Identifying linkages between aquatic habitat, geomorphology, and land use in Sourdough Creek Watershed
by Susan Kay McIlroy

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Resources and Environmental Sciences
Montana State University

Abstract:
Aquatic systems reflect the geomorphological and land use processes that shape them. System function, structure, and composition are driven by both autogenous and exogenous processes at small- and large-scales. Impacts often act synergistically, increasing the complexity and magnitude of their effects on aquatic systems. To assess these impacts, watershed scale studies are becoming more common, and an integration of research and management is beginning to emerge. Diverse user groups and differing agendas complicate watershed management and restoration, making a collaborative decision-making process imperative. Objectives of this study were to identify linkages between aquatic habitat, geomorphology, and land use in Sourdough Creek Watershed, explore potential land use impacts in the Lower Watershed, and identify a sustainable management plan for the watershed. Specific questions involved identifying potential westslope cutthroat trout reintroduction areas in the Upper Watershed and exploring statistical correlations between six land classes and the response variables of large woody debris and pool length. This study found suitable reintroduction areas as well as identified linkages between predictor variables and LWD and pool length across land classes. Although others have assessed aquatic habitat on a large-scale as well as identified potential management paradigms, this study integrates the two in order to provide a useful document for stakeholders and managers of Sourdough Creek Watershed.

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

of

Master of Science

in

Land Resources and Environmental Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

January 2004

APPROVAL

of a thesis submitted by

Susan Kay McIlroy

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

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Date Jan. 14, 2004

ACKNOWLEDGEMENTS

The list of people who guided and supported me through this project is impressive. Cliff Montagne provided perspective, knowledge, and friendship. Clain Jones and Brian McGlynn dedicated an incredible amount of time to this research. All three of them had open doors at all times, which I was extremely lucky for. Duncan Patten provided sideboards and helped me shape this project into the thesis that I wanted it to be. People that I collaborated with, especially Scott Barndt and Wally McClure, offered continuous insight. Denine Schmitz gave freely of time and energy, which I am forever grateful for. Teresa Cohn continued to remind me of the school of life and Teki Tsagaan provided advice on all fronts. Mia Pelt offered endless hours of unforgettable cups of tea on the pineapple couch. Sara Rushing continually reminded me of the pleasures of life, while Jory Ruggiero provided constant support and gave me the coolest graduation belt buckle a girl could ask for.

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ABSTRACT

Aquatic systems reflect the geomorphological and land use processes that shape them. System function, structure, and composition are driven by both autogenous and exogenous processes at small- and large-scales. Impacts often act synergistically, increasing the complexity and magnitude of their effects on aquatic systems. To assess these impacts, watershed scale studies are becoming more common, and an integration of research and management is beginning to emerge. Diverse user groups and differing agendas complicate watershed management and restoration, making a collaborative decision-making process imperative. Objectives of this study were to identify linkages between aquatic habitat, geomorphology, and land use in Sourdough Creek Watershed, explore potential land use impacts in the Lower Watershed, and identify a sustainable management plan for the watershed. Specific questions involved identifying potential westslope cutthroat trout reintroduction areas in the Upper Watershed and exploring statistical correlations between six land classes and the response variables of large woody debris and pool length. This study found suitable reintroduction areas as well as identified linkages between predictor variables and LWD and pool length across land classes. Although others have assessed aquatic habitat on a large-scale as well as identified potential management paradigms, this study integrates the two in order to provide a useful document for stakeholders and managers of Sourdough Creek Watershed.

CHAPTER 1

INTRODUCTION

Background

Aquatic systems mirror the geophysical, ecological, and human impacts that affect them over time (Stanford and Ward 1992). These drivers impact aquatic systems by altering habitat, species presence and abundance, and water quality and quantity. Differentiating between the impacts of these drivers is a difficult task. Perhaps even more challenging is managing the complex interactions within aquatic systems. In the face of water shortages and an increased concern for water quality, researchers and managers are identifying new methods of studying, understanding, and sustaining aquatic systems (Sedell et al. 1989). New research approaches simultaneously identify geophysical, ecological, and human impacts on aquatic systems while also exploring alternative management and restoration paths.

Geophysical processes interact at a complex and vast spatiotemporal scale to drive the function, form, and composition of aquatic systems. These processes occur on both long and short-term scales, and range from mountain uplift to flood events (Stanford and Ward 1992). Intertwined with geophysical drivers is a complementary suite of ecological processes that shape aquatic systems.

Human impact is the newest, and potentially most significant, driver of changes in aquatic system structure and function (Frissell et al. 1997). Water diversion, habitat alteration, fire suppression, and a myriad of other actions influence and alter rivers and streams. Significant degradation of aquatic systems in the United States is ubiquitous as water use and habitat alteration continue to increase (Dynesius and Nillson 1994). For example, in the Pacific Northwest, logging and historical "splash damming" have dramatically altered river and stream systems. Effects of these practices have resulted in potentially catastrophic and perhaps irreversible consequences for the economically and culturally important native salmonid species in the area (Young 2000). Through extensive management and restoration efforts, the native populations in the Pacific Northwest are recovering.

With a growing concern of habitat and water quality and quantity alterations in the Intermountain West, managers and researchers are increasingly examining all drivers of aquatic systems. Because driver interactions and effects are complex, assessing the geophysical, ecological, and human impacts on aquatic systems is critical. In concert with these efforts are new management and restoration efforts that incorporate multi-scale processes and interactions.

Geophysical Drivers

Geology and climate variables influence aquatic systems. Uplift is countered by erosion and deposition in a dynamic equilibrium that remains balanced over time (Leopold et al. 1964). In mountainous streams, channels are often confined by bedrock, and are shaped by terrestrial events such as mass-wasting. In contrast, unconfined valley streams meander and change structure frequently, especially if they are in unconsolidated sediment such as sand (Thorne 1997). In mountainous areas, external forces such as hillslope erosion and deposition of sediment influence aquatic systems in addition to autogenic stream processes, which more commonly drive rivers or streams in valleys (Swanson et al. 1977).

Climatic influences such as storms, drought, or the effects of fire also significantly affect aquatic systems through altered sediment load, temperature, chemical composition, flow, and river width and depth (Leigleiter et. al. 2002, Spencer et al. 2003). A study following wildfire in Glacier National Park, MT documented a number of dead westslope cutthroat trout (*Oncorhynchus clarki lewisi*); this was likely due to elevated stream temperatures and/or stress due to changes in water chemistry such as high ammonia levels (Spencer et al. 2003). The first spring following the fire, the same study found excessive algal growth in puddles and ponds, which researchers attributed to increased nitrogen and phosphorus from aerial deposition of smoke and ash.

Climate drives the amount of water in an aquatic system and generates flow changes such as peak timing, magnitude and frequency, and duration (Hornberger et al. 1998). Water flow velocities and volumes influence bank stability, substrate, vegetation communities, channel meanders, and aquatic organisms (Frissell et al. 1997, Leopold et al. 1964). Flooding can further collect organic debris and sediment from adjacent land and transfer it to aquatic systems.

Researchers are identifying possible impacts of climate warming on aquatic habitat and organisms. Eaton and Scheller (1996) modeled the estimated effects of climate warming on 57 species of fish based upon carbon dioxide predictions from the Canadian Climate Center. Results indicated a loss of about 50% of current habitat for cold water species, with greatest habitat loss for species with an already restricted range (e.g. westslope cutthroat trout). A study of the North Platte River in Wyoming predicted a habitat loss of 7-76% for cold water species with water temperature increases of 1-5 °C projected in association with climate warming (Rahel et al. 1996). The study further pointed out that warming would restrict cold water species to higher elevations with more suitable temperatures. Although climate warming is often not a consideration in studies of aquatic systems, it is nonetheless a potentially significant driver of habitat and organisms.

Ecological Drivers

As an interface between terrestrial and aquatic systems, riparian zones are critical components of the relationship between land and water (Swanson et al. 1977). Riparian zones affect the energy base, physical structure, soil and water chemistry, temperature and light regimes, and organic matter contributing to aquatic systems (Swanson et al. 1977, Naiman and Decamps 1990, Gregory et al. 1991). The presence or absence of growing vegetation contributes to the structure, form, and function of aquatic systems (Naiman and Decamps 1990, Richmond 1994, Gregory and Gurnell 1988).

Riparian vegetation regulates temperature, decreases excess nutrient and pollutant inputs from the watershed, buffers water flow into the stream, contributes large woody debris (LWD) to the adjacent aquatic system, and maintains biodiversity by providing an array of habitat (Naiman and Decamps 1990, Gregory et al. 1991). Riparian vegetation also stabilizes banks, which causes channel downcutting. Without stabilization and downcutting, streams often widen, resulting in a loss of deep pools and undercut banks, both of which are important components of aquatic habitat (Friedman et al. 1996, Scott et al. 1996, Huang and Nanson 1997, Montgomery and Buffington 1997).

Within aquatic systems, LWD traps coarse particulate organic matter and sediment, influences channel morphology and water flow, and provides habitat and cover for aquatic organisms (Marcus et al. 2002, Swanson et al. 1977). Depending on size, position, and orientation, LWD can significantly influence water flow, resulting in a pattern of heterogeneous habitat for aquatic organisms (Naiman and Decamps 1990). Organic debris dams created by LWD are important in retaining organic matter and creating pools for fish habitat (Urabe and Nakano 1998, Bilby and Likens 1980). Flebbe (1999) studied the influence of LWD on trout habitat, and found trout to be more numerous in areas with mature forests and an abundance of downed woody material. Additionally, LWD creates pools that provide over-wintering habitat for trout; a paucity of over-wintering habitat contributes to trout mortality, so LWD is critical for trout survival (Hunt 1976).

Aquatic organisms, such as fish, are integral parts of aquatic systems. As salmonids and other anadromous fish migrate to spawn and eventually die, they release biomass and other minerals upstream. Salmonid species also disturb substrate during spawning, resulting in movement of materials downstream (Williams et al. 1989). Therefore, conserving habitat for aquatic organisms promotes increased biomass cycling and habitat heterogeneity.

Human Drivers

In addition to geophysical and ecological drivers, humans impact aquatic systems through management and resource use practices (Stanford and Ward 1992). Humans have modified aquatic systems since the capacity to do so existed; the Hwang He (Yellow) River of China has been regulated for 4,000 years while in Europe flood control embankments began as early as the 11th century (Brookes 1988). Humans primarily alter the structure of aquatic systems through dams, diversions, irrigation, reduction and/or degradation of riparian habitat, and the processes associated with urbanization (Cairns and Lackey 1992, Williams et al. 1989).

Dams and diversions regulate flow in nearly every major river of the world (Dynesius and Nilsson 1994). Reduced flows increase water temperature, which impacts cold-water species such as salmonids and promotes invasion by non-natives (Stanford 1996). Dams and diversions also pose a significant threat to anadromous species by inhibiting passage. Additionally, they may kill fish that are caught in turbines or diverted out of the system for agriculture or other water uses (Stanford 1996).

Reduction and degradation of riparian areas, and especially riparian vegetation, significantly alter inputs into aquatic systems. A study in northern Japan concluded that reduction in riparian vegetation since 1947 has increased stream temperatures from 22°C to 28°C and changes since 1970 have resulted in increasing flood peaks by 1.5-2.5 times. The impact of these changes is reflected in the absence of once-abundant masu salmon (*Oncorhynchus masou*) that have migrated to cooler streams with less altered flows (Nagasaka and Nakamura 1999). A study of southern Appalachian streams positively correlated the length of deforested riparian zones with a decrease in fish abundance (Jones et al. 1999). Results suggested that limited riparian clearing may cause only minor habitat changes, but streams in forested areas are heavily impacted if riparian clearing is more than 1 km in length.

A number of studies have significantly correlated urbanization to stream degradation (White et al. 1983, Stein et al. 2002, Stewart et al. 2000, and Kondhoh and Nishiyama 2000). Increased urbanization may affect riparian vegetation and river patterns through increased flood frequency, flow duration, and stream power (Hupp 1982). Additionally, fine sediments often increase in urban systems, which negatively affects spawning and rearing habitat for salmonid species (White et al. 1983). Paul and Meyer (2001) found that the amount of impervious surfaces in urban landscapes leads to an increase in nutrient-loading, pesticides, metals, and other contaminants. In turn, these increases resulted in declines in fish, invertebrate, and algal community richness.

Comparisons of urban and rural river systems consistently show lower sinuosity, fewer pools, higher bankfull discharge, and lower median width in urban environments (Brookes 1988). A study of eight paired watersheds in the Eastern United States showed that in urban watersheds, median sinuosity was 8% lower, pools were 31% shallower, bankfull discharge was 131% higher, and median width was 26% less than in rural watersheds (Pizzuto et al. 2000). Wahl et al. (1997) also conducted a paired study of an urban and a forested watershed; although the forested watershed was larger than the urban (11 ha versus 37 ha), the urban system produced 72% greater annual streamflow volume (162 versus 94×10^3 m^3) and had a 66% greater annual sediment load (1,796 versus 1,082 kg/yr).

Channelization, which is a significant impact of urbanization, increases stream velocity, decreases habitat diversity, and decreases channel width (Brookes 1988). With an increase in stream velocity, LWD that may be contributed by adjacent vegetative zones or upriver input is washed downstream, resulting in a decrease of habitat diversity (White et al. 1983). Decreased channel width and straightened channels further influence flow regimes, resulting in decreased habitat heterogeneity.

In unchannelized systems, lateral stream movement increases habitat heterogeneity by increasing meanders. Side channels connect to main channels, increasing landscape diversity for a variety of habitat types and dispersing flow energy. Pools and slow water further complement the diversity of unchannelized systems, offering critical habitat to salmonids and other species as well as aiding in energy dispersion (Schlosser 1992). A decrease in pool habitat coupled with an increase in fine particles in urbanized systems can decrease suitable spawning and rearing habitat for trout or other salmonid fish.

Although the significance of the many drivers of aquatic systems is evident, the relative importance of each influence is difficult to assess (Jones et al. 2000). Much work has been done in the Eastern United States, but less research has been conducted in the Intermountain West characterizing the effects of land use on aquatic habitat (Forman 1998, Jones et al. 2000). Multiple research methods and approaches must be combined to assess the effects of different land uses on aquatic habitat.

Habitat Surveys

Landscape scale habitat surveys are often employed when studying aquatic systems (Overton 1997). Habitat surveys gained popularity in the 1970s as nationwide concern for aquatic habitat grew (Simonson et al. 1994). Fish habitat surveys effectively estimate fish presence and abundance without the challenge and expense of electroshocking or harvesting (Stanfield and Jones 1998; Simonson et al 1994; Fausch et al. 1988). Variables and techniques used in fish surveys differ depending on region and stream characteristics, but agencies such as the Forest Service have created standard field methodologies (Overton 1997).

Fisheries biologists and managers have expressed concern regarding the reliability, accuracy, and repeatability of habitat surveys (Overton 1997). A study by Hannaford et al. (1997) noted that the reliability of stream surveys increases with observer training and expertise. The same study found that training must include multiple locations to increase experience and subsequent accuracy. Hawkins et al. (1975) noted that a consistent methodology is necessary throughout a watershed to accurately collect data.

The R1/R4 Fish Habitat Inventory is a longitudinal survey, where data collection occurs along the entire length of an aquatic system. In addition to continuous data, site-specific transects are included (Overton 1997). Designed to be repeatable and accurate, measurements occur during the annual low (base) flow period. Besides assessing salmonid habitat, the survey produces information relevant to general aquatic habitat (e.g. habitat diversity, substrate composition, sinuosity).

Dividing aquatic systems into meaningful geomorphological sections is often the first step in a habitat survey. Separating aquatic systems into sections is useful for: 1) assessing change due to human impact or natural disturbance over time (Gordon et al. 1992); 2) comparing two or more units of different streams or sections of river; 3) extrapolating study results to other areas with similar features (Hankin and Reeves 1988); and 4) outlining the suitability of a section for alteration plans or restoration efforts (Bisson and Montgomery 1993).

Studies investigating aquatic habitat and linkages to geomorphology and/or land use may employ significantly different methodologies (Walters et al. 2003). Study design influences data collection and analysis, and therefore must be carefully considered prior to implementation. For example, the R1/R4 Survey uses the Rosgen Classification System (Rosgen 1994). The Rosgen system delineates reaches by initially identifying broad morphological characteristics and then exploring site-specific variables, such as bank erosion. Rosgen's system assigns these variables to a set of numbers and letters, grouping sections that may have significant geomorphological or land use differences based on a few characteristics. Although these delineations have proven useful as a basic communication tool, Rosgen's system appears to over-simplify the biophysical processes that create differences in stream reaches. Repeatedly, the Rosgen methodology has been used to predict fluvial behavior and channel response to disturbance, which is a misapplication of the system (Miller and Ritter 1996). Discussion of Rosgen's system reflects the numerous approaches for studying aquatic systems. For example, the Rosgen system uses a quantitative slope classification, while the Barbour et. al (1988) system uses qualitative estimates of 'low' and 'high' to delineate slope. Using slope and other measurements, Rosgen's system compartmentalizes streams into pre-determined delineations, while Barbour's system allows more flexibility for data collection and analysis. Therefore, choosing the appropriate classification system is critical, and an integration of different systems may be most effective.

One example of this integrated approach is the Montgomery and Buffington (1993) system of geomorphological characterization coupled with the Hawkins et al. (1975) system of stream ecological classifications. In the Montgomery and Buffington system, landscapes are broadly classified into valley or hillslope sections and then more specifically into channel reaches. The Hawkins system further characterizes channel reaches into habitat units, which are discrete units based on both flow patterns and channel bed shape (Hawkins et al. 1975). Both systems involve measurable ecological descriptors, with Montgomery and Buffington framing a geomorphic, process-based way of studying aquatic systems and Hawkins providing more site-specific habitat measurements (Bisson and Montgomery 1993). Each of these levels drive the distribution and abundance of aquatic organisms and habitat by influencing water flow and transport of materials (Bisson and Montgomery 1993). Within this hierarchical framework, geomorphological as well as human processes and patterns can be assessed at each level (Frissel et al. 1986).

New Management Paradigms

In conjunction with landscape scale habitat surveys, new management paradigms that address systems at a large scale are emerging. A reductionist paradigm that reduces complex data or processes to simple terms has often dominated resource management decisions, leading to a conceptual disconnect between aquatic and terrestrial systems and a lack of recognition that terrestrial management directly affects aquatic systems (Frissell et al. 1997). Specifically, reductionist management of aquatic systems has primarily focused on site-specific, direct linkages between aquatic habitat and the immediately adjacent riparian areas, often omitting important lateral and longitudinal connections (Frissell 1992). This in turn has led to a decrease in biodiversity, degraded habitat, and a conceptual separation of humans as ecosystem components (Gunderson et al. 1995, Warren 1989, Leopold 1990).

Inflexible management of aquatic systems has decreased ecosystem resiliency to natural change (Gunderson et al. 1995). Resilience is characterized by the amount of disturbance an ecosystem can absorb without changing its level of integrity (Holling 1973). Connected to the concept of resilience is ecosystem stability, or the tendency of a system to return to a state of equilibrium when disturbed (Ludwig and Holling 1997). The paradigms of stability and resilience allow for ecosystem change within a dynamic equilibrium, where oscillations in the system may initially be dramatic, but over time their amplitude quiets and the system once again reaches a stable state (Gunderson et al. 1995).

As a new understanding of the complexity of ecosystems grows, researchers and managers are identifying new ways to study aquatic systems. For example, researchers are increasingly framing aquatic systems within the context of a river continuum, or a longitudinally linked system where upriver processes greatly affect downstream dynamics (Sedell et. al 1989, Vannote et al. 1980). Exploring the connectivity between up- and down-stream is critical to understanding aquatic systems.

Aquatic systems are increasingly framed within a watershed, or an area bounded by a divide in which all water flows to a specific point (Hornberger et al. 1998). Watershed interactions are nested within a hierarchical framework, where any process is partially determined by the greater system of which it is a part (Frissell et al. 1986). Watersheds are often divided into a mosaic of private and public land, which necessitates collaboration and cooperation between local citizens and management agencies (Kraft and Penberthy 2000). Additionally, sound ecological understanding, adaptability, and inclusion of humans as ecosystem components are necessary for effective watershed management (Christensen et al. 1996). Integrative management of watersheds further necessitates addressing socioeconomic and environmental concerns simultaneously as well as including forest, range, agricultural, wetland, and urban management and processes in a watershed plan (Naiman 1994).

Conceptual models are also changing the way watersheds are researched and managed. Several models, ranging from panarchy theory (Gunderson et al. 1995) to Holistic Management (Savory and Butterfield 1999) offer new perspectives and approaches to natural resource management. Different management paradigms often include the following: 1) ecosystem dynamics that involve nonlinear variables occurring at different spatiotemporal scales (Carpenter and Levitt 1991, Levin 1992, Gunderson et al. 1995, Carpenter and Cottingham 1997, Ludwig and Holling 1997) and 2) collaborative decision-making involving participation of all stakeholders (Carpenter and Cottingham 1997).

Regardless of the types of models or study methods used, assessing aquatic habitat at the landscape scale requires a suite of interdisciplinary tools. Geophysical, ecological, and human processes intermingle in nearly every system in the world, making at least some inclusion of human impacts necessary in understanding the structure, form, and function of aquatic systems. Addressing the many facets and drivers of aquatic systems begins with viewing them in a hierarchical framework, where longitudinal and lateral influences of both the terrestrial and aquatic environment impact systems at multiple levels.

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CHAPTER 2

IDENTIFYING LINKAGES BETWEEN AQUATIC HABITAT, GEOMORPHOLOGY, AND LAND USE OF SOURDOUGH CREEK WATERSHED

Introduction

Geomorphological, ecological, and human processes impact the structure, function, and composition of aquatic systems (Stanford 1996). Impacts include altering systems longitudinally or laterally by influencing large woody debris (LWD) input, substrate composition, and channel flow. In turn, these alterations influence the presence and abundance of aquatic organisms.

Across the United States, management of aquatic systems includes conserving habitat and biodiversity as well as maintaining water quality and quantity for a growing population. Unfortunately, water resource management is frequently fragmented, with decisions in one area starkly contrasting with those made in another (Hulse and Gregory 2001). Water resource managers often face the following situations: 1) alteration of natural flooding regimes by dams and channelization; 2) reduction of surface and ground water due to human consumption; 3) an increase in sedimentation, nutrient loss, and runoff due to loss of vegetation and increased impervious surfaces; and 4) alterations of natural disturbance regimes due to fire suppression and introduction of exotic species (Jones et al. 2000).

With these challenges, managers, researchers, and land owners are exploring alternative ways to study and manage aquatic systems. Additionally, managers are addressing biodiversity and the conservation of intact systems more frequently and with increased urgency as native species grow rarer and landscapes become increasingly fragmented (Jones et al. 2001). Conservation of native species and natural landscapes necessitates a whole system approach, where all factors driving aquatic systems at a large-scale are explored. Although other research has identified linkages between aquatic habitat, geomorphology, and land use (Diez et al. 2001, Jones et al. 2001), little work has been conducted in the Intermountain West, where a growing population necessitates active conservation and management of aquatic systems. Additionally, no study has explored these linkages in addition to providing an alternative watershed management framework.

Justification for Research

In 2000, the Bozeman Watershed Council (BWC) recognized the need to gather baseline information for Sourdough Creek Watershed in Gallatin County, MT. Significant population growth in the area coupled with a lack of scientific data about the watershed prompted the Council to conduct a comprehensive ecological and geophysical assessment. The assessment examined aquatic habitat, weeds, tree stands, birds, amphibians, geology, soils, and rangeland variables. The aquatic portion was used not only for the assessment, but also to identify possible reintroduction areas for native westslope cutthroat trout (*Oncorhynchus clarki lewisi*) that historically have populated the stream. Both Sourdough Creek and its main tributary (South Fork Sourdough Creek) were examined for habitat conditions and possible native trout reintroduction areas. A number of other tributaries contribute to Sourdough Creek (e.g. Nichols Creek, Limestone Creek, and Spring Creek), but this research explored only the main stem and the South Fork, which will be referred to as Sourdough Creek Watershed for the remainder of this study. Within Sourdough Creek Watershed, an Upper and Lower Watershed were further delineated.

In conjunction with the work of the BWC, this study had the following objectives and questions:

1) Identify linkages between aquatic habitat, geomorphology, and land use in Sourdough Creek Watershed
    - -What areas in the Upper Watershed are suitable for westslope cutthroat trout reintroduction?
2) Explore the effects of land use on aquatic habitat in the Lower Watershed
    - -What statistical correlations exist between land use and quantity of LWD and pool length in the Lower Watershed?
3) Identify a management framework that will provide long-term sustainability for Sourdough Creek Watershed

Study Area

Geographical Context. Sourdough Creek, a tributary of the East Gallatin River, flows north out of the Gallatin Mountain Range and travels through Forest Service, City, County, and private land until its confluence with the East Gallatin River north of Bozeman, MT (Figure 1). The watershed is approximately 16,700 ha in size, ranging in elevation from 1,427 m where it joins the East Gallatin River to 2,967 m at the watershed divide. The Upper Watershed primarily lies within Forest Service land while the Lower Watershed is a mosaic of mostly privately owned parcels. The delineation between the two sections is at a municipal diversion dam just within the Forest Service boundary. The municipal diversion dam not only alters downstream flow and aquatic habitat, but it is also where topography begins to change from hillslope to valley.

Annual precipitation in Bozeman averages 47.5 cm, with the annual temperature averaging 6 °C. In the Upper Watershed, annual snowmelt and rainwater flow into Mystic Lake is approximately 10×10^5 m^3. Average annual water yield measured at the Forest Service boundary is 22×10^6 m^3, but may range as high as 26×10^6 m^3 with above-average annual precipitation (Story 2003). The temperature and precipitation gradient between Bozeman and the watershed divide has not been quantified, but is undoubtedly significant as elevation change is over 1,500 m (1,427 m-2,967 m).

The Upper Watershed is approximately 7,300 ha in size. Rocky ridgelines and outcrops reflect the limestone, shale, sandstone, granitic, and volcanic parent materials in the Upper Watershed (Davis and Shovic 1996). There are eighteen soil types in the Upper Watershed, ranging from Typic Cryochrepts above Mystic Lake to Typic Haploborolls near the Forest Service boundary. Landslide, alluvial and colluvial deposits are prevalent in the uppermost section of the watershed, and have contributed loam, sandy loam, and clay loam deposits to the area surrounding the lake. Downstream, narrow canyon bottoms are composed of alluvial and colluvial deposits ranging from a few feet to several hundred feet thick (Ladzinski et al. 2004).

Vegetation on north and east-facing slopes includes lodgepole pine (*Pinus contorta*), subalpine fir (*Abies bifolia*), and Douglas fir (*Abies psuedotsuga*). Lower south-facing slopes are primarily sagebrush (*Artemisia bifolia*), grasses (*Poaceae*), and open Douglas fir forests (Davis and Shovic 1996). Riparian vegetation is diverse and includes a variety of cottonwood (*Populus*), willow (*Salix*), herbs, grasses and forbs. Vegetation directly adjacent to Mystic Lake is minimal, but willows planted by the Forest Service several years ago have become somewhat established (Ladzinski et al. 2004).

The Lower Watershed consists of floodplain and terrace features along the east edge of a large low gradient alluvial fan that emerges from the mouth of Hyalite Canyon to the west. The eastern side of the watershed includes foothills and subsidiary drainages. The stream flows north along the eastern edge of the Hyalite alluvial fan and the western edge of foothills formed in Tertiary sediments. Soils include Argiborolls, Haploborolls, and Fluvaquents (Montagne et al. 1982). Vegetation in the Lower Watershed includes willows, deciduous and coniferous trees, grasses, and forbs. There are also cultivated fields, pastures, a golf course, and urban lawns in the Lower Watershed.

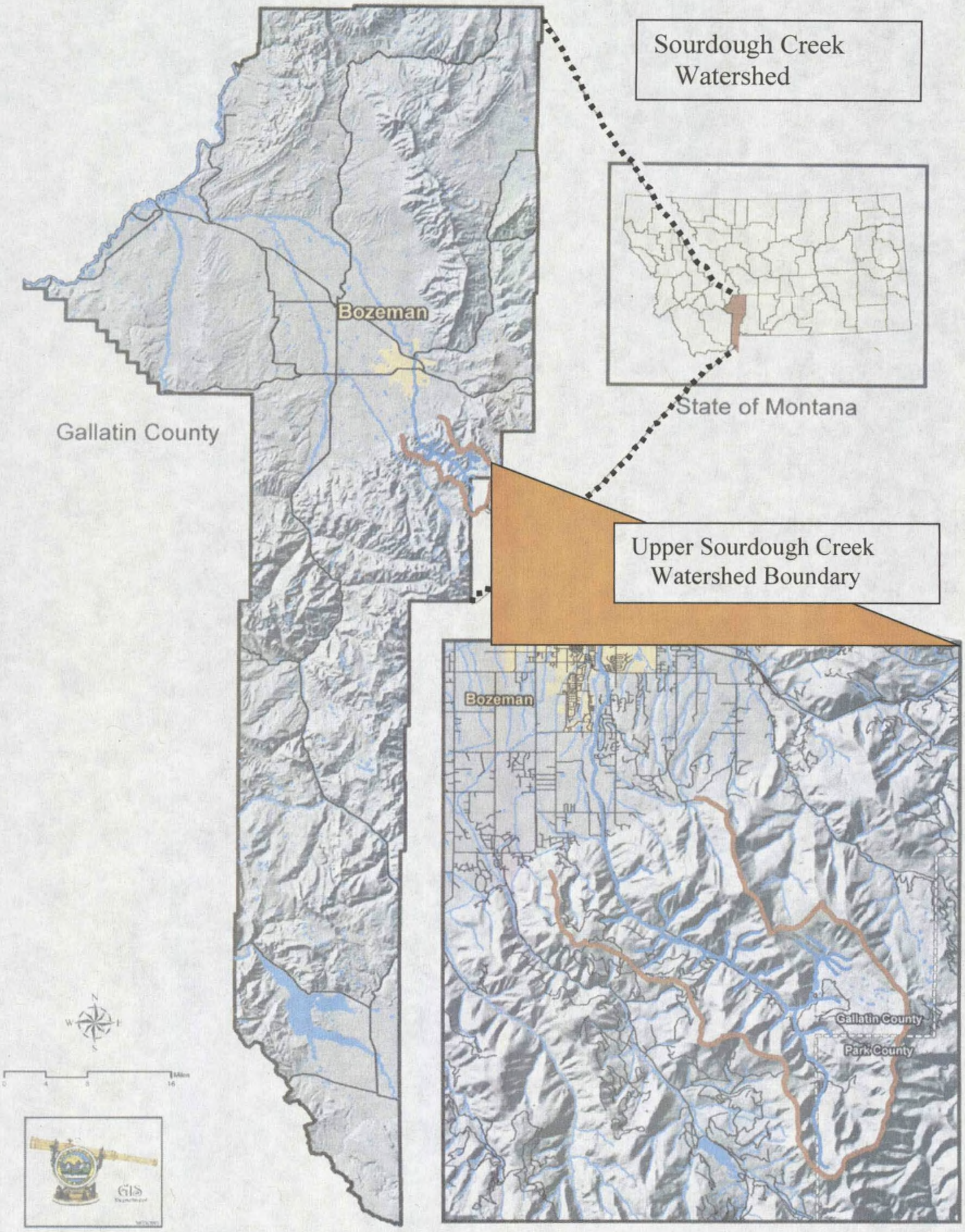

Figure 1. Sourdough Creek Watershed, including the Gallatin Range, City of Bozeman, and surrounding area.

Historical Context. There have been a number of land uses and management practices in Sourdough Creek Watershed during the past century. The Upper Watershed is primarily managed by the Forest Service, with 5,487 ha (75%) National Forest, 1,619 ha (22%) City of Bozeman land, and 194 ha (3%) Northern Pacific Railway land (Ladzinski et al. 2004). The state of Montana also has a few small holdings. In 1907, the Sourdough Creek Reservoir Company dammed Mystic Lake for flood control and water storage. This enlarged the lake's surface area from 6.39 ha to 26.30 ha, submerging and changing surrounding vegetation and habitat. In an effort to protect the water resource from human impact, the Upper Watershed was closed to the public in 1917, and remained so until 1970 (Ladzinski et al. 2004). In 1984, the dam breached, and the lake has been unregulated for 19 years.

In the Upper Watershed, road infrastructure remaining from logging 739 ha between 1960 and 1979 is the main land use legacy. In 1958, the Yellowstone Pine Company built a network of roads, including a 14.5 km road that serves as the primary access to Mystic Lake. Logging of 3.5 million board feet occurred both around Mystic Lake as well as lower in the canyon, and the Forest Service eventually thinned the lower areas to make the cuts less visually dramatic (Ladzinksi et al. 2004). Since the end of logging in 1979 there has been minimal timber management activity in the Upper Watershed.

In 1980, the City of Bozeman conducted a study of water quality, quantity, flood control, and additional dam sites for Sourdough Creek Watershed. The study noted that further urban development could significantly degrade Sourdough Creek. It also found a minor increase in sediment and bacteria above the City of Bozeman Water Treatment Plant as well as sections downstream from Kagy Blvd., near the suburban/urban interface (City of Bozeman 1980).

A 1983 study of Sourdough Creek compared urban (clearly within urban-impacted areas) and control stream sections (less, or not, impacted by artificial alteration), and found that urbanized stream sections had a decrease in canopy cover and undercut banks, a decrease in channel width, and an increase in bank erosion (White et al. 1983). The study also found an increase in stream velocity in the narrower, straighter urban channels. The researchers hypothesized that increased erosion in the urban sections was causing siltation downstream.

<u>Current Water Use.</u> Sourdough Creek supplies approximately 2/3 of the municipal water supply for Bozeman from mid-October to mid-June and approximately 1/3 of the city's supply the rest of the year. Neighboring Hyalite Creek supplies the remaining municipal water (Story 2003). Public use is about 760 L per capita per day; a 2000 census recorded 27,509 Bozeman residents. Twenty-eight water rights are filed for the stream, with the City of Bozeman the largest water right holder. The city has direct stream diversion rights for 58×10^5 m^3, with unused rights for an additional 81×10^5 m^3/yr (Ladzinski et al. 2004).

Sourdough Creek Watershed is classified as A-Closed, which mandates no change above naturally occurring turbidity or sediment. The A-Closed classification has significantly affected management options in the Upper Watershed. Fire suppression and logging restrictions due to water quality concerns have resulted in fuel loading. Small-scale prescribed burns in 1994 and 1996 were successful in reducing some fuel; however, the risk of a high-severity fire due to high fuels and resulting increased sediment load into Sourdough Creek is a definite concern (Story 2003).

In summary, there are a number of factors driving the structure, form, and function of Sourdough Creek Watershed. Assessing the impacts and interactions of these processes at a watershed scale is critical for identifying linkages and correlations between aquatic habitat, geomorphology, and land use. A landscape scale study of Sourdough Creek Watershed was therefore the approach used in this study.

Methods

Introduction

Studies investigating aquatic habitat and linkages to geomorphology and/or land use may employ significantly different methodologies (Walters et al. 2003). Study design influences data collection and analysis, and therefore must be carefully considered prior to implementation. For this study, the Montgomery and Buffington (1993) system provided a broad geomorphological classification system and the Hawkins (1975) system was useful in identifying channel differences at a smaller scale. The R1/R4 USFS Inventory provided the fieldwork methodology partly because it was used in the BWC Assessment, but more importantly because it includes commonly accepted methods of habitat surveys (Overton 1997).

Channel Reach Delineation

Following the Montgomery and Buffington system, the Upper and Lower Watershed were delineated as hillslope and alluvial valley, respectively. Two exceptions to the hillslope characterization in the Upper Watershed were Sourdough Creek Reach 2 (SCR2) and SCR6, which are low gradient alluvial valleys. Pool/riffle channel reaches predominated in the entire watershed, with occasional braided, step-pool, waterfall, and cascade sections, all identified according to the Hawkins system. Channel reaches were delineated at confluences, topographic changes, or points of infrastructure that appeared to alter flow (Figure 2, 3).

Sampling Methodology

Selection of 24 variables (Table 1) involved literature review, preliminary field visits, and initial inspection of Color Infrared Digital Orthoquad (CIR-DOQ) photos. Aquatic habitat and geomorphologic variables were measured in the entire watershed, with land use variables coarsely identified in the Upper Watershed and more extensively in the Lower Watershed. Topographic maps were used to describe variables for both sections of the watershed. Field data were collected from July 15th 2002 to October 15th 2002 in the entire watershed and again from August 1st to 31st 2003 in the Lower Watershed. Measurements occurred during base (annual low) flow. This is a standard method in habitat surveys that both enhances repeatability of subsequent studies and increases the probability of identifying pools and LWD that otherwise may be covered during high flow (Overton 1997). In the field, channel reaches were delineated and

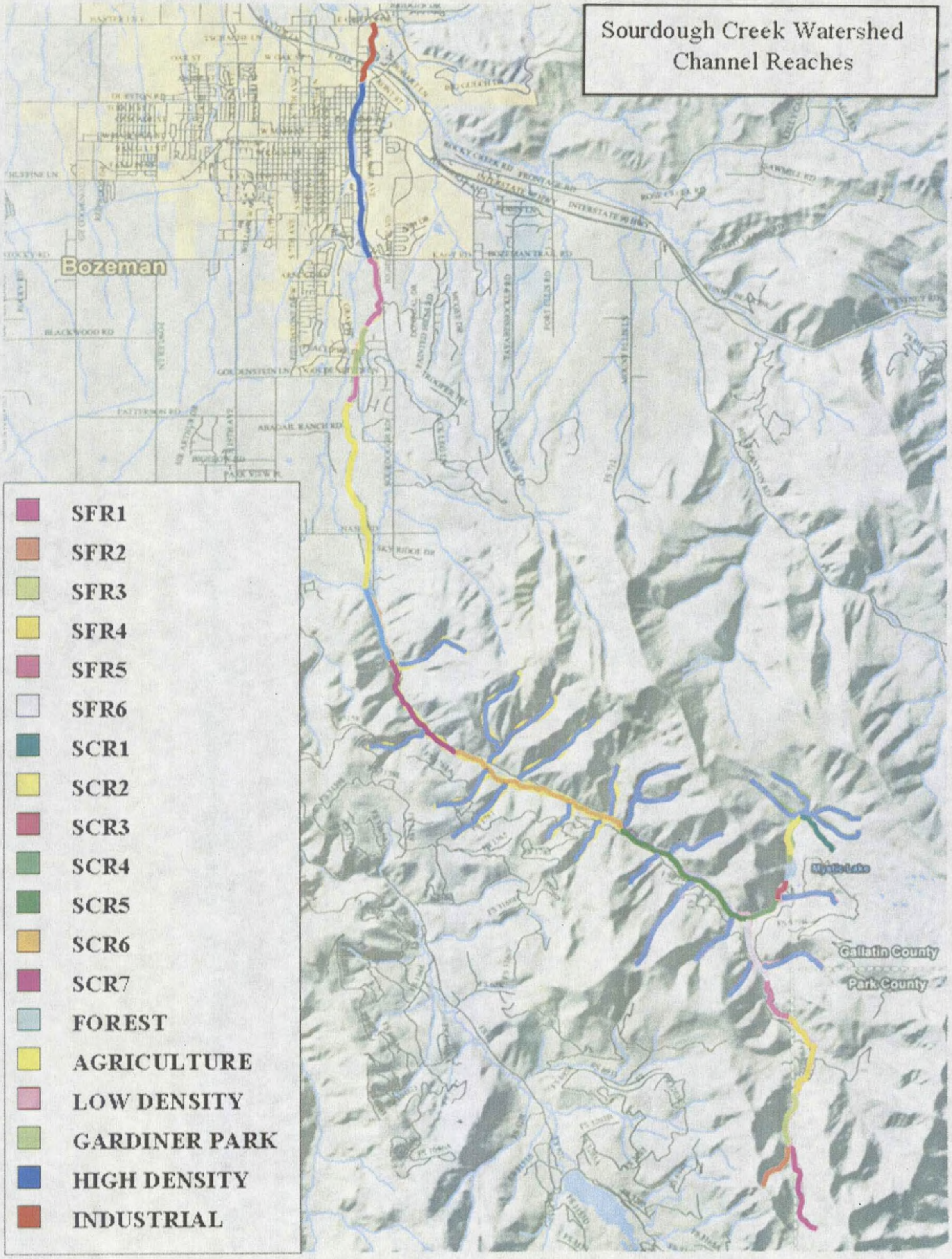

Figure 2. Channel reaches, including South Fork (SFR1-6), Upper Watershed (SCR1-7), and Lower Watershed (land classes) sections.

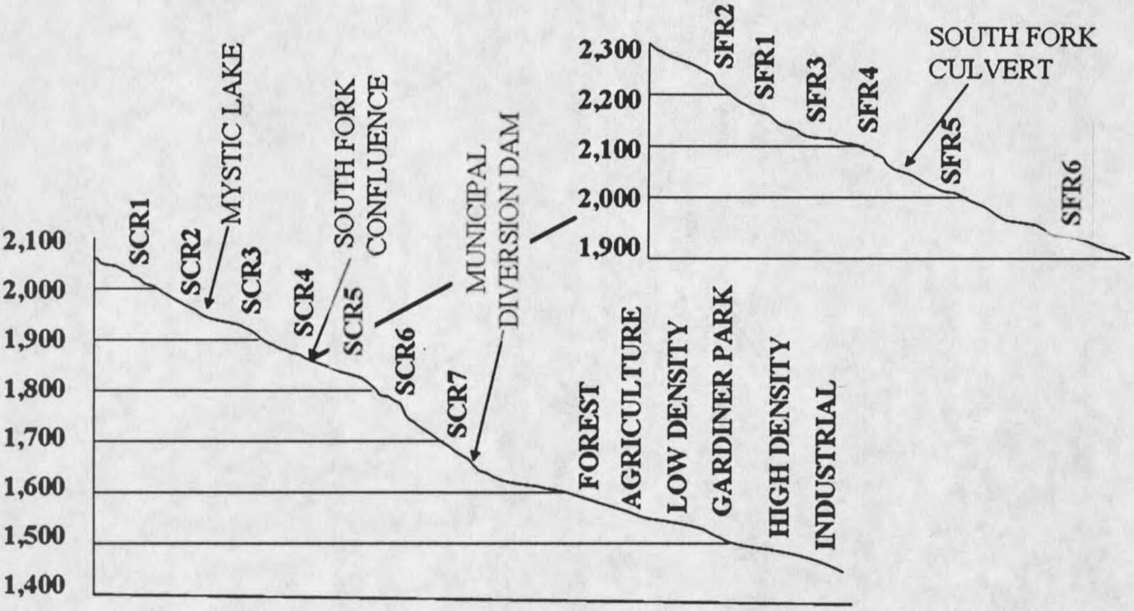

Figure 3. Channel reach elevations for Sourdough Creek Watershed.

Table 1. Geomorphology, aquatic habitat, and land use variables.

* Upper Watershed only
**Lower Watershed only

Geomorphology	Aquatic Habitat	Land Use
Sinuosity	LWD	Roads**
Elevation	Spanners	Bridges**
Basin size	Debris dams	Trails**
Gradient	Pool length	Structures**
Substrate	Pocket pools	
Bankfull width and depth**	Riprap**	
Wetted width and depth**	Canopy cover**	
Entrenchment ratio**	Riparian forest width**	
Valley width**	Unstable bank**	
	Undercut bank**	
	Local riparian area*	

the length of each reach was recorded. A number of variables were scaled to 50 m (e.g. a 100 m reach with 20 pieces of LWD was scaled to 50 m with 10 pieces) because channel reach length varied, and direct variable comparison between reaches would not have been meaningful.

Continuous data collection included riffle and pool lengths, presence of pocket pools, length of various bank characteristics, and LWD presence. Riffles were identified by surface roughness, moderate to high flow velocities, and a gradient of approximately 2% or less (Figure 4). Pools, or slow water where scouring has carved a depression in the

Figure 4. A typical riffle, with a low gradient, surface roughness, and a moderate velocity (SCR3).

channel bed or the channel has been dammed, were measured if they spanned at least two-thirds the channel width and were at least 0.2 m deep. Pocket pools have the same depth as pools, but differ in that they occupy only 10-30% of the channel width and occur in riffle habitat units (Overton 1997).

Bank characteristics, including undercut and unstable banks as well as riprap, were measured along each reach. Undercut banks were measured if they were at least 5 cm deep and no more than 10 cm above the water surface. Unstable banks were recorded if they were actively slumping, cracking, fracturing, or vertically eroding. Riprap included concrete or boulders put in place to stabilize the channel. All bank characteristics were recorded for both channel sides.

Single LWD was recorded if it was > 10 cm in diameter and 3 m long or > 2/3 the channel width. Aggregates were classified as 2 to 19 pieces of LWD, while debris dams were counted when twenty or more pieces of LWD were touching each other. For final analysis, aggregates were only separated from singles in the Upper Watershed because they occurred infrequently in the Lower Watershed. Spanners, or pieces of wood spanning the channel but not in the water, were recorded if they met the criteria for single LWD. Spanners were included in this study because of their potential future input into the stream.

In the Lower Watershed, transect measurements were randomly taken every 100-200 m within most channel reaches (Appendix A). Measurements included bankfull width and depth, wetted width and depth, substrate composition, and canopy cover percentage. Wetted width: depth ratios were also calculated as an estimate of channel entrenchment or incision.

Bankfull width is an estimate of the lateral channel width that can hold water before the stream reaches flood stage (Figure 5). Changes in both topography and vegetation aid in identifying bankfull width. Bankfull depth reflects the potential water depth at the estimated bankfull width. Wetted width is the width of the water surface measured at right angles to the direction of flow and wetted depth is the channel water depth. Both bankfull and wetted depth were measured 3 times across the channel and then divided by 4 to account for 0 depth at each bank (Overton 1997).

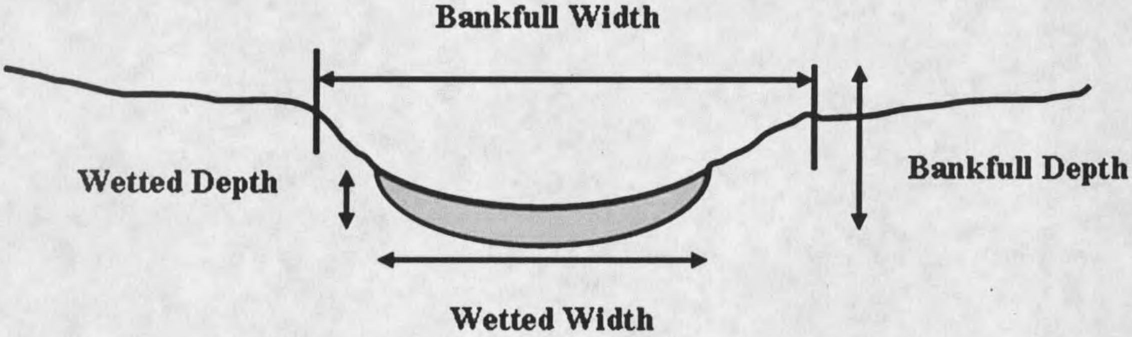

Figure 5. Bankfull and wetted width and depth measurements.

Differences in vegetation and soil as well as change in topography aid in characterizing

Substrate composition was estimated at each transect and divided into percentage clay, silt, and sand (<0.2 cm), gravel (0.2-6.4 cm), cobble (6.4-25.6 cm), boulder (25.6 cm-1 m) and bedrock (solid rock). Canopy cover was estimated using a densiometer, with measurements taken up and down the channel as well as from both banks. Percentage canopy cover was then calculated (Platts et al. 1982).

CIR-DOQs taken September 9th, 2001 were first used to delineate land classes (Figure 6 a-f). Each class was based on dominant land cover as well as number and type (e.g. commercial versus residential) of structures. Areas with < 5 structures per 50 m along the channel were classified as forest, agriculture, or industrial. Areas with 5-10 structures per 50 m were classified as low density, with areas having > 10 structures per 50 m characterized as high density. The Gardiner Park land class lies within the low density section, but was separated because as a municipal park it is managed differently than the low density land class.

Using stream field lengths, the beginning and end of each channel reach were identified on the CIR-DOQs. Within each land class, structures, roads, trails, and bridges were counted and measured within a 250 m buffer extending on either side of Sourdough Creek. Valley width was measured at the beginning, middle, and end of each land class, and encompassed the width of land at a 60 m or less elevation above the stream. Riparian forest width, which was nearly continuous in the entire Lower Watershed, was measured every 20 m along the stream and averaged per channel reach. CIR-DOQs were also used to calculate sinuosity; the straight-line down valley distance was measured for each channel reach. Thalweg (the longitudinal line of a riverbed from source to mouth) distance acquired in the field was then divided by the straight-line distance per channel reach. Distance from the municipal diversion dam for each channel reach was also measured via CIR-DOQs to characterize stream transport processes as well as

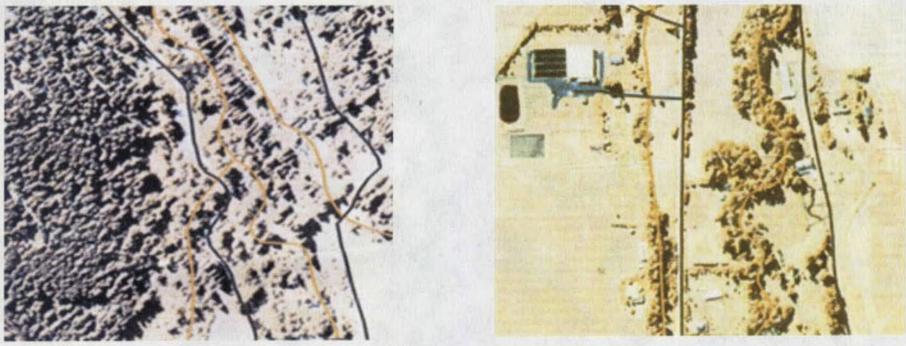

Figure a. Forested land class with Sourdough Creek the middle of the three creeks.

Figure b. Agricultural land class with the municipal diversion dam (upper left).

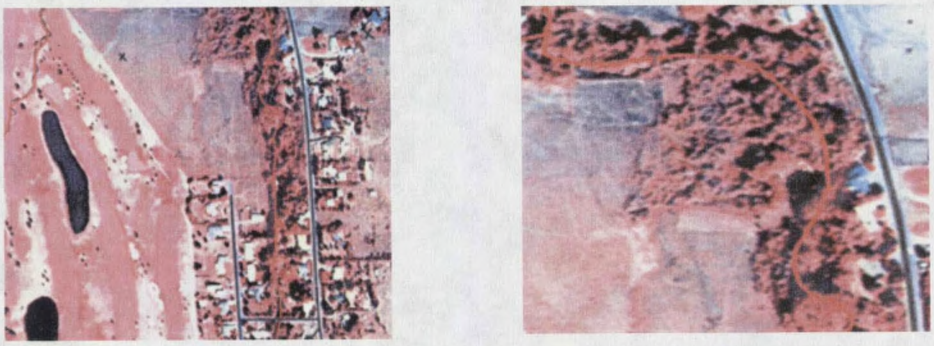

Figure c. Low Density land class with Sourdough Creek (right) and Spring Creek (through the golf course).

Figure d. Gardiner Park land class.

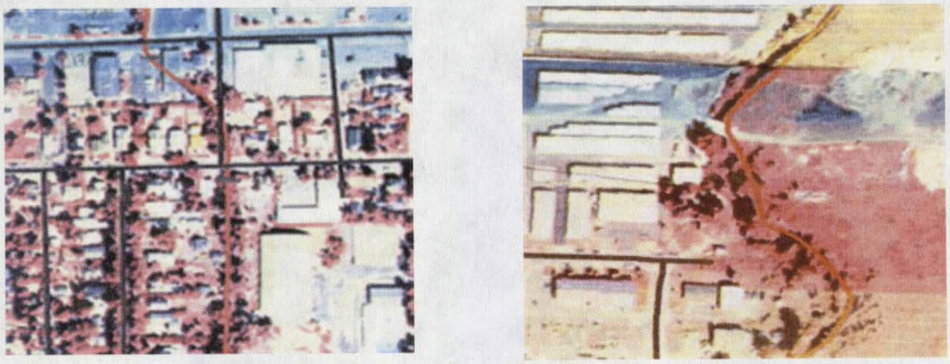

Figure e. High Density land class, including Bogert Park to the right of the creek.

Figure f. Industrial land class.

Figure 6 (a-f). Sourdough Creek in each of six land classes is shown in red or orange in each photo.

longitudinal changes along the stream. Land class variables identified on CIR-DOQs were scaled to 50 m using the same method as field data conversion.

A 10 m DEM (McGlynn and McDonnell 2003, McGlynn and Seibert 2003a, 2003b) was used in the Upper Watershed to identify basin size as well as local riparian area. Polygons were drawn from the bottom of each channel reach to delineate drainage area, and thus upstream basin size. The polygons followed topographic features influencing drainage into each channel reach. The DEM was also used in the Upper Watershed to measure local riparian area because the riparian/forest interface was unidentifiable with CIR-DOQs. Local riparian area is the area (ha) 3 m or less above the stream via the flow path. Ten meter cells along each reach were summed and divided by reach length to measure local riparian area.

Topographic maps were used to determine elevation at the beginning and end of each channel reach and gradient for the entire watershed, as well as basin area and approximate valley width for the Lower Watershed. Gradient for the Upper Watershed was determined by dividing elevation change by channel reach length. In the Lower Watershed, gradient was assessed via the same method, but only at the land class scale because elevation change within each class was minimal.

Data Analysis

Summaries for each variable were calculated across the entire watershed. In the Lower Watershed, multiple regression determined correlations between the predictor variables of distance from the municipal diversion, sinuosity, structures, and forested riparian width and the response variables LWD and pool length (Appendix B). Additionally, LWD and pool length were included as predictor variables in one another's model. Variable differences between land classes were also assessed via the Wilcoxon Rank Test (Wilcoxon 1945, 1949). The Wilcoxon test was used instead of a paired t-test to compare land class differences because the data was non-parametric and did not meet the assumption of normality for t-tests. The Wilcoxon test identified statistically significant differences at p = 0.05.

Results and Discussion

Upper Watershed Introduction

The Upper Watershed is a pristine system with heterogeneous habitat and primarily unaltered flows appropriate for westslope cutthroat trout reintroduction. Westslope cutthroat trout require isolated habitat removed from non-native competitors. Suitable habitat includes LWD and pools, which disperse energy flow, provide over-wintering habitat, and offer heterogeneous conditions. Predominantly cobble and gravel substrate is optimal for spawning and rearing, with high percent fines negatively affecting redds, or spawning grounds (Karr 1981).

Geomorphology

Geomorphologic variables that reflect both watershed and local characteristics were assessed in the Upper Watershed (Table 2). All reaches were 1st to 3rd order with low to moderate sinuosity. Reach elevation ranged from 1,597 m at the municipal diversion dam (end of SCR7) to 2,182 m at the top of South Fork Reach 1 (SFR1). Gradient averaged about 3.0% in Sourdough Creek; one exception to this was SCR1, which had a complex of cascades and step-pools and a gradient of 17.2%. South Fork gradients ranged from 5.0-19.6%. A 20 m waterfall at the upstream end of SFR2 was the highest in the Upper Watershed.

Table 2. Upper Watershed geomorphologic variables.

Channel Reach	**Elevation (m)**	**Sinuosity**	**Gradient (%)**	**Length (m)**	**Basin Size (ha)**
Hillslope Above Mystic (SCR1)	1,957-2,073	1.31	17.2	2,872	758
Valley Above Mystic (SCR2)	1,951-1,957	1.47	3.0	1,174	931
Steep Gradient Below Mystic (SCR3)	1,890-1,951	1.16	14.4	433	4,266
Above South Fork Confluence (SCR4)	1,865-1,890	1.04	3.0	949	4,326
Below South Fork Confluence (SCR5)	1,773-1,865	1.51	3.6	3,871	6,339
Bridge to Wetlands (SCR6)	1,698-1,773	1.00	2.0	4,612	7,012
Wetlands to Municipal Diversion (SCR7)	1,597-1,698	1.26	4.0	2,703	7,300
East Fork (SFR1)	2,146-2,182	1.00	5.0	752	545
Southeast Fork (SFR2)	2,146-2,231	1.16	19.6	507	545
Below East Fork (SFR3)	2,072-2,146	1.25	10.0	987	1,301
South Fork (SFR4)	2,072-2,139	1.36	10.7	847	1,301
Main Stem Above Road (SFR5)	1.926-2,072	1.27	9.4	1,978	1,598
Main Stem Below Road (SFR6)	1,865-1,926	1.29	5.0	1,611	1,656

Substrate for all reaches except SCR2 and SCR7 had predominantly hillslope material size (Figure 7). SCR2 and SCR7 had high percent fines (silt/clay and sand), with 58% and 43%, respectively. High percent fines in SCR2 are attributable to the low gradient delta created when Mystic Lake was dammed, and reflect smaller particles deposited over time. SCR7 parallels the main access road, which undoubtedly contributes fines through surface runoff into the stream. Reaches were otherwise dominated by boulder, cobble, and gravel, with the South Fork reaches having the most bedrock.

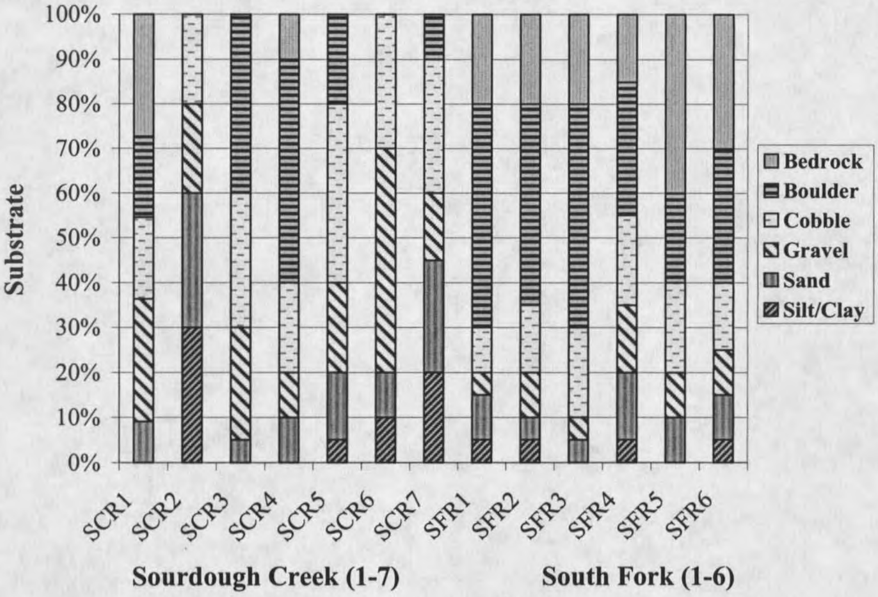

Figure 7. Upper Watershed substrate.

Local riparian area was highest in SCR2, again where the channel flows through the low gradient alluvial valley encompassing Mystic Lake (Figure 8). The second highest value was in SCR6 (also classified as alluvial valley), where a wider valley creates more potential for riparian input. The lowest riparian area, in SCR1, reflects the high gradient and narrow valley bottom of one of the highest elevation Sourdough Creek reaches.

Aquatic Habitat

Undercut and unstable banks as well as riprap were not very prevalent in the Upper Watershed (Figure 9), and were absent along the South Fork. A lack of eroding and reinforced banks is common in narrow riparian areas constrained by steep hillslopes, where large size substrate and riparian forests naturally stabilize banks (Frissell et al. 1986). Steep and incised channels also prevent stream migration, decreasing bank undercutting and instability (Bunn and Arthington 2002). SCR2 had significantly higher unstable and undercut banks when compared to other reaches; again, this is due to the

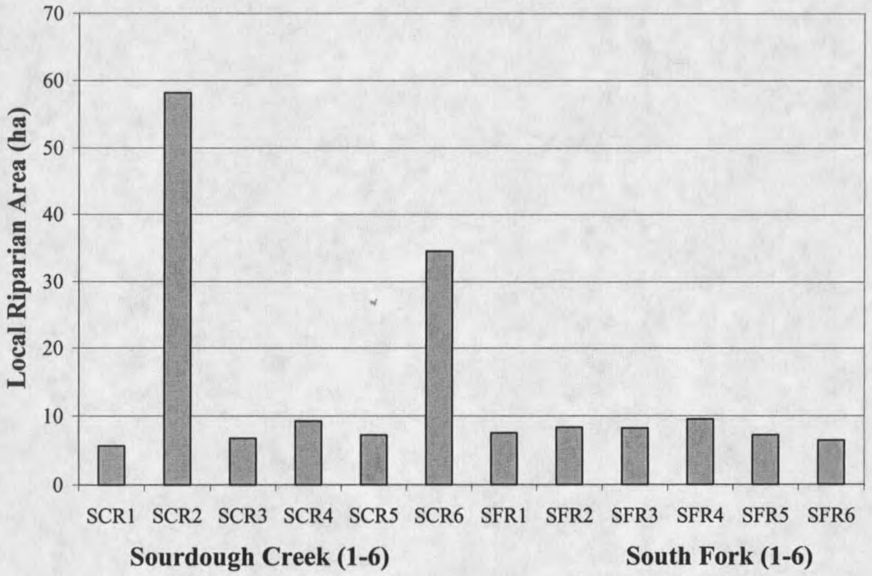

Figure 8. Local riparian area (area 3 m or less above the stream via the flow path) for the Upper Watershed. Local riparian area was summed and then divided by reach length for comparison. SCR7 was not included in the analysis because the DEM covered only part of the reach.

valley characterization and associated channel meandering in the area surrounding Mystic Lake.

Riprap was highest in SCR7, where the access road parallels the stream. Riprap prevents lateral channel migration, increases fine sediment input into aquatic systems, and precludes LWD input due to lack of adjacent riparian forest (Brookes 1988). Undercut and unstable banks should be low in riprapped areas because natural bank erosion cannot occur (Brookes 1988); results confirm this, with the highest amount of riprap coupled with low undercut and unstable banks in SCR7.

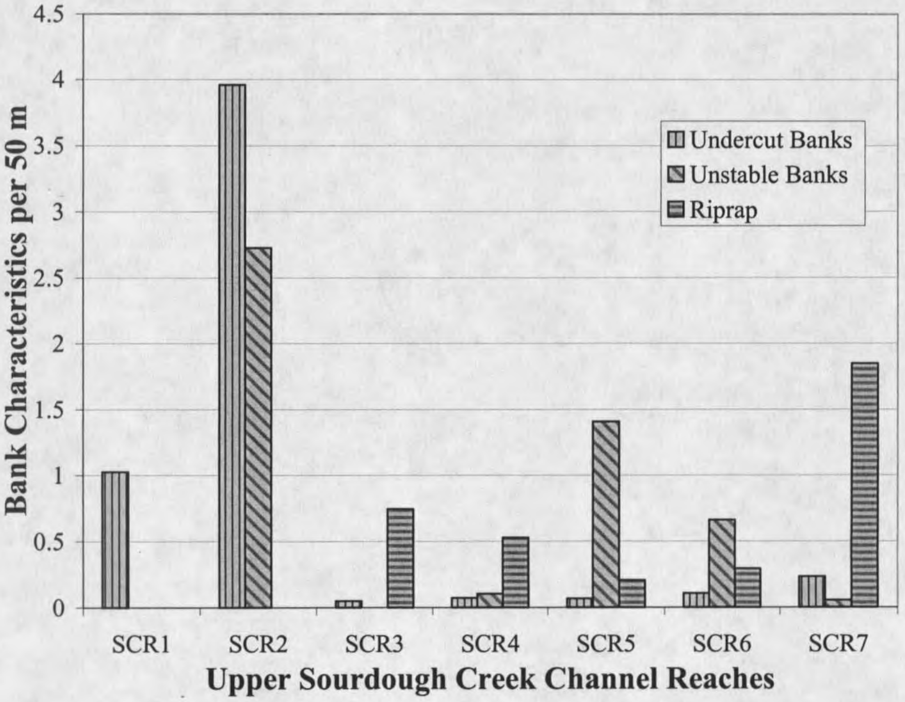

Figure 9. Upper Sourdough Creek bank characteristics.

Across the Upper Watershed, LWD and pool abundance varied greatly. In-channel and spanner LWD were high in the South Fork reaches, with the most singles and aggregates occurring in SFR3 and SFR4, respectively (Figure 10). These reaches did not share any other significant habitat similarities. Spanners were also substantially higher in the South Fork when compared to Sourdough Creek (Figure 11); greater LWD and spanner numbers indicate a denser riparian forest adjacent to South Fork reaches. Pools were sparse in the Upper Watershed, with riffles predominating in each reach (Figure 12). However, pocket pools within riffles were abundant due to boulder substrate as well as LWD input (Figure 13). Both large size substrate and abundant LWD are common in mountainous areas, where lateral hillslope contributions dominate input to aquatic systems (Frissell et al. 1986). SCR3 had the highest number of pocket pools; wood contributed by the remnants of a foot bridge increased the amount of LWD and subsequently the number of pocket pools in this reach.

LWD in the Upper Watershed was lower than expected. Although direct comparison of Sourdough Creek to other streams is not possible due to natural system variability, other pristine watersheds showed consistently higher LWD numbers. Amount of LWD in the Upper Watershed was compared to Cottonwood Creek, a USFS reference stream to the west of Sourdough Creek in the Gallatin Range. Trees in Cottonwood Creek Watershed were not historically harvested, and land use in the watershed has been minimal (Scott Barndt, personal communication). When compared to Cottonwood Creek, the Upper Watershed has relatively low LWD numbers (Ladzinski et al. 2004).

The Upper Watershed was also compared to the Salmon River in Idaho, which is used as a natural condition reference system for the USFS. The Salmon River has 97-125 pieces LWD/km and 30-40 pocket pools/km (Overton et al. 1995). Upper Sourdough Creek pieces LWD and pocket pools per km ranged from 0 (SCR2) to 36.94 (SCR5) and 6.6 (SCR1) to 110.8 (SCR3), respectively. South Fork reaches had 15.8 (SFR1) to 139.2 (SFR4) pieces LWD and 15.94 (SFR1) to 85.4 (SFR5) pocket pools per km, respectively. SFR4 had more pieces LWD per km than the reference amount, but no other reach in the Upper Watershed fell within the 97-125 range of the Salmon River. Pocket pools were more comparable to the reference numbers and were primarily found in reaches with large size substrate; this showed that substrate, rather than LWD, controlled pocket pool

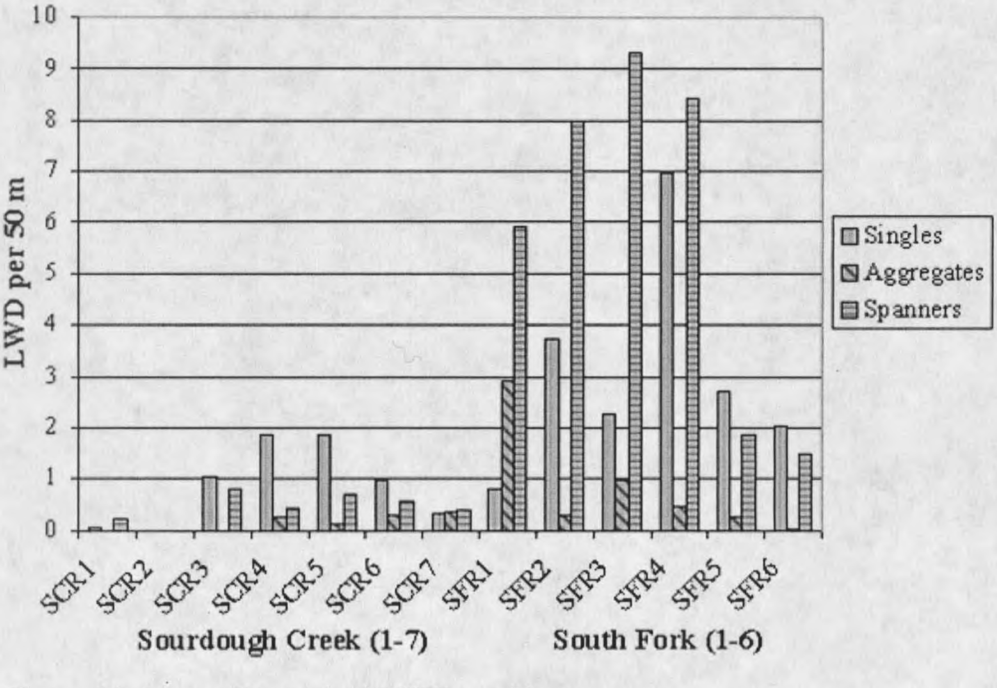

Figure 10. Upper Watershed LWD per 50 m.

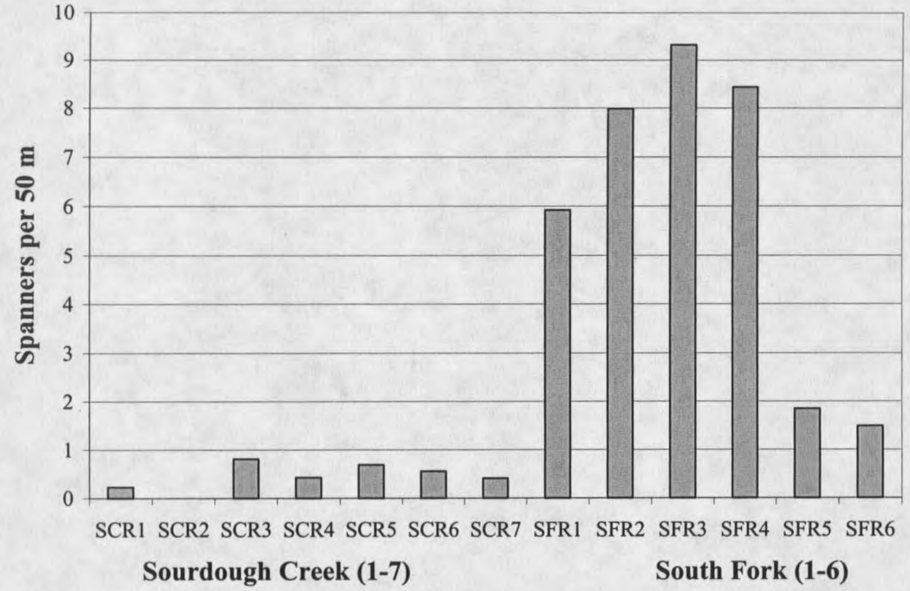

Figure 11. Upper Watershed spanners per 50 m.

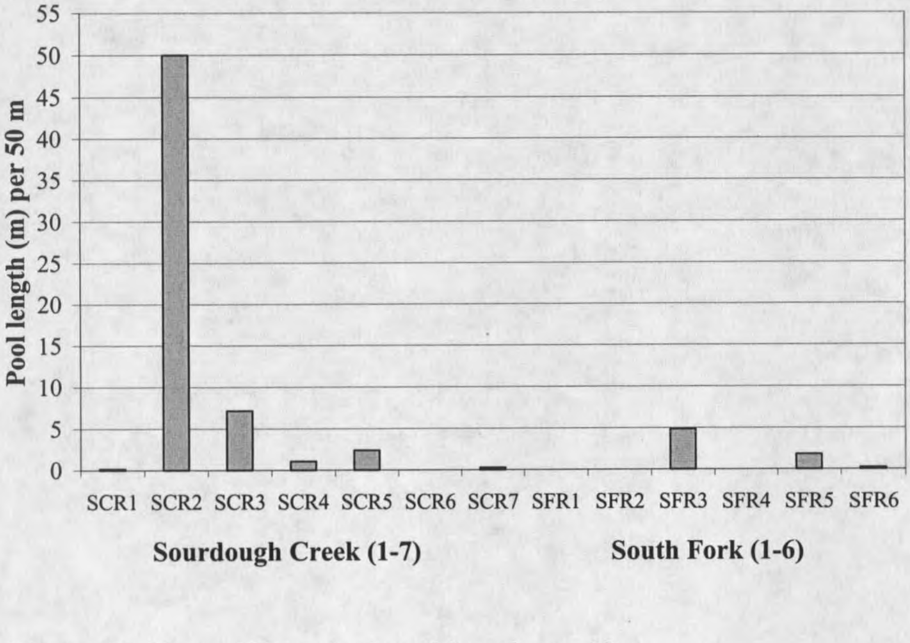

Figure 12. Upper Watershed pool length per 50 m.

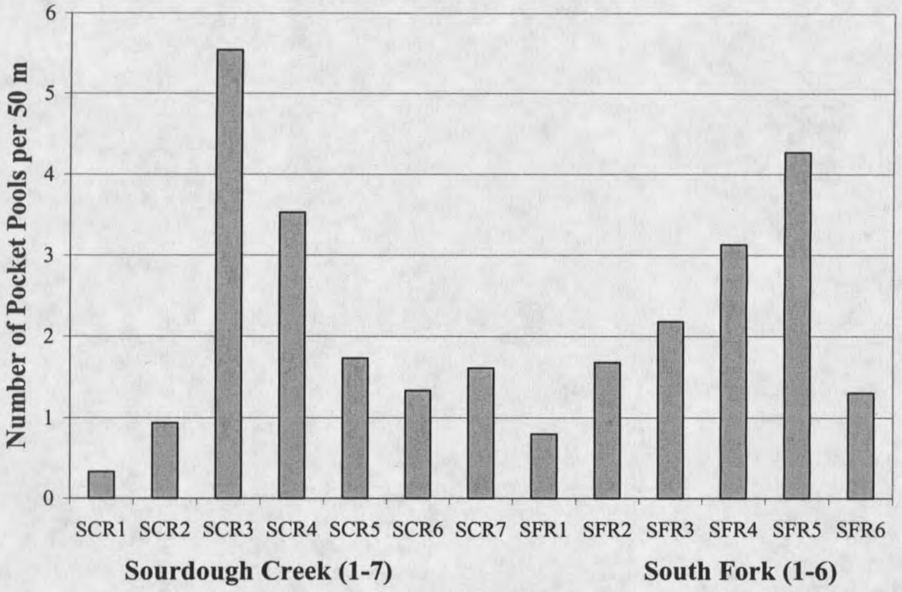

Figure 13. Upper Watershed pocket pools per 50 m.

abundance in the Upper Watershed. Stumps and old logging access roads adjacent to Sourdough Creek suggest historical riparian forest harvest, which could account for the comparatively low LWD numbers. Significantly higher LWD numbers in the South Fork (which has more limited access) further suggests the potential linkage between riparian forest harvest and low LWD numbers for Upper Sourdough Creek.

Comparison of the Upper Watershed with other studies further confirms low LWD numbers. In pristine drainages less than 14,000 ha, LWD pieces > 10 cm thick and > 2 m long range from 7-100 pieces per 100 m (Bilby and Ward 1989, Ralph et al. 1994, Diez et al. 2001). SFR2 and SFR4 are the only Upper Watershed reaches that fall within this range, with 7.5 and 13.9 LWD pieces per 100 m, respectively. The difference in 2 m length used in other studies and 3 m used in this study could contribute to comparatively low LWD numbers in the Upper Watershed; however, a connection to previous riparian forest harvest is again suggested.

Westslope Cutthroat Trout Reintroduction

Although LWD numbers are low, substrate composition, pocket pool abundance, and pool length in the Upper Watershed are suitable for westslope cutthroat trout reintroduction (Ladzinski et al. 2004). Additionally, four significant fish barriers, including the municipal diversion dam, Mystic Lake, a South Fork culvert, and a South Fork waterfall complex, could isolate native populations from non-native competitors. This is particularly important with westslope cutthroat trout species, which are often out-competed by brown (*Salmo trutta*), rainbow (*Oncorhynchus mykiss*), Yellowstone cutthroat (*Oncorhynchus clarki bouvieri*) and/or brook (*Salvelinus fontinalis*) trout populations in the Intermountain West.

Various studies have estimated that westslope cutthroat trout occupy 19-27% of their historical range in Montana (Van Eimeren 1996). However, westslope cutthroat trout can hybridize with other cutthroat trout subspecies as well as rainbow trout, and genetically pure population estimates are as low as 2-4% of historical range (McIntyre and Riemen 1995). Westslope cutthroat trout have three possible life forms, and are adfluvial (migrate to lakes), fluvial (migrate to rivers), or resident (stay in streams); all three life forms spawn in tributary streams in the spring (Liknes and Graham 1988). Spawning and rearing streams tend to be cold and nutrient poor. Fine sediment (< 0.2 cm) is often attributed to poor establishment, with > 25% fine substrate dramatically reducing the viability of spawning and rearing habitat (May 1996). High percent fines reduce oxygen flow to redds, and are therefore detrimental to westslope cutthroat trout establishment (Karr 1981). However, sediment is only one component of suitable reintroduction areas, and managers and researchers must consider a number of factors.

Bond and Lake (2003) pointed out that reintroduction often occurs in the absence of a well-constructed plan. They went on to explain that species reintroduction must consider: 1) the appropriate scale; 2) barriers to colonization; 3) introduced species; and 4) long-term and large-scale processes. In Sourdough Creek, a westslope cutthroat trout reintroduction effort needs to include these issues if it is to be effective.

The appropriate scale includes both time and space, with consideration of different life stages as important as the spatial extent of reintroduction. For example, researchers in another watershed first hypothesized that westslope cutthroat trout reintroduction attempts were failing due to habitat size, and then discovered that habitat was adequate and sediment input was deterring establishment (Bohn and Kersher 2002). The researchers had been concentrating on habitat size requirements for adult trout and had overlooked the importance of suitable spawning substrate.

Colonization barriers are important if the desired population exists; before this is applicable in Sourdough Creek, managers must replace existing fish populations with westslope cutthroat trout. Currently, brown, brook, rainbow, and Yellowstone cutthroat trout populate the stream, and must be removed in reintroduction areas to facilitate westslope cutthroat establishment and prevent hybridization (Scott Barndt, personal communication). Barriers may then actually facilitate reintroduction by isolating restored or existing habitat for westslope cutthroat trout.

The municipal diversion dam at the downstream end of SCR7 presents the largest fish barrier and the greatest habitat alteration in the Upper Watershed. Reintroduction could occur in the entire watershed above the municipal diversion dam. However, removal of all non-native species and reintroduction at such a large scale is a formidable project. Also, since competition and hybridization with other species is a concern, reintroduction in the more isolated upper reaches will probably be most effective.

SCR1 and SCR2 are isolated by Mystic Lake, largely preventing invasive species from colonizing this area. SCR2 lies in a low gradient alluvial valley, high sinuosity, and an abundance of undercut banks, all of which provide habitat and cover for trout. A Forest Service site visit in 2002 noted a number of non-native trout in the reach (Ladzinski et al. 2004). However, the high percent fines in this section are a concern for reintroduction. Even with the isolation and suitable habitat of SCR1 and SCR2, if spawning and rearing habitat is inadequate due to small substrate, reintroducing native trout to the area should not be attempted.

The road and culvert bisecting SFR6 and SFR5 and a waterfall in SFR2 could provide the lower and upper end of a reintroduction area. SFR4 and SFR5 (directly above the culvert) are suitable for fish habitat, with abundance of both pocket pools and LWD. Coupled with the barrier to non-native passage, these two reaches represent the most suitable in the Upper Watershed for removal of non-native species and reintroduction of westslope cutthroat trout.

Long-term and large-scale processes include those important for reintroduction as well as considerations at the watershed scale. With reintroduction of westslope cutthroat trout, removal of non-native fish requires either electroshocking or poisoning the existing fish population. Identifying the viability of both options as well as potential environmental ramifications (especially upstream from a municipal water supply), are clearly critical considerations. Additionally, approaching reintroduction at an ecosystem level, where habitat improvement and sustainability are included, is essential. If reintroduction efforts are detrimental for other organisms, then their utility is greatly compromised and other paths should be explored.

Lower Watershed Introduction

Geomorphology and land use have impacted aquatic habitat in the Lower Watershed. Nearly all variables showed statistically significant differences across land classes via the Wicoxon Rank Test, illustrating the potential impact of land use on aquatic system structure, function, and composition. Sinuosity was also repeatedly correlated to LWD abundance and pool length in regression analysis.

Geomorphology

Lower Sourdough Creek was classified as a 3rd order system until its confluence with the East Gallatin River, at the downstream end of the study area. Gradient in the

Lower Watershed was relatively low (<0.2%), with sinuosity averages ranging between 1.19 and 1.40 (Table 3). Average sinuosity and gradient were unconnected in the Lower Watershed. Gradient probably influenced sinuosity on a more localized level, but analysis at that scale was not included in this study. Elevation change across the Lower Watershed was 157 m, and predominant substrate was cobble, with a mix of other materials excluding bedrock (Figure 14).

Table 3. Lower Watershed geomorphologic variables.

Land Class	**Stream Elevation (m)**	**Sinuosity**	**Gradient (%)**	**Stream Length (m)**	**Basin Size (ha)**
Forest	1,591-1,597	1.24	0.4	1,375	7,540
Agriculture	1,530-1,591	1.30	1.6	3,975	8,120
Low Density	1,475-1,530	1.31	1.4	3,806	8,790
Gardiner Park	1,510-1,530	1.40	1.5	1,318	8,440
High Density	1,469-1,475	1.19	0.2	3,486	9,150
Industrial	1,440-1,469	1.29	1.8	1,629	9,300

Figure 15 shows valley width at the beginning, middle, and end of each land class. Valley width was classified as the cross-section area with an elevation of 60 m or less above the stream. In valley systems, stream input will be more localized than this width, as inputs primarily come from adjacent riparian zones (Stanford 1996). Valley width in this study was therefore used primarily as a tool for comparison among land classes instead of as an indicator of potential stream input. Valley width was greatest at

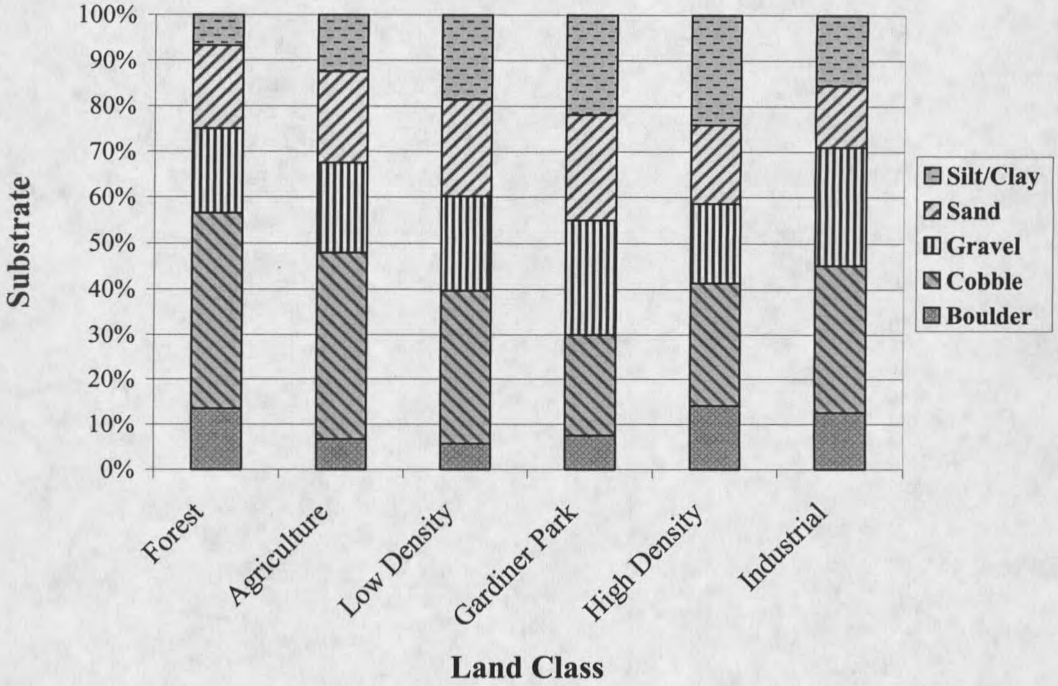

Figure 14. Lower Watershed substrate.

the forest/agriculture land class boundary, decreased in the low density land class, and then increased again in the middle of the high density land class.

Wilcoxon Rank Test

Because data did not meet the assumption of normality for a t-test, the Wilcoxon Rank Test was used instead. The Wilcoxon test evaluates whether or not the difference between the median of two populations equals 0. If so, then there is likely a significant difference between the two (Sheskin 1996). Paired relationships were analyzed between

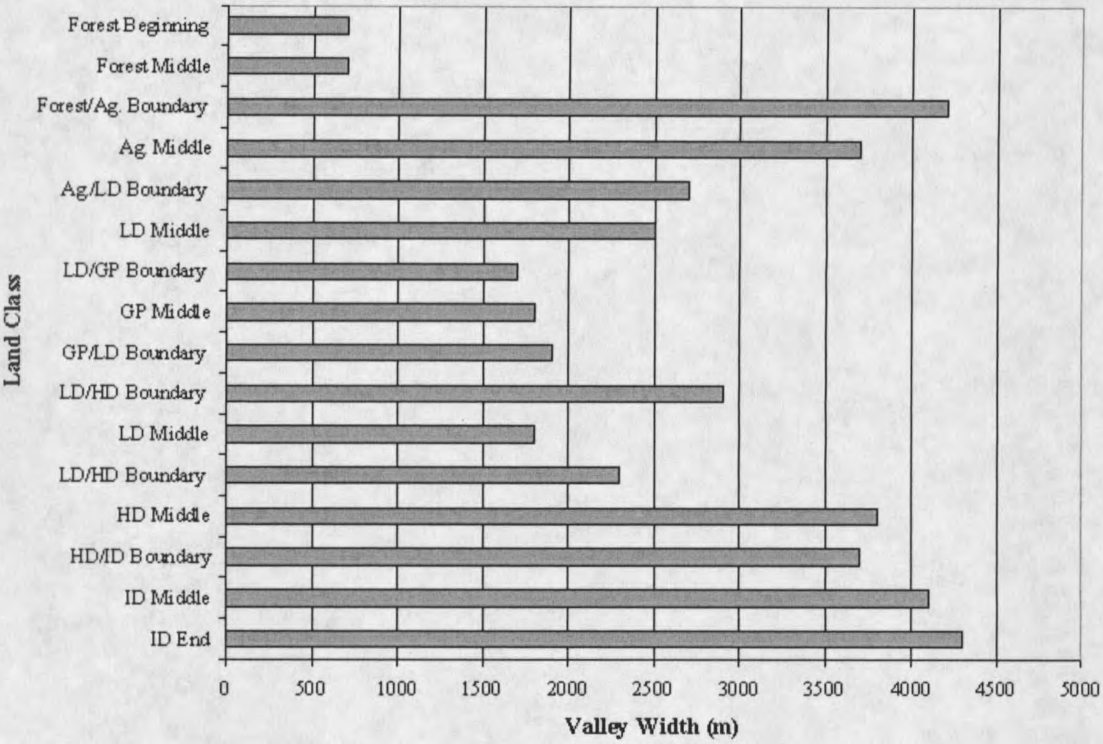

Figure 15. Valley width (m) measured as the cross-section length of area 60 m or less above the stream at the beginning, middle, and end of each land class.
Ag.-agriculture land class
LD-low density land class
HD-high density land class
GP-Gardiner Park land class
ID-industrial land class

all variables across all land classes (Appendix C), with Table 4 showing statistically significant results ($p < 0.05$). Bankfull depth was the only variable that illustrated no significant difference among land classes. P-values closer to 0 indicate a higher probability that the paired variable is statistically different. For example, there was a

Table 4. Wilcoxon rank test results of p values < 0.05.

LWD	
Forest-Agriculture	0.0040
Agriculture-Low Density	0.0000
Agriculture-High Density	0.0105
Low Density-High Density	0.0054
Gardiner Park-High Density	0.0032

Pool Length	
Forest-Gardiner Park	0.0388
Agriculture-High Density	0.0048
Gardiner Park-High Density	0.0156
Gardiner Park-Industrial	0.0243

Pocket Pools	
Forest-Low Density	0.0001
Forest-Industrial	0.0237
Agriculture-Low Density	0.0004
Low Density-Gardiner Park	0.0026
Low Density-Industrial	0.0000
High Density-Industrial	0.0074

Riparian Width	
Forest-High Density	0.0034
Forest-Industrial	0.0001
Agriculture-High Density	0.0000
Agriculture-Industrial	0.0000
Low Density-High Density	0.0000
Low Density-Industrial	0.0000
Gardiner Park-High Density	0.0001
Gardiner Park-Industrial	0.0001
High Density-Industrial	0.0008

Canopy Cover	
Forest-High Density	0.0084
Forest-Industrial	0.0081
Agriculture-High Density	0.0150
Low Density-High Density	0.0095
Low Density-Industrial	0.0133
Gardiner Park-Industrial	0.0021
High Density-Industrial	0.0006

Spanners	
Forest-Agriculture	0.0048
Forest-Low Density	0.0000
Forest-High Density	0.0079
Agriculture-Low Density	0.0388
Agriculture-Gardiner Park	0.0061
Agriculture-Industrial	0.0363
Low Density-Gardiner Park	0.0000
Low Density-Industrial	0.0002
Gardiner Park-High Density	0.0092

Wetted Depth	
Forest-Agriculture	0.0170
Low Density-High Density	0.0330

Entrenchment Ratio	
Forest-High Density	0.0362
Low Density-High Density	0.0249

Wetted Width	
Forest-Agriculture	0.0000
Forest-Low Density	0.0314
Forest-Industrial	0.0050
Agriculture-Low Density	0.0001
Agriculture-Gardiner Park	0.0039
Agriculture-High Density	0.0000
Agriculture-Industrial	0.0284
Low Density-High Density	0.0328
Gardiner Park-High Density	0.0157
High Density-Industrial	0.0002

Bankfull Width	
Forest-Agriculture	0.0145
Forest-High Density	0.0001
Agriculture-Low Density	0.0161
Agriculture-High Density	0.0000
Low Density-Gardiner Park	0.0009
Low Density-High Density	0.0006

Table 4 (continued).

Sinuosity	
Agriculture-High Density	0.0141
Low Density-High Density	0.0080
Gardiner Park-High Density	0.0070

Structures	
Forest-Agriculture	0.0275
Forest-Low Density	0.0009
Forest-Gardiner Park	0.0001
Forest-High Density	0.0002
Forest-Industrial	0.0156
Agriculture-Low Density	0.0000
Agriculture-Gardiner Park	0.0032
Agriculture-High Density	0.0000
Agriculture-Industrial	0.0014
Low Density-High Density	0.0004
Gardiner Park-High Density	0.0001

Riprap	
Forest-High Density	0.0037
Agriculture-High Density	0.0012
Low Density-High Density	0.0006
Gardiner Park-High Density	0.0053
Industrial-High Density	0.0072

Unstable Banks	
Forest-Gardiner Park	0.0000
Forest-High Density	0.0001
Forest-Industrial	0.0017
Agriculture-Low Density	0.0001
Agriculture-Gardiner Park	0.0474
Low Density-Industrial	0.0000
Gardiner Park-High Density	0.0445
Gardiner Park-Industrial	0.0045
High Density-Industrial	0.0274

Undercut Banks	
Forest-Low Density	0.0000
Agriculture-Low Density	0.0007
Low Density-High Density	0.0075

Statistically significant difference in pool length when both the agricultural and Gardiner Park land classes where compared to the high density land class. The p-value of the agriculture-high density comparison was 0.0156, whereas the Gardiner Park-high density p-value was 0.0048. This shows that the difference between the medians in the Gardiner Park and high density land classes is more statistically significant than between the agriculture and high density land classes, although both have a $p\text{-value} < 0.05$.

Regression Analysis

LWD was positively correlated to distance downstream in the forested section, sinuosity and riparian forest width in the agricultural section, and sinuosity in the Gardiner Park and industrial sections (Figure 16 a-d). Pool length was positively correlated to sinuosity and/or LWD in every land class except forest and high density (Figure 17 a-d). Since sinuosity and LWD were strongly correlated covariables, LWD was removed from the analysis because it had lower R^2 values and higher p-values than sinuosity. Regression analyses were also used to explore the effects of sinuosity on LWD and pool length in the entire Lower Watershed (Figure 18, 19). Correlations were less strong on a landscape scale, but both LWD and pool length were connected to sinuosity with R^2 values of 0.32 and 0.28, respectively.

The regression analyses showed the connections between land classes and the response variables. Regression equations were all linear, except for in the agricultural land class, where the LWD equation was a multiple linear regression. The absence of many significant multiple regressions is potentially due to the small sample sizes, which ranged from 10 samples in the forest land class to 39 in the agricultural land class. Although linear relationships predominated in this study, correlations between LWD and pools and the chosen predictor variables did correspond with other studies (Diez et al. 2002, White et al. 1983). Interestingly, structures were not correlated to either LWD or pool length. Although the literature review showed no study that used structures as a predictor variable of LWD and/or pool length, it is intuitive that denser structures indicate a more urbanized environment, hence one with less LWD input from adjacent riparian forests and lower pool length due to increased channelization.

Large Woody Debris Distribution and Abundance

Lower Watershed LWD generally decreased with distance downstream, although numbers were higher in the agricultural section than in the forested section (Figure 20). LWD was highest in the agricultural and Gardiner Park land classes, with the Wilcoxon test showing significant variance between agricultural LWD and every other land class except Gardiner Park. In the forest land class, low LWD numbers were unexpected due to a wide riparian forest width and a high potential for LWD input from the Upper Watershed. Both the municipal diversion and an agricultural dam a few 100 m downstream probably cause low LWD numbers. Although both diversions generally reduce flow, managers sometimes allow higher flows, causing pulses that undoubtedly

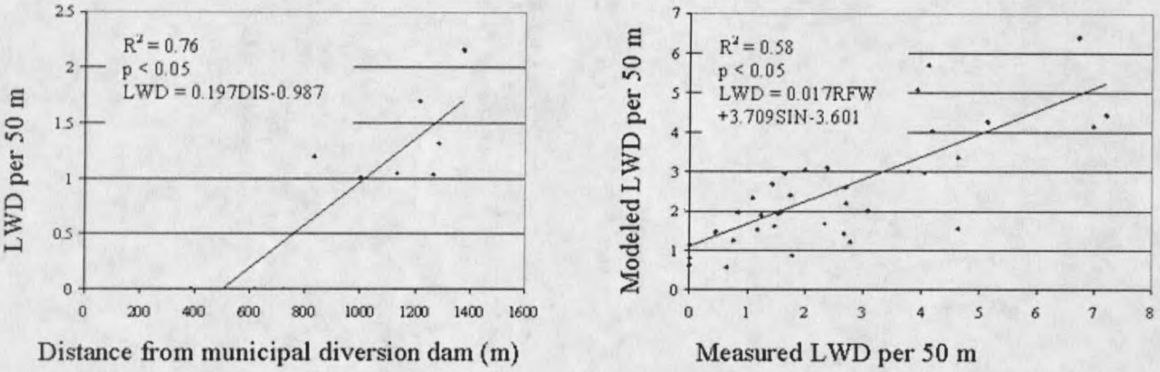

Figure a. Relationship between forest LWD and distance (DIS) from the municipal diversion dam (m).

Figure b. Relationship between agricultural land class LWD and the predictor variables riparian forest width (RFW) and sinuosity (SIN) shows an increase in LWD with increasing RFW and SIN.

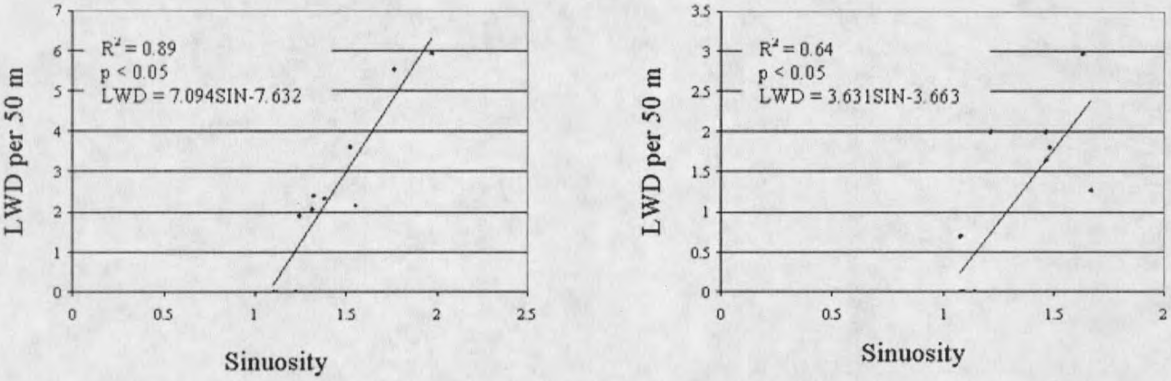

Figure c. Relationship between Gardiner Park LWD and sinuosity.

Figure d. Relationship between industrial LWD and sinuosity.

Figure 16 a-d. Regressions of land class LWD and predictor variables.

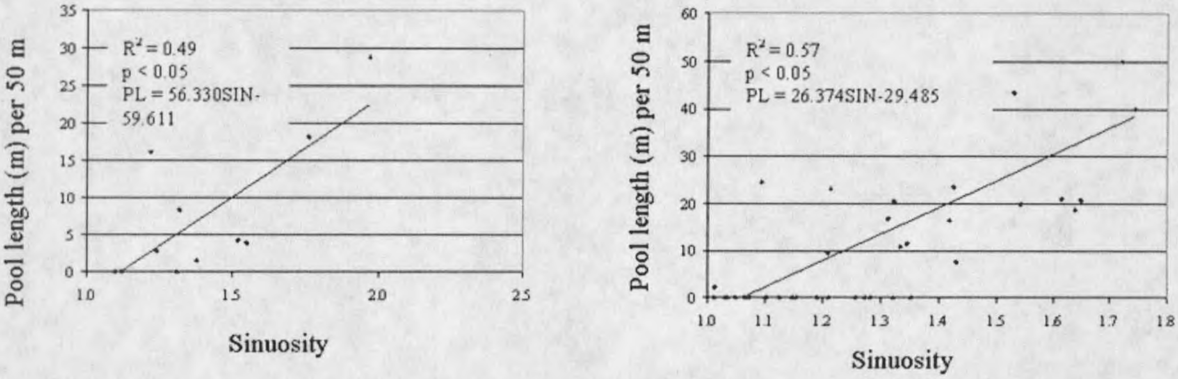

Figure a. Agricultural land class

Figure b. Gardiner Park land class

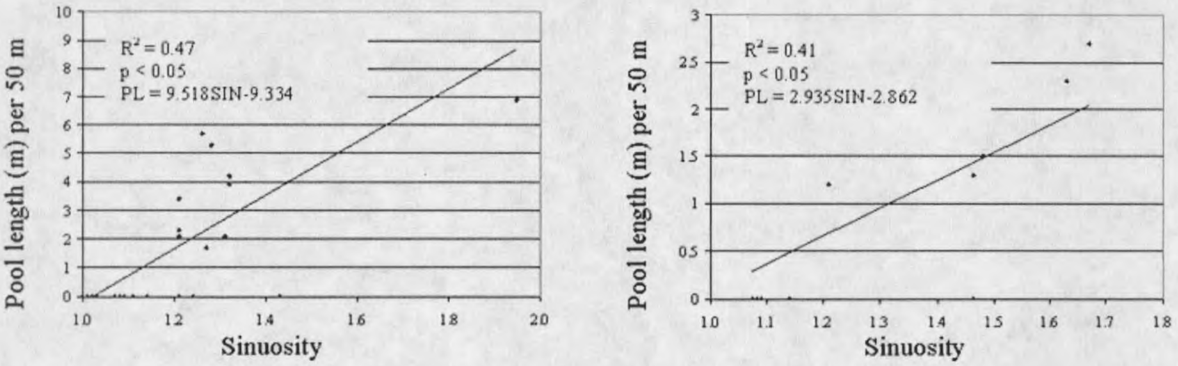

Figure c. High density land class

Figure d. Industrial land class

Figure 17 a-d. Regressions of land class pool length and sinuosity.

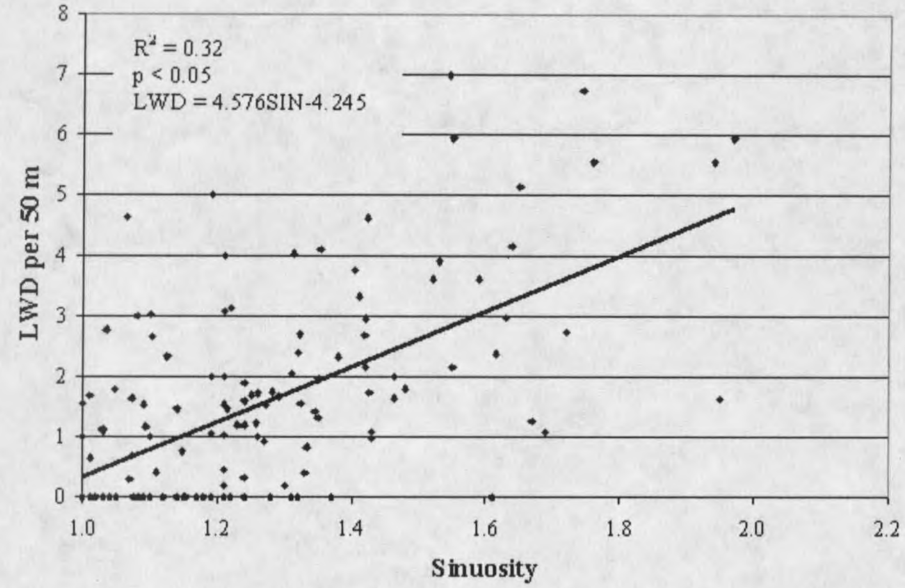

Figure 18. Relationship between Lower Watershed LWD and sinuosity (SIN).

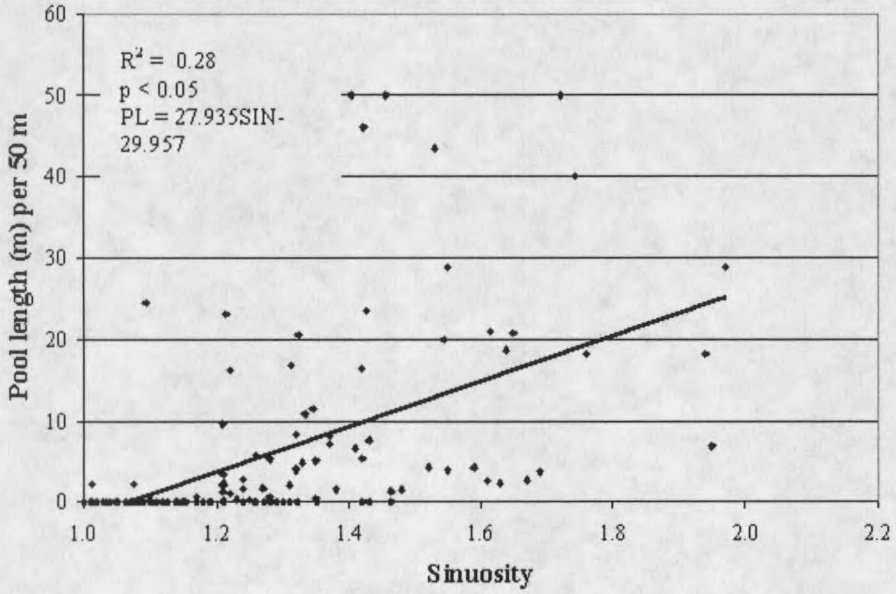

Figure 19. Relationship between Lower Watershed pool length (m) per 50 m and sinuosity (SIN).

move wood downstream. Wood removal is also common to prevent both diversions from becoming blocked (James Goehrung, personal communication). Additionally, although the forested land class has the highest riparian forest width, there is no riparian forest on the east side of the stream, where the access road prevents any direct LWD contribution.

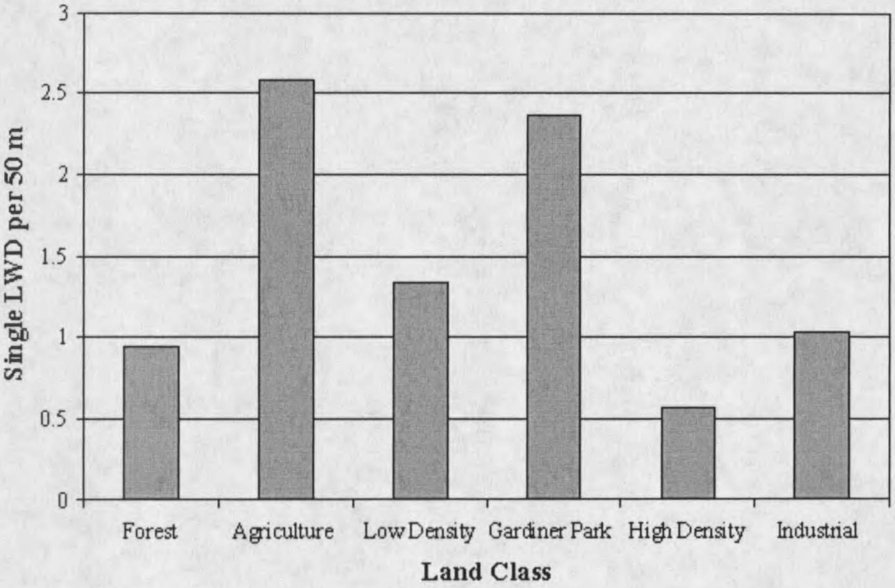

Figure 20. Lower Watershed single LWD, with amounts ranging from 2.6 pieces per 50 m (agricultural land class) to 0.6 pieces per 50 m (high density land class).

Riparian Forest

Riparian forest width declined with distance downstream, as is often the case with distance from headwaters (Hulse and Gregory 2001; Figure 21). Figure 22 shows that canopy cover is fairly constant (around 50%) until the industrial land class, where it drops to 35%. Canopy cover percentage was highest in the high density area; although

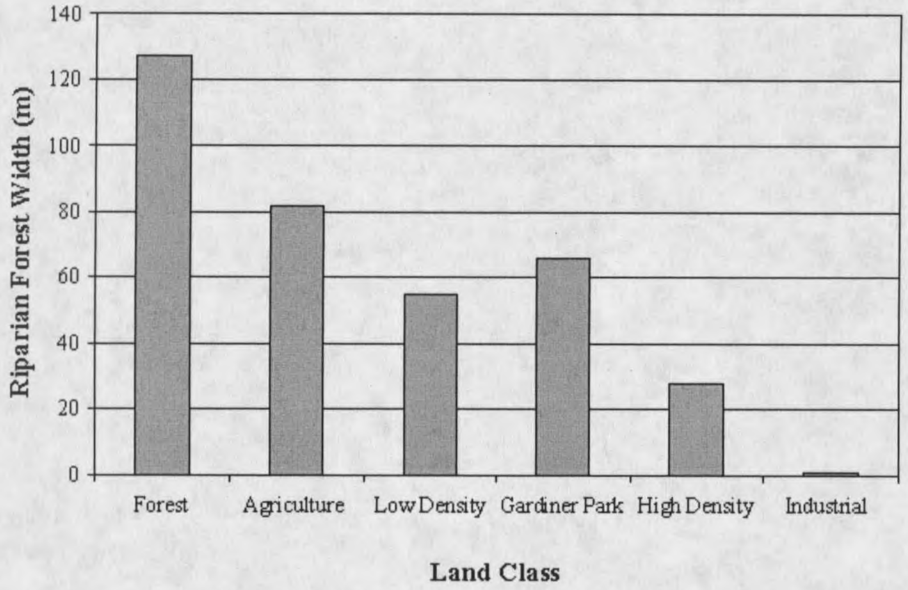

Figure 21. Lower Watershed riparian forest width (m), which showed a decreasing trend in the Lower Watershed.

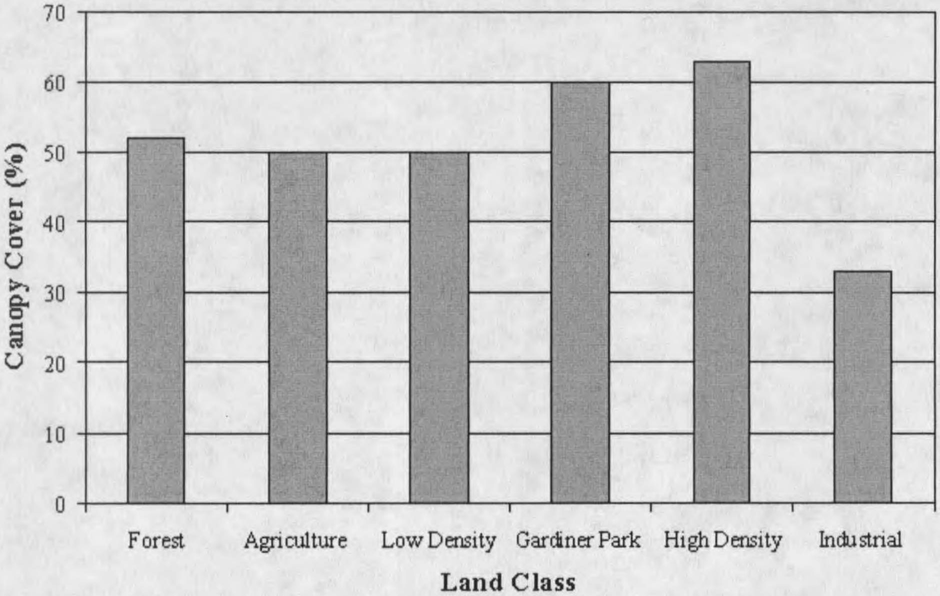

Figure 22. Lower Watershed canopy cover (%).

the riparian forest zone was not wide in this section, adjacent vegetation was denser than expected.

Riparian forest width was statistically correlated to LWD only in the agricultural land class, which was unexpected because it is often connected to in-stream wood abundance (Swanson et al. 1982, Diez et al. 2001, Bilby and Ward 1989). Riparian forest harvest or replacement of native forests with planted vegetation often decreases LWD, while wider riparian forest zones increase LWD abundance (Diez et al. 2001). Although the agricultural land class had the only significant correlation between riparian forest width and LWD, both variables showed the same trend of decreasing downstream except for higher numbers in Gardiner Park. Because Gardiner Park is managed as a municipal park, active wood removal and riparian forest harvest must be less prevalent than in the other land classes. Although regression analysis did not show multiple correlations between riparian forest width and LWD, input of adjacent vegetation is clearly critical for LWD abundance.

Spanner Presence and Abundance

Spanners, which will eventually be LWD contributed to the aquatic system, illustrated no decreasing trend throughout the land classes (Figure 23). Spanners are often more prevalent with a wider riparian forest (Swanson et al. 1982), but did not show a connection to riparian forest width in this study. Spanners were most abundant in Gardiner Park, which had an average riparian forest width (66 m). Again, the Gardiner

Park section of Sourdough Creek probably is not subjected to active wood removal, resulting in the high spanner numbers.

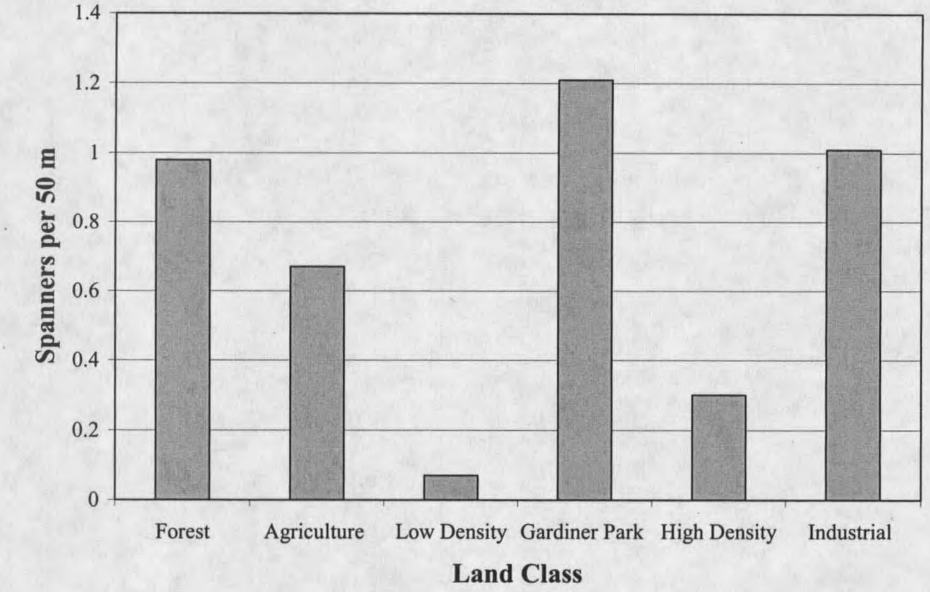

Figure 23. Lower Watershed spanners.

Debris Dams

Debris dams were sparse in the Lower Watershed (Figure 24), with the most continuous dam in the agricultural land class, where beavers constructed a 260 m complex that created long pools and forced water into a number of backwater channels (Figure 25). Debris dams were absent in the forest land class, and most abundant in the high density land class (5 m per 50 m), which was an unexpected result. However, debris dams in the high density land class were predominantly near the industrial land class (north of the city of Bozeman), where active channel management probably declines. The lack of any debris dams in the forest land class further illustrates the effects of the municipal diversion and agricultural dams on flow and habitat heterogeneity.

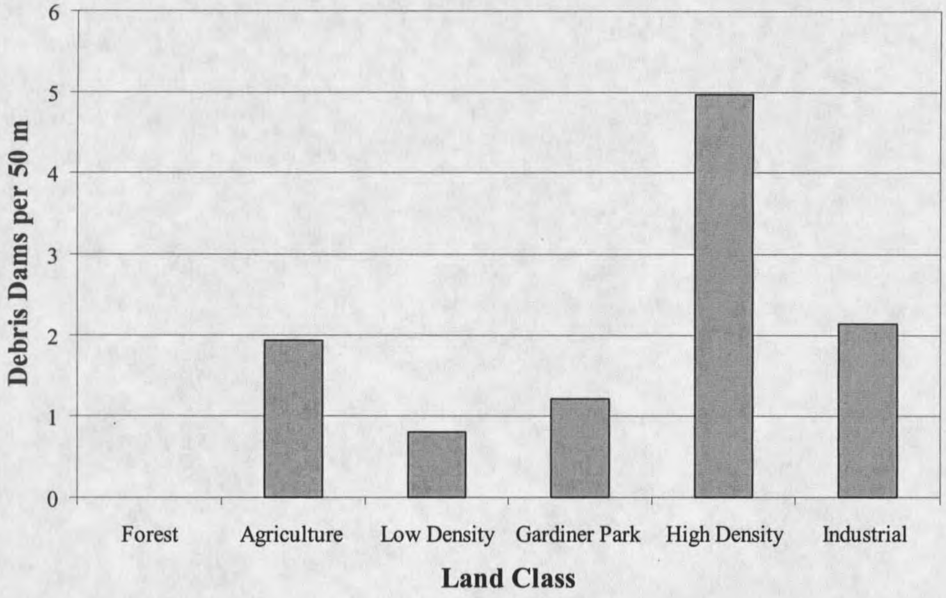

Figure 24. Lower Watershed debris dams per 50 m.

Debris dams influence the structure and function of aquatic systems (Gregory et al. 1991) by creating fish habitat and dispersing energy flow. They also push water towards stream banks, increasing erosion and widening channels. Debris dams have not been widely studied (Bilby and Ward 1989, Deiz et al. 2001), but their contribution to aquatic habitat heterogeneity is nonetheless apparent. Debris dams in the Lower Watershed contained more fish than any other habitat, illustrating the importance of the long and deep pools they create. Debris dams are often abundant in valley systems (Bilby and Likens 1980),

Figure 25. A debris dam complex in the agricultural section created long and deep pools, increasing habitat heterogeneity.

and their low numbers in the Lower Watershed again indicate active wood removal and human habitat alterations.

Pools and Sinuosity

Pool length was nearly four times higher in the agricultural area and decreased in the land classes downstream (Figure 26). Pool length was lowest in the forested section, probably due to the road that parallels the stream and prevents channel migration as well as flow alterations caused by the two diversion dams. Pocket pools in the Lower Watershed were most abundant in the forest and agricultural sections (Figure 27). The forest land class had the second-highest percent boulder substrate (13.5%); although this was only slightly lower than the high density land class (14.1%), much of the boulders in the high density section were placed as riprap, and did little to create pocket pools. The agricultural land class had the highest LWD amount (2.58 pieces/50 m), which again contributes to pocket pool abundance (Frissell et al. 1986).

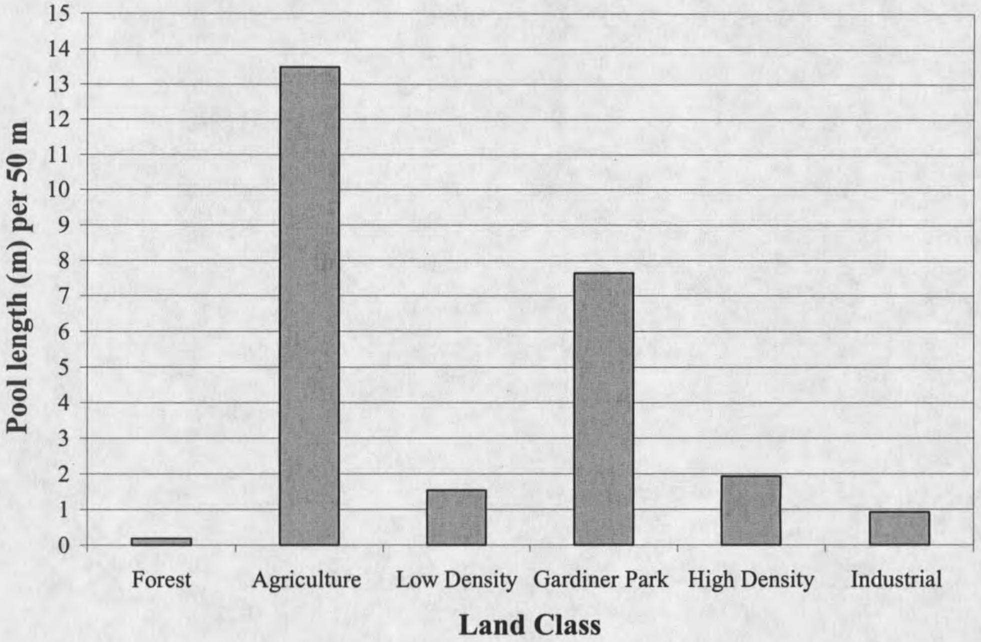

Figure 26. Lower Watershed pool length.

The Wilcoxon test showed only three statistically significant differences in sinuosity, probably because sinuosity values ranged from just 1.19 to 1.31. As expected, sinuosity was highest in the agricultural land class and lowest in the high density land class. The high density land class had low pool length and LWD numbers; sinuosity was the primary predictor variable for both of these in linear regressions. Within the high density land class, many reaches had sinuosity values of about 1.0, which is a straight

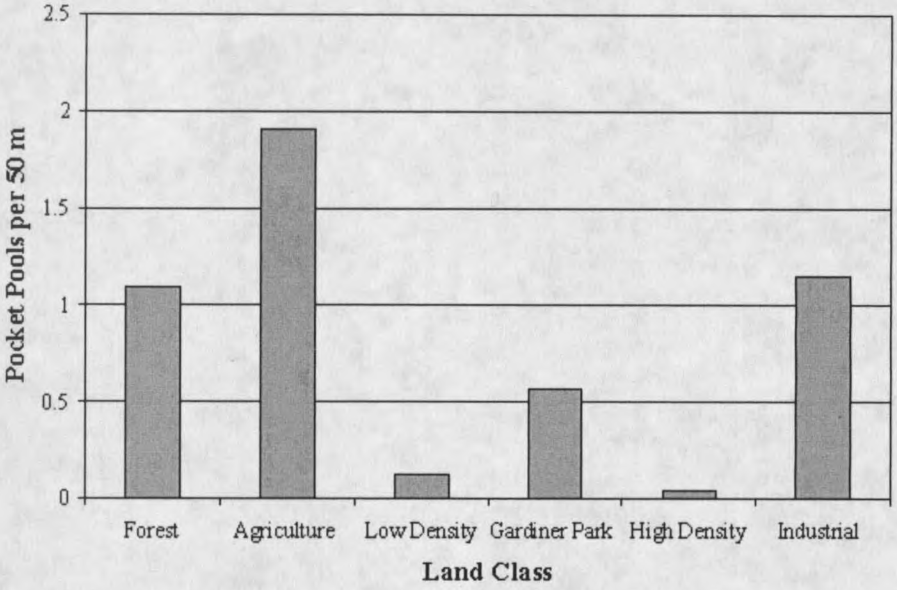

Figure 27. Lower Watershed pocket pools per 50 m.

channel. In the absence of meanders, flow velocities increase, stream depth increases, and habitat heterogeneity declines (Brookes 1988). Therefore, even though sinuosity did not statistically differ much between land classes, variance within land classes probably influenced the aquatic system more than total means used for comparison.

Sinuosity and valley width were greatest in the agricultural section, but a connection between the two did not occur in any other land class. For example, the high density land class had a wide valley and low sinuosity, whereas Gardiner Park had a narrower valley and higher sinuosity. Although valley width often drives sinuosity (Frissel et al. 1986), channelization and other human impacts more significantly affect channel meanders in Sourdough Creek Watershed (White et al. 1983).

Low sinuosity causes lower quality aquatic habitat, negatively impacting organisms and system integrity. Sinuosity influences distribution and abundance of different habitat units as well as substrate composition (Frissel et al. 1986). Additionally, many organisms have evolved in response to natural flow regimes, and flow alterations impact their presence and success. Natural patterns of longitudinal and lateral connectivity are essential for many species' survival, and these both decline with channelized systems. Altered flow regimes also facilitate invasion and success of non-native species (Bunn and Arthington 2002). Although all of these impacts were not quantified in the Lower Watershed, channelized sections in the high density and forest land class undoubtedly experience all or some of these effects.

Bank and Channel Characteristics

Bank characteristics, including undercut and unstable banks as well as riprap showed no trends in the Lower Watershed (Figure 28). Undercut and unstable banks were most likely connected to high sinuosity in the agricultural land class (1.30), with channel migration increasing bank instability and subsequent erosion (Rosgen 1994). Unstable banks increase LWD contribution to the stream (Diez et al. 2001), which was reflected in the high LWD numbers in the agricultural land class. Riprap was nearly three times higher in the high density area when compared to the other land classes. High density riprap was dispersed throughout the land class, but many sections had > 30 m of continuous riprap.

Channel characteristics varied little between land classes (Figure 29). The high density land class had the second lowest wetted width, in contrast with other studies (Pizzuto 2000, Wahl 1997). Additionally, although flow was not recorded, the high density land class had much deeper water than the other classes, again conflicting with other literature (Pizzuto 2000). In the high density land class, much of the channel was

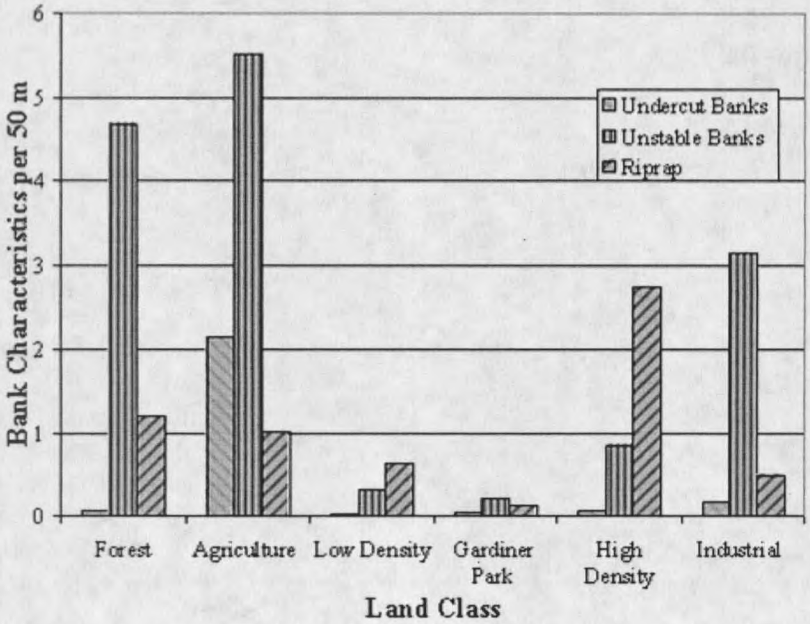

Figure 28. Lower Watershed bank characteristics per 50 m.

controlled with concrete or boulders, preventing the channel from becoming wider. Numerous storm pipes also drained directly into the stream, adding to stream volume and at least partially accounting for the higher flow observed in the high density land class. The high density area also had the lowest entrenchment (wetted width: depth) ratio (Figure 30), which reflects the incised and controlled channel reaches in that section.

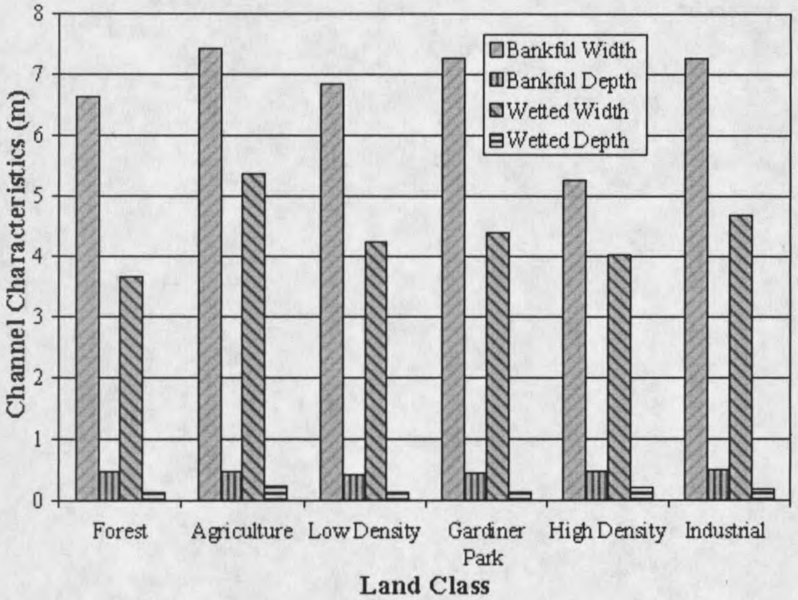

Figure 29. Lower Watershed channel characteristics per 50 m.

The highest entrenchment ratio was in the industrial section, where channels lack the confinement evident in the high density area.

Channel characteristics were not connected to LWD or spanners in any land class. Other research has shown a correlation between wetted width and LWD abundance in natural systems (Diez et al. 2002, Ralph et al. 1994), which was not seen in this study. Channel width is often connected to LWD abundance, with wider channels facilitating LWD movement downstream more easily than narrow channels (Bilby and Ward 1989). Channel width varied little between land classes, which perhaps explains the lack of correlation with LWD.

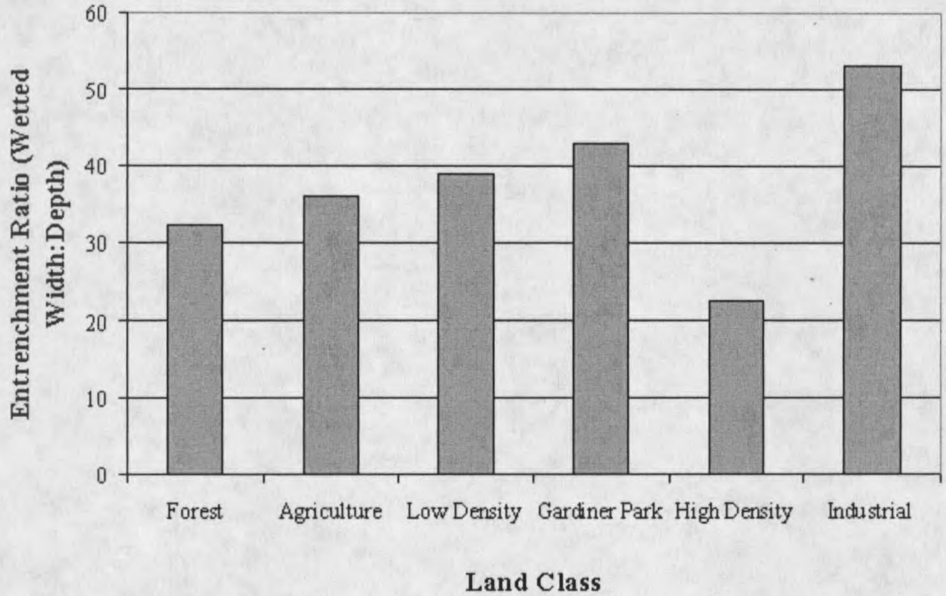

Figure 30. Lower Watershed entrenchment ratios.

Low entrenchment ratios increase the potential for LWD input in natural systems, as floods can more easily move LWD into the aquatic system (Rosgen 1994). Lower

Watershed entrenchment ratios showed no connection to LWD input, with ratios increasing with distance downstream as opposed to decreasing as LWD did. The exception to this increasing trend was the high density land class, which had the lowest entrenchment ratio; the high density class also had the second to lowest LWD number. Low entrenchment ratios often increase spanners, as wood more frequently falls across the channel instead of into it (Diez et al. 2001). The high density land class had a dense canopy cover and the lowest entrenchment ratio, and therefore spanners should be abundant in this land class. However, low spanner numbers in the high density land class suggest active wood removal and a further connection between land use and aquatic habitat. This results from floodplain development and stream confinement, and reflects active stream management in the high density section (Ladzinski et al. 2004).

Land classes

Structures, roads, and bridges were greatest in the high density land class (Table 5). This is clearly due to the study design, as the high density area was characterized by the greatest number of structures. Trail density was greatest in the high density land class. This is due to the Galligater Linear Trail and Pete's Hill recreation areas, both of which were within the 500 m stream buffer. In the low density area, bridges were most numerous. Many residents with bridges had also cleared riparian vegetation on the east side of the stream (houses were almost exclusively located on the west side), and seeded small lawns. Gazebos and tree houses were particularly dense along this stretch of

Table 5. Land class variables per 50 m within a 500 m buffer.

Land Class	**Roads (m)**	**Trails (m)**	**Bridges**	**Structures**
Forest	50	0	0.00	0.08
Agriculture	127	0	0.03	1.12
Low Density	47	3	0.17	3.67
Gardiner Park	35	9	0.10	2.01
High Density	203	43	0.13	14.13
Industrial	151	0	0.16	3.63

stream, indicating recreational use directly adjacent to the stream. Potential contribution of fertilizer and other inputs into the stream throughout the low density land class would be interesting to explore in future work.

Conclusion

This study identified linkages between aquatic habitat, geomorphology, and land use in Sourdough Creek Watershed. The Upper Watershed reflects common hillslope characteristics, with predominantly steep gradients and large size substrate. LWD in Sourdough Creek was not as abundant as expected, which is perhaps due to historical riparian harvest. Reintroduction of westslope cutthroat trout is a possibility, but will require a comprehensive management plan and should be attempted in the context of habitat conservation and enhancement. If reintroduction is detrimental for ecosystem processes or other organisms, then its utility is questionable.

In the Lower Watershed, land classes were repeatedly connected to aquatic system change. The Wilcoxon test showed significant differences when variables were compared among land classes, suggesting impacts of different land uses on aquatic habitat. Higher sinuosity was connected to an increase in LWD and pool length in every regression except one; land use practices which reduce or restrict sinuosity will therefore result in less LWD and shorter pools. Conserving existing channel meanders as well as exploring restoration in highly-impacted sections of the Lower Watershed are therefore critical considerations for decision-makers.

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CHAPTER THREE

SOURDOUGH CREEK WATERSHED MANAGEMENT

Introduction

Sourdough Creek Watershed, in the early 1900s and before, existed in a dynamic equilibrium between disturbance and recovery. Fire and slope erosion as well as landslides contributed sediment that was periodically flushed by natural flooding events. LWD and pools created heterogeneous habitat, and native westslope cutthroat trout populated the Upper Watershed.

Contemporary disturbances in Sourdough Creek Watershed shape the system in different ways; damming, clearcutting, and channelizing are only some of the myriad effects that humans have on the system. In this situation, the City of Bozeman, federal and state management agencies, and the surrounding residents have a great opportunity to make management decisions which meet the needs of water quality and quantity while also enhancing ecological and social functions of the watershed. This process could take a number of paths, but "adaptive management" outlines a strong and effective approach for watershed management.

Geomorphology, land use, and land management clearly differentiate the upper and lower sections of Sourdough Creek Watershed. Although dichotomies exist between the two areas, their management as an ecosystem is critical for sustaining the entire system. The watershed therefore must be viewed within a holistic context, where researchers and managers work collaboratively to assess system dynamics at both small- and large-scales.

Managing for watersheds requires a paradigm shift, or a "basic metamorphosis" (Leopold 1990), where decisions involve entire systems and the abiotic and biotic resources that interact within them. Effective watershed management includes attention to: 1) sustainability; 2) adaptability and accountability; 3) complexity and connectedness; 4) context and scale; 5) humans as ecosystem components; 6) sound ecological modeling and understanding; and 7) monitoring and goals (Christensen et al. 1996).

Sustainability

Sustainability is the maintenance of ecological integrity such that an entire system and organisms within it may express their intrinsic capacity (Frissell et al. 1997). Sustainability provides a long-term framework for system function and integrity. It additionally involves improvement or restoration of function, structure, and composition in degraded or altered ecosystems (Gunderson 1995). Sustainability precludes all other aspects of ecosystem management, and is generally the core of a watershed plan.

Adaptability and Accountability

Decision-makers may follow a number of watershed management plans; one possibility is adaptive management. The primary goal of adaptive management is to develop an optimal management structure for an ecosystem instead of managing for a certain condition or state (Johnson 1999). It emphasizes active learning of all stakeholders as well as acceptance of ecosystem "surprise" (i.e. when an ecosystem responds in an unexpected way to disturbance or management) (Holling 1990). Adaptive management also focuses on resiliency, or the ability of a system to return to one of many states of equilibria following a perturbation (Gunderson 1995). Its implementation often proceeds without the minimum scientific data set generally deemed necessary for management, and instead emphasizes a cyclical process, with continual collection of knowledge for replanning and reanalyzing management decisions (Johnson 1999). Additionally, adaptive management recognizes natural variability, spatial heterogeneity, and nonlinear causation. Recognition of these factors leads to systems that are more resilient to disturbance or management gone array (Holling 1990).

Adaptively managing Sourdough Creek Watershed would differ greatly from current practices. Management in the watershed is not only separated between the upper and lower sections, but is often a top-down approach, where federal, state, or city officials make decisions without input from all stakeholders. Critical issues in Sourdough Creek Watershed include increasing biodiversity, conserving and restoring habitat, maintaining water quality and quantity, and defining a successful fire management plan (Figure 31). Applying adaptive management in Sourdough Creek Watershed will include collaborative decision-making that identifies flexible strategies for addressing ecosystem disturbance and surprise.

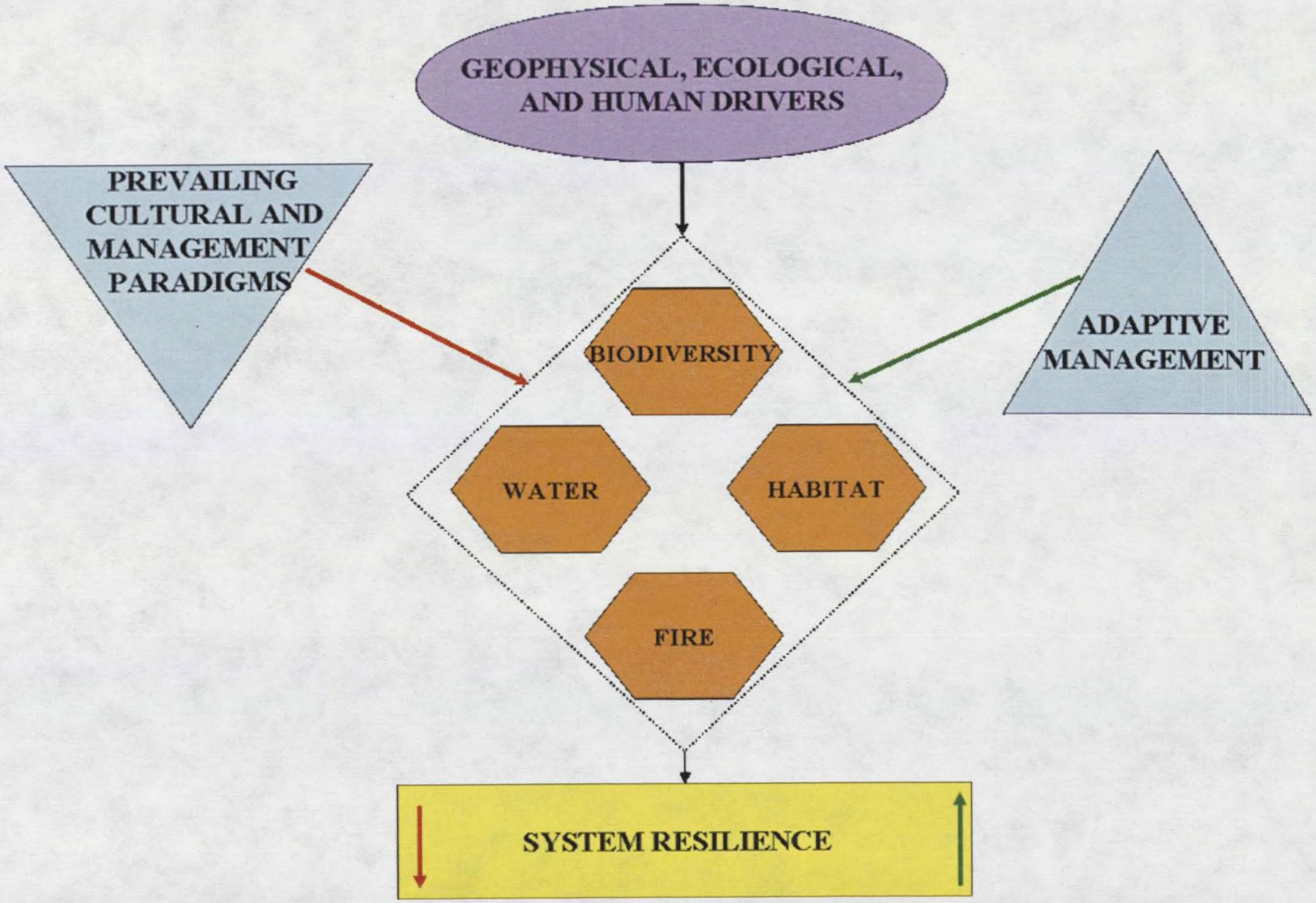

Figure 31. The effects of different management paradigms on system resilience.

Complexity and Connectedness

Although management has historically focused on one species (e.g. salmon in the Pacific Northwest), overall complexity of communities as well as the abiotic factors that influence them is critical for sustainability (Frissell et al. 1997). The concepts of complexity and connectedness emphasize that biodiversity and conservation of continuous habitat strengthens ecosystems and makes them more resilient to disturbance (Christensen et al. 1996). Viewing aquatic systems as part of a greater whole while also identifying distinct differences within the system is essential for effective research and management (Sedell et. al 1989).

One model that addresses connectivity within aquatic systems is the River Continuum Concept (RCC), which identifies rivers as longitudinally linked systems where small- and large-scale processes affect dynamics up-and down-stream (Vannote et al. 1980). The RCC outlines a necessary balance between processes contributing to stabilization (e.g. debris dams) and those causing instability (e.g. floods). With channelized systems and/or dams, altered flood regimes and decreased LWD largely prevent these processes from influencing aquatic systems, causing a lack of connectivity and decreasing the possibility of longitudinal exchanges of energy and materials (Malmqvist 2002).

Sourdough Creek Watershed has numerous breaks in connectivity, the most significant of which are the municipal diversion dam, channelization throughout the Lower Watershed, and the underground sections of the stream in the high density land class. The municipal diversion dam provides necessary water to the city of Bozeman, but construction of a side channel with constant flow would facilitate material and organism movement up and downstream. Decreasing channelization in the Lower Watershed would increase connectivity, potentially allowing movement of fish from the East Gallatin into Sourdough Creek for spawning. Underground sections of the stream throughout the high density land class deter passage of fish and other organisms (Scott Barndt, personal communication). Creation of a different channel that circumnavigates downtown would be a significant effort, but one that would greatly increase the connectivity and habitat condition of Sourdough Creek.

Context and Scale

Determining an appropriate scale is critical for effective research and management (Malmqvist 2002). Rarely do management delineations coincide with watershed boundaries, nor does any component of a system exist independently of innumerable abiotic and biotic connections. Practitioners of adaptive management address these factors by conceptualizing aquatic systems in a regional context (Teclaff 1996); managing these systems within a watershed framework is particularly important because they often cross numerous public and private boundaries.

Separation of the Upper and Lower Watershed is the most overt example of distinctly different management approaches in Sourdough Creek Watershed. Although some stakeholders have met collaboratively as members of the Bozeman Watershed Council for over a decade, managers continue to make decisions about the two sections without a watershed framework or the ownership of all involved parties. Addressing these disparities will involve a strong organization that invites all stakeholders to collaborate in management decisions at the watershed scale.

Sound Ecological Understanding and Modeling

A repeated theme in resource management is the lack of exchange between management officials, land owners, recreationalists, researchers, and local governments (Gunderson 1995). Currently, management and restoration often fails to consider ecological principles; to remedy this, academics could condense knowledge into easily-assimilated factsheets or focus on extension programs that disseminate knowledge to a broad population (Freeman and Ray 2001). This approach is particularly important for private land, where site-specific management decisions often occur with no ecological knowledge or consideration (Dale et al. 2001).

Managers, researchers, and citizens are increasingly concerned that the spatial scale of many ecological studies is inadequate to capture meaningful patterns and processes of organisms and their environments. Although this may often be the case, a common misconception with ecosystem or watershed management is that only large-scale research is useful. Instead, incorporating multiple research scales and techniques is the core of ecological understanding at the watershed scale (Christensen et al. 1996). For example, limnologists are more apt to study systems holistically while fisheries biologists often take a more site-specific approach. These seemingly dichotomous approaches are both useful and important if idea exchanges occur and all research is nested within the umbrella goal of watershed management. The difficulty arises when different research methods lead to conflicting management and restoration approaches (Hinch 1991).

Humans as Ecosystem Components

As nearly no ecosystem in the world is at least in some way impacted by humans, actively including humans in management decisions is intuitive, but often overlooked. To increase and maintain stakeholder participation, a management body must develop a regional framework where policies stem from collaborative decision-making. Smaller grass-roots organizations may be more effective than larger groups in accomplishing this because there is more of a vested interest and greater understanding of local ecosystems. These smaller groups are bridging the gap between science and society, and often turn to Technical Advisory Committees or universities for expert advice and ecological information (Freeman and Ray 2001). A study in the Midwestern United States found that citizen watershed groups are receptive to working with university researchers, but the information exchange must be clear, succinct, and easily integrated into management and educational initiatives (Freeman and Ray 2001).

Humans have altered Sourdough Creek in a myriad of ways, including alteration of the stream's hydroperiod, removal of channel forming agents, and clearing of riparian vegetation for homes and cultivated fields. Additionally, stakeholders have strived to conserve the existing integrity of the stream and implement habitat improvements. Sourdough Creek is also highly valued for recreation, aesthetics, and sustained water quality and quantity.

In addition to historical and contemporary human interactions with Sourdough Creek, growing population trends indicate that human impacts on the stream will increase in the future. Gallatin County is the fastest growing area in Montana, with the most dramatic population increase occurring since 1990 (Hansen 2003). With such significant growth, encouraging Bozeman citizens to participate in watershed decision-making is an opportunity that managers should promote. Another method of involving people in Sourdough Creek Watershed is offering incentives for water conservation that currently do not exist. If Bozeman citizens internalized that their water use greatly impacted innumerable aspects of aquatic systems, they would make a more concerted effort to conserve this seemingly expendable resource.

Monitoring

Monitoring is essential because much about ecosystems and the effects that management has on them remains an enigma; without monitoring, there is no way to test the effectiveness of management decisions (Noss and Cooperrider 1994). Monitoring as a component of adaptive management is cyclical, with project implementation occurring only after a number of preliminary steps (Figure 32). Scoping, which is the first step in monitoring, is the identification of the problem(s) or issue(s) of interest while an inventory involves gathering existing data or making initial field observations. The experimental design defines program goals, indicators for monitoring, and the project framework. Sampling is actual data gathering, and it is far more meaningful if the aforementioned steps have been properly addressed. The next step involves periodic data analysis, with the possibility of adjusting management with the information gained. Model validation is testing how well the chosen indicators correspond to ecosystem change. For example, if macroinvertebrate abundance and diversity are indicators of the amount of fine sediments, model validation confirms or refutes a correlation between increased fines and other aquatic organisms. If the chosen indicator is the only component of the system that reacts to the identified impact, then it does little to reflect

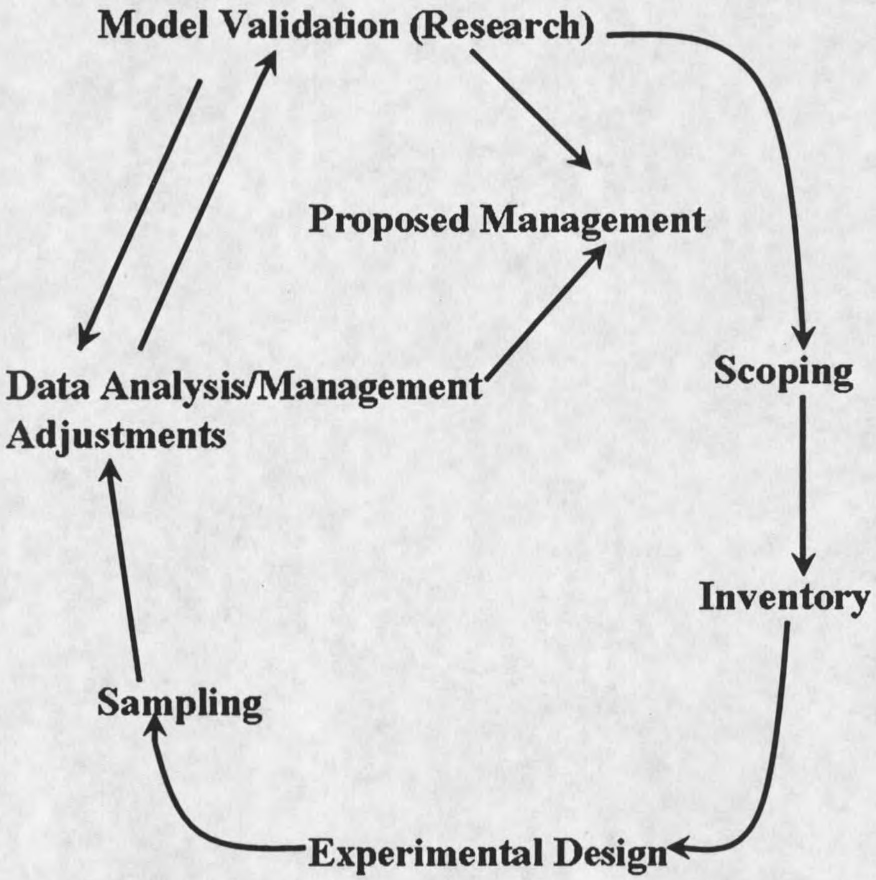

Figure 32. The monitoring cycle under adaptive management (Adapted from Noss and Coopperrider 1994).

ecosystem-wide response. The final step in the process is proposed management, which is flexible and changes as the other components of the plan are reassessed (Noss and Coopperrider 1994).

This study addressed the scoping and inventory aspect of a monitoring plan. Existing data provides a framework for monitoring, and the following discussion presents potential approaches for future work. The monitoring goals could include maintaining water quality and quantity and improving biodiversity and habitat. Indicators might be fish and macroinvertebrate abundance and diversity; species of both react to changes in water temperature, sediment input, and habitat alterations (Karr 1981). Fish sampling by electro-shocking would identify fish diversity and abundance, which is critical if westslope cutthroat trout reintroduction occurs. Trained citizens could consistently sample macroinvertebrates; studies have repeatedly used macroinvertebrate abundance and diversity to indicate system disturbance or chronic stress over time (Malmqvist 2002). The remaining steps of the monitoring plan would involve a collaborative process, with university researchers advising stakeholders about statistical analysis and project design. Although this occurs on a small-scale currently, university research and involvement in Sourdough Creek Watershed could be far more comprehensive. The proposed management plan would include agreement from all stakeholders; a local watershed council could engage and educate Bozeman citizens and management officials and provide a forum for decision-making.

Goals

As with monitoring, this study provides a framework for goals and restoration opportunities. The goal of sustaining watershed integrity could encompass a number of projects. Addressing fire suppression is one possible project in the Upper Watershed. There are numerous restoration possibilities in the Lower Watershed, but implementation without the aid of a comprehensive plan may actually prove more detrimental than no action.

Upper Watershed Fire Suppression

The effects of fire management may severely alter the structure, function, and composition of an entire landscape (Spencer et al. 2003). However, fire management often focuses on the terrestrial environment. Fire surrogate treatments such as thinning may be effective for the terrestrial system, but its effects can negatively influence aquatic systems more than a high-severity fire through changes in water temperature, water chemistry, and habitat (Frissell et al. 1997, Spencer et al. 2003).

In the Upper Watershed, the risk of high-severity fire due to fire suppression and logging restrictions is a definite concern (Mark Story, personal communication). With its A-Closed classification, the state-mandated sediment standard for the stream is 30% over natural; this could definitely be exceeded with a number of fire scenarios (Mark Story personal communication). The severity of a fire and its subsequent effects on Sourdough Creek span a continuum of possibilities, and are dependent on variables such as fuel load, climate, and fire management. Modeling is one approach to explore potential fire impacts, and offers a viable place to begin within a fire management plan. A number of models exist, and watershed managers would benefit from collaborating and choosing the the most appropriate model for Sourdough Creek.

A high-severity fire would kill vegetation, increase erosion, and potentially cause hydrophobicity (soil-sealing), resulting in increased sediment load into the stream. Ash and sediment could inundate the City of Bozeman Water Treatment Plant, resulting in decreased (or lack of) filtering capacity. In addition to taxing the water treatment plant, increased sediment would impact aquatic systems and organisms. If fine sediments (particles < 0.2 cm) exceed 40%, they markedly decrease survival of trout eggs and juveniles (Stanford and Ward 1992). On a short-term scale, this would decrease trout populations in the stream. However, even a high-severity fire would contribute LWD and larger substrate to the system as well, increasing habitat heterogeneity over a longer timeframe. Additionally, because fire has been actively suppressed in the Upper Watershed, the aquatic system may be sediment-starved. If this is the case, then sediment contributed to Sourdough Creek following fire could actually improve ecosystem function and restore balance to the system.

The Bozeman Watershed Assessment includes a comprehensive stand exam of the Upper Watershed (Ladzinski et al. 2004). Coupled with modeling and stakeholder input, decision-makers can develop an effective fire management plan. Again, implementation must be within a watershed scale; prescribed burns or selective logging are definite possibilities, but must proceed with consideration of their potential effects for the entire watershed.

Lower Watershed Restoration

Restoration is the identification and alteration of processes that constrain an organism and/or environment (Frissell et al. 1997). Restoration of aquatic systems often only address site-specific impacts and managers sometimes fail to incorporate watershed processes into project design. For effective restoration of aquatic systems, disturbance regimes, hydraulic channel heterogeneity, sediment dynamics, and anthropogenic impacts are necessary considerations (Naiman 1992). Although the scope of this project did not include all of these factors, suggestions for restoration can nonetheless provide a framework for future work.

Restoration in the Lower Watershed would involve increasing sinuosity and LWD abundance. Common restoration approaches include: 1) constructing asymmetrical cross-sections; 2) developing bars; 3) increasing floodplains; 4) creating pools and riffles; and 5) increasing sinuosity (Rinaldi and Johnson 1997). Each of these actions would aid in the development of the others (e.g. asymmetrical cross-sections would increase sinuosity). Stream restoration in a channelized system may cause more erosion and instability if not properly approached (Brookes 1988). Implementing extensive engineering work and/or manual placement of LWD in the channel would therefore require input from many disciplines as well as a comprehensive management framework (Rinaldi and Johnson 1997, Shields et al. 1995).

These approaches in the Lower Watershed would be most useful, and most difficult to achieve, in the high density land class. Although average sinuosity did not vary much between the high density and other land classes (1.19 versus the highest value of 1.40 in Gardiner Park), many high density reaches had values of 1.00, which is a straight channel. The high density land class effectively separates the industrial land class from the upstream land classes, and high density restoration would increase connectivity along the entire Lower Watershed. However, restoration in the high density section would potentially increase flooding in the terrestrial environment and damage adjacent property. A potential restoration area in the high density land class is Bogert Park, which lies 250 m south of Main Street and is 307 m in length. The Bogert Park section of the creek had a sinuosity of 1.24, riparian forest width of 29 m, 0.33 pieces LWD per 50 m, a wetted width of 4.66 m, and no slow water. None of these variables differed significantly from the other high density channel reaches, but the open park on the east side of the creek makes the section a suitable area for restoration. Although Bogert Park is a small section of the Lower Watershed, restoration would potentially be useful for education and outreach, where the community could see the benefits of stream restoration.

Conclusion

Implementing adaptive watershed management in Sourdough Creek Watershed would involve a significant paradigm shift, but is a possibility nonetheless. Within an adaptive management framework, decision-makers would: include all stakeholders, continually learn from their actions, and incorporate resiliency and surprise in a management framework. Within this framework, management, monitoring, and restoration efforts would be more effective than current practices, and could perhaps provide a model for other watershed managers to follow.

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CHAPTER 4

SUMMARY

This study identified linkages between aquatic habitat, geomorphology, and land use of Sourdough Creek Watershed and explored potential effects of land use in the Lower Watershed. Additionally, limiting factors and suitable habitat for westslope cutthroat trout in the Upper Watershed were explored. In the Lower Watershed, regression analysis identified drivers of LWD and pool length and the Wilcoxon Rank Test showed variance between six land classes.

Habitat conditions in the Upper Watershed were relatively pristine, with geomorphology shaping the aquatic system more than land use. High gradients, large size substrate, and riffle habitat predominated in all but SCR2. LWD abundance was low when compared to watersheds of similar size; the paucity of LWD is likely due to riparian forest logging. To increase LWD abundance, managers should preserve the existing riparian forest and consider direct placement of wood in the channel.

SFR4 and SFR5 provide the most suitable and isolated habitat for westslope cutthroat trout populations. A barrier at the downstream end of SFR5 would prevent migration of non-native species, facilitating establishment and sustainability of a westslope cutthroat trout population. Although this appears a likely possibility, managers and stakeholders should discuss the utility of reintroduction, identify an appropriate project scale, explore watershed processes that would inhibit or facilitate reintroduction, and incorporate habitat conservation in any plan.

Increased sediment load from a high-severity fire is a concern for both aquatic organisms and city of Bozeman residents. However, high-severity fires are part of a properly functioning ecosystem, and may actually be more beneficial for aquatic habitat than surrogate fire treatments such as thinning. Under a new paradigm of adaptive management, knowledge of ecosystem processes and potential impacts at the watershed scale would drive decision-making, greatly increasing the success of any fire plan.

Across the Lower Watershed land classes, abundance of LWD and pool length were correlated to riparian forest width, sinuosity, and distance from the municipal diversion dam. Riparian forest was widest in the forest land class, but lack of riparian forest on the east side of the creek and the upstream municipal diversion dam likely caused low LWD abundance. The agriculture land class, with the second widest riparian forest width, had the most LWD and longest pools in the Lower Watershed. All but one of the regression analyses included sinuosity as a predictor variable, indicating that channel meanders increase LWD abundance and pool length. The opportunity exists to preserve (and where possible extend) riparian forest width, restore channel meanders, and increase channel connectivity in the Lower Watershed. Because stream restoration may be more detrimental to aquatic habitat than no action, managers should use the collaborative decision-making, flexibility, and continual learning of adaptive management in project design.

The Wilcoxon Rank Test identified variable differences between land classes. The test found statistically significant differences ($p < 0.05$) with every variable except bankfull width, indicating that land use influences aquatic habitat. A larger sample size in future work would probably elucidate more differences between land classes as well as increase the statistical significance between variables.

Applying adaptive management to Sourdough Creek Watershed provides an alternative paradigm for decision-makers. Adaptive management emphasizes continual learning, and aims to create the most effective management model instead of striving for one steady state. It manages for resilience, and recognizes that an ecosystem exists within multiple states of equilibria. Within adaptive management, monitoring and restoration become cyclical processes, where a feedback loop initiates replanning and reanalyzing data as necessary. The success of adaptive management lies in its flexibility and full stakeholder participation, and its application would undoubtedly provide an effective framework for long-term sustainability of Sourdough Creek Watershed.

APPENDICES

APPENDIX A

LAND CLASS TRANSECT MEASUREMENTS

Forest Site	Bankfull Width	Bankfull Depth	Wetted Width	Wetted Depth	Entrench. Ratio	Boulder	Cobble	Gravel	Sand	Silt/Clay	Canopy Cover(%)	Densiometer
1	6.98	0.34	3.20	0.11	20.84	20.00	80.00	0.00	0.00	0.00	51.88	11.75
2	7.83	0.46	4.02	0.10	16.91	0.00	80.00	20.00	0.00	0.00	58.63	13.25
3	5.97	0.68	3.84	0.11	8.74	0.00	70.00	20.00	10.00	0.00	70.00	16.00
4	8.87	0.36	3.51	0.14	24.78	10.00	50.00	10.00	30.00	0.00	47.38	10.75
5	6.00	0.55	0.72	0.25	10.91	0.00	30.00	40.00	30.00	0.00	73.38	16.75
6	6.40	0.36	3.00	0.10	17.63	0.00	90.00	10.00	0.00	0.00	24.75	5.50
7	6.55	0.83	3.30	0.24	7.94	0.00	10.00	20.00	40.00	30.00	74.50	17.00
8	6.80	0.42	2.65	0.10	16.27	40.00	30.00	15.00	15.00	0.00	73.38	16.75
9	5.10	0.63	3.90	0.23	8.16	20.00	10.00	0.00	60.00	10.00	22.50	5.00
10	7.38	0.41	4.05	0.10	18.00	60.00	20.00	10.00	10.00	0.00	63.25	14.50
Mean	6.61	0.50	3.22	0.15	32.21	13.45	42.93	18.45	18.10	6.72	52.06	12.73
STDEV	1.28	0.15	1.18	0.18	5.81	20.71	21.08	14.95	15.87	12.77	19.41	4.09

Agriculture Site	Bankfull Width	Bankfull Depth	Wetted Width	Wetted Depth	Entrench. Ratio	Boulder	Cobble	Gravel	Sand	Silt/Clay	Canopy Cover(%)	Densiometer
1	5.85	0.56	3.54	0.11	10.39	10.00	70.00	0.00	20.00	10.00	27.00	6.00
2	4.72	0.38	3.21	0.18	12.59	0.00	30.00	30.00	20.00	20.00	39.38	8.75
3	6.90	0.24	5.66	0.21	28.40	0.00	10.00	60.00	20.00	10.00	70.00	16.00
4	6.72	0.51	5.62	0.18	13.10	0.00	40.00	30.00	20.00	10.00	73.38	16.75
5	6.40	0.40	5.20	0.30	16.00	0.00	40.00	0.00	20.00	40.00	2.25	0.50
6	6.52	0.55	5.60	0.14	11.85	0.00	20.00	30.00	20.00	30.00	68.88	15.75
7	7.07	0.43	5.64	0.10	16.64	0.00	60.00	0.00	30.00	10.00	49.63	11.25
8	6.00	0.38	4.96	0.09	16.00	10.00	60.00	10.00	20.00	0.00	46.25	10.50
9	8.51	0.43	4.15	0.17	20.02	20.00	10.00	0.00	20.00	50.00	47.38	10.75
10	8.24	0.68	4.98	0.26	12.21	0.00	40.00	15.00	25.00	20.00	74.50	17.00
11	8.29	0.60	5.67	0.13	13.82	15.00	30.00	30.00	25.00	0.00	59.88	13.75
12	6.90	0.59	5.67	0.11	11.79	20.00	60.00	10.00	10.00	0.00	55.25	12.50
13	7.90	0.63	5.54	0.15	12.48	5.00	75.00	5.00	10.00	5.00	61.00	14.00
14	7.44	0.32	4.72	0.08	23.25	20.00	30.00	25.00	25.00	0.00	0.00	0.00

15	7.12	0.44	5.24	0.13	16.37	0.00	40.00	20.00	30.00	10.00	46.25	10.50
16	8.94	0.48	7.93	0.10	18.63	30.00	20.00	45.00	5.00	0.00	63.25	14.50
17	6.77	0.41	4.81	0.13	16.39	40.00	30.00	15.00	15.00	0.00	74.50	17.00
18	6.49	0.38	4.72	0.16	17.08	5.00	80.00	10.00	10.00	0.00	74.50	17.00
19	7.96	0.34	6.78	0.07	23.41	0.00	40.00	30.00	20.00	10.00	28.13	6.25
20	7.95	0.40	6.12	0.11	19.88	0.00	25.00	12.00	40.00	20.00	36.13	8.25
21	7.89	0.39	6.09	0.19	20.34	0.00	65.00	15.00	10.00	10.00	56.38	12.75
22	6.41	0.27	5.41	0.78	24.19	0.00	75.00	5.00	5.00	15.00	70.00	16.00
23	8.70	0.54	5.59	0.16	16.17	5.00	10.00	5.00	15.00	55.00	39.50	9.00
24	9.39	0.69	5.25	0.38	13.61	0.00	55.00	35.00	10.00	0.00	27.13	6.25
25	6.52	0.43	4.76	0.53	15.34	0.00	40.00	20.00	30.00	10.00	59.88	13.75
26	9.02	0.26	5.58	0.40	34.69	0.00	35.00	45.00	20.00	0.00	35.00	8.00
27	9.21	0.47	6.27	0.73	19.60	0.00	25.00	30.00	45.00	0.00	53.00	12.00
Mean	7.40	0.45	5.36	0.22	35.98	6.67	41.29	19.70	20.00	12.41	49.57	11.29
STDEV	1.16	0.12	0.93	0.19	5.57	18.90	21.98	19.86	20.88	23.39	20.62	4.73

Low Density Site	Bankfull Width	Bankfull Depth	Wetted Width	Wetted Depth	Entrench. Ratio	Boulder	Cobble	Gravel	Sand	Silt/Clay	Canopy Cover(%)	Densiometer
1	6.71	0.43	4.12	0.09	15.79	0.00	60.00	20.00	15.00	5.00	19.13	4.25
2	8.08	0.35	5.67	0.09	23.09	0.00	60.00	20.00	0.00	20.00	29.25	6.50
3	6.00	0.39	3.32	0.10	15.46	0.00	40.00	40.00	20.00	0.00	32.75	7.50
4	7.47	0.38	4.11	0.19	19.92	0.00	30.00	30.00	20.00	20.00	39.50	9.00
5	5.52	0.51	3.51	0.09	10.76	0.00	30.00	10.00	30.00	30.00	54.13	12.25
6	5.70	0.59	4.33	0.25	9.69	20.00	60.00	0.00	10.00	10.00	74.50	17.00
7	6.10	0.47	3.88	0.18	13.03	0.00	50.00	0.00	20.00	30.00	56.38	12.75
8	6.40	0.34	3.85	0.10	18.93	30.00	40.00	20.00	5.00	5.00	31.63	7.25
9	6.43	0.29	4.21	0.11	21.95	0.00	50.00	10.00	20.00	10.00	62.13	14.25
10	6.19	0.23	4.63	0.07	27.51	0.00	80.00	10.00	10.00	0.00	71.13	16.25
11	5.60	0.59	3.57	0.19	9.52	0.00	0.00	0.00	30.00	70.00	55.25	12.50
12	8.44	0.29	4.55	0.10	29.10	15.00	23.00	25.00	35.00	0.00	12.38	2.75
13	6.10	0.52	4.05	0.25	11.66	0.00	15.00	25.00	40.00	20.00	50.75	11.50

14	7.59	0.34	3.95	0.09	22.66	0.00	25.00	40.00	25.00	10.00	31.63	7.25
Mean	6.60	0.41	4.13	0.13	39.01	4.64	40.21	17.86	20.00	16.43	49.86	10.07
STDEV	0.94	0.11	0.58	0.06	6.51	19.03	20.58	21.03	24.62	18.60	19.04	4.36

Gardiner Park Site	Bankfull Width	Bankfull Depth	Wetted Width	Wetted Depth	Entrench. Ratio	Boulder	Cobble	Gravel	Sand	Silt/Clay	Canopy Cover(%)	Densiometer
1	8.23	0.25	4.18	0.08	33.59	0.00	40.00	30.00	20.00	10.00	56.38	12.75
2	8.29	0.35	4.01	0.07	23.69	20.00	20.00	30.00	15.00	15.00	56.38	12.75
3	7.65	0.24	4.60	0.19	31.88	0.00	40.00	30.00	15.00	15.00	68.88	15.75
4	7.70	0.19	4.70	0.13	40.53	10.00	30.00	25.00	25.00	10.00	20.38	4.75
5	8.25	0.24	3.51	0.19	34.38	20.00	15.00	0.00	25.00	40.00	73.38	16.75
6	8.32	0.21	3.75	0.26	39.62	0.00	0.00	0.00	30.00	70.00	73.38	16.75
7	8.90	0.11	5.43	0.08	80.91	0.00	20.00	25.00	40.00	15.00	58.75	13.50
8	8.01	0.19	4.91	0.06	42.16	10.00	15.00	60.00	15.00	0.00	68.88	15.75
Mean	8.17	0.22	4.39	0.13	40.84	7.50	22.50	25.00	23.13	21.88	59.55	13.59
STDEV	0.40	0.07	0.64	0.07	17.23	8.86	13.63	19.09	8.84	22.51	17.37	3.94

High Density Site	Bankfull Width	Bankfull Depth	Wetted Width	Wetted Depth	Entrench. Ratio	Boulder	Cobble	Gravel	Sand	Silt/Clay	Canopy Cover(%)	Densiometer
1	5.31	0.26	3.20	0.09	20.42	25.00	15.00	20.00	20.00	20.00	76.50	17.00
2	6.04	0.64	4.67	0.16	9.51	15.00	15.00	0.00	40.00	30.00	76.50	17.00
3	3.90	0.29	3.70	0.12	13.54	65.00	20.00	10.00	5.00	0.00	52.88	11.75
4	6.28	0.50	4.20	0.20	12.56	25.00	5.00	10.00	20.00	40.00	74.25	16.50
5	3.56	0.34	3.56	0.10	10.53	0.00	50.00	20.00	0.00	30.00	73.13	16.25
6	4.27	0.40	4.27	0.15	10.68	0.00	10.00	20.00	25.00	45.00	75.38	16.75
7	3.75	0.65	3.75	0.40	5.77	0.00	0.00	10.00	40.00	50.00	76.50	17.00
8	4.21	0.43	4.21	0.13	9.91	0.00	30.00	35.00	15.00	20.00	72.00	16.00
9	6.40	0.51	3.69	0.24	12.48	10.00	40.00	25.00	25.00	0.00	74.25	16.50
10	6.71	0.54	4.66	0.39	12.47	0.00	75.00	15.00	0.00	10.00	37.13	8.25

11	7.32	0.46	4.18	0.13	15.81	15.00	40.00	25.00	0.00	20.00	6.75	1.50
12	3.25	0.54	3.76	0.19	5.99	15.00	45.00	0.00	35.00	5.00	72.25	16.50
13	6.00	0.47	3.40	0.12	12.77	60.00	15.00	15.00	0.00	10.00	68.88	15.75
14	3.40	0.48	2.80	0.19	7.16	0.00	20.00	20.00	15.00	45.00	74.50	17.00
15	4.00	0.33	2.65	0.20	12.01	40.00	15.00	35.00	0.00	0.00	42.88	9.75
16	4.40	0.40	2.70	0.17	10.92	0.00	20.00	20.00	10.00	50.00	11.38	2.75
17	3.40	0.56	2.40	0.20	6.09	30.00	15.00	0.00	10.00	45.00	51.88	11.75
18	3.20	0.48	2.95	0.16	6.69	20.00	25.00	10.00	15.00	40.00	41.75	9.50
19	3.60	0.55	3.24	0.21	6.61	10.00	20.00	70.00	0.00	0.00	56.38	12.75
20	3.70	0.46	3.00	0.12	7.99	20.00	30.00	50.00	0.00	0.00	5.63	1.25
Mean	5.25	0.46	4.01	0.19	22.43	14.09	27.27	17.27	17.27	24.09	63.20	14.05
STDEV	1.36	0.13	0.46	0.11	3.74	17.29	24.43	23.47	20.27	19.08	22.52	5.00

Industrial Site	Bankfull Width	Bankfull Depth	Wetted Width	Wetted Depth	Entrench. Ratio	Boulder	Cobble	Gravel	Sand	Silt/Clay	Canopy Cover(%)	Densiometer
1	6.16	0.47	4.26	0.14	13.11	15.00	25.00	60.00	0.00	0.00	74.50	17.00
2	5.21	0.34	4.33	0.22	15.19	20.00	40.00	35.00	5.00	0.00	74.50	17.00
3	5.21	0.51	4.36	0.20	10.22	10.00	25.00	50.00	15.00	0.00	74.50	17.00
4	7.70	0.42	3.67	0.16	18.33	10.00	30.00	20.00	10.00	0.00	13.50	3.00
5	3.90	0.41	3.90	0.12	9.63	0.00	40.00	20.00	30.00	10.00	6.75	1.50
6	5.79	0.49	4.88	0.10	11.86	0.00	70.00	15.00	10.00	5.00	0.00	0.00
7	7.62	0.74	4.11	0.33	10.33	0.00	70.00	10.00	10.00	10.00	0.00	0.00
8	10.06	0.58	4.88	0.41	17.50	0.00	15.00	15.00	30.00	40.00	0.00	0.00
9	9.75	0.43	5.18	0.13	22.94	0.00	50.00	25.00	15.00	10.00	0.00	0.00
10	8.84	0.59	3.54	0.24	15.03	0.00	0.00	20.00	40.00	40.00	0.00	0.00
11	8.84	0.31	6.55	0.10	28.24	0.00	70.00	20.00	10.00	0.00	0.00	0.00
12	7.80	0.60	6.30	0.02	13.00	10.00	35.00	25.00	20.00	10.00	14.63	3.25
Mean	7.24	0.49	4.66	0.18	53.10	5.42	39.17	26.25	16.25	10.42	32.57	4.90
STDEV	2.31	0.12	0.96	0.11	5.60	18.93	22.22	22.47	11.70	14.53	32.37	7.39

APPENDIX B

LAND CLASS REGRESSION VARIABLES

Structures per 50 m

Forest	Agriculture	Low Density	Gardiner Park	High Density	Industrial
0.00	0.00	1.00	1.85	8.63	1.43
0.00	0.00	1.49	2.35	14.48	1.17
0.00	0.00	1.00	1.52	6.79	2.34
0.00	0.00	1.00	1.83	2.56	2.43
0.00	0.00	1.00	3.22	5.63	2.02
0.00	0.00	10.09	3.50	1.50	3.01
0.00	0.00	5.31	4.54	6.91	2.65
0.00	0.00	4.43	2.28	0.87	2.76
0.00	0.00	5.29	1.42	0.41	2.12
	1.00	1.71	1.33	0.00	1.04
	2.00	2.01		3.96	1.21
	10.00	1.85		3.24	
	0.00	2.35		4.01	
	0.00	5.00		4.36	
	0.00	3.24		6.54	
	0.00	3.68		6.01	
	0.00	6.41		5.69	
	0.00	2.22		5.64	
	0.00	1.00		4.98	
	0.00	1.00		4.66	
	0.00			3.27	
	0.00			3.89	
	0.00			3.75	
	0.00			3.69	
	0.00			3.21	
	0.00			3.92	
	0.00			4.01	
	0.00			4.67	
	0.00			4.83	
	0.00			4.97	
	0.00			5.09	
	0.00			6.34	
	0.00			4.00	
	0.00			5.20	
	0.00				
	0.00				
	0.00				
	0.00				

LWD per 50 m

Forest	Agriculture	Low Density	Gardiner Park	High Density	Industrial
0.00	4.62	1.08	2.33	0.00	0.00
0.00	6.73	1.10	5.54	0.93	0.00
0.00	1.24	4.00	0.00	0.00	0.00
1.20	0.00	1.60	2.16	0.00	0.00
1.01	2.38	0.00	3.62	1.63	2.00
1.05	0.00	0.00	1.90	0.19	0.00
1.70	2.70	3.13	2.40	0.00	1.65
1.04	1.79	3.33	5.93	0.00	0.69
1.32	1.56	0.00	0.00	1.54	2.00
2.16	4.04	1.97	2.06	3.56	1.27
	2.69	0.20	0.00	2.98	1.81
	6.98	1.67		0.00	2.97
	0.65	0.00		0.00	
	1.73	0.00		0.00	
	3.03	0.00		0.00	
	1.42	5.00		0.00	
	1.75	2.96		4.20	
	4.61	0.41		2.10	
	0.76	1.73		5.70	
	2.00	0.00		8.20	
	1.64	0.00		0.00	
	1.18			0.00	
	0.00			4.20	
	1.47			0.00	
	2.75			0.00	
	0.83			0.00	
	4.11			0.00	
	3.91			3.90	
	0.45			0.00	
	4.16			0.00	
	2.67			0.00	
	3.77			0.00	
	2.33			0.00	
	7.21			0.00	
	1.54			0.00	
	5.12				
	3.08				
	1.09				
	2.78				

Riparian Forest Width (m)

Forest	Agriculture	Low Density	Gardiner Park	High Density	Industrial
123	72	52	45	71	2
23	210	48	115	44	1
232	49	80	36	36	1
110	27	79	82	47	2
45	43	53	40	29	1
234	38	34	48	97	1
214	54	106	77	17	2
250	34	70	114	36	1
21	39	49	47	27	1
25	102	144	87	59	1
	56	59	35	43	1
	121	37		23	1
	24	64		30	
	43	22		28	
	215	28		21	
	78	78		17	
	74	25		30	
	101	45		82	
	35	70		26	
	134	29		27	
	154	117		29	
	64			24	
	23			21	
	42			0	
	79			0	
	37			0	
	255			0	
	179			0	
	34			12	
	93			21	
	56			27	
	84			27	
	66			22	
	157			22	
	48			23	
	104				
	67				
	38				
	58				

Distance from Municipal Diversion Dam (m)

Forest	Agriculture	Low Density	Gardiner Park	High Density	Industrial
389	1641	5431	6398	9425	12907
620	1681	5567	6431	9533	13138
724	1725	5647	6489	9609	13205
832	2085	5835	6591	9823	13334
999	2127	6142	6661	9862	13386
1133	2193	6172	6871	10129	13596
1216	2230	6268	7020	10154	13792
1265	2426	7631	7079	10277	13864
1286	2458	7751	7116	10342	13915
1375	2500	7878	7206	10463	14099
	2561	8387	7586	10492	14223
	2616	8507		10594	14352
	2924	8657		10643	
	2973	8682		10768	
	3006	8927		10806	
	3071	8983		10834	
	3271	9020		10854	
	3335	9143		11098	
	3467	9186		11134	
	3492	9212		11177	
	3624	9237		11484	
	3677			11657	
	3847			11719	
	3881			11734	
	4131			11797	
	4251			12118	
	4324			12139	
	4475			12174	
	4697			12276	
	4756			12365	
	4831			12432	
	4911			12463	
	4956			12522	
	5023			12698	
	5163			12723	
	5216				
	5268				
	5314				
	5404				

Sinuosity

Forest	Agriculture	Low Density	Gardiner Park	High Density	Industrial
1.21	1.06	1.69	1.38	1.21	1.08
1.10	1.74	1.03	1.94	1.27	1.09
1.10	1.26	1.21	1.12	1.28	1.14
1.23	1.15	1.24	1.55	1.21	1.08
1.10	1.62	1.17	1.59	1.95	1.21
1.19	1.01	1.15	1.24	1.21	1.14
1.25	1.32	1.22	1.32	1.37	1.46
1.21	1.05	1.41	1.55	1.21	1.07
1.35	1.32	1.17	1.22	1.21	1.46
1.42	1.31	1.35	1.31	1.11	1.67
	1.42	1.30	1.21	1.21	1.48
	1.54	1.29		1.14	1.63
	1.01	1.61		1.43	
	1.43	1.04		1.24	
	1.10	1.28		1.24	
	1.35	1.19		1.09	
	1.28	1.42		1.32	
	1.42	1.33		1.31	
	1.15	1.26		1.26	
	1.19	1.18		1.37	
	1.07	1.19		1.24	
	1.09			1.07	
	1.03			1.32	
	1.21			1.00	
	1.72			1.00	
	1.33			1.00	
	1.35			1.00	
	1.53			1.32	
	1.21			1.00	
	1.64			1.09	
	1.10			1.02	
	1.40			1.00	

Pool Length per 50 m

Forest	Agriculture	Low Density	Gardiner Park	High Density	Industrial
0.00	0.00	3.70	1.54	2.10	0.00
0.34	40.00	0.00	18.18	1.70	0.00
0.16	0.00	0.00	0.00	5.30	0.00
0.32	0.00	1.60	3.92	2.30	0.00
0.22	21.00	0.65	4.29	6.90	1.20
0.00	0.00	0.00	2.86	3.40	0.00
0.22	0.00	1.04	8.39	7.20	0.00
0.12	0.00	6.67	28.81	0.00	2.20
0.42	20.48	0.00	16.22	0.00	1.30
0.00	16.80	5.12	0.00	0.00	2.70
	16.39	0.00	0.00	0.00	1.50
	20.00	0.00		0.00	2.30
	2.27	2.67		0.00	
	23.52	0.00		0.00	
	0.00	0.61		0.00	
	11.54	0.00		0.00	
	0.00	5.41		4.20	
	46.09	4.88		2.10	
	0.00	0.00		5.70	
	0.00	0.00		8.20	
	0.00	0.00		0.00	
	24.50			0.00	
	0.00			4.20	
	23.12			0.00	
	50.00			0.00	
	10.83			0.00	
	0.00			0.00	
	43.48			3.90	
	0.00			0.00	
	18.64			0.00	
	0.00			0.00	
	50.00			0.00	

APPENDIX C

WILCOXON RANK TEST RESULTS

```
data:  x: forestlwd in Wilcoxson , and y: agriclwd in Wilcoxson
rank-sum normal statistic with correction Z = -2.8802, p-value = 0.004

data:  x: forestlwd in Wilcoxson , and y: lowlwd in Wilcoxson
rank-sum normal statistic with correction Z = -1.0683, p-value = 0.2854

data:  x: forestlwd in Wilcoxson , and y: garlwd in Wilcoxson
rank-sum normal statistic with correction Z = -1.8883, p-value = 0.059

data:  x: forestlwd in Wilcoxson , and y: lowlwd in Wilcoxson
rank-sum normal statistic with correction Z = -1.0683, p-value = 0.2854

data:  x: forestlwd in Wilcoxson , and y: highlwd in Wilcoxson
rank-sum normal statistic with correction Z = 1.5266, p-value = 0.1269

data:  x: forestlwd in Wilcoxson , and y: indilwd in Wilcoxson
rank-sum normal statistic with correction Z = -0.1352, p-value = 0.8925

data:  x: agriclwd in Wilcoxson , and y: lowlwd in Wilcoxson
rank-sum normal statistic with correction Z = 2.0997, p-value = 0.0358

data:  x: agriclwd in Wilcoxson , and y: garlwd in Wilcoxson
rank-sum normal statistic with correction Z = 0.3164, p-value = 0.7517

data:  x: agriclwd in Wilcoxson , and y: highlwd in Wilcoxson
rank-sum normal statistic with correction Z = 5.3995, p-value = 0

data:  x: agriclwd in Wilcoxson , and y: indilwd in Wilcoxson
rank-sum normal statistic with correction Z = 2.5588, p-value = 0.0105

data:  x: garlwd in Wilcoxson , and y: highlwd in Wilcoxson
rank-sum normal statistic with correction Z = 2.9508, p-value = 0.0032

data:  x: lowlwd in Wilcoxson , and y: highlwd in Wilcoxson
rank-sum normal statistic with correction Z = 2.7825, p-value = 0.0054

data:  x: lowlwd in Wilcoxson , and y: indilwd in Wilcoxson
rank-sum normal statistic with correction Z = 0.9993, p-value = 0.3176

data:  x: garlwd in Wilcoxson , and y: highlwd in Wilcoxson
rank-sum normal statistic with correction Z = 2.9508, p-value = 0.0032

data:  x: lowlwd in Wilcoxson , and y: garlwd in Wilcoxson
rank-sum normal statistic with correction Z = -1.0201, p-value = 0.3077

data:  x: garlwd in Wilcoxson , and y: indilwd in Wilcoxson
rank-sum normal statistic with correction Z = 1.8864, p-value = 0.0592

data:  x: highlwd in Wilcoxson , and y: indilwd in Wilcoxson
rank-sum normal statistic with correction Z = -1.3892, p-value = 0.1648

data:  x: forestslow in Wilcoxson , and y: agricslow in Wilcoxson
rank-sum normal statistic with correction Z = -1.0726, p-value = 0.2834

data:  x: forestslow in Wilcoxson , and y: lowslow in Wilcoxson
rank-sum normal statistic with correction Z = -1.2377, p-value = 0.2158

data:  x: forestslow in Wilcoxson , and y: garslow in Wilcoxson
rank-sum normal statistic with correction Z = -2.0664, p-value = 0.0388
```

```
data:  x: forestslow in Wilcoxson , and y: highslow in Wilcoxson
rank-sum normal statistic with correction Z = 0.3449, p-value = 0.7302

data:  x: forestslow in Wilcoxson , and y: indislow in Wilcoxson
rank-sum normal statistic with correction Z = -0.5807, p-value = 0.5615

data:  x: agricslow in Wilcoxson , and y: lowslow in Wilcoxson
rank-sum normal statistic with correction Z = 1.6429, p-value = 0.1004

data:  x: agricslow in Wilcoxson , and y: garslow in Wilcoxson
rank-sum normal statistic with correction Z = 0.2677, p-value = 0.7889

data:  x: agricslow in Wilcoxson , and y: highslow in Wilcoxson
rank-sum normal statistic with correction Z = 2.8198, p-value = 0.0048

data:  x: agricslow in Wilcoxson , and y: indislow in Wilcoxson
rank-sum normal statistic with correction Z = 1.6306, p-value = 0.103

data:  x: lowslow in Wilcoxson , and y: garslow in Wilcoxson
rank-sum normal statistic with correction Z = -1.3941, p-value = 0.1633

data:  x: lowslow in Wilcoxson , and y: highslow in Wilcoxson
rank-sum normal statistic with correction Z = 1.4134, p-value = 0.1575

data:  x: lowslow in Wilcoxson , and y: indislow in Wilcoxson
rank-sum normal statistic with correction Z = 1.1211, p-value = 0.2622

data:  x: garslow in Wilcoxson , and y: highslow in Wilcoxson
rank-sum normal statistic with correction Z = 2.4171, p-value = 0.0156

data:  x: garslow in Wilcoxson , and y: indislow in Wilcoxson
rank-sum normal statistic with correction Z = 2.2527, p-value = 0.0243

data:  x: highslow in Wilcoxson , and y: indislow in Wilcoxson
rank-sum normal statistic with correction Z = 0.0275, p-value = 0.9781

data:  x: forestsin in Wilcoxson , and y: agricsinu in Wilcoxson
rank-sum normal statistic with correction Z = -0.943, p-value = 0.3457

data:  x: forestsin in Wilcoxson , and y: lowsin in Wilcoxson
rank-sum normal statistic with correction Z = -1.4632, p-value = 0.1434

data:  x: forestsin in Wilcoxson , and y: garsin in Wilcoxson
rank-sum normal statistic with correction Z = -1.9081, p-value = 0.0564

data:  x: forestsin in Wilcoxson , and y: highsin in Wilcoxson
rank-sum normal statistic with correction Z = 0.6444, p-value = 0.5193

data:  x: forestsin in Wilcoxson , and y: indisin in Wilcoxson
rank-sum normal statistic with correction Z = 0, p-value = 1

data:  x: agricsinu in Wilcoxson , and y: lowsin in Wilcoxson
rank-sum normal statistic with correction Z = -0.3063, p-value = 0.7594

data:  x: agricsinu in Wilcoxson , and y: highsin in Wilcoxson
rank-sum normal statistic with correction Z = 2.4541, p-value = 0.0141

data:  x: garsin in Wilcoxson , and y: highsin in Wilcoxson
rank-sum normal statistic with correction Z = 2.6988, p-value = 0.007
```

```
data:  x: agricsinu in Wilcoxson , and y: garsin in Wilcoxson
rank-sum normal statistic with correction Z = -1.1359, p-value = 0.256

data:  x: agricsinu in Wilcoxson , and y: indisin in Wilcoxson
rank-sum normal statistic with correction Z = 0.0222, p-value = 0.9823

data:  x: lowsin in Wilcoxson , and y: garsin in Wilcoxson
rank-sum normal statistic with correction Z = -0.9331, p-value = 0.3507

data:  x: lowsin in Wilcoxson , and y: highsin in Wilcoxson
rank-sum normal statistic with correction Z = 2.6528, p-value = 0.008

data:  x: lowsin in Wilcoxson , and y: indisin in Wilcoxson
rank-sum normal statistic with correction Z = 0.8039, p-value = 0.4214

data:  x: garsin in Wilcoxson , and y: indisin in Wilcoxson
rank-sum statistic W = 153, n = 11, m = 12, p-value = 0.2115

data:  x: indisin in Wilcoxson , and y: highsin in Wilcoxson
rank-sum normal statistic with correction Z = 1.1127, p-value = 0.2659

data:  x: agricrw in Wilcoxson , and y: forestrw in Wilcoxson
rank-sum normal statistic with correction Z = -0.8435, p-value = 0.3989

data:  x: forestrw in Wilcoxson , and y: lowrw in Wilcoxson
rank-sum normal statistic with correction Z = 1.137, p-value = 0.2555

data:  x: forestrw in Wilcoxson , and y: garrw in Wilcoxson
rank-sum statistic W = 122, n = 10, m = 11, p-value = 0.4262

data:  x: forestrw in Wilcoxson , and y: highrw in Wilcoxson
rank-sum normal statistic with correction Z = 2.9273, p-value = 0.0034

data:  x: forestrw in Wilcoxson , and y: indirw in Wilcoxson
rank-sum normal statistic with correction Z = 3.9244, p-value = 0.0001

data:  x: agricrw in Wilcoxson , and y: lowrw in Wilcoxson
rank-sum normal statistic with correction Z = 0.9303, p-value = 0.3522

data:  x: agricrw in Wilcoxson , and y: garrw in Wilcoxson
rank-sum normal statistic with correction Z = 0.3162, p-value = 0.7519

data:  x: agricrw in Wilcoxson , and y: highrw in Wilcoxson
rank-sum normal statistic with correction Z = 5.5301, p-value = 0

data:  x: agricrw in Wilcoxson , and y: indirw in Wilcoxson
rank-sum normal statistic with correction Z = 5.1856, p-value = 0

data:  x: lowrw in Wilcoxson , and y: garrw in Wilcoxson
rank-sum normal statistic with correction Z = -0.2924, p-value = 0.77

data:  x: lowrw in Wilcoxson , and y: highrw in Wilcoxson
rank-sum normal statistic with correction Z = 5.0052, p-value = 0

data:  x: lowrw in Wilcoxson , and y: indirw in Wilcoxson
rank-sum normal statistic with correction Z = 5.0468, p-value = 0

data:  x: garrw in Wilcoxson , and y: highrw in Wilcoxson
rank-sum normal statistic with correction Z = 3.8823, p-value = 0.0001
```

```
data:  x: garrw in Wilcoxson , and y: indirw in Wilcoxson
rank-sum normal statistic with correction Z = 4.0322, p-value = 0.0001

data:  x: indirw in Wilcoxson , and y: highrw in Wilcoxson
rank-sum normal statistic with correction Z = -3.36, p-value = 0.0008

data:  x: agricww in Wilcoxson , and y: forestww in Wilcoxson
rank-sum normal statistic with correction Z = -0.2233, p-value = 0.8233

data:  x: forestww in Wilcoxson , and y: lowww in Wilcoxson
rank-sum normal statistic with correction Z = -3.4423, p-value = 0.0006

data:  x: forestww in Wilcoxson , and y: highww in Wilcoxson
rank-sum normal statistic with correction Z = -1.6795, p-value = 0.0931

data:  x: forestww in Wilcoxson , and y: highww in Wilcoxson
rank-sum normal statistic with correction Z = -1.6795, p-value = 0.0931

data:  x: forestww in Wilcoxson , and y: garww in Wilcoxson
rank-sum statistic W = 57, n = 10, m = 11, p-value = 0

data:  x: agricww in Wilcoxson , and y: lowww in Wilcoxson
rank-sum normal statistic with correction Z = -5.2994, p-value = 0

data:  x: agricww in Wilcoxson , and y: garww in Wilcoxson
rank-sum normal statistic with correction Z = -4.6963, p-value = 0

data:  x: agricww in Wilcoxson , and y: highww in Wilcoxson
rank-sum normal statistic with correction Z = -2.8208, p-value = 0.0048

data:  x: agricww in Wilcoxson , and y: indiww in Wilcoxson
rank-sum normal statistic with correction Z = -1.4992, p-value = 0.1338

data:  x: lowww in Wilcoxson , and y: garww in Wilcoxson
rank-sum normal statistic with correction Z = -2.0624, p-value = 0.0392

data:  x: lowww in Wilcoxson , and y: highww in Wilcoxson
rank-sum normal statistic with correction Z = 3.3585, p-value = 0.0008

data:  x: lowww in Wilcoxson , and y: indiww in Wilcoxson
rank-sum normal statistic with correction Z = 3.0584, p-value = 0.0022

data:  x: garww in Wilcoxson , and y: highww in Wilcoxson
rank-sum normal statistic with correction Z = 3.9412, p-value = 0.0001

data:  x: garww in Wilcoxson , and y: indiww in Wilcoxson
rank-sum normal statistic with correction Z = 3.6013, p-value = 0.0003

data:  x: highww in Wilcoxson , and y: indiww in Wilcoxson
rank-sum normal statistic with correction Z = 0.7321, p-value = 0.4641

data:  x: fbw in Wilcoxson.channel , and y: agbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = -2.4438, p-value = 0.0145

data:  x: fbw in Wilcoxson.channel , and y: ldbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = 0.3241, p-value = 0.7458

data:  x: fbw in Wilcoxson.channel , and y: garbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = -1.31, p-value = 0.1902
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data:  x: fbw in Wilcoxson.channel , and y: hdbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = 3.968, p-value = 0.0001

data:  x: fbw in Wilcoxson.channel , and y: indbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = -0.8455, p-value = 0.3978

data:  x: fbd in Wilcoxson.channel , and y: abbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = 0.1722, p-value = 0.8633

data:  x: fbd in Wilcoxson.channel , and y: ldbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = 1.2573, p-value = 0.2087

data:  x: fbd in Wilcoxson.channel , and y: garbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = 0.6642, p-value = 0.5066

data:  x: fbd in Wilcoxson.channel , and y: hdbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -0.2238, p-value = 0.8229

data:  x: fbd in Wilcoxson.channel , and y: indbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -0.5016, p-value = 0.616

data:  x: abbd in Wilcoxson.channel , and y: ldbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = 1.1556, p-value = 0.2478

data:  x: abbd in Wilcoxson.channel , and y: garbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = 0.6288, p-value = 0.5294

data:  x: abbd in Wilcoxson.channel , and y: hdbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -0.5598, p-value = 0.5756

data:  x: abbd in Wilcoxson.channel , and y: indbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -0.9135, p-value = 0.361

data:  x: ldbd in Wilcoxson.channel , and y: garbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -0.1366, p-value = 0.8914

data:  x: ldbd in Wilcoxson.channel , and y: hdbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -1.3302, p-value = 0.1834

data:  x: ldbd in Wilcoxson.channel , and y: indbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -1.5958, p-value = 0.1105

data:  x: garbd in Wilcoxson.channel , and y: hdbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -0.9409, p-value = 0.3467

data:  x: garbd in Wilcoxson.channel , and y: indbd in Wilcoxson.channel
rank-sum statistic W = 71, n = 8, m = 12, p-value = 0.3431

data:  x: hdbd in Wilcoxson.channel , and y: indbd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -0.4867, p-value = 0.6265

data:  x: fww in Wilcoxson.channel , and y: abww in Wilcoxson.channel
rank-sum normal statistic with correction Z = -4.7146, p-value = 0

data:  x: fww in Wilcoxson.channel , and y: ldww in Wilcoxson.channel
rank-sum normal statistic with correction Z = -2.1518, p-value = 0.0314

data:  x: fww in Wilcoxson.channel , and y: garww in Wilcoxson.channel
rank-sum normal statistic with correction Z = -2.0482, p-value = 0.0405
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data:  x: fww in Wilcoxson.channel , and y: hdww in Wilcoxson.channel
rank-sum normal statistic with correction Z = -0.0712, p-value = 0.9432

data:  x: fww in Wilcoxson.channel , and y: indww in Wilcoxson.channel
rank-sum normal statistic with correction Z = -2.8085, p-value = 0.005

data:  x: fwd in Wilcoxson.channel , and y: agwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -2.3872, p-value = 0.017

data:  x: fwd in Wilcoxson.channel , and y: ldwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = 0.2985, p-value = 0.7653

data:  x: fwd in Wilcoxson.channel , and y: barwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = 0.4433, p-value = 0.6576

data:  x: fwd in Wilcoxson.channel , and y: hdwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -2.6161, p-value = 0.0089

data:  x: fwd in Wilcoxson.channel , and y: indwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -1.6926, p-value = 0.0905

data:  x: agwd in Wilcoxson.channel , and y: ldwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = 1.8569, p-value = 0.0633

data:  x: agwd in Wilcoxson.channel , and y: barwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = 1.4741, p-value = 0.1405

data:  x: agwd in Wilcoxson.channel , and y: hdwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -0.2907, p-value = 0.7713

data:  x: agwd in Wilcoxson.channel , and y: indwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = 0.1826, p-value = 0.8551

data:  x: ldwd in Wilcoxson.channel , and y: barwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = 0.3761, p-value = 0.7068

data:  x: ldwd in Wilcoxson.channel , and y: hdwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -2.1545, p-value = 0.0312

data:  x: ldwd in Wilcoxson.channel , and y: indwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -1.5212, p-value = 0.1282

data:  x: barwd in Wilcoxson.channel , and y: hdwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -1.5789, p-value = 0.1144

data:  x: barwd in Wilcoxson.channel , and y: indwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = -1.1586, p-value = 0.2466

data:  x: hdwd in Wilcoxson.channel , and y: indwd in Wilcoxson.channel
rank-sum normal statistic with correction Z = 0.1559, p-value = 0.8761

data:  x: fent in Wilcoxson.channel , and y: agent in Wilcoxson.channel
rank-sum statistic W = 794, n = 29, m = 27, p-value = 0.6025

data:  x: fent in Wilcoxson.channel , and y: leent in Wilcoxson.channel
rank-sum statistic W = 612, n = 29, m = 14, p-value = 0.5132

data:  x: agent in Wilcoxson.channel , and y: garent in Wilcoxson.channel
rank-sum statistic W = 464, n = 27, m = 8, p-value = 0.4058
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data:  x: fent in Wilcoxson.channel , and y: garent in Wilcoxson.channel
rank-sum statistic W = 523, n = 29, m = 8, p-value = 0.3169

data:  x: fent in Wilcoxson.channel , and y: hdent in Wilcoxson.channel
rank-sum statistic W = 828, n = 29, m = 20, p-value = 0.0362

data:  x: fent in Wilcoxson.channel , and y: indent in Wilcoxson.channel
rank-sum statistic W = 629, n = 29, m = 12, p-value = 0.5812

data:  x: agent in Wilcoxson.channel , and y: leent in Wilcoxson.channel
rank-sum statistic W = 548, n = 27, m = 14, p-value = 0.6152

data:  x: agent in Wilcoxson.channel , and y: garent in Wilcoxson.channel
rank-sum statistic W = 464, n = 27, m = 8, p-value = 0.4058

data:  x: agent in Wilcoxson.channel , and y: hdent in Wilcoxson.channel
rank-sum statistic W = 752, n = 27, m = 20, p-value = 0.0249

data:  x: agent in Wilcoxson.channel , and y: indent in Wilcoxson.channel
rank-sum statistic W = 567, n = 27, m = 12, p-value = 0.4253

data:  x: leent in Wilcoxson.channel , and y: garent in Wilcoxson.channel
rank-sum statistic W = 153, n = 14, m = 8, p-value = 0.6163

data:  x: leent in Wilcoxson.channel , and y: indent in Wilcoxson.channel
rank-sum statistic W = 212, n = 14, m = 12, p-value = 0.252

data:  x: garent in Wilcoxson.channel , and y: hdent in Wilcoxson.channel
rank-sum statistic W = 159, n = 8, m = 20, p-value = 0.0285

data:  x: garent in Wilcoxson.channel , and y: indent in Wilcoxson.channel
rank-sum statistic W = 101, n = 8, m = 12, p-value = 0.2083

data:  x: hdent in Wilcoxson.channel , and y: indent in Wilcoxson.channel
rank-sum statistic W = 304, n = 20, m = 12, p-value = 0.3261

data:  x: agbw in Wilcoxson.channel , and y: ldbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = 2.4062, p-value = 0.0161

data:  x: agbw in Wilcoxson.channel , and y: garbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = 0.0393, p-value = 0.9687

data:  x: agbw in Wilcoxson.channel , and y: hdbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = 5.0464, p-value = 0

data:  x: agbw in Wilcoxson.channel , and y: indbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = 0.3196, p-value = 0.7493

data:  x: ldbw in Wilcoxson.channel , and y: garbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = -1.1948, p-value = 0.2322

data:  x: ldbw in Wilcoxson.channel , and y: hdbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = 3.4306, p-value = 0.0006

data:  x: ldbw in Wilcoxson.channel , and y: indbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = -0.8491, p-value = 0.3958

data:  x: garbw in Wilcoxson.channel , and y: hdbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = 3.3314, p-value = 0.0009
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data:  x: garbw in Wilcoxson.channel , and y: indbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = 0, p-value = 1

data:  x: hdbw in Wilcoxson.channel , and y: indbw in Wilcoxson.channel
rank-sum normal statistic with correction Z = -3.2709, p-value = 0.0011

data:  x: abww in Wilcoxson.channel , and y: ldww in Wilcoxson.channel
rank-sum normal statistic with correction Z = 3.8361, p-value = 0.0001

data:  x: abww in Wilcoxson.channel , and y: garww in Wilcoxson.channel
rank-sum normal statistic with correction Z = 2.8878, p-value = 0.0039

data:  x: abww in Wilcoxson.channel , and y: hdww in Wilcoxson.channel
rank-sum normal statistic with correction Z = 5.1535, p-value = 0

data:  x: abww in Wilcoxson.channel , and y: indww in Wilcoxson.channel
rank-sum normal statistic with correction Z = 2.1913, p-value = 0.0284

data:  x: ldww in Wilcoxson.channel , and y: garww in Wilcoxson.channel
rank-sum normal statistic with correction Z = -0.9558, p-value = 0.3392

data:  x: abww in Wilcoxson.channel , and y: hdww in Wilcoxson.channel
rank-sum normal statistic with correction Z = 5.1535, p-value = 0

data:  x: abww in Wilcoxson.channel , and y: indww in Wilcoxson.channel
rank-sum normal statistic with correction Z = 2.1913, p-value = 0.0284

data:  x: ldww in Wilcoxson.channel , and y: hdww in Wilcoxson.channel
rank-sum normal statistic with correction Z = 2.1347, p-value = 0.0328

data:  x: ldww in Wilcoxson.channel , and y: indww in Wilcoxson.channel
rank-sum normal statistic with correction Z = -1.621, p-value = 0.105

data:  x: hdww in Wilcoxson.channel , and y: indww in Wilcoxson.channel
rank-sum normal statistic with correction Z = -3.0948, p-value = 0.002

data:  x: garww in Wilcoxson.channel , and y: hdww in Wilcoxson.channel
rank-sum normal statistic with correction Z = 2.4163, p-value = 0.0157

data:  x: garww in Wilcoxson.channel , and y: indww in Wilcoxson.channel
rank-sum normal statistic with correction Z = -0.4245, p-value = 0.6712
```