554	P=0.0070
Error	328	0.0297		

Tables 4-5. Analysis of variance results for number of preyed consumed by black bullheads.

Source of Variation	df	MS	F	Significance
Community Type	2	12.8906	1.0118	P=0.3677
Turbidity	1	4.8167	0.3781	P=0.5402
Community Type *Turbidity	2	57.3906	4.5045	P=0.0137
Error	90	12.7407		

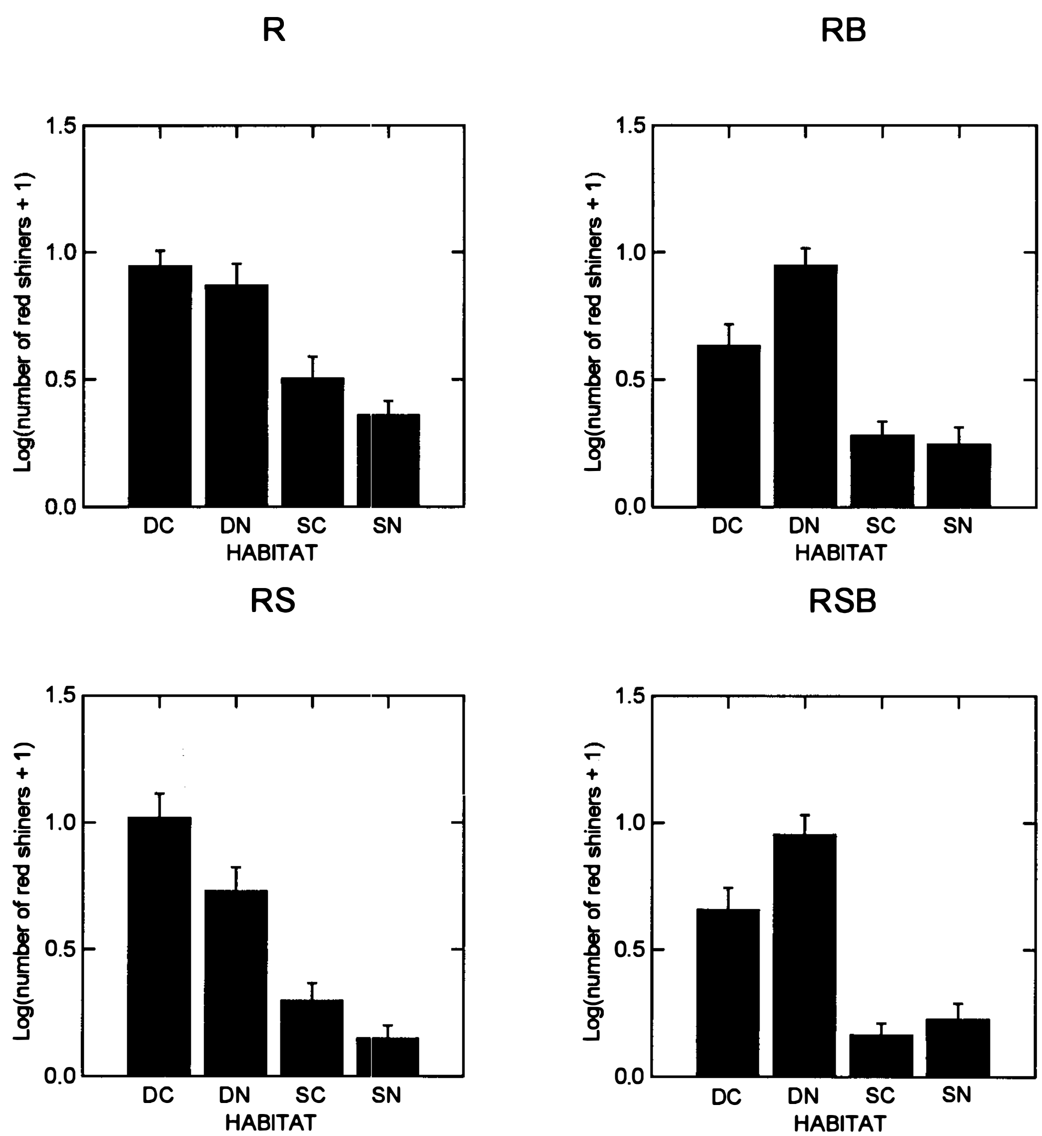


Figure 4-3. Log_{10}(number of red shiners +1) within four habitat types (DC=deep areas with cover, DN=deep areas without cover, SC= shallow areas with cover, and SN= shallow areas without cover) under four different community types (R=red shiners, RB=red shiners and black bullheads, RS=red and sand shiners, and RSB=red and sand shiners and black bullhead).

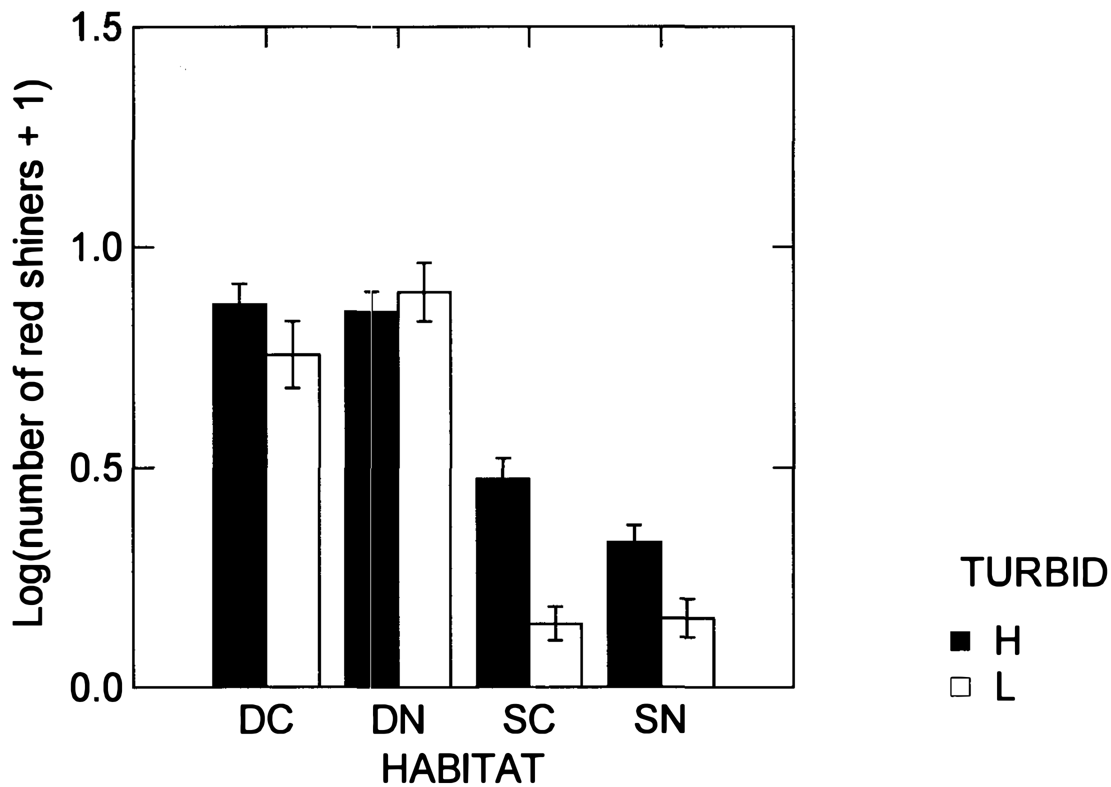


Figure 4-4. Log_{10}(number of red shiners + 1) within four different habitat types (DC=deep areas with cover, DN=deep areas without cover, SC= shallow areas with cover, and SN= shallow areas without cover) under two different turbidity levels.

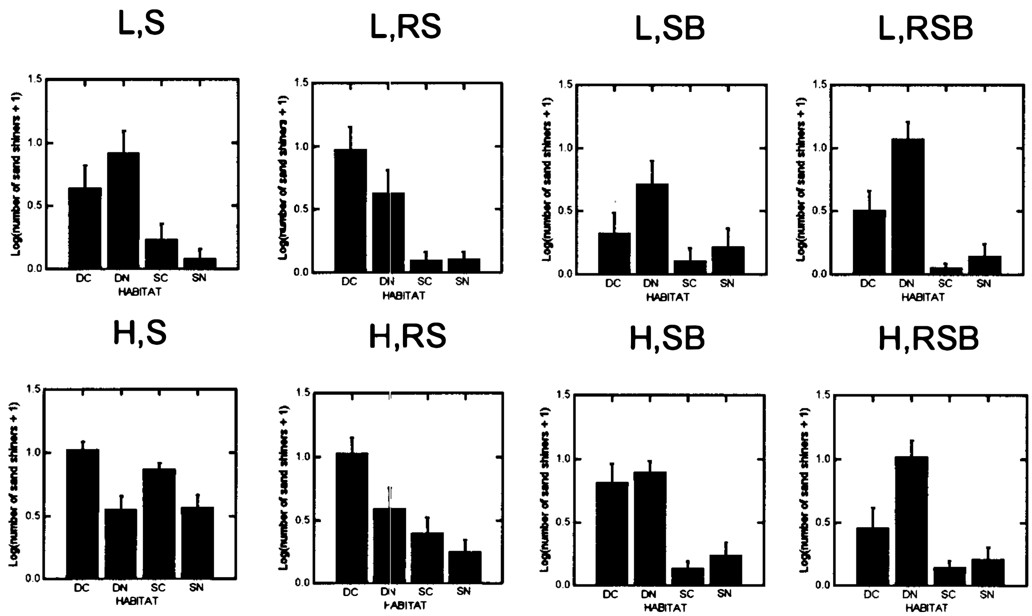


Figure 4-5. Log_{10}(number of sand shiners + 1) within four habitat types (DC=deep areas with cover, DN=deep areas without cover, SC= shallow areas with cover, and SN= shallow areas without cover) under 8 combinations turbidity (H=high, and L=low) and community type (R=red shiners, RB=red shiners and black bullheads, RS=red and sand shiners, and RSB=red and sand shiners and black bullhead).

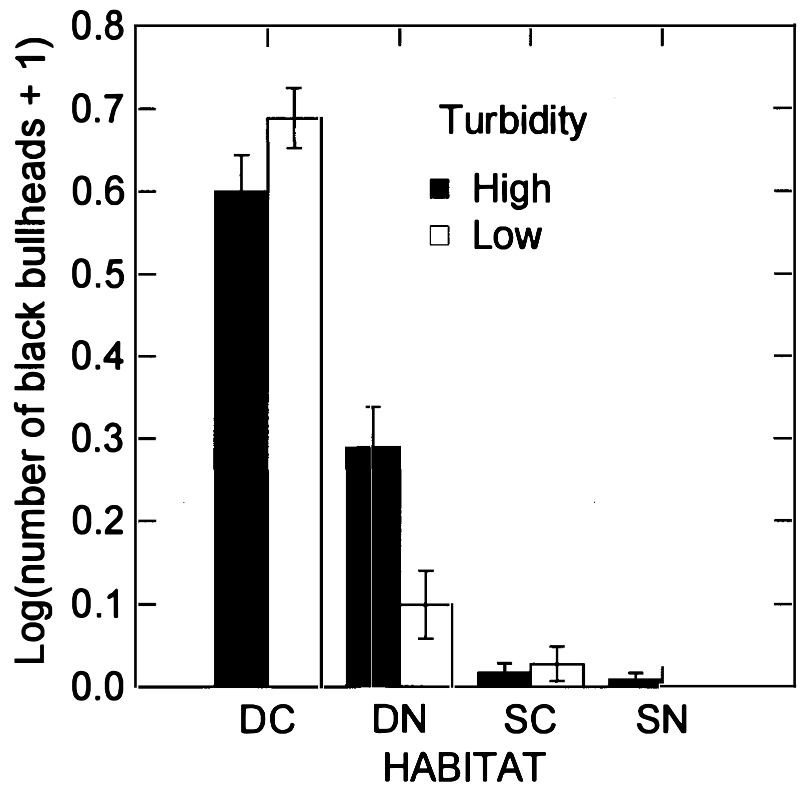


Figure 4-6. Log_{10}(number of black bullheads +1) within four different habitat types (DC=deep areas with cover, DN=deep areas without cover, SC= shallow areas with cover, and SN= shallow areas without cover) under two levels of turbidity.

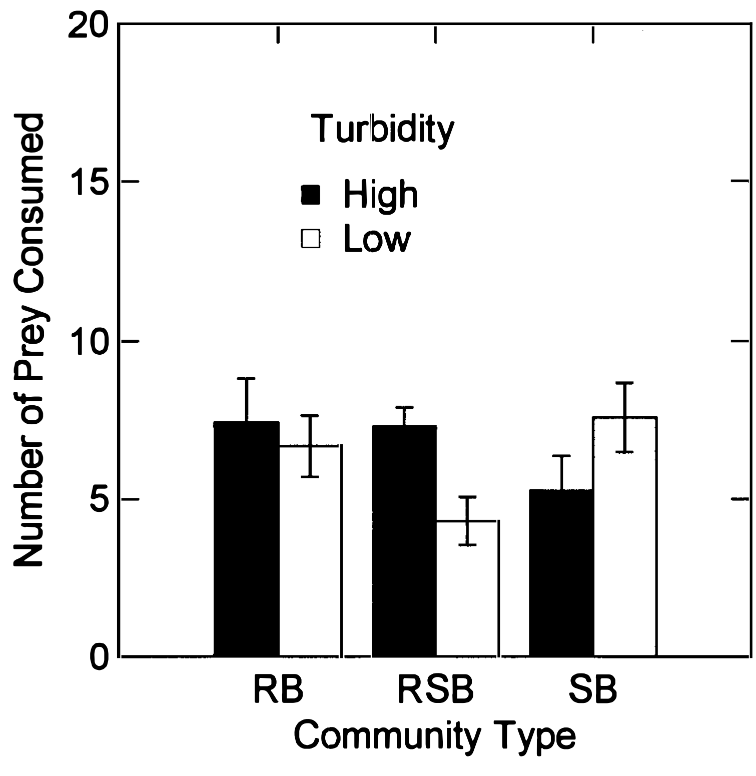


Figure 4-7. Number of prey consumed by black bullheads within three community types (RB=red shiners and black bullheads, RS=red and sand shiners, and RSB=red and sand shiners and black bullhead) and two turbidity levels.

Discussion

Fish in prairie streams readily adjust to changing environmental conditions, but during drought biotic interactions may intensify and be moderated by habitat complexity. Habitat complexity in prairie streams may come in the form of large woody debris that is important as cover during drought (Walsh 1992). However, some prairie streams are high in suspended solids due either to natural causes or to landuse activities that have altered sediment transport dynamics (Waters 1995). High suspended solids create turbid conditions that are known to affect fish behavior (Newcombe and MacDonald 1991). My findings provide insight into the interactions of habitat complexity, community dynamics, and turbidity on habitat partitioning by stream fishes that may be useful to consider in habitat protection and restoration efforts.

My findings suggest that predation is more important than competition in partitioning habitat use by minnow species. Two small minnow species (red and sand shiners) used the deeper pockets of water more than the shallow areas. Also, minnow use of deep areas showed no apparent selection for that which contained woody debris. However, although not completely unambiguous, minnows tended to more frequently use deeper areas without cover when bullheads were occupying deep areas with cover. These results are similar to that found in the James River in eastern South Dakota during dry periods (Tol 1976; Walsh 1992).

An implication is that pockets of water with woody debris may be critical for the resistance of some species (predator and prey) to extirpation during drought. Systematic removal of woody debris from the channel and bank consequently removes existing sources of inputs and potential loss of critical drought habitat patches. Consequently, the resilience (ability to repopulate) of species that depend on these habitat patches may also be reduced when higher flows resume.

These habitat use patterns may mimic unperturbed stream conditions; however, the effects of suspended solids common in perturbed prairie streams occur when fish change their behavioral activity patterns (Newcombe and MacDonald 1991). My findings indicate that high turbidity changed the behavior of prairie stream fishes. High turbidity modified physical habitat use by both minnow species and a predator. Presumably high turbidity served as cover for fish, which would explain more frequent use of shallow areas by minnows and more frequent use of deeper areas without woody debris by the larger predator. These finding suggest that in some prairie streams high levels of turbidity can govern fish-habitat relations. In fact, the use of habitat by fish during low flows may become more generalized in turbid streams than in clear streams.

My experimental study simplified low flow conditions in order to isolate and define mechanisms of habitat use by fish in prairie streams. Although other important mechanisms associated with selection of habitat may included other life-history needs (e.g., food search, reproductive strategies, thermal refuge), my laboratory results indicate that during drought conditions 1) habitat complexity may be more important to larger predators than to smaller minnows, 2) competition between minnows may not be as critical as predation in mediating habitat use, and 3) high turbidity induces greater generality in habitat-use patterns. Future studies that view prairie river habitat as habitat patches nested within the landscape (system) level, and explore the effects of systemic level differences in turbidity at low flows on fish-habitat relations will likely prove beneficial to prairie stream protection and restoration efforts designed to maintain their physical, chemical, and biological integrity.

Chapter 5.

Implications for Protection and Restoration of Prairie Streams in South Dakota

Overview of Research Approach

My research approach was based on a premise that assessments of the health of rivers and streams in prairie environments would benefit from studies that 1) examine the role of systemic processes in moderating physical habitat and fish community attributes among geologic-climatic settings, 2) establish links between systemic processes and local interactions on fish attributes and physical habitat within a geologic and climatic setting, and 3) test the role of biotic and abiotic interactions on habitat partitioning by fish under critical flow scenarios common in prairie streams. My research has three complementary parts: two field studies and a laboratory experiment.

Research Hypotheses and Summary of Findings

The first field study tested the hypothesis that systemic processes moderate physical riverine environments in distinct ways between a semi-arid region and a subhumid region and that fish community attributes provide biological analogs that are also distinct. This hypothesis was supported in two respects. First, "harsher" streamflow patterns in the Bad River limit species richness and community complexity compared with the more "benign" streamflows in the Big Sioux River, which had both greater species richness and community complexity. The one obvious exception to the expected was that the Bad River had higher proportions of insectivores and less omnivores when compared to the Big Sioux River. Second, physical habitat in the Bad River did not show the rate of physical changes longitudinally like that of the Big Sioux River. As predicted, many of the community attributes did not change on the longitudinal axis as extensively as that in the Big Sioux River.

My findings show that after taking into account the effects of large-scale streamflow patterns on fish communities, it is possible to discern a river continuum in physical and biological terms. Furthermore, these field results suggest that a hierarchical classification based on nested geomorphic units and processes would define a framework that would help identify differences in physical heterogeneity among the large watersheds in prairie rivers of South Dakota. For example, preliminary "segment" delineation (GIS laboratory at SDSU, Wildlife and Fisheries Sciences) of rivers in South Dakota show that within the Bad River system about 6 major stream segments occur, while within the portion of the Big Sioux River system I studied about 24 stream segments occur. This corroborates with my stream "reach" results that show the Bad River changes less along its length than does the Big Sioux River.

The second field study tested the hypothesis that in a subhumid region the interactions of local variables have greater influence on physical habitat and fish communities in smaller streams than in rivers. For physical habitat, this hypothesis was partially supported. I did expect to find that local riparian vegetation (herbaceous) in small streams provided more local cover and it did, but only in streams with watersheds <150 km^2 or less than 3 m wide. I qualify this finding by stating that a large range of physical conditions were found in sites among tributaries that draw my suspicion that systemic controls in subwatersheds may vary and in turn mask some of the local interactions (i.e., some may be altered hydrologically more than others). In contrast, LWD was present only where woody vegetation was present in the riparian areas of the lower sites and remained fairly constant among these sites. I must qualify my findings for LWD by stating that woody vegetation is not the prominent vegetation in smaller streams and, furthermore, if this study had sampled woody habitat along the lower mainstem reaches of the Big Sioux River a broader picture of the effects of systemic processes would have been discerned.

In terms of fish communities, a large range in attribute values in tributaries could not be explained by a substantial number of variables and those that showed correlations were often with variables related positively to stream size (e.g., channel width) rather than substrate or riparian-related cover. My findings suggest that other variables are important to fishes in tributaries, such as, water quality, flow regime, reproduction, and recolonization rates. Variation in these factors among tributaries could mask the effects of physical habitat. Thus, more emphasis should be placed on these factors.

In the laboratory experiment I tested two research hypotheses. My first hypothesis stated that habitat use by minnow species commonly tolerant of low flow conditions will be generalized in the absence of competitors or predators, but will be partitioned in the presence of competitors or predators. My findings show that minnow species were not generalized in the absence of competitors or predators, but that they selected deeper areas over shallow areas with no preference for cover. Also, the presence of a competitor did not induce habitat partitioning but the presence of a predator that preferred deep areas with cover tended to induce slightly greater selection of deep areas with cover where the predator was mostly absent. My second hypothesis stated that turbidity will reduce habitat partitioning because visual perception among species will be impeded. My findings supported this hypothesis to the extent that all species were more general in their habitat use when turbidity was high. These findings exemplify the complex interactions that can occur between fish cover, biotic interactions, and water quality and expresses the need to protect or restore physical heterogeneity to compensate for changing conditions, particularly low flows during drought.

Management Implications for Protection and Restoration of Prairie Streams

My research was directed at two goals, provide managers with 1) a framework to assess the influence of local and systemic processes on fish and fish cover, and 2) basic insight into fish use of cover as influenced by habitat and biotic interactions at low flow. Toward those ends, I provide the four basic implications of my research that are interrelated and should prove useful to habitat protection and restoration efforts.

First, the efficacy of defining systemic controls on fish and fish habitat relative to flow regime and physical habitat continua using a stream reach, transect sampling method was substantiated in geologically and climatically distinct prairie streams of South Dakota. Thus, this assessment approach should continue as it holds promise to assess streams on a watershed-by-watershed basis. Furthermore, coupling this approach with GIS information will define the first three layers of a hierarchical classification for prairie streams (i.e., system, segment, reach).

Second, tributary watersheds need to be monitored as part of larger river management plans. Currently, the cumulative effects of landuse in the Big Sioux River watershed of South Dakota have partially affected the river's hydrology and water quality, which is mostly the sum of effects from tributaries. My study shows that tributaries reflect a range in the health of their watersheds. Efforts that protect or restore water quality, hydrology, riparian vigor, and channel patterns of tributaries need to be promoted so that the health of the Big Sioux River can be enhanced or protected from further degradation.

Third, habitat heterogeneity is probably critical during low flows in prairie streams. With the loss of habitat volume during drought, habitat complexity creates living space for predator and prey and may counter the effects of biotic interactions. Therefore, management involvement in river projects needs to emphasize minimization of activities that reduce instream complexity (e.g., snagging, channelization, sedimentation, clear cutting of riparian trees).

Fourth, sampling procedures used in this study should become standard. These procedures measure several physical traits that other disciplines are able to comprehend in terms of their expertise.

Research Needs

I identify three research needs.

First, semi-arid watersheds and, to a lesser extent, sub-humid watersheds may require assessments to evaluate the pool characteristics (i.e., patch structure) during extended drought periods to assess the importance of these as refugia and subsequently as sources of fish following the resumption of flows.

Second, an in-depth comparison of systemic controls (flow patterns and physical patterns) among all mainstem prairie rivers in South Dakota (east and west) would facilitate a fuller understanding of how variation in fish and physical habitat relate to subtle or discrete differences in natural systemic processes or human land and water use.

Third, because systemic alterations to the hydrological environments in tributary watersheds may be causing the lack of relationships between fish and habitat with local variables, a new approach is needed that assesses the integrity of the entire subwatersheds. I suggest that the stream ecologies of severely impacted watersheds be compared with least impacted watersheds.

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Appendix A

Definitions and measurements procedures for site variables (adapted from Wolman 1954; Platts etal. 1983; Robison and Beschta 1990; Gordon et al. 1992; Dolloff 1994; Simonson et al. 1994).

Transect – A line that extends from the left bank to the right bank, perpendicular to stream flow.

Channel bank (stream bank) – The sides of the channel (or stream) that typically restrict lateral movement of water and sediment.

Channel bottom (stream bed) – The bottom portion of the channel (or stream) that typically does not restrict lateral movement of sediment and water.

Bankfull – That point on the channel bank where flows begin to crest that bank and move onto the floodplain.

Bank top – Often the same point as bankfull except in stream that are incised.

Incised – Describes channels or streams with bottoms that have or are in the process of downcutting into the landscape. High, steep, eroding banks are often associated with incised streams.

Channel Morphometry

Stream width (m) - Horizontal distance along transect, measured perpendicular to streamflow from left edge of water to right edge of water at existing water surface, to nearest 0.1 m.

Stream depth (m) - Vertical distance from existing water surface to channel bottom; measured at three equally spaced points along transect, to nearest 0.1 m.

Channel bottom depth (m) - Horizontal distance along transects, measured perpendicular to stream flow, measured as that section classified as stream bed not stream bank, to the nearest 0.1 m.

Bankfull width (m) - Horizontal distance along transects, measured perpendicular to stream flow, from top of low bank to a point of equal height on opposite bank, to nearest 0.1m. See Harrelson et al. (1994) for useful indicators of bankfull.

Bankfull depth (m) - Vertical distance from the plane of bankfull with to the channel bottom or bank, measured at a number of equally spaced points along the transect to adequately describe mean bankfull depth and cross-section, to the nearest 0.1 m.

Width:depth ratio - An index of cross-sectional shape, where both width and depth are measured at the bankfull level, unitless.

Bank height (m) - Vertical distance along transect from edge of channel bottom to level land on top of bank, measured to the nearest 0.1 m. Does not refer to bankfull height.

Stream bottom slope (%) - The amount of vertical drop per unit of horizontal distance along the channel bottom, measured with surveyor's level.

Stream surface slope (%) - The amount of vertical drop per unit of horizontal distance along the water surface, measured with surveyor's level.

Bed and Bank Material

Channel bed substrate - Composition of bed material classified into size categories similar to Wolman's pebble count. A substrate particle is selected off the bed surface (except for fine substrates) at 8 equal distances along each transect in the channel and placed into one of the following categories:

Detritus (organic matter)

Clay (< 0.004 mm; inorganic matter; retains shape when compressed)

Silt (0.004-0.062 mm; inorganic matter does not retain shape when compressed)

Sand (0.062-2 mm)

Very Fine Gravel (2-4 mm)

Fine Gravel (4-8 mm)

Medium Gravel (8-16 mm)

Coarse Gravel (16-32 mm)

V. Coarse Gravel (32-64 mm)

Cobble (64-128 mm)

Large Cobble (128-256 mm)

Boulder (256-512 mm)

Large Boulder (>512 mm)

Stream bed substrate - If the channel is not completely inundated, then this is the composition of bed material with the wetted channel classified in to size categories similar to Wolman's Pebble count. A substrate particle is selected off the inundated bed surface at 8 equal distances along each transect in the stream and placed into one of the categories listed above.

Bank substrate - Composition of bank material classified into size categories similar to Wolman's Pebble Count.

Streambank and Riparian Characteristics

Streambank length - the linear distance along the transect from the junction of the stream bed and the stream bank to the top of the bank, measured to the nearest 0.1 m.

Streambank vegetation - A measurement of bank resistance to erosion due to vegetation, measured as the linear distance along the streambank length, which is vegetated by perennial herbaceous plants (grasses, forbs and aquatic species), shrubs or trees.

Streambank erosion - A measurement of bank instability along the transect line measured as the linear distance of exposed and eroded bank soils having very little to no structural support from vegetation during high flows. This does not include area of deposition where soils can be bare.

Streambank deposition - The Stream bank length that is neither vegetated not eroded.

Streambank slope (degree) - The angle formed by the downward slope of the stream bank and the horizontal stream bottom.

Riparian buffer with (m) - The condition of the land contour on the horizontal distance along the transect line from the stream's edge out 10 m. If the land is completely disturbed, then the riparian buffer is 0. If the land is completely undisturbed, then the buffer width is recorded as >10m. It may be appropriate to measure or approximate buffer widths beyond 10 m. Buffer widths <10 m should be measured to the nearest 1 m.

Riparian land use - The land use on the bank contour over the horizontal distance along the transect line from the stream's edge out 10 m. Land use classes are adapted from Simonson et al. (1994).

Vegetation use by animals - The condition of the vegetation by any land use (but primarily grazing and row cropping) on the transect line over the contour of the bank from the stream's edge out 10 m. Rating procedures are described by Platts et al. (1983).

Streamflow Characteristics

Streamflow (Q, cms) - The volume of water moving past a given stream cross section per unit of time.

Physical Fish Cover

Overhanging vegetation - If present, the bankside, banktop, and non-inundated vegetation that currently overhangs the water surface. Measured as the horizontal distance along the transect line from the water's edge to the furthest point over the water surface that the vegetation protrudes, to the nearest 0.1 m.

Undercut bank - If present, the horizontal distance along the transect line from the furthest point of bank protrusion and the furthest undercut of the bank, to the nearest 0.1 m.

Instream vegetation - If present the inundated macrophytic vegetation (submergent or emergent) within the stream channel. Measured as the total horizontal distance along the transect that has instream vegetation present as described, to the nearest 0.1 m.

Large woody debris (LWD), occurrence of - Generally, LWD are pieces of wood that are minimally 10 cm in diameter and 3 m long that occur within the bankfull channel providing potential cover for organisms. Measured along the transect and within one mean stream width separately as the number of pieces within the stream different zones.

Large woody debris (LWD), volume and orientation - Volume (cubic meters) of those same pieces within four zones calculated by measuring length and diameter of each piece of LWD. Orientation is recorded as the degrees to which the woody debris is predominately orientated with respect to the channel. Woody debris orientated completely upstream (i.e., root wad on downstream end) would be recorded as 180 while that orientated perpendicular to the channel would be recorded as 90, and that orientated completely downstream (i.e., root wad on upstream end) would be recorded as 0. See Robison and Beshta (1990).