Assessment of streambank erosion along the North Fork Flathead River, northwestern Montana

by John Helms Ruth

A thesis submitted in partial fullfillent of the requirements for the degree Master of Science in Earth Sciences
Montana State University

Abstract:
Aerial photographs and field surveys were used to evaluate rates of channel migration and streambank erosion along a 55-km stretch of the North Fork Flathead River. Aerial photographs from 1945 and 1981 were overlaid to analyze channel changes in planform morphology. Analysis revealed numerous areas of lateral channel migration which cut both floodplain alluvium and large cutbanks composed of Tertiary claystones and glacial-fluvial materials. Field surveys were used to estimate the height dimension for volume calculations, and masses were obtained by combining these volumes with bank-material bulk densities. Stepwise multiple regression on several geomorphic variables (floodplain width, sinuosity, stream gradient, discharge, stream power, and bank characteristics) was then used in an attempt to identify factors which influence quantities of sediment contributed by streambank erosion along different reaches of the study area.

Examination of the planform geometry revealed that the North Fork's active floodplain has widened throughout most of the study area. The estimated migration rates in floodplain alluvium ranged from 0.0 to 6.8 meters per year (m yr^-1). Migration rates for the claystones and glacial materials were 0.0 to 1.4 m yr^-1 and 0.1 to 1.8 m yr^_1, respectively. The migration rates reported for floodplain alluvium are comparable to those reported in other streambank erosion studies.

The results of the regression analyses revealed that type of lower bank material and bend sinuosity weakly explained variations in migration and erosional volumes when controls were considered for the entire study area. The relationships between type of lower bank material and the medium and high volume estimates were substantially increased when these volume estimates were divided by floodplain width. Type of lower bank material and stream power emerged as statisically significant when the river was analyzed in sections. Overall, regression results did not explain much of the variance between erosional controls and streambank erosion, indicating that the North Fork Flathead River represents a complex environment in terms of streambank processes.

The methodology of measuring erosional areas from aerial photograph tracings and computing volumes from field surveys of bank heights is a useful first approximation to quantify streambank erosion. However, the large variability associated with natural systems prevents the development of a predictive model.

The streambank erosion totals estimated in this study suggest that bank erosion is a major contributor to the sediment yield of this basin and that large volumes of sediment are placed at least temporarily in storage following bank erosion. The complexity of factors related to streambank erosion and sediment yield makes assessment of past or future environmental impacts difficult.

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ABSTRACT

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CHAPTER 1

INTRODUCTION

Scope and Purpose

The desirability of clean water is a topic that has received progressively more attention in recent years. Preservation of water quality and maintenance of sufficient usable quantities of water are now major concerns throughout the world. Protecting this valuable natural resource is essential for the preservation and enhancement of human society and ultimately the existence of mankind. In order to protect our hydrologic environment the spatial and temporal dynamics of natural systems need to be better understood.

Sediment pollution of surface waters is one of many processes that degrades our water-resource base. Impacts include problems with eroded sediment itself, such as turbidity and aquatic habitat destruction, and with sediment-associated pollutants, such as pesticides and nutrients (Phillips, 1986). In addition to impacts to water quality and fisheries, increased sediment loads can alter stream channel morphology. The majority of this sediment results from streambank erosion and erosion by overland flow. Although the factors influencing these processes have been identified, quantifying specific sediment sources has proved quite difficult. The prohibitive expense of sampling numerous sources within a drainage basin restricts most research involving sediment budgets to estimation of the quantities of sediment produced over large areas. A consequence of evaluating sediment yield at limited sampling sites is that sediment as a non-point source of pollution is difficult to quantify spatially.

In addition to reducing water clarity and quality, sediments rich in nutrients can promote eutrophication. Nutrients such as phosphorus can be adsorbed to clay minerals, transported, and later released to promote aquatic growth. This growth may reduce oxygen resources within the water body as plants die and are oxidized. Many sources contribute to nutrient loading and distinguishing their relative magnitudes is critical for proper land management (Pimentel et al., 1976; Clapham, 1981). Domestic wastewater and agricultural runoff are large contributors of the nutrient phosphorus yet their relative input in comparison to natural nutrient sources is poorly known.

Both human activities and natural processes may accelerate erosion and sedimentation with subsequent potential for sediment pollution and nutrient loading. In order to evaluate the causes and magnitudes of impacts on surface waters it is helpful to understand conditions prior to change for purposes of comparison. However, evaluation of natural systems is often complicated by changing land use and climatic variations. Hence, the difficulty of quantifying streambank erosion is a consequence of both spatial and temporal variations in human activities and natural systems.

This research examines streambank and cutbank erosion and its controls along a 55 kilometer (34 mile) stretch of the North Fork of the Flathead River over a 36 year (1945-1981) time frame. The North Fork Flathead River is essentially a gravel-cobble bed river which is locally incised into lithified Tertiary deposits and semi-consolidated

Quaternary glacial materials. The streambanks of this river consist primarily of cobbles and gravels overlain by alluvial sand and silt. In addition, deposits 5-35 meters high of claystones and glacial outwash outcrop adjacent to the channel throughout the study area. To simplify the discussion which follows throughout the remainder of the thesis, any bank that consisted of Tertiary or Quaternary age sediments is termed a cutbank and the shorter banks of alluvial materials are named streambanks.

The primary questions addressed in this research project were: 1) Can aerial photograph analysis and field surveys reasonably estimate volumes of sediment produced by streambank erosion? 2) If so, what values approximate the volumes of sediment produced by streambank erosion along a 55 km section of the North Fork of the Flathead River? 3) Can multivariate regression be used to identify the important geomorphic controls on channel migration and streambank erosion? This project is unique because streambank erosion has never been quantified by measuring erosional areas from aerial photographs and quantifying their volumes over several kilometers of river. In addition to the hydrologic and geomorphic significance of these results, this study provides information important for evaluating the North Fork's sediment and phosphorus budgets.

Investigations into streambank erosion were initiated to complement a concurrent hydrology study (1986-1988) by the Montana Bureau of Mines and Geology. The Bureau study examined the pre-mining baseline hydrologic conditions for the North Fork and a few selected tributaries to allow assessment of the impact of the proposed Cabin Creek coal mine.

Information regarding water quality and sediment yields from the MBMG study will be utilized by the International Joint Commission's Boundary Waters Group for evaluating impacts once mining begins. An important aspect of the Bureau's study examined the relationship between discharge, sediment yield, and phosphorus transport.

Knapton (1978) concluded from earlier water quality studies that suspended sediment resulting from high runoff is responsible for much of the phosphorus that moves downstream. Streambank erosion along the North Fork contributes to this sediment yield and is a potential source of phosphorus input. Increased nutrient loading and subsequent eutrophication of Flathead Lake have been emphasized in several studies (Ellis and Stanford, 1986, 1988; Flathead River Basin Environmental Impact Study Steering Committee, 1983; Stanford et al., 1983). The distinction of Flathead Lake as the United States' largest natural freshwater lake west of the Mississippi River and its relatively pristine waters are reasons to attempt to minimize human impacts. A better understanding of natural sediment and phosphorus contributions from streambank erosion will help in evaluating human impacts upon Flathead Lake.

Streambank Erosion and Its Controls

Streambank erosion has been examined with a variety of qualitative and quantitative approaches. Much of this work has concentrated on the morphology and erosional processes within alluvial channels, although some workers have examined channel changes in bedrock (lithified sediment). Most studies have focused on fluvial dynamics, lateral migration rates, processes of erosion, channel planform changes, and factors influencing channel change. The review which follows examines the multitude of factors that influence bank erosion and prior efforts to quantify and predict rates. A discussion of high energy gravel bed rivers and channel migration rates in bedrock illustrates results from settings that are similar to the North Fork.

Many bank erosion studies have researched lateral migration rates within floodplain alluvium and glacial till over short time periods (five years or less) (e.g., Wolman, 1959; Twidale, 1964; Hill, 1973; Knighton, 1973; Hooke, 1980). These workers utilized erosion pins at several sites to measure migration rates and described the dominant hydrological and meteorological processes influencing erosion. Important results that emerged from their studies include: 1) fluctuations in river stage are most likely to cause bank erosion when banks have high moisture contents; 2) frost action by itself and aided by streamflow is an important contributor to bank erosion; 3) the erosional effectiveness of a particular discharge is not only a function of its magnitude but also its variability of duration and frequency (Knighton, 1973); and 4) the two most prevalent processes of bank erosion are corrasion and slumping, where corrasion is influenced primarily by river stage and slumping by antecedent precipitation (wet banks) conditions (Hooke, 1979).

Lateral channel migration rates have also been studied in bedrock channels (Crickmay, 1959; Shepherd and Schumm, 1974; Brakenridge, 1985). Crickmay (1959), for example, reported a lateral bedrock erosion rate of 0.3 $m \cdot yr^{-1}$ (1 $ft \cdot yr^{-1}$) over a ten year period along the Pembina River in

Alberta, Canada. His study used aerial photographs to examine the breaching of a meander neck incised into "Pleistocene deposits", and concluded that lateral corrasion in bedrock was more likely from a stream that was in grade and that vertical corrasion was really a "special case" for streams out of grade. Flume experiments by Shepherd and Schumm (1974), on the other hand, indicated that lateral or vertical erosion along bends of incised meandering streams was controlled by the quantity of sediment entrained by channel-forming discharges.

The morphology of meanders in bedrock channels is also influenced by discharge (Tinkler, 1971; Baker, 1977). Tinkler found that effective flows for bedrock meander migration have a recurrence interval from 10 to 50 years and that flows with a recurrence interval of 1.5 years had little effect on bedrock channel morphology. Similarly, Baker (1977) reported that the limestone streams of central Texas require a rare, high magnitude flood to scour the bouldery alluvium and vegetation and produce significant channel change. He also proposed that drainage basins in areas of highly variable floods have a large potential for catastrophic response and that this response is related to the channel's resistance to scour.

Another study within an arid setting by Graf (1981) supported the concept of catastrophic channel change. His work on the braided sand bed of the Gila River in Arizona indicated that most assumptions of equilibrium were not appropriate for this river, and that catastrophic adjustment was an important process in channel change.

Whether uniform or catastrophic in nature, streambank erosion is influenced by many factors (i.e., geology, hydrology, climate, flora, fauna, and people). The multitude of causes and their relationship to one another through space and time have frustrated attempts to develop a predictive model for channel erosion (and hence sediment yield). The short time frame (2-100 years) of most channel stability studies emphasizes the intermittent or episodic nature of erosion. Hickin (1983), for example, considered river morphology at this time scale to be generally a non-equilibrium property and that the formative processes associated with equilibrium were more appropriate at a geomorphic time scale (100-100,000 years). Hence, the constraints of time may preclude the development of sophisticated process models that can predict rates and locations of bank erosion in river channels.

The dominant erosional processes operating in cobble-gravel rivers and morphologies (like many sections of the North Fork Flathead River) have been investigated by several workers (e.g., Church, 1983; Ferguson and Werritty, 1983; Nanson and Hickin, 1986; Desloges and Church, 1987). Church (1983) used aerial photography to investigate morphological change on the Bella Coola River in British Columbia, Canada, and concluded that this river has become more stable since the late nineteenth century. He attributed this partially to the exhaustion of neoglacial sediment supplies. Sediment was stored in the Bella Coola River in "sedimentation zones" which were areas of lateral instability. These zones were connected by stable, cobble paved "transport reaches". Ferguson and Werritty (1983) examined the River Feshie in Scotland, and documented five years of change through repetitive surveying and photography. The episodic advance of medial and lateral bars over one reach involved diagonal bar progradation with bank erosion opposite accreting bar margins.

Rivers like those discussed above and the North Fork Flathead River are classified as "wandering gravel bed rivers" (Neil, 1973). This term describes a river that is neither entirely meandering or braided, but rather one that exhibits a combination of these patterns. Stable, single thread channel reaches alternate with multi-thread laterally unstable sections. At higher discharges, avulsion and chute incision of point bars can transform single channels into multiple channel systems. Overall, sinuosity is less than that encountered for meandering rivers. This type of river is characterized by wide shallow channels developed in cobbles and gravels. These wandering gravel channels are common in upland areas and glaciated mountain valleys. Such rivers produce variable sediment supply which may require long periods of time in order to assess sediment production. This description of a "wandering gravel bed" is appropriate for the alluvial channels of the North Fork Flathead River, but does not address the influences of bedrock.

Another important factor in river morphology that influences bank stability is the bend curvature defined as the ratio of curvature radius to channel width (r/w). The radius of curvature is defined by the arc described along the center of the channel between points of inflection on the bend and the straight line distance between these points. The value for the curvature radius is the distance from its origin at the line between the inflection points to the center of the channel. In both closed pipes and open channels of uniform cross section, flow resistance is at a minimum when this ratio is between 2 & 3 (Bagnold, 1960). Field studies on floodplain alluvium by Hickin and Nanson (1975) and Nanson (1980b) indicated that channel areas with the highest migration rates were located on bends where r/w values were near 3. Begin's (1981) theoretical analysis of stream curvature and bank erosion based on the momentum equation of flow also found that channel migration was at a maximum for r/w values between 2 & 4.

Bank migration is also related to stream power. In their latest paper, Nanson and Hickin (1986) examined channel morphologies for different rivers over several decades, and concluded that the rate of channel migration was dependent on stream power (essentially the product of discharge and slope), channel width, bank height, radius of curvature, and the force per unit area of the outer bank which resists channel migration. This resisting force is a function of the size of the sediment at the base of the channel. Utilizing stepwise multiple regression analysis, they reported that the volumetric sediment erosion rate at the outer bank of a meander bend (bend curvature was held between 2 & 3) was dependent primarily on stream power and the grain size of sediment at the base of the outer bank.

Although many factors have been identified by numerous workers, it is still unclear which variables are most important in controlling the rate and location of streambank erosion. Extensive work by Hickin (1974, 1984, with Nanson 1975, 1984) and Nanson (1980a, 1980b, 1986, with Hickin 1983, 1986) on several rivers in British Columbia and Alberta, Canada, addresses this problem and generally integrates the results of streambank research to date. Overall, these studies indicate that streambank erosion is a function of the stream's sediment load and that prediction is primarily a sediment transport function, especially in wandering gravel bed rivers.

Description of Study Area

The North Fork of the Flathead River originates in the MacDonald and Clark ranges of British Columbia and flows 45 km before crossing south into Montana to form the western boundary of Glacier National Park (Figure 1). After crossing the Canadian border it flows for 93 km to reach its confluence with the Middle and South Forks of the Flathead River. The Middle and South Forks drain pristine watersheds within the Great Bear and Bob Marshall Wildernesses, respectively. The Flathead River then reaches a temporary base level at Flathead Lake south of Kalispell before flowing on to join the Clark Fork River and ultimately the waters of the Columbia River.

The North Fork watershed drains over 2903 km^2 (1,121 mi^2) with nearly 40 per cent of this area in British Columbia (Knapton, 1978). The river meanders and braids freely as a cobble-gravel alluvial channel from its headwaters to where Camas Creek emerges from Glacier Park. Above Camas Creek the river is locally contained by intermittent outcrops of Tertiary claystones and terraces of glacial outwash. Below Camas Creek the river has incised into Precambrian metasediments and its lateral movement is restrained (Dalby, 1983). The 55 km study area was located between the international border and Logging Creek which is upstream from Camas Creek. The length of the study area was defined by the overlap coverage of the aerial photography for the years 1945 and 1981.

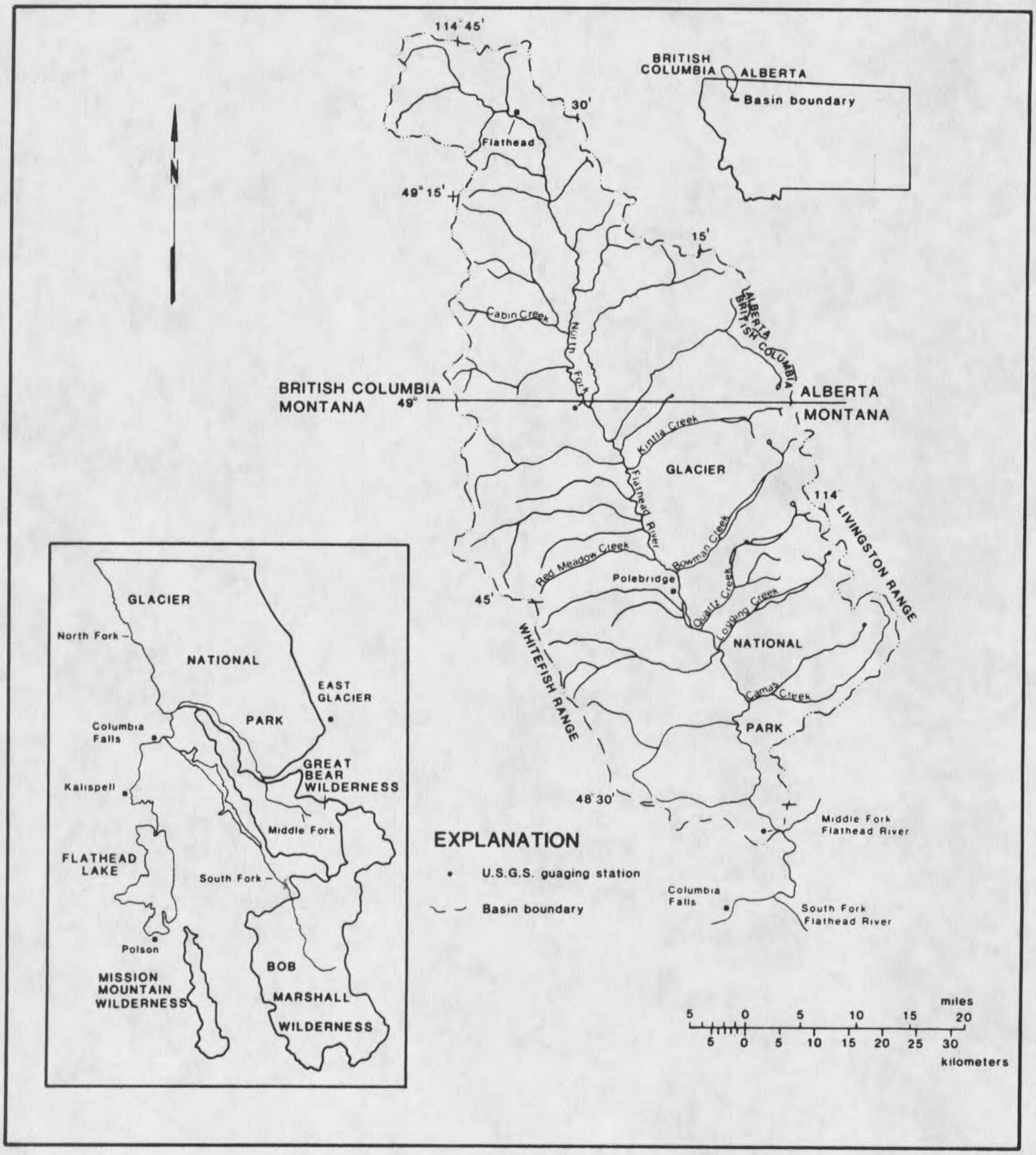

Figure 1. Location map showing study area, U.S.G.S. gaging stations, and wilderness setting of the Flathead River system.

The geology of the North Fork drainage area south of the Canadian border is dominated by the metamorphosed Precambrian sedimentary rocks of the Belt Super Group (Barnes, 1963). This group of formations consists of well consolidated argillites, siltites, quartzites, meta-dolomites and limestones. In addition, Paleozoic sandstones and limestones and Cretaceous sandstones and conglomerates outcrop in the northeastern end of the Whitefish Range within Montana (Constenius, 1982). Minor amounts of igneous rocks intrude the Precambrian sediments in the form of dikes and sills. Cenozoic sediments through which the river flows above Camas Creek are represented by both fine and coarse grained clastic rocks of the Tertiary Kishenehn Formation, Quaternary glacial materials and recent alluvial deposits.

The North Fork is located within a graben type structure called the Kishenehn Basin. This graben lies immediately west of the Lewis thrust salient and is a manifestation of structural features imparted during Laramide structural compression (Constenius, 1982). The basin was established during the late Paleocene or early Eocene by a reversal in the regional stress field from compression to extension (McMehan and Price, 1980). Extension occurred along structural weaknesses in the form of shear zones associated with the Lewis thrust. The Kishenehn Basin is bounded on the east by the southwest dipping Flathead-Roosevelt listric-normal-fault system. Cenozoic sedimentation filled the graben in the down dropped block (Constenius, 1982).

The present-day geomorphology has been described by Dalby (1983). He described the banks of various reaches of the North Fork as being stable, slightly unstable, moderately unstable, and highly unstable based on the degree of braiding and the presence of islands and mid-channel bars. His mapping also identified several erosional and depositional fluvial geomorphic features, such as major terraces, gravel bars and islands, eroding banks, major sediment sources, and bedrock.

Dalby (1983) identified three distinct reaches on the river south of the border. The upper 37 km (23 mile) and lower 31 km (19 mile) sections of the North Fork appear to be either in equilibrium or degrading very slowly (downcutting). The incision of the channel into Tertiary claystones in the upper section and downcutting through Precambrian metasediments in the lower section provided evidence for downcutting. A central 26 km (16 mile) section is primarily in a state of aggradation with highly braided, unstable channel reaches. This project examined the first 55 km south of the border which included Dalby's upper section and most of his central section.

Discharge and sediment yield data have been collected by the U.S. Geological Survey from the North Fork at the Canada-U.S. border since 1929 and near Columbia Falls, Montana since 1911 (Figure 1). During the past 25 years, North Fork streamflows have averaged 28 $m^3 \cdot s^{-1}$ (979 cfs) at the international boundary and 91 $m^3 \cdot s^{-1}$ (3,210 cfs) at the Columbia Falls station (Knapton, 1978). In June of 1964 the largest flood on record produced instantaneous peak flows of 462 $m^3 \cdot s^{-1}$ (16,300 cfs) at the Canadian border and 1,957 $m^3 \cdot s^{-1}$ (69,100 cfs) at its confluence with the Middle Fork. This event corresponded to the 50 year flood at the border and exceeded the 100 year flood at the downstream gaging site (Dalby, 1983). Mean annual suspended sediment loads for the border station are 119,730 tonnes per year ($t \cdot yr^{-1}$) (132,000 tons/yr) and

251,700 $t \cdot yr^{-1}$ (277,500 tons/yr) for the downstream station near Columbia Falls, Montana using the flow-duration sediment-transport-curve method and suspended-sediment data collected by the U.S. Geological Survey (1976-1977 water years) (Dalby, 1983). Nutrient loads for the North Fork are generally low except during periods of high flow. Nutrient loads for the mainstem Flathead River, which is the major tributary for Flathead Lake, may carry as much as 200 metric tons of phosphorus associated with sediment into the lake during spring runoff (Ellis and Stanford, 1988). Research by Knapton (1978) indicated that there was a close relationship between suspended sediment and phosphorus, and that nutrient transport was accomplished by sorption of nutrients onto clay particles.

Sediment yield from tributaries to the North Fork is influenced by lake storage and the level of human development within the tributary drainage. Numerous lakes along the east side of the river within Glacier National Park act as traps to store sediment. Consequently, these drainages yield less sediment than drainages without lakes. In general, the tributaries east of the river are primarily roadless, pristine watersheds protected by National Park status. The drainages west of the river lie within the Flathead National Forest and are utilized for logging in addition to recreation. Thus, the presence of roads and devegetation associated with logging characterize the tributaries west of the river.

The climate and weather patterns in the Flathead River Basin vary drastically over short distances and with changes in elevation. Total precipitation of 51 $cm \cdot yr^{-1}$ at Flathead Lake contrasts with totals in excess of 250 $cm \cdot yr^{-1}$ received by the mountains in the northwestern corner of Glacier National Park (Flathead River Basin Level B Study of Water and Related Impacts, 1976). The growing season also varies radically from 120-130 days in the valley near Kalispell to only 30 days a year in Polebridge, Montana. Storm fronts generally originate over the Pacific Ocean and approach from the northwest or west. The majority of precipitation arrives as snow between October and April. Spring rains and summer thunderstorms provide the remainder of the precipitation.

The multitude of climatic zones in the Flathead basin creates a variety of plant environments. Vegetation changes from grasses, sagebrush, and prickly pear cactus along Flathead Lake to forests of lodgepole pine, western larch, spruce, fir, and cedar adjacent to the North Fork. This abundance and variety of vegetation along the North Fork provides security and food for a diverse animal population.

Presently, large stands of lodgepole pine are being decimated by the mountain pine beetle and associated clearcutting of diseased trees. It is still unclear how this devegetation has affected the hydrology of the North Fork. Increased runoff due to decreased infiltration and evapotranspiration may accelerate streambank erosion through higher discharges and flashier regimes.

Thesis Organization

This introductory chapter has described the natural resources contained within the Flathead River Basin. Concerns about water quality, wildlife habitat, and preserving the overall natural character of the Flathead Basin have stimulated a variety of studies. Both natural and human actions can initiate change in a natural system and distinguishing their impacts is important for proper land management. In this instance, the influence of large floods and devegetation due to pine beetle epidemics on streambank erosion are difficult to decipher and are further complicated by the increasing impacts of people. This project quantified bank erosion without delineating numerically the various processes which influence it. Quantification of streambank erosion helps us to understand the magnitudes of channel change and provide insights about sediment transport and storage. Despite the constant state of flux within the natural system, the results of this project provide a starting point for differentiating sources of sediment yield and for future comparisons to other research which examines streambank erosion.

The second chapter describes the methods and data sources that were used to investigate streambank erosion along the North Fork Flathead River. Initial reconnaissance of the field area provided a reference for evaluating the aerial photography. Analysis of 1945 and 1981 aerial photographs, and field surveying of the streambank heights allowed for calculation of erosional volumes and weights. Through field studies and map analysis, geomorphic variables were measured and examined with regression analysis to assess their influence on bank erosion rates.

The third chapter examines the results of these measurements and describes channel changes which occurred between 1945 and 1981. This section reports both the qualitative and quantitative differences which were observed during this time period. The results of the computer regression analysis are used to illustrate the difficulty of identifying important geomorphic controls on rates of bank erosion.

The final chapter compares this project to others. Erosional volumes and masses are compared to sediment yield data for the North Fork system as reported by Dalby (1983). Migration rates, erosional volumes, and the results of the statistical analysis are then compared with findings from studies involving similar rivers in other parts of the world. The results of these comparisons lead, in turn, to several conclusions concerning sediment storage, changes in the North Fork's floodplain, and the concept of transport versus sedimentation reaches. The chapter concludes with several suggestions for future streambank erosion work along the North Fork Flathead River.

CHAPTER TWO

METHODS AND DATA SOURCES

Initial Reconnaissance

The up river (northern) end of the field area was accessed by driving 93 kilometers (58 miles) from Columbia Falls, Montana, along the west side of the river to the International border between Montana and British Columbia, Canada (Figure 1). The river can be seen from several points along this gravel road although the majority of its length is hidden by forest. The river can also be viewed at several places from a road along its east side within Glacier National Park. The field area was best accessed by floating through it on a rubber raft. The raft was equipped with a rowing frame so that several days worth of food and equipment could be packed. Trips several days long were the most practical logistically because of the field area's remoteness, and the ordeal and expense of shuttling vehicles.

Initial reconnaissance focused on the location, stratigraphy, and extent of the large cutbanks that occur along the river in the study area. Many of these large banks are located where the river cuts laterally against its older terrace. The stratigraphy of the large cutbanks is variable. At some locations Tertiary claystones are overlain by Quaternary age glacial-fluvial deposits. In other areas, cutbanks consist of only one of these units. The presence and extent of the Tertiary claystones was of interest because of the potential clays have for phosphorus adsorption. One consequence of streambank erosion is the possibility of nutrient enrichment from phosphorus-rich sediment and subsequent eutrophication downstream. Thirty four large cutbanks exist between the border and Logging Creek which enters approximately 55 river kilometers (34 miles) downstream from the border. These banks ranged from tens of meters to almost a kilometer in length, with heights up to 46 meters. In addition to the large cutbanks that suggested sediment input, numerous areas of actively eroding smaller streambanks were also located. The smaller banks consisted of 1-2 meters of alluvial sands and silts overlying gravels and cobbles.

The three units are easily distinguished in the field by the following lithologic characteristics (Figures 2 and 3). The Tertiary claystones are primarily light to dark grey, silty claystones. Occasionally the claystones were interbedded with dark brown, carbonaceous siltstones. A few cutbanks of claystones near the northern end of the field area showed some reddish-orange units. The glacial-fluvial materials are characterized by poorly to well sorted, semi-consolidated, sands, gravels, and cobbles. These materials cover the Tertiary claystones and a distinct contact between the glacial materials and claystones was often evidenced by seeps and springs. The floodplain alluvium is composed of unconsolidated sands and silts overlying gravels and cobbles. Once the erosional settings were differentiated both spatially and lithologically throughout the field area, areal photography was analyzed to document and quantify lateral river migration.

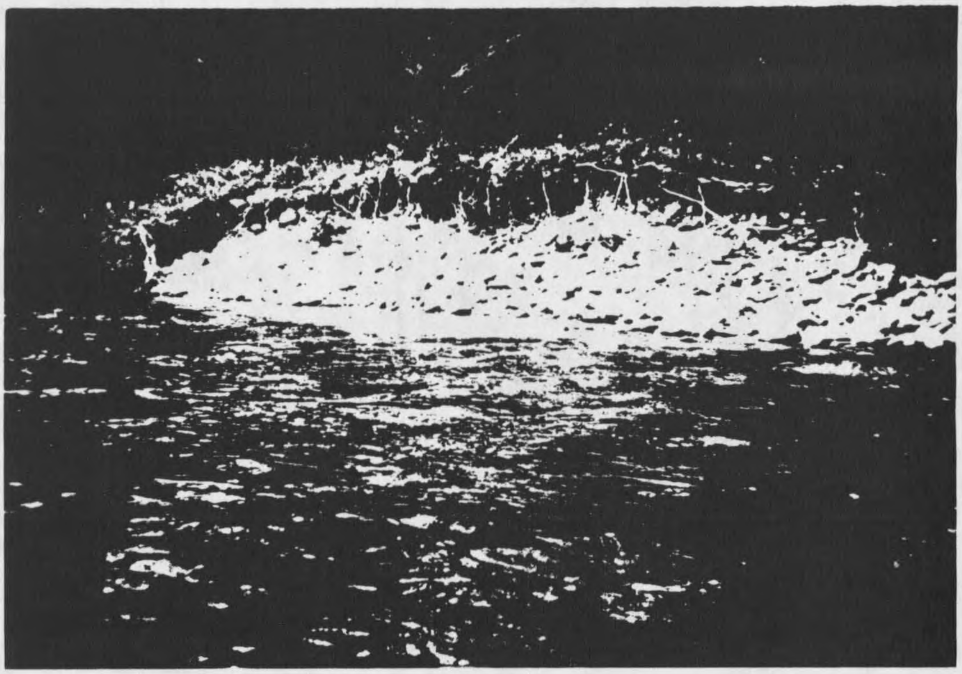

Figure 2. Typical streambank found along the North Fork Flathead River illustrating alluvial sands and silts overlying gravels and cobbles.

Figure 3. Typical cutbank along the North Fork Flathead River showing the Tertiary claystones in the lower bank overlain by Quaternary fluvial-glacial materials.

Aerial Photograph Analysis

Aerial photographic coverage of the North Fork of the Flathead River for the years 1945 and 1981 was examined, so that the study examined erosion which occurred over a 36 year timeframe. The 1945 photographs were the oldest photographs available and were obtained from the National Archives in Washington, D.C. The 1981 photographs were obtained from the United States Department of Agriculture (USDA). The 1981 set was chosen because of availability and similarity of coverage to the 1945 photographs. Both the 1945 and 1981 photographs were taken in August and reflect approximately similar river discharges. Discharges for the North Fork at the border and the downstream gaging station for August 1945 were $8 \cdot m^3\ s^{-1}$ ($284\ ft^3 \cdot s^{-1}$) and $31\ m^3 \cdot s^{-1}$ ($1084\ ft^3 \cdot s^{-1}$), respectively. Average discharges for the same stations in August 1981 were $11\ m^3 \cdot s^{-1}$ ($407\ ft^3 \cdot s^{-1}$) and $50\ m^3 \cdot s^{-1}$ ($1775\ ft^3 \cdot s^{-1}$), respectively. The photographs were used to trace the active floodplain for each time frame, and these tracings were then superimposed to locate and measure lateral erosional change. Once the erosional areas were determined, then field inspection and surveying could proceed to obtain the heights of these areas for volume calculations.

The scales of the 1945 and 1981 photographs were 1:25,800 and 1:24,000, respectively. A Saltzman projector was used to enlarge the photographs and trace maps at a common scale of 1:6,850. The technique involved the enlargement and tracing of a section of the 1981 river and then registration of the 1945 river section to this overlay. Registration was accomplished using cultural features, such as roads and houses, and some natural features that showed little change over this time span. The natural features that were used included meadows, ponds, and the edges of river terraces. However, registration using natural features was difficult because of boundary definition and subtle morphologic changes through time. This approach was utilized only where cultural features were absent on the 1945 photographs. The photos were enlarged so that the edges of the active floodplain could more easily be defined and to provide better resolution for the tracings.

The following description of criteria for defining the active floodplain is essential for understanding how the erosional area maps (Appendix A) were constructed. The floodplain is the flat area adjoining the channel constructed by the river in the present climate and overflowed at times of high discharge (Dunne and Leopold, 1978). The floodplain is primarily a depositional feature formed from a combination of within channel (point bar accretion) and overbank deposition (Lewin, 1978). However, when major floods have a low sediment content erosion (scouring) may occur upon the floodplain (Burkham, 1972). The edge of the active floodplain corresponds to the boundary of recently transported fluvial sediment. In this study, the bank represented the edge of the active floodplain for areas where channel banks were well defined. The boundary in areas lacking well defined banks was defined by the lateral distribution of un-vegetated bed sediment. Thus, this study defined the active floodplain by channel banks, the presence of flood debris, and the absence of vegetation (trees and shrubs). In contrast to the active floodplain, the non-active or abandoned floodplain is an area no longer under construction and is termed a terrace (Dunne and Leopold, 1978).

Once the tracings were constructed, the 1981 results were superimposed on the 1945 results to locate erosional areas. These erosional areas were then traced so they could be measured. Additional tracings were then made in order to establish high and low estimates (and margins of error) for areas of change. A line 2 mm inside the area which paralleled the perimeter of the area produced the low estimate. The high estimate was developed in a similar fashion with a line drawn 2 mm outside the original and parallel to its perimeter. One millimeter represented 6.8 m at the scale used. These high and low areal estimates were produced to indicate the probable minimum extent of errors that might have resulted from inadequacies arising from the width of the pen trace, pen wiggle, photograph registration, and misinterpretation of the floodplain edge. Two millimeters was the estimated cumulative error for these inadequacies, the majority of which arose from photograph registration. In these ways, low, medium ("best"), and high areal estimates were produced for each of the 174 alluvial streambanks and 34 cutbanks that were identified.

The erosional areas were measured using a Measuronics Linear Distance Measurer. This device utilizes a camera that projects an image onto a computer screen. Areas are measured by digitizing chosen polygons. This technique provided consistency in measuring the 624 erosional areas identified in this study and avoided having to retrace the polygons. Hence, this procedure also eliminated additional error that might otherwise have arisen from the retracing of the erosional areas with a planimeter.

Field Surveying

After the erosional areas were identified and calculated, the bank heights were measured in the field so that volume calculations could be made. Bank heights were measured after peak runoff during July and early August. The heights of the smaller streambanks were measured directly with either a tape or stadia rod within ± 0.3 m. The large cutbanks were surveyed with transits within ± 0.3 m as well. Since the heights of these erosional areas varied spatially the recorded data for the cutbanks represented the greatest height observed.

Initial field work to obtain height data focused on the small alluvial streambanks. Many of these streambanks were of considerable length, and varied in height, so a visual estimate of height was chosen that best represented each streambank. Alluvial streambank heights varied between 0.3 and 2.2 m with most streambanks being in the 1.0-1.3 m range. The 0.3 m streambanks were located where the river had braided into several small meandering channels off the main channel. The streambanks were located where the vertical bank intersected a break in slope and no consideration was given to the depth of the thalweg. Measurement of the heights of the banks in relation to the depth of the thalweg was not possible because river stage and flow velocities prohibited wading. Most of the 174 alluvial streambanks were examined in the field except for areas where the river was highly braided. The heights in the braided sections were arbitrarily assigned a height of 0.3 m.

After the height data had been collected for the small streambanks, surveying equipment was utilized to measure the heights of the large