An examination of channel geomorphology, hydraulic characteristics, and fish habitat in Cottonwood Creek on the Montana University Systems Bandy Ranch
by Stephanie Ann Hallock

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University

Abstract:
A baseline study was completed in the summer of 2003 on Cottonwood Creek along the portions that flow through the Bandy Ranch. This reach will likely be the host for studies of management practices and corresponding channel change in the future.

This study was initiated after the closure of an irrigation ditch in 2002, raising interest in the immediate and long term impacts on the channel. Data collection focused on fish habitat, channel geomorphology, macroinvertebrate composition, and riparian vegetation. The methods in this study could be repeated in future studies at the ranch.

The riparian health of Cottonwood Creek was established from a variety of field observations. Lack of large woody debris, lack of overhead cover, and lack of deep pools were found to be limiting factors on this stretch of Cottonwood Creek.

Macroinvertebrate data showed that the most upstream reach might be under more stressed conditions compared to the rest of the reaches. Channel geometry has been steady over the period of 1996-2003, while Rosgen classification showed that the creek was in a transition state. Hydraulic modeling was performed, and showed that small changes in flow during low flow periods have little effect on stream physical conditions. A thorough fish assessment was not included in this study, and would complete the baseline data set.

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APPROVAL

Of a thesis submitted by

Stephanie Ann Hallock

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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ABSTRACT

A baseline study was completed in the summer of 2003 on Cottonwood Creek along the portions that flow through the Bandy Ranch. This reach will likely be the host for studies of management practices and corresponding channel change in the future. This study was initiated after the closure of an irrigation ditch in 2002, raising interest in the immediate and long term impacts on the channel. Data collection focused on fish habitat, channel geomorphology, macroinvertebrate composition, and riparian vegetation. The methods in this study could be repeated in future studies at the ranch.

The riparian health of Cottonwood Creek was established from a variety of field observations. Lack of large woody debris, lack of overhead cover, and lack of deep pools were found to be limiting factors on this stretch of Cottonwood Creek. Macroinvertebrate data showed that the most upstream reach might be under more stressed conditions compared to the rest of the reaches. Channel geometry has been steady over the period of 1996-2003, while Rosgen classification showed that the creek was in a transition state. Hydraulic modeling was performed, and showed that small changes in flow during low flow periods have little effect on stream physical conditions. A thorough fish assessment was not included in this study, and would complete the baseline data set.

INTRODUCTION

The focus of this thesis is the stream ecosystem in Cottonwood Creek on the Montana University System's Bandy Ranch in the Blackfoot River Watershed. This thesis is not the traditional hypothesis test, but is the examination of a collection of baseline data and corresponding research methods that could be duplicated in future studies in the same location.

Objectives

The primary objectives of this study were to develop a base-line data set of parameters that 1) measure stream ecosystem health in Cottonwood Creek on the Bandy Experimental Ranch and 2) can be used to evaluate the long term changes in channel morphology and in-stream habitat.

Supporting objectives of this study were as follows: 1) examine stream cross-section data on Cottonwood Creek from 1996 to 2003 to identify a possible channel response, 2) gather habitat data to describe the impact of increased late summer flows on habitat quality and distribution in Cottonwood Creek, 3) perform a riparian assessment to quantify current riparian health, and 4) perform macroinvertebrate studies as an indirect measure of water quality.

Description of paper

Due to the non-traditional nature of this thesis, there is an extensive literature review that is a broad overview of many different subjects. The literature review focuses on concepts important to hydraulic engineering as well as the biological sciences, all of which relate to different aspects of the stream ecosystem (chapter 2). Topics discussed include fish habitat characteristics, irrigation impacts on the stream ecosystem, the relationship between vegetation and bank stability, and an overview of river hydraulics. It is hoped that this background information will not only give the reader an understanding of the complex nature of stream ecosystems but that it will be valuable when future studies are completed.

Other chapters focus on the observations and results of the study. A description of the Blackfoot River Watershed is given in chapter 3 while chapter 4 focuses on the Bandy Ranch itself. Chapter 5 describes the methods used in this study which will be repeated in future work. The baseline data is summarized in Chapter 6. Finally, chapter 7 offers a discussion of the collected data and gives recommendations for the future. These conclusions are broad in scope because of the limited years of data.

LITERATURE REVIEW

Why Are We Concerned With Low-Order Streams?

In recent years, there has been a focus on restoring fish habitat that has been lost or degraded due to human activity. Agriculture, grazing, mining, logging, and recreation all have led to changes in the physical, chemical, and biological condition of many western streams. Small streams are often the most directly impacted by these activities. Such streams have unique geomorphology that results from a combination of "flow conditions, sediment transport, distribution of channel roughness elements, and management activities" (Beschta and Platts, 1986). Channel change is a natural process and streams can undergo this change in subtle ways through the year. Channel change impacts the whole stream ecosystem from riparian vegetation to macroinvertebrate and fish populations. Determining what changes are due to natural conditions and which changes are human caused is the challenge that watershed managers face when making mangement decisions.

The increased demand for water has impacted management practices over the last few decades and has made management of water resources increasingly complex. In the western United States, irrigation is often used to maintain forage for cattle grazing. In 1990, 98% of surface water withdrawals were for irrigation purposes comprising of 9,990 thousand acre-feet of water in the state of Montana (Moore et al, 1996). Many of the same water bodies used for irrigation also contain important habitat for threatened native fish populations. As a result of the awareness of how water management has impacted these fish populations, instream flow methodologies have been developed to determine minimum flow requirements for waterways depending on their designated use. According to Colby (1990), the key to preserving fish habitat in arid regions like Montana, where water is heavily diverted, are adequate instream flows.

Some people question the importance of enhancing habitat on small streams. They are more concerned with the fishery on large rivers and believe that money should be focused there. However, small streams play an important role in the life history of native trout species like Bull Trout (*Salvelinus confluentus*) and Westslope Cutthroat Trout (*Oncorhynchus clarki lewisi*). Protecting these smaller tributaries will help maintain a sustainable fishery. Goldman (1994) notes that

> "fish are extremely vulnerable to a variety of dangers during their early life stages. Due to their high fecundity, a small change in the proportion of offspring that survive the critical early life stages translates into large difference in the abundance of year classes that can persist over their life span. Survival is positively correlated to body size."

By increasing the habitat quality and quantity for fry and juvenile trout, there is a higher probability of a greater number of trout reaching adulthood and returning to their birth areas to spawn.

Fish Populations and Habitat

The relationship between fish populations and stream habitat is complex. Trout need spawning, incubation, feeding, and rearing habitats. Many factors influence fish distribution. These factors include chemical properties such as pH and dissolved oxygen, and physical properties such as water temperature, velocity, water depth, cover, and substrate composition. Competition within and between species along with predation, food availability, and disease also play a role in habitat selection (Leftwich et al, 1997). Each of these factors must be studied if the limiting factor for a given fish population is to be understood. Often stream habitat enhancement projects focus on one aspect, such as cover, while another limiting factor is actually causing a bottleneck in the population.

Habitat forming processes are often impacted by land use and many of these processes that create habitat "operate on time scales of decades or longer" (Roni et al, 2002). It often hard for scientists to study habitat change because of the time involved to observe habitat change as well as the lack of funding to do so. "Several years may also be required for optimum physical conditions to develop after restoration or enhancement, and fish populations may not respond for several more years" (Reeves et al, 1991). Often times fish habitat enhancement projects only change where the fish are located in the channel instead of actually increasing fish biomass as a whole. This is known as redistribution. The only way to detect if habitat change has caused an impact in biomass is to look at the whole drainage and not just a particular section of stream.

Examining the stream ecosystem is essential to habitat enhancement projects. There are many spatial scales that should be considered depending on the study involved. Macrohabitat analysis concerns regional scale, mesohabitat analysis looks at the stream system as a whole, and microhabitat analysis involves the actual habitat present like pools and riffles (Rabeni and Sowa, 1996). Understanding how these spatial scales are interlinked plays a vital role in determining the impact of land management activities on a stream. Fish habitat is a combination of the characteristics of the watershed that create it.

A stream's physical habitat consists of fast and slow water habitat types. Fast water types consist of riffles, glides, and runs. Slow water habitats are pools which can be formed by scour or damming. During low flows, much of the water volume of a stream resides in pools (Beschta and Platts, 1986). During high flow events, pools dissipate energy. These same high flows flush out sediment from riffle areas. Changes in longitudinal profile, sinuosity, roughness, and hydraulic radius all can result from changes in flow, sediment deposition/removal, and structures in the stream (Beschta and Platts, 1986). Many studies have shown that placement of instream structures into a channel cause pool frequency, depth, sediment retention, and woody debris retention to increase (Roni et al, 2002). The addition of instream structures also increases habitat complexity. Beschta and Platts (1986) note that "although generalization is difficult, the effects of sediment availability and streamside land use seem to be more important than possible flow changes brought about by management practices" in impacting habitat formation.

The spatial distribution of pools and riffles is important and can have impacts on fish distribution. Pool-riffle morphology is common in many streams. It has been observed that deep pools with low velocities and plenty of cover support stable fish populations (Beschta and Platts, 1986). For the most part, older trout prefer deeper water. Correlations have been made between yearling and adult biomass with pool volume and depth (Horan et al, 2000). However, good quality pools might still not be enough to support fish populations. For example, young-of the-year fish quite frequently choose lower quality pools to rear in until they are large enough to compete with the larger fish that are present in the deeper pools. Riffles provide food and spawning areas for salmonids. Salmonids often select spawning areas that are not in the "best" riffle habitats in order to provide their young with high quality rearing areas and thus increase their survival (Beschta and Platts, 1986). The surface area and the lower amount of fines in the bed material in riffle areas cause these areas to be highly productive in terms of macroinvertebrate production. However, though not a permanent barrier, riffles can also be barriers to fish passage under certain conditions. Low flows produce the greatest difference between stream habitats. Long riffle reaches become barriers because they "may significantly reduce daily excursions between habitat patches and limit the ability of fish to track variability in food resources and predator densities" (Lonzarich et al, 2000). Because of the variations in habitat use, it has been found that a variety of habitats, such as both shallow and deep pools, are needed to support a healthy fishery. Complexity is the key to fish diversity, and diversity leads to a sustainable fish population. Discharge interacts with the physical and biological aspects of the channel to create this complexity.

Flow in natural channels is three-dimensional. Variations in time and space make water flow complex; yet understanding the velocity patterns in a channel is required to understand the distribution of organisms in the channel. Flow patterns must be considered if fish habitat management plans are to be implemented. Because of this complexity, an "average" water velocity is used in hydraulic calculations. In open channels, average velocity is around 85% of the surface velocity at 0.6 of the depth from the surface (Giller and Malmqvist, 1998; Julien 1995). This can be verified using the

Prandtl-Von Karmen log velocity profile for turbulent flow (Julien, 1995). An example of an idealized velocity profile is shown in figure 2.1.

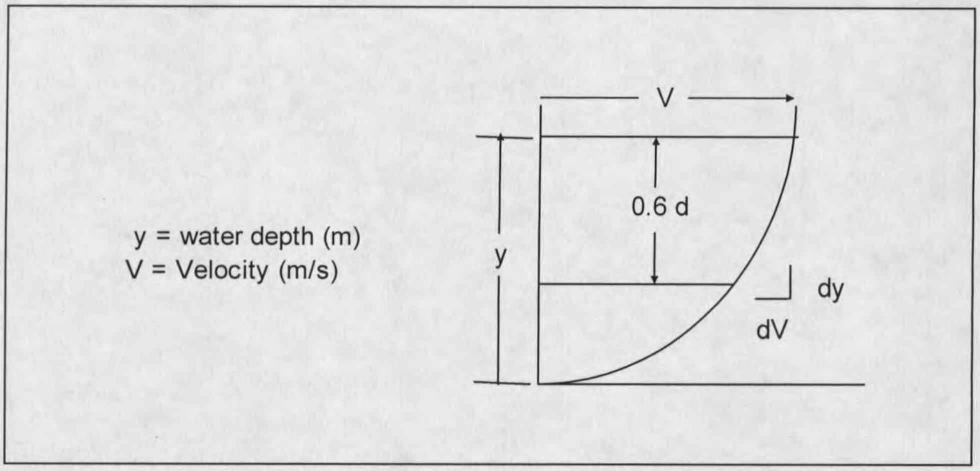

Figure 2.1. Idealized velocity profile for a natural channel.

Another relationship between water velocity and depth is the Reynolds number. This is a dimensionless quantity that is often used to describe fluid flow:

$$\mathrm{Re} = \frac{VD}{\nu} \qquad (2.1)$$

where;

Re= Reynolds number,

V= velocity (m/s),

D= characteristic length (m),

ν= kinematic viscosity of the fluid (m^2/s).

Reynolds numbers below 2000 indicate laminar flow and values greater than 2000 indicate turbulent flow. These two flow regimes create vastly different habitat settings for aquatic organisms. Reynolds number can also be interpreted as an indicator of the

various lift and drag forces experienced by an aquatic organism. According to Giller and Malmqvist (1998), "both the movement of the fluid and the movement of the animal will govern the Reynolds number." Thus, small macroinvertebrates and protozoa that live close to the stream bed have low Reynolds values because of the low velocities there. Organisms that have low Reynolds values are more subject to viscous forces than inertial forces. Macroinvertebrtes live initially at low Re (1-10) areas and have Reynolds numbers higher than 1000 (Giller and Malmqvist, 1998). Fish and other large organisms are more subject to inertial forces and have higher Reynolds values. Trout, for example, have Reynolds numbers ranging from 50,000-200,000 (Giller and Malmqvist, 1998). In order to holds its position in the channel, a fish must use enough energy to overcome the shear stress it is experiencing (Giller and Malmqvist, 1998). Thus each species of aquatic organism reacts in different ways to flow conditions and because of this, changes in flow conditions influence the composition and structure of a stream community.
It can best be summed up as: "the reason why we find certain species in a particular aquatic habitat has to do with the ability of these organisms to utilize and survive under the special set of biotic and abiotic conditions that characterize the habitat" (Giller and Malmqvist, 1998).

Velocity and the drag, lift, and shear forces experienced by fish and macroinvertebrates are more important biologically then the range of discharges (Giller and Malmqvist, 1998). Velocity is considered to be the greatest limiting factor for various fish lifestages. Velocity is involved in influencing community structure, stream carrying capacity, reducing effects of predation on younger fish, and the choosing of spawning sites (Utah State, 1976). Most cobble and gravel bed streams have hydraulically rough flow patterns and flow close to the bed can be complex due to irregularities. In many cases, high velocities can occur close to the bed. Rocks and other materials present on the bed cause flow separation downstream and create a dead zone where the current is lessened. These areas are depositional and are also resting areas for organisms from the current (Giller and Malmqvist, 1998). Depth is the second most important factor in stream habitat. Depth helps maintain pool and riffle quality, wetted areas for spawning, fish passage both up and downstream, and helps maintain food producing riffles (Utah State, 1976).

As velocity of water increases, so too does the magnitude of shear stress. Therefore, flood events help shape the channel due to the large shear stress they exert on the stream bed and banks. Particle size and the amount of bed load are also related to shear stress and velocity because shear stress is proportional to the square of the velocity (Giller and Malmqvist, 1998). The variation in flow and shear stress helps creates the habitat template of streams.

One common formula used to describe the relationship between velocity, area, slope, and roughness to flow rate in an open channel is Manning's Equation (Chow 1959):

$$Q = \frac{C}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad (2.2)$$

where;

Q = flow rate (m^3/sec),

C = 1.00 for SI units and 1.486 for English units,

n = Manning's roughness coefficient,

A = cross-sectional area (m^2),

R = hydraulic radius (m),

S = slope (m/m).

Mannings equation was derived for uniform flow conditions (i.e. that the depth, area, and velocity in a reach are constant and that the energy line, water surface, and bed slopes are equal). For natural streams, where these parameters change, the standard step method, as detailed in the methods section in this thesis, can be used with Manning's equation to predict water surface profiles that result from the interaction of discharge with the channel characteristics.

Irrigation Impacts on the Stream Channel

Irrigation diversions can alter flow regimes and sediment transport capacity, in turn impacting channel morphology. Sediment deposition can occur below a diversion if the stream flow is reduced without a reduction in sediment loading. This sediment provides substrate for vegetation to establish in areas that were previously inundated. Channel bed friction increases and further promotes sediment deposition and thus a reduction in channel size (Bohn and King, 2000). As the width decreases, there is also a "loss of lateral aquatic habitat and complexity, which has important implications for fish and macroinvertebrate populations" (Ryan, 1997). Variations in flow due to irrigation demands can also impact the channel. Wohl and Carline (1996) found that recruitment in salmonid numbers may decrease due to variable flow rates in degraded streams. In regards to flow reduction, surface velocity is the hydraulic variable that is most influenced by irrigation withdrawals (Reiser and White, 1990).

Still, it is hard in some ways to predict channel response to irrigation diversions. This is because in many cases, water is not diverted during higher critical flows which shape the channel about every 1.5 years (Ryan, 1997). Diverting during discharges that are below bankfull may not produce any "noticeable" change to the channel. Ryan (1997) notes that diversion impacts depend on the total amount of water diverted, how the peak and sustained flows have changed, and the time that the diversion has been operating. During dry years, lower peak flows can impact the channel morphology but these changes are often "removed" during extreme flow events of wetter years. It is also can be hard to link certain changes in channel dimensions to irrigation diversions because sediment transport from upstream sources, riparian vegetation, and large woody debris are just a few of the many hydraulic controls that might be causing the channel change. Another factor that makes channel prediction difficult is the direct manipulation of the channel by irrigators themselves. Irrigators can alter the channel by straightening the channel, adding riprap to the banks, and by removing large woody debris and other instream features to improve irrigation efficiency. "The wide variety of channel types, the adjustment of individual channels to local factors, and potential time lags between perturbation and channel response" as well as direct human impacts make it hard to predict the reasons for channel change (Montgomery et al, 1993).

Complexity plays an important role in the persistence of fish populations. Horan et al (2000) mention that an isolated population needs more area to survive in a stream segment that lacks complexity versus a highly complex one. Complexity influences the "size, structure, distribution, and stability of populations" (Horan et al, 2000). Diversity in water depth, velocity, and substrate adds complexity to a stream ecosystem. Hydraulic and structure variation also increase the ability of a stream to support life. During extreme events, complexity enables a population to persist where it would fail otherwise. It is also thought that predation is less in complex habitats because the ability of predators to catch prey is reduced (Horan et al, 2000). It has been found that an increase in cover can increase salmonid abundance. In fact, some fish prefer overhead cover to instream cover (Horan et al, 2000).

Effect of Grazing

Overgrazing is one land use that impacts complexity. Some of the results of over grazing included upland erosion, loss of riparian vegetation, breakdown of streambanks, and a lower water table. Streams also have poorer instream structure and an overabundance of nutrients in overgrazed pastures (Meehan, 1991). As a result, fish populations decrease or move elsewhere. Cattle concentrate in riparian areas during certain times of the year to feed on high quality forage. If the area is overgrazed for extended periods, small trees and shrubs may be eliminated from the riparian area (Maloney et al, 1999). According to Maloney et al (1999), "improvements in vegetation and stream channel morphology have generally taken 10 years or more after exclusion of cattle". They also note that protecting streams from grazing, by fencing for example, increases the amount of stream cover, increases the quality of riparian vegetation, and improves channel morphology.

Overgrazing can also cause a decrease in biomass, vigor, and a change in composition of the riparian vegetation (Kauffman and Krueger, 1984). Cattle grazing changes the composition and density of plant species in the riparian zone. One study found that shrubs provided 75% of cover, in an area that was devoid of shrub cover 10 years previously, when the cattle excluded from the area (Kauffman and Krueger, 1984). Because of the impacts that cattle have on the riparian zone, grazing management is very important in minimizing fish habitat degradation. Kauffman and Krueger (1984) note that "aquatic ecosystems can be restored through intensive livestock management at a lower cost than through installation of instream improvement structures".

Irrigation Impacts on Stream Biology

Though physical changes may be hard to see, the result of lower flow regimes due to irrigation does have an impact on the chemical and biological characteristics of the stream. Temperature, dissolved oxygen, nutrient transport are some factors impacted by lower flows. Water temperature can increase as the result of irrigation diversions (Rockford, 1998). Nutrient transport is reduced because flow is reduced. The reduction in velocity due to flow reduction leads to a reduction in intersediment velocity flowing through the spawning gravels. As a result, dissolved oxygen levels are lowered. Freezing in the redds can also be caused by low flows, especially in areas that have high sediment concentrations (Reiser and White, 1990). Lower flow rates can cause water temperature to increase. High temperatures are of concern because they stimulate fish metabolism and have a negative effect on swimming ability and feeding rate (Horan et al, 2000). Higher temperatures also make it harder for species like Bull trout to compete with introduced species like Brown trout. It should also be noted that different life stages of many aquatic species are "triggered by seasonal fluctuations in light, nutrient delivery, and water flow" (Ryan, 1997).

Species like Bull trout and Westslope Cutthroat trout require certain instream flows in order to maintain their populations. It is believed that the minimum instream flow to maintain sustainability is 30% of the average annual flow for the whole year (Moore et al, 1996). If a channel is diverted heavily enough, fish populations can become isolated and migration can be stopped. Irrigation diversions reduce cover, spawning area, and rearing capacity of the stream (Reiser and White, 1990). Trout respond to these reductions by moving to more suitable habitat but deposited eggs obviously cannot respond and are left to deal with these reductions.

Irrigation diversions often create barriers to fish movement during low flows. These barriers have caused decreases in fish populations due to the reduction in the number of fish able to migrate downstream or return upstream to spawn. Horan et al (2000) note that "bull trout also appear to be sensitive to fragment size and will be vulnerable to extinction if fragmentation continues to limit their range, especially in small headwater streams." Many irrigation diversions on small streams utilize horizontal boards that span the stream and are anchored by supports on the bank. Water backs up behind the dam and is funneled into a ditch. During times when water is not diverted, the boards are removed and water flows freely through the structure. Removal of these dams has been noted to increase "migratory fish usage of previously disjunct areas" (Schmetterling et al, 2002). In order to increase fish passage through these structures, denil fish ladders or other fishway structures can be installed at the diversion. Fish species and size both play a role how well these structures aid in fish passage (Schmetterling et al, 2002). Another alternative to increase fish passage is for the complete removal of the structure.

Managing streams for fish passage is difficult because the time of migration and the time of spawning vary from species to species. Westslope trout migrate and spawn during spring high flows. Diversion dams often have little impact on fish movement at this time because water is not being diverted. This is often not the case for fall spawners like Bull Trout. Bull trout enter tributaries during the summer months when irrigation diversions are active and then migrate downstream after spawning.

Riparian Vegetation and Slope Stability

Geomorphologic and hydrologic processes are the primary drivers of riparian ecosystems but slope, elevation, water quality, bed sediment, and streamside vegetation also influence the riparian zone. Riparian areas are open systems with large amount of energy and nutrient exchanges between the stream ecosystem and the upland ecosystem (Kauffman and Krueger, 1984). These areas have higher diversity and productivity then the adjacent uplands. "It is believed that, on land, the riparian/stream ecosystem is the single, most productive type of wildlife habitat, benefiting the greatest number of species" (Kauffman and Krueger, 1984). Riparian vegetation provides insects and organic material for the organisms residing within the stream. In fact, up to 90% of the organic matter that supports headwater streams comes from the surrounding vegetation (Kauffman and Krueger, 1984). Riparian vegetation helps buffer a stream from excess sediment inputs. These riparian areas also serve as travel corridors for big game as they move between their summer and winter ranges.

Land use can impact riparian vegetation in negative ways. It has been observed that disturbances like trampling can cause a riparian vegetation to change to plant species that have shallower and weaker roots (Winward, 2000). These species are not adapted to withstand the erosive forces of high flows and erode easily. Stabilizer species, on the other hand, have root masses that are deep and fibrous as well as strong crowns which enables these plants to buffer the bank against water shear stress. They also catch sediment which helps rebuild eroding banks. It is said that these "species play a significant role in attaining and maintaining proper functioning of riparian and aquatic ecosystems" (Winward, 2000). Geyer willow is an example of a stabilizer plant species. Consequently, knowing the species composition of a riparian zone can indicate the health of the system and streambank stability.

Riparian vegetation is influenced by factors upstream which may cause shifts in community type due to shifts in propagule delivery, to change in the water table or channel form. This must be taken into account when trying to determine the impacts that adjacent land use has on riparian vegetation. Riparian species such as alder, cottonwoods, birch, and willow have become adapted to colonizing disturbed areas or newly developed gravel or sand bars. Some grasses and sedges also colonize these areas. Water sources, valley slope, elevation, climate, and substrate characteristics all lead to the development and function of a riparian system. Land use can alter the water table, discharge level, and sediment supply, ultimately impacting plants directly which in turn causes human induced changes to the plant communities. Water level and sediment size combine to favor certain species over others. For example, willows prefer areas that are dominated by silts and clays while cottonwoods prefer areas that are sandy. Sedges and willows colonize areas that have ground water depths from 0.2 m to 0.4 m from the surface while cottonwoods can handle drier conditions and grow in areas with ground water depths of 0.6 m (Law et al, 2000).

Riparian ecosystems are unique because they are the interface between land and water. These ecosystems are driven by water flow. Establishment of vegetation initiates bank building through sediment entrapment as well as protection during high flows. Variation in discharge truncates vegetative succession, regularly resetting the "succession trajectory". As a result, succession in riparian areas are unpredictable because disturbances vary in magnitude and frequency. Vegetation is known as the great integrator. A stream ecosystem gains stability by having a diversity of functional groups. As a result, even if a population is wiped out, another population can take its place and there is no net loss in biomass or species richness. Bank erosion is a natural process that is the response of the channel to its conditions (Leopold et al, 1964). However, excess erosion can cause vast alteration in stream morphology. Streams with unstable banks tend to more shallower and wider than streams that have more armored banks. Landowners often place rock riprap on eroding streambanks to prevent erosion. However, rock riprap often increases near-bank velocities due to its smooth face and thus smaller roughness. Erosion of the channel bed and downstream banks is enhanced and scour around the riprap may enhance bank erosion at the site (Lee et al 1997). Understanding how bank erosion as well as bank building happens is important in evaluating channel change

In Montana, the soil may be unsaturated during certain times of the year. In this case, the soil has increased cohesion due to matric suction as described by (Simon et al, 2000):

$$c_a = c' + (\mu_a - \mu_w)\tan\phi^b = c' + \psi\tan\phi^b \tag{2.3}$$

where;

c_a = apparent cohesion (kPa),

c' = effective Cohesion (kPa),

μ_a = pore-air pressure (kPa),

μ_w = pore-water pressure (kPa),

θ^b = 10 to 20 degrees, describes increase in shear strength due to an increase in matric suction,

ψ = matric suction (kPa).

However, when water levels decrease very rapidly bank instability is promoted. This is due to the loss of water pressure since the water level in the channel decreases.

(ASCE, 1998). After water levels have decreased and the banks have time to dry out and recover, cohesion increases.

Vegetation can be very effective at protecting streambanks during extreme conditions. Beshta and Platts (1986) note that during flood periods, bank vegetation becomes a "mat" that reduces velocity and this reduction in velocity causes sediments to settle. As these sediments begin to settle, the channel will narrow and deepen as the bank is built up. Besides protecting banks during high flow periods, vegetation can also be beneficial during winter low flows. Degraded streams often are very susceptible to anchor ice formation. Vegetation can help reduce ice cover; trees and shrubs can reduce the erosive impact of floating ice during melting events (Beshta and Platts, 1986). Bank vegetation is essential to maintaining a dynamically stable stream channel.

Vegetation can promote bank stability by adding strength to the soil via their roots that in turn increases the resistance to failure (FISRWG, 1998). This is viewed by many to be the most important way that plants enhance bank stability. For example, one study showed that the tensile strength of soil with roots present was 10 times greater than soil samples with no roots (Lawler et al, 1997). This addition of tensile strength is important because soil tends to be weak in tension and stronger in compression (Simon and Collison, 2002). Plant roots are the opposite being stronger in tension and weaker in compression. Combining soil with vegetation helps increase the soils tensile strength and thus adds strength to the streambank. Shear stresses in the soil are then transferred to tensile stresses in the roots. The semi-continuous root system of plants transfers the load from high stress regions to regions of lower stress (Abernathy and Rutherfurd, 2001).

Tractive forces also develop between the soil and the root fibers to add additional strength between the fibers and the surrounding matrix. Because of this, the spatial density of the roots is also important in soil strength.

As soil depth increases, the strength of the roots decreases. Most of the reinforcement by plant roots are concentrated in the top 20 cm of the bank and a sharp boundary occurs below (Simon and Collison, 2002). Beyond the root zone failure planes are not reinforced. Knowing the distribution of strength with depth is important in predicting the effect of roots on stability. If the bank is taller than the root zone, reinforcement might not be effective since bank failure can occur underneath. This is often the case with cantilever banks. Riparian vegetation can strengthen cantilevered banks via root reinforcement. However, bank failure due to flow erosion and tensile failure occur below the root zone. These root strengthened cantilevers fail by beam or shear (ASCE, 1998). Thorne and Tovey (1981) developed an equation to predict stable widths for a cantilever bank (described in figure 2.2):

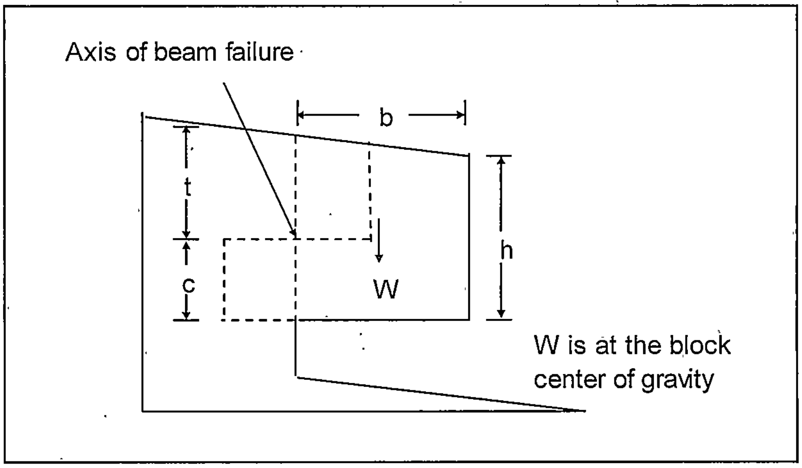

Figure 2.2. Failure of a cantilever bank.

The stable bank width is;

$$b = \sqrt{\frac{\sigma_t t^2 + \sigma_c c^2}{\gamma h}} \tag{2.4}$$

where;

b = Stable bank width (m),

σt, σc = Tensile and Compressive Strengths (kN/m^2),

t = Block height under tensile stress (m),

c = Block height under compressive stress (m)

h = Total block height (m),

γ = Saturated bulk density (kN/m^3).

The size and density of plant roots impacts their mechanical effect on the soil. The tensile strength of the roots depends on the species. Abernathy and Rutherfurd (2001) found that root tensile strength can be expressed as a non-linear function of root diameter raised to a species specific exponent. Strength within a species depends on the environment, seasonality, root orientation and diameter. Tests have shown that as the root mass increases, the shear strength increases linearly (Wu et al, 1988). How the root density is distributed then can be assumed to exert a strong influence over how the root reinforcement is distributed (Abernathy and Rutherfurd, 2001). Bank stability is less impacted by the differences in tensile strength of interspecies roots compared to interspecies differences in root distribution. A parameter that has been developed to measure density is the root-area-ratio (Abernathy and Rutherfurd, 2001):

$$\frac{Ar}{Aw} = \frac{\sum n_i a_i}{Aw} \tag{2.5}$$

where;

Ar = sum of the cross-sectional area of the roots intersecting the profile wall (m^2),

Aw = the wall's total cross-sectional area (m^2),

n_i = number of roots in size-class i,

a_i = average cross-sectional area of the roots in size-class i (m^2).

High concentrations of flexible, long roots per unit volume of soil favor soil strength. Grasses have a high root area ratio which gives them their strength instead of stronger roots (Simon and Collison, 2002). It has been found that roots with a diameter greater than 20 mm do not contribute significantly to soil strength (Abernathy and Rutherfurd, 2001). These roots instead act as anchors.

BLACKFOOT RIVER WATERSHED

The Blackfoot River Watershed in central Montana has a diversity of land uses, including logging, grazing, mining, crop production, and recreation, that have all impacted fish and wildlife populations to some extent. Bull trout and westslope cutthroat trout are of specific interest to fisheries biologists of the Blackfoot watershed due to their current population. Westslope cutthroat trout are listed as a species of special concern. Rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), and brook trout (*Salvalinus fontinalis*) also are trout species that occupy the Blackfoot. Fisheries biologists have noted that the numbers and size of sport fish in the Blackfoot River have declined over the last couple decades (Rothrock et al, 1998). Declines in benthic macroinvertebrate populations have also occurred. Habitat assessment of 19 principal tributaries of the Blackfoot in 1988 and 1989 revealed significant habitat degradation (Pierce et al, 1997). Further studies from 1990-1996 showed 26 of 33 additional streams to be impaired. As a result, local groups including landowners, federal and state agencies, and non-profit groups like Trout Unlimited, have come together to try to restore lost habitat, reduce non-point source pollution, remove migration barriers, and increase instream flows. The Bandy Ranch, located by Ovando, MT is a participant of this effort and is the focus of this thesis.

Bull trout populations have declined in the Blackfoot watershed due to spawning and rearing habitat degradation, competition, hybridization with brook trout, and irrigation practices (Swanberg, 1997). Bull trout are the largest native piscivore in the

Blackfoot river and they have a high fecundity and diverse age structure. Fluvial bull trout rear in 2^{nd}-3^{rd} order tributaries during their first 3-4 years and then migrate downstream. At age 5-7 they are sexually mature. These fish spawn in September or October (Swanberg, 1997). Both spawners and non-spawners use tributaries over the summer to avoid warm temperatures in the Blackfoot River. These fish spawn every year or every other year during their lifetime. Bull trout require clear, cold, complex, and connected habitat. They prefer cold water less than 15 C. The U.S. Fish and Wildlife Service has listed Bull Trout as a threatened spices under the Endangered species act (Federal Register, June 10, 1998).

Watershed Description

The Bandy Ranch is part of the Blackfoot River watershed. The Blackfoot River flows from the top of the continental divide westward 212 kilometers (132 miles) to the Clark Fork River by Missoula, MT. Figure 3.1 shows a land use map of the watershed. The watershed is composed of 6,070 square kilometers (1.5 million acres) with 49% of the watershed being federal lands. Other major land owners include the state of Montana, Plum Creek Timber Company, and private owners. This area is relatively undeveloped with ranching and logging being the main economic uses. Glacial activity during the Pleistocene era has helped shape the landforms of the region. Upland communities include grasslands, pine forests, and sagebrush steppe. Vegetation includes ponderosa pine (*Pinus ponderosa*), Douglas fir (*Psendotsuga monziessi*), cottonwood (*Populus*