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

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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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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.