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
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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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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

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.

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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.

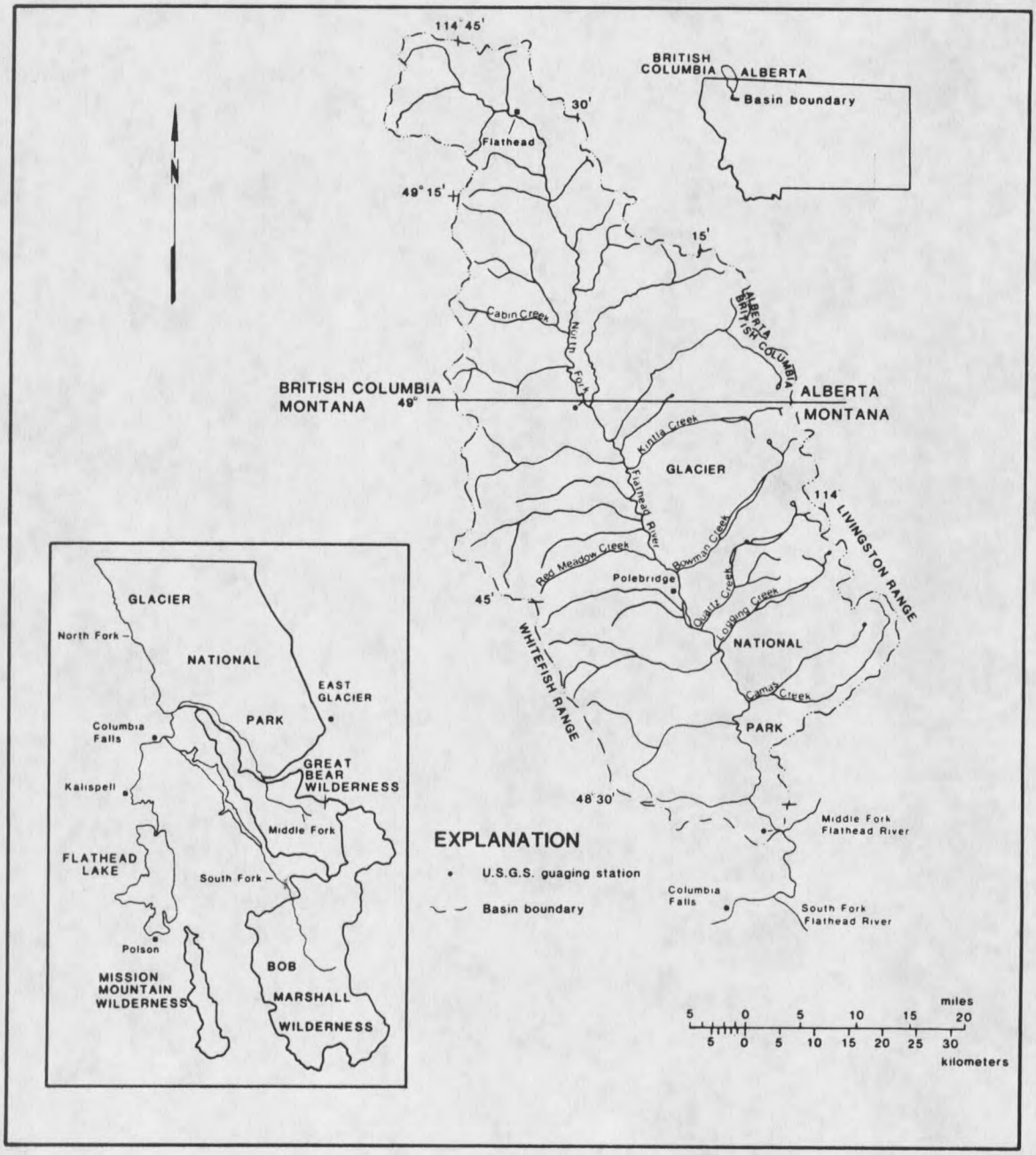

Figure 1. Location map showing study area, U.S.G.S. gaging stations, and wilderness setting of the Flathead River system.

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.

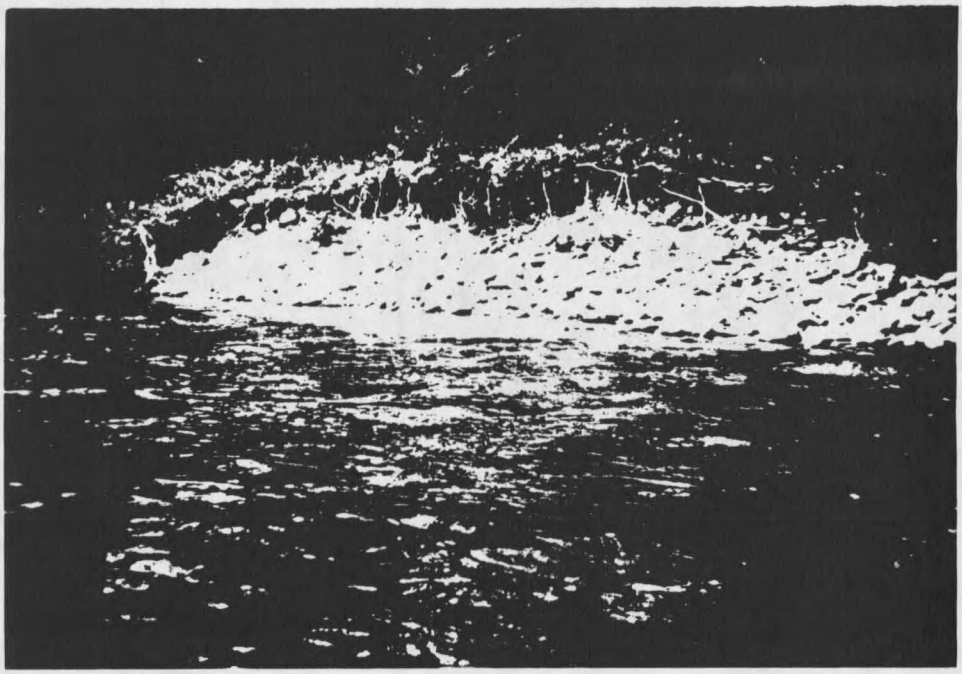

Figure 2. Typical streambank found along the North Fork Flathead River illustrating alluvial sands and silts overlying gravels and cobbles.

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 $m^3 \cdot s^{-1}$ (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

cutbanks. Vertical heights for both the Tertiary Kishenehn Formation claystones and Quaternary glacial sediments were measured at each cutbank, so that erosional volumes could be calculated for both units. The visually estimated maximum height was selected for measurement on each bank. Two transits were used to make the measurement because it was impossible to measure the horizontal distances across the river to the base of the cutbanks. In addition, it was generally not physically possible to climb these large cutbanks to measure the slope distance of the units, and then recalculate their vertical thicknesses.

The heights of the cutbanks were measured by setting up two transits a known distance apart on the point bar across from the cutbank of interest (Figure 4). Instrument heights for each transit were measured from a common point at the waters' edge. The transits were used to swing interior angles to a common point at the contact or the top of the unit in question. The lengths of the sides were computed once the angles were measured for this horizontal triangle, and the height of the unit was then calculated using the measured vertical angles. Each transit was used independently to calculate the height of the unit in question, so that each height was cross-checked and verified. These measurements were repeated unless the two heights varied by less than ± 0.3 m. These heights were then averaged to produce the height estimates reported here. The base of the cutbank was considered to be at the waters' edge because measurement from the thalweg channel bottom was not practical. The waters' edge was considered useful as a base because the river stage approximated mid-summer flow which was similar to the flows recorded on both sets of aerial

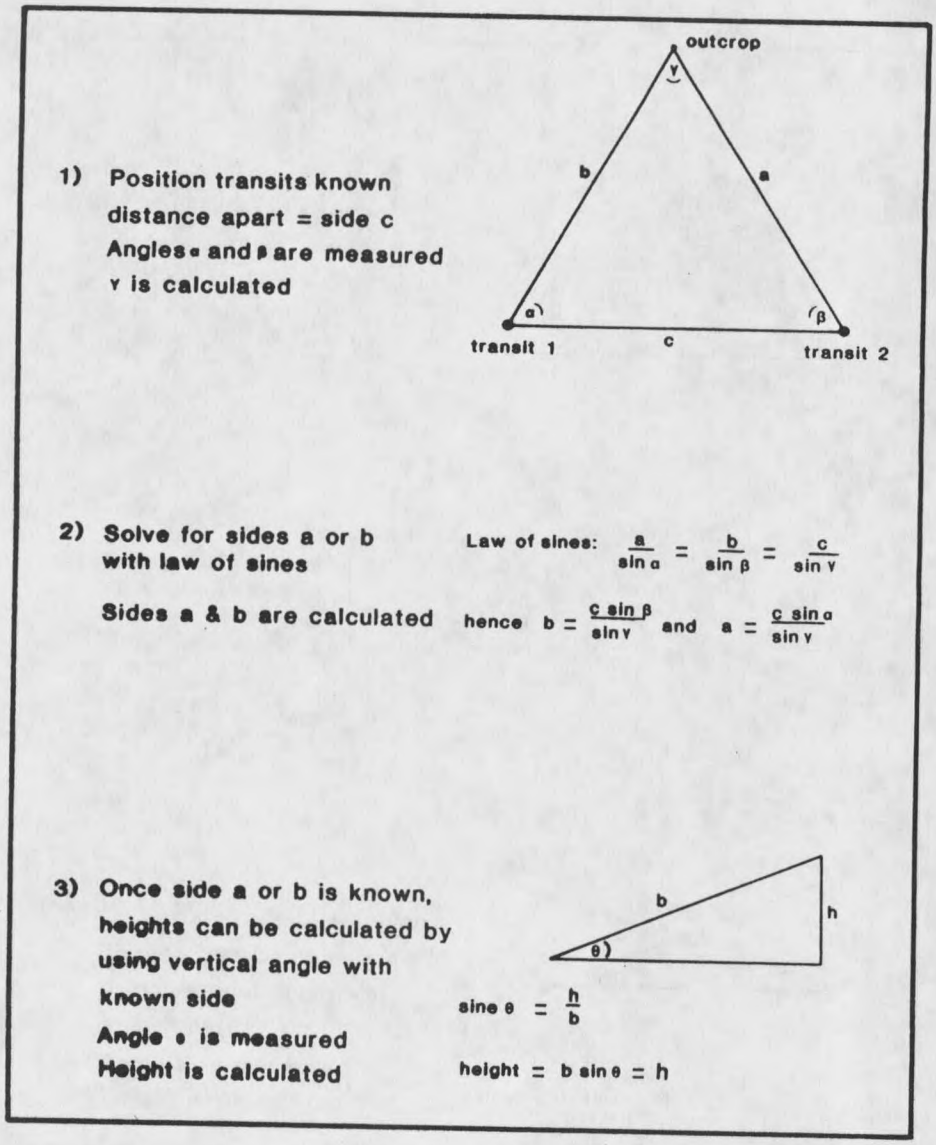

Figure 4. Diagram showing transit set up and calculations for estimating bank heights.

photographs. Surveying from established bench marks was not necessary because the cutbanks varied spatially in height and the objective with generating these measurements was to estimate erosional volumes.

Measuring the "best" (most representative) and maximum heights for the 174 streambanks and 34 cutbanks, respectively, reflects the time expended on this part of the project and the character of the banks

themselves. The alluvial streambanks did not vary much in terms of height, making the choice of the "best" (most representative) height for measurement relatively straightforward. The highly irregular topography and slopes of the cutbanks, on the other hand, meant that five or more height measurements per cutbank would have been required to match the precision and accuracy achieved with the heights of the alluvial streambanks. The maximum cutbank heights were measured to ensure reproducibility within the time and manpower constraints affecting this project. The general approaches outlined here were varied in three situations (cutbanks 1, 8, and 11) where two or more representative heights were attributed to long stretches of bank. Single measurements were made for each section, and these measurements were then weighted according to river length, to produce weighted averages for these banks.

Calculation of Erosional Volumes and Masses

The erosional areas and heights were computed on Montana State University's Honeywell CP6 mainframe computer system utilizing the "SPSSX" software package (SPSS Inc.,1986). Programs were written with this package and used to calculate the erosional volumes and weights for each erosional area. These programs calculated sediment masses at each site by multiplying the erosional area (m^2) by its height (m) by an estimate of the sediment's density ($t \cdot m^{-3}$). The average bulk densities for dry sediment reported by Telford et al. (1976) for alluvium, sand, and clay were used to transform volumes to masses. This meant that bulk densities of 1.54 $g \cdot cm^{-3}$ (tonnes$\cdot m^{-3}$) for alluvium, 1.60 $g \cdot cm^{-3}$ for sand, and 1.70 $g \cdot cm^{-3}$ for claystones were used for the erosional

materials in this study area. The SPSSX programs also calculated erosional volumes and masses for alluvium, Tertiary claystones, and Quaternary glacial sediments for each river reach and totals for the entire study area separately. A river reach in this study was one river mile and reach numbers corresponded to maps of the river constructed in 1935 by the United States Army Corps of Engineers (United States Army Corps of Engineers, 1935).

Measurement and Analysis of Erosional Controls

Several variables were measured or estimated so an attempt could be made to identify the most significant factors contributing to erosion at each site. The variables that were examined in this study fall into three general categories -- geomorphic, hydrologic, and sedimentological -- and their measurement and estimation are discussed in that order (Table 1). The variables marked with an asterisk in Table 1 were measured or estimated for each of the 208 erosional sites identified in the study area. Once these values were generated they were compiled into a computer data base so that they could be statistically analyzed with a SPSSX stepwise multiple regression program written for this part of the analysis. Erosional volumes and total migration were treated separately as the dependent variable and the three categories of variables listed in Table 1 were treated as the independent variables for this analysis. Several additional comments about the measurement and estimation of values for these variables are warranted.

The active floodplain width was measured every 50 m throughout the length of the study area. The width for each erosional site or bank was

Table 1. Definitions for erosional controls examined in this study.

Variable	Definition
Geomorphic Variable	
Active floodplain width*	located by channel banks, vegetation lines, and flood debris - denotes present floodplain under construction
Channel width	denotes bankfull discharge, varies with discharge magnitudes
Reach sinuosity*	reach length along center of active floodplain/straight-line valley length
Bend sinuosity*	reach length along center of active floodplain adjacent to erosional area/ straight line distance between bank ends
Bend radius	length of radial line determined by constructing a circle which overlays the arc inscribed along the center of the channel and terminates at the inflection points of the bend
Bend curvature	ratio of bend width to channel width (r/w)
Hydrologic Variable	
Discharge*	represents additional flow between the border and Columbia Falls gaging stations. Calculated by using the difference in average flows between the two stations times the ratio of contributing tributary area to total area between stations
Gradient*	local channel gradients near streambanks measured from longitudinal profile produced by 1935 Army Corps of Engineers study
Stream power*	product of gradient and discharge
Sedimentological Variable	
Sediment type*	type of lower bank material (glacial, claystones, or alluvium)

* Denotes variables incorporated in multiple stepwise regression tried in this study.

calculated by averaging the widths that were measured for each site. Active floodplain widths ranged from 14 to 214 m with an average width being 64 m. The active floodplain width was used instead of the channel width because numerous erosional areas were located along the edges of the floodplain. In addition, aerial photograph tracings were constructed for the active floodplain because differences in discharge between the two sets of photographs would generate different channel widths.

The other geomorphic variables measured were reach and bend sinuosities. The reach sinuosities were calculated by measuring the straight line distance between the ends of each reach and the length along the center of the 1945 active floodplain. The latter length was then divided by the straight line distance to determine the sinuosity for one river mile. A sinuosity value was thus generated for 34 reaches. Sinuosity was also measured for each of the 208 erosional areas within the study area. Sinuosities were determined by measuring the straight line and center of the active floodplain distance from points at the upper (north) and lower (south) ends of each bank. These points were located by drawing a line across and perpendicular to the sides of the 1945 active floodplain trace at the ends of each bank. Sinuosities were computed between each pair of lines. The sinuosity value for each streambank and cutbank is the quotient of the floodplain length (based upon the centers) and the straight-line valley length. Bend radius was examined but not utilized in this study. Several studies have mentioned this variable (Bagnold, 1960; Leopold and Wolman, 1960; Begin, 1981), although only two have proposed objective methods

for measuring it (Nanson and Hickin, 1983; O'Neill and Abrahams, 1985). The problem is largely a function of operator bias associated with determining points of inflection for the bend in question. This problem is especially acute and difficult to overcome in rivers like the North Fork Flathead River with highly variable channel patterns (Appendix A).

The hydrologic variables considered were discharge, gradient, and stream power. Discharge was estimated by utilizing the mean annual discharges that cross the Canadian-U.S. border and those measured at the Columbia Falls station approximately 16 km downstream from Logging Creek for the period between 1929 and 1981. In order to avoid using a linear relationship for increasing discharge downstream, the areas of the various contributing tributaries were measured. These areas were then divided by the entire area of drainage contribution to the study area. Each fraction of drainage contribution was then multiplied by the difference between the discharge at the Columbia Falls station and the discharge at the Canadian-U.S. border. The advantage of weighting discharge by tributary drainage area is that downstream changes in discharge can be estimated for numerous locations along ungaged river sections. Though prevailing weather patterns, slope, aspect, lake storage, and other factors influence runoff within a drainage basin the weighted discharge method is a better first approximation than using a linear relationship. In particular, it attributes most of the discharge to the largest tributaries and therefore provides for variable additions at different locations along the North Fork.

River channel gradients were measured at each streambank or cutbank using the longitudinal profiles produced by the United States

Army Corps of Engineers in their 1935 survey of the North Fork Flathead River valley. Each gradient was calculated by finding the vertical change and dividing by the 1935 channel length. The channel length was determined by measuring an equal distance up and down river of where the erosional area fell on the longitudinal profile and the vertical change was calculated over this distance. Thus, a gradient was measured adjacent to each erosional area. Once the discharge and gradient were measured, stream power was calculated by multiplying these two variables together. Stream power, as originally defined, is the product of water density, the gravitational constant, discharge, and water slope (Bagnold, 1977). The product of the first two variables is the specific weight of water and can be ignored because they remain nearly constant for all stream power calculations and are relatively unimportant for purposes of comparison (Nanson and Hickin, 1986).

The sedimentological variables are represented by three types of lower bank materials. These sediment types -- Tertiary claystones, Quaternary glacial-fluvial sediments, and Recent floodplain alluvium-- were observed in the field.

Multiple Regression of Erosional Variables

A stepwise multiple regression or multivariate analysis allows several independent variables to be statistically tested to determine whether they are related to a dependent variable. The purpose of this analysis was to investigate which independent variables have the greatest impact on either channel migration or erosional volumes. The dependent variables that were examined included the low, medium, and

high eroded-sediment volume estimates and channel migration distances for each streambank and cutbank. Erosional areas located within the center of the active floodplain along braided sections of the river where channel migration distance could not be measured were excluded from the analysis involving migration distance as the dependent variable. The active floodplain width, reach and bend sinuosity, discharge, stream-bed gradient, stream power, and type of sediment at river level were tried as independent variables (Table 1).

The dependent variables were separately regressed against the independent variables for a variety of data sets. One regression examined all of the streambanks and cutbanks throughout the entire study area. Other sets investigated the 174 alluvial streambanks and 29 cutbanks of claystones over the 55 km study area separately. The 5 cutbanks with glacial materials in the lower bank were not examined separately due to their small sample number. This small number (n=5) is less than the recommended sample size (n>30) for statistical tests (Clark and Hosking, 1986). Finally, regressions were run for all the streambanks and cutbanks comprising the upper, middle, and lower thirds of the study area separately. The study area was divided into three sections as follows -- reaches 104-113, reaches 92-103, and reaches 80-91 -- for this part of the analysis.

The multiple regression in SPSSX operates by determining whether or not any independent variables are statistically correlated with the chosen dependent variable. The program first selects the independent variable which displays the greatest correlation with the dependent variable and quantifies its contribution as a percentage. It then

selects other independent variables and adds their correlations if these variables satisfy specific criteria related to the F statistic.

The F statistic tests how well the regression model fits the data through an analysis of variance. The F statistic is the ratio of the mean square regression to the mean square residual distributed with (p) and (N - p - 1) degrees of freedom within the numerator and denominator, respectively. A variable enters the equation only if the probability associated with the F test is less than or equal to the .05 default (SPSS Inc., 1986).

If the first variable meets this criterion then the second variable is selected based on its highest partial correlation coefficient. If the second variable passes the entry criterion it enters the regression equation. At this point, the first variable is examined to see if it should be removed according to the .10 removal criterion. The enter criterion must be less than the removal criterion to prevent the same variable from being repeatedly entered and removed. After each step in the multiple regression, variables already entered are examined for removal. The program stops selecting variables when no additional variables satisfy the entry and removal criteria (SPSS Inc., 1986).

The multiple correlation coefficient, R, describes the goodness of fit of the regression line to the data points in multiple regression, similar to the simple correlation coefficient (r) in bivariate regression. The R value is therefore a correlation between the observed value for the dependent variable and the predicted value from the least squares surface. Unlike the simple bivariate correlation coefficient, r, which shows the direction of the relationship between two variables

by its sign (positive or negative), R ranges from 0 to +1 (Clark and Hosking, 1986). The value R represents: (the proportion explained by X_1 and X_2) = (proportion explained by X_1) + (additional potential proportion explained by X_2) x (proportion not explained by X_1). R^2 is given by $R^2_{y12} = r^2_{y1} + r^2_{y2.1} \times (1-r^2_{y1})$. The increase in magnitude of R is in part dependent on the interrelatedness of the independent variables. If intercorrelations amongst the variables are quite high, R will not increase much with each additional variable. Independent variables that are less related will likely increase R significantly (Clark and Hosking, 1986).

A measure of the goodness of fit of a linear model is a statistic called the coefficient of determination or R^2. In addition to being the square of the correlation coefficient between the variables x and y, it is the square of the correlation coefficient between the observed value of the independent variable and the predicted value of this variable from the fitted line. If all the observations fall on the regression line then $R^2 = 1$. A zero value for R^2 indicates that there is no linear relationship between the dependent and independent variables, although a nonlinear relationship is still possible.

The sample R^2 is generally an optimistic estimate of how well the model fits the population, because the model usually does not fit the population as well as it fits the sample. The adjusted R^2 statistic is adjusted for the number of independent variables in the regression and the sample size. The adjusted R^2 attempts to correct R^2 to more closely describe the goodness of fit of the model to the population.

CHAPTER 3

RESULTS

Introduction

The initial focus of this study was to examine streambank erosion solely at the large cutbanks of claystones and glacial materials. A number of these prominent banks were thought to be major sediment sources for the North Fork (Dalby, 1983) and thus the primary objective was to quantify erosion in these areas. Initial reconnaissance of the field area and inspection of the aerial photographs showed that significant lateral erosion had also occurred at numerous places in floodplain alluvium. Consequently, erosional areas were identified and measured at streambanks composed of claystones, glacial-fluvial materials, and floodplain alluvium. Qualitative and quantitative assessments of bank erosion in all three types of environments are provided in this chapter.

Qualitative Assessment of Bank Erosion

A variety of erosional processes contribute to the degradation and migration of streambanks and cutbanks along the North Fork. Processes of fluvial erosion resulting from the river include corrasion, shear, and undercutting with associated collapse. Rilling and gullying as a consequence of overland flow and sapping are additional processes which contribute to bank erosion. The most prevalent sediment delivery

process observed by the author at the cutbanks was slumping, which at many locations, appeared to have been initiated by sapping.

Sapping, with associated mass wasting and erosion, is produced where precipitation infiltrates through the permeable glacial sands and gravels, and emerges at the contact of the impermeable claystones. Numerous springs and seeps are located at this contact along many of the cutbanks. These springs eventually erode headward producing large amphitheater shaped bowls in the glacial materials. Large slump features are located within many of these bowls. This sapping also leads to gullying of the claystones at several sites. At some cutbanks slumping occurs in the Tertiary claystones. The infiltrating water saturates the claystones which leads to slumping as a result of increased pore pressure and weight. Mass wasting and sapping are thus important mechanisms for sediment delivery to the river from banks of both unconsolidated sands and gravels and lithified clay sediments. Fluvial action acts to entrain and remove eroded material at these large banks although mass wasting and overland flow are initially responsible for bank erosion. As a result, processes not related to river morphology and hydraulics appear to strongly influence sediment delivery to the stream from the cutbanks of glacial materials and claystones.

Erosion by both corrasion, shear, undercutting, and collapse appeared to be the primary mechanisms for lateral migration within the smaller banks of floodplain alluvium. Throughout the study area 1 m high banks of alluvial silts, sands, and gravels were observed to be eroded by these processes. Extensive root systems of trees, shrubs, and grasses appeared to have little effect in stopping erosion at these

sites once they are undercut. Collapse, as a consequence of undercutting, was observed to have taken place in the spring shortly after peak runoff. Falling river stage exposes saturated banks that are more susceptible to collapse from undercutting in contrast to more stable dry banks found at other times of the year. Erosion at the smaller alluvial banks is most influenced by bank moisture resulting from river stage rather than infiltration. The small streambanks composed of floodplain alluvium are subject to yearly inundation, and thus river morphology and hydraulics appear to be important factors influencing erosion along the smaller banks of alluvium.

Quantitative Assessment of Bank Erosion

Quantification of erosional volumes for each area of migration revealed total volumes of sediment eroded within the study area, amounts of sediment yielded from each of the three streambank materials, and erosional differences between reaches. In order to compare these results to sediment yield data compiled by the United States Geological Survey (U.S.G.S.), volumes of sediment were converted to masses of sediment. Migration rates for each of the three streambank materials were then computed for comparison amongst each other and for comparison with other studies.

Total Erosional Volumes and Masses

The unit which produced the greatest erosional volumes was the Quaternary glacial sediments followed by floodplain alluvium and Tertiary claystones (Figure 5). This result occurred despite the greater spatial distribution of erosional input from floodplain

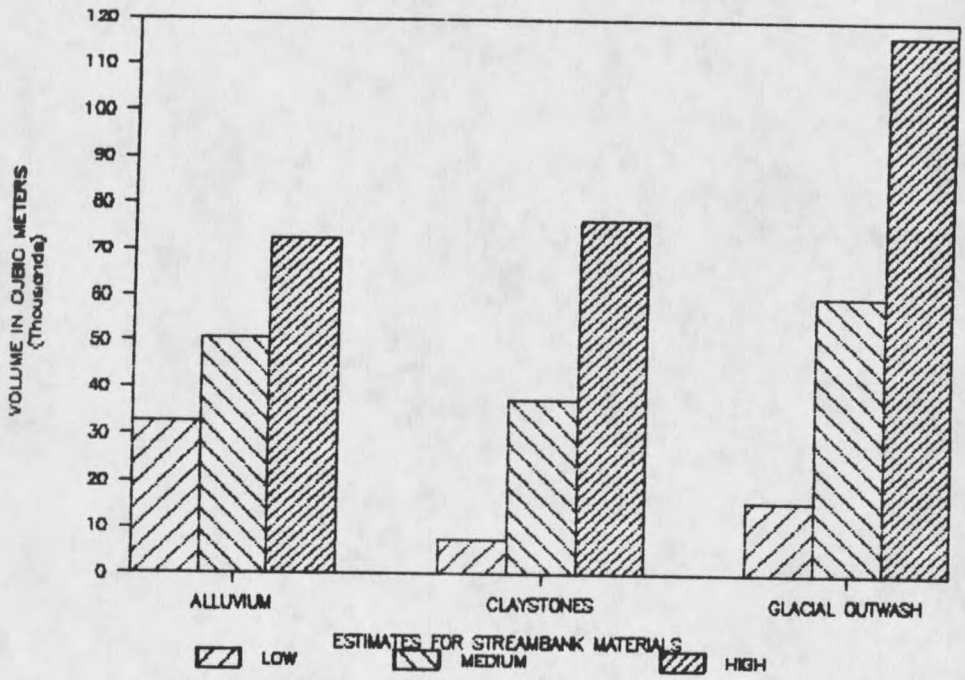

Figure 5. Low, medium, and high estimates of average annual erosional volumes input from the three bank materials for 55 kilometers (34 miles) of river.

alluvium. The medium erosional volume estimates ranged from 59,800 $m^3 \cdot yr^{-1}$ for the glacial materials to 50,600 $m^3 \cdot yr^{-1}$ for floodplain alluvium, and 37,300 $m^3 \cdot yr^{-1}$ for the claystones. The range between low and high volume estimates for the three materials were as follows: alluvial materials -- 32,600 to 72,300 $m^3 \cdot yr^{-1}$, claystones -- 7,500 to 76,500 $m^3 \cdot yr^{-1}$, and glacial materials -- 15,900 to 117,000 $m^3 \cdot yr^{-1}$. Low, medium, and high volume estimates were generated for each streambank material to assess the sensitivity of the results to map location errors, as discussed in Chapter 2. Volume estimates for the glacial materials and claystones are very sensitive to floodplain definition because of the greater heights of these units.

The volumes were combined with dry bulk densities to compute the

masses of sediment contributed from the three different types of materials (see Chapter 2). The medium estimates for erosional masses are 77,900 $t \cdot yr^{-1}$ (tonnes$\cdot yr^{-1}$) for floodplain alluvium, 63,500 $t \cdot yr^{-1}$ for the claystones, and 95,700 $t \cdot yr^{-1}$ for the glacial outwash (Figure 6). The low and high mass estimates ranged from 50,200 to 111,400 $t \cdot yr^{-1}$ for alluvium, 12,800 to 130,000 $t \cdot yr^{-1}$ for claystones, and from 25,400 to 186,400 $t \cdot yr^{-1}$ for glacial outwash.

Once average erosional volumes and masses were estimated for each of the three streambank materials, the values were summed to obtain average erosional volumes and masses for the combination of all sediment types (Figure 7). Annual average erosional volumes for all sediment types ranged from a low estimate of 56,000 $m^3 \cdot yr^{-1}$ to a high estimate of 265,800 $m^3 \cdot yr^{-1}$. The medium and preferred estimate was 147,700 $m^3 \cdot yr^{-1}$. Annual average erosional masses ranged from a low estimate of 88,400 $t \cdot yr^{-1}$ to a high estimate of 427,800 $t \cdot yr^{-1}$ with a medium estimate of 237,100 $t \cdot yr^{-1}$ (Figure 7). The estimates reported in Figures 4 through 7 represent the average annual amounts of streambank erosion during a 36 year period along 55 km (34 miles) of river. Total erosional volumes were calculated by reach for each of the different streambank materials. Figure 8 illustrates total volumes of floodplain alluvium eroded for each reach over the 36 year period. Reaches 103-105 showed very little erosion of alluvium because seven of the 34 large cutbanks exist along this 3 mile (5 km) stretch of the river.

Total erosional volumes were calculated by reach for each of the different streambank materials (Appendix B). Figure 8 illustrates total volumes of floodplain alluvium eroded for each reach over the 36 year

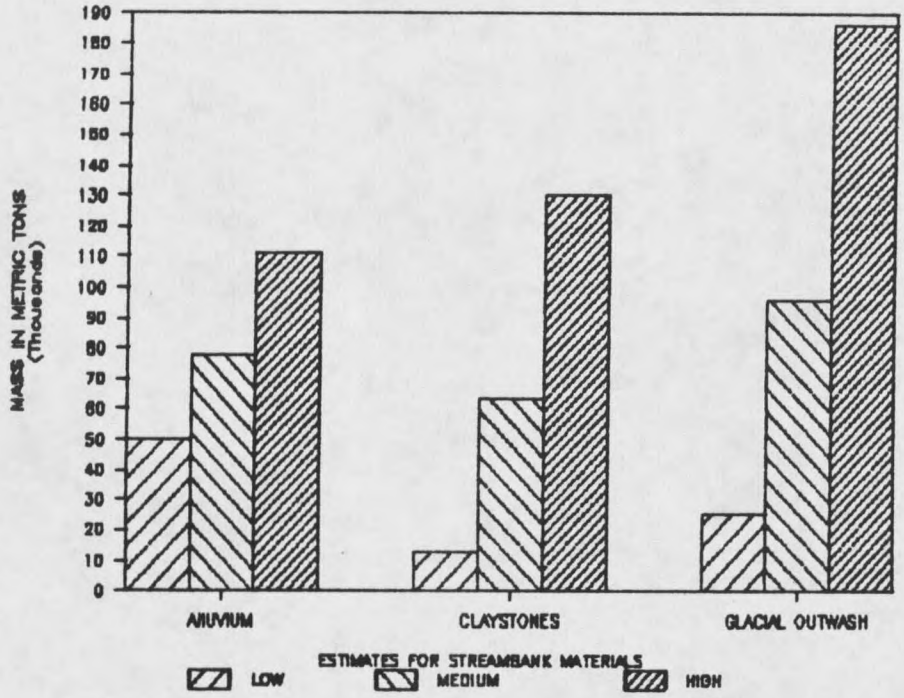

Figure 6. Low, medium, and high average estimates of erosional masses input from the three bank materials between 1945 and 1981.

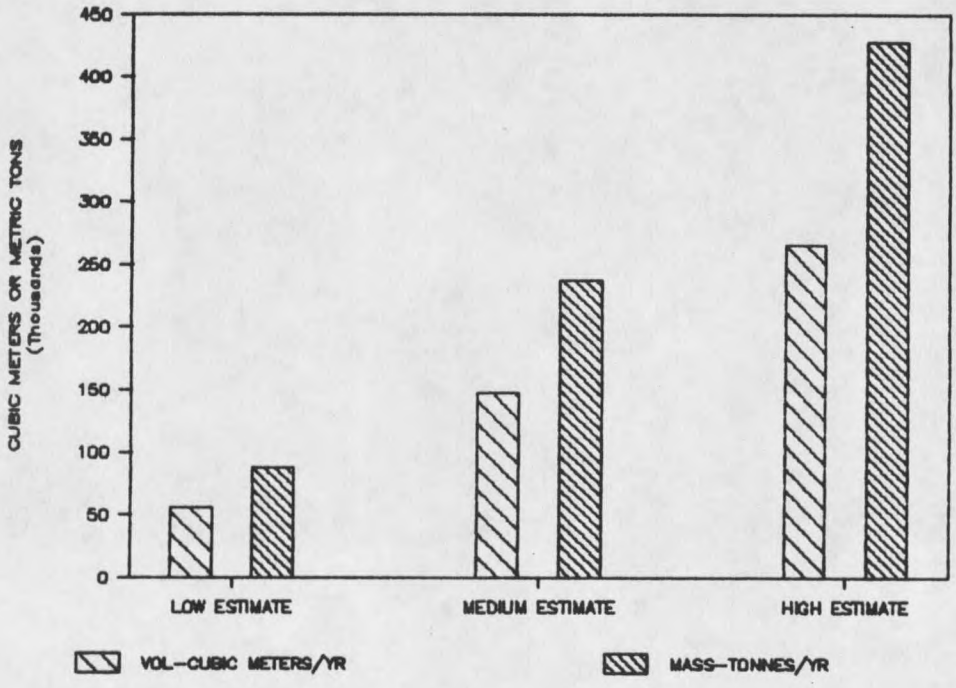

Figure 7. Low, medium and high estimates of the average erosional volumes and masses produced by bank erosion between 1945 and 1981.

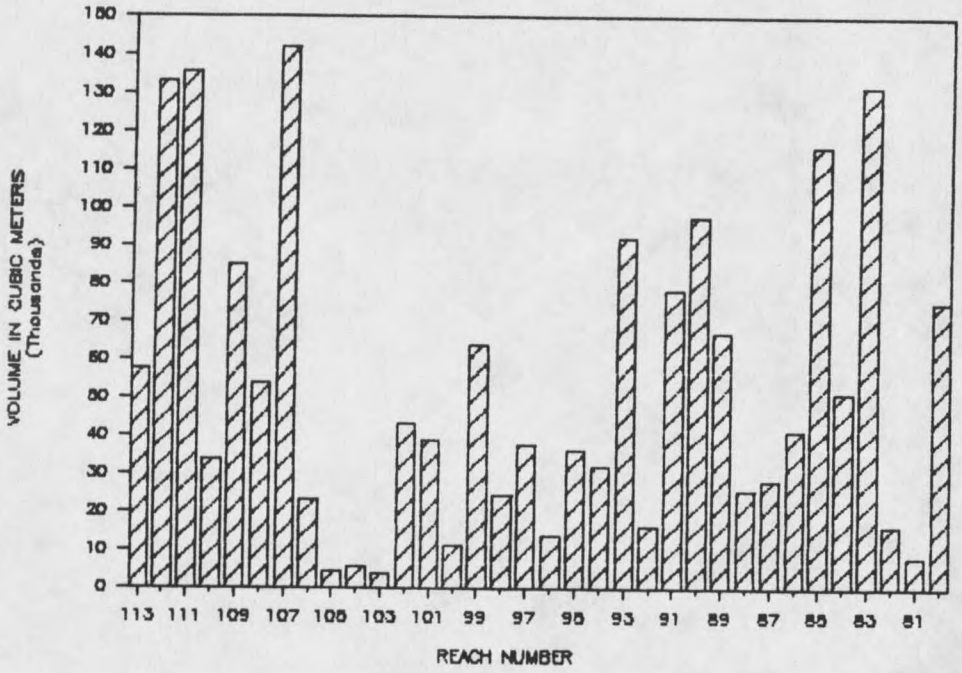

Figure 8. Total erosional volumes of floodplain alluvium contributed by river reach between 1945 and 1981 (medium estimate).

period. Reaches 103-105 showed very little erosion of alluvium because seven of the 34 large cutbanks exist along this 3 mile (5 km) stretch of the river. Reach 81 also was a small contributor of alluvium because of the presence of a large cutbank. Figure 8 shows that erosion of alluvial streambanks occurred throughout the field area and that alluvium was contributed from all 34 reaches within the study area.

Figures 9 and 10 illustrate erosional volumes by reach for the Quaternary glacial sediments and the Tertiary claystones, respectively. Erosional input from these materials was not as evenly distributed as the alluvium. The glacial sediments and claystones are located where the North Fork cuts laterally into older terraces and/or incises vertically into lithified Tertiary sediments.

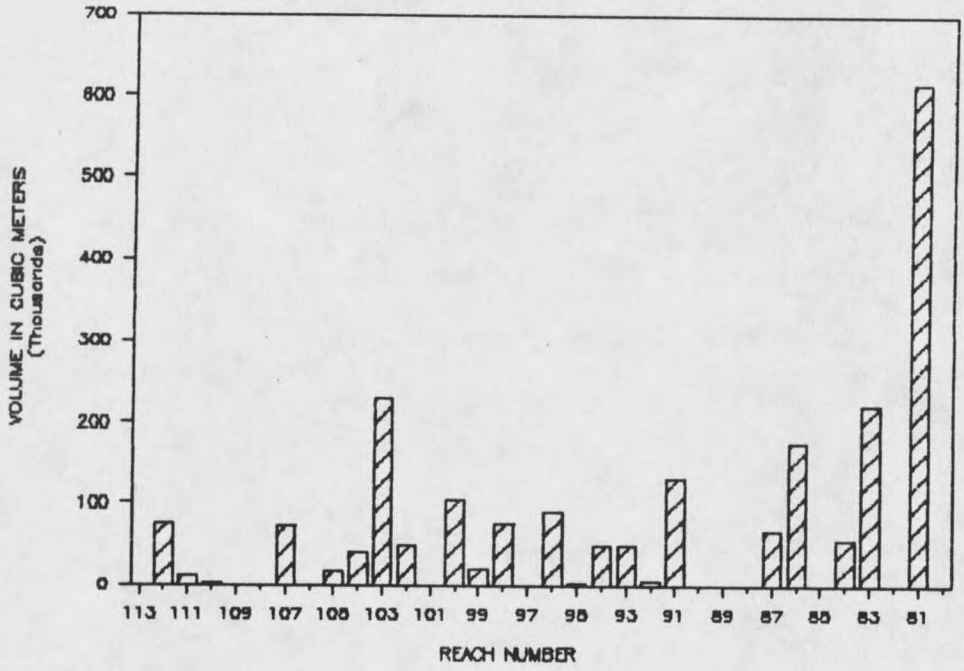

Figure 9. Total erosional volumes of Quaternary glacial-fluvial sediments contributed by river reach between 1945 and 1981 (medium estimate).

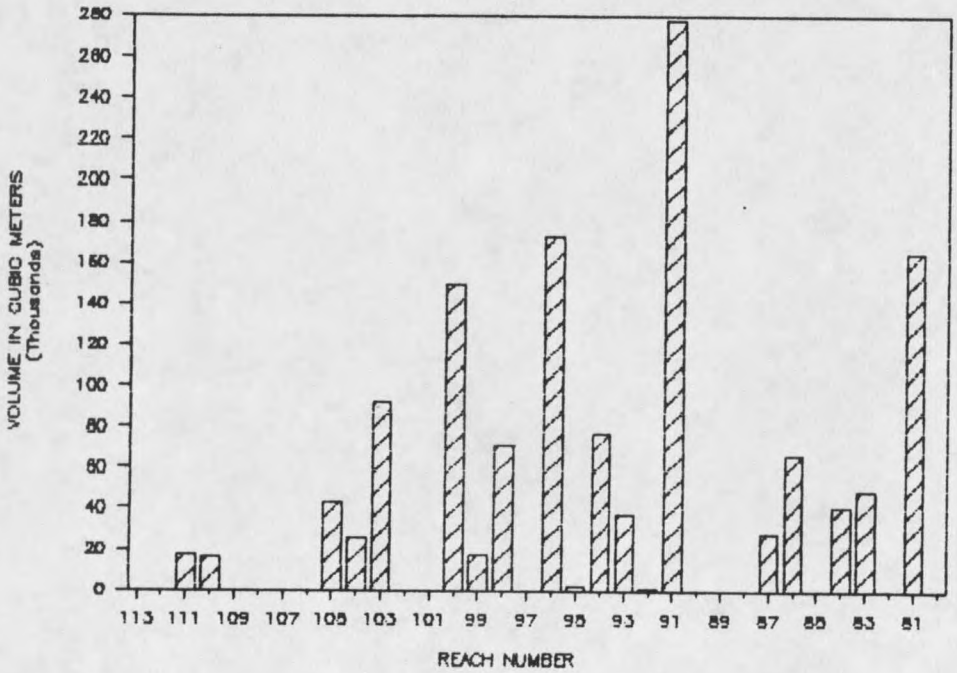

Figure 10. Total erosional volumes of Tertiary claystones contributed by river reach between 1945 and 1981 (medium estimate).

Total volumes of sediment were tallied by reach (Figure 11) to illustrate river segments that produced the greatest erosional volumes. The international border (northern study-area boundary) is within reach 113 and Logging Creek (southern study-area boundary) is at the bottom of reach 80. The large spike at reach 81 results from extensive erosion of a 29 m high cutbank. Note that every 3 to 5 km (2 or 3 miles) the erosional volumes increase and then decline for 2 to 3 km (1 or 2 miles).

Migration Rates

Total migration and migration rates were calculated for each of the 174 alluvial streambanks and 34 cutbanks of claystones and glacial materials (Table 8, Appendix B). Migration was estimated from the point of maximum lateral movement. Total migration for streambanks composed of alluvium ranged from 3.5 to 243.0 m. Lateral migration was defined as zero for areas of erosion that took place at alluvial streambanks located along islands or gravel bars within the channel. Migration rates were not calculated at these areas because migration direction was impossible to define. Total migration for the 29 cutbanks where claystones composed the lower bank ranged from 0 to 52 m. Total migration ranged from 3 to 55 m for the 5 banks where glacial materials were located in the lower bank. Migration was examined at all of the cutbanks whether they moved or not; hence, a zero value indicates no movement (Appendix B). Migration rates for the alluvial streambanks ranged from 0.1 to 6.8 $m \cdot yr^{-1}$ with an average for all alluvial banks of 1.3 $m \cdot yr^{-1}$. Migration rates for the cutbanks in which claystones formed the lower bank material ranged from 0 to 1.5 $m \cdot yr^{-1}$. The average

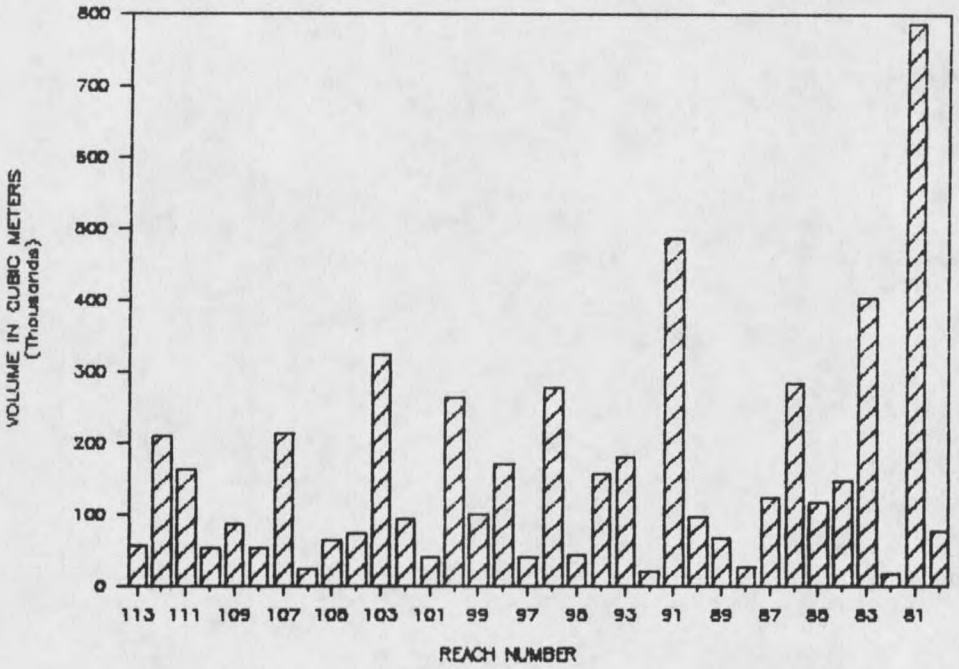

Figure 11. Total volumes of streambank erosion produced by each reach for all three sediment types (medium estimate).

migration rate for the claystones was 0.3 $m \cdot yr^{-1}$. Migration rates for the 5 cutbanks with glacial materials in the lower bank ranged from 0.1 to 1.8 $m \cdot yr^{-1}$ with an average migration of 1.0 $m \cdot yr^{-1}$ and standard deviation of .69.

Erosional Controls

A stepwise multiple regression program, SPSSX, was used in an attempt to understand the controls and quantities of sediment contributed by streambank erosion. The program regressed seven independent variables (controls) against a dependent variable of either total migration or erosional volume. The multiple regressions examined the relationship between these variables for seven cases. Four of the

cases investigated erosional controls in different spatial frameworks, two examined specific sediment type, and one case scaled erosional volumes to river size.

Erosion from all sediment types was examined for the entire study area (55 km), and for three different parts (lengths) of the river separately. The three equal (18.2 km) lengths divided the study area into lower (reaches 80-91), middle (reaches 92-103), and upper sections (reaches 104-113). Erosional controls were thus examined over four different river lengths. Various length units were investigated; however, the division of the study area into thirds produced the greatest number of explanatory variables and highest adjusted R^2 values. A high R^2 value implies that a large percentage of the total variation can be explained by the regression, and that a strong relationship exists between the independent and dependent variables. The fifth and sixth regressions compared erosional controls with migration and volumes throughout the study area for streambanks composed of floodplain alluvium and claystones, respectively.

Table 2 summarizes the regression results using all the streambanks and cutbanks within the study area. The results show a weak relationship between the type of lower bank material and bend sinuosity independent variables, and the dependent variables of migration and erosional volume. Adjusted R^2 values for total migration indicate that 9.4% of the variation in total migration is explained by the combination of streambank type and bend sinuosity. Type of lower bank material explains 6.6% of the variation and bend sinuosity explains another 2.8%. Erosional volumes were also weakly explained by sediment type and bend

Table 2. Regression results for all cutbanks and streambanks along the entire study area.[1,2,3]

Independent Variables	Dependent Variables			
	Total Migration	Low Volume	Medium Volume	High Volume
type of lower bank material	6.6	6.9	2.3	2.8
floodplain width	-	-	-	-
gradient	-	-	-	-
discharge	-	-	-	-
stream power	-	-	-	-
reach sinuosity	-	-	-	-
bend sinuosity	9.4	-	2.5	3.2

1) Dashes indicate no significant relationship
2) Numbers are adjusted R^2 values
3) All streambanks with total migration and bend sinuosity greater than zero (migration and bend sinuosity could not be calculated for in channel erosional areas).

sinuosity (Table 2). For example, 2.3% of the variation in the medium volume estimate is explained by type of lower bank material, and when combined with bend sinuosity, the two variables explained 2.5% of the variation for this dependent variable.

Table 3 reports the regression results for the different sections of the river. Regressions for the upper section (Table 3a) indicate that discharge explains 27.4% of the variation in total migration, and that this variable combined with bend sinuosity, explains 38.9% of the total variation in migration. Less variation was explained for the other dependent variables. Bend sinuosity, by itself, explained 28.1 and 19.2% of the variation in the low and medium volume estimates, respectively. For this river section, which includes 55 alluvial, 3 glacial, and 6 claystone banks, type of sediment did not explain any of the variation in total migration.

Table 3. Regression results for all 174 streambanks and 34 cutbanks along three sections of the North Fork.[1,2,3]

a) Reaches 104-113, upper 1/3 of study area, 55 alluv.-3 glac.- 6 clay

Independent Variables	Dependent Variables			
	Total Migration[4]	Low Volume	Medium Volume	High Volume
type of lower bank material	-	-	-	-
floodplain width	-	-	-	-
gradient	-	-	-	-
discharge	27.4	-	-	-
stream power	-	-	-	-
reach sinuosity	-	-	-	-
bend sinuosity	38.9	28.1	19.2	-

b) Reaches 92-103, middle 1/3 of study area, 39 alluv.-2 glac.-15 clay

Independent Variables	Dependent Variables			
	Total Migration[4]	Low Volume	Medium Volume	High Volume
type of lower bank material	10.5	20.8	36.5	38.7
floodplain width	-	-	-	-
gradient	-	-	-	-
discharge	-	-	-	-
stream power	-	35.3	-	-
reach sinuosity	-	-	-	-
bend sinuosity	-	-	41.1	47.1

c) Reaches 80-91, lower 1/3 of study area, 80 alluv.-0 glac.-8 clay

Independent Variables	Dependent Variables			
	Total Migration[4]	Low Volume	Medium Volume	High Volume
type of lower bank material	-	35.9	6.4	7.7
floodplain width	-	-	-	-
gradient	-	-	-	-
discharge	-	-	-	-
stream power	-	54.9	7.5	8.4
reach sinuosity	-	-	-	-
bend sinuosity	-	-	-	-

1) Dashes indicate no significant relationship
2) Numbers are adjusted R^2 values
3) Number and type of lower bank (alluvium, glacial, claystone)
4) All streambanks with total migration rates and bend sinuosity values greater than zero

For the middle third of the river (Table 3b) type of lower bank material explained 10.5% of the variation in total migration, and at least 20.8% when one of the erosional volumes was used as the dependent variable. This section included 39 alluvial, 2 glacial, and 15 claystone banks. For example, more than one-third (36.5%) of the variation for the medium volume estimate was explained by type of lower bank material, with another 4.6% explained by bend sinuosity. Similar results were obtained when the high volume estimate was used as the dependent variable. Type of lower bank material explained 20.8% of the variation in the low volume estimate and when combined with stream power the two variables accounted for 35.3% of the variation.

Less impressive regression results were obtained when the lower third of the study area was examined. This section includes 80 alluvial and 8 claystone but no glacial banks. No statistically significant relationships were uncovered between any of the independent variables and total migration for this section. Type of lower bank material and stream power were significant when volume estimates along the lower third of the study area were used as the dependent variables. The best results were obtained with the low volume estimate, as stream power explained 35.9% of the variation in low erosional volumes, and when combined with type of lower bank material, the two variables explained 54.9% of the variation.

In addition to spatially differentiating and examining erosion from several sediment types, the study investigated erosional controls for different bank sediment types. This part of the analysis eliminated sediment type as an independent variable and examined just banks of

floodplain alluvium or Tertiary claystones. Table 4 summarizes the regression results for the streambanks of alluvium, and shows that bend sinuosity consistently explained a small amount of variation in total migration and erosional volumes. Discharge and gradient were also shown to explain some of the variations in the erosional volume estimates.

The regressions for the cutbanks with claystones in the lower bank are summarized in Table 5. None of the independent variables explained any of the variation in total migration rates, although weak statistical relationships did emerge between two independent variables and variations in the volume estimates. Floodplain width explained 15.4% of the variation in the low volume estimate. Bend sinuosity explained 25.6 and 35.6% of the variation in the medium and high volume estimates, respectively. The lack of any statistical relationship between bend sinuosity and the low volume estimates may be a consequence of the methodology that was used to construct the low volume estimates. The erosional areas sometimes disappeared completely when areas with minor erosion were traced for the low estimate. This result may explain the anomalous relationships produced for the low volume estimates in Tables 3 and 6 as well.

The last regression examined whether scaling erosional volumes to river size would increase the predictability of any independent variables. The dependent variables -- low, medium, and high erosional volumes -- were divided by floodplain width to scale erosion to river size. The regression examined all the banks throughout the entire 55 km length of study area. Table 6 shows that scaling erosion to floodplain width greatly improved the correlations between type of lower bank

Table 4. Regression results for alluvial streambanks.[1,2,3]

Independent Variables	Dependent Variables			
	Total Migration	Low Volume	Medium Volume	High Volume
floodplain width	-	-	-	-
gradient	-	-	13.7	13.5
discharge	-	10.6	-	-
stream power	-	-	-	-
reach sinuosity	-	-	-	-
bend sinuosity	5.7	6.7	8.3	8.4

1) Dashes indicate no significant relationship
2) Numbers are adjusted R^2 values
3) All streambanks with total migration and bend sinuosity greater than zero (migration and bend sinuosity could not be calculated for in channel erosional areas).

Table 5. Regression results for cutbanks with claystones in the lower bank.[1,2]

Independent Variable	Dependent Variables			
	Total Migration	Low Volume	Medium Volume	High Volume
floodplain width	-	15.4	-	-
gradient	-	-	-	-
discharge	-	-	-	-
stream power	-	-	-	-
reach sinuosity	-	-	-	-
bend sinuosity	-	-	25.6	35.5

1) Dashes indicate no significant relationship
2) Numbers are adjusted R^2 values

material and the medium and high erosional volumes (compare Tables 2 and 5). Type of lower bank material explained 21.9% and 29.8% of the variation in the medium and high volume estimate, respectively, when volumes were divided by floodplain width. The correlation between variations in the type of lower bank material and the low volume estimates decreased from 6.9% to 2.7% when erosion was scaled for river

Table 6. Regression results for all cutbanks and streambanks with erosional volumes scaled to river size.[1,2,3]

Independent Variables	Dependent Variables		
	Low Volume	Medium Volume	High Volume
type of lower bank material	2.7	21.9	29.8
floodplain width	-	-	-
gradient	-	-	-
discharge	-	-	-
stream power	-	-	-
reach sinuosity	-	-	-
bend sinuosity	-	-	-

1) Dashes indicate no significant relationship
2) Numbers are adjusted R^2 values
3) All streambanks with total migration and bend sinuosity greater than zero (migration and bend sinuosity could not be calculated for in channel erosional areas).

size. Once again, this result may simply be the consequence of certain areas which were assigned zero values for the low estimate.

CHAPTER 4

DISCUSSION

This chapter examines the qualitative and quantitative results of the North Fork study and how they relate to prior studies of streambank erosion and sediment yield in more detail. The first section reviews possible explanations for the general floodplain widening observed for the North Fork. The remaining sections discuss the quantitative aspects having to do with migration rates, erosional volumes, sediment yield data, and the statistical analysis of erosional controls. The conclusions emphasize the difficulties that are encountered in understanding a dynamic, natural system and evaluating human impacts upon these systems.

Qualitative Results - Planform Changes

The planform morphology of the North Fork is characterized by a variety of straight, meandering, and braided reaches. The phrase "a wandering gravel bed river" best describes the changing morphology of this river. The active floodplain of the North Fork is predominantly gravel which produces a diversity of morphologies at discharges of varying magnitudes. A braided stretch may change to meandering and then become relatively straight as discharge increases. This changing morphology reflects how varying discharges are channeled about a variety of river bed forms. Consequently, streambanks are eroded in different

morphologic settings with changing river stage.

Changes in river planform for the North Fork are illustrated in the erosional area maps (Figures 12-30, Appendix A). An important observation from these maps is that throughout all of the 33 reaches the planform geometry has changed. Numerous depositional areas can be seen (i.e., across from Trail Creek (Figure 17) and cutbank 16 (Figure 19)) in addition to areas of erosion. The most noteworthy feature is that the active floodplain for the North Fork has widened throughout most of the study area. Causes for enlargement of the floodplain between 1945 and 1981 are speculative and probably related to several factors.

The most probable explanation for this floodplain widening is the largest flood on record which occurred in June of 1964. This flood was approximately a 50-year recurrence interval flood for the North Fork at the border and exceeded the 100 year flood at the station upstream from Columbia Falls, Montana (Dalby, 1983). The flood was initiated by an intense rain on a mature snowpack. Intense scouring associated with the 1964 flood is probably responsible for some of this erosion.

Additional untested factors that may have contributed to this floodplain widening are the mountain pine beetle epidemic and clearcutting which have occurred throughout the North Fork drainage. Devegetation of lodgepole pine forests through disease, fire, and clearcutting has the potential for increasing surface runoff with subsequent increases in sediment and water yield, river discharge, and bank erosion. A study by Potts (1984) examined impacts of the mountain pine beetle in southwestern Montana and reported that timber kill resulted in a 15% increase in water yield. Snowmelt runoff was also

advanced by two to three weeks. Intensive logging both in British Columbia and Montana is revealed in the aerial photographs by numerous clearcuts. Troendle and King (1985) in Colorado showed that timber harvesting increased annual flow and advanced the timing of peak runoff. Increased surface runoff can also promote increases in soil erosion and sediment yield to the river (Trimble, 1974). Floodplain aggradation from increased sediment loads might accelerate channel widening in addition to erosion from scouring at high discharges.

Quantitative Results

Migration Rates

Measured erosion migration rates along the North Fork for floodplain alluvium ranged from 0.1 to 6.8 $m \cdot yr^{-1}$. These values are similar to rates reported from other studies investigating erosion in floodplain alluvium (Table 7). In addition to rates, Table 7 shows the variety of methods and time frames that have been used in prior streambank research. The higher rates reported by Ferguson and Werritty (1983), Nanson and Hickin (1986), and in this study represent erosion in high-energy gravel bed rivers. The lower rates reported by the first four authors in Table 7 reflect erosion from clay rich material within predominantly lower-energy rivers. The range of low to high migration rates reported by Hooke reflects the variability of discharges associated with a variety of drainage basin sizes and how specific events can produce large amounts of erosion in silty alluvium. Thus, differences in rates may be in part a function of varying bank particle size, stream power, and the time frame being considered. Differences

Table 7. Streambank erosion studies.

author	location	spatial coverage	timeframe (years)	methods	bank type	migration rate m/yr
Wolman (1959)	Maryland	2 banks	5.0	erosion pins, surveys	cohesive silt	0.4-0.6
Twidale (1964)	Australia	5 sites 1 bend	2.5	erosion pins	alluvium silt-clay	0.6-0.8
Hill (1973)	Ireland	2 rivers several sites	2.0	erosion pins, debris trays	glacial till	.03-0.06
Knighton (1973)	England	15 sites	1.5	erosion pins	glacial till	0.02-0.2
Hooke (1979)	England	6 rivers 15 sites	2.5	erosion pins	alluvium silt-clay	0.2-16.8
Ferguson Werritty (1983)	Scotland	2 short reaches	5.0	aerial photos, surveys	bar gravels	> 10.0
Braken-ridge (1985)	Tennessee	3 terraces	--	dating alluvium, scarp retreat	limestone	0.01-0.06
Nanson Hickin (1986)	British Columbia, Alberta	18 rivers 118 sites	33.0	aerial photos, surveys	alluvium sand,silt, clay	0.0-12.6
Ruth (1988)	Montana	1 river 228 sites	36.0	aerial photos, surveys	alluvium sand-silt	0.1-6.8
					claystones	0.0-1.4
					outwash terraces	0.1-1.8

in erosional rates, however, are to be expected for different river systems for many reasons. The reported ranges for migration rates within floodplain alluvium are all within one order of magnitude of one

another which illustrates that different bank erosion studies have produced similar results.

Much less work estimating channel erosion rates in glacial outwash terraces or bedrock has been reported in the literature. Crickmay (1959) reported a lateral migration rate of 0.3 $m \cdot yr^{-1}$ for erosion into "Pleistocene deposits", which is similar to the rate reported for the claystones in this study. He did not describe the lithology of these deposits; however, a photograph of this outcrop suggested they were fine grained clastic sediments similar to the Tertiary claystones of the North Fork. Reported erosion rates for channel migration in terraces of glacial outwash are lacking and thus it was not possible to compare my results with any obtained in other studies.

Erosional Volumes

The medium estimates for erosional volumes revealed that the greatest contribution of sediment (59,800 $m^3 \cdot yr^{-1}$) came from the glacial materials, followed by floodplain alluvium (50,600 $m^3 \cdot yr^{-1}$) and lastly from the claystones (37,300 $m^3 \cdot yr^{-1}$). These totals are very similar despite the varying magnitudes and spatial extent of the different materials along this section of river. Hence, the 34 large cutbanks of claystones and outwash are supplying about the same amount of sediment as the 174 smaller streambanks of floodplain alluvium.

When erosional volumes for all three sediment types were totaled by reach (Figure 11) an interesting trend emerged. Erosional volumes appear to increase for 3 to 5 km (2 or 3 miles) and then decline for 2 to 3 km (1 or 2 miles). This alternating pattern of high and low erosional volumes may be the result of random variation because

erosional volumes were generated from different sediment types and radically different bank heights. Variable patterns of high and low bank erosion have been reported in other studies. Graf (1981), for example, reported that zones of stability and instability alternate with each other at 3.2 km (2 mile) intervals in the braided, sand-bed Gila River of central Arizona. Another study which produced similar results was conducted by Church (1983) on the gravel-bed Bella Coola River of British Columbia. He indicated that zones of instability for this river were located 3 to 5 km apart. He concluded that this pattern represented a series of transport reaches interspersed with sedimentation reaches. Areas of sedimentation or aggradation were zones of lateral instability. Patterns of erosion as reported in this study and from the work of Graf (1981) and Church (1983) should be investigated further.

Sediment Yield Data

One way to examine the streambank erosion estimates produced in this study is to compare them with published sediment yield data. The USGS collects suspended load data at the border and Columbia Falls gaging stations. Table 8 compares the bank erosion totals estimated in this study and suspended loads measured from the USGS North Fork gaging stations. The main point to note from Table 8 is that the bank erosion results are of the same order of magnitude and quite similar to the sediment yield data compiled for suspended loads. This is not a direct comparison since bank erosion contributes material which is transported as bedload and suspended load. The observation that the bank erosion value is nearly double the net suspended load value implies that

Table 8. Comparison of total sediment loads input from streambank erosion versus average suspended loads generated from the North Fork drainage basin.

	Timeframe	Sediment yield method	Mass (tonnes)/yr
Mean Annual Bank Erosion (streambank erosion) Border to Logging Creek	36 years	aerial photographs field surveys	2.4×10^5
Mean Annual Suspended Load	2 years	streamflow duration sediment transport curve method (Knapton, 1978; and Dalby, 1983)	
Border Station			1.2×10^5
Near Columbia Falls station			2.5×10^5
Net gain in suspended load between Border and Columbia Falls stations			1.3×10^5

considerable deposition and storage of sediment takes place following erosion within the North Fork drainage. The sediment in the North Fork may be temporarily stored by the channel system and moved out of the drainage periodically by large storms such as the 1964 flood. Further work with streamflow data and rating curves for both bedload and suspended load, and/or work with aerial photographs taken shortly after the 1964 flood in addition to the 1945 and 1981 photographs is needed to better explain sediment transport and storage on the North Fork Flathead River.

Statistical Analysis

Despite the variety of bank erosion research methods and projects, only three studies (Dickinson and Scott, 1979; Hooke, 1979; Nanson and

Hickin, 1986) have attempted to explain or predict erosion by statistically analyzing a set of controlling factors. The first two studies cited above examined short reaches and variables not assessed in this study. Only Nanson and Hickin (1986) analyzed variables relevant to this project.

Their study investigated bank erosion controls within alluvium on 118 bends in 18 single-thread, meandering reaches of high-energy sand and gravel bed rivers. Analysis for these bends involved regressing either mean migration rate or volumetric migration rate against mean channel width, outer bank height, size of sediment in the lower bank, discharge, gradient, and stream power. Mean migration and mean channel width were determined by calculating the arithmetic means for several bends on each of the 18 river reaches. Since channel migration is a function of bend curvature (Hickin and Nanson, 1975; Nanson and Hickin, 1983), the authors chose to statistically examine only bends with bend curvature values (radius of curvature/width) of between 2 and 4 in their statistical analysis.

The present study of the North Fork extends Nanson and Hickin's work by examining 55 km of river rather than focusing on carefully selected, single bends. The main difference is that the Nanson and Hickin study examined the controls of single thread, meandering reaches on different rivers, whereas this study investigated the controls for all planforms on just one river. By using a variety of rivers they were able to investigate a wide range of bank sediment sizes, discharges, and gradients in addition to choosing areas for which bend curvature could be easily measured. Bend curvature was not utilized in this study

because inflection points for several erosional areas on one bend could not be objectively defined for measuring radius of curvature.

The results of the regression analyses (Tables 2-5) illustrate that erosional controls for the North Fork were better explained by examining 18 km sections as opposed to the entire 55 km length. The field area was arbitrarily segmented to examine whether the explanation was improved by investigating smaller spatial units. The results were also slightly better (higher R^2) when regressions examined a particular bank sediment type (alluvium or claystones) rather than all sediment types. Thus, isolating smaller spatial units or a particular bank sediment type for analysis, appears to reduce the complexity associated with defining erosional controls. The higher adjusted R^2 values obtained by isolating river sections or bank sediment type suggests that controlling factors vary both spatially and lithologically. The regressions showed that type of lower bank material and bend sinuosity weakly explained variations in migration and erosional volumes when controls were considered for the entire river. Different statistically significant variables emerged when the river was analyzed in sections.

The discharge and stream power variables produced statistically significant relationships with bank erosion when the river was examined in sections. In the up-river third of the study area, discharge and bend sinuosity explained most of the variation in total migration and the type of lower bank material was not an important contributor to explanations of erosion rates. In the down-river two-thirds of the study area, stream power and type of lower bank material were important in explaining variations in erosional volumes but not total migration.

In Nanson and Hickin's (1986) work, river size as expressed by discharge or width and river slope provided important statistical explanations for migration rates. River size expressed by discharge and slope are essentially stream power and this explained 48% of the variation in migration rates in their analysis. In addition, they found that using the volumetric erosion rate (product of bank height and migration rate per unit area of bed) clearly increased the predictability of channel migration. Their variable, volumetric erosion rate, differed from the erosional volumes measured in this study. Volumetric erosion rate is measured per unit area of bed, and erosional volumes in the North Fork study came from measured areas. Another difference is that volumetric erosion was determined from an average of several bends, in contrast to erosional volumes which represent only one bend.

In an attempt to scale migration rate to the size of the river Nanson and Hickin (1986) divided volumetric erosion rate by mean channel width. Holding river scale constant showed that the size of the basal sediment was important in explaining 27% of the variation in volumetric erosion rate. Nanson and Hickin (1986) concluded that bank erosion was essentially a sediment entrainment problem which is a function of total stream power and sediment size.

This study revealed similar results when erosion was scaled to river size using floodplain width. The low, medium, and high erosional volumes were divided by floodplain width, and this increased the amount of variance explained by type of lower bank material for the medium and high volume estimates. The correlations between type of lower bank

material and these volumes improved from 2.3% and 2.8% to 21.9% and 29.8%, respectively, when these volume estimates were divided by floodplain width and thereby scaled to river size. It is not clear why such similar results to Nanson and Hickin (1986) were obtained in the case of stream power. It may be that differences in the methods and data sources used to estimate the geomorphic variables in the two studies explain these outcomes.

Overall, the highly variable but generally weak regression results indicate that prediction of bank erosion from a variety of erosional settings over many kilometers of river is too complex to produce good correlations between controls and erosion. The discovery that differences in lower bank materials influence rates and magnitudes of streambank erosion is not surprising. Floodplain alluvium, glacial-fluvial sediments, and claystones each present a different resisting force and thus should show some type of relationship to an eroding force. Conversely, changes in bend sinuosity would affect river hydraulics and thus create changes in the eroding forces.

Conclusions

The present North Fork River study has examined bank erosion through aerial photography and field surveys and documents that this methodology can produce reasonable estimates for volumes and masses of sediment produced by streambank erosion. The differences between high and low estimates for both volumes and masses of sediment are within one order of magnitude of one another and are of a similar magnitude to prior sediment yield data. Even though error in height variations is

difficult to measure, this methodology can produce first approximations of sediment delivery from streambanks. A more detailed survey of bank heights would further refine the erosional volume estimates. The statistical analysis, on the other hand, illustrates the difficulties that are encountered trying to explain erosion rates in terms of hydrological, morphological and sedimentological variables.

This thesis project was designed to complement a study by the Montana Bureau of Mines on the baseline hydrology conditions of the North Fork. Quantifying streambank erosion prior to mining and further land use changes provides data for future evaluation of bank erosion. A study by Miller (1986) in Tennessee documented channel aggradation and subsequent widening after the onset of strip mining. Widening was associated with the deposition of coarse gravel in the channel. Potential for increased bank erosion and channel change exists if coal mining begins in the headwaters of the North Fork. This study of the North Fork provides baseline data.

The present North Fork study also provides information important for evaluating the river's sediment and phosphorus budgets. Sediment produced from bank erosion has been quantified and differentiated both spatially and lithologically (Figures 5 and 11; and Figures 12 through 30, Appendix B). The results can thus be utilized to locate areas of instability and sediment production from different bank materials. Future studies examining streambanks on the North Fork Flathead River as potential nutrient source areas can use the erosional volume data in combination with streambank phosphorus values to quantify nutrient loads. Bank sediments may contribute phosphorus because sediments are

derived from materials such as the Permian-age Phosphoria Formation and so may be important sources of phosphorus. Quantification of nutrient source areas will help delineate specific components of the phosphorus budget within the Flathead drainage. The adsorption and desorption of nutrients on sediments, and resolution of sediment transport and storage, are processes that are not very well understood. Physical, biological, and chemical factors influence the exchange reactions between water and sediment (Lee, 1970), and these aspects will also need to be quantified to improve nutrient budgets for the Flathead Basin.

Evaluating and predicting responses within natural systems represent first steps towards protecting the environment from human impacts. Unfortunately, it is quite costly and difficult to accurately quantify or predict change because of the large variability associated with natural processes. For example, the single bank height measurements made for this study took two people four weeks to gather. Multiple measurements per bank would produce more accurate data, but would require a greater investment of resources. Similarly, the low levels of explanation computed through regression analysis in this study illustrate that "for a large study area", a natural process such as bank erosion is not easily predicted. The results of the North Fork study confirm Hookes's (1979, p. 60) conclusion that "the amount of bank erosion is controlled by a complex combination of conditions and that no single model of controls emerges". The fluvial environment is a highly dynamic system influenced by a great number of ever changing variables. Interpreting the cause and effect relationships between these variables both spatially and temporally is further complicated by climatic

variations and human-induced change.

The large 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. Floodplains provide storage space for sediment as it moves through a drainage basin and the potential for storage increases as they become wider downstream (Knighton, 1984). Ritter (1978) and Trimble (1983) have suggested that sediment yield may be a poor indicator of basin erosion and that the major portion of sediment eroded from a drainage is stored within the basin by deposition. Thus, modern river loads may reflect erosional events that occurred in the past (Ritter, 1978; Trimble, 1983). Recognition of this state of affairs and the data produced in this study are vital if we are to predict and/or evaluate the effects of future human activities in the North Fork Flathead Basin.

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APPENDICES

APPENDIX A

EROSIONAL AREA MAPS

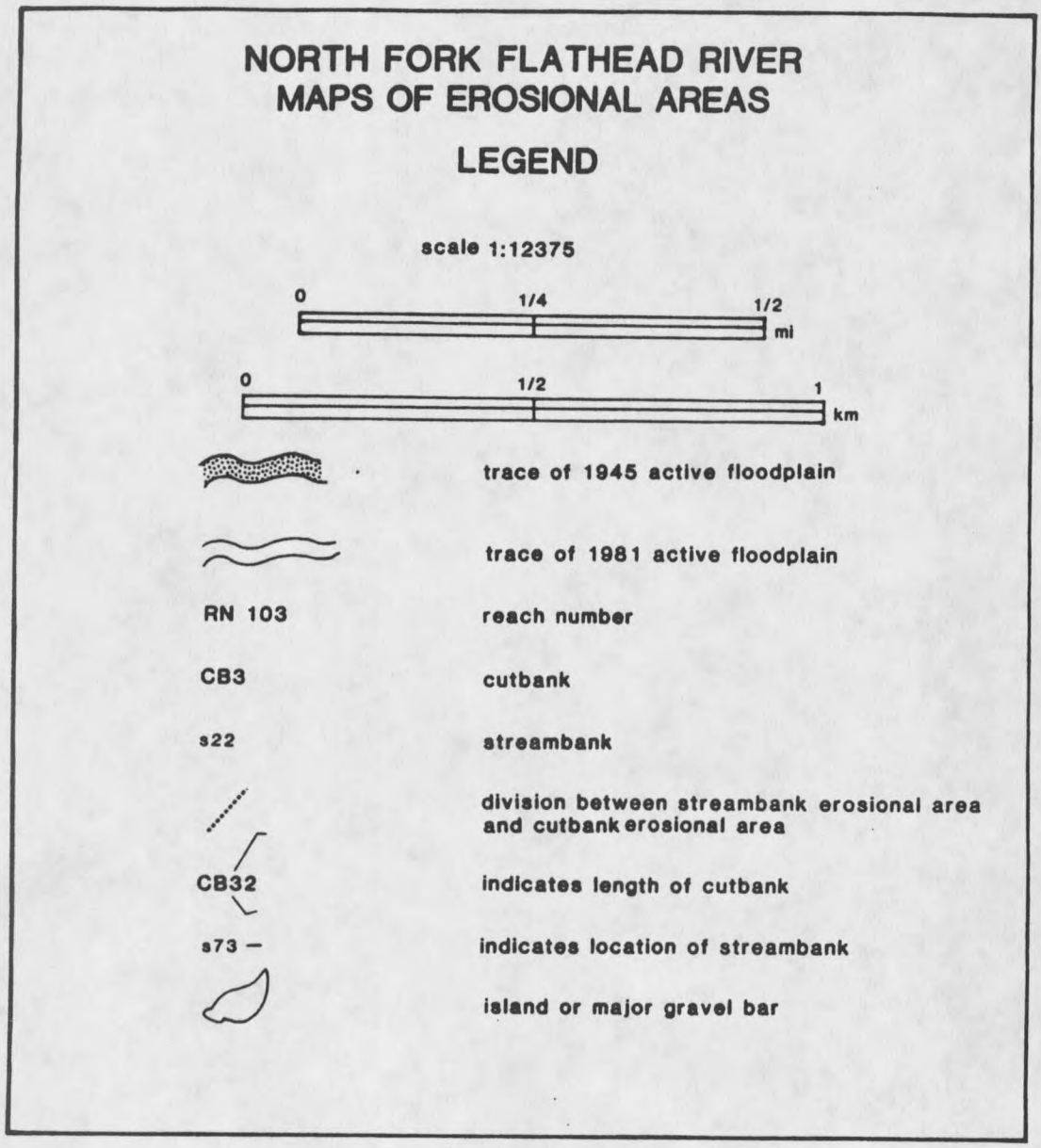

Figure 12. Legend for the North Fork of the Flathead River erosional area maps.

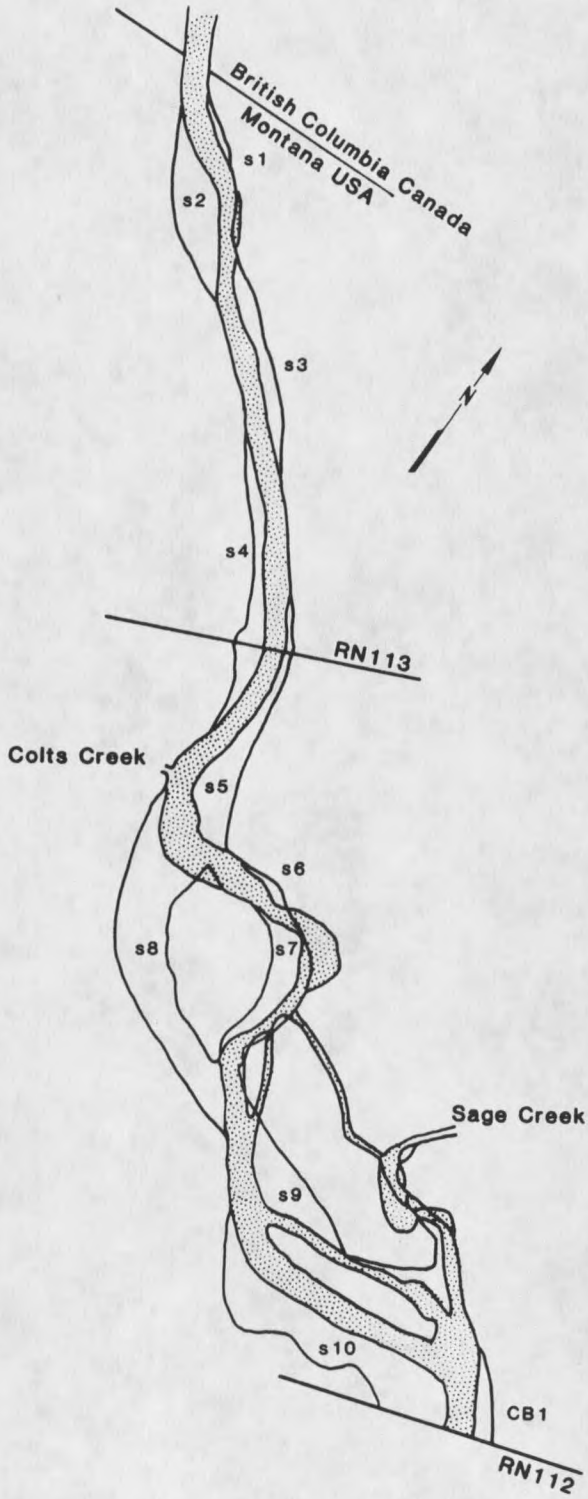

Figure 13. Erosional area map between the international border to below Sage Creek -- reaches 113 and 112.

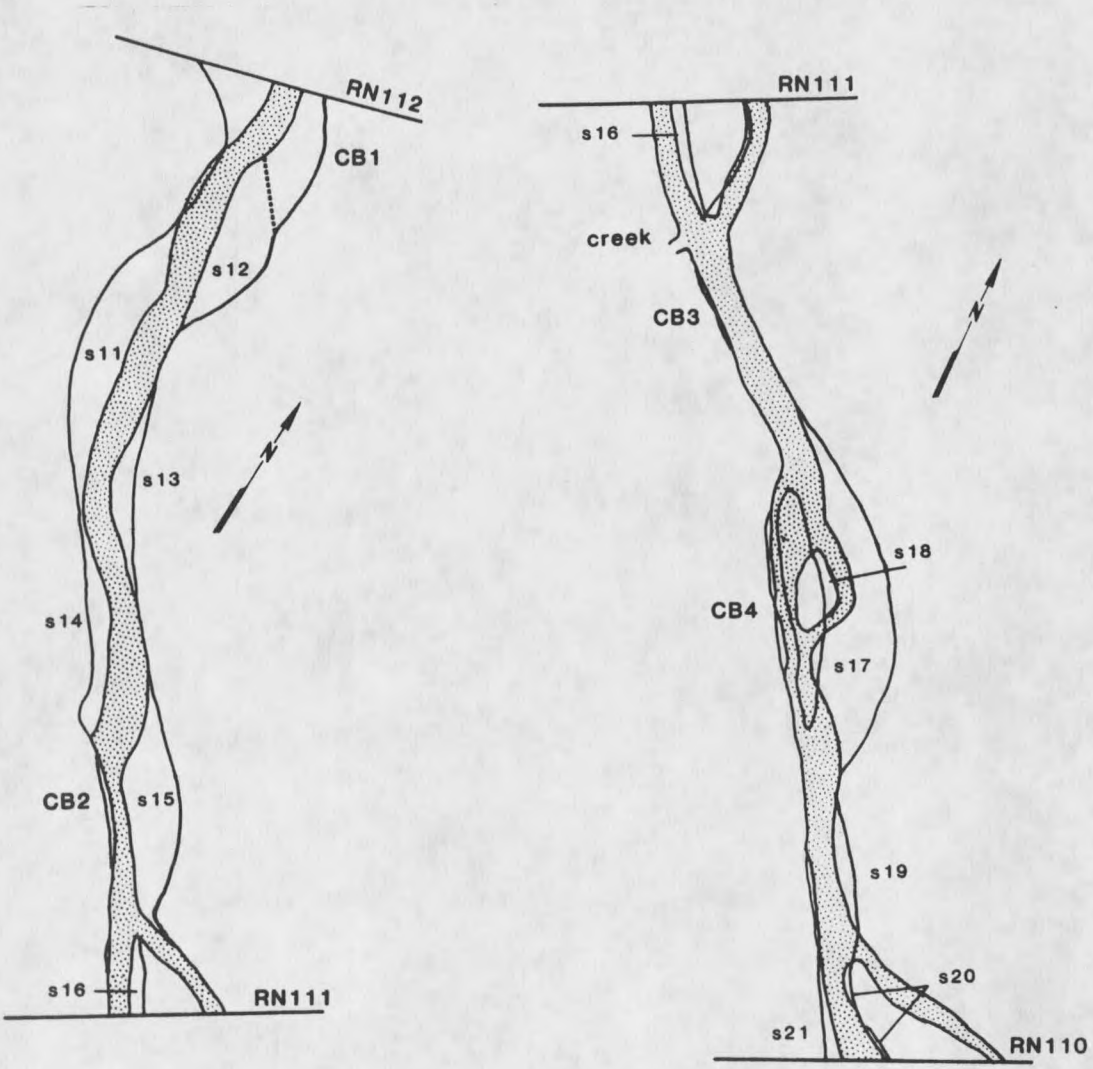

Figure 14. Erosional area map showing reaches 111 and 112.

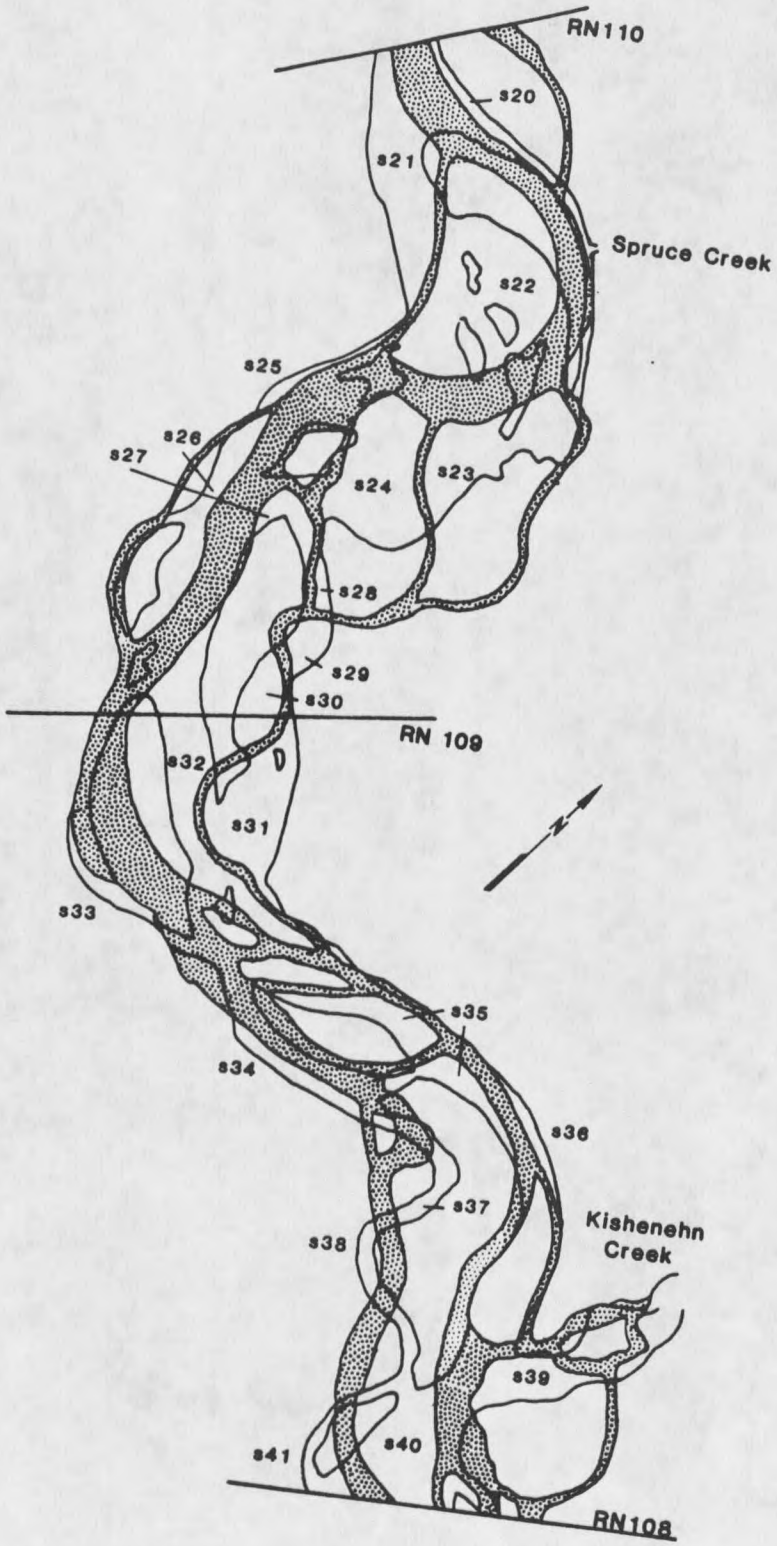

Figure 15. Erosional area map between Spruce Creek and Kishenehn Creek -- reaches 109 and 108.

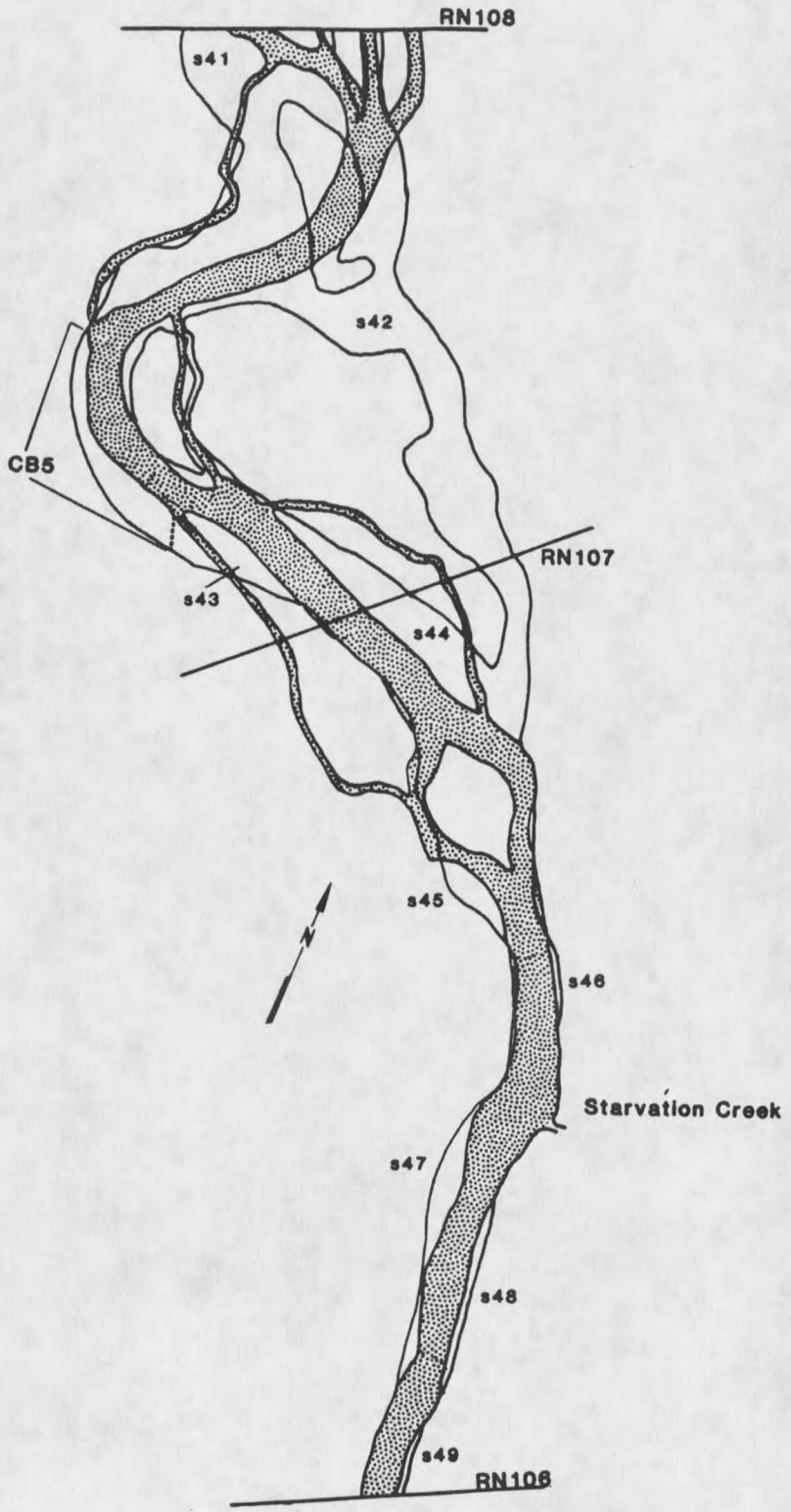

Figure 16. Erosional area map near Starvation Creek -- reaches 107 and 106.

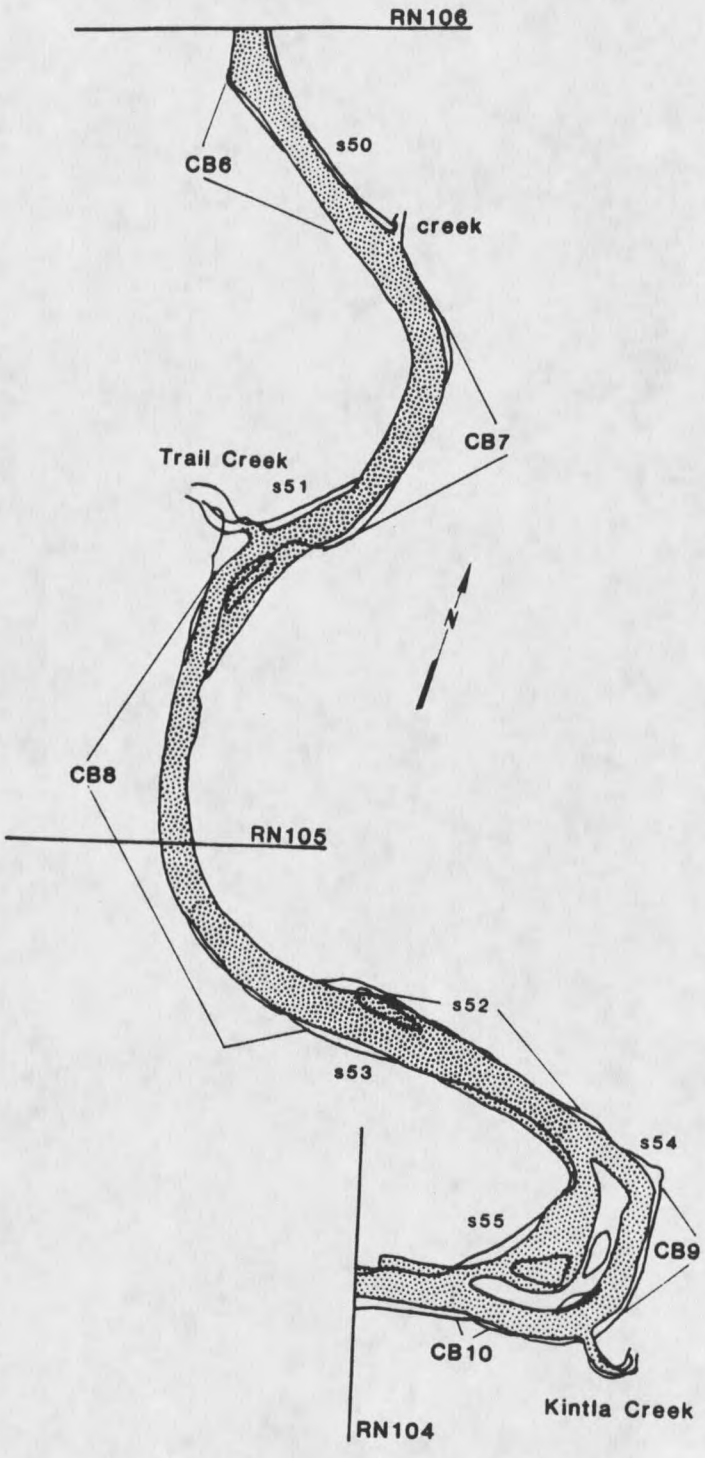

Figure 17. Erosional area map near Trail and Kintla Creeks -- reaches 105 and 104.

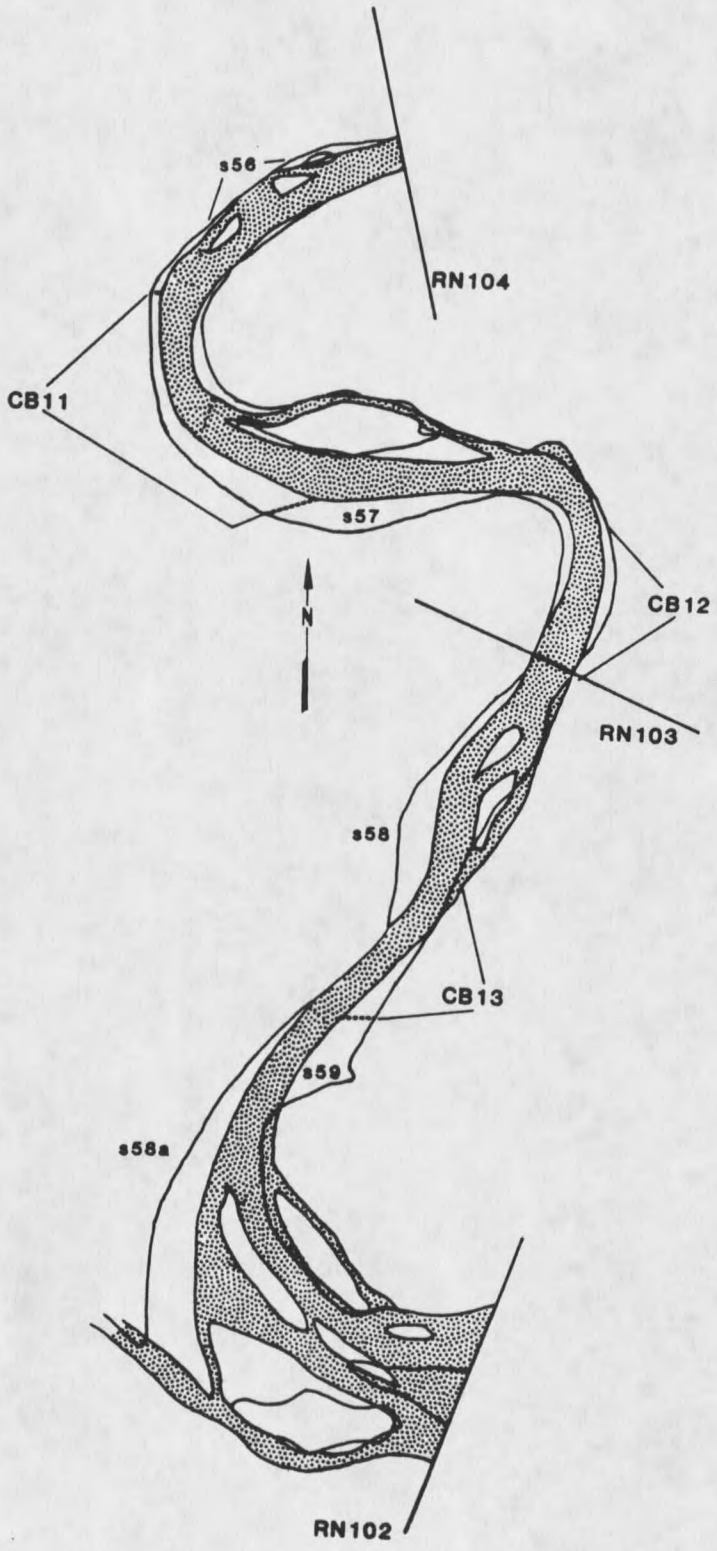

Figure 18. Erosional area map showing reaches 103 and 102.

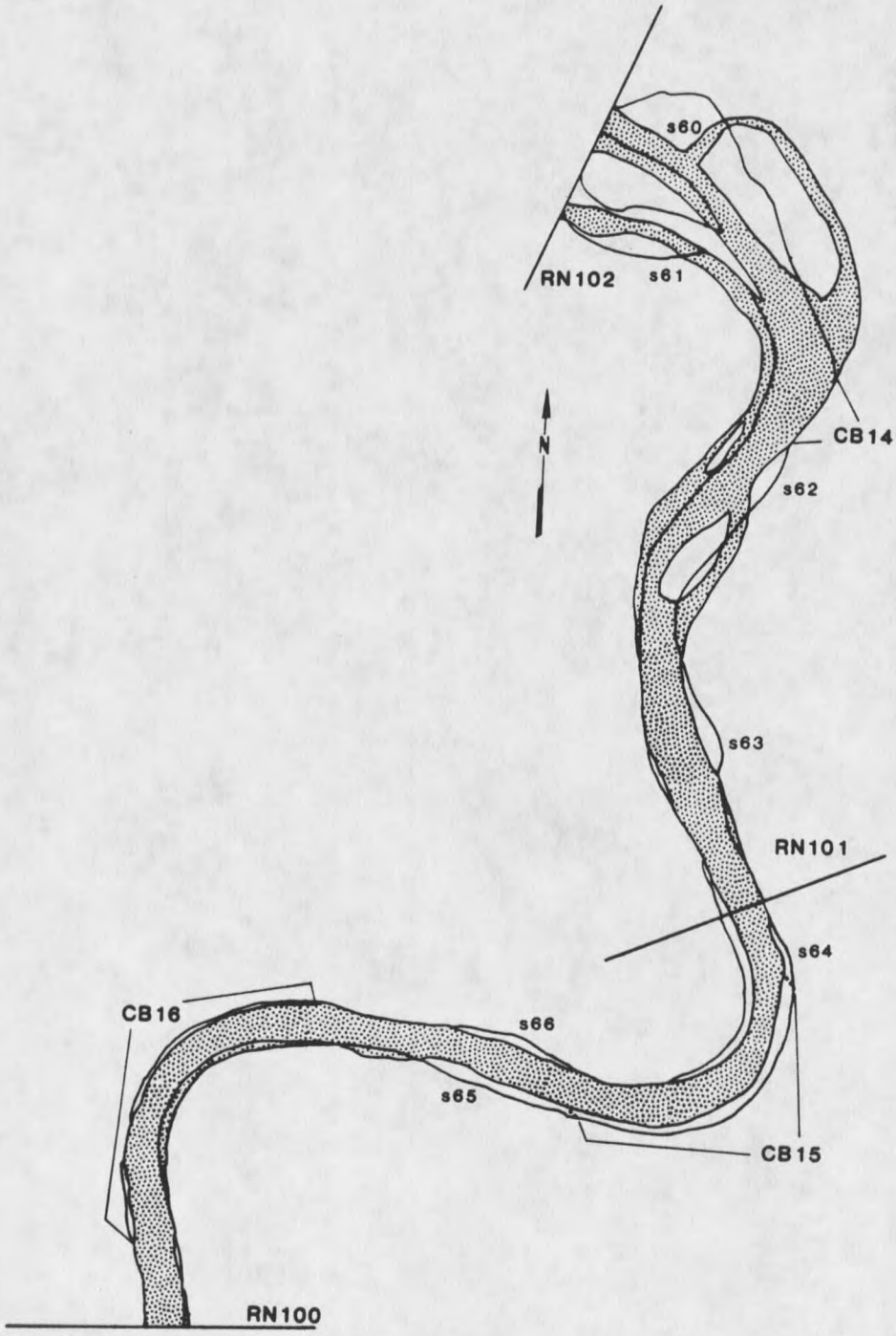

Figure 19. Erosional area map showing reaches 101 and 100.

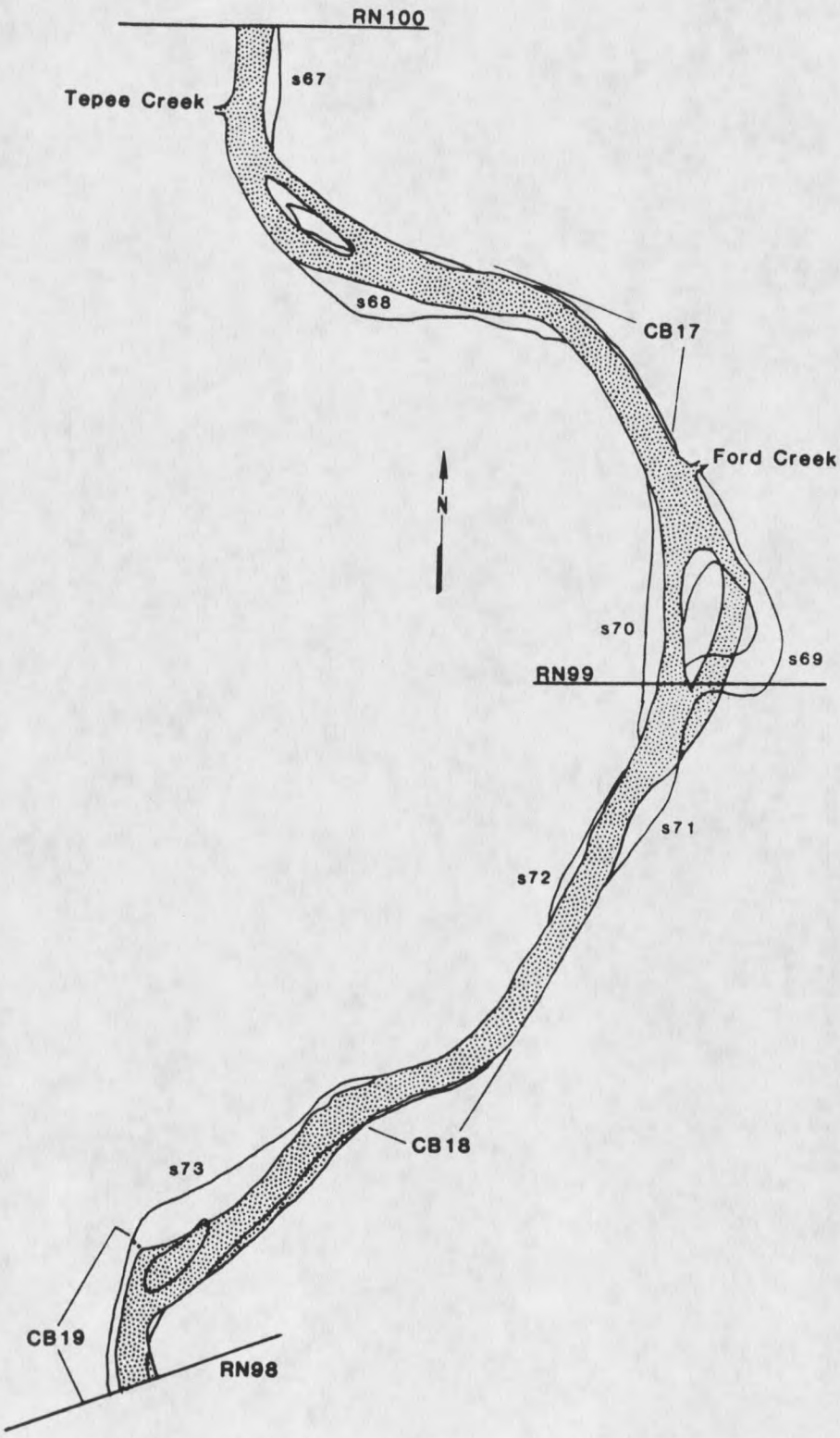

Figure 20. Erosional area map near Tepee and Ford Creeks -- reaches 99 and 98.

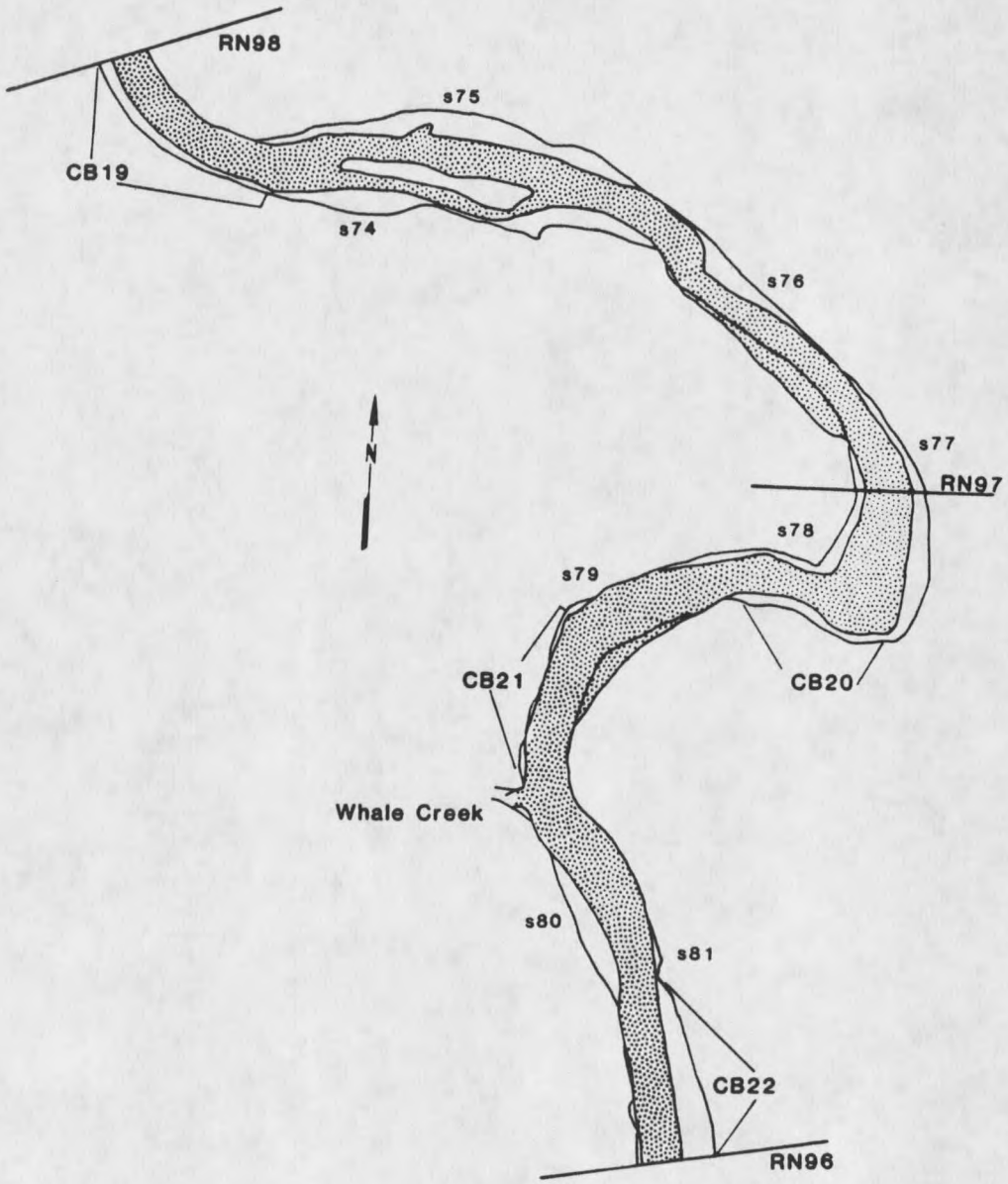

Figure 21. Erosional area map near Whale Creek -- reaches 97 and 96.

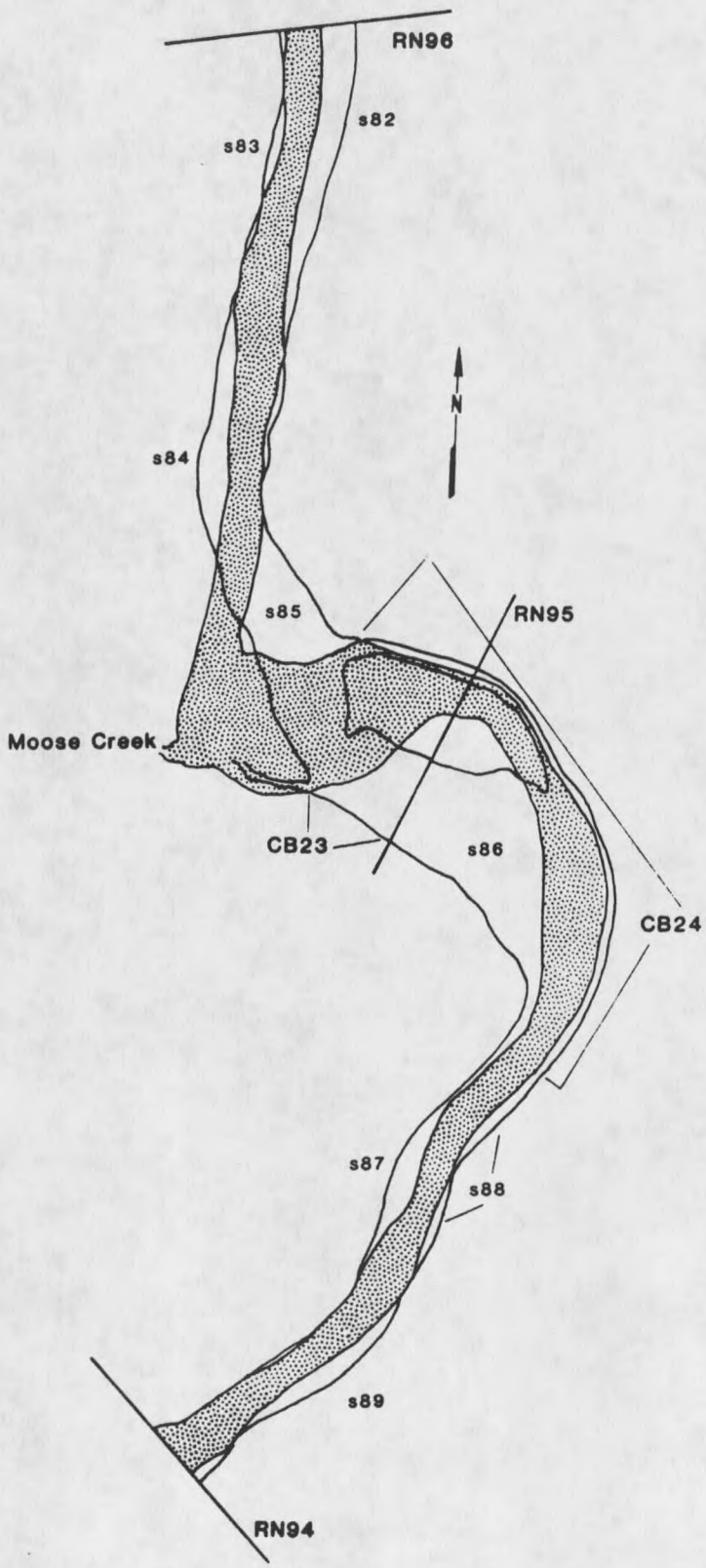

Figure 22. Erosional area map near Moose Creek -- reaches 95 and 94.

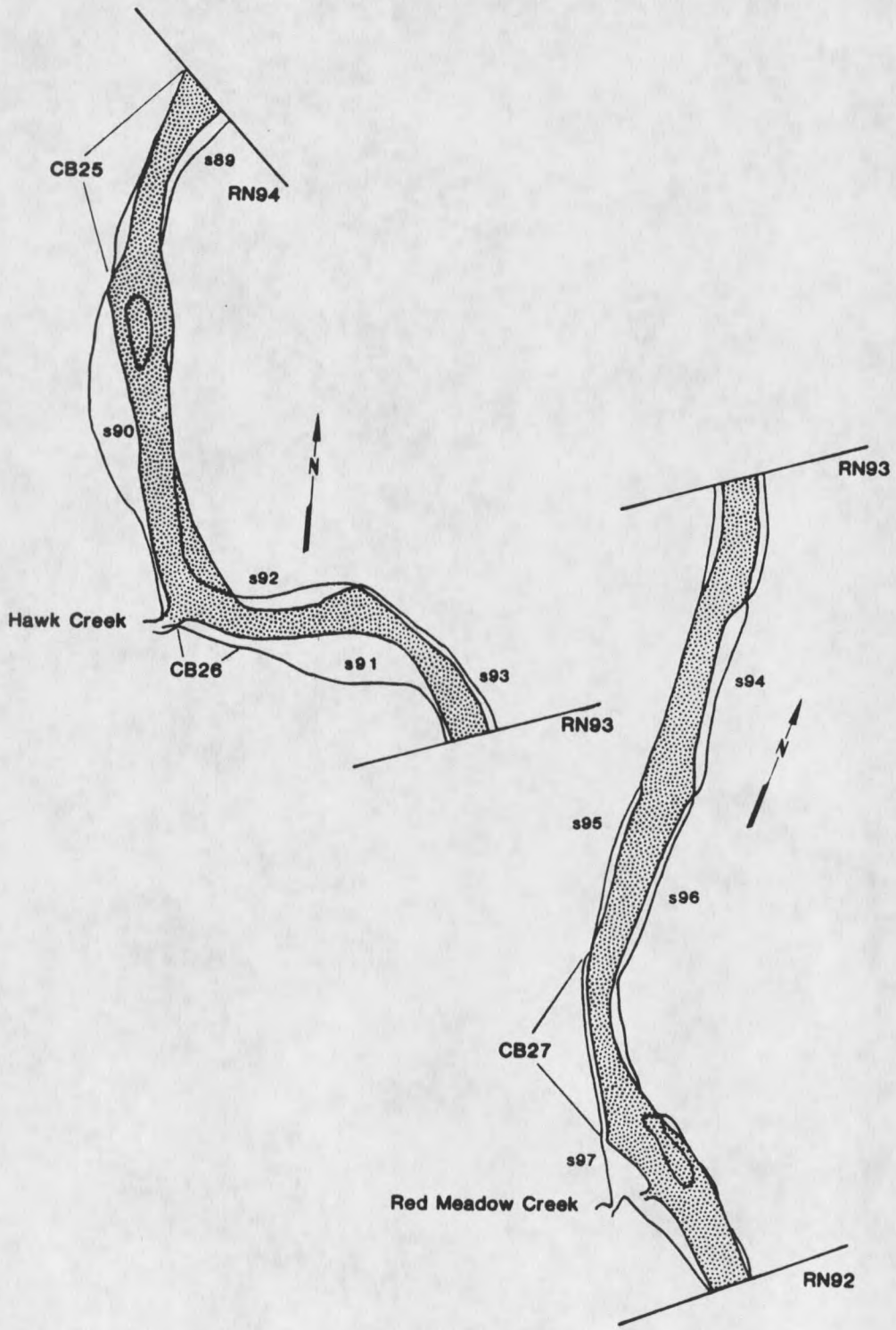

Figure 23. Erosional area map near Hawk and Red Meadow Creeks--reaches 93 and 92.

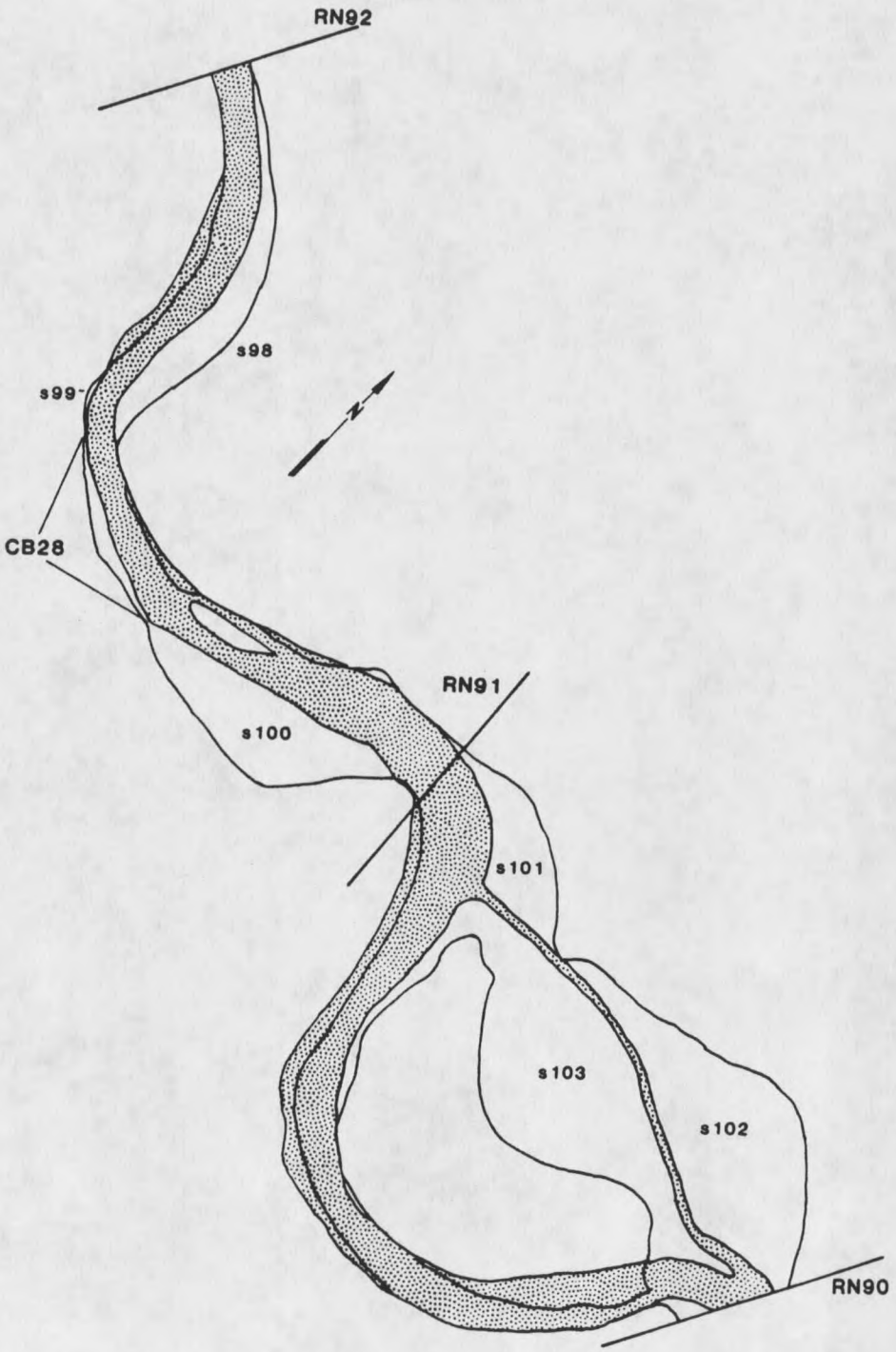

Figure 24. Erosional area map showing reaches 91 and 90.

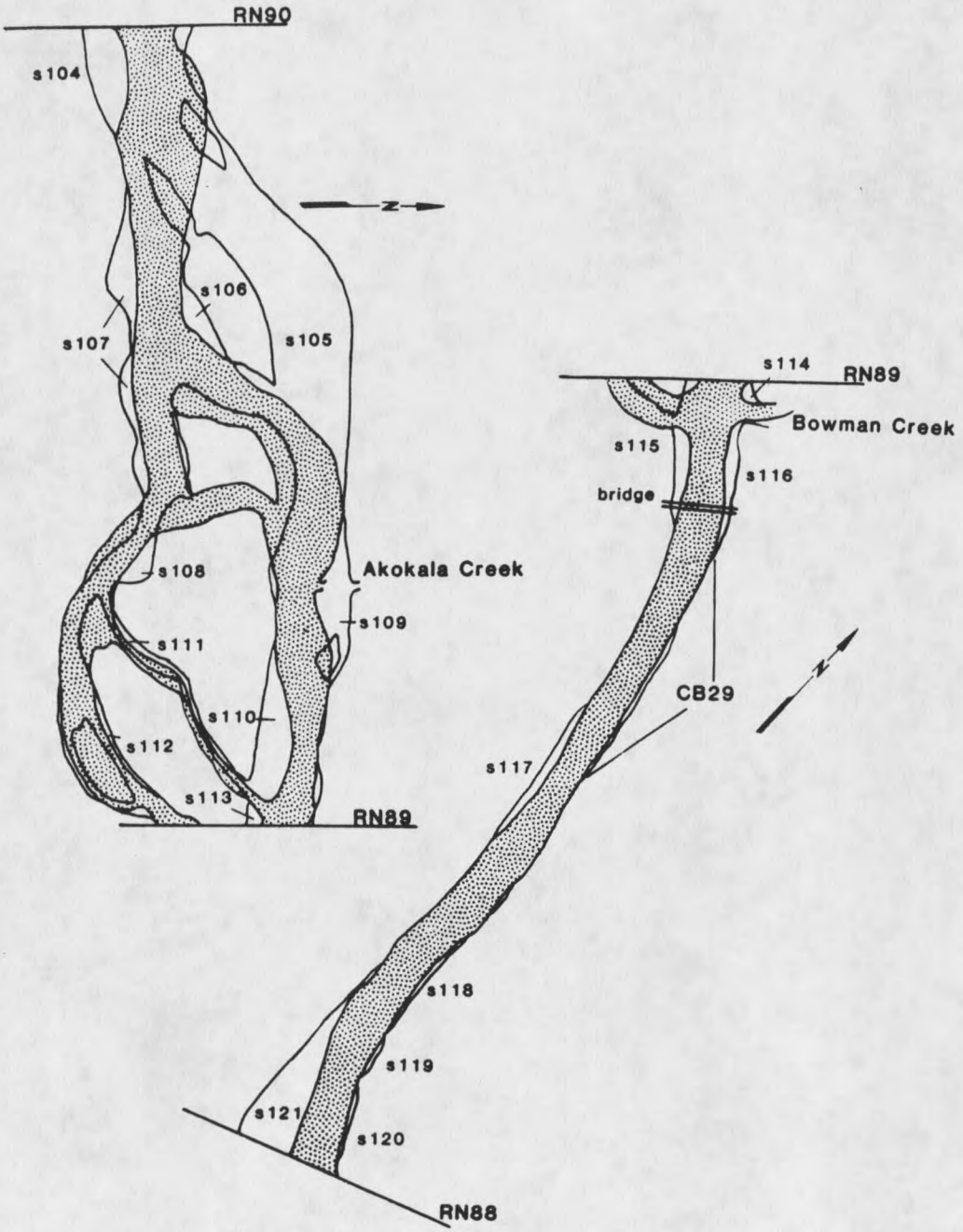

Figure 25. Erosional area map near Akokala and Bowman Creeks -- reaches 89 and 88.

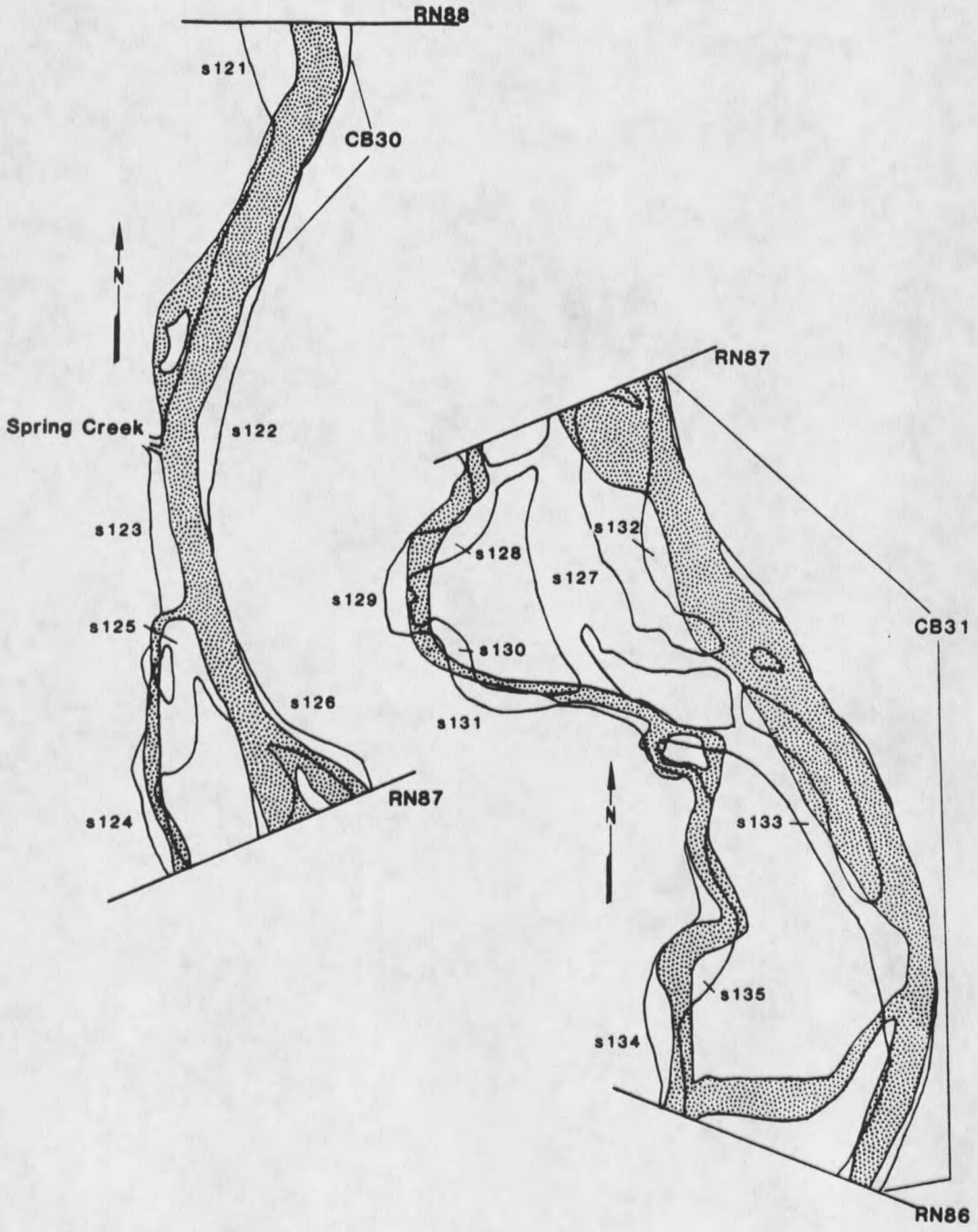

Figure 26. Erosional area map near Spring Creek -- reaches 87 and 86.

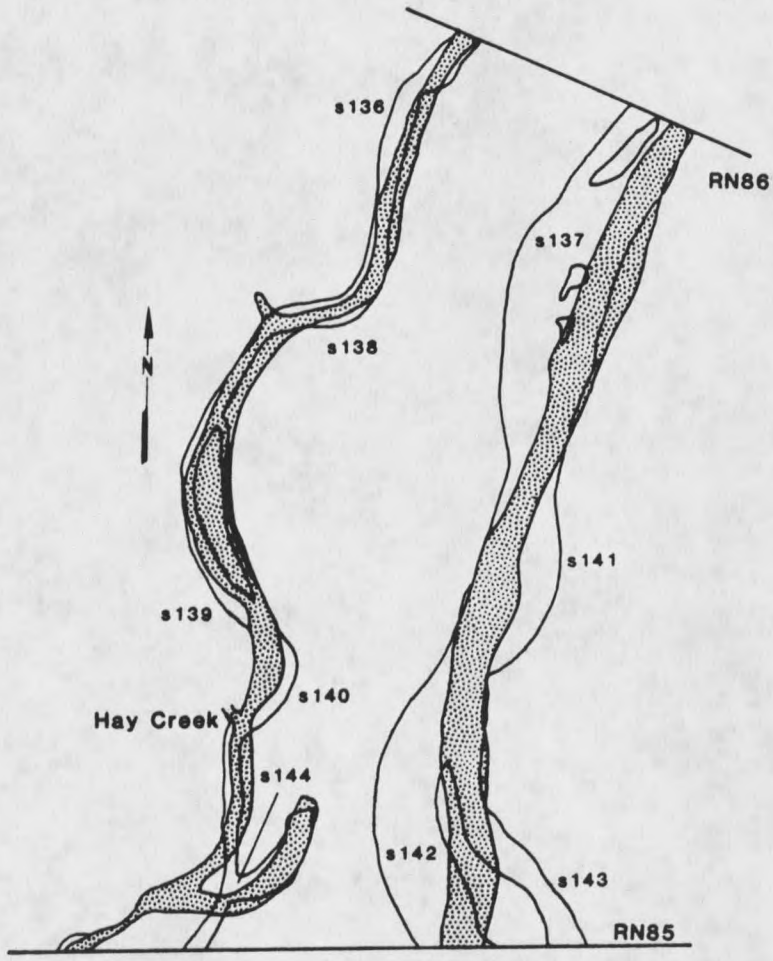

Figure 27. Erosional area map near Hay Creek -- reach 85.

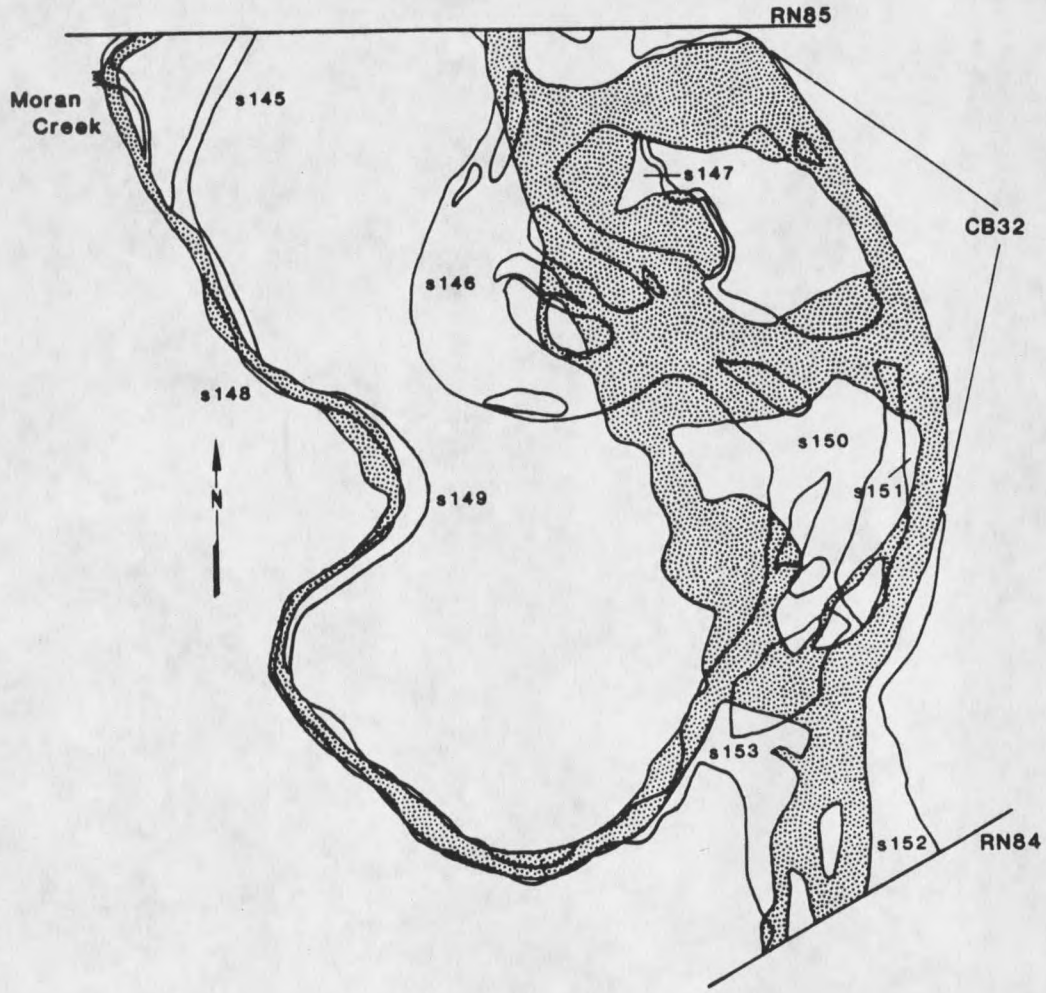

Figure 28. Erosional area map near Moran Creek -- reach 84.

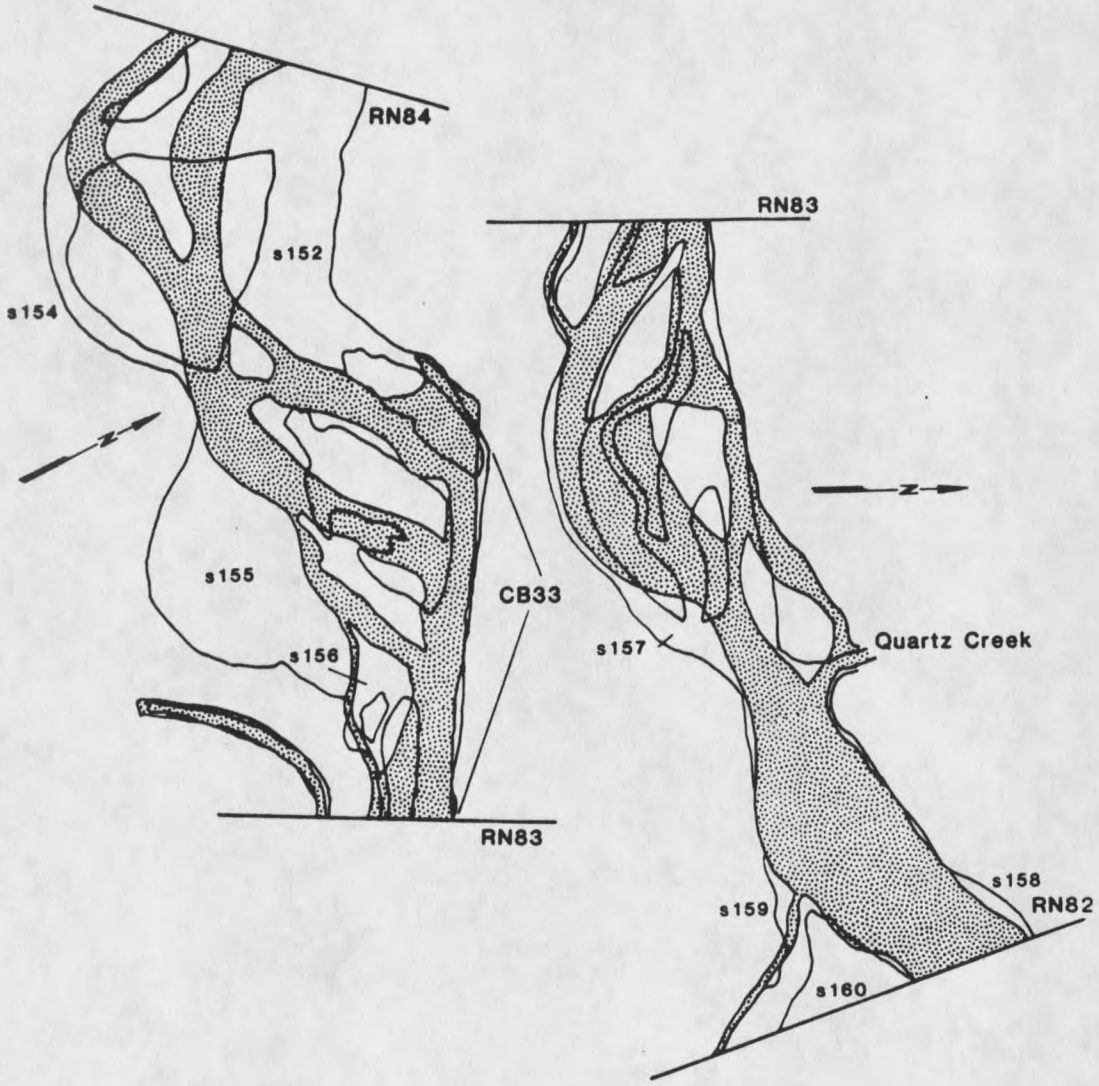

Figure 29. Erosional area map near Quartz Creek -- reaches 83 and 82.

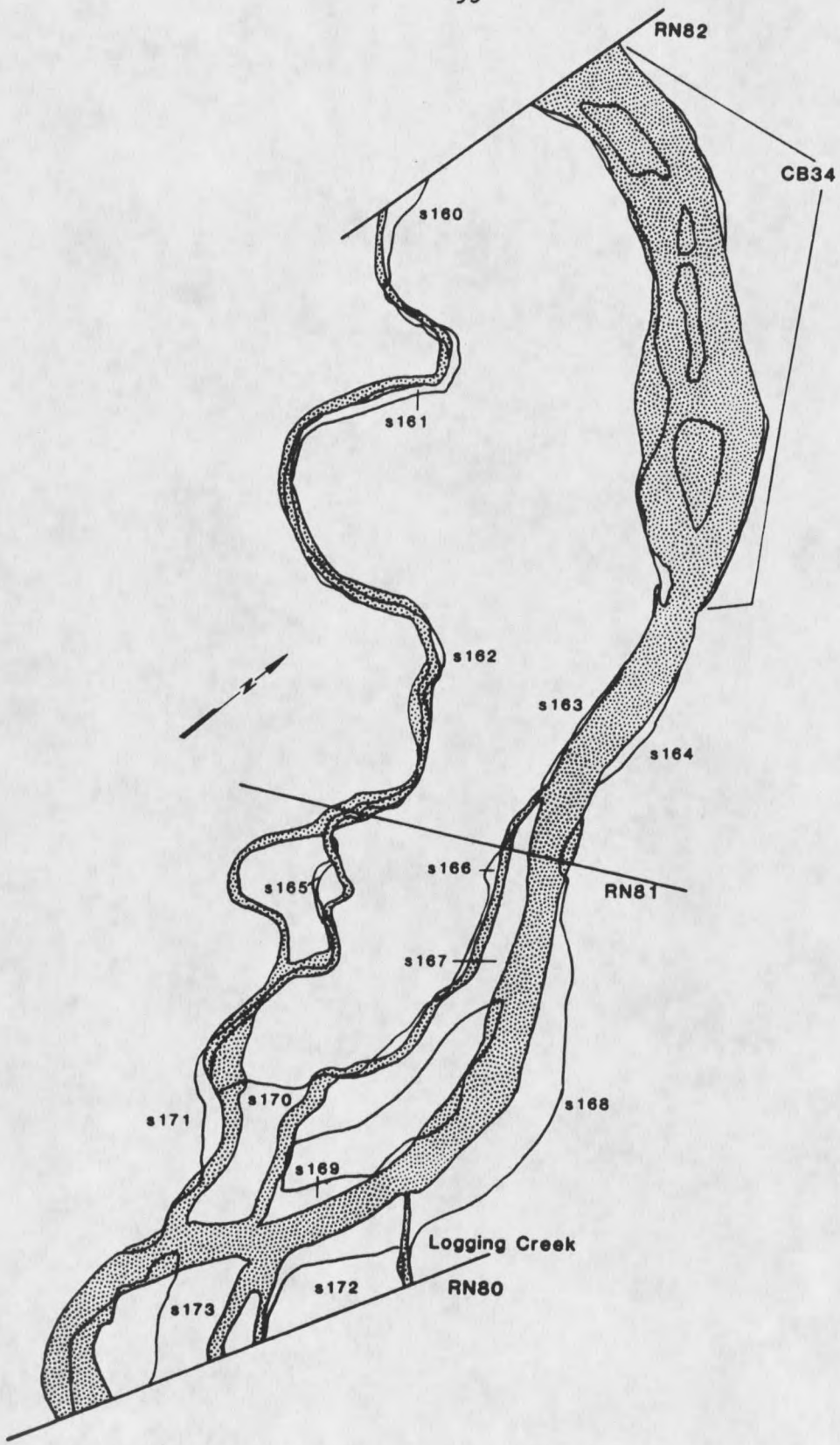

Figure 30. Erosional area map near Logging Creek -- reaches 81 and 80.

APPENDIX B

EROSIONAL VOLUMES AND MIGRATION RATES

Table 9. Erosional volumes and migration rates.

bank number	reach number	type of bank *	alluvium height (m)	claystone height (m)	glacial height (m)	total bank height (m)	low volume estimate (m^3)	medium volume est. (m^3)	high volume est. (m^3)	total migration (m)	average migration rate (m/yr)
1.	113.	1.	1.4	0.0	0.0	1.4	0.	1440.	4853.	7.0	0.2
2.	113.	1.	1.8	0.0	0.0	1.8	14506.	24005.	34405.	69.6	1.9
3.	113.	1.	1.5	0.0	0.0	1.5	4343.	12224.	22767.	20.9	0.6
4.	113.	1.	2.0	0.0	0.0	2.0	7844.	20006.	36941.	48.7	1.4
5.	112.	1.	1.4	0.0	0.0	1.4	10409.	18726.	30528.	66.1	1.8
6.	112.	1.	0.9	0.0	0.0	0.9	328.	1136.	2550.	17.4	0.5
7.	112.	1.	0.2	0.0	0.0	0.2	619.	1276.	1810.	0.0	0.0
8.	112.	1.	1.8	0.0	0.0	1.8	47353.	67287.	86870.	73.1	2.0
9.	112.	1.	0.6	0.0	0.0	0.6	4110.	6683.	9200.	69.6	1.9
1.	112.	4.	0.0	0.0	8.0	8.0	49825.	74995.	98951.	66.1	1.8
10.	112.	1.	0.9	0.0	0.0	0.9	27951.	37933.	47900.	87.0	2.4
11.	111.	1.	2.0	0.0	0.0	2.0	48074.	64284.	83137.	76.6	2.1
12.	111.	1.	1.2	0.0	0.0	1.2	11763.	19059.	22488.	17.4	0.5
13.	111.	1.	1.5	0.0	0.0	1.5	1309.	5567.	11794.	24.4	0.7
14.	111.	1.	2.1	0.0	0.0	2.1	9349.	19623.	31547.	24.4	0.7
15.	111.	1.	1.2	0.0	0.0	1.2	18977.	26421	33666.	83.5	2.3
2.	111.	3.	0.0	10.0	6.0	16.1	0.	27018.	82548.	7.0	0.2
16.	111.	1.	0.2	0.0	0.0	0.2	78.	658.	1320.	0.0	0.0
3.	110.	3.	0.0	9.6	2.7	12.2	0.	7945.	9778.	3.5	0.1
4.	110.	2.	0.0	3.7	0.0	3.7	0.	9623.	17528.	3.5	0.1
17.	110.	1.	0.9	0.0	0.0	0.9	20809	30706.	38696.	52.2	1.4
18.	110.	1.	0.2	0.0	0.0	0.2	142.	402.	608.	0.0	0.0
19.	110.	1.	0.9	0.0	0.0	0.9	572.	2586.	3591.	24.4	0.7
20.	109.	1.	0.2	0.0	0.0	0.2	0.	982.	2187.	0.0	0.0
21.	109.	1.	0.9	0.0	0.0	0.9	21546.	28527.	36641.	76.6	2.1
22.	109.	1.	0.2	0.0	0.0	0.2	4871.	6169.	7642.	0.0	0.0
23.	109.	1.	0.6	0.0	0.0	0.6	7641.	10269.	11837.	87.0	2.4
24.	109.	1.	0.6	0.0	0.0	0.6	14902.	17784.	21168.	104.4	2.9
25.	109.	1.	0.6	0.0	0.0	0.6	510.	2513.	5008.	17.4	0.5
26.	109.	1.	0.6	0.0	0.0	0.6	7738.	11596.	15357.	34.8	1.0
27.	109.	1.	0.2	0.0	0.0	0.2	440.	942.	1520.	0.0	0.0
28.	109.	1.	0.6	0.0	0.0	0.6	213.	805.	1693.	17.4	.5
29.	109.	1.	0.6	0.0	0.0	0.6	1496.	2451.	3472.	69.6	1.9
30.	109.	1.	0.6	0.0	0.0	0.6	4022.	5549.	7145.	69.6	1.9
31.	108.	1.	0.6	0.0	0.0	0.6	9053.	12461.	16461.	132.2	3.7
32.	108.	1.	0.2	0.0	0.0	0.2	3104.	4517.	6135.	0.0	0.0
33.	108.	1.	0.6	0.0	0.0	0.6	1183.	3386.	6713.	27.8	0.8
34.	108.	1.	1.5	0.0	0.0	1.5	4378.	11348.	17480.	31.3	0.9
35.	108.	1.	0.2	0.0	0.0	0.2	645.	1237.	2004.	0.0	0.0
36.	108.	1.	1.2	0.0	0.0	1.2	896.	4038.	8768.	20.9	0.6
37.	108.	1.	0.3	0.0	0.0	0.3	694.	1462.	2309.	34.8	1.0

Table 9--Continued

bank number	reach number	type of bank *	alluvium height (m)	claystone height (m)	glacial height (m)	total bank height (m)	low volume estimate (m^3)	medium volume est. (m^3)	high volume est. (m^3)	total migration (m)	average migration rate (m/yr)
38.	108.	1.	1.5	0.0	0.0	1.5	2344	5183.	8806.	34.8	1.0
39.	108.	1.	0.3	0.0	0.0	0.3	1957.	3176.	4260.	62.6	1.7
40.	108.	1.	0.2	0.0	0.0	0.2	2561.	3606.	4713.	0.0	0.0
41.	108.	1.	0.2	0.0	0.0	0.2	2366.	3227.	4085.	0.0	0.0
42.	107.	1.	1.2	0.0	0.0	1.2	85355.	110956.	136836.	104.4	2.9
5.	107.	4.	0.0	0.0	3.7	3.7	46543.	71290.	98389.	55.7	1.5
43.	107.	1.	0.9	0.0	0.0	0.9	4607.	7784.	11507.	52.2	1.4
44.	107.	1.	0.9	0.0	0.0	0.9	16603.	23140.	28447.	69.6	1.9
45.	106.	1.	1.2	0.0	0.0	1.2	2988.	5883.	8612.	48.7	1.4
46.	106.	1.	1.1	0.0	0.0	1.1	0.	901.	3220.	10.4	0.3
47.	106.	1.	1.2	0.0	0.0	1.2	6435.	13204.	22493.	45.2	1.3
48.	106.	1.	0.6	0.0	0.0	0.6	0.	2296.	5180.	13.9	0.4
49.	106.	1.	0.6	0.0	0.0	0.6	0.	807.	2494.	10.4	0.3
50.	105.	1.	0.6	0.0	0.0	0.6	0.	1626.	3792.	10.4	0.3
6.	105.	3.	0.0	5.9	10.4	16.3	0.	11480.	50486.	7.0	0.2
7.	105.	3.	0.0	22.8	5.3	28.1	0.	47235.	191220.	10.4	0.3
51.	105.	1.	0.3	0.0	0.0	0.3	1198.	2589.	3803.	17.4	0.5
8.	104.	4.	0.0	0.0	17.0	17.0	0.	6378.	10120.	3.5	0.1
52.	104.	1.	0.3	0.0	0.0	0.3	23.	997.	2750.	7.0	0.2
53.	104.	1.	0.9	0.0	0.0	0.9	0.	1748.	5485.	17.4	0.5
54.	104.	1.	0.6	0.0	0.0	0.6	0.	366.	838.	3.5	0.1
9.	104.	3.	0.0	18.2	24.4	42.6	0.	59698.	132189.	3.5	0.1
55.	104.	1.	0.6	0.0	0.0	0.6	542.	1868.	3445.	27.8	0.8
56.	103.	1.	1.2	0.0	0.0	1.2	0.	366.	2416.	17.4	0.5
10.	104.	2.	0.0	6.7	0.0	6.7	0.	0.	0.	0.0	0.0
11.	103.	4.	0.0	0.0	18.7	18.7	58747.	151367.	264176.	31.3	0.9
57.	103.	1.	0.0	0.0	0.0	.3	2034.	3707.	5090.	48.7	1.4
12.	103.	3.	0.0	12.3	10.4	22.7	62143.	169581.	276245.	17.4	0.5
58.	102.	1.	2.1	0.0	0.0	2.1	9926.	22044.	34840.	62.6	1.7
58a.	102.	1.	0.6	0.0	0.0	0.6	6846.	12907.	18334.	69.6	1.9
59.	102.	1.	0.6	0.0	0.0	0.6	5287.	7772.	9891.	55.7	1.5
13.	102.	4.	0.0	0.0	14.2	14.2	8224.	49088.	86003.	17.4	0.5
60.	101.	1.	0.3	0.0	0.0	0.3	3734.	6570.	9449.	87.0	2.4
61.	101.	1.	1.2	0.0	0.0	1.2	17465.	28377.	39936.	34.8	1.0
62.	101.	1.	0.8	0.0	0.0	0.8	291.	1469.	2734.	24.4	0.7
14.	101.	3.	0.0	7.6	4.1	11.7	0.	0.	0.	0.0	0.0
63.	101.	1.	0.8	0.0	0.0	0.8	584.	2498.	4852.	27.8	0.8
64.	100.	1.	0.8	0.0	0.0	0.8	0.	286.	1612.	13.9	0.4
15.	100.	3.	0.0	14.3	10.8	25.1	14983.	230702.	482927.	20.9	0.6
65.	100.	1.	1.5	0.0	0.0	1.5	0.	4628.	12344.	20.9	0.6
66.	100.	1.	1.2	0.0	0.0	1.2	946.	6150.	14510.	13.9	0.4
16.	100.	3.	0.0	6.4	1.8	8.2	0.	22442.	76502.	13.9	0.4
67.	99.	1.	0.9	0.0	0.0	0.9	913.	4798.	10865.	24.4	0.7

Table 9--Continued

bank number	reach number	type of bank *	alluvium height (m)	claystone height (m)	glacial height (m)	total bank height (m)	low volume estimate (m^3)	medium volume est. (m^3)	high volume est. (m^3)	total migration (m)	average migration rate (m/yr)
68.	99.	1.	1.5	0.0	0.0	1.5	20123.	33949.	51427.	83.5	2.3
17.	99.	3.	0.0	4.6	5.5	10.1	0.	37095.	100091.	10.4	.3
69.	99.	1.	0.9	0.0	0.0	0.9	7510.	13478.	19627.	73.1	2.0
70.	99.	1.	1.2	0.0	0.0	1.2	5172.	11117.	19208.	38.3	1.1
71.	98.	1.	1.4	0.0	0.0	1.4	3344.	8834.	14278.	38.3	1.1
72.	98.	1.	0.9	0.0	0.0	0.9	0.	1586.	3915.	17.4	0.5
18.	98.	3.	0.0	1.7	1.5	3.2	0.	5108.	14210.	20.9	0.6
73.	98.	1.	0.8	0.0	0.0	0.8	8469.	13937.	20520.	62.6	1.7
19.	98.	3.	0.0	6.9	7.4	14.4	12920.	140539.	292132.	17.4	0.5
74.	97.	1.	0.8	0.0	0.0	0.8	5109.	12664.	20572.	41.8	1.2
75.	97.	1.	0.9	0.0	0.0	0.9	4369.	14449.	25040.	45.2	1.3
76.	97.	1.	0.9	0.0	0.0	0.9	4887.	10473.	15121.	34.8	1.0
77.	96.	1.	0.9	0.0	0.0	0.9	1801.	6663.	11826.	34.8	1.0
78.	96.	1.	0.9	0.0	0.0	0.9	457.	1846.	3071.	20.9	0.6
20.	96.	3.	0.0	25.5	5.9	31.5	34634.	194488.	346061.	17.4	0.5
79.	96.	1.	1.2	0.0	0.0	1.2	0.	884.	1865.	10.4	0.3
21.	96.	3.	0.0	2.7	2.7	5.5	0.	4373.	24233.	3.5	0.1
80.	96.	1.	0.6	0.0	0.0	0.6	1915.	4049.	6518.	38.3	1.1
22.	96.	3.	0.0	0.6	2.4	3.0	37896.	63557.	87959.	52.2	1.4
81.	96.	1.	0.9	0.0	0.0	0.9	0.	160.	297.	3.5	0.1
82.	95.	1.	1.1	0.0	0.0	1.1	7261.	16311.	23807.	38.3	1.1
83.	95.	1.	1.2	0.0	0.0	1.2	0.	3654.	8734.	17.4	0.5
84.	95.	1.	0.9	0.0	0.0	0.9	6642.	13076.	20975.	34.8	1.0
85.	95.	1.	0.2	0.0	0.0	0.2	2594.	3365.	4222.	0.0	0.0
23.	95.	3.	0.0	1.2	2.7	4.0	4691.	5302.	10346.	17.4	0.5
86.	94.	1.	0.2	0.0	0.0	0.2	8599.	9997.	11036.	0.0	0.0
24.	94.	3.	0.0	7.0	4.4	11.4	2115.	125033.	308690.	13.9	0.4
87.	94.	1.	1.2	0.0	0.0	1.2	4621.	13887.	24093.	38.3	1.1
88.	94.	1.	0.9	0.0	0.0	0.9	569.	4841.	9312.	20.9	0.6
89.	94.	1.	1.5	0.0	0.0	1.5	1143.	3063.	9606.	34.8	1.0
25.	93.	3.	0.0	4.9	7.0	11.9	14526.	74247.	143490.	17.4	0.5
90.	93.	1.	1.5	0.0	0.0	1.5	22593.	34991.	49253.	76.6	2.1
91.	93.	1.	1.2	0.0	0.0	1.2	16780.	26743.	31543.	87.0	2.4
92.	93.	1.	1.2	0.0	0.0	1.2	4256.	9496.	15174.	27.8	0.8
26.	93.	3.	0.0	5.0	4.7	9.8	0.	13509.	32119.	24.4	0.7
93.	93.	1.	2.1	0.0	0.0	2.1	1173.	20826.	61454.	24.4	0.7
94.	92.	1.	0.6	0.0	0.0	0.6	107.	716	3341.	3.5	0.1
95.	92.	1.	0.6	0.0	0.0	0.6	0.	27.	841.	13.9	0.4
96.	92.	1.	1.5	0.0	0.0	1.5	1914.	6622.	12570.	24.4	0.7
97.	92.	1.	0.9	0.0	0.0	0.9	3607.	8693.	16492.	59.2	1.6
27.	92.	3.	0.0	2.3	12.6	14.8	0.	4444.	66467.	3.5	0.1
98.	91.	1.	1.2	0.0	0.0	1.2	14729.	28437.	41792.	66.1	1.8
99.	91.	1.	0.6	0.0	0.0	0.6	0.	728.	1565.	7.0	0.2

Table 9--Continued

bank number	reach number	type of bank *	alluvium height (m)	claystone height (m)	glacial height (m)	total bank height (m)	low volume estimate (m^3)	medium volume est. (m^3)	high volume est. (m^3)	total migration (m)	average migration rate (m/yr)
28.	91.	3.	0.0	24.0	11.3	35.4	158110.	408511.	644261.	20.9	.6
100.	91.	1.	0.9	0.0	0.0	0.9	39895.	48693.	55612	125.3	3.5
101.	90.	1.	0.2	0.0	0.0	0.2	3049.	3820.	4585.	38.3	1.1
102.	90.	1.	0.9	0.0	0.0	0.9	65897.	76522.	88554.	215.7	6.0
103.	90.	1.	0.2	0.0	0.0	0.2	14593.	17316.	19853.	0.0	0.0
104.	89.	1.	0.9	0.0	0.0	0.9	8297.	12174.	15463.	69.6	1.9
105.	89.	1.	0.6	0.0	0.0	0.6	35325.	42206.	49796.	139.2	3.9
106.	89.	1.	0.2	0.0	0.0	0.2	134.	412.	697.	0.0	0.0
107.	89.	1.	0.9	0.0	0.0	0.9	1189.	4007.	7291.	20.9	0.6
108.	89.	1.	0.2	0.0	0.0	0.2	96.	294.	546.	0.0	0.0
109.	89.	1.	0.6	0.0	0.0	0.6	2772.	5032.	7813.	55.7	1.5
110.	89.	1.	0.2	0.0	0.0	0.2	709.	1842.	2552.	0.0	0.0
111.	89.	1.	0.2	0.0	0.0	0.2	0.	430.	1355.	0.0	0.0
112.	89.	1.	0.2	0.0	0.0	0.2	0.	330.	881.	0.0	0.0
113.	89.	1.	0.2	0.0	0.0	0.2	33.	160.	356.	0.0	0.0
114.	88.	1.	0.5	0.0	0.0	0.5	0.	278.	776.	17.4	0.5
115.	88.	1.	0.9	0.0	0.0	0.9	465.	2387.	4273.	20.9	0.6
116.	88.	1.	0.9	0.0	0.0	0.9	600.	2452.	5088.	24.4	0.7
117.	88.	1.	0.9	0.0	0.0	0.9	372.	3625.	7269.	13.9	0.4
29.	88.	3.	0.0	23.5	21.3	44.8	0.	0.	0.	0.0	0.0
118.	88.	1.	0.2	0.0	0.0	0.2	0.	247.	533.	7.0	0.2
119.	88.	1.	0.2	0.0	0.0	0.2	0.	47.	213.	3.5	0.1
120.	88.	1.	0.2	0.0	0.0	0.2	0.	40.	172.	3.5	0.1
121.	88.	1.	0.9	0.0	0.0	0.9	24208.	16583.	39431.	90.5	2.5
30.	87.	3.	0.0	8.8	21.3	30.2	0.	94871.	243152.	13.9	0.4
122.	87.	1.	0.5	0.0	0.0	0.5	2176.	8663.	13753.	38.3	1.1
123.	87.	1.	1.2	0.0	0.0	1.2	5784.	11083.	16413.	41.8	1.2
124.	87.	1.	0.3	0.0	0.0	0.3	1046.	3542.	5848.	20.9	0.6
125.	87.	1.	0.2	0.0	0.0	0.2	1626.	2493.	3459.	0.0	0.0
31.	86.	3.	0.0	8.8	23.2	32.0	0.	242302.	539779.	13.9	0.4
126.	87.	1.	0.8	0.0	0.0	0.8	610.	2544.	5549.	17.4	0.5
127.	86.	1.	0.2	0.0	0.0	0.2	7183.	9563.	11863.	0.0	0.0
128.	86.	1.	0.3	0.0	0.0	0.3	692.	1378.	2190.	41.8	1.2
129.	86.	1.	0.3	0.0	0.0	0.3	1127.	1964.	2970.	38.3	1.1
130.	86.	1.	0.3	0.0	0.0	0.3	350.	859.	1368.	41.8	1.2
131.	86.	1.	0.3	0.0	0.0	0.3	884.	1834.	2796.	34.8	1.0
132.	86.	1.	0.8	0.0	0.0	0.8	3409.	5962.	8633.	41.8	1.2
133.	86.	1.	0.8	0.0	0.0	0.8	13539.	14254.	31509.	27.8	0.8
134.	86.	1.	0.3	0.0	0.0	0.3	1925.	4599.	7577.	41.8	1.2
135.	86.	1.	0.3	0.0	0.0	0.3	263.	750.	1256.	45.2	1.3
136.	85.	1.	0.3	0.0	0.0	0.3	696.	2257.	3843.	24.4	0.7
137.	85.	1.	0.9	0.0	0.0	0.9	39203.	53193.	67038.	111.4	3.1
138.	85.	1.	0.3	0.0	0.0	0.3	301.	1291.	2459.	20.9	0.6

Table 9--Continued

bank number	reach number	type of bank *	alluvium height (m)	claystone height (m)	glacial height (m)	total bank height (m)	low volume estimate (m^3)	medium volume est. (m^3)	high volume est. (m^3)	total migration (m)	average migration rate (m/yr)
139.	85.	1.	0.3	0.0	0.0	0.3	16.	560.	1340.	20.9	0.6
140.	85.	1.	0.3	0.0	0.0	0.3	608.	1636.	2703.	20.9	0.6
141.	85.	1.	0.9	0.0	0.0	0.9	12759.	20820.	28630.	66.1	1.8
142.	85.	1.	0.9	0.0	0.0	0.9	24791.	31782.	38836.	97.4	2.7
143.	85.	1.	0.2	0.0	0.0	0.2	3162.	4402.	5476.	0.0	0.0
144.	85.	1.	0.2	0.0	0.0	0.2	19.	253.	463.	0.0	0.0
145.	84.	1.	0.2	0.0	0.0	0.2	1095.	2359.	3684.	0.0	0.0
146.	84.	1.	0.5	0.0	0.0	0.5	29102.	33670.	38708.	160.1	4.4
147.	84.	1.	0.2	0.0	0.0	0.2	461.	777.	1095.	0.0	0.0
148.	84.	1.	0.3	0.0	0.0	0.3	0.	294.	904.	3.5	0.1
32.	84.	3.	0.0	20.0	26.9	46.9	0.	96054.	345868.	3.5	0.1
149.	84.	1.	0.3	0.0	0.0	0.3	1900.	3806.	5666.	38.3	1.1
150.	84.	1.	0.2	0.0	0.0	0.2	4629.	5764.	6765.	0.0	0.0
151.	84.	1.	0.2	0.0	0.0	0.2	69.	293.	622.	0.0	0.0
152.	83.	1.	0.9	0.0	0.0	0.9	72666.	91251.	105110.	191.4	5.3
153.	84.	1.	.2	0.0	0.0	0.2	2835.	4222.	5348.	0.0	0.0
154.	83.	1.	0.3	0.0	0.0	0.3	2624.	4827.	6633.	0.0	0.0
155.	83.	1.	0.5	0.0	0.0	0.5	30835.	34709.	42330.	243.6	6.8
156.	83.	1.	0.2	0.0	0.0	0.2	730.	1238.	1747.	0.0	0.0
33.	83.	3.	0.0	5.5	25.0	30.5	26548.	270175.	641025.	3.5	0.1
157.	82.	1.	0.5	0.0	0.0	0.5	2489.	6473.	10689.	87.0	2.4
158.	82.	1.	0.9	0.0	0.0	0.9	1150.	5072.	8809.	24.4	0.7
34.	81.	3.	0.0	6.0	22.6	28.6	309747.	779599.	1230858.	17.4	0.5
159.	82.	1.	0.3	0.0	0.0	0.3	42.	353.	830.	24.4	0.7
160.	82.	1.	0.3	0.0	0.0	0.3	2208.	4270.	6481.	59.2	1.6
161.	81.	1.	0.3	0.0	0.0	0.3	136.	2191.	4360.	31.3	0.9
162.	81.	1.	0.3	0.0	0.0	0.3	0.	235.	573.	13.9	0.4
163.	81.	1.	0.8	0.0	0.0	0.8	0.	1669.	4608.	3.5	0.1
164.	81.	1.	0.9	0.0	0.0	0.9	192.	3763.	7154.	17.4	0.5
165.	80.	1.	0.2	0.0	0.0	0.2	0.	176.	543.	0.0	0.0
166.	80.	1.	0.3	0.0	0.0	0.3	0.	1054.	2215.	20.9	0.6
167.	80.	1.	0.5	0.0	0.0	0.5	11055.	17008.	22011.	87.0	2.4
168.	80.	1.	0.9	0.0	0.0	0.9	27539.	36574.	45699.	76.6	2.1
169.	80.	1.	0.2	0.0	0.0	0.2	505.	1282.	2018.	0.0	0.0
170.	80.	1.	0.2	0.0	0.0	0.2	2868.	3810.	4709.	0.0	0.0
171.	80.	1.	0.3	0.0	0.0	0.3	1012.	2111.	3223.	38.3	1.1
172.	80.	1.	0.9	0.0	0.0	0.9	6762.	11075.	15528.	48.7	1.4
173.	80.	1.	0.2	0.0	0.0	0.2	1156.	1964.	2656.	0.0	0.0

* Type of bank 1) Recent floodplain alluvium
2) Tertiary claystone
3) Tertiary claystone overlain by Quaternary glacial-fluvial sediments
4) Quaternary glacial-fluvial sediments

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