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Bank erosion and metal loading in a contaminated floodplain system upper Clark Fork River Valley Montana

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Bank Erosion and Metal Loading in a Contaminated Floodplain System, Upper Clark Fork River Valley, Montana

By

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Abstract

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Director: Johnnie N. Moore

Field mapping and aerial photographic analyses were used to examine and quantify channel and floodplain changes in the upper Clark Fork River Valley. The effects that tailings deposits, vegetation, channel morphology, and bank stratigraphy have on bank erosion were also investigated. Within the study areas, there is substantial channel migration. The outside of meanders at Grant-Kohrs Ranch National Historic Site are eroding at approximately 0.5 meters/year, and all the banks are migrating at 0.19 $m^2/m/yr$. Approximately 740m^2 of floodplain are reworked each year at this site, and it will take around 1000 years to rework the Grant-Kohrs Ranch floodplain (and the tailings deposited there) once. Most of the meander belt is contaminated with metals-rich tailings deposits (As (metalloid), Cu, Cd, Pb, and Zn). At the present erosion rates, several tons of these metals are loaded to the river channel each year. The position of eroding banks is controlled dominantly by the morphology of the river channel. The coincidence of riffles on meander bends is associated with the largest amount of erosion and cutbank formation. Most of the erosion is occurring during extreme flow events. The presence of vegetation and tailings thickness seem to have little affect on the position and amount of erosion. The unconsolidated/non-cohesive gravel and pre-mining floodplain deposits at the base of the banks are easily eroded, leaving overhangs that can cave into the river channel. Banks are unstable partly due to the lack of deep-penetrating roots into the lower layers. The deposition of tailings on the floodplain has elevated the floodplain surface, exacerbating the effects from metals loading and preventing plants from reaching moisture and stabilizing the lower levels of the banks. Vegetation cover also appears to be mostly controlled by moisture. During dry years, woody vegetation is senescent/dead in some floodplain areas but grows again during wet years. Although fairly stable over long time periods, slickens also seem to adjust their coverage with changes in moisture. Overall, the floodplain system is extremely variable and dynamic, and these factors much be taken into account for future restoration and management plans.

Acknowledgements

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INTRODUCTION

Heavy metals in aquatic systems are closely associated with particulate matter (Gibbs 1977; Lambing 1991). Therefore, fluvial processes are extremely important in the transport and redistribution of metals, especially downstream from mine sites that act as sources for metal contaminated sediment (Miller 1997). Numerous studies document the transport, deposition, and remobilization of metal-enriched, mining sediments (Gilbert 1917; Lewin, et al. 1977; Graf 1979; Lewin, et al. 1983; Knighton 1989; James 1991; Miller, et al. 1998). Most of these investigations show that the transport processes vary from river to river, and even between river reaches. They also indicate that the dispersal of mining waste by river processes generally depends on threshold events caused by mining induced changes in water and sediment supply. A small change in one of the variables may lead to minor geomorphic changes, but once the shift in sediment or discharge reaches a critical point, the river can undergo significant alterations in erosivity, channel bed and/or floodplain height, sinuosity, width-to-depth ratios, river plan form, et cetera (Knighton 1989; Miller 1997). These changes in geomorphic forms and processes greatly influence the distribution and potential remobilization of the sediment and heavy metals within a watershed (Lewin and Macklin 1987).

During the late 1800s and early 1900s, large-scale mining and milling operations near Butte and Anaconda, Montana, produced large amounts of gold, silver, copper, and other metals. The removal and subsequent processing of these metals created vast quantities of contaminated tailings that were disposed of in and along the headwater tributaries of the Clark Fork River (Quivik 1998). Periodic high discharges in these streams eroded and transported a portion of the tailings, which were ultimately re-

deposited throughout the upper Clark Fork River Valley. The redistribution of mining wastes has resulted in elevated concentrations of As (metalloid), Cd, Cu, Mn, Pb, and Zn in the system's sediments and water, and the potential effect of these metals on life in the river, as well as in the floodplain, is an ongoing concern (Rice and Ray 1985; Moore and Luoma 1990; Axtmann and Luoma 1991; Smith, et al. 1998). The entire river corridor is now the target of a major EPA Superfund restoration effort (EPA 2002).

Throughout the Deer Lodge Valley, the Clark Fork River exhibits most of the behaviors of a meandering river system. Like most meandering alluvial rivers, the channel is constantly winding across the floodplain, eroding the outside of meander bends, and depositing material on the inside of the bends (Hickin and Nanson 1975; Hooke 1984; Knighton 1998). Numerous factors contribute to these processes, including a river's flow properties, channel geometry, bank material, biological activity, and anthropogenic inputs (Knighton 1998). Previous observations in the study reach showed that the floodplain morphology has been drastically altered by deposition of mining wastes and that a significant portion of the banks along the Clark Fork River are undergoing erosion (Riparian Wetland Research Program (RWRP) 1996; R2 Resources, Inc. 1998). Because the Clark Fork River floodplain, including the study reach, contains tailings and soils with elevated metals concentrations (Brooks 1988; Nimick 1990, Shafer and Associates 1997), bank erosion provides a mechanism for contaminated sediments to return to the river (Nimick 1990; Smith, et al. 1998). In turn, the fine sediments clog gravel beds, which are important to fish and benthic invertebrates, and increase the metal loads in the river itself (Nagorski 1993; Smith, et al. 1998).

The purpose of this work is to examine and quantify channel and floodplain changes within the study reach, and ascertain the role of deposited mine tailings in those changes. Floodplain vegetation dynamics, stratigraphy, morphology, and bank erosion were investigated to determine the amount of alteration, as well as the processes responsible for them. Studying the floodplain modifications and adjustments within the study reach is important because it leads to a better understanding of the effects of floodplain deposition and storage of contaminated sediments within the Upper Clark Fork Basin, as well as their remobilization. Further evaluation provides rates and magnitudes of change in the river system today, as well as indicates how current and future anthropogenic alterations may affect the system, including the movement and effects of metal-contaminated sediments. On a broader level, this study may also provide additional data on how rivers adjust to large influxes of fine-grained sediment and mine waste.

Previous Work

Due to its Superfund designation, the floodplain of the upper Clark Fork River has been examined by a number of researchers. Rice and Ray (1985), LeJeune, et al. (1996), CH2MHill (1996), the RWRP (1996), Kaputska (2002), and Rice (2002) completed studies on the communities, extent, and vitality of vegetation within the floodplain. These studies showed that metals in the floodplain sediments, along with land use practices such as grazing, seem to decrease the vigor of many plant types and their respective communities, especially in the upper valley. However, many important species, such as willows (*Salix spp.*), exhibit a surprising level of metal tolerance as well

(Rice and Ray 1985, RWRP 1996, Lejeune, et al. 1996). Also, a few researchers have noted that the presence of woody vegetation decreases bank erosion within the valley (RWRP 1996; Smith, et al. 1998).

Investigations documenting the extent, stratigraphy, and chemistry of tailings have been completed by Brooks (1988), Moore and Louma (1990), Nimick (1990), and Shafer and Associates, Inc. (1997). These studies show that tailings are deposited throughout the floodplain, especially in the Deer Lodge Valley, but that the thickness and metal concentrations are highly variable.

Geomorphic changes within the Upper Clark Fork have also been documented. Brooks (1988) found numerous small channels running through the floodplain at her study site and attributed them to a cycle of aggradation from mine tailings, followed by degradation once mining ceased and the sediment supply was cut off. The RWRP (1996) estimated tailings thickness and noted general channel characteristics and the locations of bank cutting in 1994. Nimick (1990) and Smith, et al. (1998) speculated that the tailings deposits are fairly simple, homogenous flood deposits from suspension settle-out during the 1908 flood. Using channel centerline data from 1960 and 1989 air photos, R2 Consulting calculated erosion rates for the whole upper basin. R2 Consulting used these data in combination with suspended and bedload sediment data to model sediment and metal movement throughout the valley. Finally, Smith, et al. (1998) provided a comprehensive review of the movement of contaminated particulate through the Clark Fork System.

This study differs from the previous studies by providing a detailed analysis of one river reach within the Deer Lodge Valley, and comparing it to river sections

upstream and downstream within the valley. It attempts to describe floodplain alterations, as well as evaluate the processes that are causing these changes, in detail, unlike many of the other studies which tend to make generalizations about the whole upper valley based on limited site investigations. Areas of erosion, as opposed to centerline offsets (linear), were estimated from numerous aerial photograph comparisons and many hours were spent evaluating and observing the banks along the same stretch of river.

Site Description

The primary reach of concern is the 4 km of Clark Fork River within Grant-Kohrs Ranch National Historic Site, directly north of Deer Lodge, Montana (Figure 1). The river bisects the ranch, flowing from south to north. Two small tributary streams, Cottonwood and Johnson Creeks, and a small spring fed creek enter the river within the ranch property. The Kohrs-Manning Irrigation Ditch, which traverses the ranch, diverts water from the channel just south of the property. The floodplain makes up a large portion of the ranch land, with the rest consisting of elevated benches cut by small tributaries. The low gradient (.0020), meandering (sinuosity = 1.62) channel is composed primarily of gravels, with some sandy stretches, arranged in a series of point bars, riffles, and pools, separated by long continuous runs (RWRP 1996).

Two other sites were selected for air photo analysis, one just downstream from Racetrack, MT, and the other just upstream from Garrison, MT (Figure 2). These two floodplain segments possess similar characteristics to the Grant-Kohrs Ranch site, and

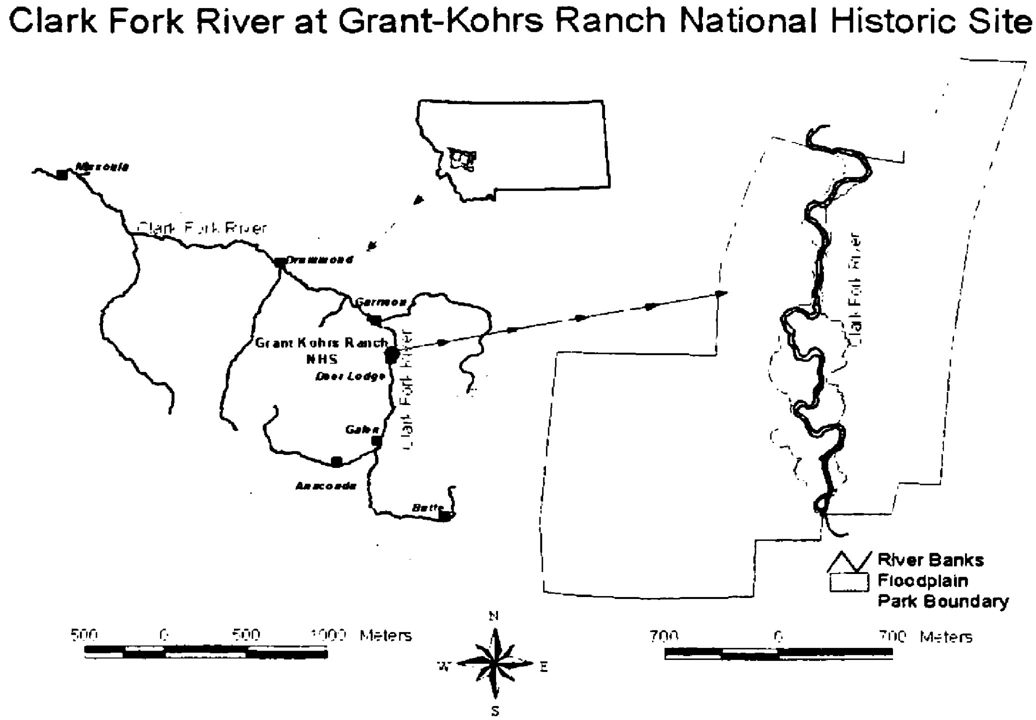


Figure 1. Location Map for the study reach, Grant-Kohrs Ranch, NHS.

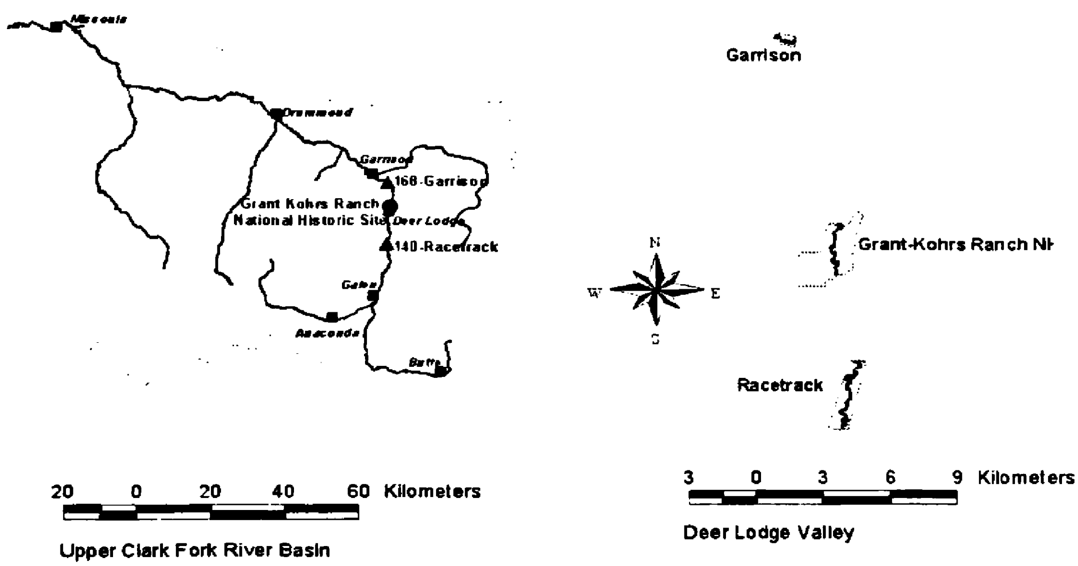


Figure 2. Site locations for additional aerial photography analysis along the Clark Fork River in the Deer Lodge Valley. Garrison site lies upstream from Grant-Kohrs Ranch NHS, and the Racetrack site is downstream.

although no fieldwork was completed in these areas, the descriptions of the Grant-Kohrs Ranch site generally apply to them as well.

The geology of the Deer Lodge Valley consists mostly of Quaternary alluvium and Tertiary basin fill, with some Cretaceous sedimentary rock in the uplands. The basin fill consists of volcanic clays and gravels (Figure 3: Raines and Johnson 1996). Although often covered with tailings, the native floodplain soils are mostly fluvial silts, fine-to-coarse sands, and gravels, with small areas of wetland soils (RWRP 1996; Moynahan 1999; Rice and Ray 1985). The soils formed primarily from overbank and bar deposits from the river. A layer of tailings can be found in almost all of the exposed banks along the reach and in auger holes throughout most of the floodplain. As in other reaches of the Deer Lodge Valley, geochemical remobilization has lead to contamination in the sediment lying under the tailings, as well as the soil water and groundwater (Brooks 1988; Nimick 1990; Moore and Woessner 2001).

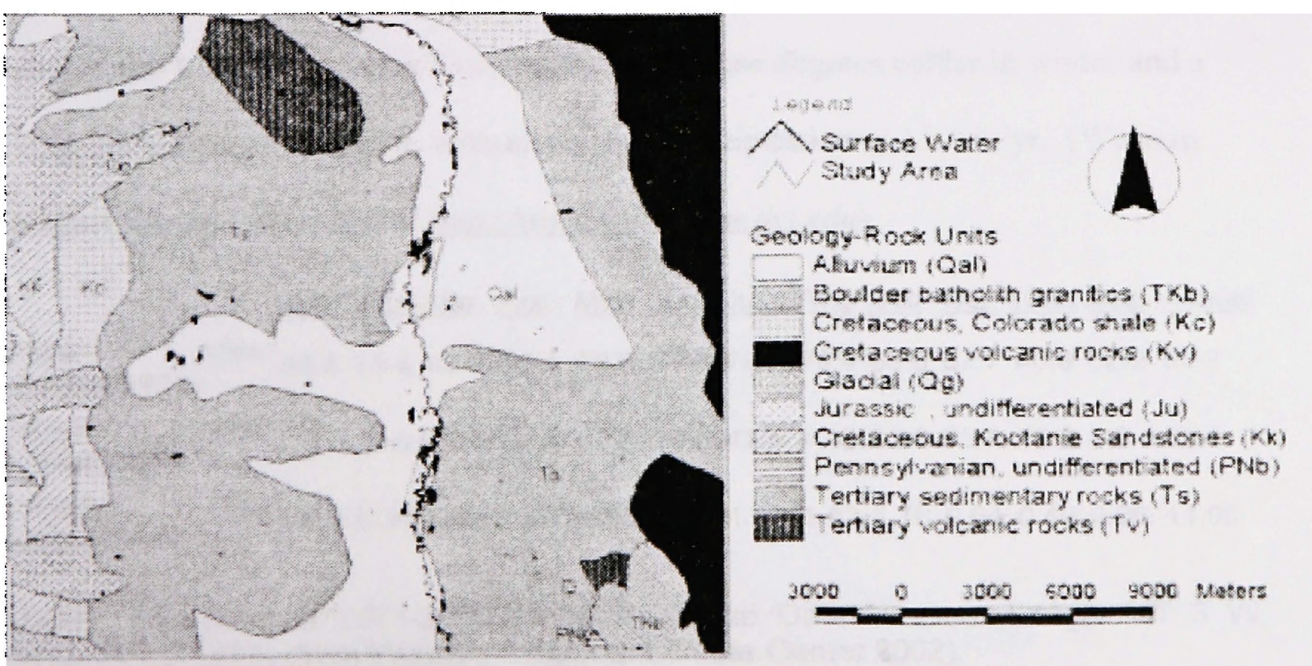


Figure 3. Geologic Map of Deer Lodge Valley, MT (Raines and Johnson 1996). The small black areas in the "Ts" and "Qal" are ponds and lakes.

The woody vegetation in the study reach consists of Geyer willow (*Salix geyeriana*), sandbar willow (*Salix elugia*), and water birch (*Betula occidentalis*) with various grasses dominating the rest of the vegetation (Rice and Ray 1985; Lejuene, et al. 1996). A few cottonwood trees (*Populus trichocarpa*) are scattered on the inside of meander bends, well back from the banks. In many areas, the vegetation is relatively short and canopy cover is reduced. In addition, there are large areas almost completely void of living plants, known as "slickens." However, slickens do support bunches of metal tolerant grasses such as tufted hairgrass (*Deschampia cespitosa*) (Rice and Ray 1985; RWRP 1996).

Overall, the Deer Lodge Valley is characterized by a cool, dry climate. Average maximum temperatures range from 41°F to 80°F in the summer months and 9°F to 33°F in the winter (Table 1). Extremes range from –40°F to 100°F. The average precipitation is 11 in/yr, with the majority of the rain falling in early summer. The range over the 42 year period of record is 6 to 19 in/yr. The climate upstream at Butte, Montana, is similar to that at Deer Lodge. Average Temperatures are a few degrees colder in winter and a few degrees warmer in summer, with an average precipitation of 12.5 in/yr. (Western Regional Climate Center 2002: http://www.wrcc.sage.dri.edu).

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Temperature (F)	Max.	32.8	38.4	46.5	55.1	63.0	71.9	79.3	79.4	69.6	57.7	40.9	32.9	55.8
Average Temperature (F)	Min.	9.0	13.9	20.6	25.6	32.8	39.0	42.5	40.9	33.0	25.1	15.9	9.3	25.7
Average Precipitation (in.)	Total	0.36	0.36	0.45	0.74	1.80	1.80	1.50	1.43	1.16	0.64	0.40	0.36	11.00

Table 1. Summary of 1971-2000 Monthly Climate Data for Deer Lodge, MT 3 W, MONTANA (242275) (from Western Regional Climate Center 2002).

A USGS gage site with a 24 year continuous record (1978-2002) is located just upstream of the study site in Deer Lodge, MT (12324200). The drainage area above the gage is 995 km^2. The hydrograph reveals discharges dominated by spring snow runoff, with the largest peak flows probably correlating to rain-on-snow events (Figure 4). The maximum average monthly discharge is 508cfs (14.4cms) in June and the lowest is 108cfs (3.1cms) in August. The highest peak flow on record is 2500cfs (70.8cms) in May, 1981. Higher discharges probably occurred prior to gage installation, including the 1908 flood of record at downstream Missoula, Montana (Clark Fork River Above Missoula Gage-12340500) (*http://mt.waterdata.usgs.gov/nwis*), which was estimated at 4000-5000cfs through Deer Lodge, MT. Newspaper articles and gage data indicate that other large floods occurred in 1887, 1892, 1894, 1898, 1899, 1902, 1938, 1948, and 1975 (CH2MHill 1987; Smith, et al. 1998).

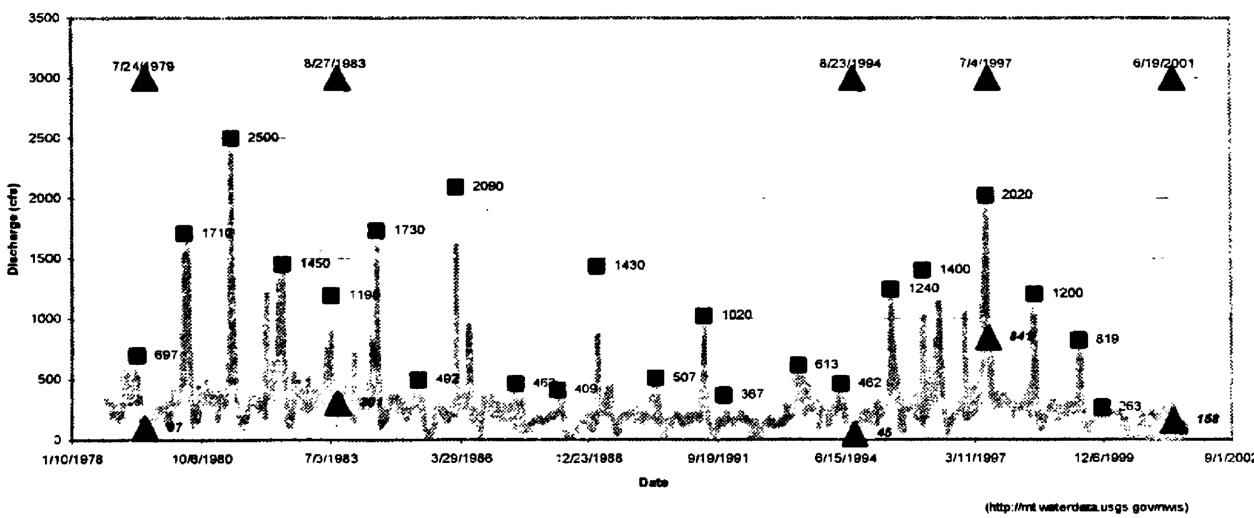


Figure 4. Daily Discharge at USGS Stream Gage Station, Deer Lodge, MT (12324200). Squares represent annual peak flow data, and triangles represent dates of aerial photography used in this study with corresponding discharges. (USGS 2001: http://mt.waterdata.usgs.gov/nwis).

Historical Analysis

Data Collection

When studying river and floodplain changes, a historical analysis provides important information about the onsite and upstream impacts to a river reach, as well as changes to the channel and floodplain. Kondolf and Larson (1995) suggest using historical documents, newspaper accounts, maps, cross sections, discharge data, and aerial photographs to create a framework for analyzing river changes. Although these historical analyses may seem easy enough to accomplish, they can actually be quite difficult and time consuming, especially if data is not readily available which is commonly the case.

For this study, aerial photographs were the most useful and easily obtained source of historical data (Table 3). The analysis of the photographs will be discussed in a later section. Attempts were made to locate various historical maps including old land survey maps, railroad survey maps, road maps, and topographic maps, with varying levels of success. When obtained, United States Geological Survey (USGS) topographic maps and historic road maps generally had scales that were too large and showed little detail, whereas late 1800-early 1900 Milwaukee and Northern Pacific railway surveys often omitted the river channel because the scale and coverage areas were too small. A few of the maps represented an artistic expression of the river location rather than actual ground conditions. The useful maps will be discussed along with the aforementioned aerial photographs.

Cross sections and discharge data at USGS stream gage sites on the Upper Clark Fork were also problematic. The data rarely go back farther than 30 years, which is

unfortunate considering the magnitude and duration of the upstream impacts to the river. Also, cross section data collected at the Deer Lodge gage site (12324200) proved fairly difficult to obtain, and were not always taken at the same location or at the same elevation, therefore making a comparative analysis inadvisable. Additional cross sections, such as those completed at road or railway bridges, were unavailable or not helpful.

Fortunately, a few reviews of the history of the Deer Lodge Valley (Horstman 1984), Grant-Kohrs Ranch (Eckberg 2002), and the mining history at Butte and Anaconda (Quivik 1998) have been completed. The following historical information introduces the landuse pressures in the valley and their effects on the river's sediment and water supply.

Pre-settlement History

Prior to settlement, Native Americans from the various local tribes used the valley primarily as a highway to the buffalo grounds southeast of the valley, and there is little evidence that they stayed for extended periods of time (Horstman 1984). Early European-American explorers in the region mostly consisted of trappers and missionaries. Their journal articles and letters depict the Deer Lodge Valley as an area of dense populations of willows and water birch, as well as abundant wildlife. Warren Ferris, a fur trapper who explored the valley in 1831, described it as "decorated with groves and thickets of aspen, birch, and willow, and occasional clusters of currant and gooseberry bushes." The river itself was depicted as "clear, deep, rapid, and not fordable at high water (quoted in Horstman 1984). " Conrad Kohrs corroborated this account in the early 1860s by referring to the river as "a beautiful stream with water clear and

sparkling, and alive with the finest trout (quoted in Eckberg 2002)," and even in 1892, Evermann (1892) remarks that, although the river is in bad shape, "the banks, usually low, are covered with a pretty heavy growth of alders, willows and other small bushes."

The trappers were after beaver, which seemed to be abundant in the tributaries and maybe along the main channel as well (Horstman 1984; Smith, et al. 1998). Although the beaver were trapped out by the 1840s, some researchers believe that beaver dams had a profound effect on the floodplain, keeping the water table higher, the morphology varied, and helping to support the large amounts of vegetation within the valley prior to the impacts of settlement (Smith, et al. 1998). Evidence for the dams include various layers of peat and small gravels in the higher stratigraphic positions of the river banks (Smith, et al 1998), and buried dams in the floodplain sediment (Hansen, personal communication), however little corroberative evidence can be found within the study reach.

Settlement in the valley began in the 1850s with gold discoveries at Gold Creek and Bearmouth, MT. By the 1860s, almost every drainage in the valley had been prospected (Horstman 1984; Quivik 1998). Agriculture and logging followed to support the miners who located in the valley, and by the late 1800s, mining and its various support industries had seriously affected both the river and its floodplain.

Post-settlement History: Agriculture

Researchers have reported that inappropriate agriculture and livestock management can result in the degradation of riparian zones (Knox 1977; Kauffman and Krueger 1984; Trimble 1994). Reduced and altered vegetation along streams and rivers

commonly accompanies increased grazing and farming, which can lead to higher sediment loads in runoff, as well as increased bank erosion. Livestock can also directly affect the banks through trampling. Channel changes, such as widening and shallowing or large shifts in lateral position (increased sinuosity and cutoffs), often follow, especially if the river discharges are reduced by irrigation. It seems probable that the increased grazing through the late 1800s contributed to increased sediment loads in the Clark Fork River. Also, the continuation of grazing through the last century has probably caused increased bank erosion rates, and therefore led to higher metal loading to the river channel and downstream floodplain (Nimick 1990).

Richard Grant introduced large scale grazing to the Deer Lodge Valley in the 1850s, and by the mid-1860s his son, Johnny Grant, had established a herd of several thousand cattle. A.K. McClure, a correspondent from the Engineering and Mining Journal visiting the valley in 1867, wrote that "the largest herds of the finest cattle dot the prairie in every direction (quoted in Horstman 1984)." Soon after, the valley became overcrowded and overgrazed. Hay and grain crops were produced to offset the grazing demand, and by the 1880s and 1890s commercial agriculture was well established. Also, sheep were added to the already well-grazed meadows and fields (Horstman 1984). Large-scale grazing continues in the Deer Lodge Valley to this day, and is the most common cause of bank alteration within the valley (Nimick 1990; RWRP 1996).

Johnny Grant started the ranch that encompasses the study area in 1859 with 250 horses and 800 cows. He ran it until 1866 when he sold the land and cattle to Conrad Kohrs. In addition to grazing, the ranch's bottomlands were used to produce hay, and the uplands were plowed for grains. The amount of area used for haying increased in the

1880s, when Kohrs drained all the lower fields, which indicates that the floodplain was much wetter than it is today. Like most of the ranches in the area, extensive irrigation ditches were constructed to provide water for the crops within the ranch, including the Kohrs-Manning Ditch, which delivers water for various agricultural activities further north. The ranch was, and is, primarily used for cattle, horses, sheep, various hay and grain crops, and recreation, although the numbers and types of animals have decreased. Grazing in the ranch's riparian zone ended in 1994 due to environmental concerns (Eckberg 2002), however the vegetation has yet to recover and upstream grazing presumably contributes sediment to the channel and floodplain within the reach.

Post-settlement History: Mining

Mining can also have a profound effect on riparian systems. Increased sediment supplies and changes in water quantities and timing accompany mining and mining waste disposal, which often lead to drastic changes in the geomorphology of the channel (Miller 1997). The River Ystwyth, Wales (Lewin, et al. 1983), the Ringarooma River, Tazmania (Knighton 1989), the Carson River, Nevada (Miller, et al 1998), and the Bear River, California (James 1991) all experienced large sediment load increases and subsequent changes in geomorphology due to upstream mining activity. The evidence for large increases in sediment production and transport in the Clark Fork River, as well as the subsequent effects, can be found throughout the historical literature. Although livestock and other forms of agriculture have probably altered the channel and floodplain of the river, mining has caused the largest and most noticeable impacts to the study reach.

In 1864, miners discovered gold in Silver Bow Creek, a headwater stream of the Clark Fork River. By 1866, the peak of gold mining on Silver Bow, hydraulic mining had been established and numerous ditches diverted water from other drainages to help wash the stream gravel (Horstman 1984; Quivik 1998). At that time, there was approximately one miner for every twenty feet of stream (Quivik 1998). The miners, their water monitors, and the associated ditches increased the amount of water to the drainage, but more importantly, they also washed hundreds of tons of sediment down the creek towards the Clark Fork River. The increase in sediment resulted in the "murky" condition of Silver Bow Creek noted by A.K. McClure (Horstman 1984).

The gold ran out at the end of the 1860s, and emphasis switched from the placers to copper lodes. Copper mining at Butte drastically increased with the electrification of the U.S. in the 1880s. Butte constructed its first smelter and stamp mill in 1865, its first concentrator in 1881, and smelting operations in Anaconda, on Warm Springs Creek, began in 1885. These large scale processing centers crushed, cooked, and concentrated hundreds of tons of rock and metal per day, disposing the highly contaminated waste material into their respective headwater streams. The amount of sediment they added to the streams dwarfed that washed in by the placer miners. Prior to the 1870s, an estimated 100,000 tons of tailings were dumped along Silver Bow Creek, but by the early 1880s, that number had increased by a factor of 10. By the 1890s, Butte and Anaconda were producing a combined 1400 tons of tailings per day, or a little over 0.5 million tons per year (Table 1: Quivik 1998). Silver Bow Creek was so clogged with tailings that smelters and concentrators were forced to build elevators, riprap banks, dams, and ditches in order to manage the wastes (Quivik 1998).

Year	Quantity
1888	800* tons/day
1895	705 tons/day
1896	730 tons/day
1897	1105 tons/day
1898	1080 tons/day

Table 2. Tailings Production at Butte, MT, in the late 1800s (Quivik 1998). All values are for copper works only except *1888, which includes both copper and silver works. Tons/day in English units.

Many of these actions, in combination with newly constructed, roads, railroads, and bridges, constrained flows and probably caused the tailings to spread further downstream across the lower Silver Bow and upper Deer Lodge Valley floodplains. In the 1890s, farmers in these valleys increased this downstream dispersal by constructing dikes and levees to keep high water and tailings out of their fields (Quivik 1998). In Deer Lodge, levees likely created a "bottleneck" effect where the river's energy was considerably slower both up and downstream of the city. These reaches of lower energy probably allowed for an increase in the extent and thickness of tailings deposition in the adjacent floodplain.

Evidence for the additional loading of fine sediment could be seen all along the Clark Fork River. In Silver Bow Creek and the Upper Deer Lodge Valley, new beds of sand and gravel built up in the streambed and in low lying areas of the floodplain, and the water downstream was constantly red and turbid from the mud (Quivik 1998). In 1892, Evermann (1892) conducted a survey of the fisheries in the Columbia River Drainage and describes the Clark Fork River at Deer Lodge, MT, in the following manner:

> In some portions it is made up of a constantly shifting mass of fine silt-like material from the concentrators and reduction works at Anaconda and Butte. The entire length of the river, the water is full of this solid matter in suspension. The amount of solid matter carried down by the [Clark Fork River] from this source must be very considerable, and of course proves fatal to all kinds of fish. We seined the river very thoroughly in the vicinity of Deer Lodge and did not find any fish whatever (Evermann 1892).

Evermann refers to the river as "muddy" all the way to its confluence with the Little Blackfoot River (Garrison, MT), and Charles Warren, a Deer Lodge resident in the 1860s and 1870s, also refers to the river as muddy and unfishable during this time (Quivik 1998). Neither observer mentions tailings in the floodplain, however. In the early 1900s, farmers noticed that irrigation water, diverted from the Clark Fork, was killing their fields, and farmers in and upstream of Racetrack, MT, began finding tailings in low lying areas of their land from irrigation and flood deposition (Quivik 1998).

Presumably tailings were affecting the study area as well, although no records were found referring to them until 1908. That year, a large flood inundated the floodplain and deposited large quantities of tailings as it receded (Eckberg 2002). This flood impacted the entire valley, and many researchers attribute almost all of the floodplain tailings deposition to this one event (Nimick 1990, Smith, et al 1998). Con Warren, the ranch caretaker in the late 1920s and 1930s, described the floodplain at the study site during those years as containing "kind of yellowish colored dirt with

essentially nothing growing on it and lots of animal carcasses lying around." He also stated, "...the river was a mess. It was about the color of coffee with cream in it." Much of the work on the ranch in those years concerned plowing up the irrigated fields and floodplain land affected by tailings and dumping any of the extra hay, manure, et cetera on them, in order to reclaim the land for agricultural use (Eckberg 2002).

Fortunately, the large sources of contaminated sediment were eventually cutoff when tailings ponds were built to trap the contaminated material, and as the mining boom came to a close. The Opportunity Ponds were constructed downstream of Anaconda in 1911, and the Warm Springs Ponds were built in 1919 at the confluence of Silver Bow and Warm Springs Creeks. By 1950, the Warm Springs Ponds were filled and an additional pond was constructed. Subsequent fillings have resulted in increased wall heights (1969), and further renovations (1996) (Quivik 1998). The last mill to dump tailings into Silver Bow Creek closed in 1932 (Quivik 1998), although tailings deposited along the channel continue to be entrained and moved downstream during high flows (Smith, et al. 1998).

METHODS

Field Mapping

The first phase of the project was to classify and map the riverbanks along the study reach based on river processes and bank shape. The banks were divided into depositional lengths (point bars) and erosional lengths (cut banks). Erosional banks were then classified as concave or convex based on their overall profile shape (Figure 5) (RWRP 1996). These shapes were chosen because they generally represent the degree of bank erosion activity. Concave banks are usually indicative of active cutting, whereas convex banks are generally more stable. Breaks in vegetation cover were also used in defining bank segments, however, the boundaries were usually gradational.

For each segment, percentages of slumping, overhanging, and woody vegetation cover within 2 meters of the bank were visually estimated. Measurements of undercutting depth and tailings thickness were made with a Jacob's staff divided into 10 cm intervals, and the averages over the bank segment were noted. In this study, "overhanging" is the physical trait of erosion beneath the bank, whereas "undercutting" is the horizontal depth of erosion under the overhang. Types of vegetation (shrubs, grass, forbs, etc.), evidence of tailings (salts, adjacent slickens, senescent/dead vegetation), and other attributes of each bank segment were also noted. Although ocular surveys are inherently difficult to reproduce, data was gathered and mapped primarily for reconnaissance and to generally estimate the magnitude of slumping and the amount of shrubs along the banks. Methods were borrowed from the RWRP (Hansen, et al 1998) and the USGS (1998), and mapping and visual estimates were made by the same

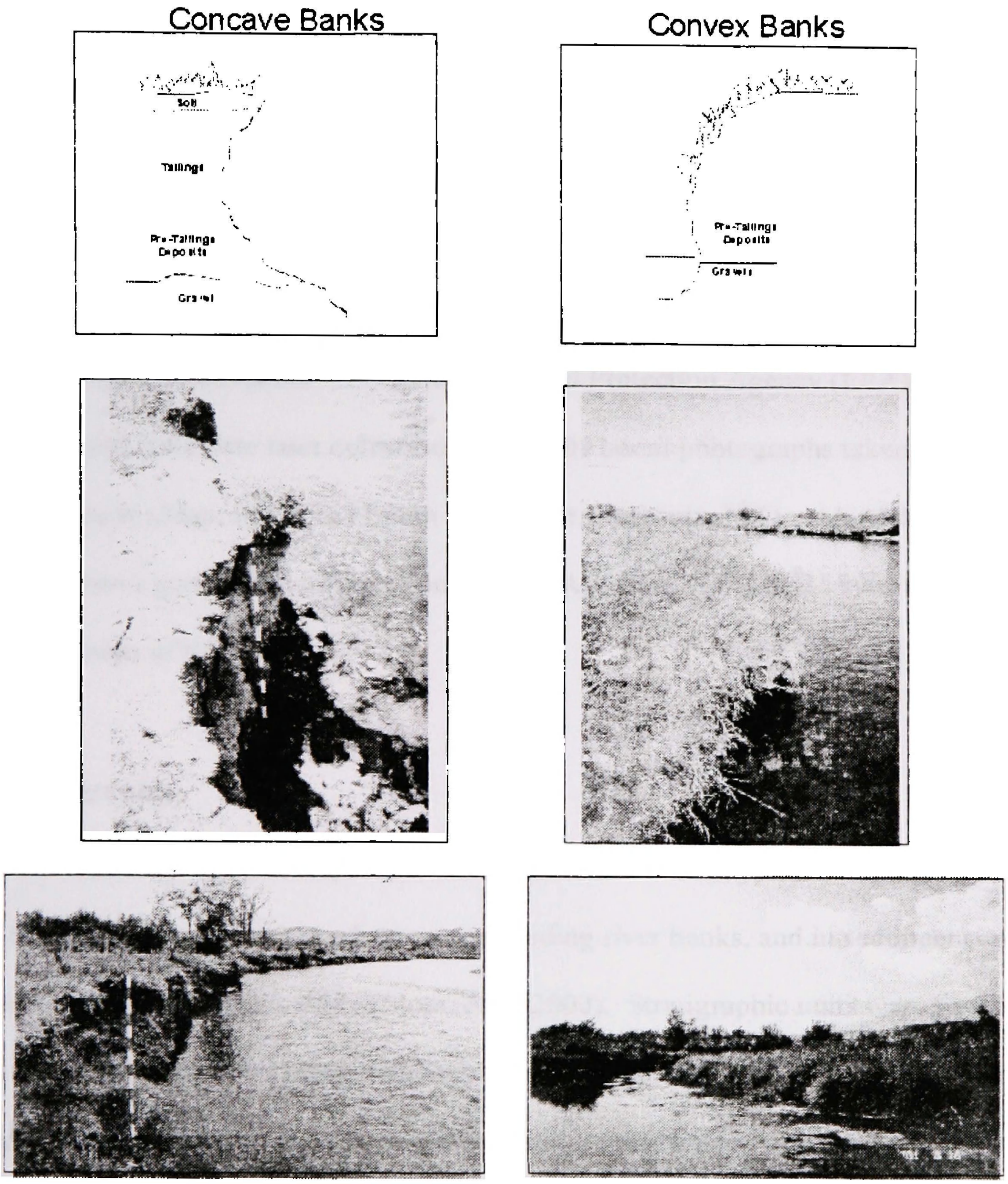


Figure 5. Examples of concave and convex banks. Shapes are based on the general streamside curve of the bank.

investigator (Benjamin Swanson) to minimize the variability introduced by using different observers. The estimated error is listed in Table 5.

Riverbanks were mapped with a Trimble Pathfinder Global Positioning System (GPS) with a resolution of +/- 1 meter. While carrying the GPS, the researcher walked the top of the banks as close to the edge as possible (within about 0.5 m). The final GPS readings for the west banks were consistently offset around 4 meters from the banks on the georeferenced 1997 Environmental Protection Agency (EPA) aerial photographs, and were later corrected to the 2001 aerial photographs taken specifically for this study (Map, Inc., 1613 South Ave. West, Missoula, MT). All of the data were entered into a geographic information system (ArcView 3.2: ESRI 1996) to produce various maps of the banks.

Stratigraphy

The description, sampling, and measurement of floodplain stratigraphy were done at freshly exposed vertical surfaces along eroding river banks, and in sediment cores taken during a previous study (Moore, et al. 2002). Stratigraphic units were based mostly on color and grain size (1989), although topographic and stratigraphic position, primary sedimentary structures, and degree of weathering also helped differentiate between units (Nimick 1990; Miller, et al. 1998).

Because of limitations in the common dating techniques, the different stratigraphic units were not dated. ^{137}Cs and ^{210}Pb isotope dating techniques do not extend back far enough to distinguish between mining and pre-mining sediments, and ^{14}C dating will not give accurate ages for modern floodplain sediments. Attempts were made

in dating historical artifacts, such as ceramic shards, horse carts, and old bottles, but all led to dead ends. There are a few cottonwoods available for dendrochronology studies in the study reach, but they were left undisturbed for conservation reasons. One possibility for future dating is to use willows for dendrochronology. Recent research at Colorado State University has successfully used willow roots to obtain reasonable dates for various sediment units (Woods, personal communication).

Planform Channel Changes

Erosion

Aerial photographs have been used in many studies to measure long term bank erosion, because they offer information on channel adjustment, allow assessment of channel modifications over large areas, and they can assist in selecting field study sites (Hooke 1979; Nanson and Hicken 1986; Lawler 1993; R2 Resource Consultants 1997; Harmel, et al. 1999). Changes in the planform channel morphology were detected by comparing EPA, Grant-Kohrs Ranch NHS (presumably National Resource Conservation Service (NRCS)), and NRCS aerial photographs (http://www.apfo.nrcs.usda.gov) from 1947, 1960, 1979, 1983, 1994, 1997, and 2001 (Table 3). The 1997 photo was obtained from the EPA in a digital (600 dpi) georeferenced format. The park service staff and the NRCS provided the older photographs, which were scanned at 600 dpi. Lastly, Map, Inc. took pictures of the study area in June of 2001. These photographs were subsequently digitized at 1200 dpi. Digital copies of all the photographs were loaded into an ArcView Geographic Information System (ESRI 1996) and georeferenced by matching fixed points in the images to the 1997 photograph using the ArcView Image Analyst extension (Ormsby and Alui 1999). An 1868 land survey map (Johnson 1869) and 1914 river profile map (Marshall 1914) were also consulted as part of the comparisons, but they were less accurate and therefore only used for general comparisons.

Year	Date Taken	Discharge (cfs)	Obtained From
1947	8/14/1947	*226*	Grant-Kohrs Ranch NHS
1960	7/29/1960	*160*	NRCS
1979	7/24/1979	97	Grant-Kohrs Ranch NHS
1983	8/27/1983	301	Grant-Kohrs Ranch NHS
1994	8/23/1994	45	Grant-Kohrs Ranch NHS
1997	7/4/1997	841	Grant-Kohrs Ranch NHS (from EPA)
2001	6/19/2001	158	Map, Inc (U. of Montana, Geol. Dept.)

Table 3. Aerial Photography Information. Discharges for 1947 and 1960 are estimates based on correlation between Clark Fork at Deer Lodge (12324200) and above Missoula USGS gages (12340500). All other discharge data obtained from USGS gage at Deer Lodge, MT.

Initially, the pre-1997 photos were matched, in their entirety, to the 1997 image by linking "fixed" points, such as the corners of structures, fence corners, or vegetation. For the 2001 photographs, crosses of white plastic sheeting, with 4 feet by 0.5 foot arms, were laid in and near the floodplain to act as ground control points. The center of each cross was located by GPS, and these location data were used to reference the crosses on the digital image. Unfortunately, both of these methods resulted in total root mean square (RMS) errors of around 10 pixels (~4 m), which was considered too high for the precision needed. The high error was likely due to distortion in the aerial photographs and poor GPS resolution (+/- 1 m).

To remove the error due to the distortion, the images were "clipped" into smaller pieces centered on the river, and then the smaller images were referenced to the 1997 photo. Most of the obvious fixed points (fences, buildings, etc.) were cut from the smaller images or were difficult to see, so each image was georeferenced by matching the centers of approximately 30 shrubs or trees per image. For the most part, this method worked well. The total RMS for each clipped image ranged from 0.2 m to 0.9 m, and the average error was 0.4 m. See Appendix A for RMS data.

After registering the photographs, the next step was to digitize the banks in ArcView and calculate bank lengths. Each year's mosaic was placed at a 1:400 scale and lines were drawn along the banks within the images (Figure 6). The 2001 banks mapped by GPS were adjusted to fit the morphology on the 2001 georeferenced images. A major problem with digitizing the banks this way, as with using shrubs to reference the photos, is that they are often difficult to see due to photo resolution, distortion, shadows, vegetation, and differences in water levels (Figure 6). Enlarging and rescanning the air photos at larger scale (1200 dpi) and completing some image processing would possibly overcome some of the image problems. This was not done because we were unable to locate the negatives of the older photos to produce enlargements. The differences due to water levels at the study site is likely small because the discharges in 1947, the oldest photo used for analysis, and 2001, the most recent photograph, are similar (Table 3 and Figure 4), and the eroding banks are usually high, steep, and fairly easy to identify.

The centerlines of the river were also digitized on the aerial photographs. Line segments of 16m were connected down the estimated center of each year's channel. In reaches with multiple channels, the line was drawn down the presumed main channel based on current channel configuration (2001-2002) and geomorphic conditions on the aerial photographs. A research assistant repeated the digitization for the 1983 and 1997 centerlines, and the errors were within +/- 3m in total length and +/-0.5m in perpendicular offsets. Other channel features, such as riffles, were mapped in the field on

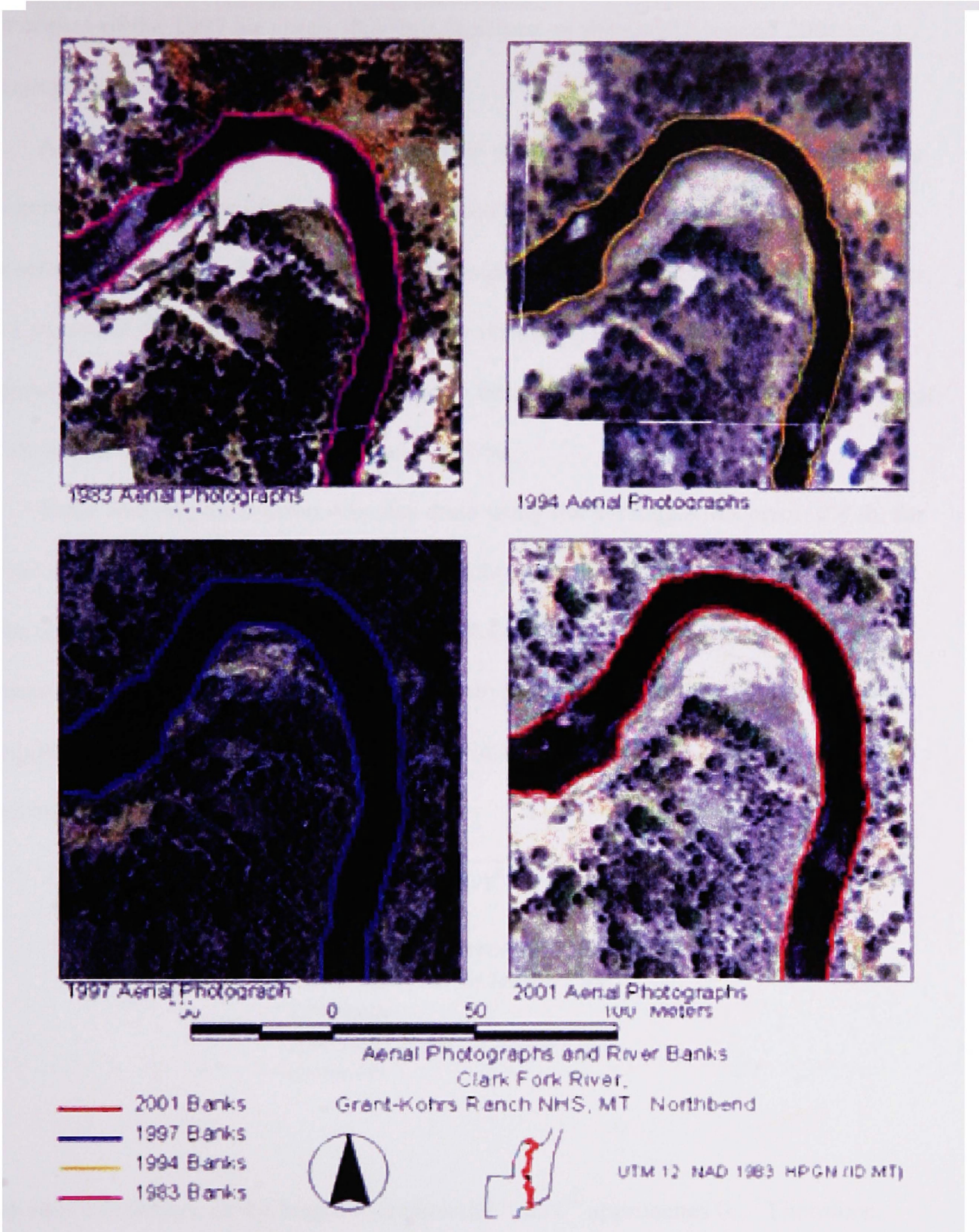


Figure 6. Examples of digitized bank lines and vegetation between photograph years. Notice that individual shrubs are located in the same spot from photograph to photograph.

paper copies of the 1997 air photo, and then digitized on the georeferenced 2001 photographs.

After overlaying the banks from each set of photographs, relative bank positions were compared and areas of erosion were located and digitized within ArcView. Areas were selected only if the distance between the older bank and the 2001 bank was greater than 1 m, and if the banks seemed to be clearly retreating from the oldest banks to the youngest. This process was redone twice for 5 bends on the 1983 photos and the average area error was +/- 3%, with a range of +/- 1 to 5%.

Error analysis for erosion was also done using the average RMS error, 0.4 m, for each set of images. The RMS error is an absolute error, and therefore, a point in space can be off by the RMS error in any direction. Assuming that the erosion areas are rectangular, then the RMS error is 0.4 m for both the length and the width. Area for a rectangle equals the length multiplied by the width, so the error can be found with the following equation

$$A_e = \sqrt{(\Delta L / L)^2 + (\Delta w / w)^2} \quad \text{(Taylor 1982).}$$

A_e=Fractional error in erosion area
ΔL=RMS error in length (.4m)
L=length
Δw=RMS error in width (.4m)
w=width

In the above equation, as the length increases the "$\Delta L/L$" approaches 0. Therefore, assuming a high length:width ratio, the "$\Delta L/L$" term becomes insignificant and the error equation becomes $A_e = \Delta w / w$.

Unfortunately, the erosion area shapes are not actually rectangular. Widths vary across the areas, and are usually thicker in the center and narrow at either end. Measurements of the length and average width were taken at random erosion areas from the 1983 data, and the calculated ratios ranged from 8:1 to 15:1, with a typical value of 11:1. To find the relationship between width and area in rectangles with a length:width ratio of 11:1, areas were calculated using theoretical pairs of length and width values, with each pair possessing this ratio. A power curve was fit to a plot of the theoretical widths versus the calculated areas with the resulting equation being $w = .3015A^{0.5}$, where *w=width*, and *A=Area*. This equation was then used to calculate the representative widths of the erosion areas (average width assuming a length:width ratio of 11:1) measured on the aerial photographs . The final error for each area was calculated by dividing the average RMS error (.4 m) by its representative width ($A_e = \Delta w / w$). Using this method results in higher errors for smaller areas, so as the level of detection is approached for channel changes on the photographs the error increases dramatically. The median error value for all of the areas digitized for a photograph year was used to represent the error for that year's erosion (See Appendix D).

Volume of eroded sediment for each year is the area multiplied by an average bank height for the ranch taken from a previous study (Moore and Woessner 2001). Error for the calculated volumes was calculated by using the equation

$$V_e = \sqrt{A_e^{\,2} + H_e^{\,2}} \quad \text{(Taylor 1982)}$$

where
V_e=*Fractional error in volume*
A_e=*Fractional error in erosional area (see description)*
H_e=*Fractional error in bank height (stdev/avg).*

Multiplying the volume of eroded material by the bulk density produced the mass of eroded sediment returning to the river. A bulk density of 1400 kg/m^3 (1.4 g/cm^3) was used based on standard values for fine sands and compacted muds and clays (http://www.geology.iupui.edu/research/SoilsLab/procedures/bulk/Index.htm). The fractional error is the same as the error for the volume of eroded material.

The same methods were used to compare 1983 and 1997 aerial photographs at the Garrison and Racetrack sites. The geology, soils, vegetation, and channel characteristics at these sites are similar to the Grant-Kohrs Ranch site (RWRP 1996; Smith, et al. 1998). However, due to problems with access, no fieldwork was done at the two sites. Attempts were also made at comparing sequential photographs of reaches of the Boulder, Smith, and Ruby Rivers in western Montana (Figure 7). The locations were chosen to match the USGS gage station information for Deer Lodge, including peak discharges, average discharge, and basin area. Relative sinuosity, valley size, and land use (same as Clark Fork, sans tailings) were also taken into account. Photographs were obtained from the NRCS and rectified as above. Unfortunately, the small-scale, quality, and distortion of the photographs made rectification difficult at best. The photos were referred to qualitatively instead.

To investigate whether or not the channel was widening or narrowing, channel widths were measured from the air photos at 55 sections in the straighter reaches within the study area (Nanson and Hickin 1986). The fixed sections were located perpendicular to the 2001 channel, and measurements were made along them from bank to bank (Figure 8). The investigator and a research assistant repeated these measurements, and errors ranged from 0 to 2.7%, but the average error was 0.7%. The data were analyzed for

significant width changes of greater than 1 m both between consecutive years, and between each year's widths and the 2001 widths. The statistical analysis was accomplished using box plots, paired t-tests, and Wilcoxon ranked sum tests in StatView (SAS Institute, Inc. 1998).

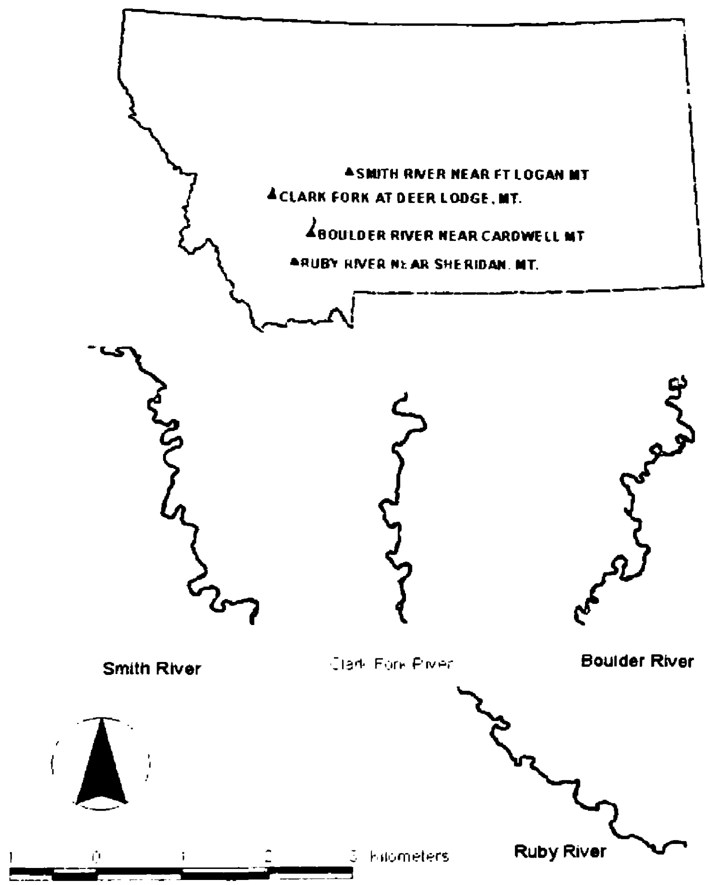


Figure 7. Locations and planform channel shapes for the Boulder, Smith, Ruby, and Clark Fork River reaches used in a general comparison of erosion. All of the reaches have similar basin sizes, discharges, sinuosities, land uses, and vegetation characteristics. Only the Clark Fork River has severe impacts from mine wastes. USGS Streamflow Gages: Boulder River at Cardwell (06033900), Clark Fork River at Deer Lodge (12324200), Ruby River at Sheridan (06022500), and Smith River at Fort Logan (06076690).

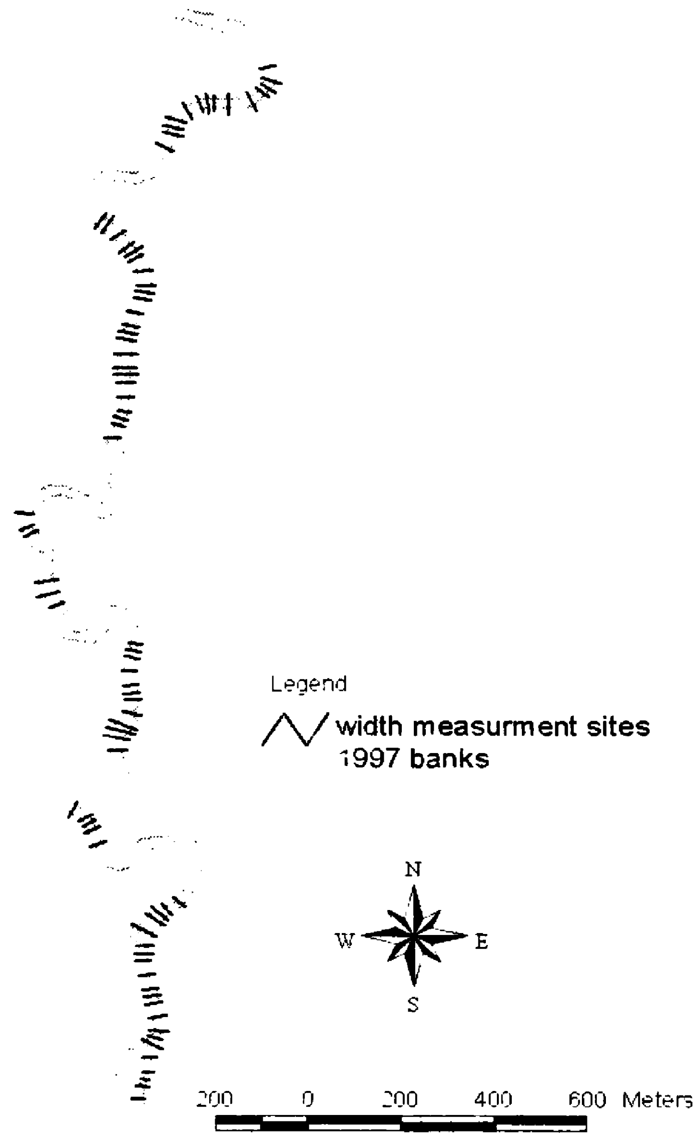


Figure 8. Location map for fixed transects where width measurements were taken. Measurements were taken at these transects on each of the aerial photographs used in this study.

Metal Loading

During a previous study (Moore and Woessner 2001), sediment samples were collected at 15 riverbank locations within the study site, and analyzed for metals. This data, in combination with the erosion data from this study, allowed the researcher to calculate the mass of excess metals being returned to the channel in this reach of river. For the chemistry study, multiple samples were taken at each bank location, with each sample taken over some range of the bank height. The average metal concentration at a bank site (Table 12) was obtained by summing the product of the percentage of the total bank height over which each sample was collected and the metal concentration of the sample. The metal concentrations were then averaged over all the sites. The error is the standard deviation of these concentrations divided by the final average for each metal. To obtain the amount of each metal being eroded from the bank, the average concentrations were multiplied by the mass of eroded sediment, with errors given by

$$M_e = \sqrt{S_e^2 + C_e^2} \quad \text{(Taylor 1982)}$$

M_e=Fractional error of the mass of metal eroded from bank
S_e=Fractional error of the mass of sediment eroded from bank
C_e=Fractional error of the concentration of the metal (stdev/average).

Along with the 1983 erosion data from the ranch, the investigator also quantified erosion for sites upstream and downstream of the ranch within the Deer Lodge Valley. Erosion data for the upstream site was 4 km downstream from the study area of Brooks (1988), and the downstream site was close to the study area of Moore and Hochella (unpublished data). The Moore and Hochella investigation did not include enough sampling sites to adequately characterize the floodplain geochemistry. However, the

average metal concentrations at these sites fell within 1 standard deviation of the average concentrations found at Grant-Kohrs Ranch. Therefore, to allow a better determination of variability, the ranch data was used to calculate metal loading in this reach as well.

The floodplain chemistry data from the Brooks study (1988) were used to find the metal loading for the upstream study reach. She presented average metal concentrations and their standard deviations over each of 5 stratigraphic units within the floodplain sediment profile, as well as the average thickness of these units. Weighted average concentrations were calculated for each metal by multiplying the average concentration of a unit by the ratio of that unit's average thickness to the average thickness of the stratigraphic profile, and then adding the results. The same steps were also used to obtain a final standard deviation for each metal concentration. Once the average metal concentrations were found, the method for finding the mass of each metal eroded from the banks was the same as for the study reach (discussed above). The total mass of each metal eroded from 1983 to 2001 was obtained by adding the masses for each of the three study areas, with error calculated with the following formula

$$M_t = \sqrt{M_{grko}^2 + M_{racetrk}^2 + M_{garrison}^2} \qquad \text{(Taylor 1982)}$$

where
M_t=*Fractional error of the total mass of metal over all 3 sites, 1983-2001*
M_{grko}=*Fractional error of the mass of metal from Grant-Kohrs Ranch NHS, 1983-2001*
$M_{racetrk}$=*Fractional error of the mass of metal from upstream reach*
$M_{garrison}$=*Fractional error of the mass of metal from downstream reach*

Curvature

To determine if the size and curve of the meander bends affected erosion rates, radius of curvature versus erosion was also analyzed using ArcView. With the scale set to 1:2500, circular polygons were fitted to the 1983 and 2001 river centerlines wherever there was an obvious curve (Hooke 1984; Nanson and Hickin 1986). If a river curve was asymmetrical, the circle was fit to the upstream portion of the curve to best represent the stress caused as the water rounds the meander. The investigator and a research assistant repeated the curve fitting process numerous times and found it to be very subjective. Error from all the original trials ranged from +/- 1% to 40%, with the average being +/- 19%. Further refinement of the procedures yielded errors from 1% to 20% with an average of 9%. Similar numbers were obtained within each investigator's trials. Error tended to increase with circle radii greater than 75 m and less than 15 m, as well as when centerline curves were asymmetrical or came to a point. Each curve's radius was compared to the corresponding erosional area and the maximum width of that area. Regression analysis was completed in Microsoft Excel.

Vegetation and Slickens Dynamics

The last aspect of the planform floodplain analysis was to investigate vegetation and slicken changes. To accomplish this, the air photos were again reviewed and compared in ArcView. The same limitations, such as shadows, resolution, and color, that applied to georeferencing the photos and digitizing the banks applied to the slickens and vegetation analysis. These problems made digitizing the actual areas unreliable, so a more qualitative analysis was completed by comparing shapes, vegetation cover and color, and dimensions of selected slickens areas. Adobe Photoshop was used to adjust the contrast, brightness, and color of the 1997 air photos, which were darker, so they would match the color of the other photos, and therefore, make it easier to see differences in vegetation. To determine if slickens were changing in shape or size over time, their dimensions at the widest and longest points were compared from year to year.

Part of the project was to evaluate the effectiveness of woody vegetation in providing channel stability. A brief look at cutbank and shrub group location indicated that there was substantial erosion occurring at sites both with and without woody vegetation (Figure 11). A more detailed evaluation was conducted at the 7 largest erosion areas within the study reach. Vegetation cover within the area of erosion for both 1983-2001 and 1979-2001 was classified as shrub, mixed-shrub, mixed-grass, or grass dominated (Harmel, et al. 1999). The vegetation at the widest point of erosion was also noted, as was the average width of erosion based on the area of erosion divided by the centerline length of the area.

RESULTS AND DISCUSSION

Bank Inventory

Stratigraphy

The banks along the Clark Fork River within Grant-Kohrs Ranch usually consist of four stratigraphic layers or units (Figure 9). The top layer (ca. 10 cm thick) is a sandy/silty, poorly consolidated soil, usually containing varying amounts of organic material and roots. The soil unit overlies a thicker layer (10 to 80 cm) of grayish-orange tailings composed of fine sand and silt. The tailings are usually lighter in color than the underlying units, and show orange and yellow mottling. Beneath the tailings lies a layer of grayish-brown silt/mud (20 to 50 cm) that is believed to be pre-tailings floodplain deposits. A layer of sandy gravel and cobbles lies beneath the pre-tailings floodplain deposits, and are probably channel lag and bar deposits. This coarser layer is the lowest stratigraphic unit exposed in the banks. Its thickness is unknown, but it is found throughout the entire study area. This overall stratigraphic package is prevalent throughout the riparian area, both on the ranch and within the valley, and is seen in cores as well as bank exposures (Brooks 1988; Nimick 1990; Moore, et al. 2002). However, the thickness of each unit is variable and any one unit may pinch out from one bank exposure to another (Nimick 1990).

Tailings can be found in almost all of the banks exposed along the river (Figure 14). These deposits are quite complex. The bedforms, organic layers, coloration, and layering within them vary from bank segment to bank segment, even over short distances. Where exposed in cutbanks or animal paths, the average tailings thickness is 40 cm, although these vary between 10 and 80 cm. The areas that lack tailings include a few

short lengths where the channel has eroded into the edge of the meander belt (Points A and B, Figure 14a and Point A, Figure 14c), and near the constructed sewage ponds at the north end of the park (Point C, Figure 14a). Tailings thickness was rarely measured in the convex banks because tailings were generally not exposed and restrictions were placed on digging within the park. However, many of the convex bank segments exhibited evidence of tailings, such as adjacent slickens areas, salts forming on the lower banks, senescent/dead vegetation, tailings indicative vegetation (i.e., tufted hairgrass (*Deschampsia cespitosa*)), or small exposures in animal paths.

Bank Attributes

The banks of the Clark Fork River within the Grant Kohrs Ranch National Historic Site were classified based on their morphology. Table 5 and Figures 11 through 17 (indexed in Table 4) summarize the data. The entire inventory data set can be found in Appendix C. The basic classification consists of two main types of banks, concave and convex (Figure 5). The convex banks tend to be found in the straight reaches of the river and along the inside bends of meanders. Concave banks are found on the outside of meander bends and where riffles direct the flow into the banks. An example of this distribution is shown in Figure 11. The straight channel in the lower half of the figure, point A, consists of convex banks, except where a riffle directs the water into the west bank, point B, where the bank is concave. Also, the banks associated with the meander at point C are convex on the inside of the bend (east bank) and concave on the outside (west bank). These general relationships extend throughout the entire study reach along the Clark Fork River.

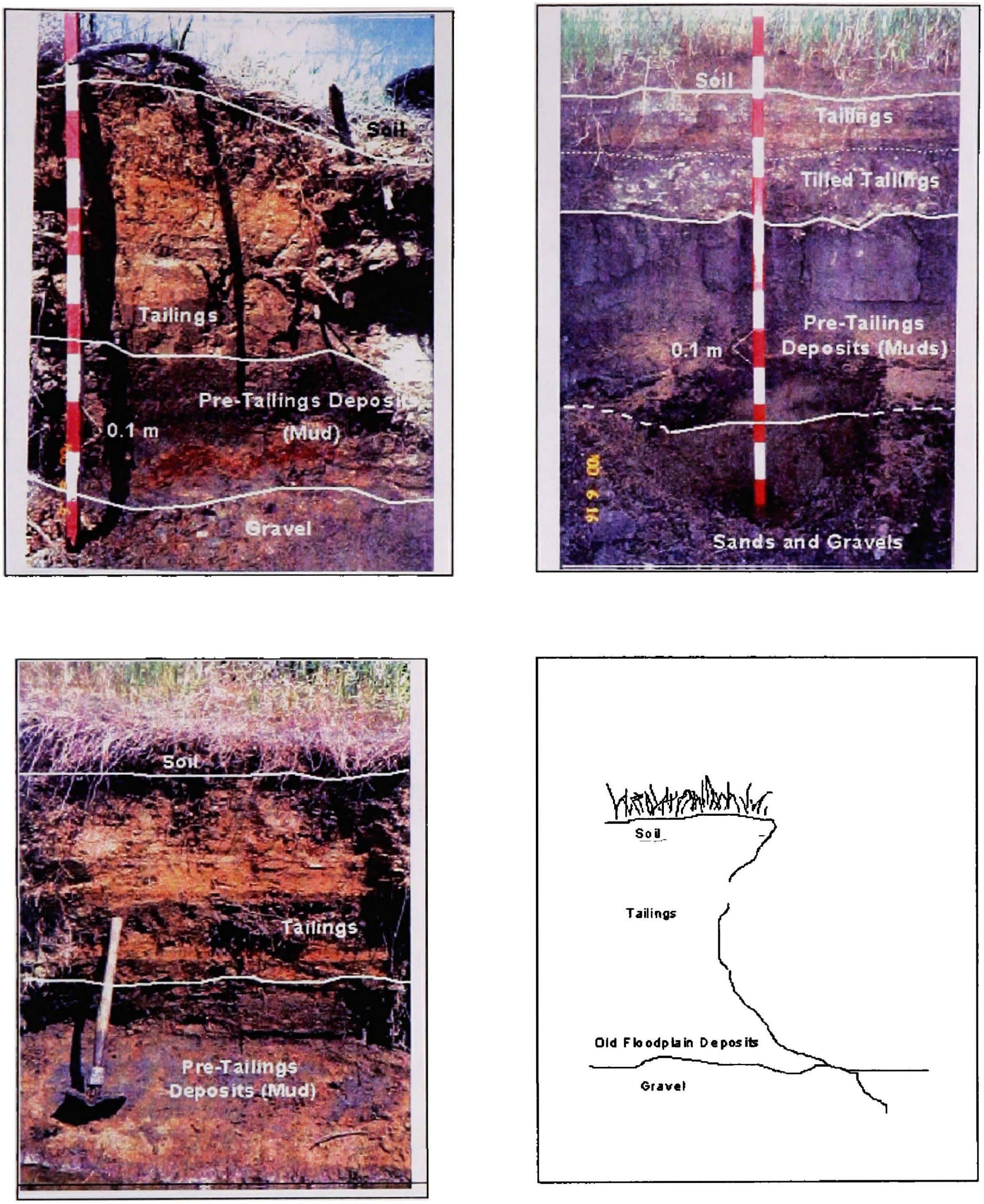


Figure 9. General Bank Stratigraphy. Top 10 cm is soil with tailings, followed by approximately 40 cm of tailings, 40 cm of grey mud, and then a coarse sand and gravel layer.

Figure 11	Convex and Concave Shapes
Figure 12	Percentage of Overhanging Along Bank
Figure 13	Depth of Undercutting
Figure 14	Percentage of Slumping Along Bank
Figure 15	Tailings Thickness
Figure 16	Percentage of Vegetation Cover at Bank
Figure 17	Percentage of Shrubs within 2m of Bank

Table 4. Index to Bank Inventory Figures

Lengths of 2001 Surveyed Banks

Concave Banks	3146m
Convex Banks	6055m
Total Surveyed Banks	9201m

Attributes of Concave Banks *total length=3146m*	**mean**	**% error**	**Total Length Affected (m)**
% of slumping along bank	43	+/-10	1367
% of overhanging along bank	28	+/-10	896
% of bank face with vegetation cover	39	+/-10	1214
% of bank with woody vegetation within 2 m	20	+/-15	624
avg thickness of tailings (cm)	44	+/-10	Na
avg depth of cutting under overhangs (cm)	30	+/-10	Na

Attributes of Convex Banks *total length=6055m*	**mean**	**% error**	**Total Length Affected (m)**
% of slumping along bank	5	+/-10	278
% of overhanging along bank	46	+/-10	2777
% of bank face with vegetation cover	84	+/-10	5062
% of bank with woody vegetation within 2 m	32	+/-15	1958
avg thickness of tailings (cm)	37	+/-10	Na
avg depth of cutting under overhangs (cm)	35	+/-10	Na

Table 5. Summary of bank attributes from visual and GPS bank survey (see Appendix C).

Overall, the riverbank inventory included 9200 m of banks, of which 3145 m (34%) were concave "cutbanks" and the remaining 6045 m (66%) (Table 5) were the more stable convex shapes (Figure 11). Both bank types are susceptible to undercutting and therefore, a large portion of each type can be described as overhanging or cantilevered. Most of the erosion initiates in the lower gravel and mud layers, which often leaves the tailings, soil, and vegetation overhanging the river. These overhanging banks occur in 46% of the convex segments, with horizontal cuts typically 30 cm in depth at the base of the bank. Overhangs occur in only 28% of the concave bank segments, with a similar cut depth of about 30 cm (Table 5 and Figures 12 and 13). Concave-bank undercuts usually occur in the middle portion of the bank and are not as clearly defined as those seen in convex banks, probably due to the obscuring effect of the eroded upper bank falling to the base. As mentioned previously, most of the undercutting takes place in the gravels and pre-tailings deposits which leaves the tailings layer overhanging. These overhangs eventually fall into the river, where they protect the bank until the next high flow (Figure 10). The percentage of slumping along the banks is shown in Figure 15. Despite the higher percentage of overhangs, the convex segments possess slumps along only 5% of the banks, whereas slumps are present along 43% of the concave banks. Slumping mostly occurs at riffles and meander bends where cutbanks are forming and there seems to be a strong relationship between concave banks and slumping (Figures 11 and 15).

Woody vegetation along the banks consist mostly of small

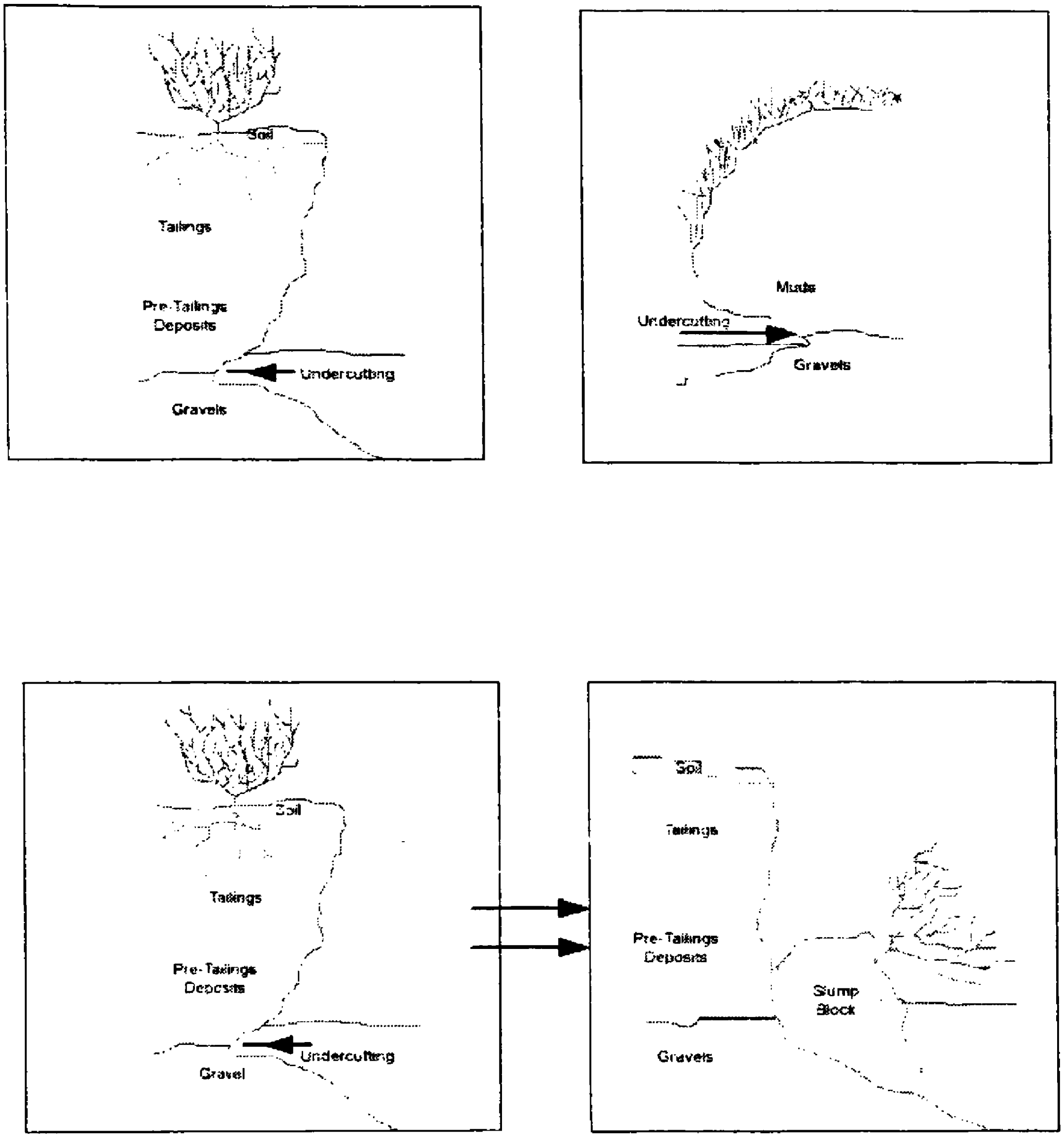


Figure 10. Examples of undercutting and mechanism of erosion. Erosion occurs in the basal sands and gravels, undercutting the bank until the downward stress overcomes the strength of the material and a block fails.

(~1 m high) water birch (*Betula occidentata*) and various willows (*Salix* sp.). Various grasses and weeds dominate the rest of the vegetation (Rice and Ray 1985; RWRP 1996). Figures 16 and 17 summarize these data. Convex banks are commonly more vegetated than the concave banks (84% vs. 39%, respectively), and have more woody vegetation within 2 m of the bank (32% vs. 20%, respectively). However, it is not clear whether the banks are more stable due to the vegetation, or if there is more vegetation because the banks are more stable. Other factors, such as watering, grazing practices, thickness of the non-tailings alluvium layer, and fluvial geomorphology can allow for a more stable bank, and therefore allow more vegetation to take hold (RWRP 1996).

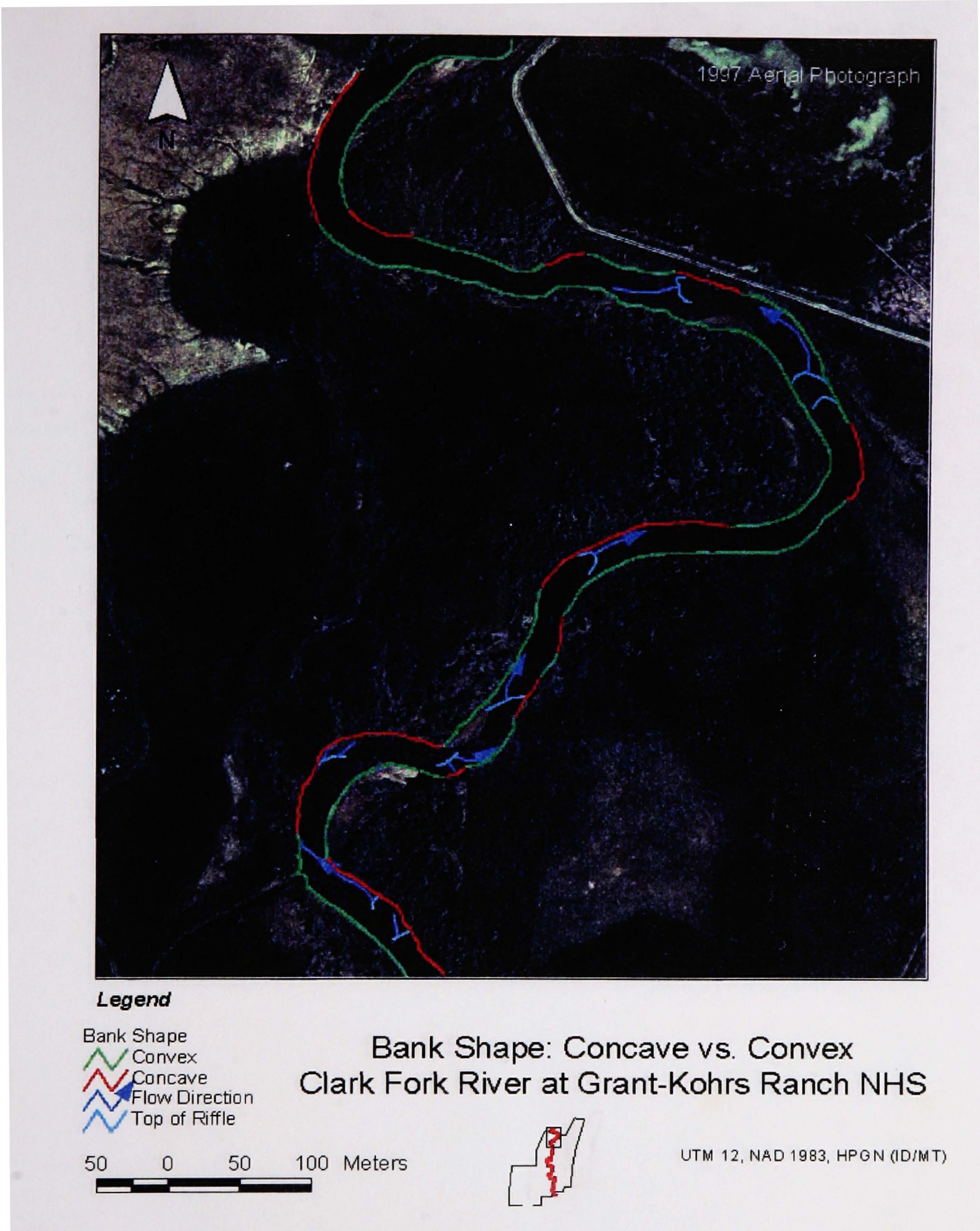


Figure 11a. Locations of Convex and Concave Banks (Figure 5) within Grant-Kohrs Ranch NHS. Also shows the location of riffles and the general direction of flow coming off of them.

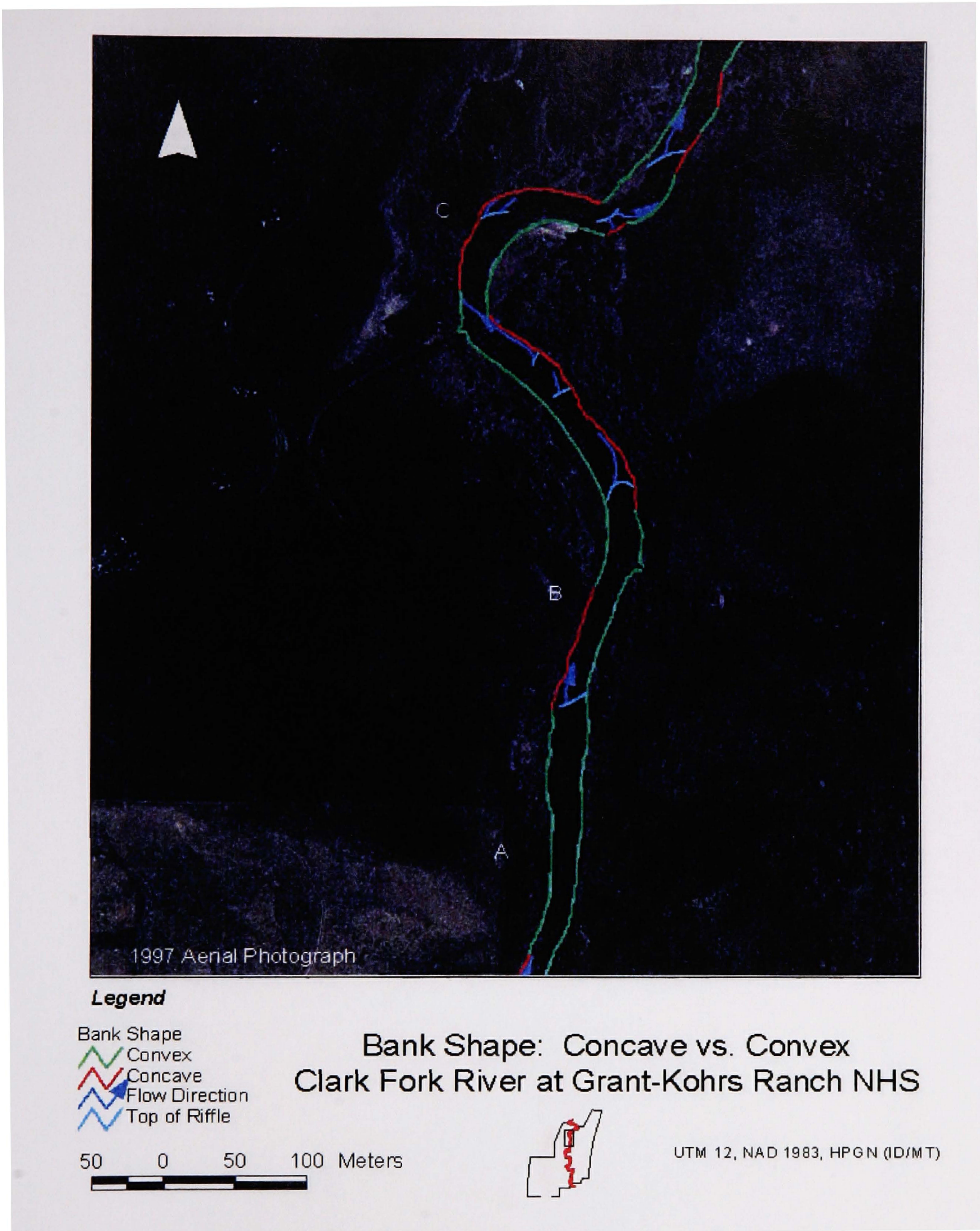


Figure 11b. Locations of Convex and Concave Banks (Figure 5) within Grant-Kohrs Ranch NHS. Also shows the location of riffles and the general direction of flow coming off of them.

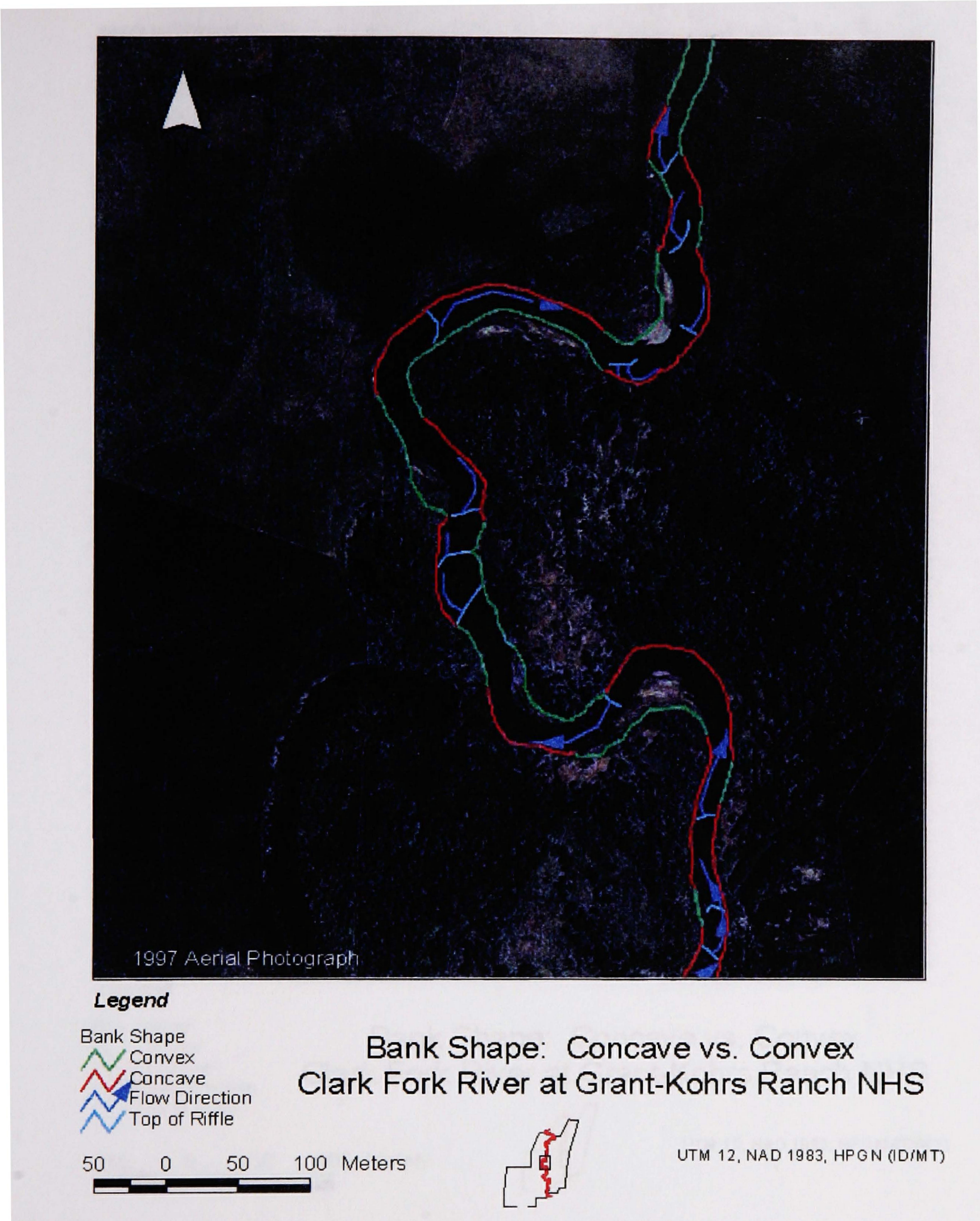


Figure 11c. Locations of Convex and Concave Banks (Figure 5) within Grant-Kohrs Ranch NHS. Also shows the location of riffles and the general direction of flow coming off of them.

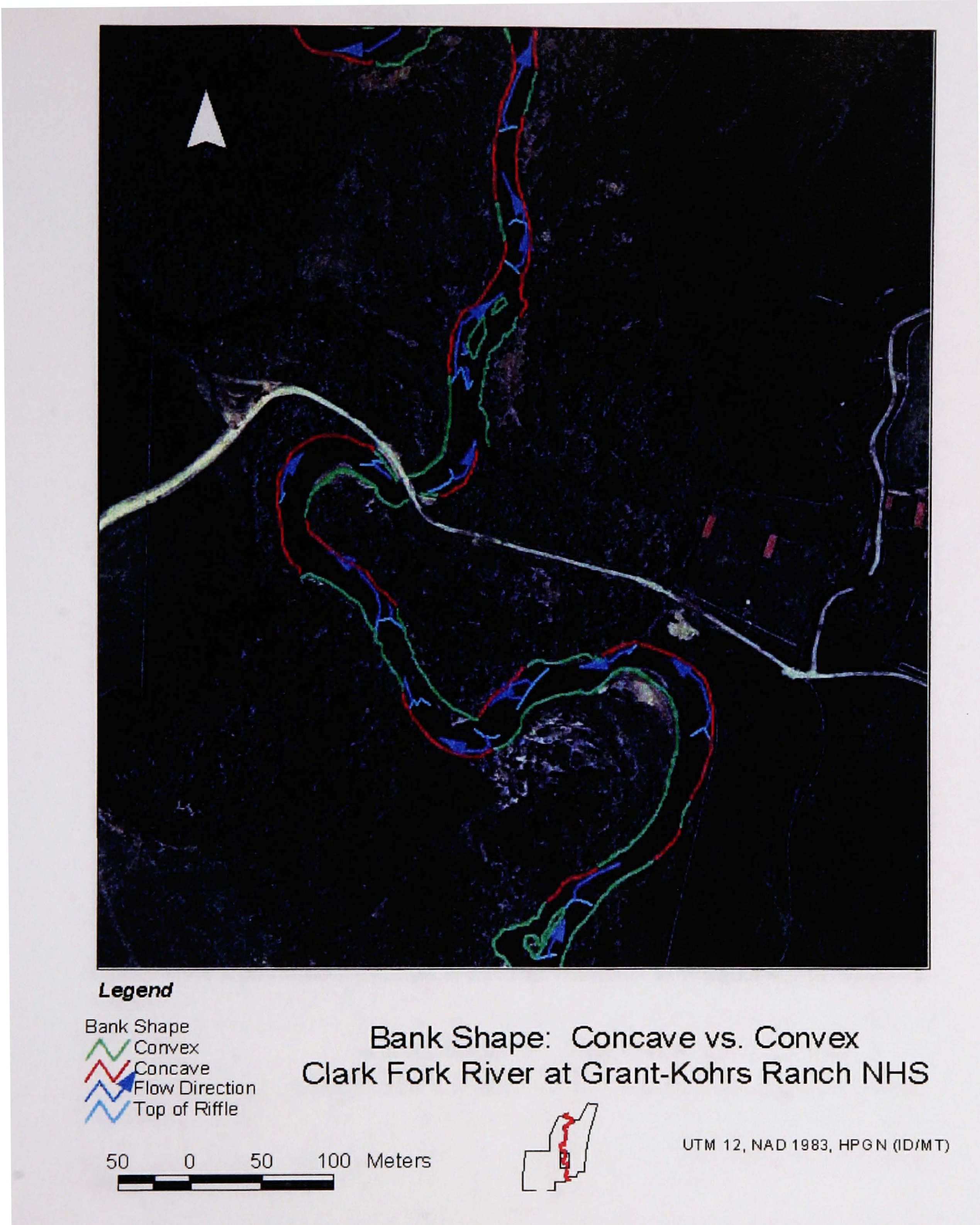


Figure 11d. Locations of Convex and Concave Banks (Figure 5) within Grant-Kohrs Ranch NHS. Also shows the location of riffles and the general direction of flow coming off of them.

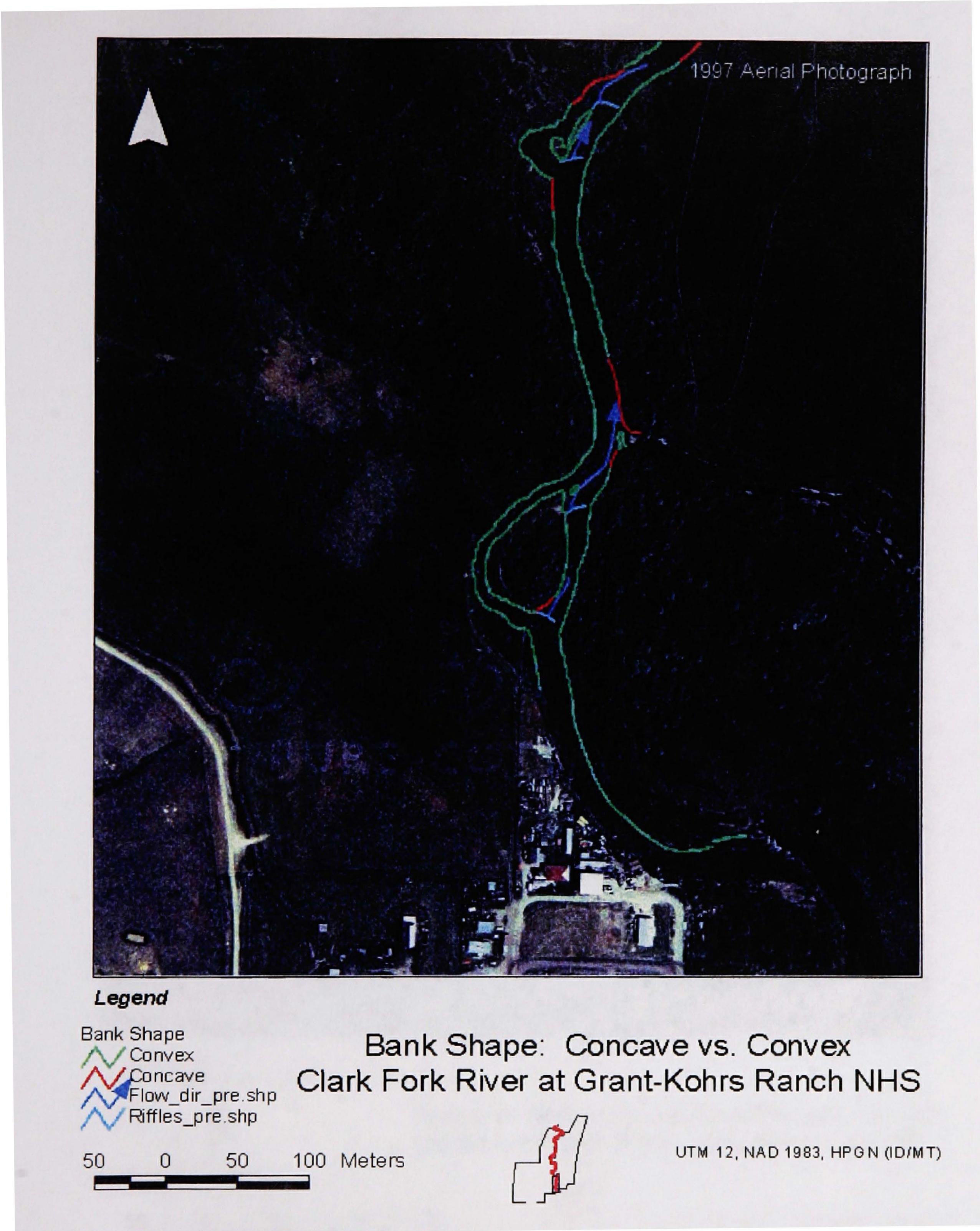


Figure 11e. Locations of Convex and Concave Banks (Figure 5) within Grant-Kohrs Ranch NHS. Also shows the location of riffles and the general direction of flow coming off of them.

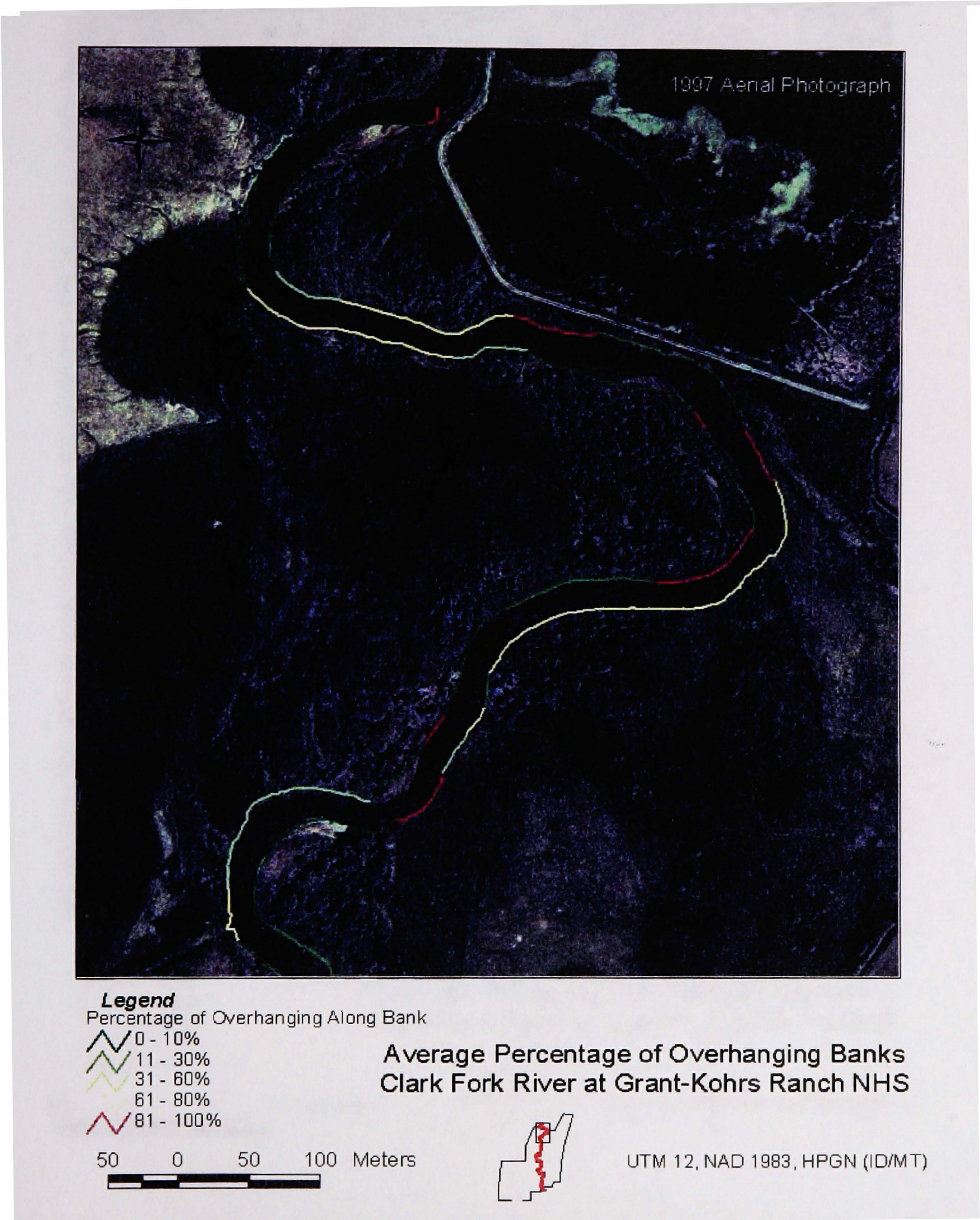


Figure 12a. Average percentage of overhanging (cantilevered) banks within a bank segment.

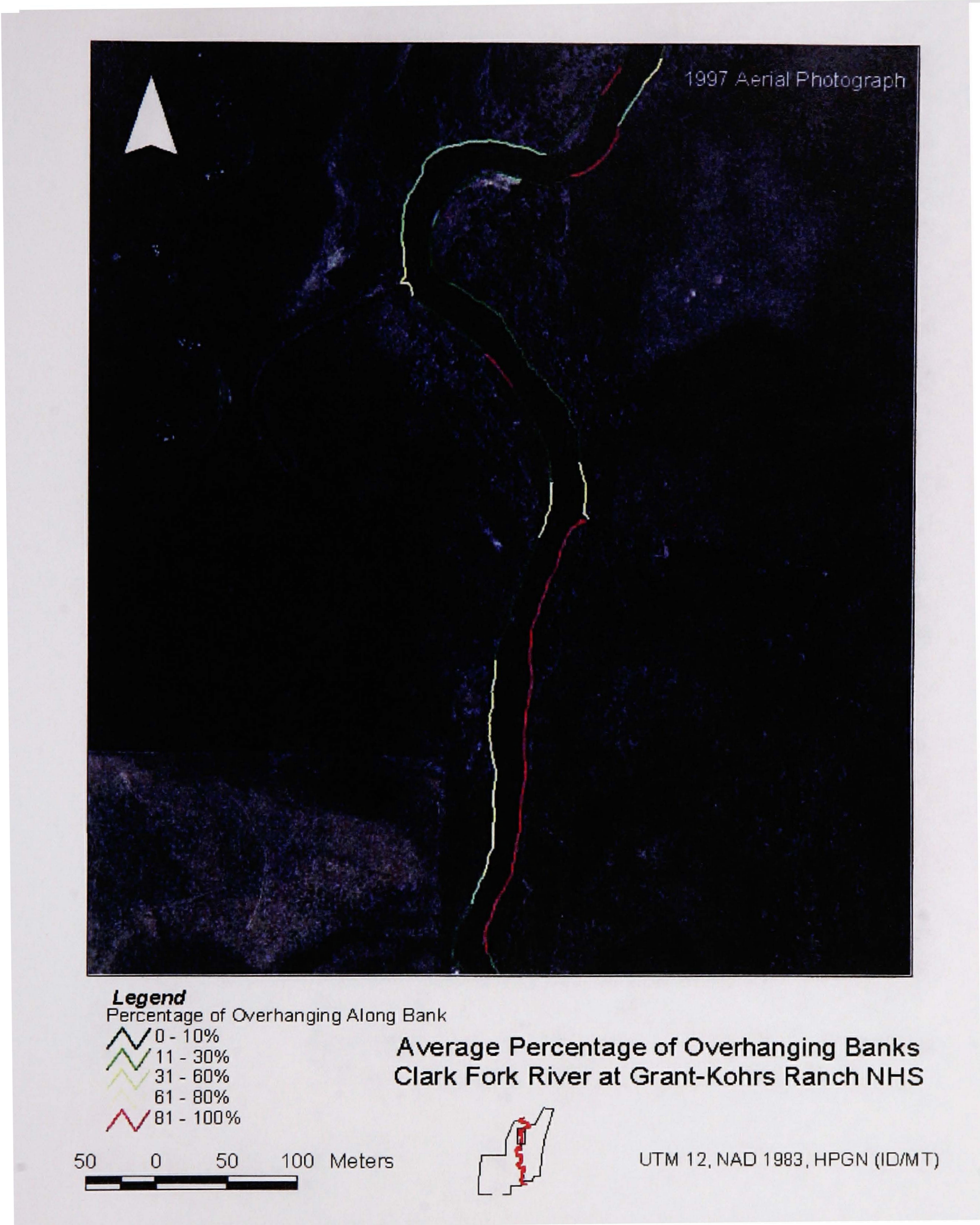


Figure 12b. Average percentage of overhanging (cantilevered) banks within a bank segment.

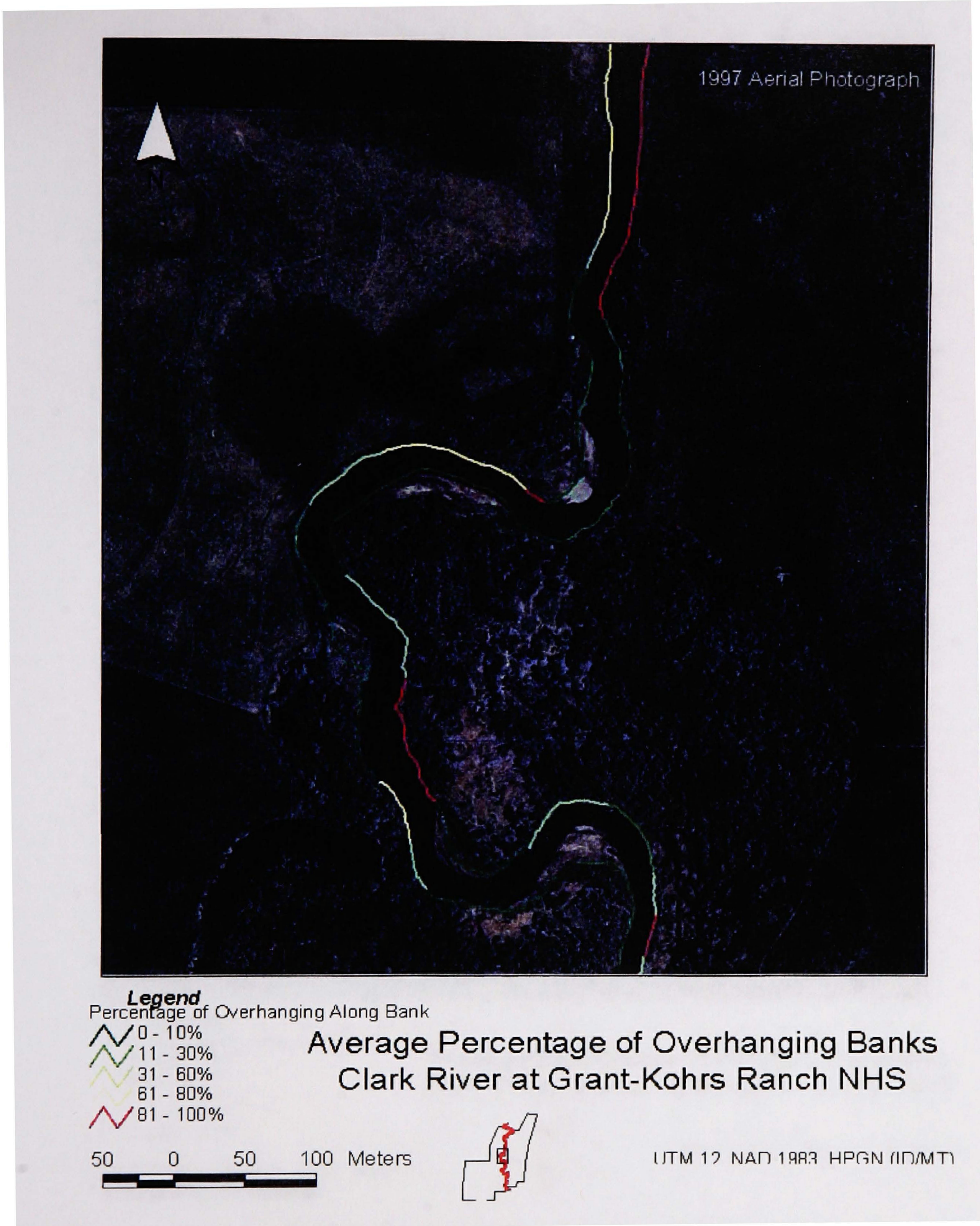


Figure 12c. Average percentage of overhanging (cantilevered) banks within a bank segment.

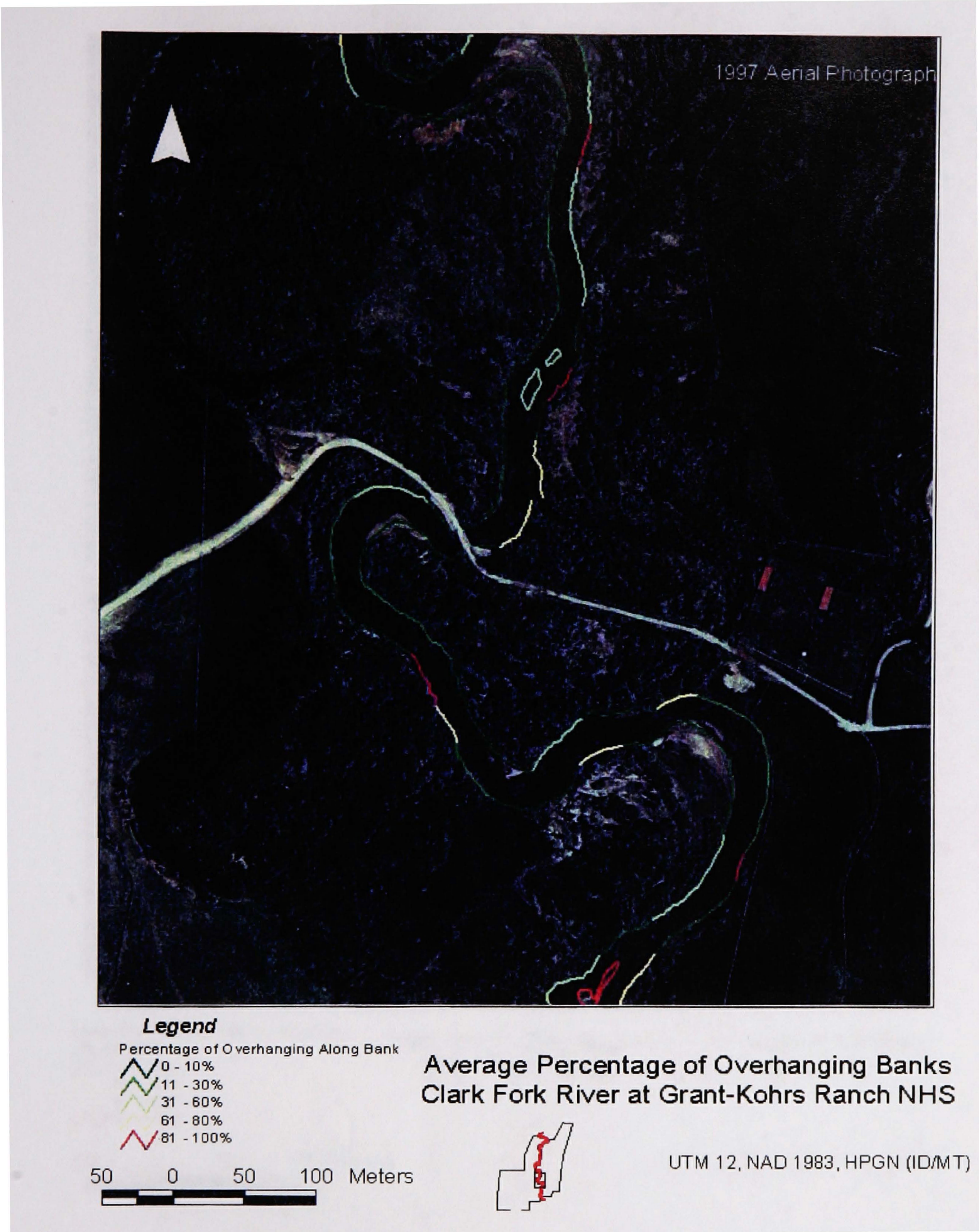


Figure 12d. Average percentage of overhanging (cantilevered) banks within a bank segment.

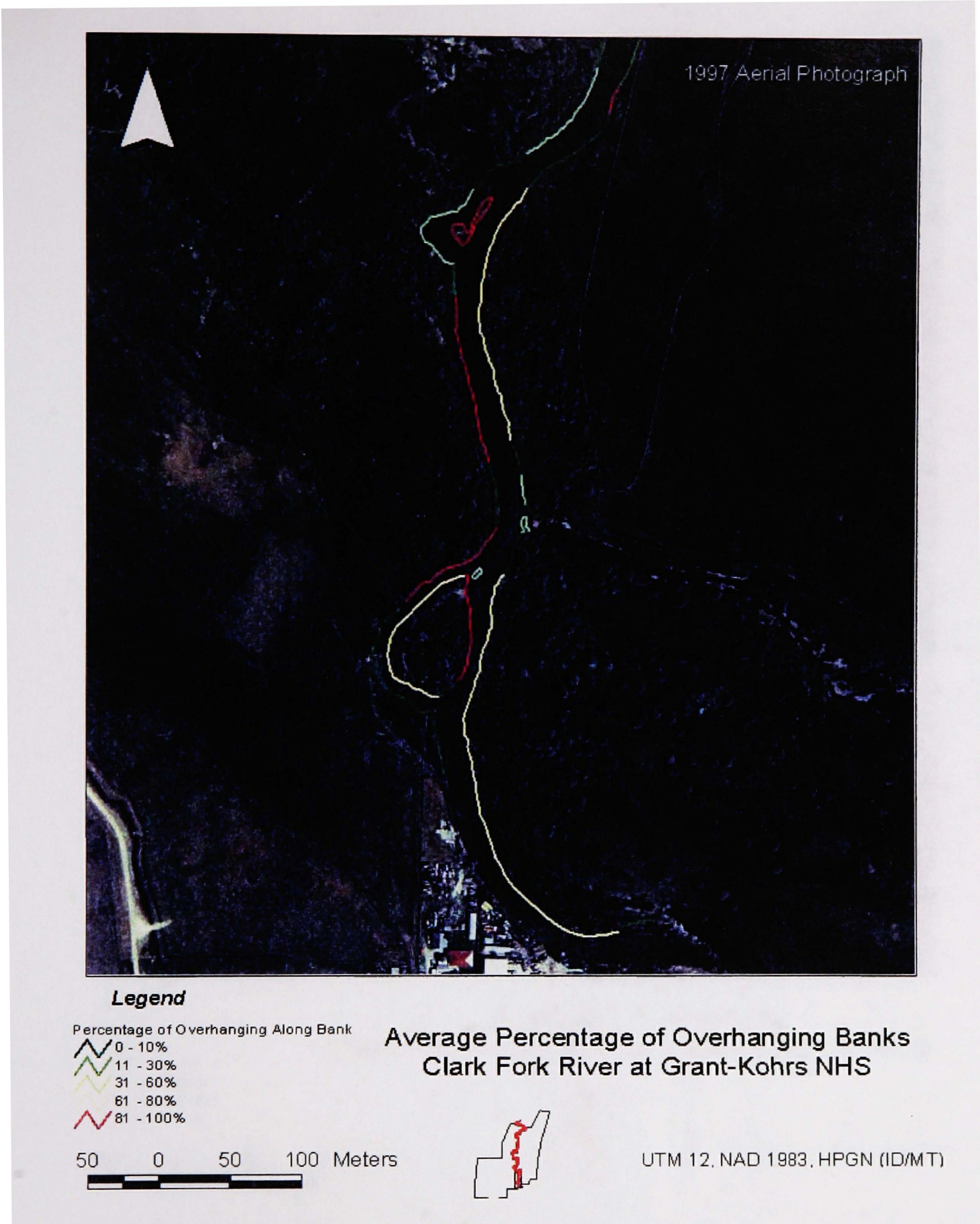


Figure 12e. Average percentage of overhanging (cantilevered) banks within a bank segment.

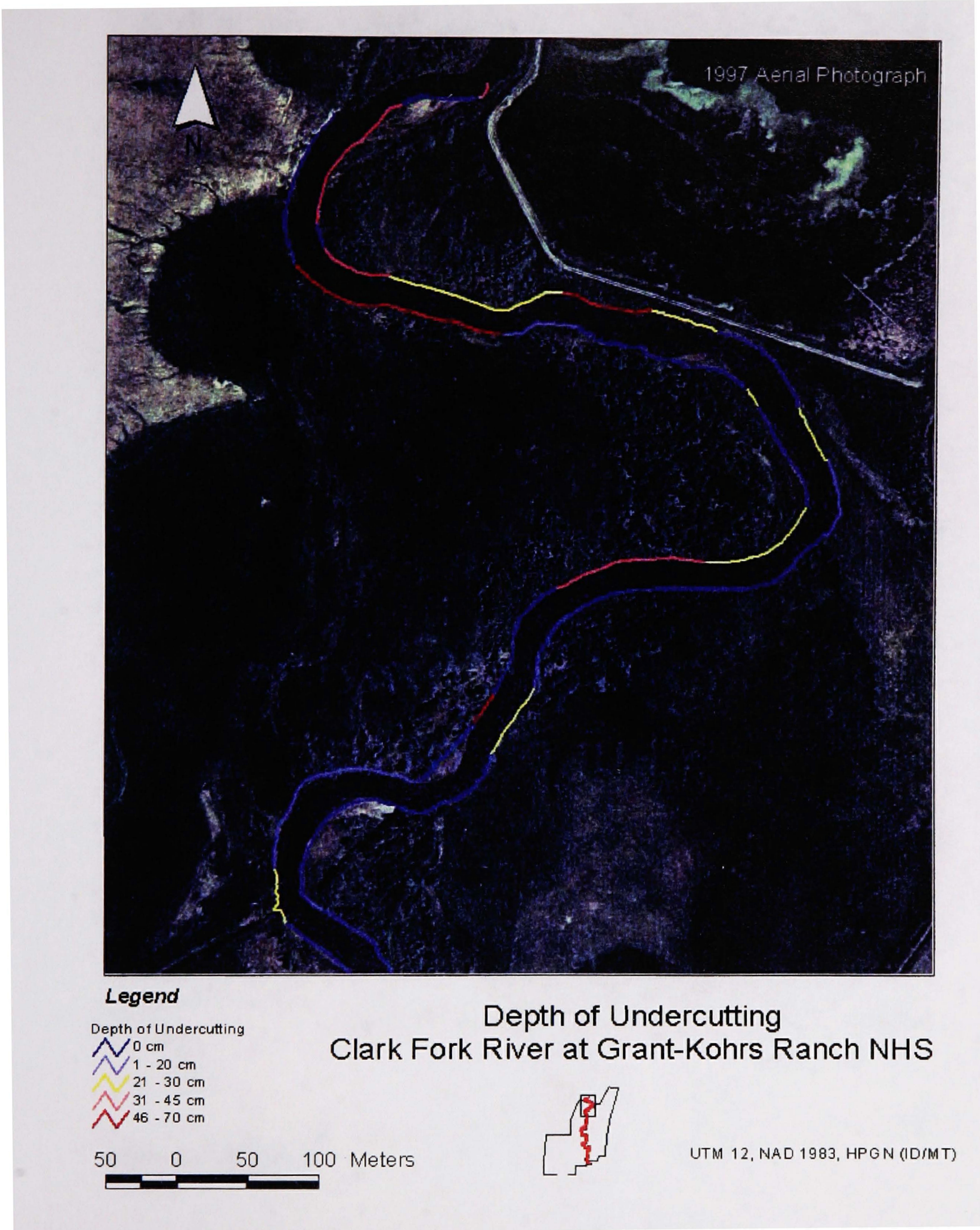


Figure 13a. Depth of horizontal undercutting beneath overhanging (cantilevered) banks within a bank segment.

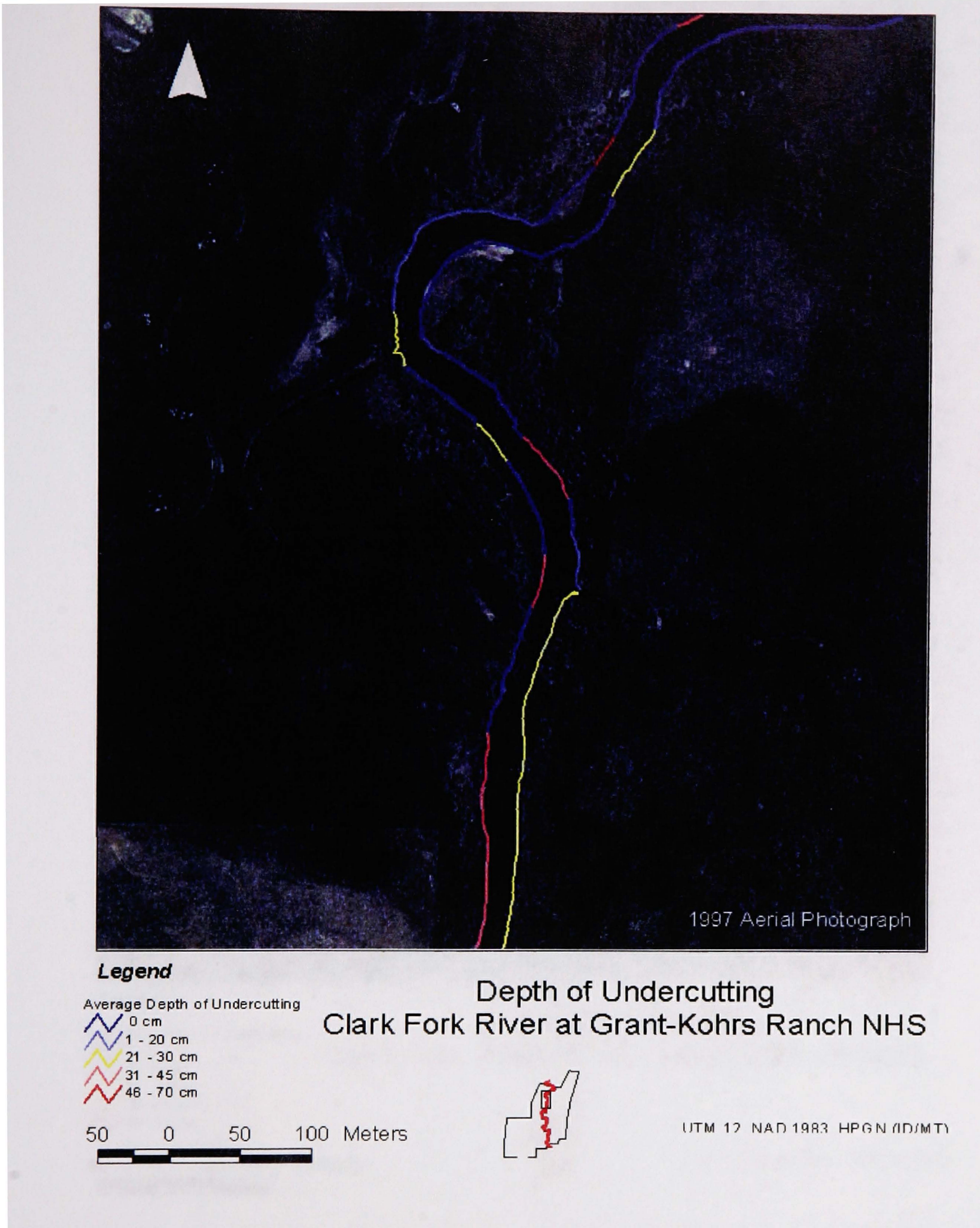


Figure 13b. Depth of horizontal undercutting beneath overhanging (cantilevered) banks within a bank segment.

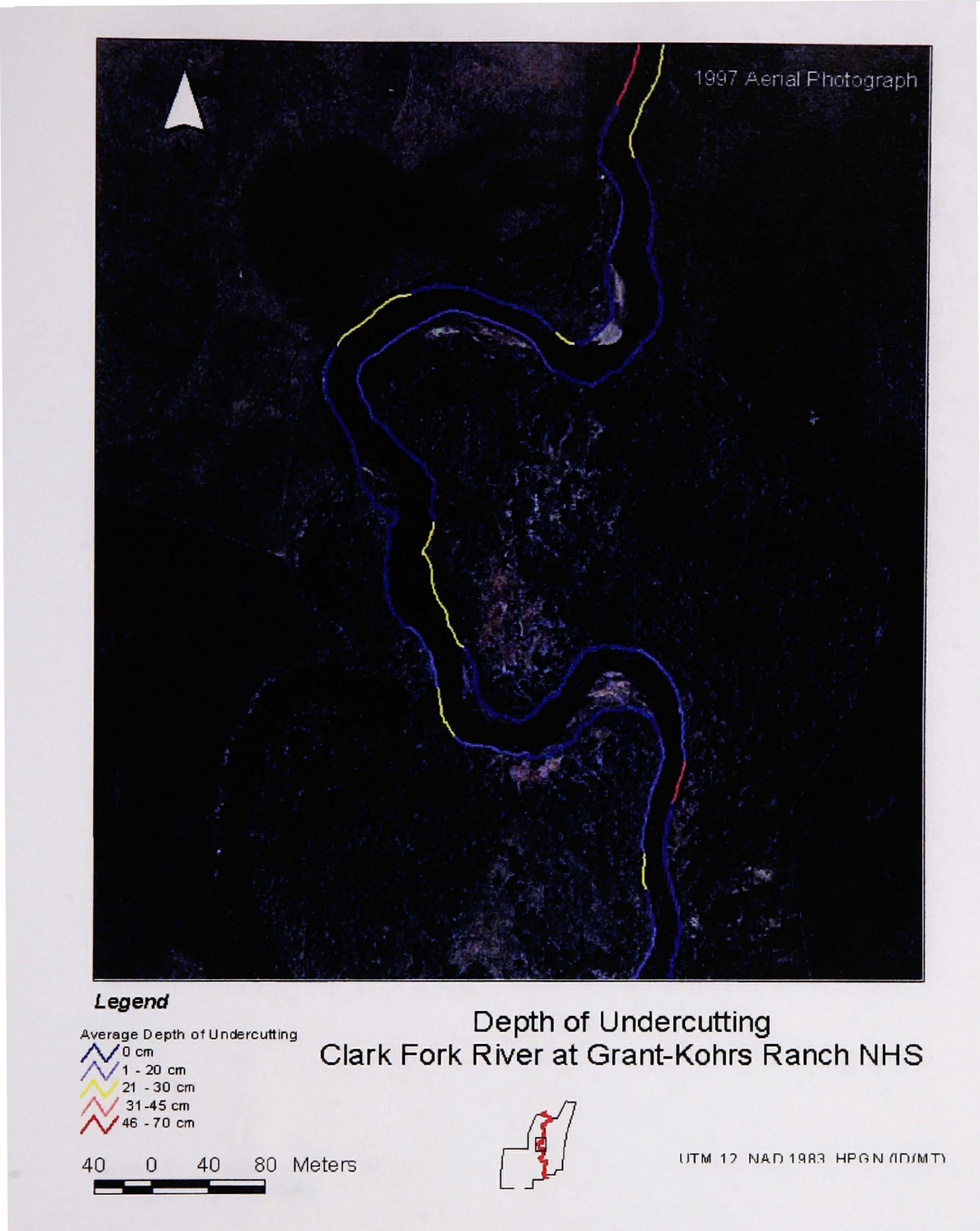


Figure 13c. Depth of horizontal undercutting beneath overhanging (cantilevered) banks within a bank segment.

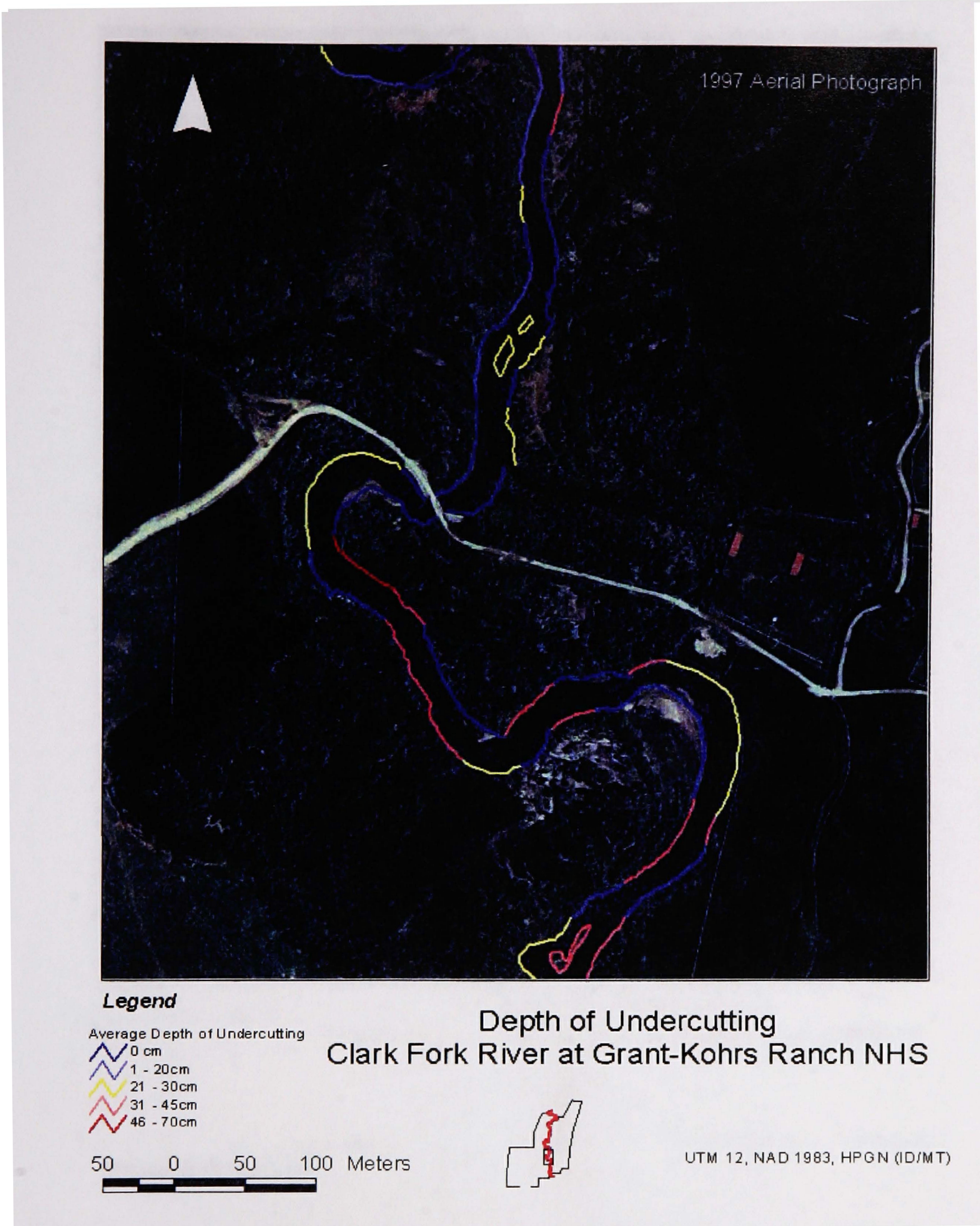


Figure 13d. Depth of horizontal undercutting beneath overhanging (cantilevered) banks within a bank segment.

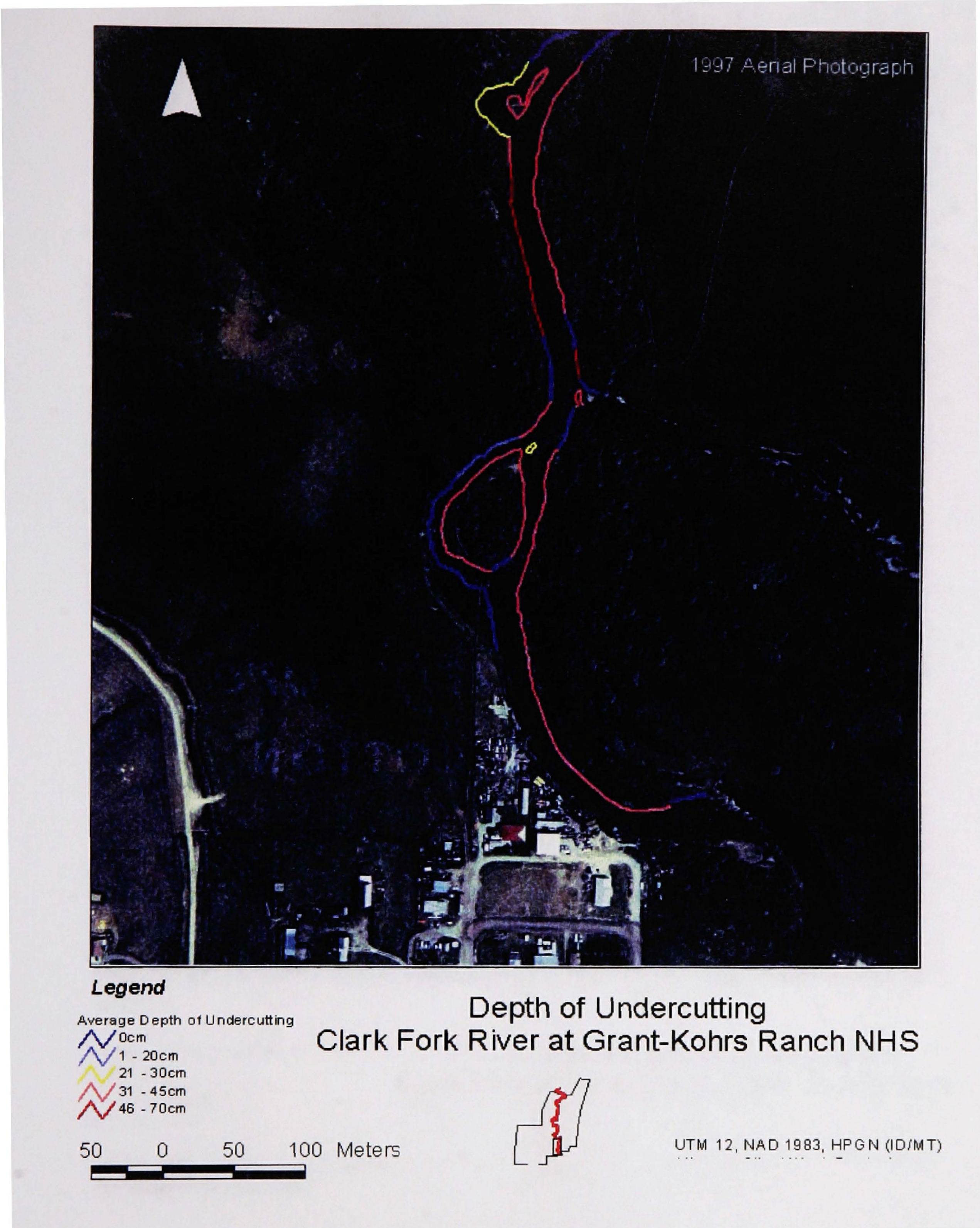


Figure 13e. . Depth of horizontal undercutting beneath overhanging (cantilevered) banks within a bank segment.

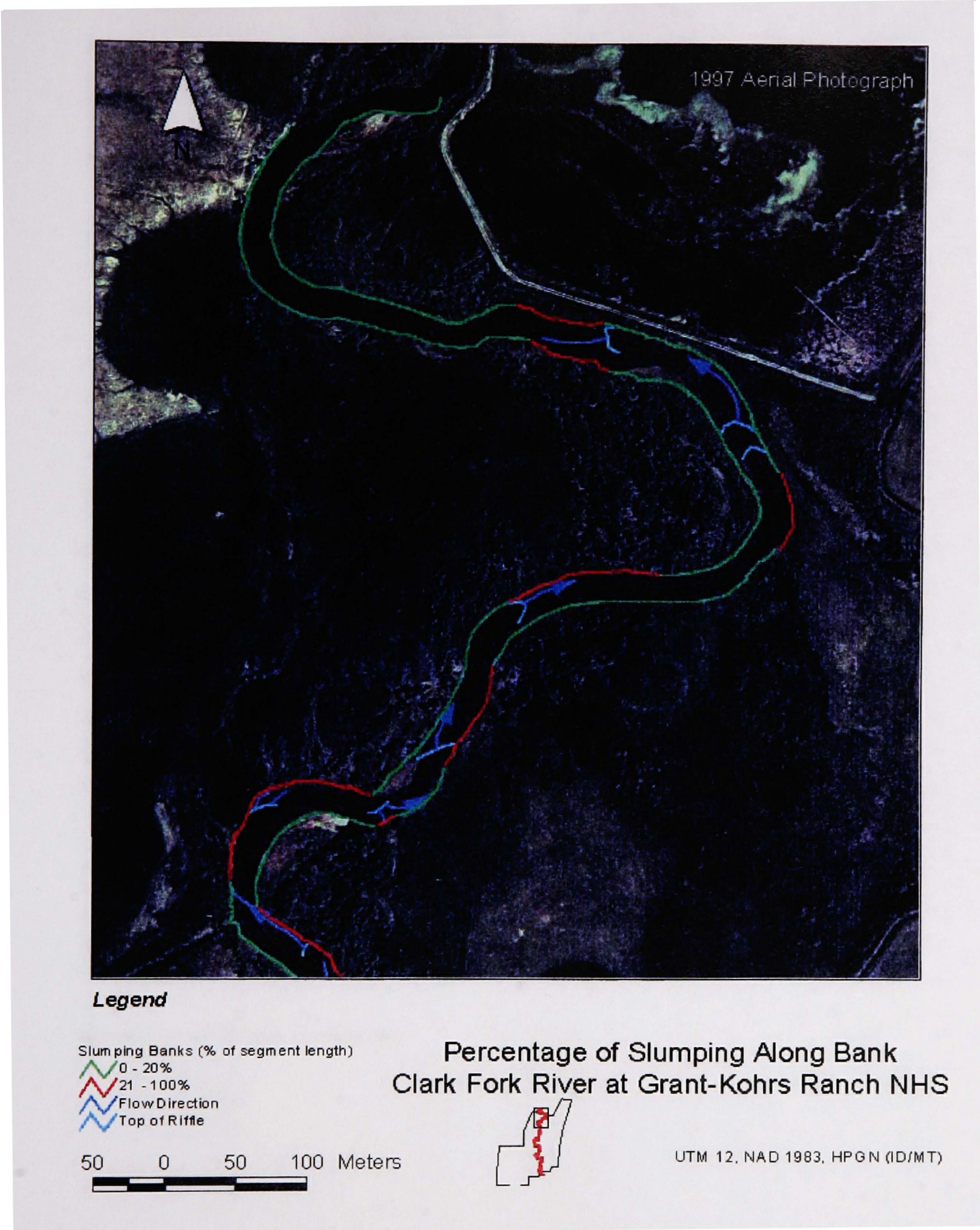
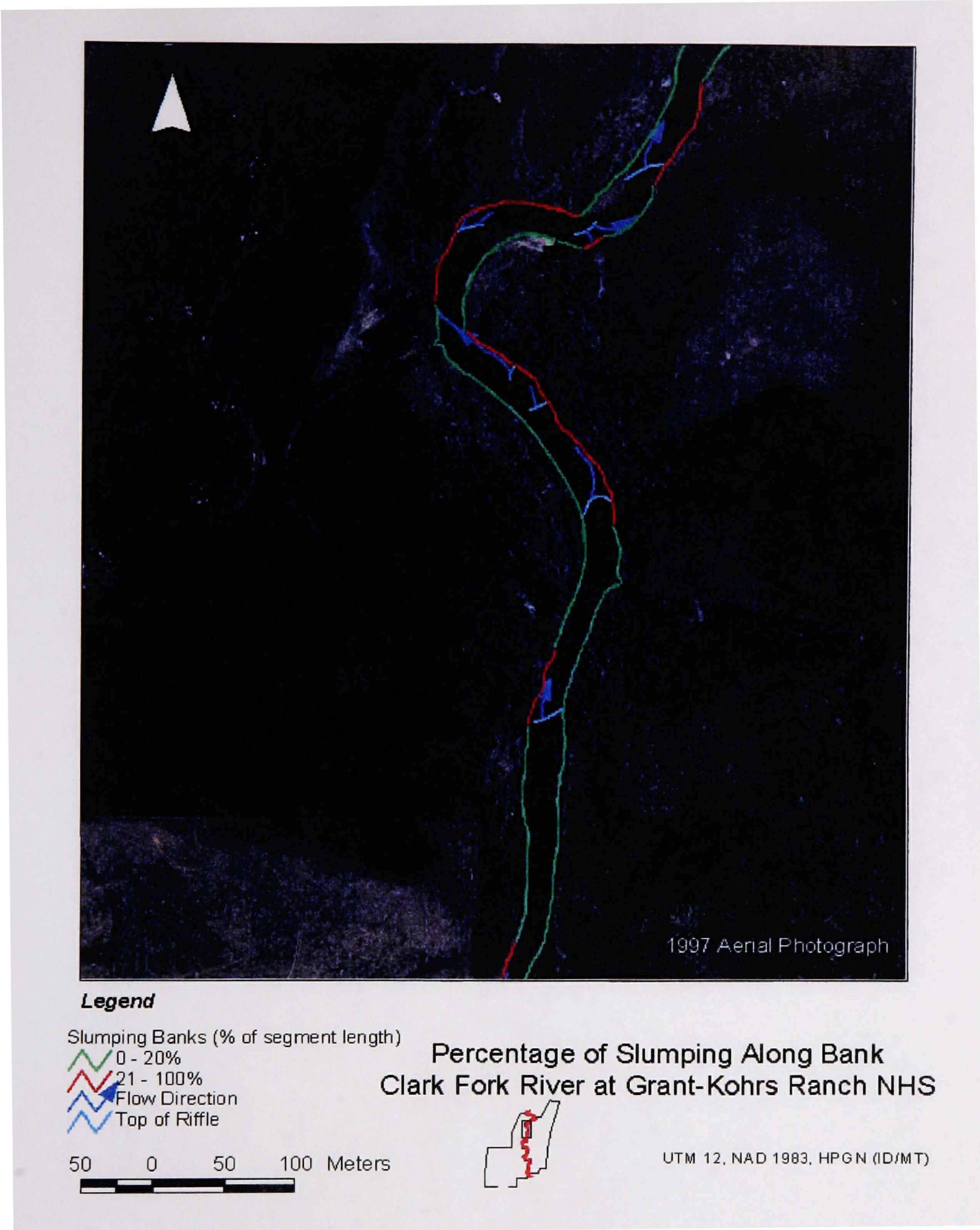


Figure 14a. Percentage of slumping along each bank segment. Riffle location and direction of flow are also depicted.



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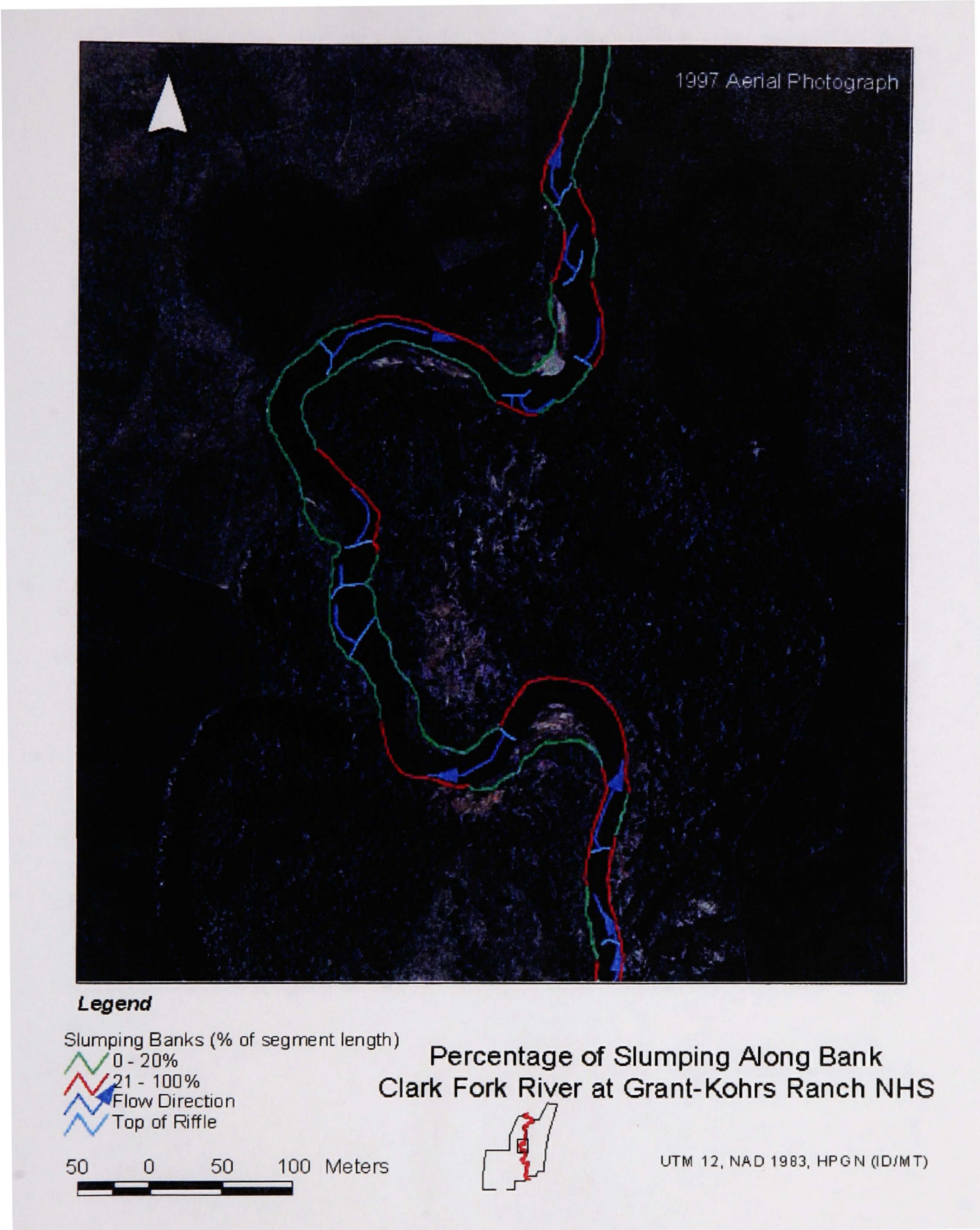


Figure 14c. Percentage of slumping along each bank segment. Riffle location and direction of flow are also depicted.

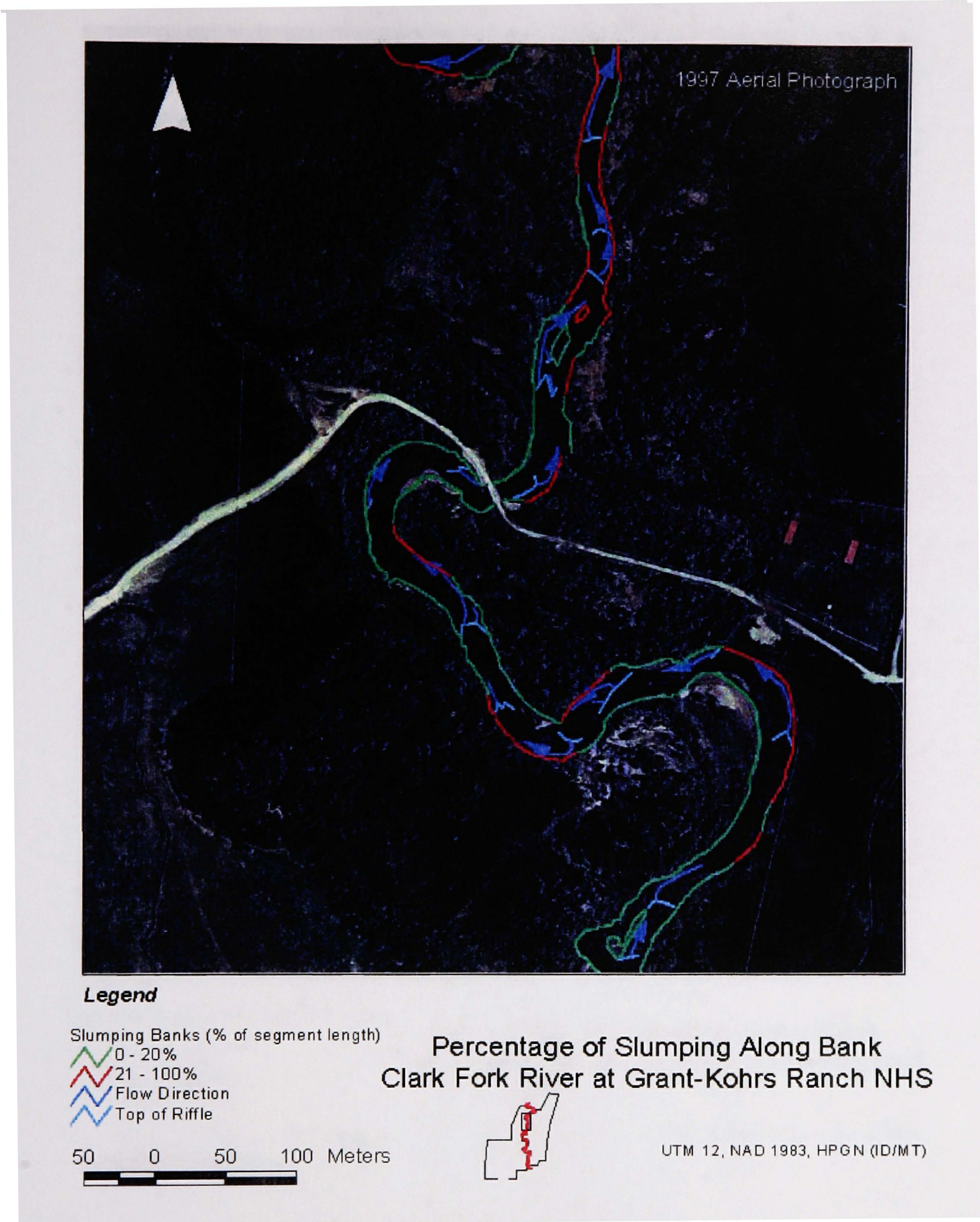
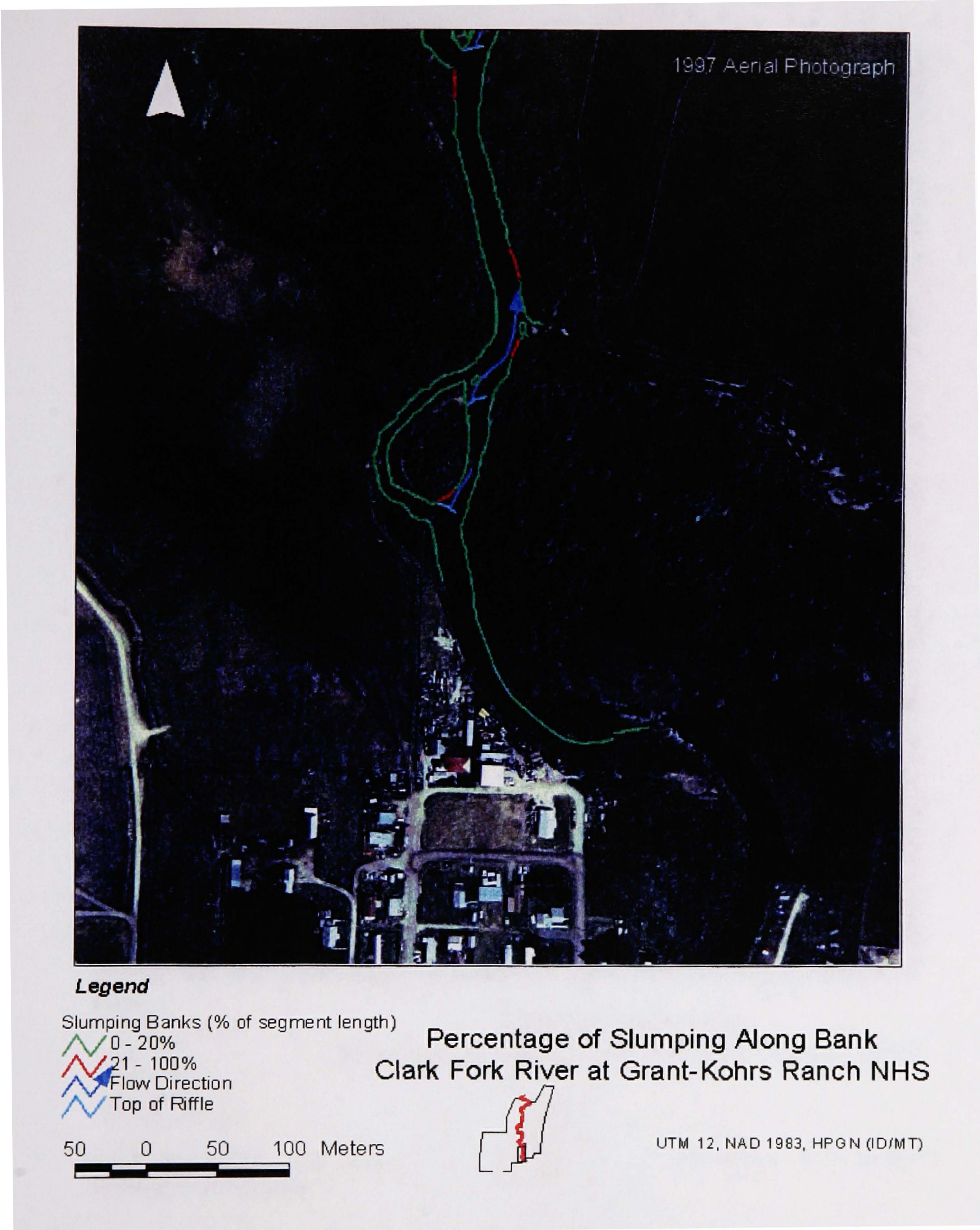


Figure 14d. Percentage of slumping along each bank segment. Riffle location and direction of flow are also depicted.



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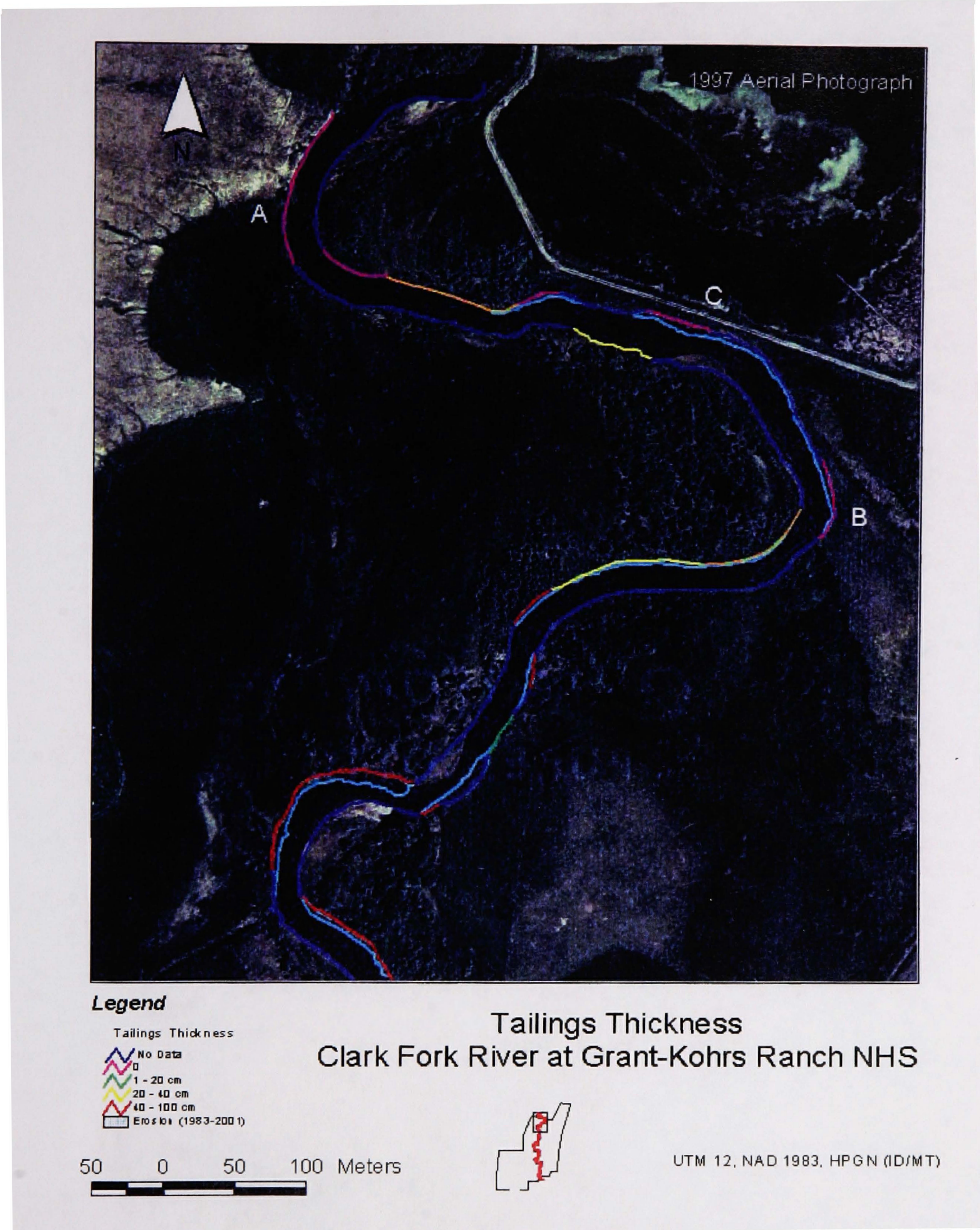


Figure 15a. Average thickness of the tailings layer along each bank segment. Light blue lines outline the streamward side of the area eroded between 1983 and 2001.

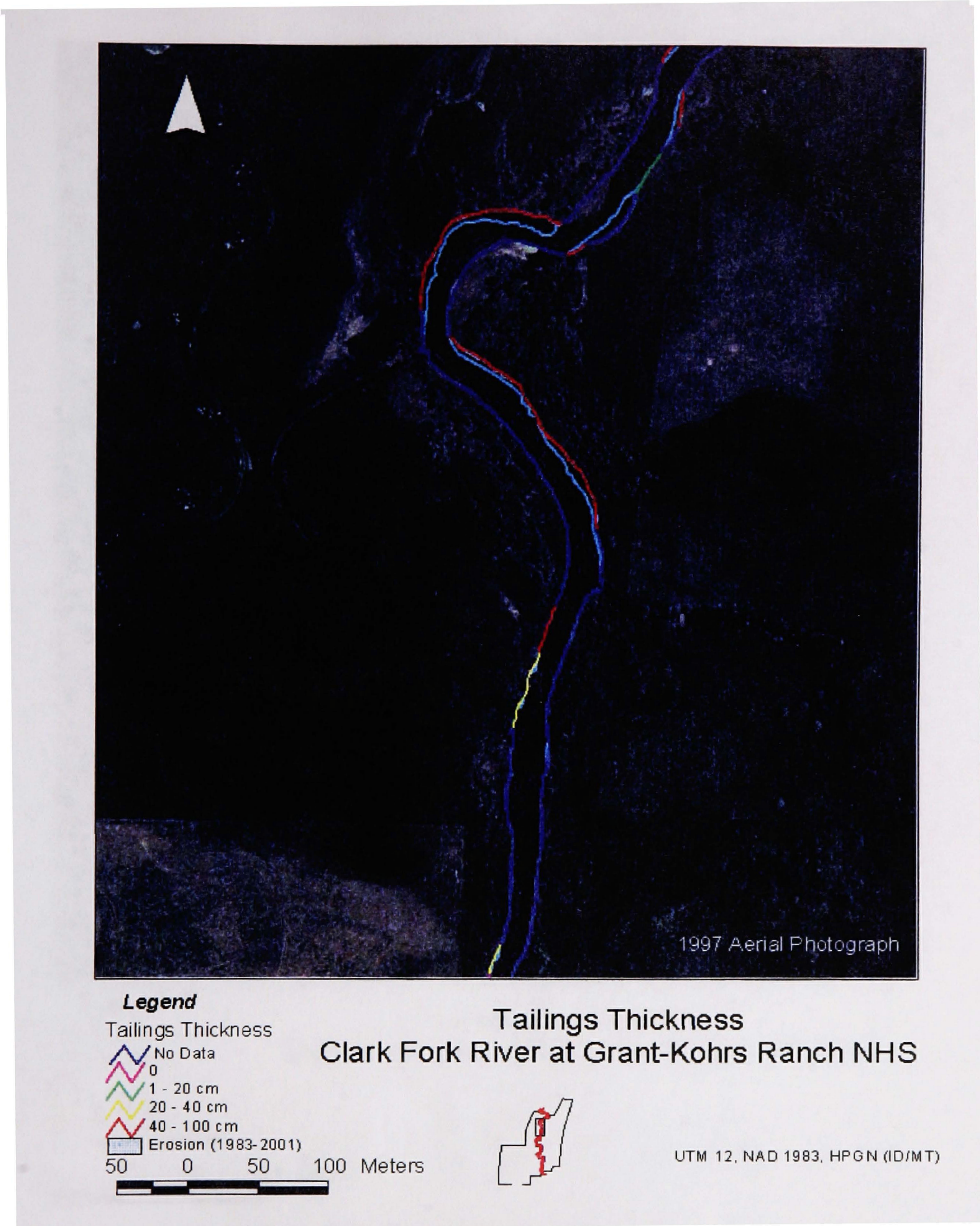


Figure 15b. Average thickness of the tailings layer along each bank segment. Light blue lines outline the streamward side of the area eroded between 1983 and 2001.

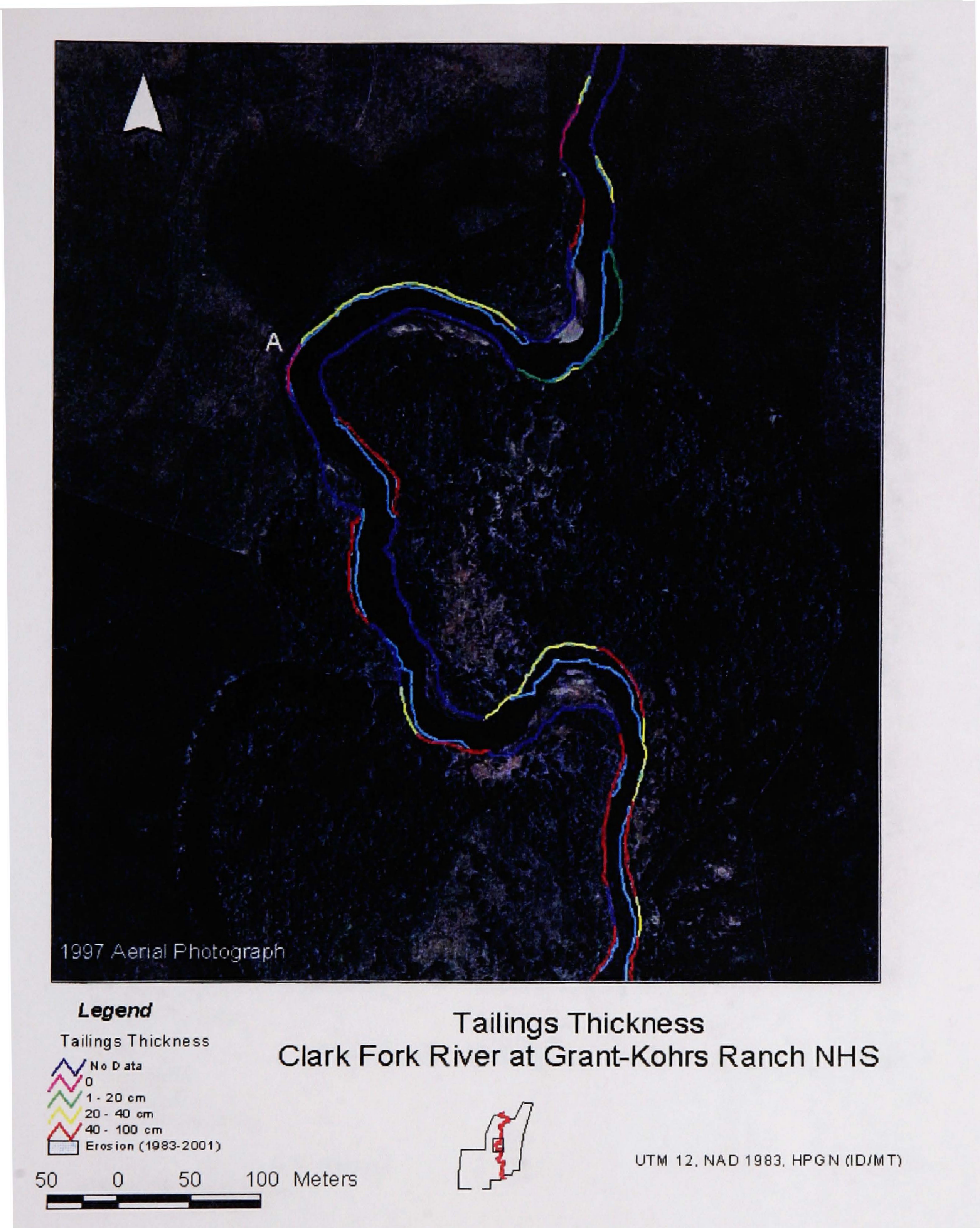


Figure 15c. Average thickness of the tailings layer along each bank segment. Light blue lines outline the streamward side of the area eroded between 1983 and 2001.

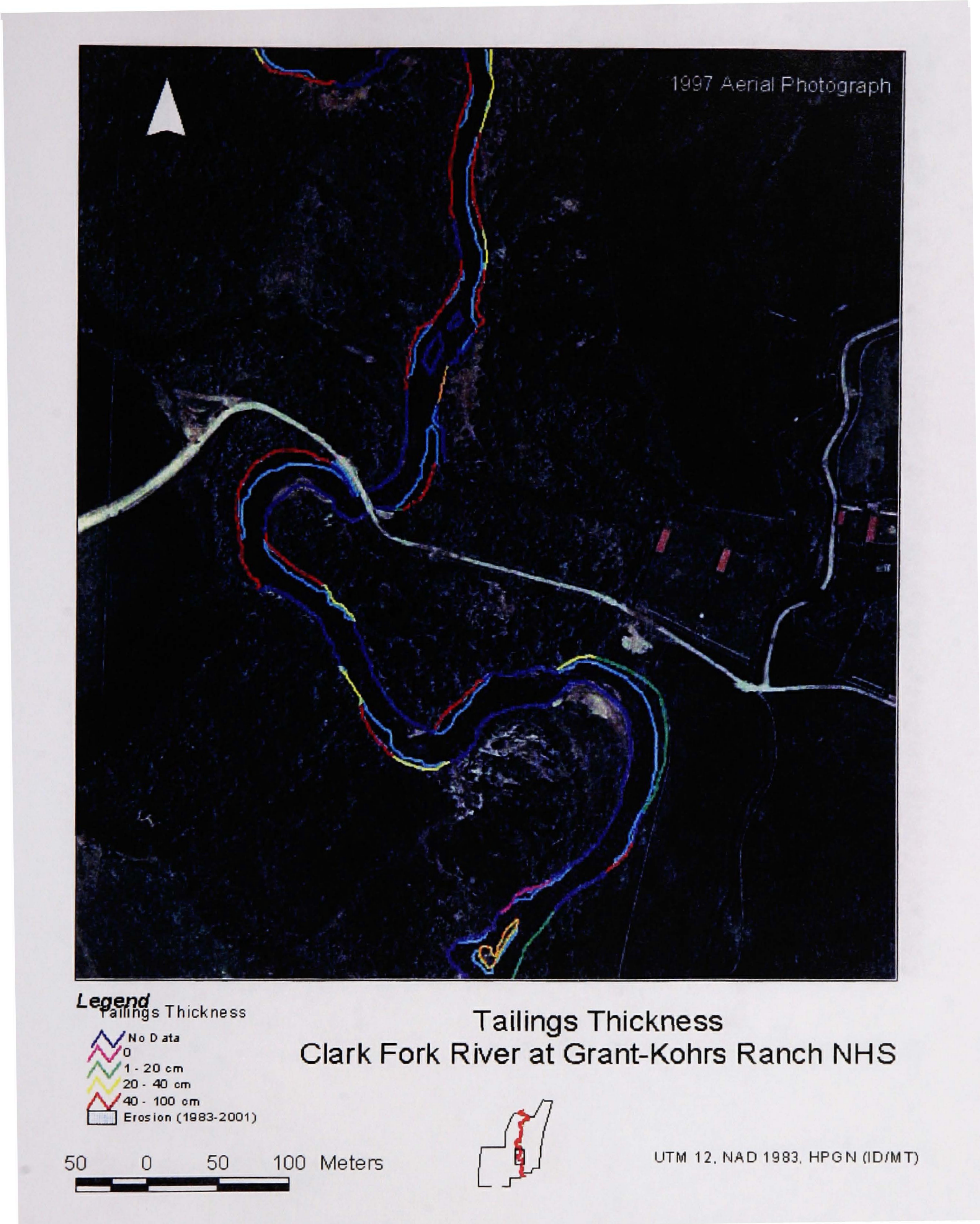
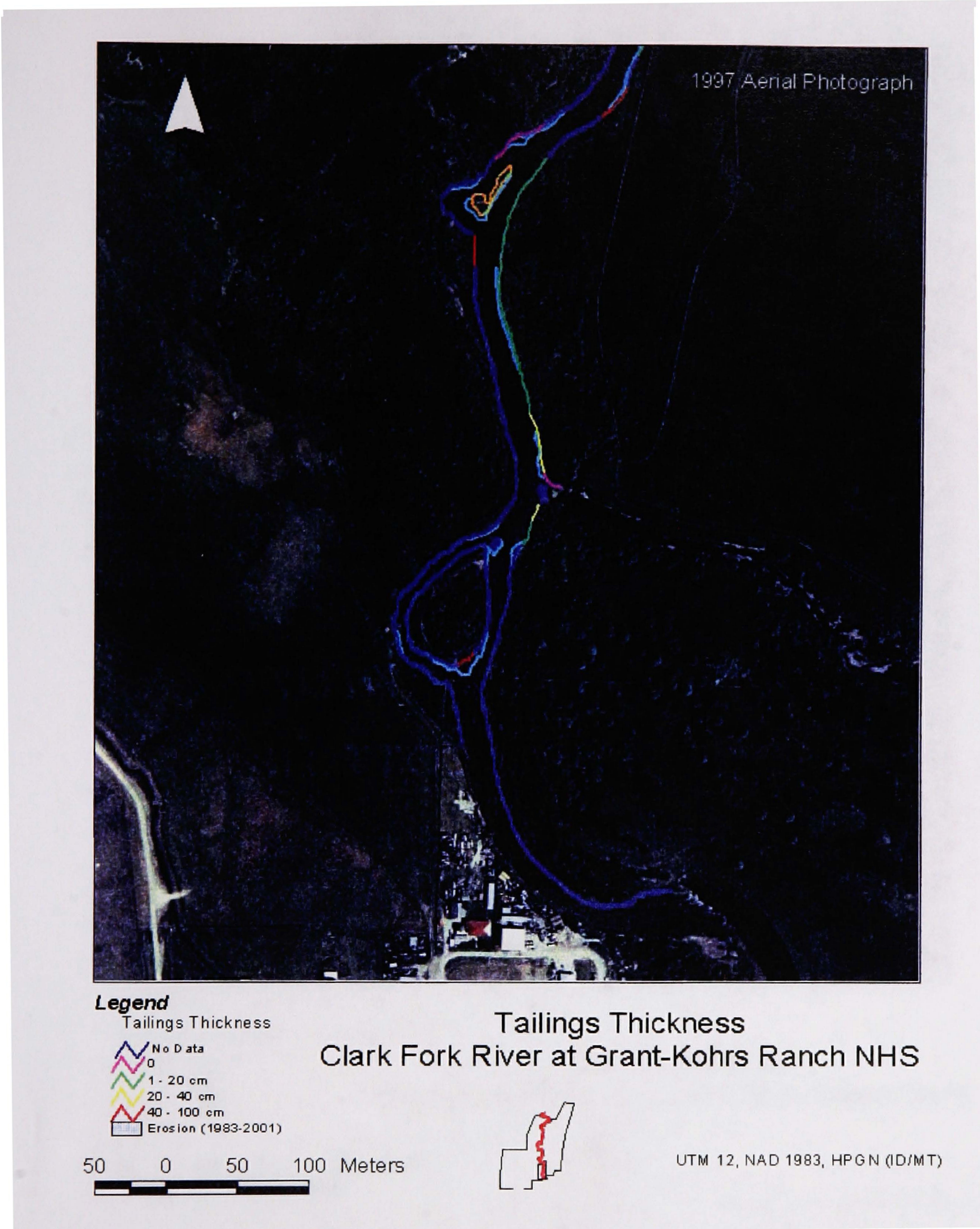


Figure 15d. Average thickness of the tailings layer along each bank segment. Light blue lines outline the streamward side of the area eroded between 1983 and 2001.



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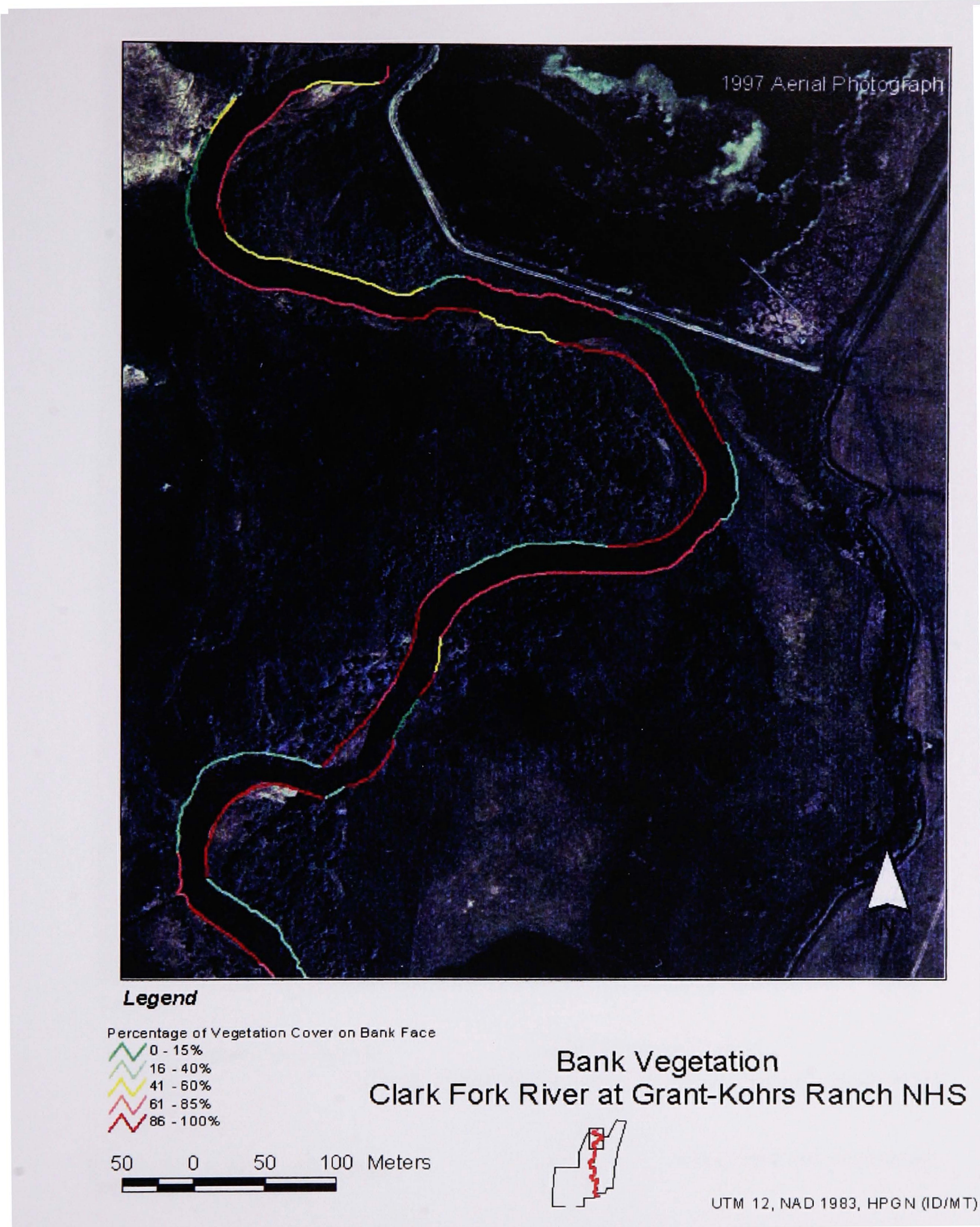


Figure 16a. Percent of bank segments covered in vegetation. Vegetation type was not designated.

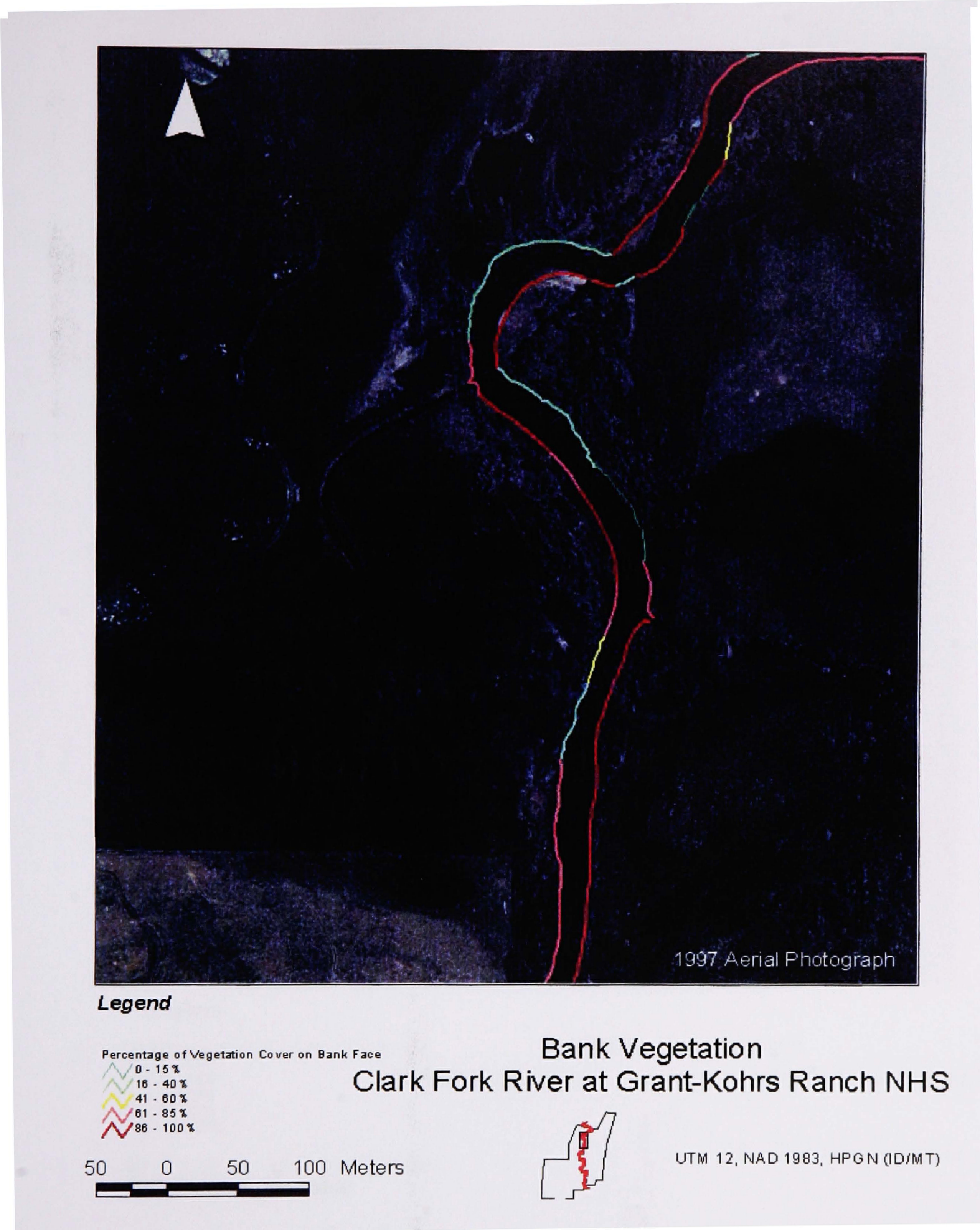


Figure 16b. Percent of bank segments covered in vegetation. Vegetation type was not designated.

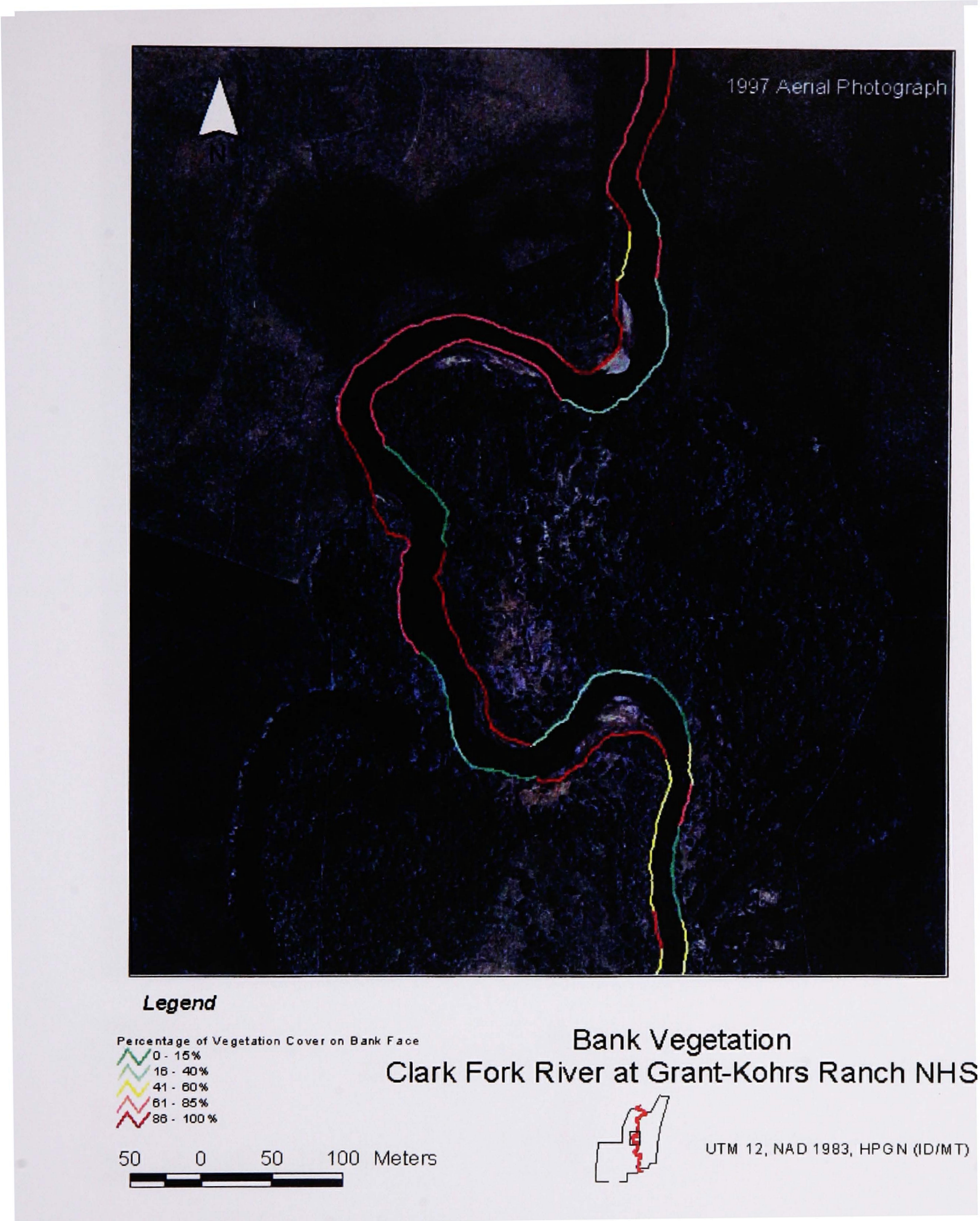


Figure 16c. Percent of bank segments covered in vegetation. Vegetation type was not designated.

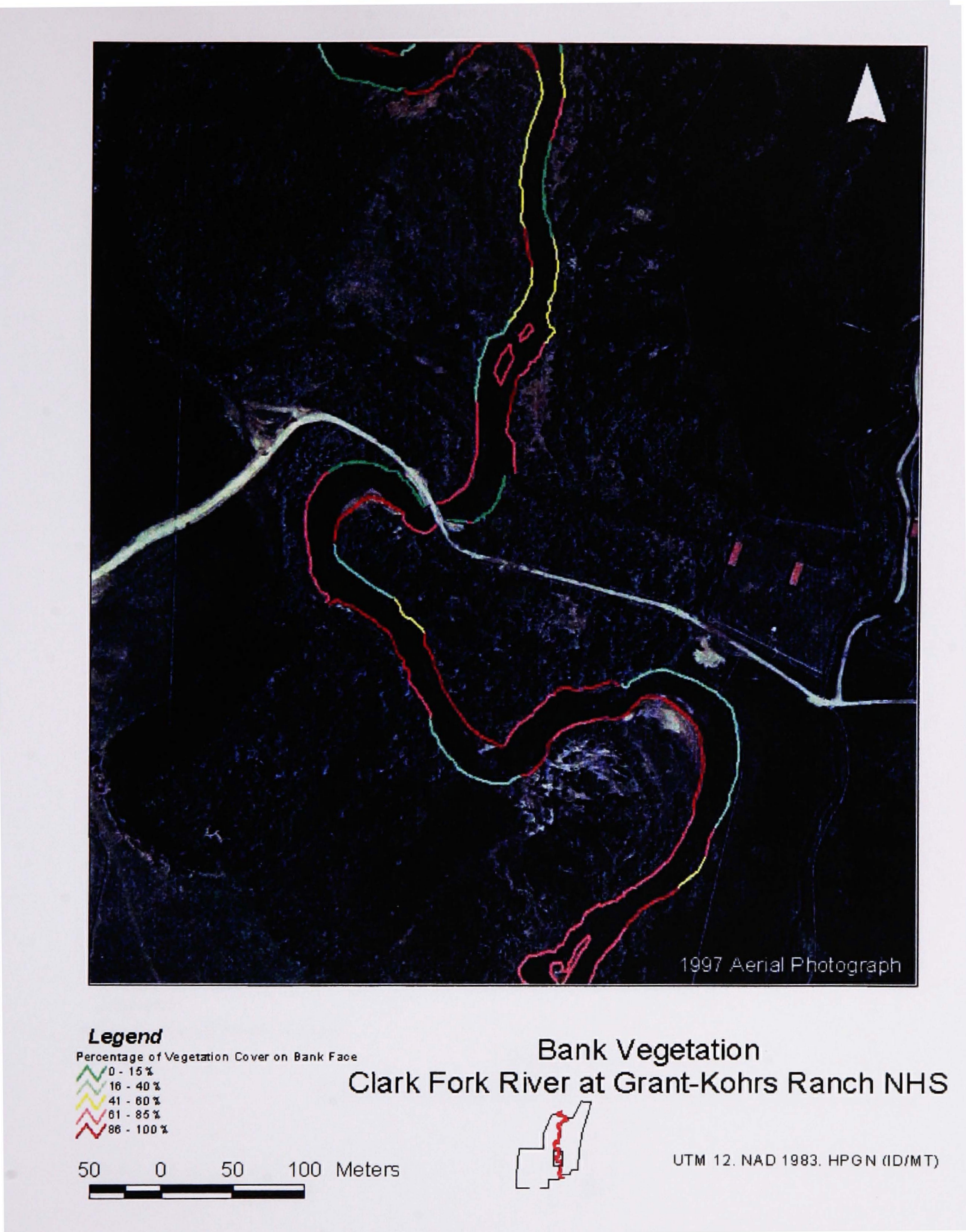


Figure 16d. Percent of bank segments covered in vegetation. Vegetation type was not designated.

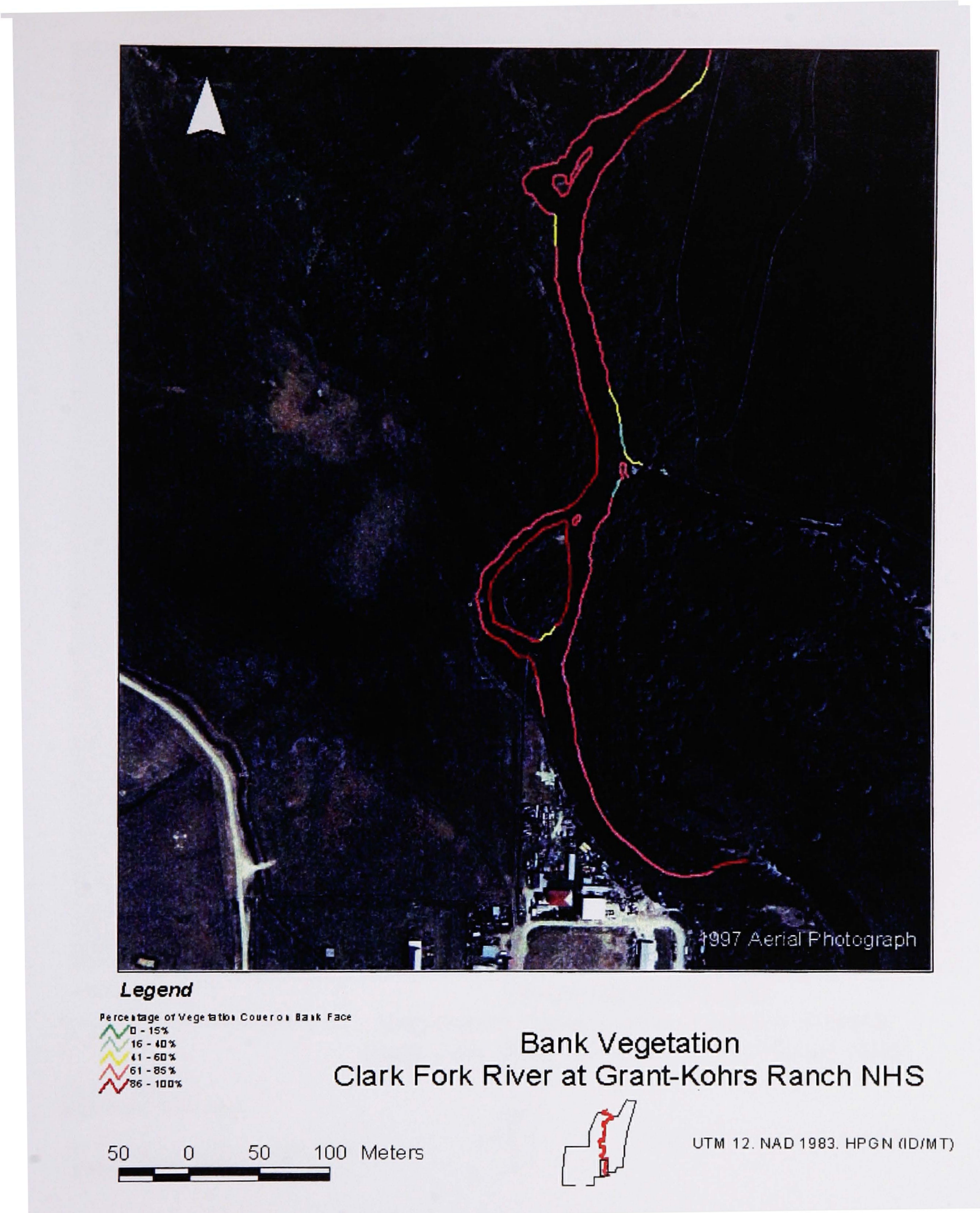


Figure 16e. Percent of bank segments covered in vegetation. Vegetation type was not designated.

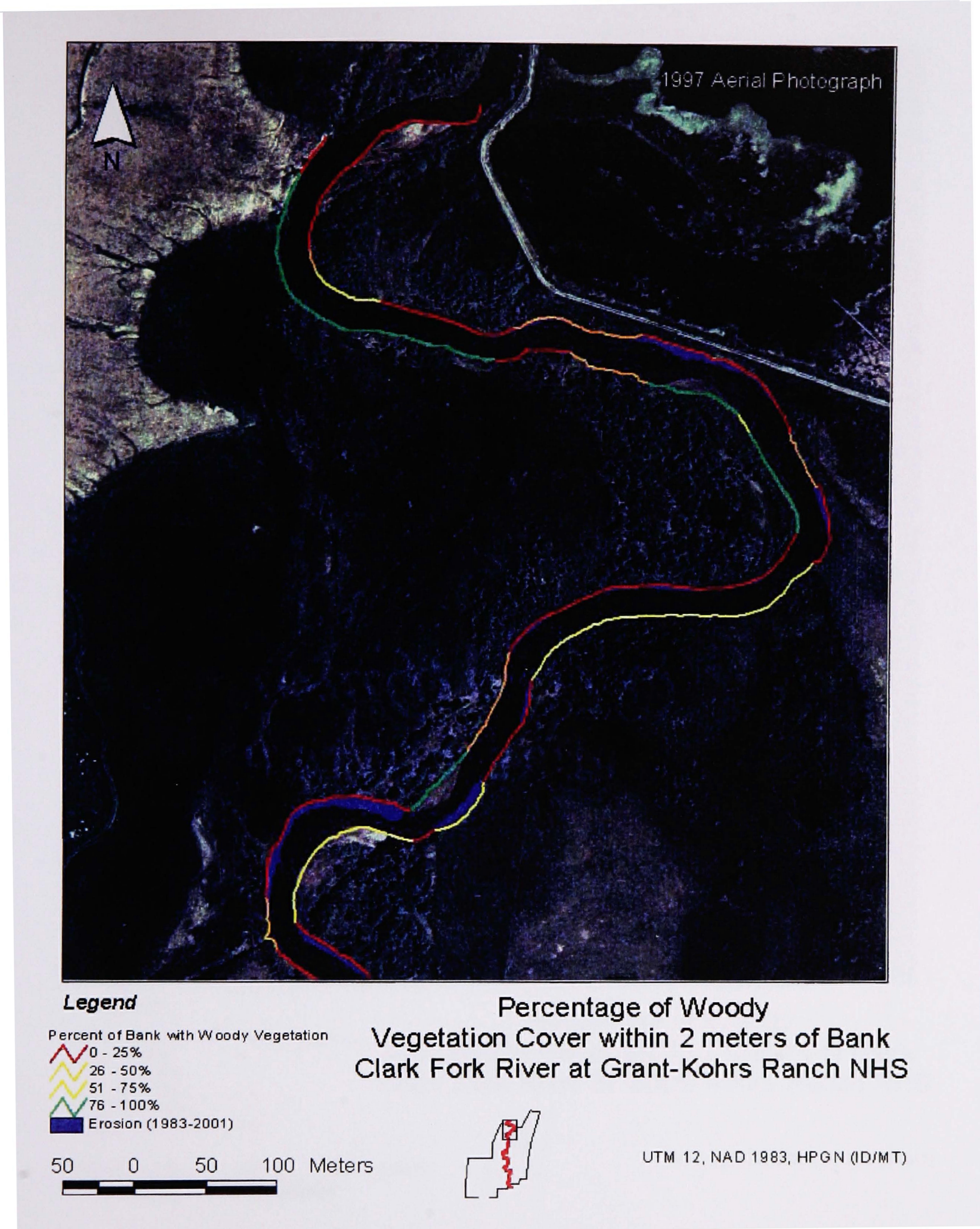


Figure 17a. Percentage of woody vegetation cover within 2 m of a bank segment. Woody vegetation includes *Salix elugia, Salix geyeriana,* and *Betula occidentalis*.

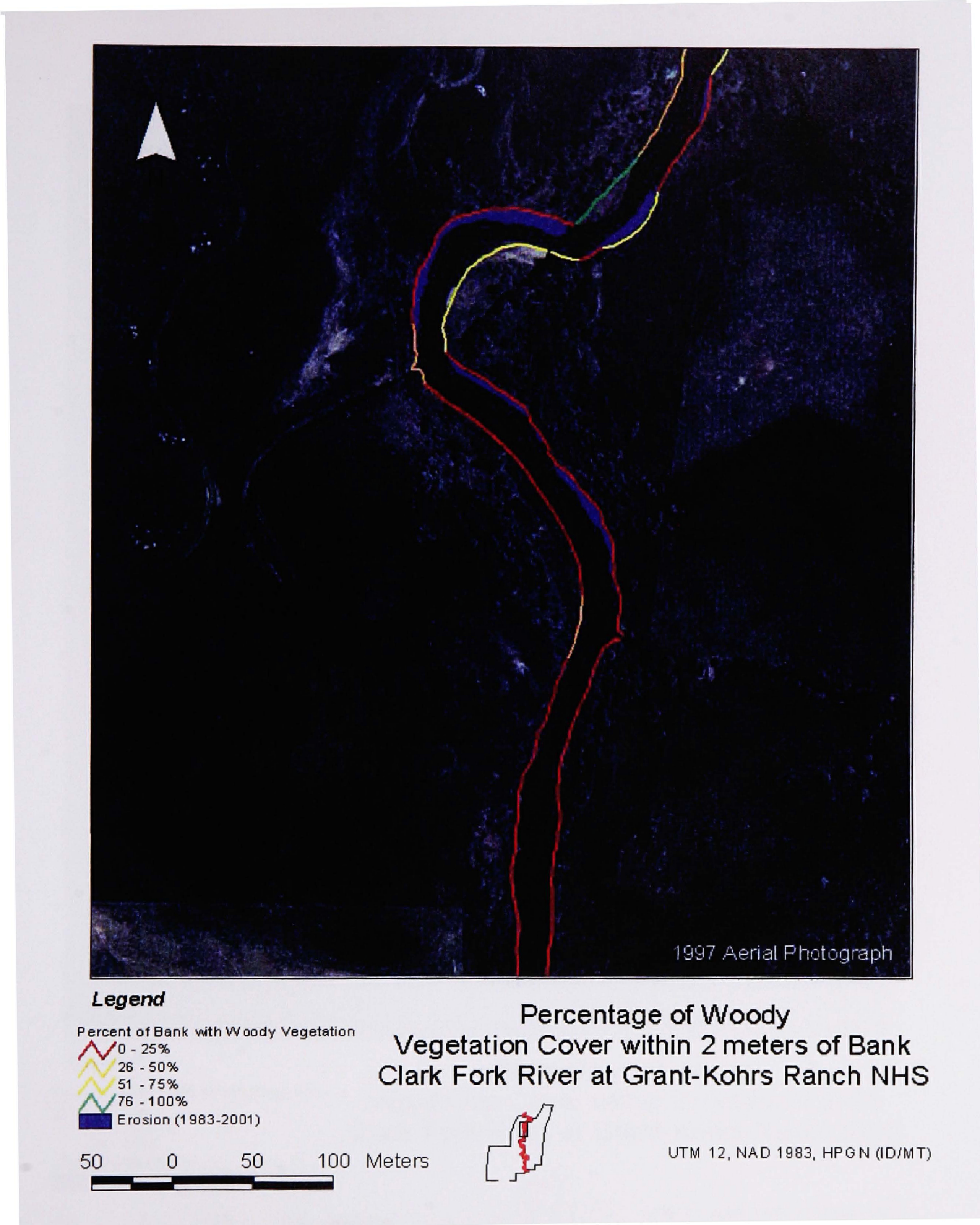


Figure 17b. Percentage of woody vegetation cover within 2 m of a bank segment. Woody vegetation includes *Salix elugia, Salix geyeriana,* and *Betula occidentalis*.

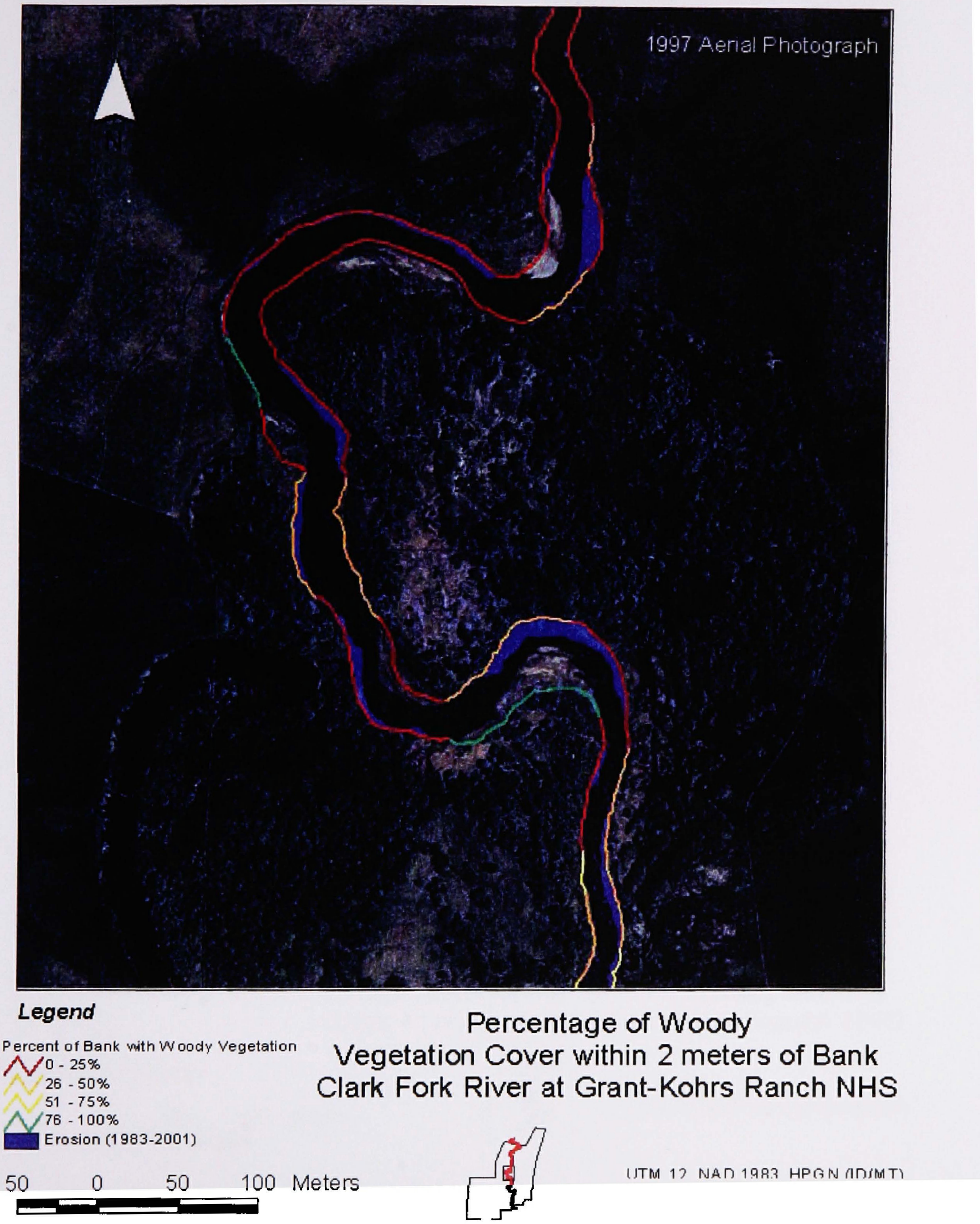


Figure 17c. Percentage of woody vegetation cover within 2 m of a bank segment. Woody vegetation includes *Salix elugia, Salix geyeriana,* and *Betula occidentalis*.

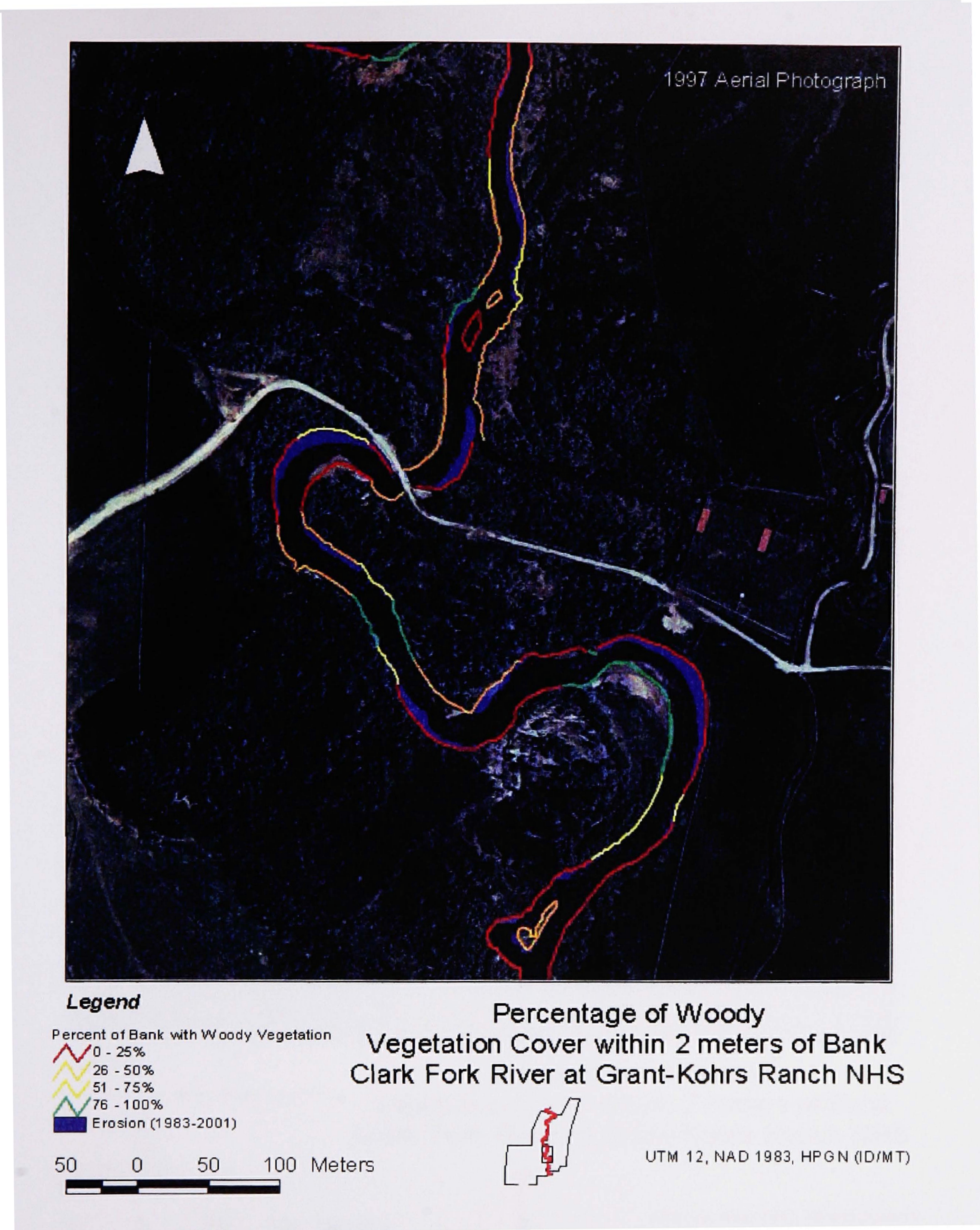


Figure 17d. Percentage of woody vegetation cover within 2 m of a bank segment. Woody vegetation includes *Salix elugia, Salix geyeriana,* and *Betula occidentalis*.

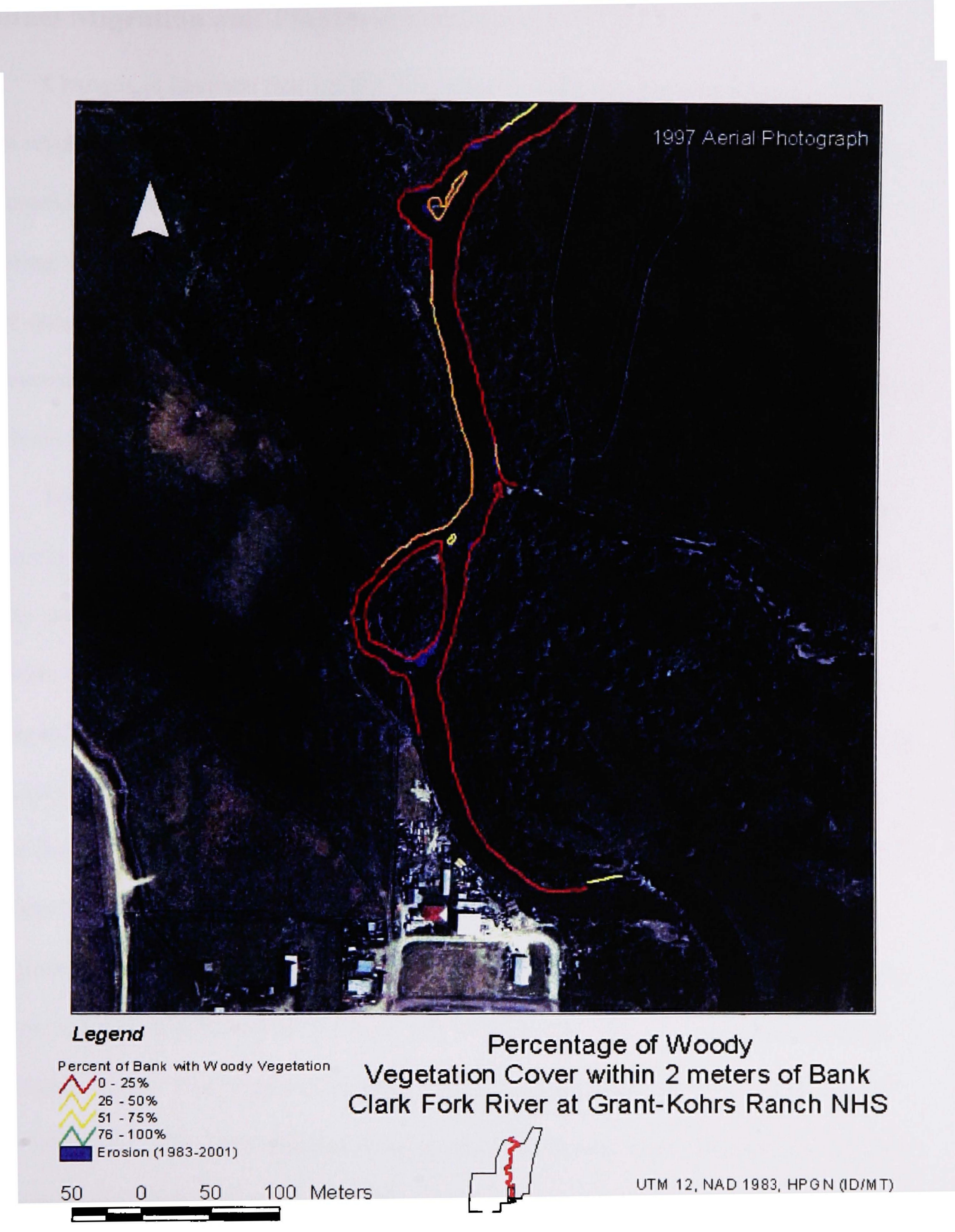


Figure 17e. Percentage of woody vegetation cover within 2 m of a bank segment. Woody vegetation includes *Salix elugia, Salix geyeriana,* and *Betula occidentalis*.

Channel Migration and Planform Changes

Changes in land use that lead to alterations in sediment loads and water discharge often result in transformations in channel shape. Increases in water can lead to bank and bed erosion, and decreases can cause bed aggradation and channel widening. Raising and lowering the sediment load usually will have the opposite effect of the same change in water quantity (Miller 1997; Knighton 1998). Although little data exists to show alterations in the Clark Fork River's cross-section over time, changes in the aerial view of the channel can be observed.

The general planform shape of the study reach channel does not seem to change drastically when comparing maps from 1868, 1914, and 1997 (Figure 18). The channel has the same basic configuration, and the meander bends are in the same general locations. However, considerable differences exist as well. Almost immediately, one notices the more prominent changes between the 1868 channel and the later channels. In 1868, meander bends are not as pronounced throughout the reach, and in the southern half of the map there are multiple channels. By 1914, the meander bends become larger and more irregular. Just south of the section-line junction, the multiple channel configuration of 1868 has become a single channel with the old eastern branch capturing the flow and the western branch probably left with mostly stagnant water and sediment from higher flows. The biggest difference can be seen between the "~e" and the "4485" on the 1914 map. The 1868 channel is being abandoned, and a new channel has formed just to the east of the section line. Unfortunately, some of these differences are likely due to inaccuracies in the 1868 survey drawing (River locations were only recorded at section line crossings. The river was drawn in from those points.), but the large

differences, such as the major shift in channel position, are probably real. Due to the proximity of the new channel to the north-south section line, it seems likely that the surveyor would have included this channel if it existed at the time of the survey.

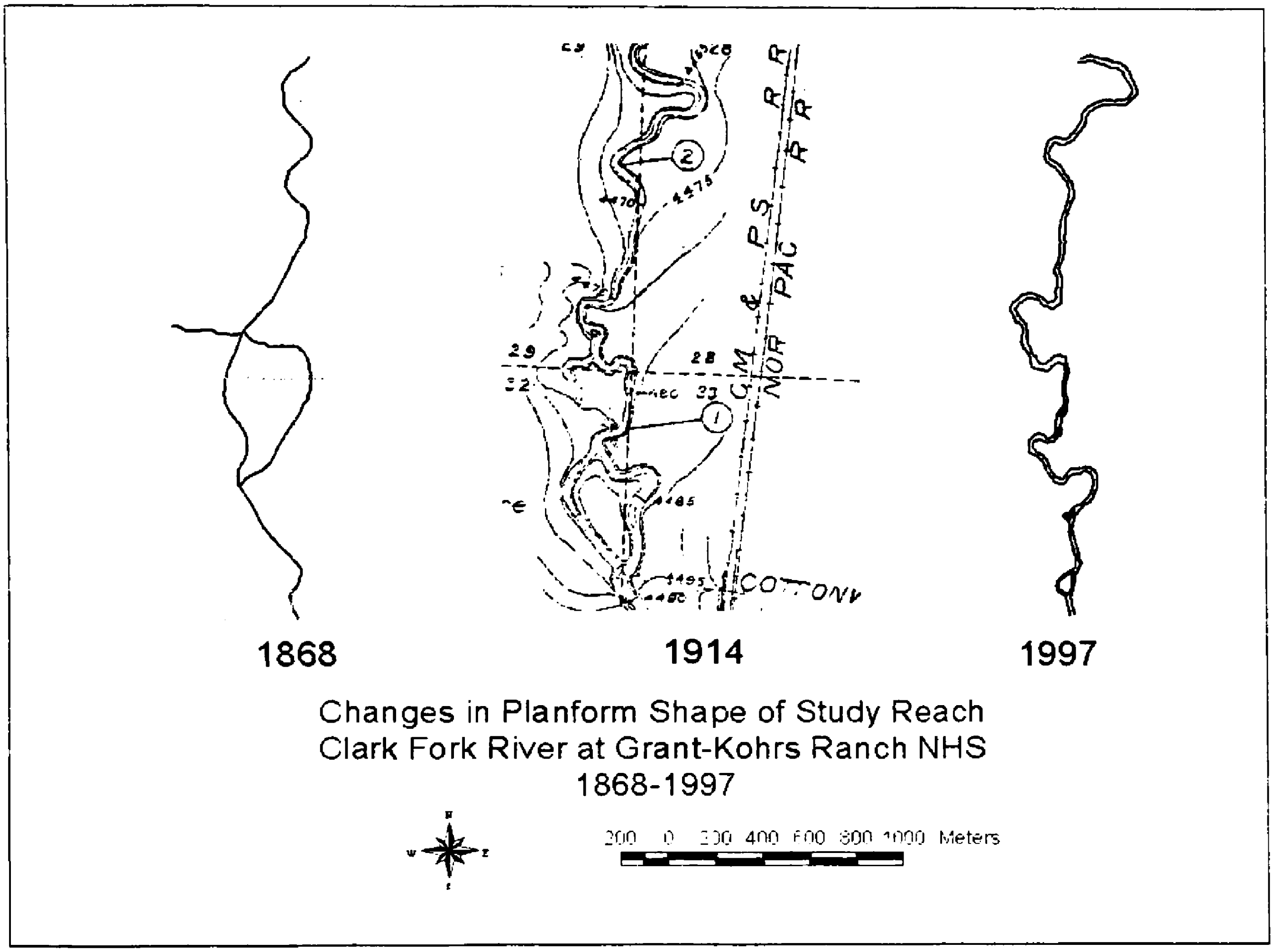


Figure 18. Changes in planform channel shape at Grant-Kohrs Ranch NHS from 1868-1997. 1868 map is the general land survey completed that year (Johnson 1869), the 1914 map is from a longitudinal profile study of the Clark Fork River (Marshall 1914), and the 1997 map is digitized bank lines from the 1997 EPA aerial photographs.

Between 1914 and 1997, the planform geometry appears to change very little. Meander bends are in the same locations and are the same general shapes. Although not depicted on the 1997 map, the abandoned channels (dotted on 1914 map) are filled with sediment and have become shallow ponds and wetland areas. However, there are subtle differences between the 1914 channel and the 1997 channel. Figure 19 shows a trend of increasing sinuosity (*river length/valley length*) from 1947 to 2001, and this change in sinuosity can easily be seen in the lengthening of the meander arms (extension) and the general downstream directional changes of the bend apex (rotation) in Figure 20 (Hooke 1986). The sinuosity changes are not large, which indicates that little has happened here between 1947 and 2001. However, the changes do indicate that the river is trying to minimize its slope through the reach in order to accommodate its water and sediment load.

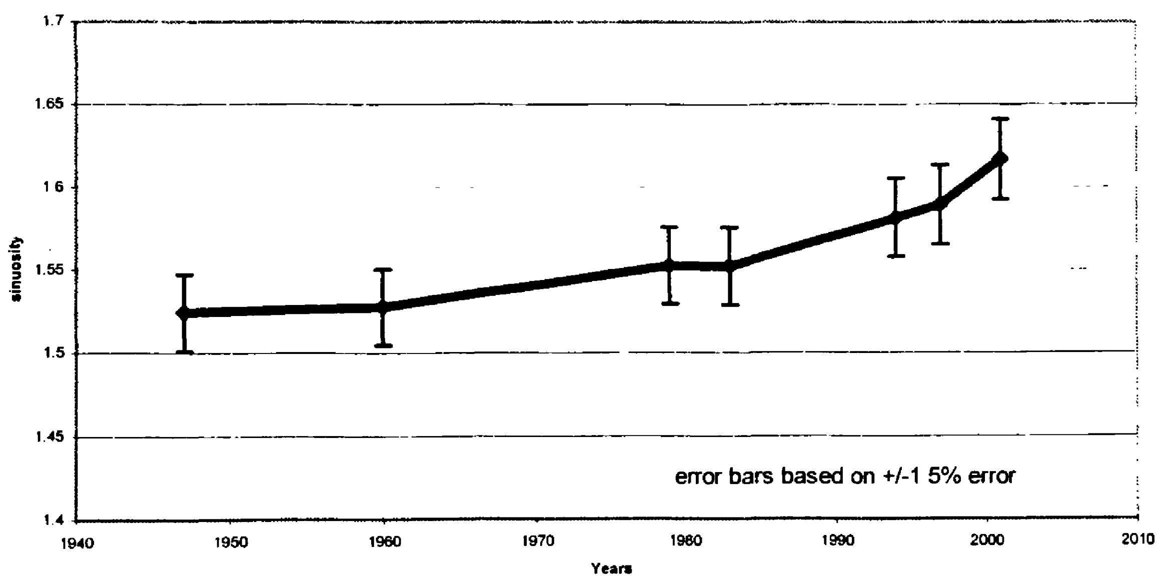
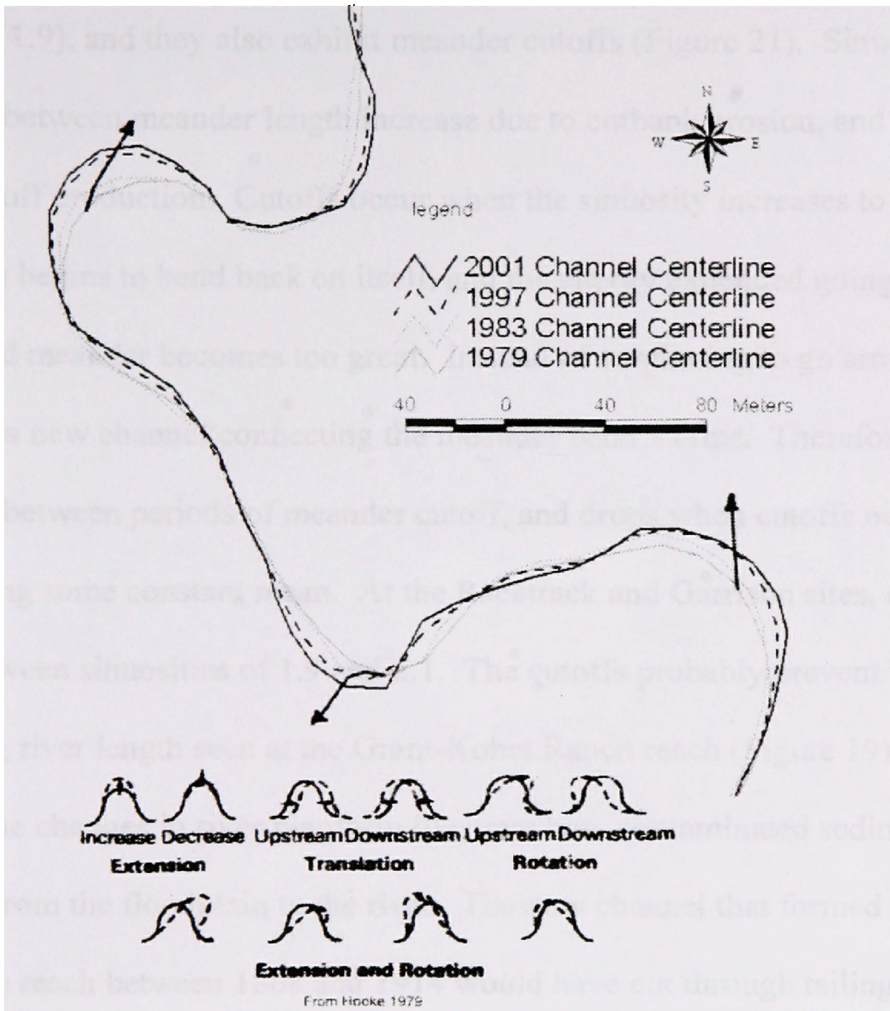


Figure 19. Change in sinuosity (*channel length/valley length*) at Grant-Kohrs Ranch NHS from 1947-2001. Error bars based on 1.5% error from repeated length measurements.



Changes in Meander Bends from 1979 to 2001
Grant-Kohrs Ranch NHS

Figure 20. Changes in meander bend shape from 1979 to 2001. Meander arms are lengthening (extension) and meander apex is moving downstream (rotation). Lower diagram from Hooke 1979.

Rotational and extensional adjustments can also be seen in the meander bends at the Racetrack and Garrison reaches. However, both of these reaches have a higher sinuosity (1.9), and they also exhibit meander cutoffs (Figure 21). Sinuosity is basically a balance between meander length increase due to cutbank erosion, and river shortening due to cutoff production. Cutoffs occur when the sinuosity increases to the point where the stream begins to bend back on itself, and the energy expended going around the lengthened meander becomes too great. Instead of continuing to go around the bend, the river cuts a new channel connecting the meander bend's arms. Therefore, sinuosity increases between periods of meander cutoff, and drops when cutoffs occur, thereby maintaining some constant mean. At the Racetrack and Garrison sites, cutoffs seem to occur between sinuosities of 1.9 and 2.1. The cutoffs probably prevent the trend of increasing river length seen at the Grant-Kohrs Ranch reach (Figure 19).

The changes in river planform illustrate how contaminated sediment can be returned from the floodplain to the river. The new channel that formed in the southern half of the reach between 1868 and 1914 would have cut through tailings material deposited in the floodplain prior to the change. Although on a smaller scale, meander cutoffs would also cut through and remove tailings material from the surface of the floodplain and point bars. Finally, even without large channel changes, meander bend growth continually erodes the previously deposited tailings from the floodplain.

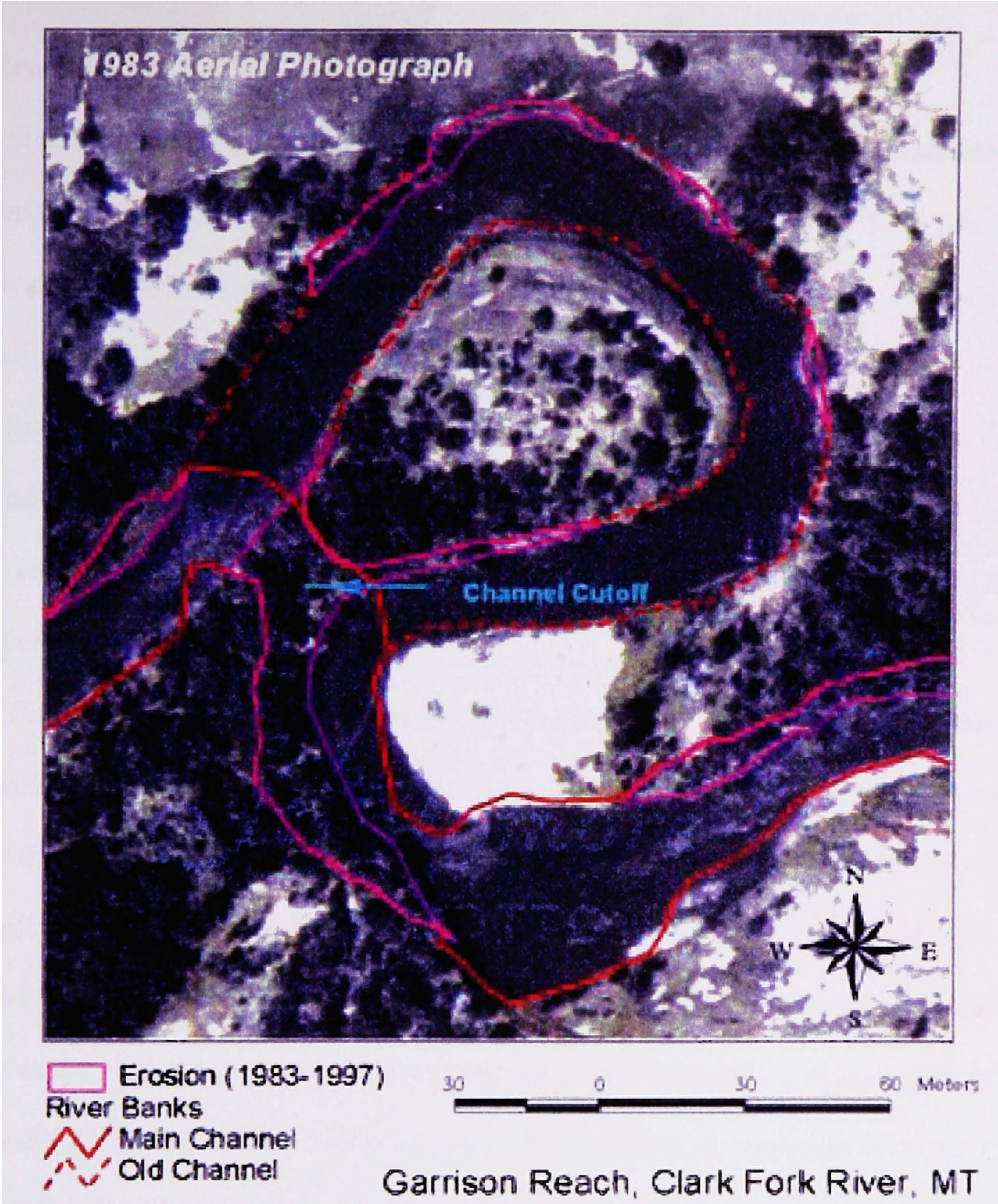


Figure 21. Meander cutoff in the Garrison study reach. The main flow went around the bend in 1983, but by 1997 the river had cut through the neck of the bend, leaving relatively stagnant water in the old channel. At the cutoff, the river removed a significant number of shrubs.

Bank Erosion

Streams and rivers, both stable and unstable, migrate within their floodplains. Sediment is eroded from the outside of meander bends and deposited on the inside of these bends. Bank erosion also occurs along straight channel reaches, but it usually occurs slightly downstream from the middle of meander bends (Leopold, et al. 1964). In stable channels, erosion is balanced by deposition of an approximately equivalent amount of sediment on point bars and other areas where sediment loads exceed transport capacity (Madej, et al. 1994; Kondolf and Micheli 1995). These typical responses are seen at Grant-Kohrs Ranch NHS as well.

The meander, labeled "Northbend," shown in Figure 22, provides an example of the overlaid banks and their corresponding areas of erosion. It clearly shows a retreating bank on the outside of the meander and an advancing point bar on the inside. The upper map depicts bank erosion between 1983 and 2001, which removed around 1160 m^2 of material from the outside of the bend (north). The distance of bank retreat and point bar advance at the widest points are similar at this location, 13 m and 15 m respectively, and the rates for both are around .72 m/yr (Figure 22). This rate is consistent with the 40 m of retreat since 1947 (.74 m/yr). The lower map shows the area of erosion and bank retreat between the later photograph years (1983-1994, 1994-1997, and 1997-2001). Between 1983 and 1994, 435 m^2 of sediment eroded from the right bank of this bend, from 1994-1997, 623 m^2 were removed, and from 1997 to the present, the bank lost 102 m^2 of material (Figure 22). Rates of retreat ranged from .35 m/yr from 1997 to 2001 to 2.1 m/yr between 1994 and 1997.

Figure 22 shows some examples of bank retreat from 1983 to 2001 on bends throughout the study site. The rates and areas are variable, but the average rate over all six locations is 0.5 m/yr (+/-.2 m/yr). The point bars are also advancing at similar rates, balancing erosion on the outside of the meander with deposition on the inside. The area of erosion at 8 meander bends within the Grant-Kohrs reach, including the six bends depicted in Figure 23, are presented in Table 6 (see Appendix B for Locations). These bends are the largest contributors to bank erosion within the study site. The total amount of erosion between a given photograph year and 2001 is given in the top half of the table, and the bottom table presents data from the interval between the photograph years. Since 1947, 21,300 m^2 (+/-570m^2) (53% of the total erosion) of material has been eroded at these meander bends, which is approximately 50 m^2/yr at each bend. The quantity of erosion at these bends is variable from bend to bend, and from year to year (Table 9 and Figure 24). Also, the rate of erosion changes over time, with a period of high erosion rates between 1979 and 1983 and between 1994 and 1997. Although the river is reworking the floodplain terraces, the area of erosion in meander bends seems to be approximately balanced by the area of deposition in the point bars (Figures 22 and 23).

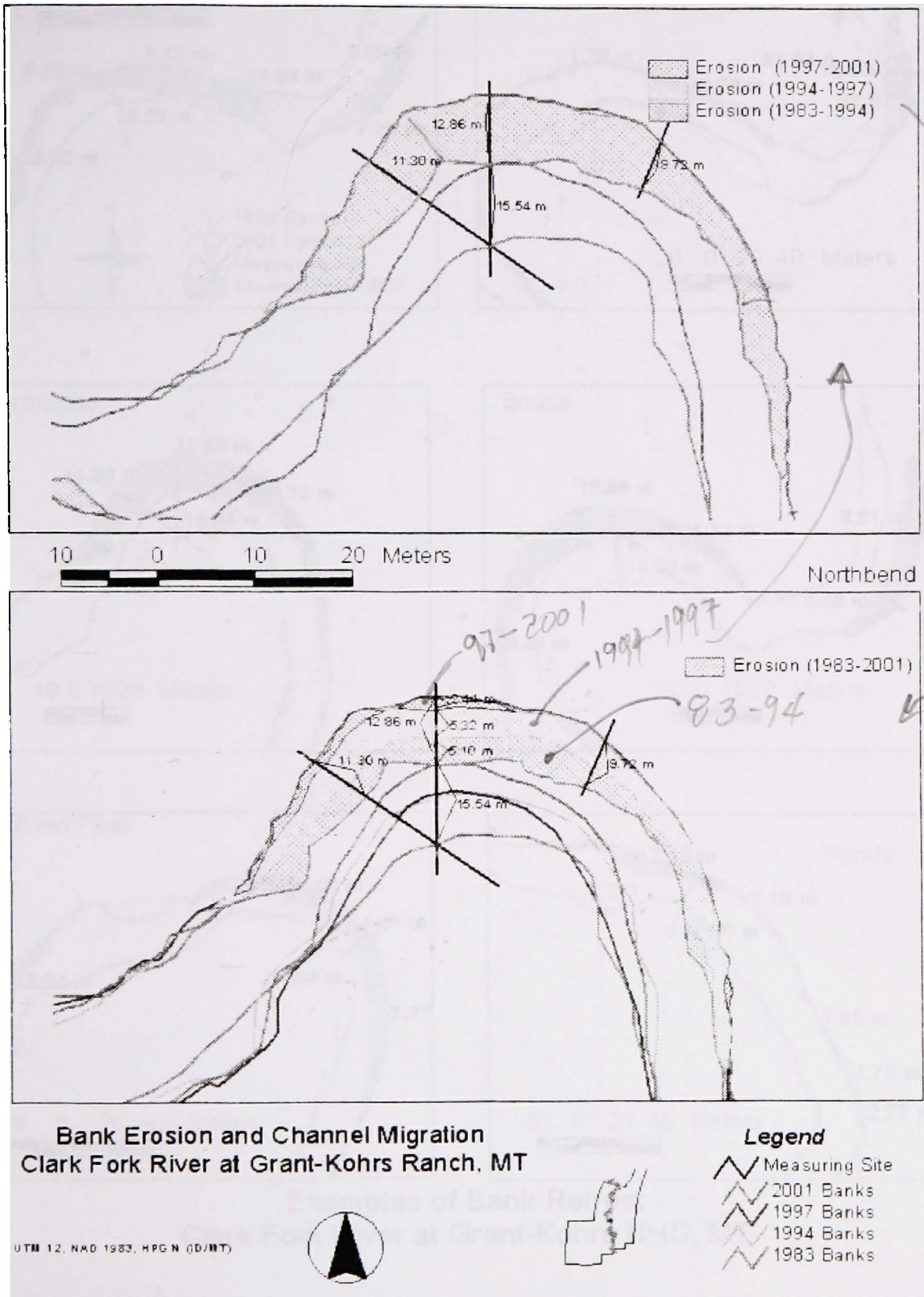
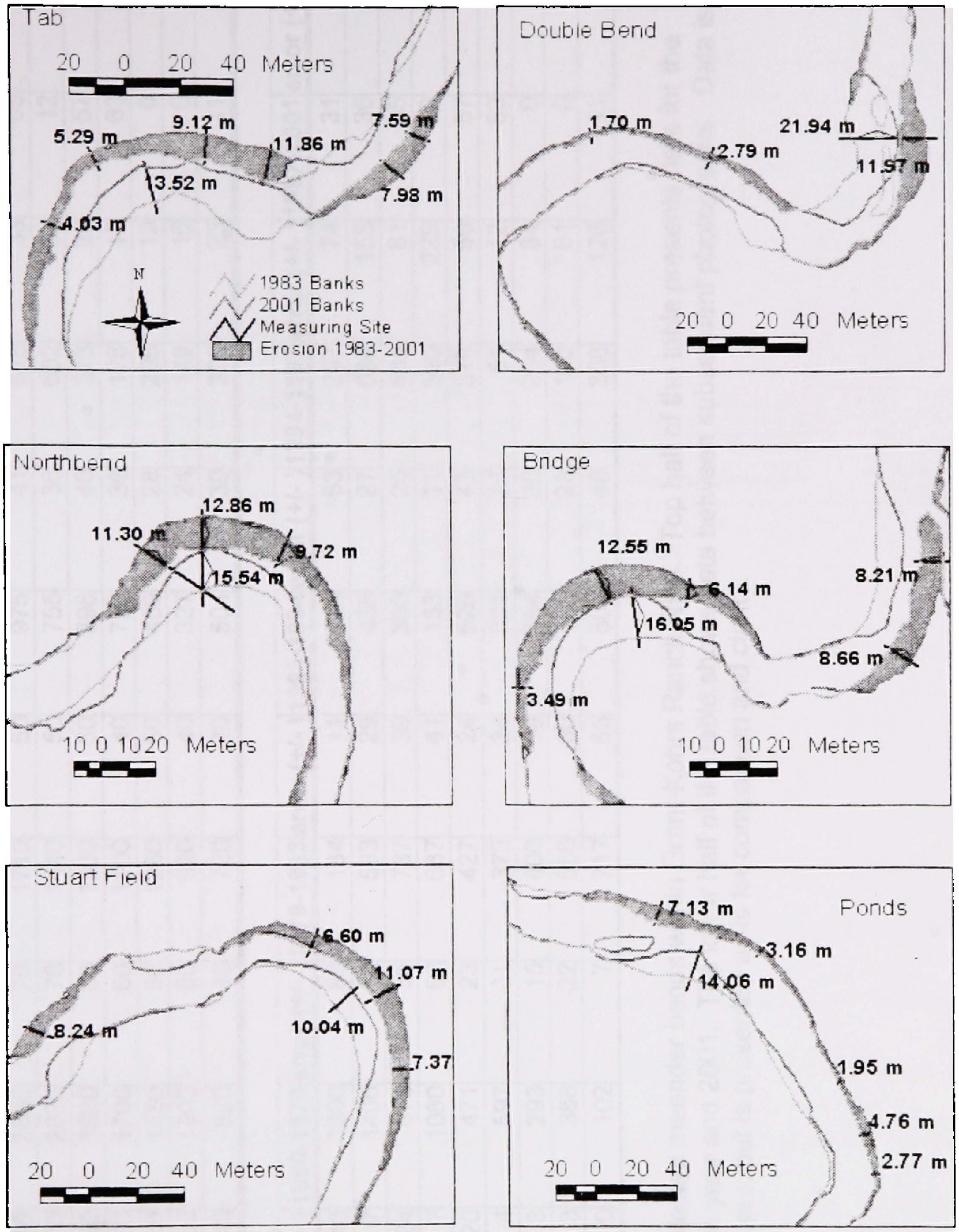


Figure 22. Bank Erosion and Channel Migration at "Northbend." An example of overlaid banks and the corresponding erosion and deposition. Flow direction is from east to west.



Examples of Bank Retreat
Clark Fork River at Grant-Kohrs NHS, MT

Figure 23. Examples of bank retreat at 6 of the bends within the study reach. Average rates of retreat at the bend apex are 0.5 m/yr. The deposition roughly matches the erosion. Flow direction is from south to north.

bend	1947-2001	error (+/-)	1960-2001	error (+/-)	1979-2001	error (+/-)	1983-2001	error (+/-)	1994-2001	error (+/-)	1997-2001	error (+/-)
Stuart	4090	90	2940	70	1140	50	951	41	328	24	31	7
Northbend	3350	80	3140	70	1740	60	1160	50	724	36	36	8
Tabs	3260	80	2590	70	1710	60	975	41	615	33	85	12
Double East	2710	70	2530	70	1440	50	755	36	602	33	12	5
Bridge South	2270	60	1800	60	1330	50	898	40	373	26	57	10
West South	1790	60	1700	60	1100	40	726	36	125	15	63	11
Ponds	1620	50	1550	50	1260	50	459	28	205	19	0	0
West North	1360	50	1300	50	920	40	327	24	148	16	0	0
Bridge North	820	40	820	40	720	40	504	30	308	23	11	4
	1947-1960	error (+/-)	1960-1979	error (+/-)	1979-1983	error (+/-)	1983-1994	error (+/-)	1994-1997	error (+/-)	1997-2001	error (+/-)
Stuart	1160	40	1800	83	184	11	623	53	297	74	31	7
Northbend	212	7	1400	60	583	29	435	27	688	155	36	8
Tabs	674	24	873	36	737	39	360	25	530	81	85	12
Double East	181	7	1080	50	687	41	153	11	590	229	12	5
Bridge South	471	20	471	23	427	24	526	43	315	59	57	10
West South	92	4	597	31	373	24	601	77	61	12	63	11
Ponds	69	3	293	15	800	58	254	28	204	84	0	0
West North	55	3	388	22	588	50	179	23	148	61	0	0
Bridge North	0	0	102	7	717	55	504	48	308	128	11	4

Table 6. Area of erosion at selected meander bends within Grant-Kohrs Ranch NHS. Top half of the table presents data for the intervals between a photograph year and 2001. The lower half of the table shows data between subsequent photographs. Data is only correct to 3 significant figures, but is presented as-is for comparison and clarity.

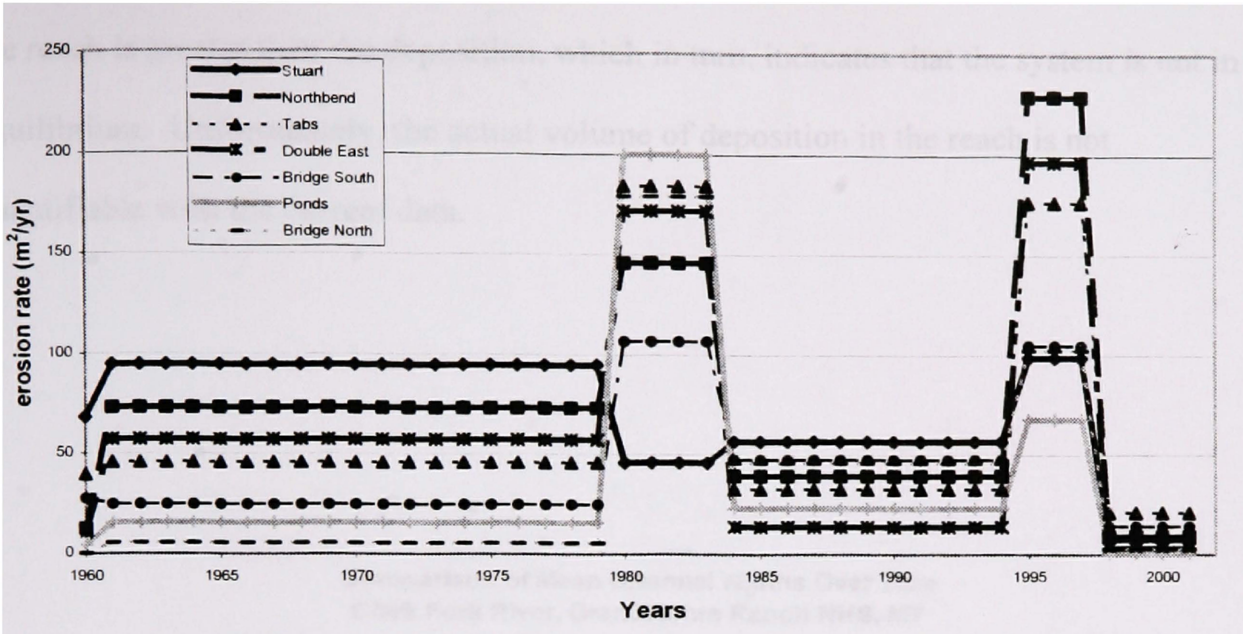


Figure 24. Erosion rates at selected meander bends over time. Higher erosion rates occur from 1979 to 1984 and 1994 to 1997 for most of the bends.

Besides eroding at meander bends, it also appears that the channel is eroding in many of the straighter reaches of the study area. Widths were measured at 55 locations in straight reaches and slight bends that do not exhibit cutbank or point bar development, and then evaluated for widening or narrowing. A statistical analysis showed that the channel has clearly widened between 1947 and 2001 (Figure 25 and Table 7). Changes in width occur at a fairly constant rate over the 1947-1979 time interval, followed by a large increase in width between 1979 and 1983. The widening rate returns to a slower pace until the 1994-1997 time interval where another jump occurs. These jumps probably correlate to the erosion caused by large flows in 1981 and 1997. The material removed from these straighter reaches does not demonstrate corresponding deposition

like the cutbank-point bar system. This observation indicates that the overall erosion in the reach is greater than the deposition, which in turn, indicates that the system is not in equilibrium. Unfortunately, the actual volume of deposition in the reach is not quantifiable with the current data.

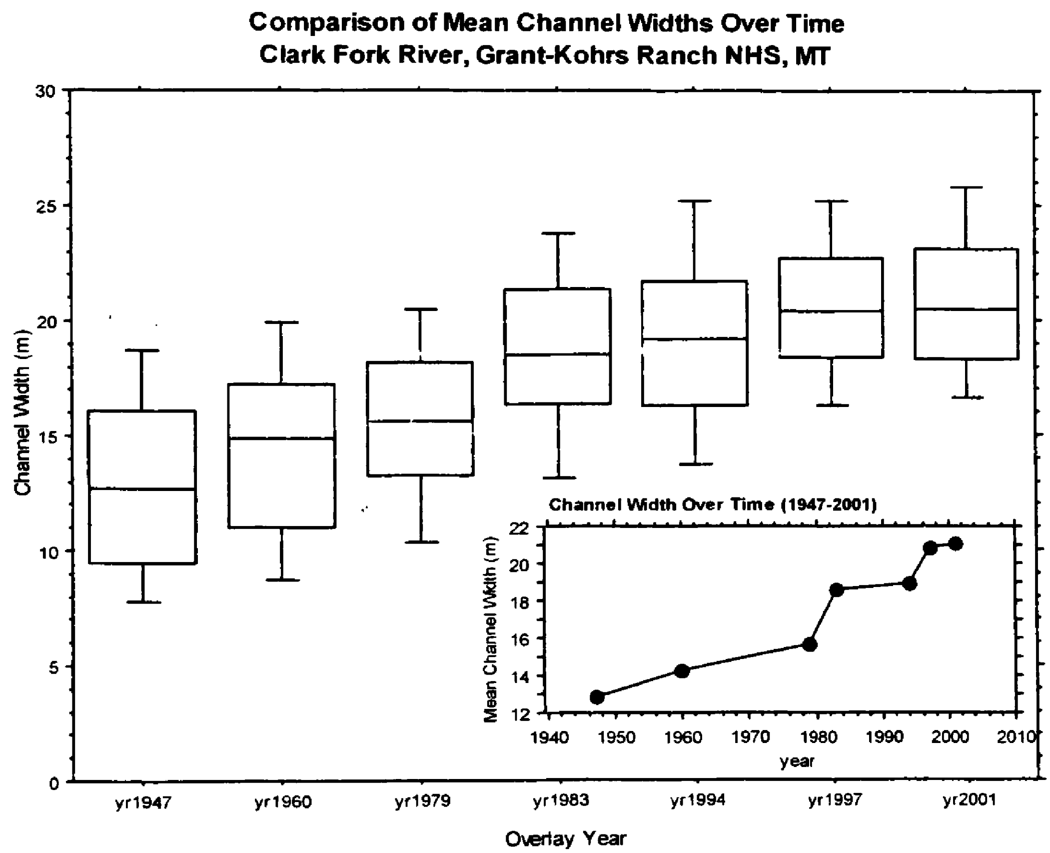


Figure 25. Changes in channel width between photograph years. X-axis is the photograph year, and the Y-axis is the width in meters. Box plots shows statistically significant increase in width from study year to study year. Lower plot depicts change in widths over time. The slopes of the lines represent the rate at which the channel is widening.

Statistics (p-values) for Change in Channel Width

Time Span	Mean Diff	Paired t-test	Wilcoxon RST
2001-1997	0.266	0.062	0.0554
2001-1994	2.15	<.0001	<.0001
2001-1983	2.458	<.0001	<.0001
2001-1979	5.429	<.0001	<.0001
2001-1960	6.802	<.0001	<.0001
2001-1947	8.256	<.0001	<.0001
1997-1994	1.884	<.0001	<.0001
1994-1983	0.308	0.4083	0.0007
1983-1979	2.971	<0.0001	<.0001
1979-1960	1.373	0.0001	<.0001
1960-1947	1.454	0.0041	0.0008

Table 7. Statistics for channel width change between the photograph years.

Total Erosion

Channel widening and meander bend erosion within Grant-Kohrs Ranch NHS removed large areas of floodplain terrace over the 54 years of air photo analysis. Between 1947 and 2001, the river eroded 39,850 m^2 (+/- 4780 m^2) of soil from the banks, which is about 740 m^2/yr (Table 8). The largest amount of erosion, 11,740 m^2 (+/- 1430 m^2) occurred between 1960 and 1979, which was also the largest gap between photographs. The highest erosion rate, 2230 m^2/yr, occurred between 1979 and 1983. This rate probably corresponds to the high flow in 1981, the highest recorded at the Deer Lodge gage.

The descriptions of the Clark Fork River at Deer Lodge prior to mining indicate that very little erosion was occurring at that time, and even with all of the sediment and water yield impacts since then, the current rate of bank erosion at Grant-Kohrs Ranch does not seem to be extremely high. Over the entire 4 km of study reach at Grant-Kohrs Ranch, the average rate of erosion from 1947 to 2001 is 0.19 m/yr (Table 8). This rate, and the rate for the 1983-2001 period (0.18 m/year), are similar to the rates found for the Garrison and Racetrack sites, .19 m/year. The rates also seem to compare well with those obtained by R2 Consultants, Inc (1997) (Table 11).

An attempt to compare Clark Fork erosion rates with reaches of other Western Montana rivers possessing similar discharge, land use, basin characteristics, and vegetation was also made, notably reaches of the Boulder, Ruby, and Smith Rivers. Unfortunately, the aerial photography obtained for the comparisons were taken at relatively high altitudes (small scale) and the sections containing the river were usually along the edges of the photographs leading to significant distortion. Because of these

Aerial Erosion Between Photograph Year and 2001							
Interval	area (m^2)	error (%)	error +/- (m^2)	erosion/yr (m^2/yr)	error (m^2/yr)	rate/length of river (m^2/m)/yr	error ($m^2/m/$)yr
1947-2001	39850	12	4780	738	89	0.187	0.022
1960-2001	33300	9	3010	812	73	0.206	0.019
1979-2001	21560	8	1740	980	79	0.249	0.020
1983-2001	12640	15	1950	702	108	0.178	0.027
1994-2001	6970	20	1400	996	200	0.253	0.051
1997-2001	730	38	280	183	70	0.046	0.018
Garrison 1983-2001	6550	15	980	364	54	0.187	0.014
Racetrack 1983-2001	24010	12	2800	1330	52	0.189	0.013
Total 1983	43200	24	10570	2400	587	0.186	0.149

Aerial Erosion Between Photograph Years							
Interval	area (m2)	error (%)	error +/- (m2)	erosion/yr (m2/yr)	error (m2/yr)	rate/length of river (m2/m)/yr	error (m2/m/)yr
1947-1960	6550	15	980	504	75	0.128	0.019
1960-1979	11740	12	1430	618	75	0.157	0.019
1979-1983	8920	17	1560	2230	390	0.566	0.099
1983-1994	5670	25	1430	515	130	0.131	0.033
1994-1997	6240	43	2690	2080	900	0.528	0.228
1997-2001	730	38	280	183	70	0.046	0.018

Table 8. Area eroded from banks at the 3 study reaches along the Clark Fork River for different time intervals. "Rate/length of river" is the rate of erosion normalized for the length of the reach (3950 m). High error values for the later years are due to smaller erosional areas (see Methods). Data are for Grant-Kohrs Ranch NHS, unless labeled otherwise ("Garrison" and "Racetrack"). Data is only correct to 3 significant figures, but is presented as-is for comparison and clarity.

Volume of Erosion Between Photograph Year and 2001							
Interval	Volume *(m^3)*	error *(%)*	error +/- *(m^3)*	volume/year *(m^3/yr)*	error *(m^3/yr)*	rate/length of river *(m^3/m)/yr*	error *(m^3/m)/yr*
1947-2001	46630	22	10190	864	189	0.219	0.048
1960-2001	38960	20	7940	950	194	0.241	0.049
1979-2001	25230	20	5040	1150	230	0.292	0.058
1983-2001	14790	24	3540	822	197	0.209	0.050
1994-2001	8160	27	2210	1160	320	0.294	0.081
1997-2001	860	42	364	215	91	0.055	0.023
Garrison 1983-2001	7660	24	1810	426	101	0.219	0.052
Racetrack 1983-2001	28100	22	6090	1560	110	0.222	0.016
Total 1983	50550	31	15430	2800	860	0.217	0.218

Volume of Erosion Between Photograph Years							
Interval	Volume *(m3)*	error *(%)*	error +/- *(m3)*	volume/year *(m3/yr)*	error *(m3/yr)*	rate/length of river *(m3/m)/yr*	error *(m3/m)/yr*
1947-1960	7670	24	1810	590	139	0.150	0.035
1960-1979	13740	22	3010	723	158	0.184	0.040
1979-1983	10430	25	2630	2610	660	0.662	0.168
1983-1994	6630	31	2070	603	188	0.153	0.048
1994-1997	7300	47	3420	2430	1140	0.617	0.289
1997-2001	860	42	360	215	90	0.055	0.023

Table 9. Volume eroded from banks at the 3 study reaches along the Clark Fork River for different time intervals. "Rate/length of river" is the rate of erosion normalized for the length of the reach (3950 m). Data are mostly for Grant-Kohrs Ranch NHS, unless labeled otherwise. Volume of eroded sediment based on areas (Table 9) and an average bank height of 1.2 m from bank chemistry samples (Moore and Woessner 2001). Data is only correct to 3 significant figures, but is presented as-is for comparison and clarity.

Mass of Erosion Between Photograph Year and 2001							
Interval	mass *(tons)*	error *(%)*	error +/- *(tons)*	mass/yr *(tons/yr)*	error *(tons/yr)*	mass/length of river *(kg/m/yr)*	error *(kg/m/yr)*
1947-2001	65280	22	14360	1210	250	307	64
1960-2001	54540	20	11120	1330	270	338	69
1979-2001	35300	20	7050	1610	320	407	81
1983-2001	20710	24	4960	1150	280	292	70
1994-2001	11420	27	3910	1630	440	414	112
1997-2001	1200	42	510	300	130	76	32
Garrison 1983-2001	10720	24	2530	600	140	151	36
Racetrack 1983-2001	39340	22	8520	2190	160	555	40
Total 1983	70770	31	21600	3940	1200	998	305

Mass of Erosion Between Photograph Years							
Interval	mass *(kg)*	error *(%)*	error +/- *(kg)*	mass/yr *(kg/yr)*	error *(kg/yr)*	mass/length of river *(kg/m/yr)*	error *(kg/m/yr)*
1947-1960	10740	23	2440	830	188	210	48
1960-1979	19240	22	4220	1010	220	257	56
1979-1983	14590	25	3690	3650	920	927	234
1983-1994	9290	31	2900	844	263	214	67
1994-1997	10220	47	4790	3410	1600	865	405
1997-2001	1200	42	510	301	127	76	32

Table 10. Mass of sediment eroded from banks at the 3 study reaches along the Clark Fork River for different time intervals. "Rate/length of river" is the rate of erosion normalized for the length of the reach (3950 m). Data are for Grant-Kohrs Ranch NHS, unless labeled otherwise. Mass obtained by multiplying volumes (Table 10) by a bulk density of 1400 kg/m^3. Data is only correct to 3 significant figures, but is presented as-is for comparison and clarity.

problems, quantification of erosion was difficult, so a more general analysis was done. based on eroded vegetation, apparent distances from fence lines and buildings, etc. It appeared that the Boulder and Ruby River reaches were eroding their banks at a much greater rate than the study reaches along the Clark Fork, whereas the Smith River reach seemed to possess erosion rates similar to the study reaches. Finally, the obtained rate of erosion for the Clark Fork River was at the low-end of erosion rates found in the literature (Hickin and Nanson 1984; Hooke 1980; Lawler 1993; Knighton 1998) (Table 11). However, finding studies including rivers with characteristics similar to the Clark Fork proved to be difficult, and the impetus for many of the completed studies is that a major erosion problem existed to begin with. Therefore, the literature data may be biased towards higher erosion rates.

River, Location	Erosion Rate (m/yr)	Years of Measurment	Source
Axe, Devon	0.15-0.46	2	Hooke 1980
Bollin-Dean, Cheshire	0-0.9	2	Knighton 1973
Colville, Alaska	0.1-4.0	3	Walker, et al 1987
Des Moines, Iowa	2.4-3.7	37	Odgaard 1987
East Nishnabotna, Iowa	2.1-3.2	7	Odgaard 1987
Exe, Devon	0.62-1.18	2	Hooke 1980
Ilston, Wales	0.04-0.31	2	Lawler 1986
Mississippi, Louisiana	4.5	17	Stanley, et al 1966
Watts Branch, Maryland	0.5-0.6	2	Wolman 1959
Western Canada	0.57-7.26	21-33	Nanson and Hickin 1986
Wisloka, Poland	8-11	2	Klimek 1974
		Above from Knighton (1998, page 117)	
Clark Fork, Montana (range)	0-1.8	29	R2 Resource Consultants 1997
Clark Fork, Montana (average)	0.18	29	R2 Resource Consultants 1997

Table 11. Erosion rates cited from the literature (From Knighton 1998). Clark Fork River erosion data is from R2 Resource Consultants (1997).

The 1947-2001 interval covers the longest time span for this study, so presumably incorporates the highest variance in flow, landuse changes, and other factors contributing to erosion. Therefore, the erosion rate for that time period, 740 m^2/yr, best represents the "long-term" erosion rate. The length of time it will take to rework all the contaminated floodplain soils can be calculated by multiplying the area of contamination by this "long term" erosion rate. According to the CH2MHill (1987) maps of the extent of metal contamination, there are approximately 700,000 m^2 of floodplain affected by mine tailings within the Grant-Kohrs Ranch study reach. It will take approximately 1000 years to rework this entire area one time. The estimated 28 million m^2 of contaminated floodplain (CH2MHill 1987) spread equally along the entire 69.2 km of the Deer Lodge Valley yields about 180 m^2 of contamination per meter of river. At an erosion rate of .19 m^2/m/yr, it will take approximately 1000 years to rework these soils once, as well. However, the amount of time to truly rework the contaminated area is probably much longer. Erosion does not take place in all directions at an equal rate. The channel will migrate at varying speeds along its reach depending on obstructions, variations in soil erosivity, the amount and location of meander cutoffs, and other factors. Over the next 1000years, some areas will be reworked numerous times, whereas some may not get reworked at all. In addition, the contaminated sediments, although diluted with some clean sediment from tributaries and banks upstream, will not be "clean" after one cycle of erosion and deposition. It will probably take numerous cycles of bank and floodplain erosion to considerably lower metal concentrations within the floodplain deposits.

Metal Loading

From 1947 to 2001, 46,630 m^3 (+/- 10,190) of sediment moved from floodplain storage into the channel at Grant-Kohrs Ranch (Table 9). Because the banks possess varying amounts of tailings material, and therefore metals, the eroded sediments are a large source of Arsenic (metalloid), Copper, Cadmium, Lead, and Zinc introduced into the riverbed and the water. Table 12 provides metal concentrations for the 15 bank profile sites within Grant-Kohrs Ranch NHS (Moore and Woessner 2001). The concentrations vary substantially from site to site. For example, As concentrations range from 11 to 569 mg/kg with an average of 200mg/kg, copper ranges from 37 to 4068 mg/kg with an average of 1524 mg/kg, and lead ranges from 65 to 522 mg/kg with an average of 210 mg/kg (Table 12). Not all of the metals can be attributed to mine waste. The native soils contain background concentrations of metals, but these concentrations are much lower than those found in the tailings, often by more than a factor of 10 (Moore and Woessner 2001: Table 13).

By multiplying the mean metal concentrations (with background concentrations subtracted) by the total mass of eroded sediment, the amount of excess metals loaded to the channel was calculated. In the Grant-Kohrs Ranch study reach 12,440 (+/- 8730) kg of excess As, 183 (+/- 86) kg of excess Cd, 98,480 (+/- 82,520) kg of excess Cu, 12,630 (+/- 8,750) kg of excess Pb, and 57710 (+/- 29,610) kg of excess Zn were dumped into the river via bank erosion between 1947 and 2001(Table 14-18). The high amount of error seen in the calculated metal loads can mostly be contributed to the high variability in the metal concentration data (Table 12 and 19: Brooks 1988; Moore and Woessner

rs the entire spectrum of conditions, from metal-free banks to extremely high levels of metals.

Bank	Height	As	Cd	Cu	Pb	Zn
	cm	mg/kg	mg/kg	Mg/kg	mg/kg	mg/kg
BP1	150	230.13	4.97	3120.40	231.07	1159.93
BP2	140	213.64	3.13	1300.57	226.51	876.71
BP3	125	266.20	4.98	3655.20	237.72	1147.60
BP4	100	188.00	2.08	1067.61	291.60	653.90
BP5	80	313.38	4.44	2607.94	522.13	1219.63
BP6	120	569.33	5.72	4068.25	472.83	1690.00
BP7	90	263.22	4.27	854.22	205.89	995.56
BP8	110	55.27	1.13	152.36	56.20	240.55
BP9	110	133.45	4.02	977.82	118.65	801.91
BP10	120	11.83	0.58	37.16	20.17	64.75
BP11	120	107.42	3.73	767.48	146.25	626.25
BP12	100	132.40	5.79	1069.00	145.00	1496.00
BP13	100	106.50	5.36	1115.90	99.30	1255.00
BP14	150	144.60	3.02	1133.55	148.47	812.93
BP15	140	273.93	3.79	939.71	235.79	953.71
Means	117	200.62	3.80	1524.48	210.50	932.96
Stdev	21.36	133.65	1.58	1232.75	138.28	432.42
%error	18.26	66.62	41.61	80.86	65.69	46.35

Table 12. Average metal concentrations at bank profile sites (Moore and Woessner 2001). Large errors represent amount of variability in chemistry data.

Chemistry Background Values		
As	10	mg/kg
Cd	1	mg/kg
Cu	16	mg/kg
Pb	17	mg/kg
Zn	49	mg/kg

Table 13. Background concentrations of As and metals in floodplain deposits (Moore and Woessner 2001).

Arsenic								
Interval	mass *(kg)*	excess mass *(kg)*	error *(%)*	error +/- *(kg)*	mass/yr *(kg/yr)*	error *(kg/yr)*	mass/length of river *(kg/m/yr)*	error +/- *(kg/m/yr)*
1947-2001	13100	12440	70	8730	230	162	0.058	0.041
1960-2001	10940	10400	70	7250	254	177	0.064	0.045
1979-2001	7080	6730	70	4680	306	213	0.078	0.054
1983-2001	4160	3950	71	2800	219	156	0.056	0.039
1994-2001	2290	2180	72	1570	311	224	0.079	0.057
1997-2001	241	229	79	181	57	45	0.015	0.011
Interval	mass *(kg)*	excess mass *(kg)*	error *(%)*	error +/- *(kg)*	mass/yr *(kg/yr)*	error *(kg/yr)*	mass/length of river *(kg/m/yr)*	error +/- *(kg/m/yr)*
1947-1960	2160	2040	70	1440	157	111	0.040	0.028
1960-1979	3860	3670	70	2570	193	135	0.049	0.034
1979-1983	2920	2780	71	1980	695	495	0.176	0.126
1983-1994	1870	1770	74	1300	161	118	0.041	0.030
1994-1997	2050	1950	81	1590	650	530	0.165	0.135
1997-2001	241	229	79	180	57	45	0.015	0.011

Table 14. Mass of Arsenic eroded into the Clark Fork River at Grant-Kohrs Ranch NHS. Data is only correct to 3 significant figures, but is presented as-is for comparison and clarity.

Cadmium								
Interval	mass *(kg)*	excess mass *(kg)*	error *(%)*	error +/- *(kg)*	mass/yr *(kg/yr)*	error *(kg/yr)*	mass/length of river *(kg/m/yr)*	error +/- *(kg/m/yr)*
1947-2001	248	183	47	86	3	2	0.001	0.000
1960-2001	207	153	46	71	4	2	0.001	0.000
1979-2001	134	99	46	46	4	2	0.001	0.001
1983-2001	79	58	48	28	3	2	0.001	0.000
1994-2001	43	32	50	16	5	2	0.001	0.001
1997-2001	5	3	59	2	1	0	0.000	0.000
Interval	mass *(kg)*	excess mass *(kg)*	error *(%)*	error +/- *(kg)*	mass/yr *(kg/yr)*	error *(kg/yr)*	mass/length of river *(kg/m/yr)*	error +/- *(kg/m/yr)*
1947-1960	41	30	47	14	2	1	0.001	0.000
1960-1979	73	54	47	25	3	1	0.001	0.000
1979-1983	55	41	49	20	10	5	0.003	0.001
1983-1994	35	26	52	14	2	1	0.001	0.000
1994-1997	39	29	63	18	10	6	0.002	0.002
1997-2001	5	3	59	2	1	0	0.000	0.000

Table 15. Mass of Cadmium eroded into the Clark Fork River at Grant-Kohrs Ranch NHS. Data is only correct to 3 significant figures, but is presented as-is for comparison and clarity.

Copper								
Interval	mass (kg)	excess mass (kg)	error (%)	error +/- (kg)	mass/yr (kg/yr)	error (kg/yr)	mass/length of river (kg/m/yr)	error +/- (kg/m/yr)
1947-2001	99520	98470	84	82520	1820	1530	0.462	0.388
1960-2001	83150	82270	83	68610	2010	1670	0.510	0.424
1979-2001	53810	53250	83	44350	2420	2020	0.614	0.513
1983-2001	31570	31240	84	26340	1740	1460	0.442	0.371
1994-2001	17410	17230	85	14690	2460	2100	0.624	0.533
1997-2001	1830	1810	91	1650	450	410	0.114	0.104
Interval	mass (kg)	excess mass (kg)	error (%)	error +/- (kg)	mass/yr (kg/yr)	error (kg/yr)	mass/length of river (kg/m/yr)	error +/- (kg/m/yr)
1947-1960	16370	16200	84	13610	1250	1050	0.317	0.266
1960-1979	29340	29020	84	24310	1530	1280	0.388	0.325
1979-1983	22240	22010	85	18650	5500	4660	1.396	1.183
1983-1994	14160	14010	87	12140	1270	1100	0.322	0.279
1994-1997	15580	15420	93	14410	5140	4800	1.305	1.218
1997-2001	1830	1810	91	1650	450	410	0.114	0.104

Table 16. Mass of Copper eroded into the Clark Fork River at Grant-Kohrs Ranch NHS. Data is only correct to 3 significant figures, but is presented as-is for comparison and clarity.

Lead								
Interval	mass (kg)	excess mass (kg)	error (%)	error +/- (kg)	mass/yr (kg/yr)	error (kg/yr)	mass/length of river (kg/m/yr)	error +/- (kg/m/yr)
1947-2001	13740	12630	69	8750	234	162	0.059	0.041
1960-2001	11480	10550	69	7260	257	177	0.065	0.045
1979-2001	7430	6830	69	4690	310	213	0.079	0.054
1983-2001	4360	4010	70	2800	223	156	0.057	0.039
1994-2001	2400	2210	71	1570	316	224	0.080	0.057
1997-2001	253	232	78	181	58	45	0.015	0.012
Year	mass (kg)	excess mass (kg)	error (%)	error +/- (kg)	mass/yr (kg/yr)	error (kg/yr)	mass/length of river (kg/yr/m)	error +/- (kg/yr/m)
1947-1960	2260	2080	70	1450	160	112	0.041	0.028
1960-1979	4050	3720	69	2580	200	136	0.051	0.034
1979-1983	3070	2820	70	1990	710	498	0.180	0.126
1983-1994	1960	1800	73	1310	160	119	0.041	0.030
1994-1997	2150	1980	81	1600	660	533	0.168	0.135
1997-2001	253	232	78	181	58	45	0.015	0.012

Table 17. Mass of Lead eroded into the Clark Fork River at Grant-Kohrs Ranch NHS. Data is only correct to 3 significant figures, but is presented as-is for comparison and clarity.

Zinc								
Interval	mass *(kg)*	excess mass *(kg)*	error *(%)*	error +/- *(kg)*	mass/yr *(kg/yr)*	error *(kg/yr)*	mass/length of river *(kg/m/yr)*	error +/- *(kg/m/yr)*
1947-2001	60900	57710	51	29610	1070	550	0.272	0.140
1960-2001	50880	48210	51	24410	1180	600	0.299	0.152
1979-2001	32930	31200	50	15750	1420	720	0.360	0.183
1983-2001	19320	18310	52	9550	1020	530	0.259	0.135
1994-2001	10650	10100	54	5420	1440	770	0.365	0.195
1997-2001	1120	1060	63	670	265	168	0.067	0.043
Interval	mass *(kg)*	excess mass *(kg)*	error *(%)*	error +/- *(kg)*	mass/yr *(kg/yr)*	error *(kg/yr)*	mass/length of river *(kg/m/yr)*	error +/- *(kg/m/yr)*
1947-1960	10020	9500	52	4900	731	377	0.185	0.096
1960-1979	17950	17010	51	4820	895	254	0.227	0.064
1979-1983	13610	12890	53	6800	3220	1700	0.817	0.431
1983-1994	8670	8210	56	4590	746	4590	0.189	1.165
1994-1997	9530	9040	66	5960	3010	1990	0.764	0.505
1997-2001	1120	1060	63	660	265	165	0.067	0.042

Table 18. Mass of Zinc eroded into the Clark Fork River at Grant-Kohrs Ranch NHS. Data is only correct to 3 significant figures, but is presented as-is for comparison and clarity.

The mass and rate of metals reintroduced to the river at Grant-Kohrs Ranch between 1983 and 2001, combined with data from the Garrison and Racetrack sites, provide estimates of the total metal loading to the Deer Lodge Valley (Table 20). The average metal concentrations in the banks at the upstream site (Racetrack) were higher than those on the ranch so chemistry data from Brooks (1988) was used to calculate metals loading there (Table 19), instead of those from Moore and Woessner (2001). Data collected by Moore and Hochella (unpublished) near the downstream site (Garrison) fell within the error of the ranch site, and due to the small number of sampling locations for that study, the ranch chemistry data were used (Table 12). The higher metal

concentrations upstream are to be expected, as more contaminated sediment is generally deposited closer to the source of mine waste disposal, although large concentrations can also be found in areas of low energy within the floodplain and channel where the fine sediment associated with metals can be deposited (Miller 1997; Knighton 1998; Miller, et al. 1998).

Racetrack	Metals Concentrations and Error (mg/kg)				
	As	*Cd*	*Cu*	*Pb*	*Zn*
weighted avg	448	5	3205	436	1851
Stdeve	386	7	3076	330	1321
error %	86	141	96	76	71

Table 19. Arsenic and metal concentrations at Racetrack study site (from Brooks 1988).

Arsenic

Interval	mass (kg)	Excess mass (kg)	error (%)	error +/- (kg)	mass/ yr (kg/yr)	error (kg/yr)	Mass/length of river (kg/m/yr)	error +/- (kg/m/yr)
GRKO 1983-2001	4160	3950	70	2760	219	153	0.056	0.039
Garrison 1983-2001	2150	2040	70	1430	114	79	0.058	0.041
Racetrack 1983-2001	17640	17240	88	15220	958	846	0.136	0.120
Total 1983	23950	23230	133	30780	1291	1710	0.100	0.132

Cadmium

Interval	mass (kg)	Excess mass (kg)	error (%)	error +/- (kg)	mass/ yr (kg/yr)	error (kg/yr)	Mass/length of river (kg/m/yr)	error +/- (kg/m/yr)
GRKO 1983-2001	80	60	47	30	3	2	0.001	0.000
Garrison 1983-2001	40	30	47	10	2	1	0.001	0.000
Racetrack 1983-2001	210	170	142	240	9	13	0.001	0.002
Total 1983	330	260	157	400	14	22	0.001	0.002

Copper

Interval	mass (kg)	Excess mass (kg)	error (%)	error +/- (kg)	mass/ yr (kg/yr)	error (kg/yr)	Mass/length of river (kg/m/yr)	error +/- (kg/m/yr)
GRKO 1983-2001	31570	31240	84	26120	1736	1451	0.441	0.368
Garrison 1983-2001	16350	16180	84	13510	899	751	0.462	0.386
Racetrack 1983-2001	126080	125450	98	122790	6970	6822	0.990	0.969
Total 1983	174000	172870	153	265270	9604	14737	0.743	1.141

Lead

Interval	mass (kg)	Excess mass (kg)	error (%)	error +/- (kg)	mass/ yr (kg/yr)	error (kg/yr)	Mass/length of river (kg/m/yr)	error +/- (kg/m/yr)
GRKO 1983-2001	4360	4010	69	2770	223	154	0.057	0.039
Garrison 1983-2001	2260	2080	69	1430	115	79	0.059	0.041
Racetrack 1983-2001	17140	16470	78	12870	915	715	0.130	0.102
Total 1983	23760	22560	125	28200	1253	1566	0.097	0.121

Zinc

Interval	mass (kg)	Excess mass (kg)	error (%)	error +/- (kg)	mass/ yr (kg/yr)	error (kg/yr)	Mass/length of river (kg/m/yr)	error +/- (kg/m/yr)
GRKO 1983-2001	19320	18310	51	9340	1017	519	0.258	0.132
Garrison 1983-2001	10010	9480	51	4820	527	268	0.271	0.138
Racetrack 1983-2001	72820	70900	74	52390	3939	2911	0.560	0.414
Total 1983	102150	98690	103	101820	5482	5657	0.424	0.438

Table 20. Total amount of metals returned to the river between 1983 and 2001 from all 3 study sites. Data is only correct to 3 significant figures, but is presented as-is for comparison and clarity.

Using the loading rate/length of river data for each metal (1947-2001), the amount of metal input from bank erosion over the entire 69.2 km of river in the Deer Lodge Valley (Warm Springs to Garrison, MT) was estimated (Tables 21-23). Even at erosion rates of 0.19 m/yr, a large amount of metals can potentially be added into the river each year. For example, 51 metric tons of Copper, 7 tons of Arsenic, and 7 tons of Lead were loaded to the river per year from 1947 to 2001. Although this data is based on a constant erosion rate, data on the timing of erosion shows that the rate actually fluctuates depending on discharge. During relatively short periods of high flows, such as 1979-1983 or 1994-1997, the river receives increased loads of metals, whereas low flow years probably result in much lower loads.

At higher flows, some of this sediment and its associated metals likely remains in suspension to be deposited in the floodplain or behind Milltown Dam much further downstream. However, a large portion probably moves downstream slowly, as part of the bedload, or is left behind in bar deposits or in slow moving areas of the river nearer to the erosion (Smith 1979; Miller, et al 1998).

Metal	*kg/yr*	*error +/-*
As	6920	9140
Cd	70	140
Cu	51430	78980
Pb	6710	8380
Zn	29350	30320

Table 21. Metal loading rate for the entire Deer Lodge Valley. Data based on the loading rate for all 3 study areas within the valley (Table 18) multiplied by the 69200 m (43 miles) of river between Warm Springs Ponds and Garrison, MT. Data is only correct to 3 significant figures, but is presented as-is for comparison and clarity.

Metal	1997	error +/-	1994	error +/-	1983	error +/-	1979	error +/-	1960	error +/-	1947	error +/-
As	27.7	36.6	48.5	64.0	124.6	164.5	152.3	201.0	283.8	374.6	373.8	493.4
Cd	0.3	0.6	0.5	1.0	1.2	2.5	1.5	3.0	2.8	5.7	3.7	7.5
Cu	205.7	315.9	360.0	552.9	925.7	1421.6	1131.5	1737.5	2108.6	3238.2	2777.2	4264.9
Pb	26.9	33.5	47.0	58.6	120.9	150.8	147.7	184.3	275.3	343.4	362.6	452.3
Zn	117.4	121.3	205.4	212.2	528.2	545.7	645.7	667.0	1203.3	1243.0	1584.9	1637.2

Metal	1997-2001	error +/-	1994-1997	error +/-	1983-1994	error +/-	1979-1983	error +/-	1960-1979	error +/-	1947-1960	error +/-
As	27.7	36.5	20.8	27.4	76.1	100.5	27.7	36.5	131.5	173.6	90.0	118.9
Cd	0.3	0.6	0.2	0.4	0.8	1.5	0.3	0.6	1.3	2.6	0.9	1.8
Cu	205.7	315.9	154.3	236.9	565.7	868.8	205.7	315.9	977.2	1500.6	668.6	1026.7
Pb	26.9	33.5	20.1	25.1	73.9	92.1	26.9	33.5	127.6	159.1	87.3	108.9
Zn	117.4	121.3	88.0	91.0	322.8	333.5	117.4	121.3	557.6	576.0	381.5	394.1

Table 22. Estimated mass of metals (metric tons) added to the Clark Fork River within the Deer Lodge Valley. Upper section presents data for the interval between the given year and 2001. Lower table presents data between subsequent air photos. Data is based on the overall rate (from 1947-2001) multiplied by the river length. Large errors are due to the propagation of error in chemistry and erosion data. Data is only correct to 3 significant figures, but is presented as-is for comparison and clarity.

Metal	2050	error +/-	2100	error +/-	2500	error +/-	3000	error +/-
As	346	457	692	914	3460	4570	6920	9140
Cd	3	7	7	14	35	69	70	138
Cu	2570	3950	5140	7900	25720	39490	51430	78980
Pb	336	419	671	838	3360	4190	6710	8380
Zn	1470	1520	2940	3030	14680	15160	29350	30320

Table 23. Estimated mass of metals (metric tons) added to the Clark Fork River within the Deer Lodge Valley between 2000 and the given year. Data based on the overall rate (from 1947-2001) multiplied by the river length. Large errors are due to the propagation of error in chemistry and erosion data. Data is only correct to 3 significant figures, but is presented as-is for comparison and clarity.

Controls on the Distribution and Timing of Bank Erosion

Effect of Tailings

One of the main goals of this research was to evaluate whether the presence of tailings directly affects the erosion rates within the study reach. Unfortunately, separating the tailings' effects from the other variables proved difficult. Tailings are present along most of the river channel within the study reach, with varying thicknesses, except when the river flows against the Tertiary volcanic sediments at the edge of the meander belt (Figure 14). To distinguish whether or not the amount of tailings affects erosion, bank retreat at a bend where there are no tailings ("Ponds") was compared to a bend with similar vegetation where tailings do occur ("Stuart Field") (Figure 26). "Ponds" does have less erosion, but bank migration is constrained by riprap and wastewater treatment ponds directly downstream of the bank. Also, unlike most of the meander bends in the park reach, there is no riffle in this particular bend (Figure 32a, point C). Instead, the water gets deeper and much slower through the meander.

At first glance, the visible tailings thickness does seem to directly affect the occurrence or amount of erosion along the whole study reach (Figure 27 and 28), with greater erosion at bends with a thicker layer of tailings. However, this is more an artifact of the number of banks with a certain tailings' thickness. There are far more bank segments with 40-50 cm of tailings then there are banks with 0-35cm. Therefore, there is a higher probability that a large amount of erosion could occur at the 40-50 cm sites. When looked at more closely, Figures 27 and 28 also show smaller amounts of erosion in the thicker layer of visible tailings, and larger amounts of erosion where there is little or no visible tailings.

The presence of tailings may not be the main issue in contamination leading to erosion. It is not the tailings, but the concentrations of the metals within them that are disrupting the system. However, there is little relationship between the metal concentrations and erosion within the study site either (Figure 29 and 30). Plots of the relationship between metal concentrations and both erosion area and maximum erosion width exhibit a great deal of scatter, and all of the R^2 are less than 0.2. Clearly, there must be other, more important, controlling factors.

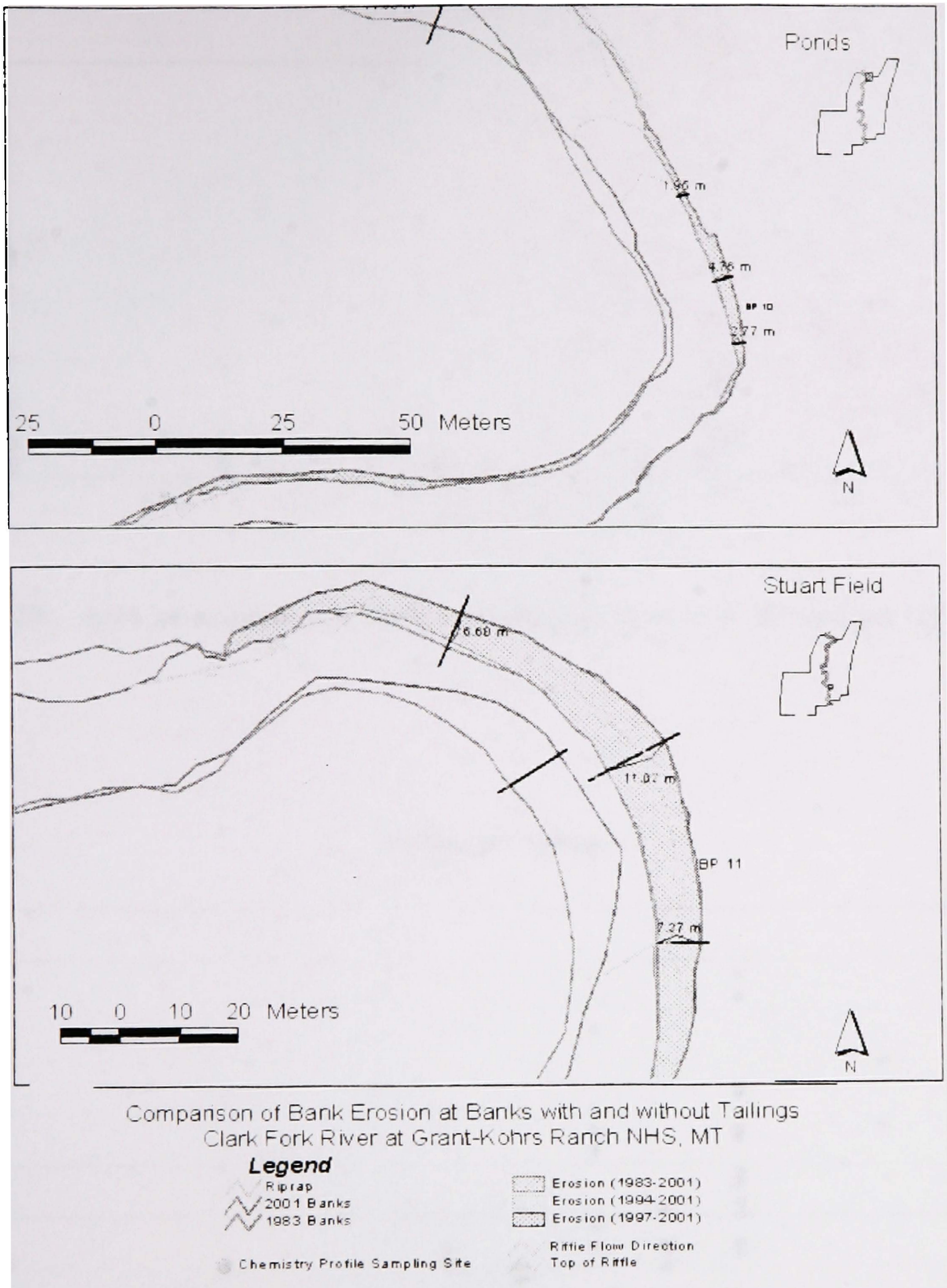


Figure 26. Comparison of bank erosion at two bank sites with and without tailings. Banks at "Ponds" do not contain tailings, whereas banks at "Stuart Field" do. However, "Ponds" is protected by riprap and water treatment plants construction downstream and has no riffle.

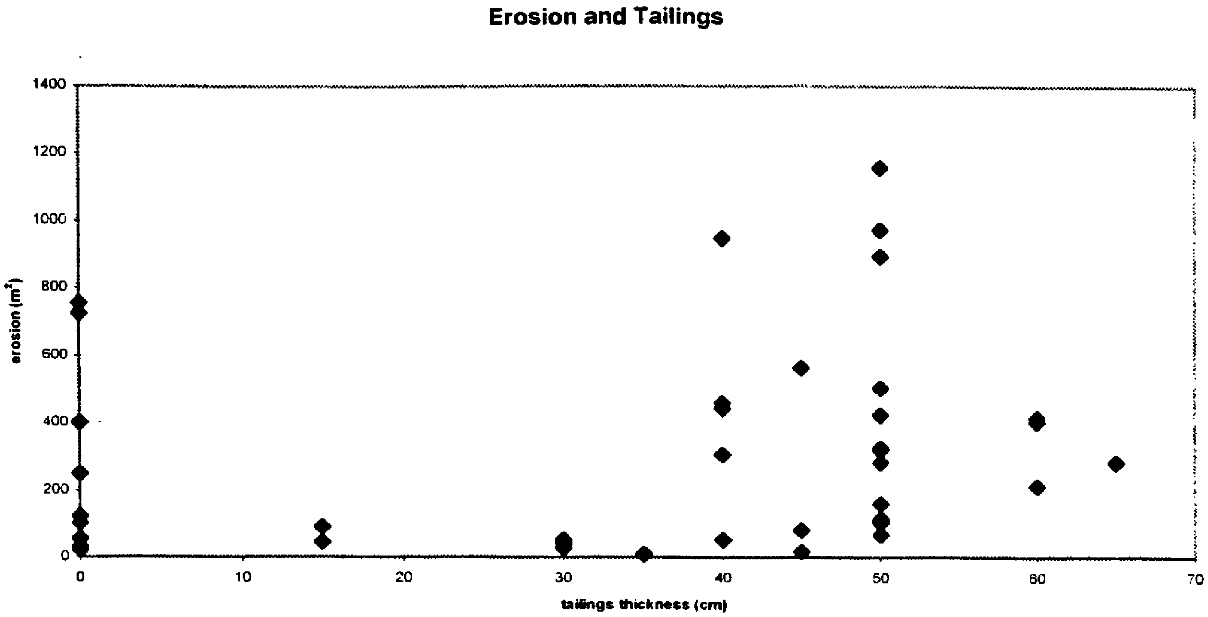


Figure 27. Area of erosion at a bank versus the thickness of the tailings layer at that bank.

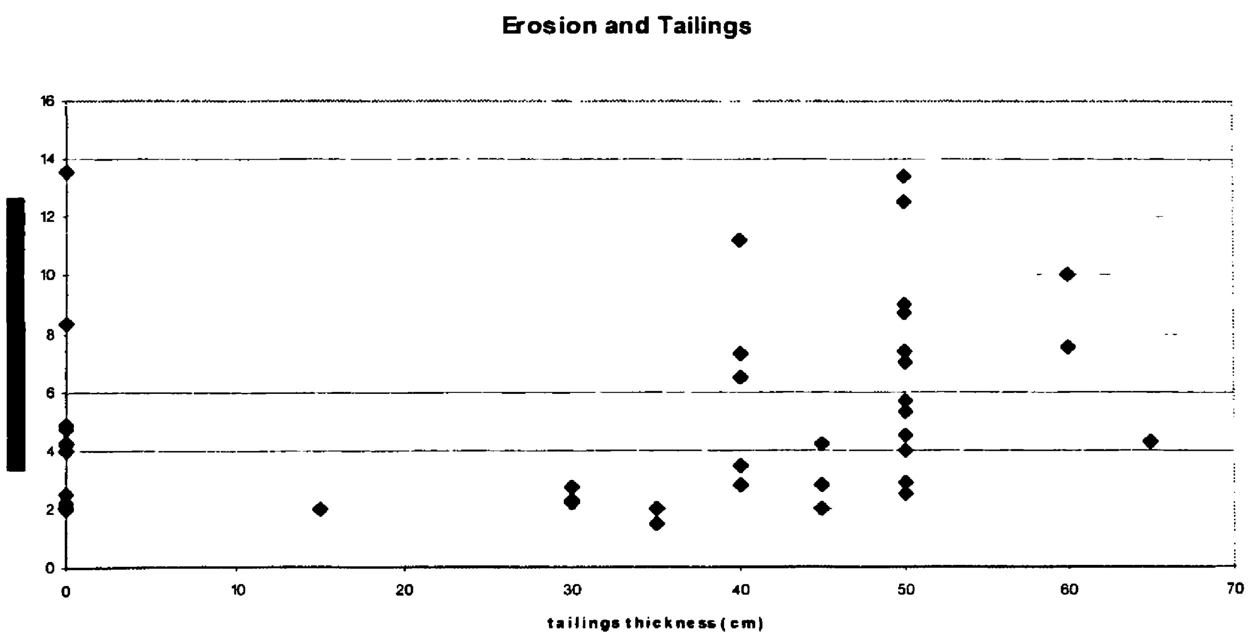
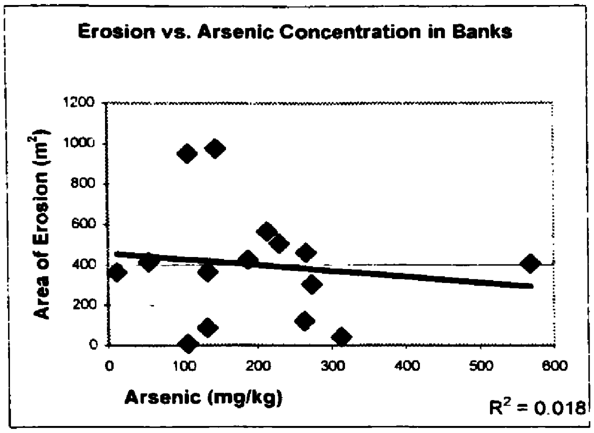
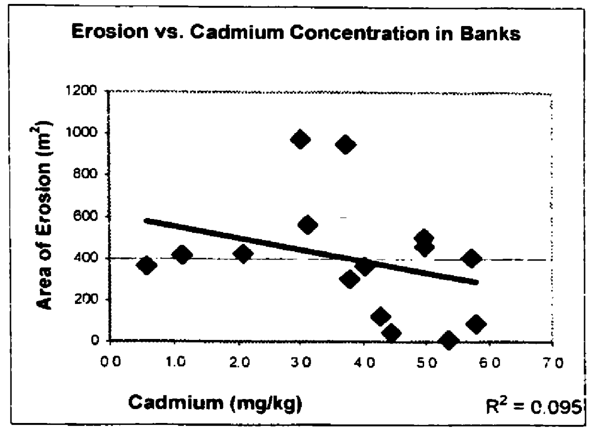
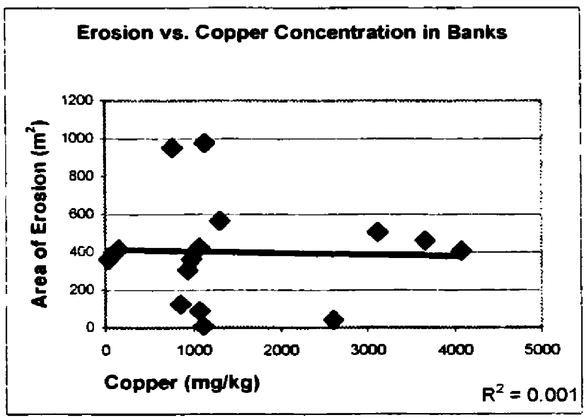
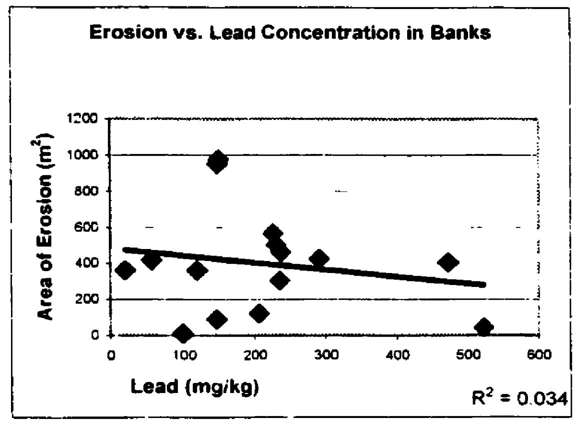


Figure 28. Maximum width of erosion at a bank versus the thickness of tailings at that bank.









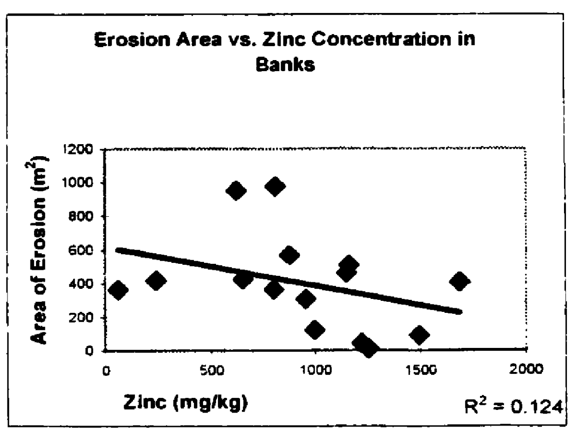


Figure 29. Area of Erosion vs. Metals Concentrations. There is no correlation between the area of erosion and any of the metals. R^2 values range from .001 (Cu) to 0.124 (Zn), and all the relationships are negative.

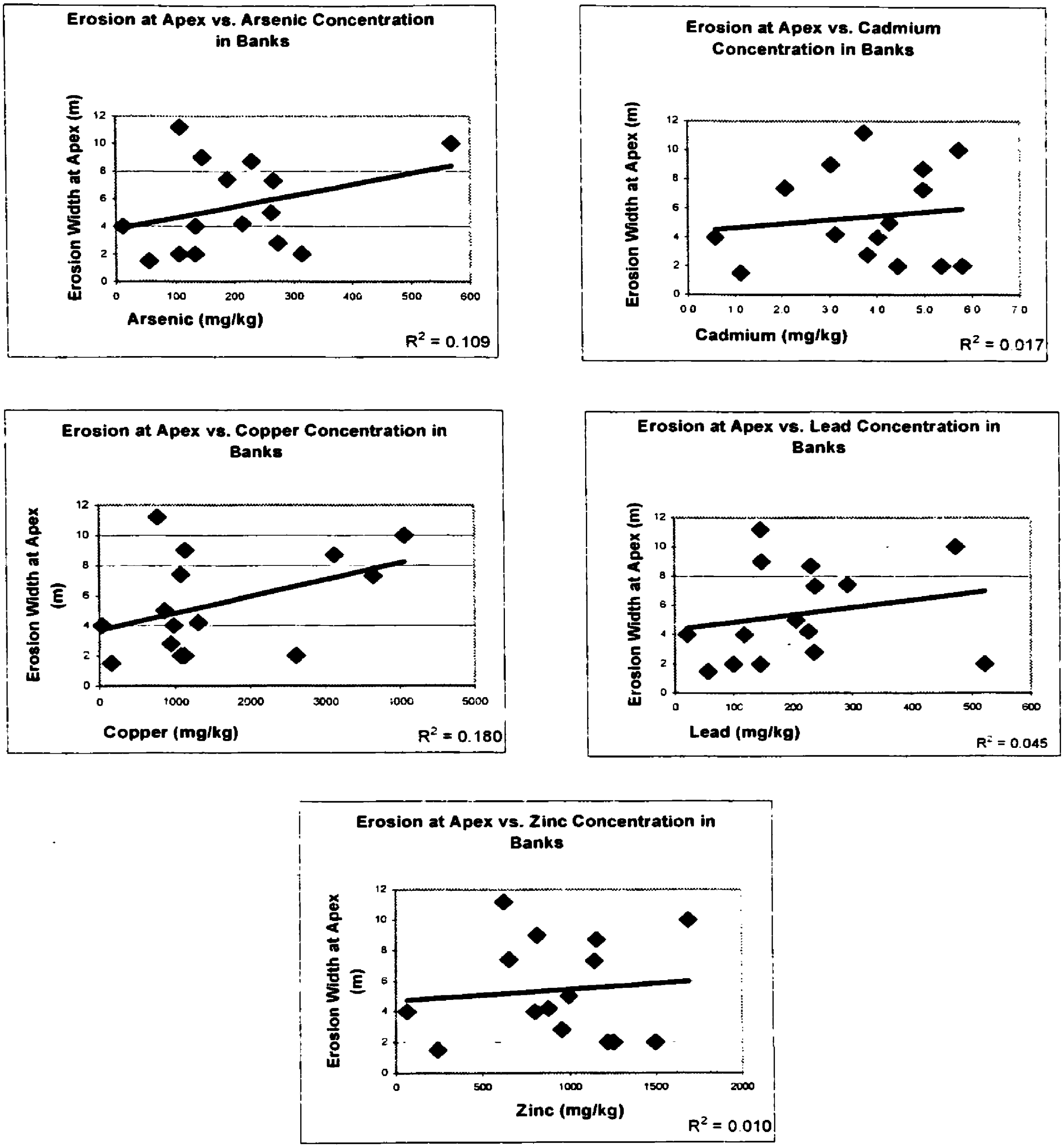


Figure 30. Maximum Width vs. Metals Concentrations. There is no correlation between the width of erosion and any of the metals. R^2 values range from .01 (Zn) to 0.179 (Cu).

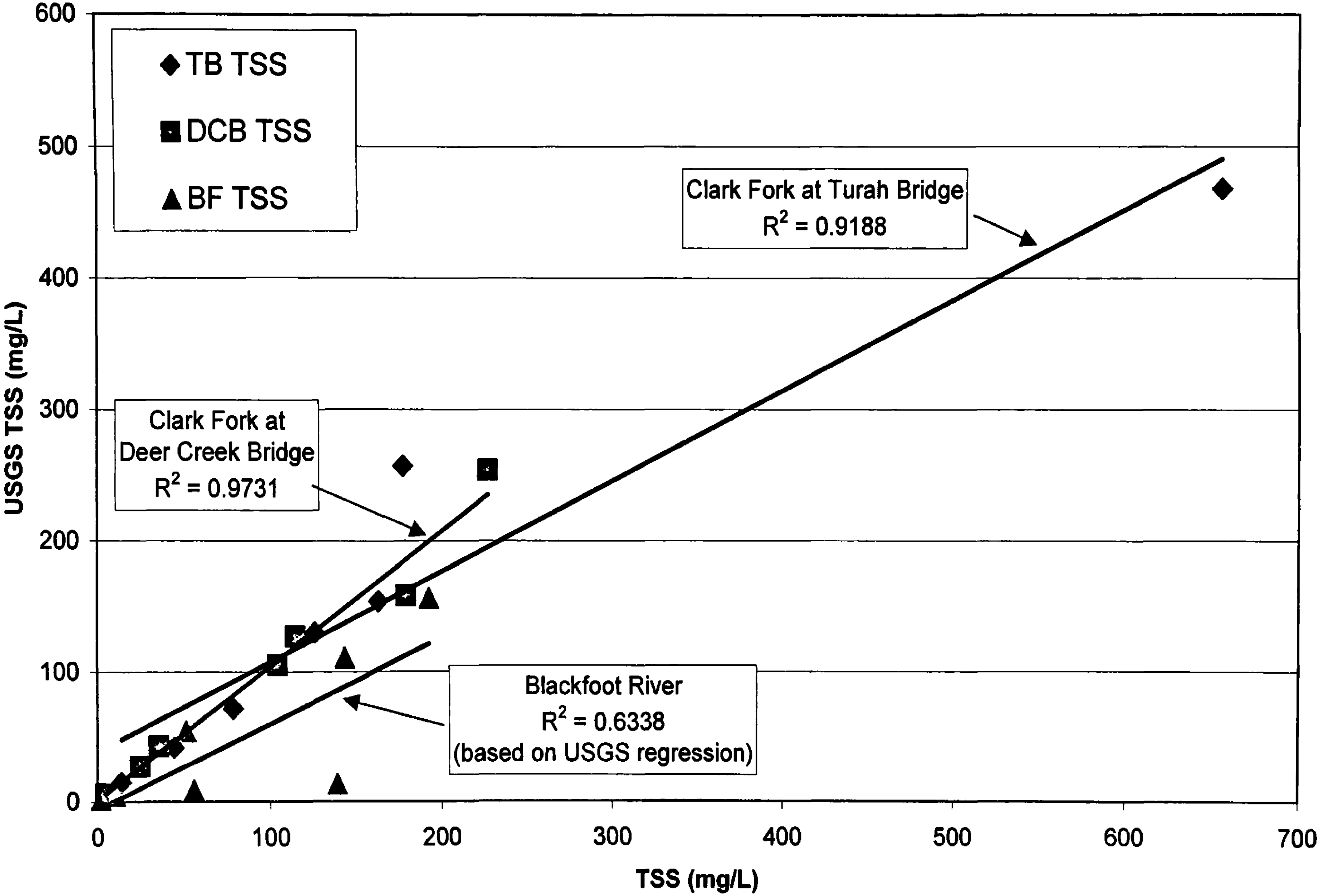


Figure 10. Suspeded Sediment Concentration: Comparison to USGS Data.

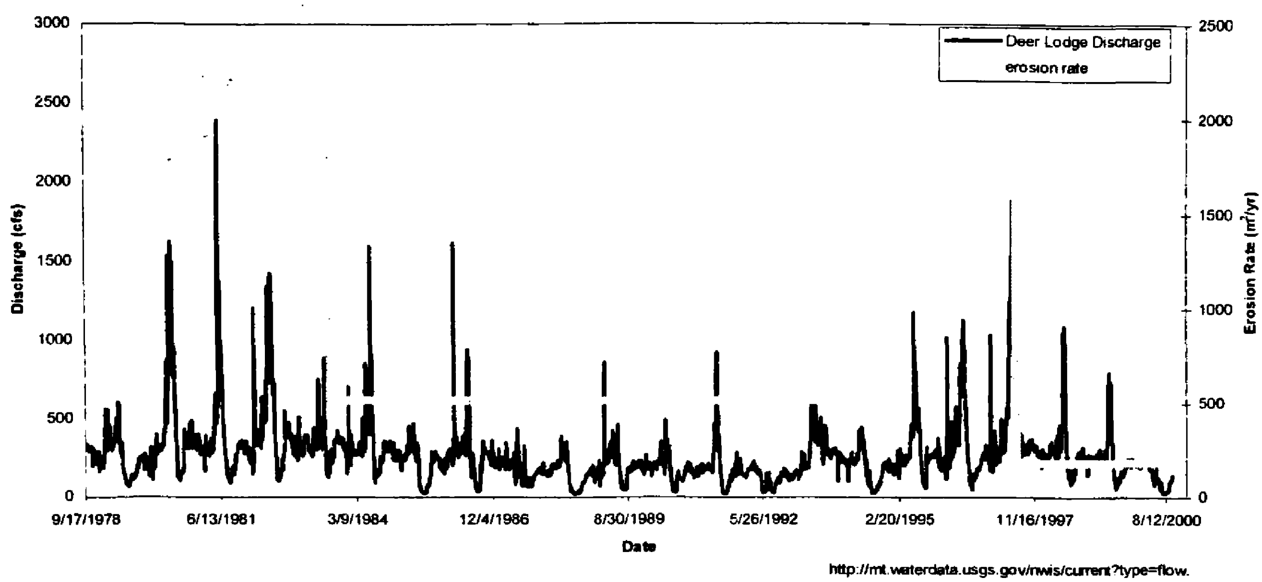


Figure 31. Discharge and Erosion Rates at Grant-Kohrs Ranch, NHS. Rates seem to be dependent on peak flows. Higher rates of erosion are associated with peaks over 1200cfs, and especially with the two highest peaks in 1981 and 1997. Discharge data from USGS gage at Deer Lodge, MT (12324200) and erosion rates from Table 8.

period (8910 m^2)(Table 8). Also, between 1997 and 2001, the flows are lower overall, with few relatively high peaks. There is a peak of around 1100 cfs (31 cms) in 1998, but it does little to increase the erosion over that time span.

Bank erosion within the study reach is probably ongoing at a small scale all the time, but the bulk of the erosion probably occurs when the peak discharge crosses a threshold. From the data presented above, it appears that flows up to 1100 cfs (31 cms) cause only nominal amounts of bank erosion, whereas the intervals containing the 2 highest flows on record (1981 and 1997) at the USGS Deer Lodge Gage result in the

largest areas of total erosion, as well as the most erosion at meander bends (Figure 24) and the greatest amount of channel widening (Figure 25). Again, even though the erosion rate is low between 1983 and 1994, the two 1600 cfs (45 cms) discharges probably resulted in most of the erosion that occurred during that period. The rate between 1983 and 1987, which covers these 2 high flows, may be relatively high, whereas the rate between 1987 and 1994, which has no flows over 1100 cfs, would probably be much lower. In addition, the 1984 and 1986 peak discharges, along with the 1998 peak flow, came just after the two largest peaks (1981 and 1997). The 1981 and 1997 flows may have eroded most of the unstable banks, leaving less material to remove in the years just after the events. Flows over 1100 cfs (31 cms) appear to cause most of the bank retreat at the study site, and large discharges continuing over a few days (1500 cfs over 2 or 3 days), such as the 1981 and 1997 floods, are probably responsible for the bulk of the sediment eroded into the river (Figure 31).

Effects of River Morphology

Although the amount of water may control the timing of the erosion, cutbank locations are probably controlled by other factors. Figure 31 shows the amount and location of riverbank erosion between 1983 and 2001 at Grant-Kohrs Ranch, as well as the riffle location and flow direction off of those riffles. It is apparent from these maps that a major control on bank erosion is the channel morphology. Specifically, major areas of erosion seem to occur at meander bends, and where riffles direct the water into the bank.

Bank erosion is closely related to the velocity conditions along the bank, which determine the magnitude of the shear stress on the bank material (Odgaard 1987; Knighton 1998). The centripetal force of the streamflow as it rounds a meander bend produces steep velocity gradients and high shear stress on the outside bank, which often results the high erosion rates in these locations (Pizzuto and Mecklenberg 1989). Similar influences can be found at and just downstream from riffles. Riffles are located where the slope increases along the channel. This change in slope often directs the flow through the system, and therefore, riffles have the ability to turn the flow direction towards the banks, as well as increase local velocity gradients. In turn, the energy and shear force on the bank materials in these locations increases, thereby increasing the erosion (Knighton 1998).

Good examples of erosion resulting from the riffles can be seen at point A in Figure 32a, point A in Figure 32c, and points A and B in Figure 32d. The tight bend at point B in Figure 32c ("Northbend") is a good example of erosion on the outside of a meander bend. The most common cause of bank erosion is the combination of meander bends and riffles. Good examples are depicted at point A in Figure 32a, point C in Figure 32d ("Stuart Field"), and the bends north of point B in Figure 32d. In river reaches where the channel is straight, with no riffles, there tends to be very little erosion. This can be seen in the straight reach in the southern half of Figure 32b. Where a riffle exists at point B, the channel has widened. There are also a few meander bends without riffles where less erosion is taking place, such as at point C on Figure 32a. The channel here is relatively deep and the water velocity at the time of study was extremely slow.

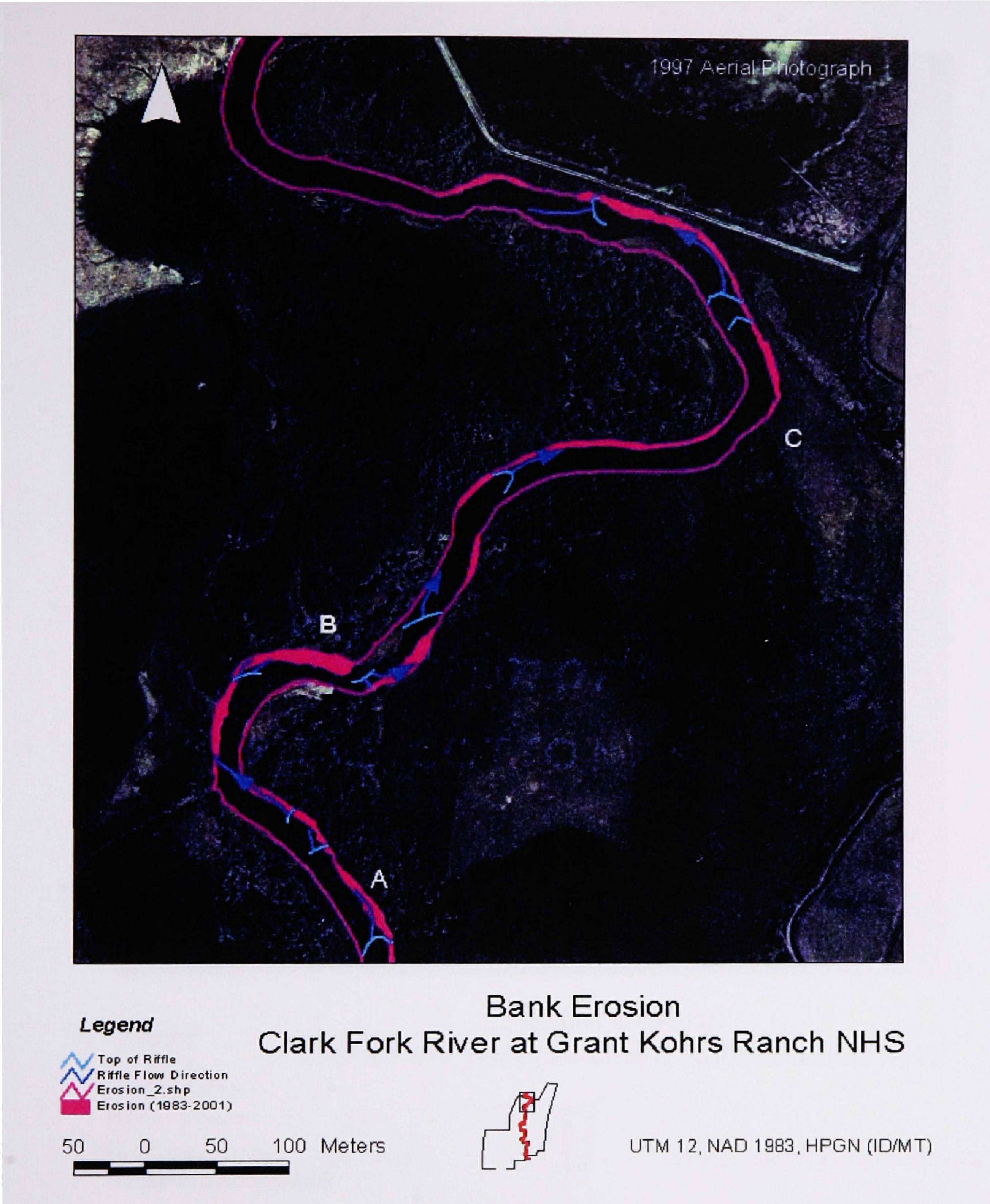


Figure 32a. Distribution of bank erosion within Grant-Kohrs Ranch NHS. Erosion is usually coincident with riffles and meander bends.

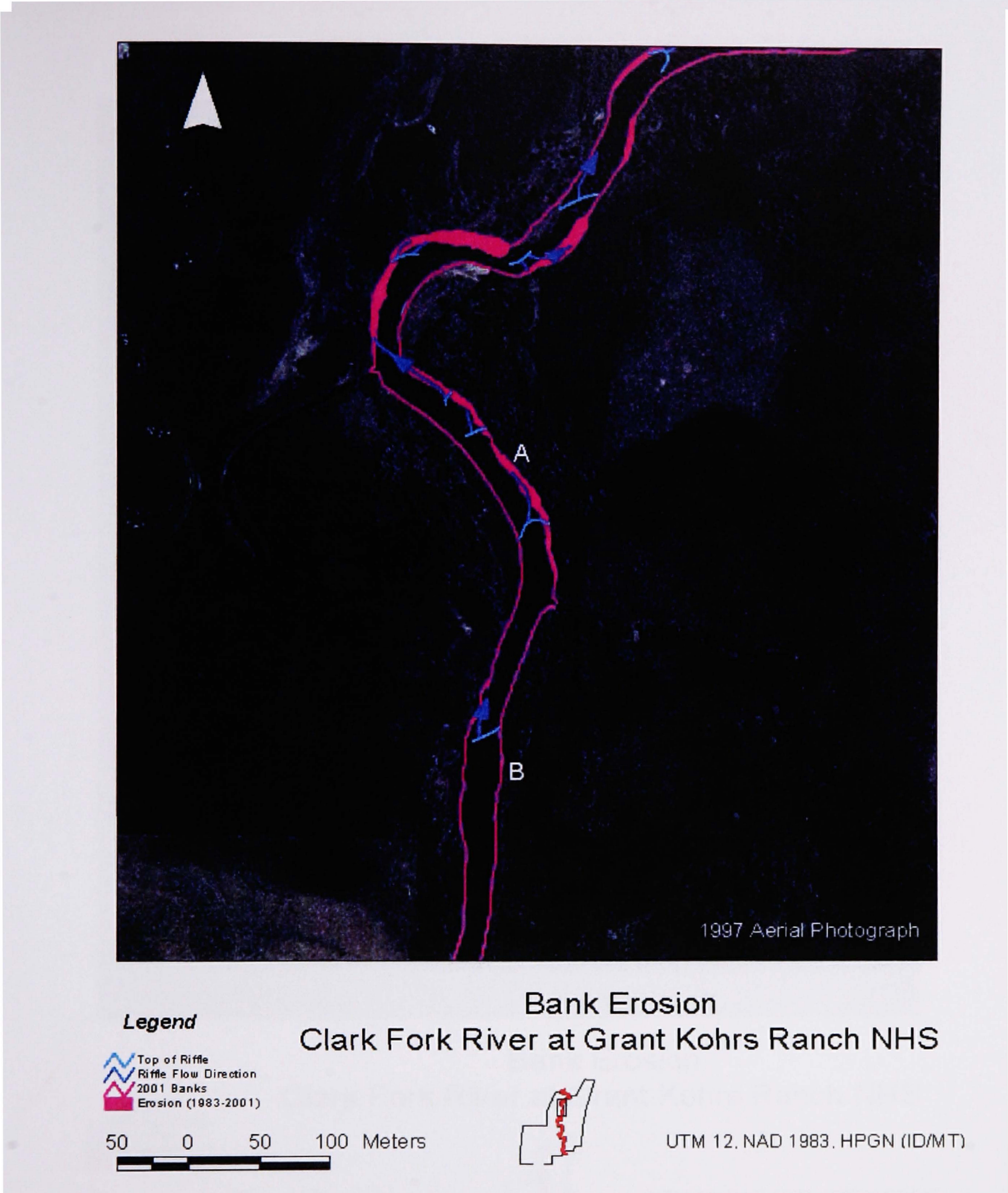


Figure 32b. Distribution of bank erosion within Grant-Kohrs Ranch NHS. Erosion is usually coincident with riffles and meander bends.

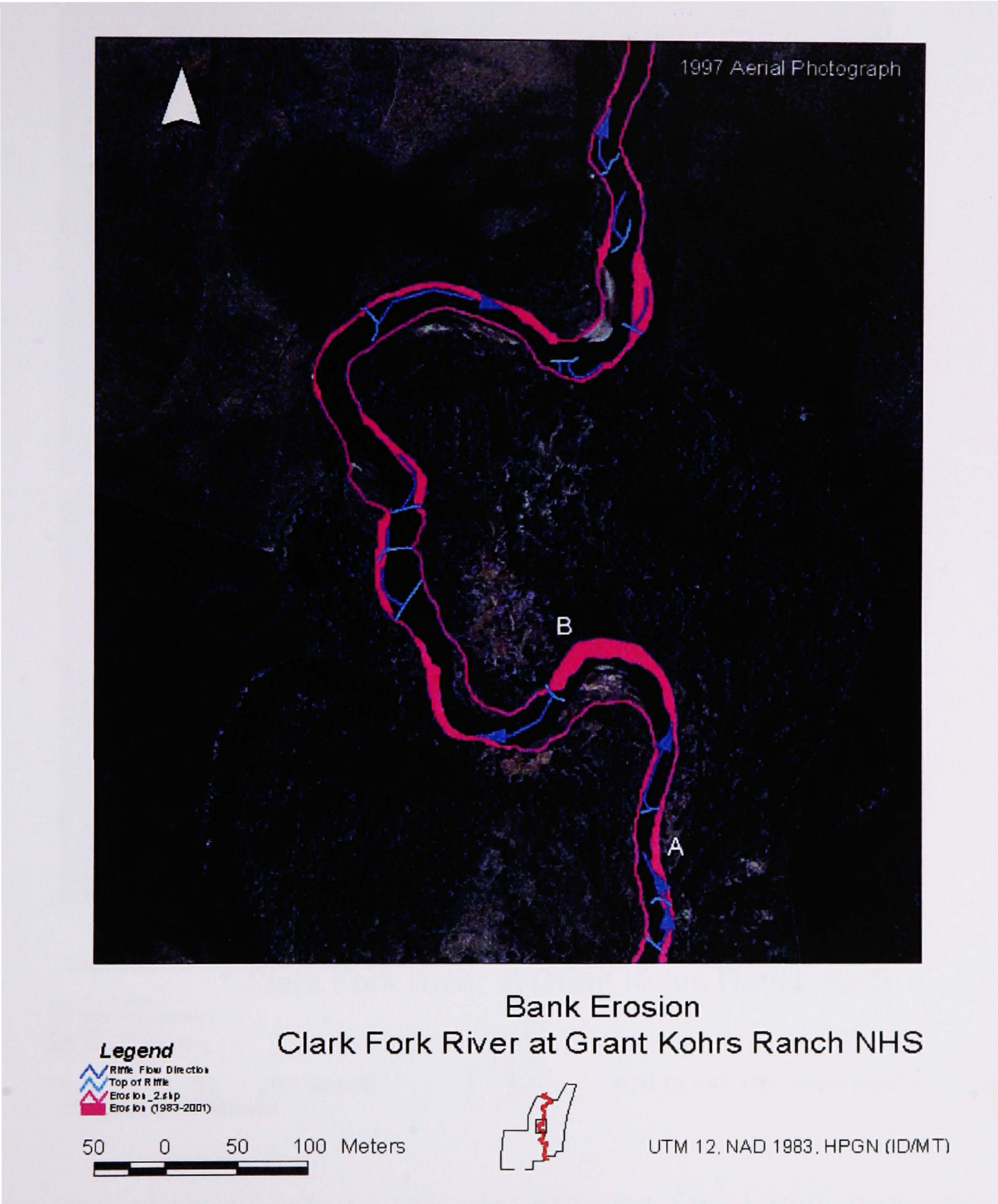


Figure 32c. Distribution of bank erosion within Grant-Kohrs Ranch NHS. Erosion is usually coincident with riffles and meander bends.

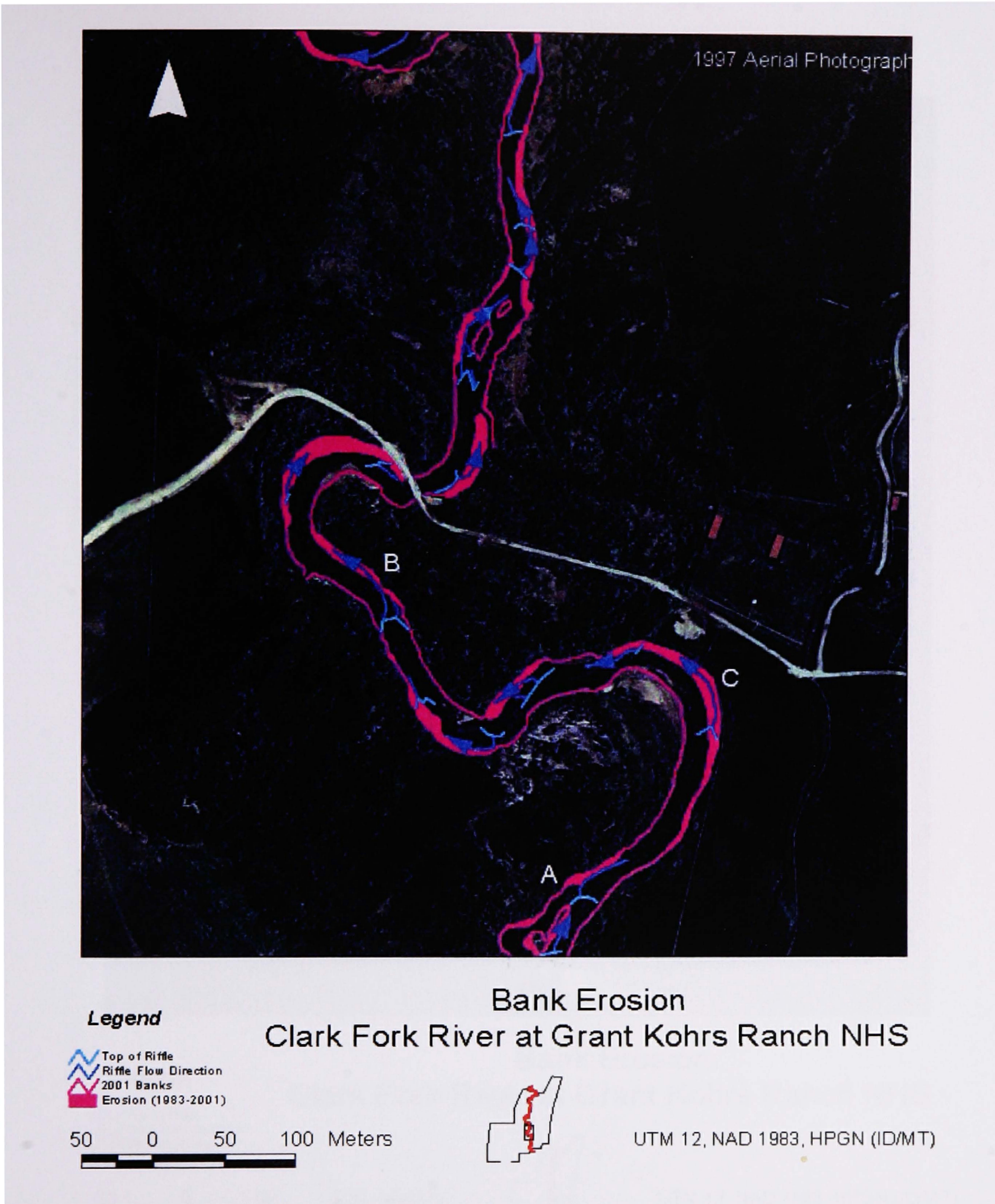


Figure 32d. Distribution of bank erosion within Grant-Kohrs Ranch NHS. Erosion is usually coincident with riffles and meander bends.

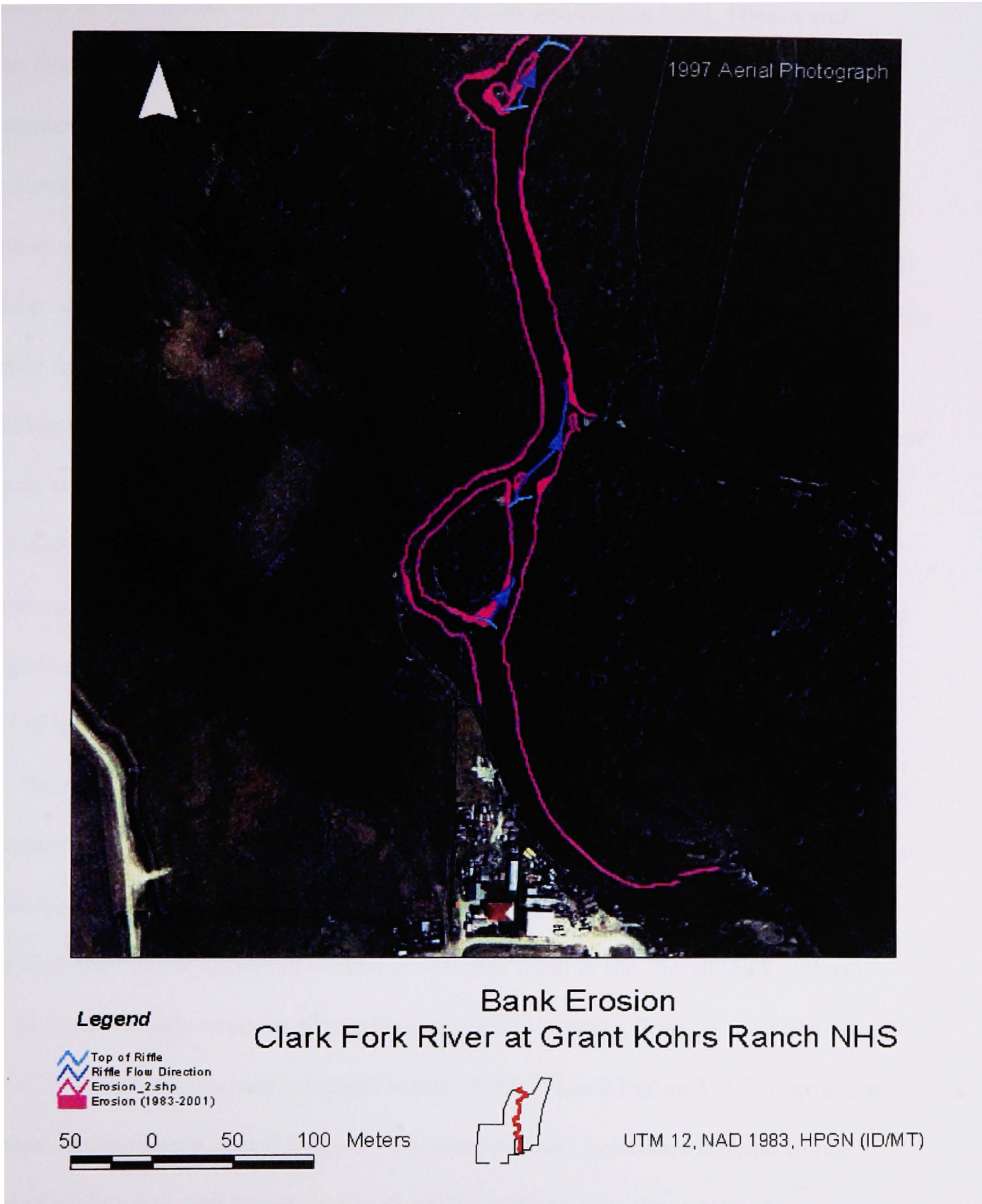
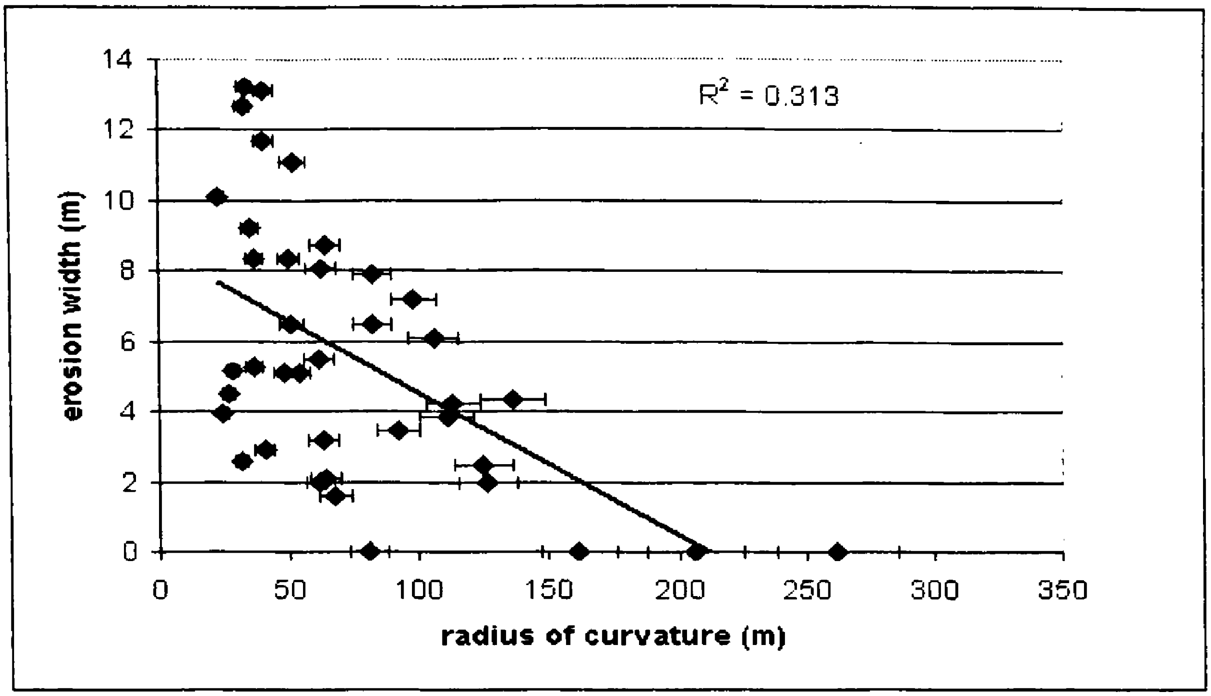


Figure 32e. Distribution of bank erosion within Grant-Kohrs Ranch NHS. Erosion is usually coincident with riffles and meander bends.

Studies have shown that the radius of curvature of a meander bend influences the erosion rate at the outside bank of the bend (Nanson and Hickin 1984; Hickin and Nanson 1986). Although the scatter within the plot (Figure 33) clearly indicates that other processes are involved, it seems that tighter bends (smaller radii) within Grant-Kohrs Ranch are associated with large amounts of erosion. The larger areas and widths of erosion occur at meander bends with radius of curvature between 35 and 50, and then they drop off considerably as the radius of curvature increases. This relationship opposes an earlier finding that radius of curvature does not effect erosion on bends in the Clark Fork River near Galen (Griffin and Smith 2002), which may be due to the large influence of woody vegetation in their study area (see discussion, page 131). Nanson and Hickin (1986) found that most bank erosion occurs when the bend tightness (*radius of curvature/average channel width*) is between 2 and 3. For the most part, this holds true at Grant-Kohrs Ranch as well, where most erosion occurs at a tightness of between 1.7 and 2.7 (Figure 34).

Because of their effect on bank erosion, the distribution and movement of riffles is an important component of this system. Riffle spacing in the study reach is about one riffle for every 98 m of channel. This spacing is 4.6 times the average channel width, slightly less than the 5-7 channel widths commonly cited in the literature (Knighton 1998). It is also highly variable throughout the reach, ranging from 22 m to 264 m apart, or 1.0 to 12.4 times the average channel width (Table 24 and Figure 35). Large changes in the spacing, seen at A and B (Figure 35), often indicate headward erosion of the channel at nickpoints, and in areas of high riffle concentration there seems to be more cutbanks (Figure 11 and Figure 32). Riffle locations are difficult or impossible to locate



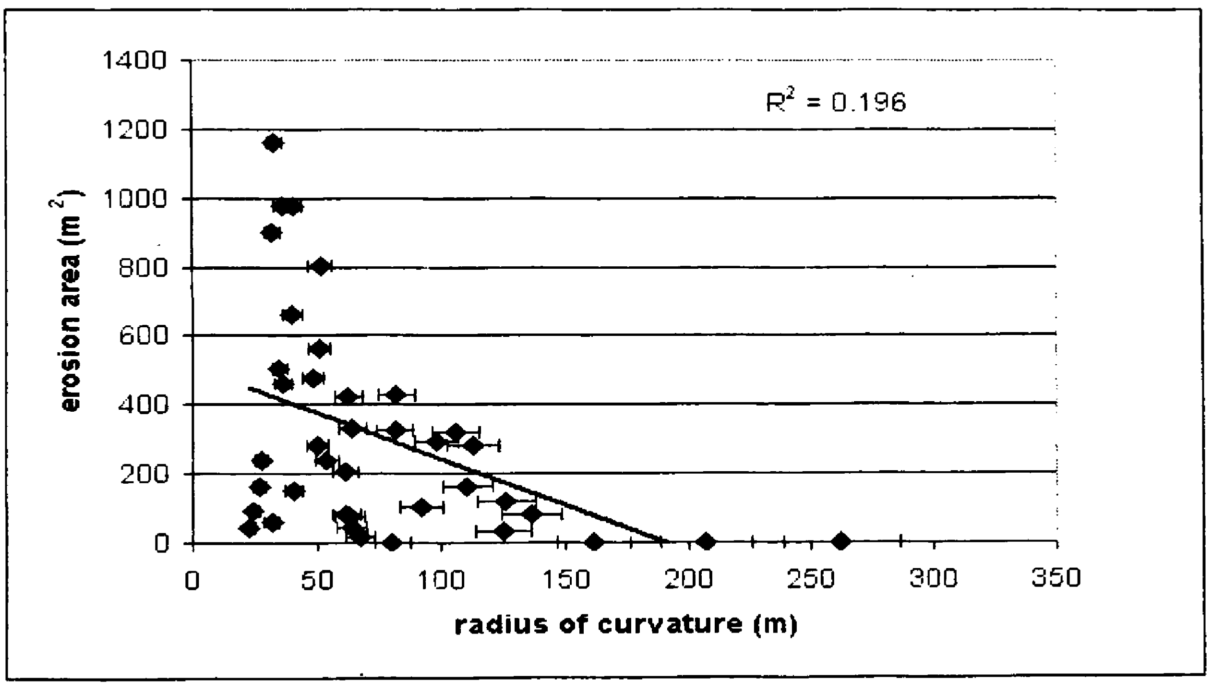
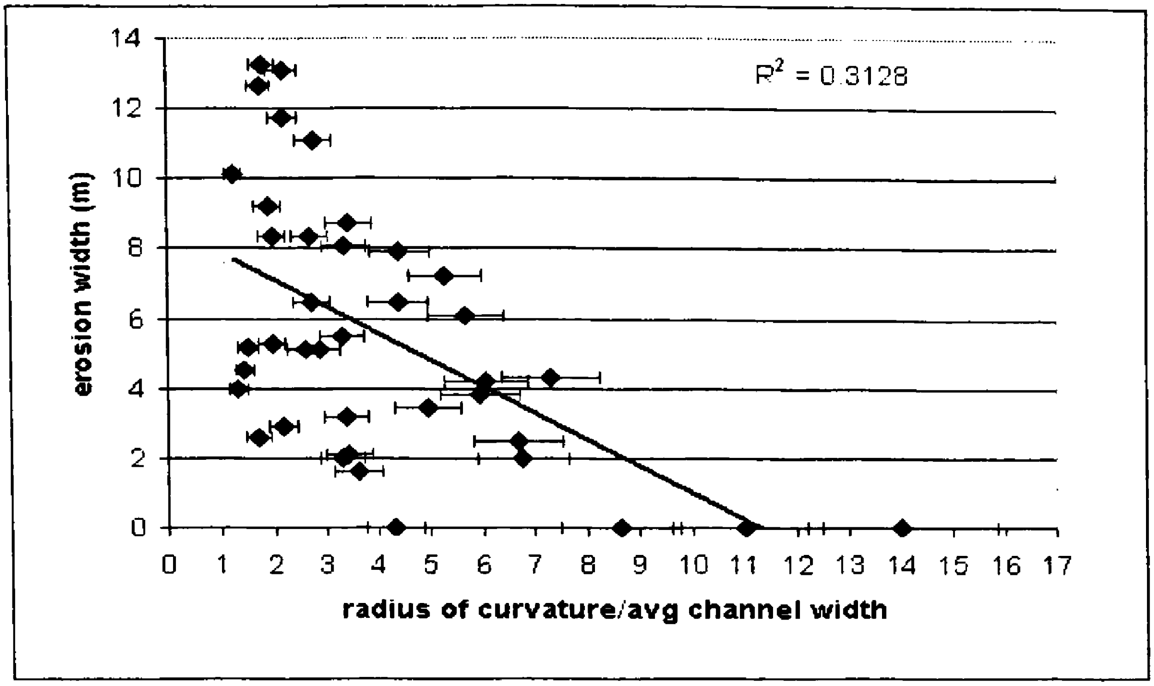


Figure 33. Effects of radius of curvature on erosion in Grant-Kohrs Ranch NHS, 1983-2001. Although there are clearly other influences, it appears that large amounts of erosion occur at bends with radii between 30 and 70 meters. Error for curvature is +/- 12%, error for erosion area is 11%, and error for erosion width is 1 m.



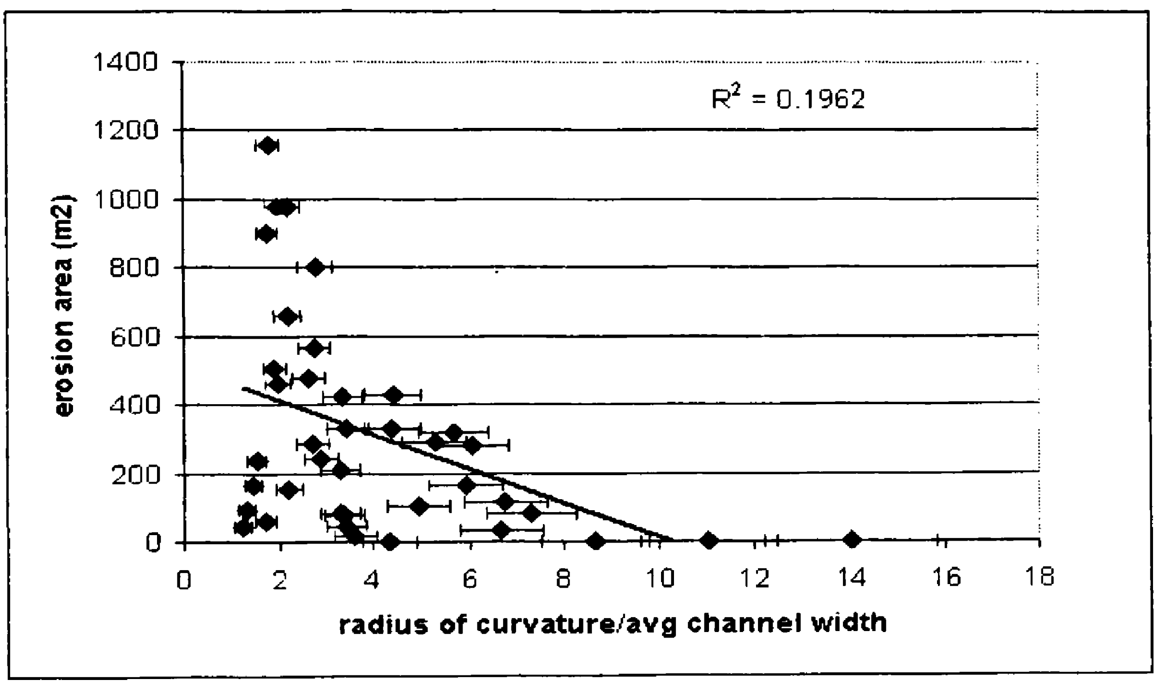


Figure 34. Effects of radius of curvature normalized by the average channel width (bend tightness) on erosion in Grant-Kohrs Ranch NHS. Erosion usually occurs at a "radius/width" between 2 and 3 (Nanson and Hickin 1979; 1984). At this study site, large amounts of erosion occur between 1.7 and 3. Error for curvature is +/- 12%, error for erosion area is 11%, and error for erosion width is 1 m.

on most of the aerial photographs, depending on the age of the pictures, the lighting, and the camera angles. They do not show up on pictures prior to 1983, and they can only be found intermittently on the newer images. Their placement when they can be found is always within a meter of the mapped 2001 locations. These data indicate that the riffles are fairly stationary over time, therefore forcing the erosion at many sites to continue along the same stretch of bank. However, it seems that the riffle locations must move as the meanders migrate due to changes in flow pattern and sediment movement, although this cannot be quantified with this data.

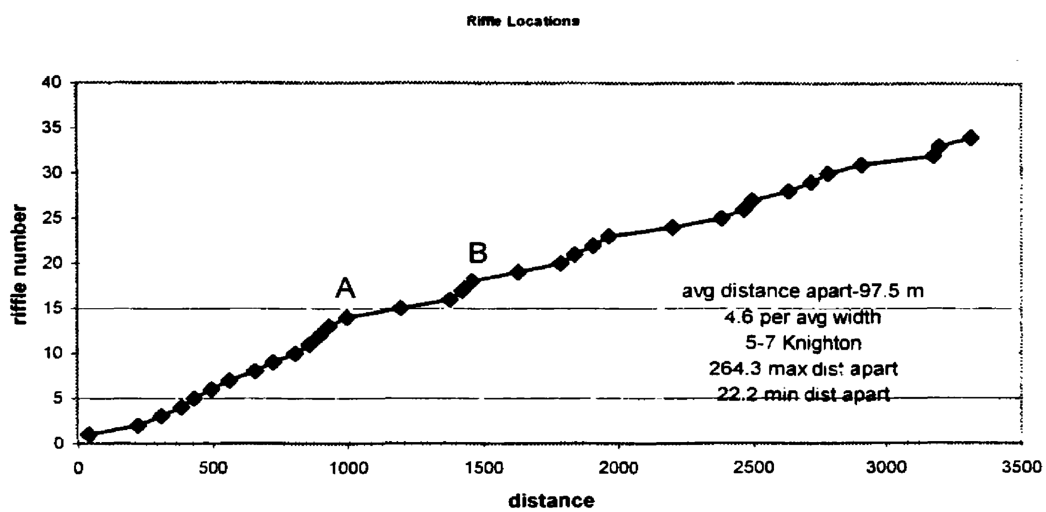


Figure 35. Riffle spacing within the study reach. "Riffle number" is the sequential number going from upstream to downstream (i.e., Riffle number 1 is the furthest upstream and riffle 34 is the furthest downstream).

Riffle Data	
Mean Spacing (m)	97
Standard Deviation of Spacing (m)	100
Mean Spacing Per Average Width	4.6
Maximum Spacing (m)	264
Max Spacing per Average Width	12.6
Minimum Spacing (m)	22
Min Spacing Per Average Width	1

Table 24. Riffle spacing data. The common value cited in the literature is one riffle every 5-7 channel widths (Knighton 1998).

Effect of Bank Material

Erosion of streambank materials occurs by two mechanisms: fluvial entrainment and mass movement of material due to gravity (Bowie 1982; Thorne 1982). Fluvial entrainment, or removal of bank material as moving water contacts the riverbank, depends on the flow's shear force acting on the bank and the bank's ability to resist this force (Thorne and Tovey 1981; Thorne 1982). The flow shear stress is a function of the flow's velocity gradient along the channel bank and bed. If the stress from the moving water exceeds the resistance of the material, particles from the bed and banks may dislodge and become entrained in the flow (Thorne 1982).

The mass movement of bank material by sloughing or sliding results from decreasing the upper bank's internal strength due to saturation, undermining, or foundation deterioration caused by seepage. (Leopold 1994; Thorne 1982). The rate of bank erosion due to mass failure depends on the gravitational forces acting on the bank material, the hydrostatic pressure on the material, and the banks tensile strength, or its internal resistance to mass failure. Once the bank fails and falls into the river, subsequent high flows can move it downstream through fluvial entrainment (Leopold 1994).

Rivers flowing through alluvial deposits often have composite banks. The base is composed of non-cohesive sand and gravel overlain by more cohesive, sandy silt and clay, overbank deposits. Thorne and Tovey (1981) found that the erosion processes operating on these lower and upper banks can be quite different. Sands and gravels are highly susceptible to erosion by fluvial entrainment, whereas the cohesive upper bank materials are usually much more resistant. Upper banks are also exposed to fewer flow events, and even at high flows, velocity measurements in bends suggest that the lower

banks are subjected to much higher shear stresses than the upper bank (Bathurst, et al. 1979).

Because fluvial erosion affects the non-cohesive lower bank more than the cohesive upper bank, the rates of erosion in the two layers differ and overhanging banks develop. Failure in the upper layers then proceed along tension cracks that form as the tensile strength of the cohesive bank material is overcome by gravitational forces acting on the overhanging bank. In a low riverbank (<5m), a tension crack may occupy a significant proportion of the bank height. When failure occurs, the slump block will topple forward into the channel, where it will protect the bank until its removal during subsequent high flows (Figure 36: Thorne and Tovey 1981).

Hooke (1979) documented both of these erosion processes (fluvial entrainment and mass failure) on the banks of the River Devon in Wales. As in the Thorne and Tovey model (1981), gravels in the lower bank were removed faster than the upper silts, which lead to overhanging banks. As the undercutting continued, blocks of soil and vegetation (including the roots) fell forward at the toe of the bank, where they were later eroded.

These same stratigraphic controls and erosion processes can be seen along the banks of the Clark Fork River in the study reach. The banks usually consist of four stratigraphic units (Figure 9): a thin soil layer, tailings, grey muds, and a basal sand and gravel unit. Overhanging banks occurred in 40% of the riverbanks, with cuts typically 30cm deep (horizontally) at the base of the bank. Tension cracks can also be found along the banks throughout the reach. Most of the undercutting takes place in the gravels and the base of the pre-tailings deposits, which leaves the more resistant tailings layer, soil, and roots hanging over the channel. The high flows likely responsible for the bulk of the

erosion may be the flows necessary to move underlying gravels and/or overcome the cohesion of the fine-sediment layers. Banks without vegetation lose some material due to shallow slipping along the face, but most banks, especially with vegetation, form cantilevers. As cutting continues, these cantilevered banks eventually become unstable (vertical stress becomes greater than the horizontal resistance) and finally fall into the river, taking the root binding vegetation with it.

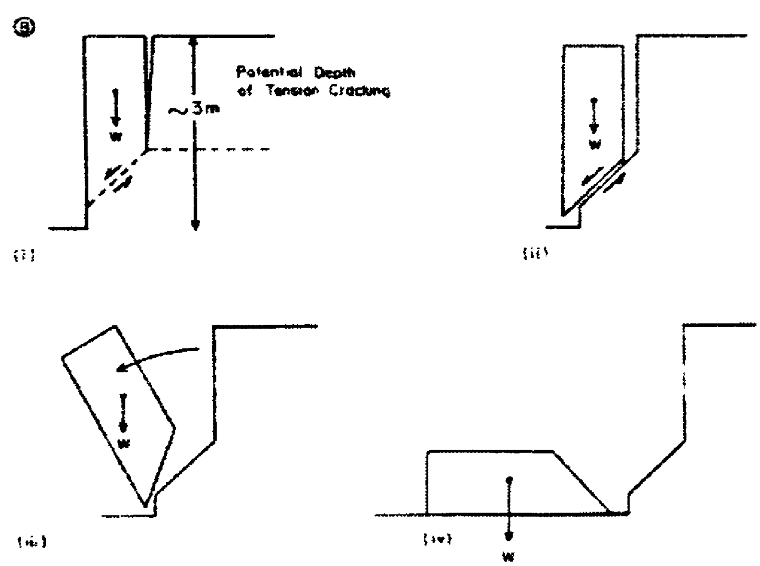


Figure 36. Tension cracks leading to bank failure (from Thorne and Tovey 1981)

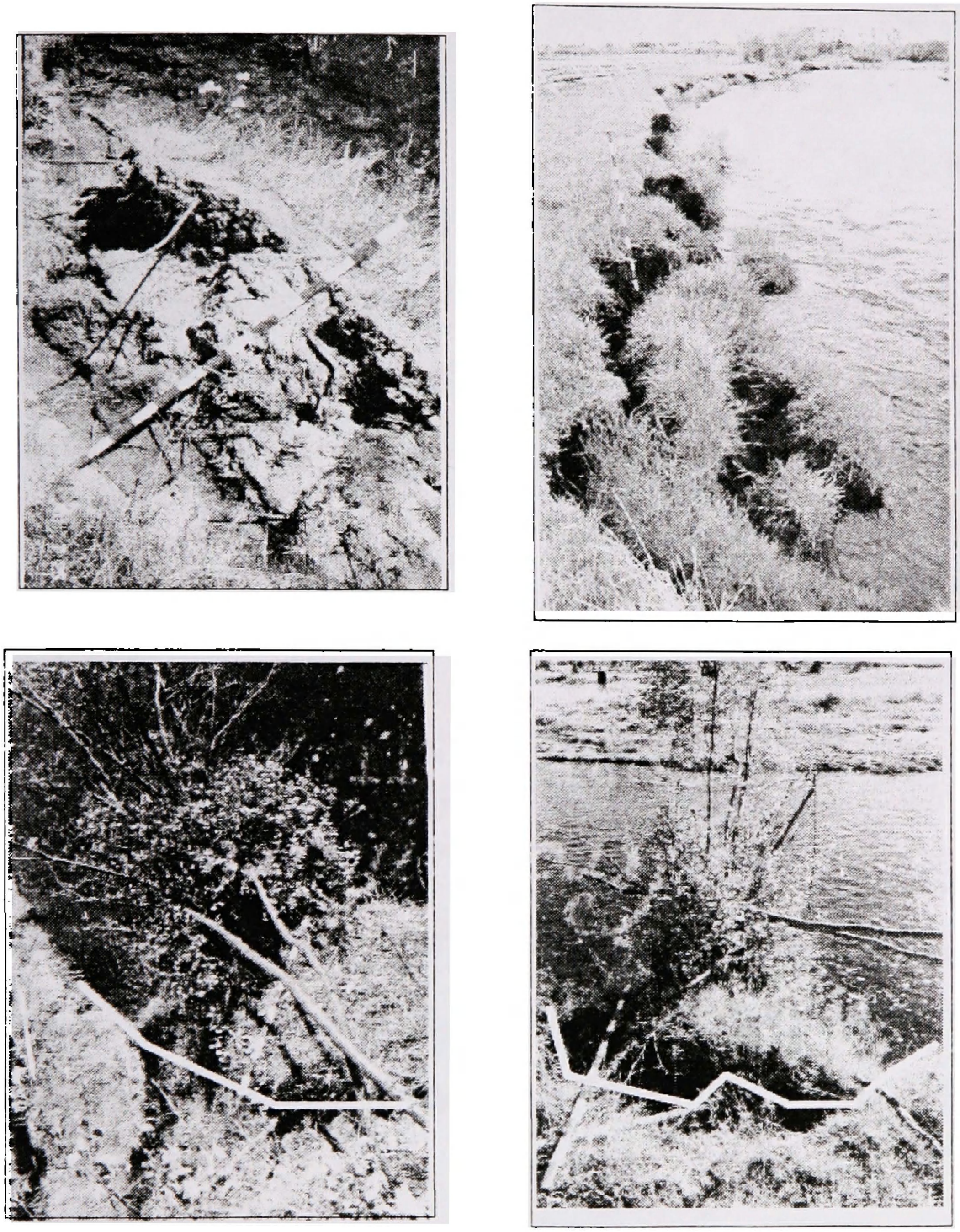


Figure 37. Examples of cantilever failure. The upper photographs exhibit blocks that have detached from the bank (iii and iv, Figure 36) in areas without woody vegetation. The lower photographs show a failed block with a shrub on top. The left photo is an looking almost straight down on the block, and the right is an oblique view. The white lines mark the approximate break from the bank (widening tension crack). Also, notice that the shrub is only about 1 meter high, which is typical in the study reach.

Effect of Vegetation

Vegetation, especially woody shrubs such as willows (*Salix* sp.), is considered an important control on bank erosion (Smith 1979; Groeneveld and Griepentrog 1985), and is often used to stabilize banks in river rehabilitation projects (Conroy and Svejcar 1991; Kondolf 1996). Riparian vegetation protects streambanks by decreasing water velocity and its erosive force, by creating a physical barrier between the water and the soil, and by increasing the shear and tensile strength of the banks. Many of the plans to reduce metal loading to the Clark Fork River involve extensive planting of willows along the channel banks (EPA 2002).

The importance of existing woody vegetation in controlling bank vegetation was examined at Grant-Kohrs Ranch NHS, and in many cases, the willows and birches do not seem to hold the banks in place. At "Bridge South" shrubs dominated the bank in 1983, but by 2001 many of the shrubs along the bank are eroded away (Figure 39). "Northbend" also lost a moderate amount of woody vegetation between 1983 and 2001. In fact, both of these vegetated bends (Bridge South and Northbend) have lost similar areas of floodplain terrace as the unvegetated "Stuart Bend" (Figure 39 and Table 26). Similar relationships were observed in the reaches up and downstream from Grant-Kohrs Ranch NHS.

Vegetation effects at the 7 largest areas of erosion at Grant-Kohrs Ranch were investigated by comparing the amount of erosion with the vegetation removed from an area, the general vegetation around the erosion on the preceding and subsequent aerial photographs, and the vegetation at the apex of erosion for both the 1979 and 1983 (Table 26). Large amounts of erosion seem to occur whether the vegetation was classified as

shrubs, grass, or a mixture of the two. For example, the vegetation at the bend with the highest amount of erosion (Northbend, also seen in Figure 39) is dominated by shrubs with some grassy areas. At the erosion's widest point, it is removing mostly shrubs ("apex veg"). Grass dominates the vegetation at the next two highest erosion sites, but shrubs are the major form of vegetation cover in 4 out of the 7 major bends. This relationship seems to hold over most of the study reach. Maps of the percentage of woody vegetation along each bank segment reveal that erosion areas do not seem to favor one level of woody vegetation over another throughout the reach (Figure 16).

Figure 38. Erosion at vegetated banks (Northbend). Bank is being cut despite the relatively thick woody vegetation. Willows at the bank are dead or dying. Also, few woody roots emerge from the lower bank.

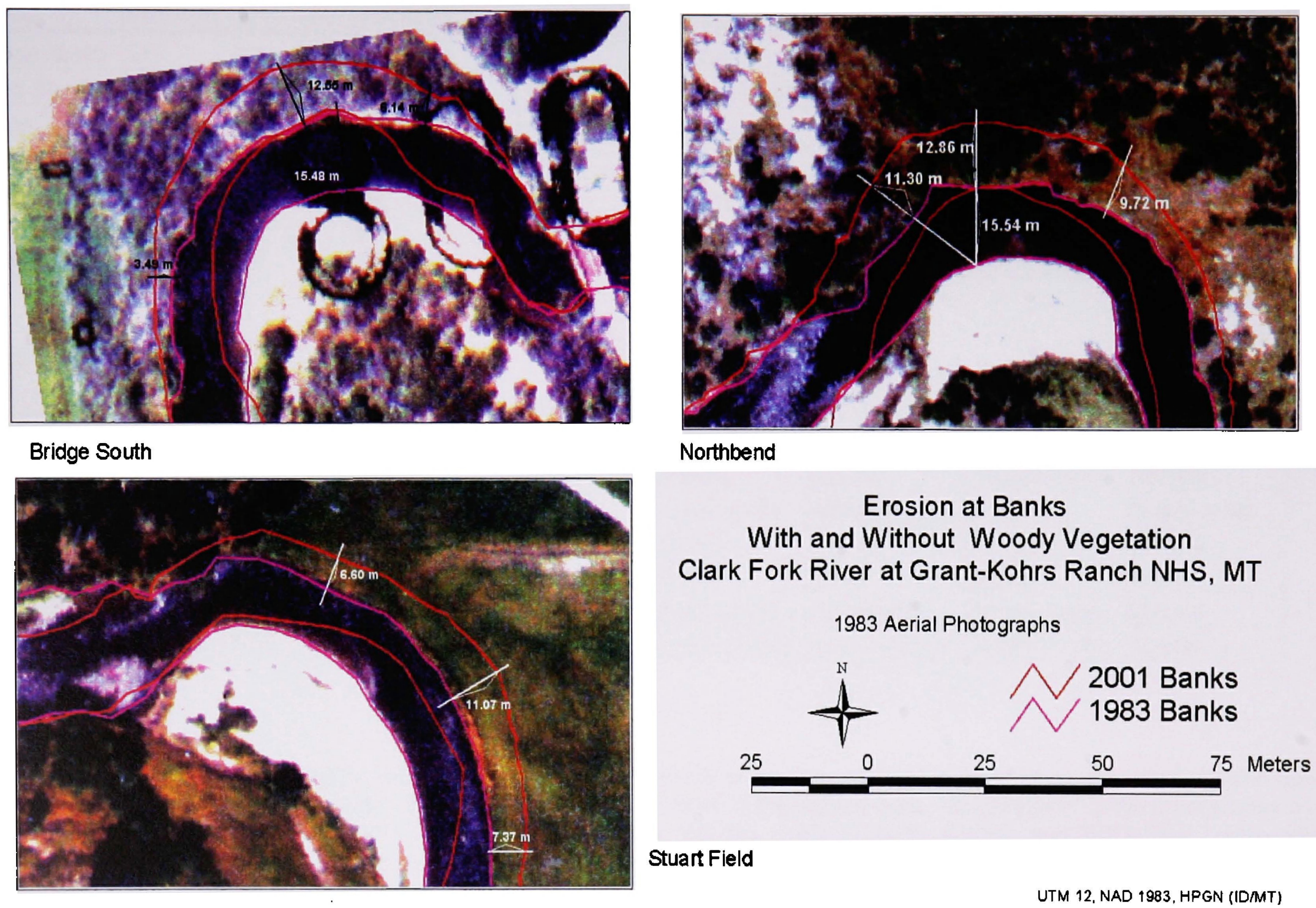


Figure 39. Erosion at banks with and without woody vegetation between 1983 and 2001. Stuart Field has little or no shrubs along its banks, whereas the other banks contain relatively thick shrubs. All three bends have similar amounts of erosion.

1979

BEND	*AREA(m^2)*	*WIDTH(m)*	*AVGWIDTH(m)*	*LENGTH(m)*	*60VEG*	*ERODED VEG*	*83VEG*	*APEX VEG*
Bridge North	717	12	7	100	shrubs	Shrubs	mixed-shrubs	Shrubs
West South	1098	14	9	122	mixed-shrubs	mixed-shrubs	mixed-shrubs	Shrubs
Stuart	1136	13	7	157	mixed-grass	Grass	grass	Grass
Bridge South	1325	17	8	159	Shrubs	Shrubs	shrubs	Shrubs
Double East	1442	23	15	99	Shrubs	mixed-grass	mixed-grass	mixed-grass
Tabs	1712	21	9	181	mixed-grass	mixed-grass	mixed-grass	Shrubs
Northbend	1742	27	13	138	Shrubs	mixed-shrubs	mixed-shrubs	Shrubs

1983

BEND	*AREA(m^2)*	*WIDTH(m)*	*AVGWIDTH(m)*	*LENGTH(m)*	*79VEG*	*ERODED VEG*	*94VEG*	*APEX VEG*
Bridge North	459	9	4	114	mixed-shrubs	mixed-shrubs	mixed-shrubs	Shrubs
West South	504	12	7	68	Shrubs	shrubs	mixed-shrubs	Shrubs
Stuart	755	13	6	121	mixed-grass	mixed-grass	grass	mixed-grass
Bridge South	898	12	7	138	Shrubs	shrubs	shrubs	Shrubs
Double East	951	11	6	158	Grass	grass	grass	Grass
Tabs	975	12	6	150	mixed-grass	mixed-grass	mixed-grass	Shrubs
Northbend	1159	13	8	153	mixed-shrubs	mixed-shrubs	mixed-shrubs	Shrubs

Table 26. Vegetation at the meander bends with the 7 highest amounts of erosion. "AREA" is the amount of eroded material between 1979 and 2001 (top) and 1983 and 2001 (bottom). "WIDTH" is the maximum width of the eroded area. "AVGWIDTH" is the eroded area divided by the centerline length of the area ("LENGTH"). The vegetation columns, "60VEG, ERODED VEG, 83VEG, and APEX VEG," correspond to the general vegetation on the previous air photo, the vegetation eroded between the previous and the current air photo, the general vegetation in the subsequent air photo, and the vegetation removed at the widest point of erosion, respectively.

Effect of Water Availability

Field observations and aerial photograph analyses reveal some major complications in relationships between the water, soil, and plants that, in turn, effect the vegetations ability to hold the banks in place. One of these complications is a change in distance from the floodplain to the water table. Floodplain water tables can fluctuate considerably over time due to a variety of natural and anthropogenic changes. Natural variability in stream flow and evapotranspiration can result in seasonal and yearly changes in alluvial water tables. Channel incision or bed aggradation may also cause groundwater levels to change. Finally, human activities such as groundwater pumping, flow diversions, dams, or in-stream mining may lead to declines in riparian water tables (Groeneveld and Griepentrog 1985, Rood, et al. 1995; Stromberg, et al 1996, Scott, et al 1999).

Willows require relatively shallow groundwater and are sensitive to drought associated with water table declines (Busch, et al. 1992; Smith, et al 1999; Scott, et al. 1999). If the declines continue, they can cause low productivity, death of leaves and fine roots, reduced stem elongation, and extreme morphological responses such as crown dieback and stand mortality (Rood, et al. 1995, Scott, et al. 1999). Scott, et al., (2000) suggests that "the integrity of riparian forests along arid region rivers with coarse alluvial floodplain soils can be threatened by physical processes and human activities that result in sustained ground water declines as small as 1 m."

Groeneveld and Griepentrog (1985) documented the link between groundwater extraction from the Carmel Valley aquifer and the decline of riparian vegetation along a two-mile section of the Carmel River, CA. The loss of root stability subsequently led to

severe bank erosion along the impacted reach (Kondolf and Curry 1986). Scott et al. (1999) observed high mortality of mature *Populus deltoides* (88%) following a groundwater decline of 1.1 m due to instream sand mining. Decreases in water table elevations of half that size reduced branch growth. A study done along an incised channel below the Alamo Dam, AZ, saw almost complete mortality of *Populus freemonti* and *Salix gooddingii* saplings following a groundwater decline of 1.1m (Shahfroth, et al. 2000). Finally, drops greater than 1m led to declines in tree vigor including visible branch die back (a common response in trees to water stress) along the flood-incised reach of the Mojave River (Scott, et al. 2000).

Matching shrubs during the aerial photography rectification process revealed changes in vegetation cover throughout the study site. In the 1983 and 1994 pictures, vegetation appears to be flourishing in some areas, whereas in other areas, shrub crowns appear to be dead or dying. However, the 1997 aerial photographs exhibit larger shrub canopies, more grass coverage, and more vegetation coverage in general. In 2001, shrubs revert to large areas of canopy dieback. In the 1997 photograph, Box A (Figure 40) shows the larger canopies and increased vegetation, especially at the riverbank and around the shrubs in the lower portion of the box, compared to the other years. Also, shrubs that appear to be flourishing in 1997 appear gray and leafless in the other photographs (Box B and the west side of Box C, Figure 40).

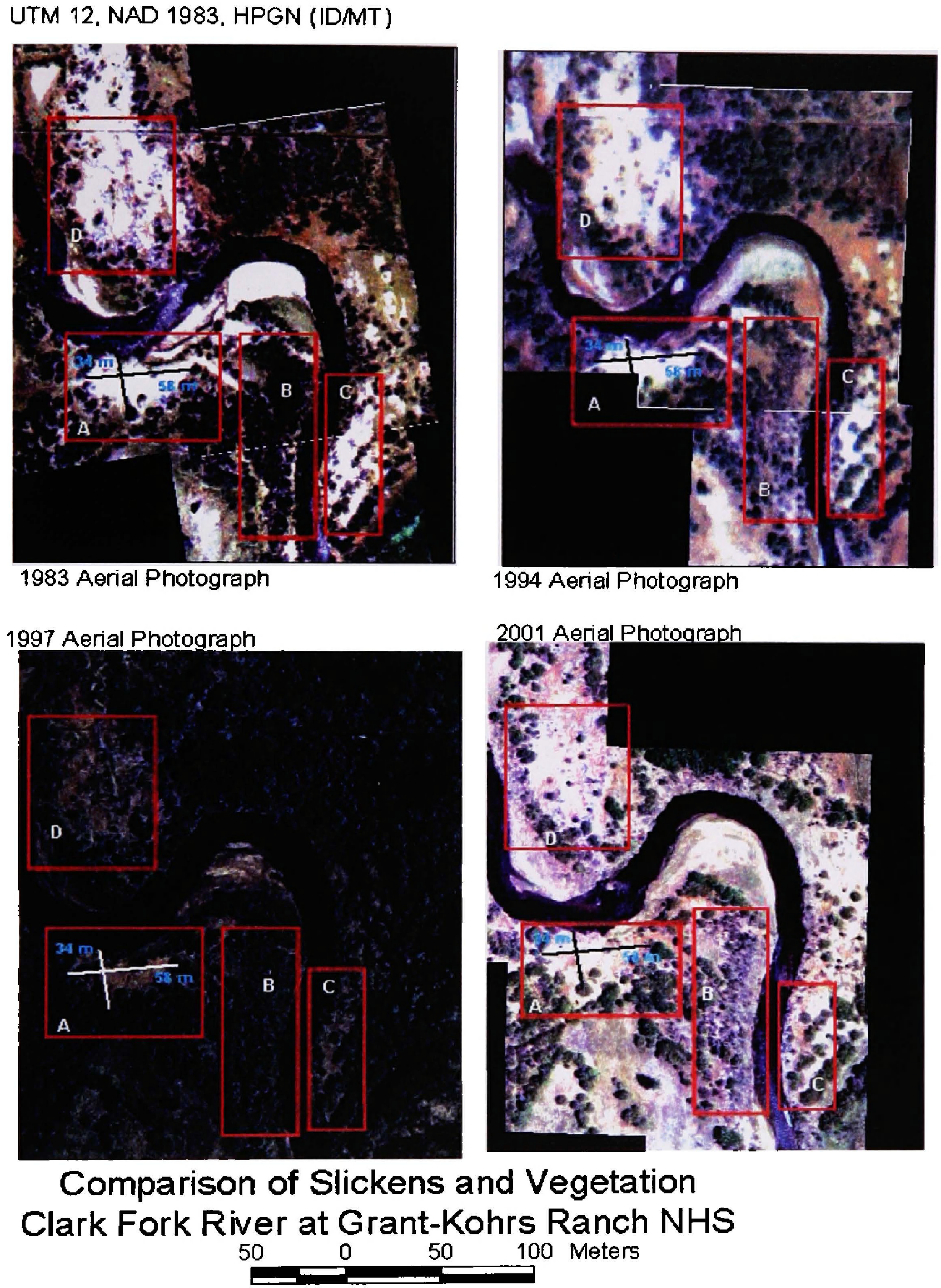
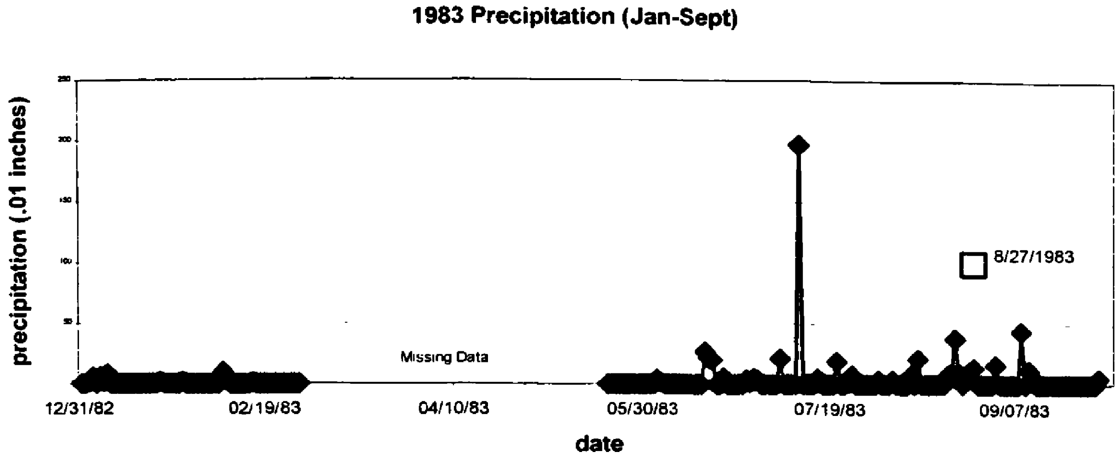


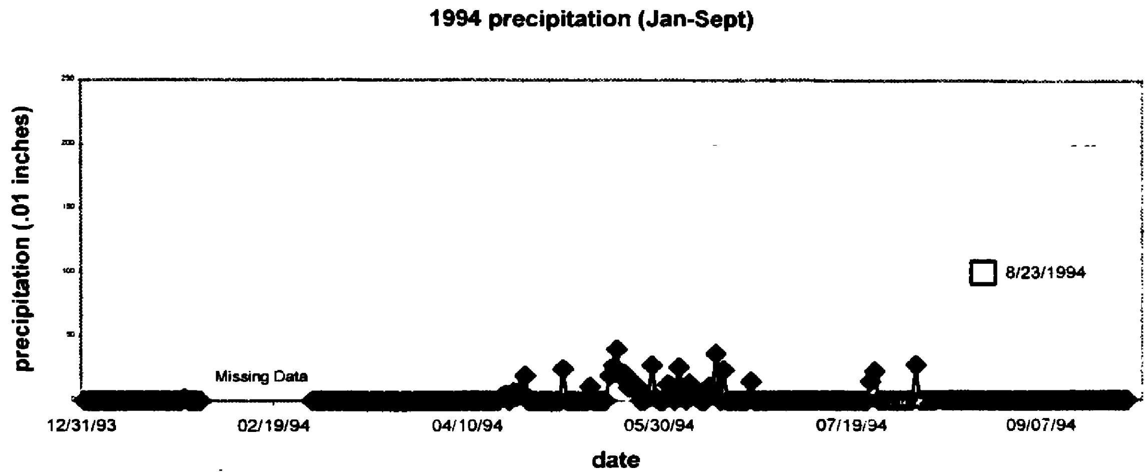
Figure 40. Comparison of vegetation coverage over time. Shrub coverage is sparse on the 1983, 1994, and 2001 aerial photographs. The 2001 photograph, however, exhibits fuller canopies and more grass.

Moisture levels seem to control these changes in plant vigor. From 2000-2001, Montana was suffering through a drought, and canopy dieback was occurring on many regional rivers (Hansen, personal communication). The 2001 photographs clearly show the effect of drier conditions at the study site, and field observations revealed large amounts of standing and fallen dead willow branches, indicating repeated periods of plant stress. The amount of precipitation (Figure 41) and discharge in the river (Figure 4 and Table 3) indicate that there was much more water available for vegetation during 1997, compared to the other photograph years.

The frequency of drought stress symptoms in the Clark Fork floodplain vegetation may be exacerbated by tailings deposition. Today's floodplain sits up to 80 cm above the pre-tailings floodplain as a result of this deposition. Assuming the same groundwater-surface water system, the increase should elicit the same vegetation responses as lowering the water table by an equal amount. The change in floodplain elevation relative to the water table increases the probability that, in dry years, vegetation will show signs of drought stress. This situation is a direct physical effect resulting from tailings deposition on the floodplain.

To further complicate the issue, the surface water and groundwater are strongly linked within the study reach (Woessner and Johnson 2001: Figure 42). Changes in river stage illicit an equal or similar response in the water table, so lower discharges result in lower water tables. Water removal from both sources greatly reduces the quantity and timing of water available in the upper soil layers for vegetation. Therefore, water diversions and groundwater pumping for irrigation, which remove large amounts of water from the system, can have a major effect on water table height. This situation is





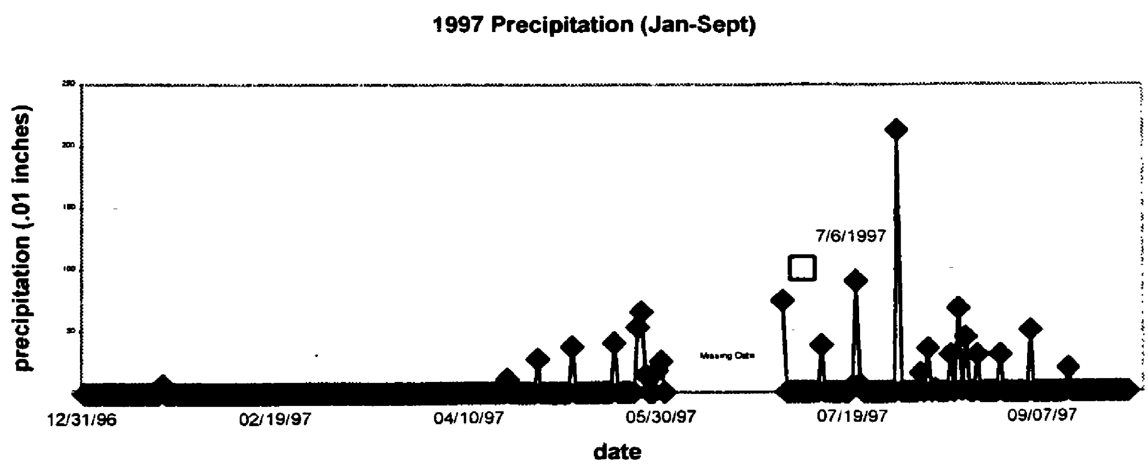


Figure 41. Precipitation at Deer Lodge in 1983, 1994, and 1997. Open boxes are the date the photographs were taken (no precipitation value).

especially true during dry years when instream flows are small and agricultural water demand is large. At one point during the 1999-2001 drought, the Kohrs-Manning Ditch passed an estimated 40-50 cfs of water, whereas the river was running at only 20 cfs (Moore and Brenuinger, personal communication). Another 40 cfs in the river may not amount to a big change in groundwater elevation, but when the amount of water being taken by other ditches and irrigation systems upstream is considered, it is obvious how these diversions exacerbate water scarcity along the river. In dry years, even the discharge peaks for the river are cut off by irrigation diversions (Figure 43). Discharges should increase throughout the spring months, when plant growth is highest, as snowmelt and precipitation accumulate. Instead of this increase, there is a short increase in discharge, followed by declining discharge as irrigation ditches are opened and pumps turned on. The increased stages are important for raising the groundwater table, wetting the upper soil layers, and keeping the floodplain wet for a longer period of time, but during low spring runoff, the diversions remove the peaks, and increase plant stress, for the entire year.

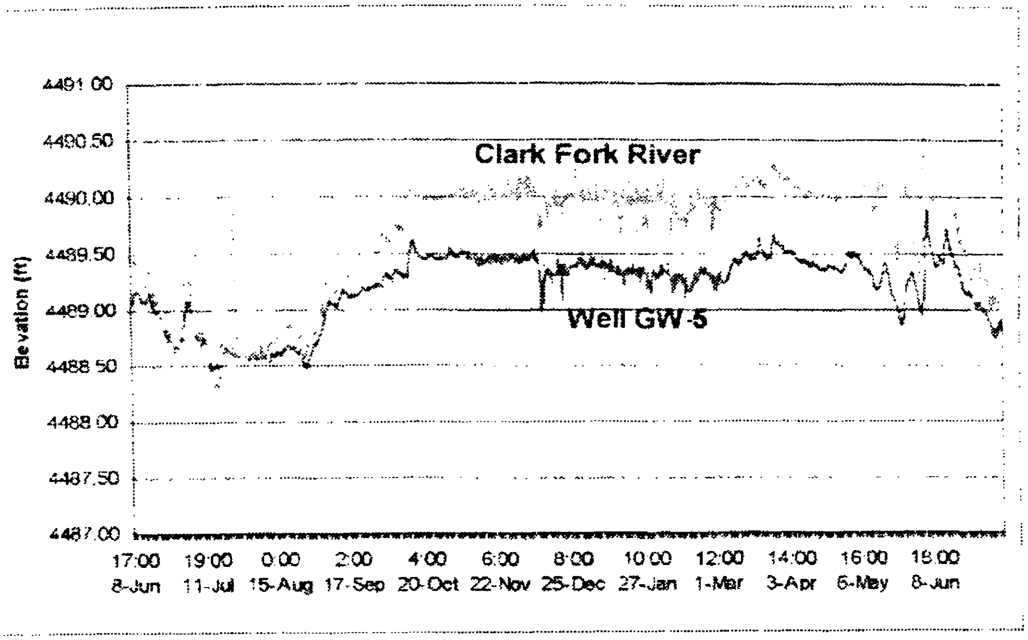


Figure 42. Relationship between water table and surface water levels at Grant Kohrs Ranch NHS (from Woessner and Johnson 2002). Changes in surface water elevation illicit similar responses in the water table.

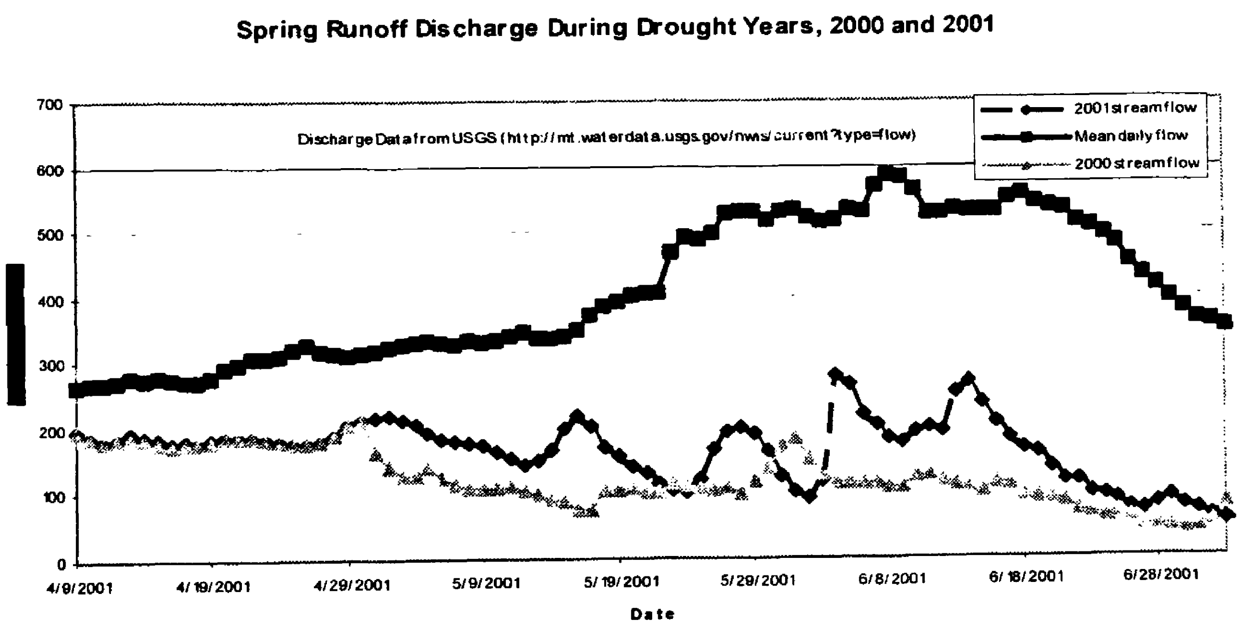


Figure 43. 2001 streamflow data showing lack of peak from late April through June attributed to water diversions. Discharge data from USGS gage station at Deer Lodge, MT (http://mt.waterdata.usgs.gov/nwis).

Metal Stress

Another problem related to increased erosion, drought stress, and tailings is a lack of deep penetrating roots. Metals in the floodplain soil stunt the root growth of the shrubs, therefore making the plants more reliant on precipitation for water, instead of soil water and groundwater, and less effective at holding the banks in place (Kaputska 2001). Toxicity of As, Cd, Cu, Pb, and Zn has been noted commonly in plants growing on mining and mineral processing wastes (Harris and Jurgunsen 1977; Alloway 1990; Lejeune, et al. 1996). Characteristic symptoms of As and metal toxicity include growth reduction, small leaves, necrotic, chloritic or otherwise discolored leaves, early leaf fall, stunted root growth, browning or death of the root meristem, and suppressed development of lateral roots (Lejeune, et al. 1996; Alloway 1990). Soil As and metal concentration above which toxicity have been reported as 20-50 ppm As, 3-8 ppm Cd, 60-125 Cu, 100-400 ppm Pb, and 70-400 ppm Zn (Alloway 1990).

Willows, including geyer willow, are often early colonizers of disturbed sites and have some tolerance to heavy metal-enriched soils (Pushon and Dickinson 1997; 1999; Fisher, et al. 2000). Combined with their ability to stabilize banks, this tolerance makes them ideal candidates for restoring metal contaminated systems. However, extremely elevated metal levels in soil and soil water do have phytotoxic effects on willows, especially high concentrations of Cu. While studying the effect of tailings' metals on the mycorrhizae of willows and poplars, Harris and Jurgensen (1977) noted that the root and top growth of trees in copper tailings (mean Cu 170 mg/kg, pH 7.7-8.1) were inhibited and mortality was common. Little or no mycorrhizae were found with the roots, therefore nutrient uptake was limited, and in turn, so was growth. In a similar study,

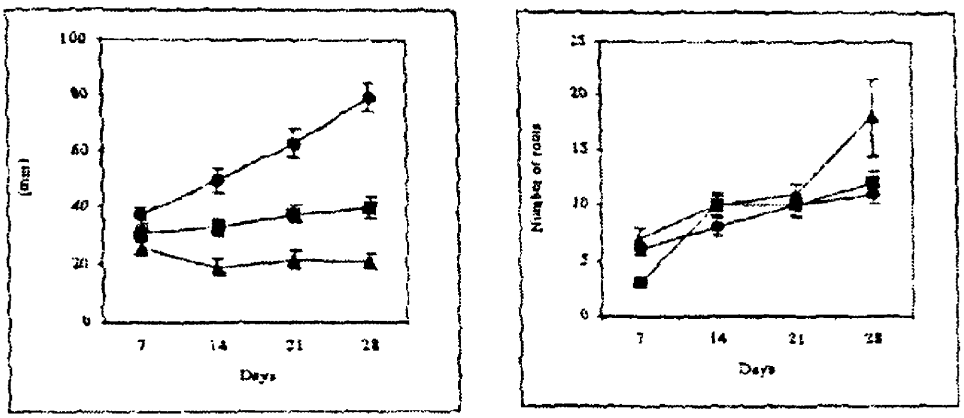
Trappe, et al. (1973) found restricted growth and rootlet development in apple trees growing in soils with high arsenic levels.

Fisher, et al. (2000), investigated the effects and depth of incorporation of soil amendments on geyer willow cuttings taken from Leadville, CO. Untreated tailings (mean Cu 414 mg/kg, pH 4.0) saw growth reductions of 85% compared to tailings treated with lime, and a third of the willows grown in the untreated tailings died (Fisher, et al. 2000)

Punshon and Dickinson (Punshon, et al. 1995; Punshon and Dickinson 1997; 1999) have probably done the most work on the effects of metals on willows. In their studies, various species of willows were exposed hydroponically to 0-0.75 ppm Cu. General trends exhibited from their research include decreases in average root length and root total as Cu concentrations increase. They also found that the number of adventitious roots (roots that grow horizontally along the soil surface) increases or stays the same (Figures 44 and 45). Copper concentrations of 1 ppm proved to be sublethal (chronic) to *Salix* plants (Punshon and Dickinson 1999). It should be noted, however, that a wide variability in growth response and mortality was seen both between and within willow species.

Although variable both aerially and with depth, metal concentrations within the upper Clark Fork Valley floodplain are often higher than the given values for phytotoxicity in the above studies. Average Cu values in floodplain sediments at the study site, as well as up and downstream, are around 2000 ppm, and maximum values can be an order of magnitude higher (Brooks 1988; Lejeune, et al. 1996; Moore and Woessner 2001). Mean As concentrations are around 400 ppm (Brooks 1988; Lejuene, et

al. 1992; Moore and Woessner 2001). Soil water within the floodplain, which can be compared to the hydroponic solutions administered in the Punshon studies, also has elevated levels of metals. As in soil water ranges from 0.005 to .225 ppm, and Cu ranges from 0.003 to 20 ppm (Brooks 1988; Woesnner and Johnson 2001).



Root elongation (mm) and adventitious root production of *Salix viminalis* in response to copper in solution over a 28-day period: ● = Control (background Cu levels); ■ = 0.25 mg Cu l^{-1}, ▲ = 0.50 mg Cu l^{-1}.

Figure 44. Relationship between roots and copper concentrations (from Punshon and Dickinson 1997).

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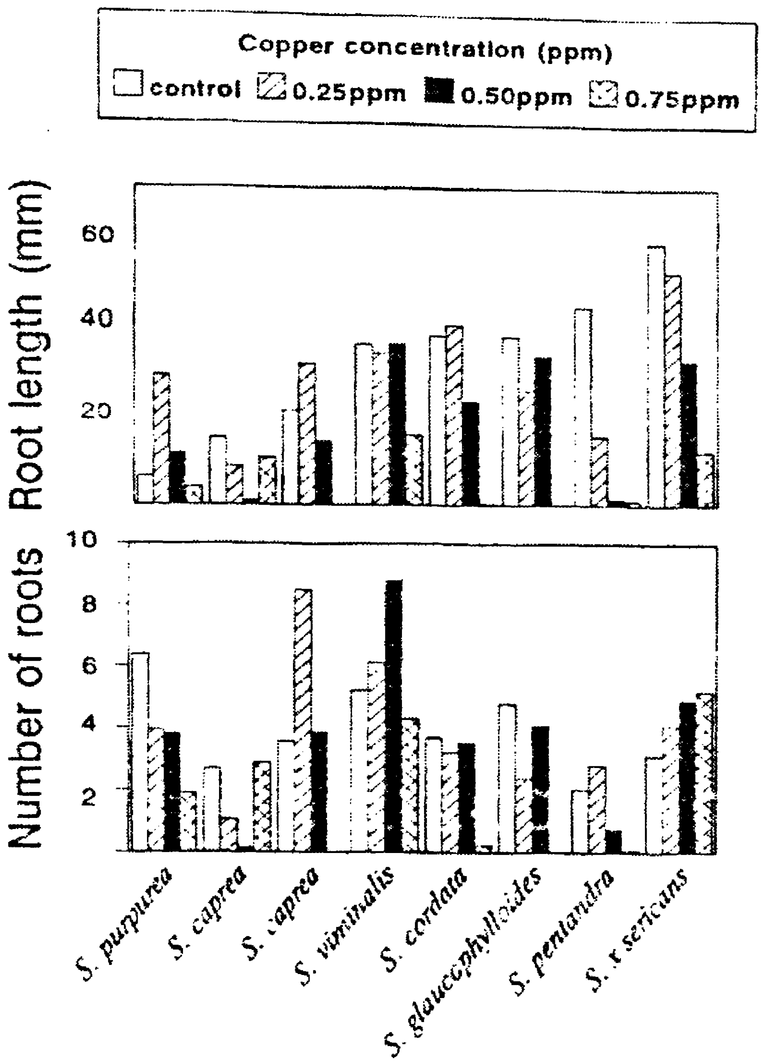

Figure 45. Relationship between roots and copper concentrations in various British willows (from Punshon, et al. 1995).

Phytotoxicity studies on the Clark Fork sediments suggest that metals affect root health and density. Standard phytotoxicity tests demonstrated that germination, shoot elongation, and root growth of alfalfa and lettuce seedlings were significantly inhibited in metals-impacted soil from the Clark Fork floodplain relative to control soils. Further work showed that poplars grown in Clark Fork tailings exhibited decreased survival, and

of the surviving plants, the mean shoot height, root length, and shoot and root mass of plants exposed to the impacted soil were significantly reduced (Lejeune, et al. 1996; Kaputska 2001).

Although there is no direct evidence for metal effects on the woody vegetation in the study site, field observations suggest that metals may be affecting the root structures and distributions in many of the same ways mentioned above (Kaputska 2001). The variability in heights, densities, and distribution of willows within the study site attests to the variability in metals resistance within the *Salix geyeriana* and *Salix elugia* species (Rice and Ray 1985), as well as the spatial variability of metal concentrations (Moore and Woessner 2001). However, some trends are still apparent. The most obvious signs that tailings material limit vegetation growth and productivity are the slickens areas. These areas are characterized by a relatively thick tailings layer lying at the surface, with little or no vegetation cover including grasses and weeds. Where woody vegetation can grow along the banks, it often consists of short willows and water birches, usually not more than a meter high. Directly along the banks, where roots are exposed and dessicated and metals can accumulate due to the wicking process described in Brooks and Moore (1989), the vegetation is often completely dead. Even in areas with relatively tall or dense vegetation, the tailings and lower bank layers are devoid of living roots which otherwise might hold the sediments in place. In many places along the banks the roots seem to be avoiding the tailings layers altogether by growing horizontally instead of vertically (Figure 39, 46, and 48).

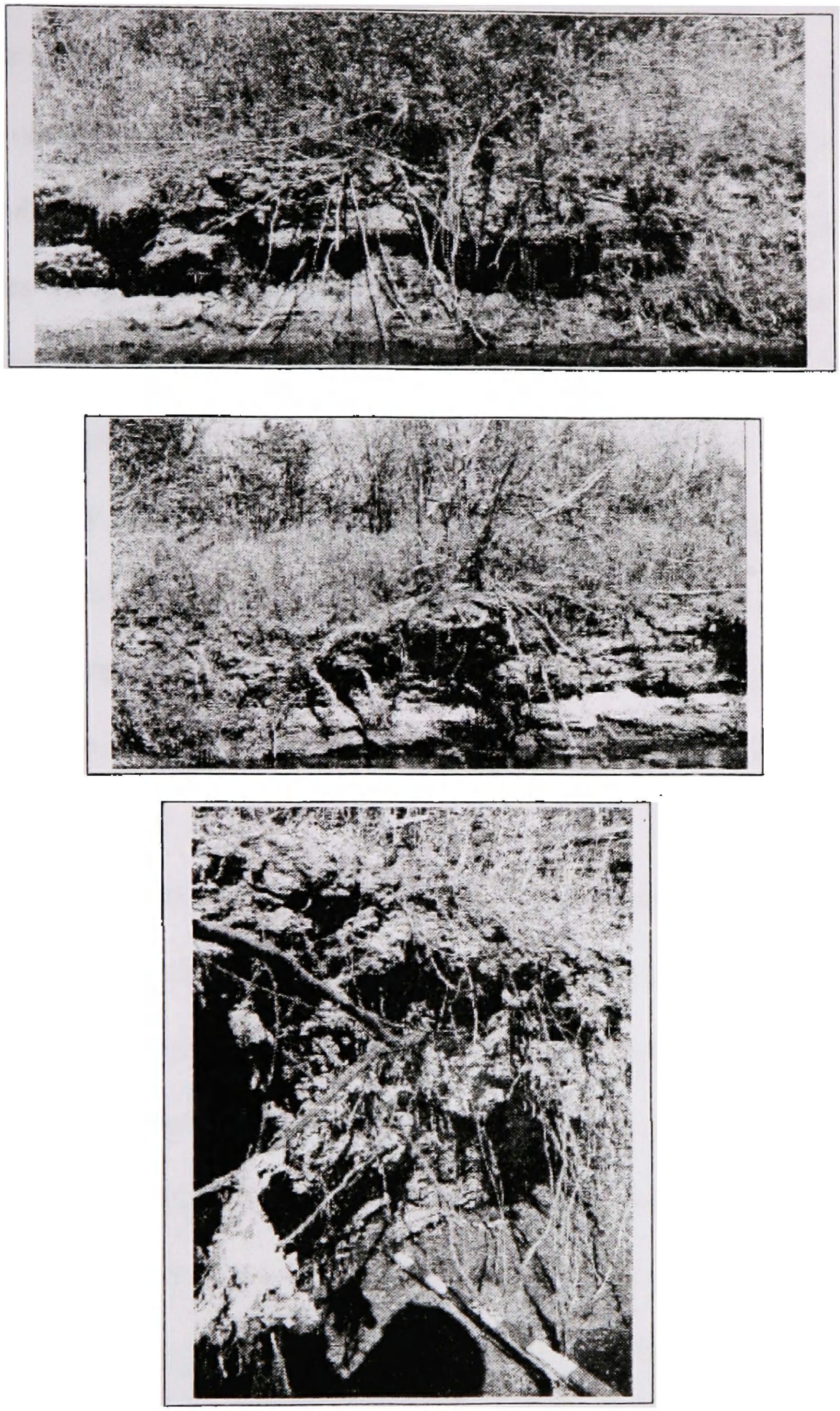

Figure 46. Example of root structure in the bank. Although difficult to see, the hanging roots emerge from the upper third of the bank, and little to no roots can be seen in the lower two-thirds.

Cohesion from root mass is highly variable along the bank, partly due to land use, but also due to the combination of water scarcity and metal stress. Erosion will occur where the cohesion is less, which in turn, could destabilize the entire bank taking the healthy shrubs with the unhealthy (Smith 2002). It seems clear that due to the water and metals issues using vegetation to stabilize the banks in this floodplain will be difficult, but the mechanism of erosion along the study reach (undercutting of the gravels) may be the most important factor on the shrubs' inability to stabilize the banks.

Separately, all three of the aforementioned problems could lead to increased bank erosion. More realistically, the combination of a "lowered" water table, and the presence of metals and composite banks results in the current inability of woody vegetation to hold the banks in place. Each issue can be related to the others, and probably exacerbates them as well.

Other investigations along the upper Clark Fork River have shown that woody vegetation decreases bank erosion, especially in the first 8 miles downstream of Warm Springs Ponds (Griffin and Smith 2001; Hansen, personal communication). Observation at sites just downstream from Warm Springs Ponds, and at one site within the Racetrack reach, reveal that vegetation is undeniably limiting the amount of bank erosion. In these locations, the vegetation is much taller and healthier than in the rest of the floodplain. More importantly, many of the shrubs are growing out of the base of the banks, which is enabling them to maintain the banks' stability (Figure 47). However, it is not clear how or why these shrubs exist in this condition. Differences in water table, soil texture and material, and historical landuse are just some of the factors that could allow for increased

shrub vigor in these locations. The lower bank position increases access to water, but the presence of salts along the bank and slickens adjacent to the willows indicate that there are also metals within the soil and soil water. The plants could also have established on banks that were stable to begin with. It seems likely that a feedback mechanism exists where a bank needs to be stable in order to support vegetation, and once established, the vegetation reinforces the bank stability. The woody vegetation growing in these places may be growing in banks that supported healthy shrubs prior to tailings deposition, and for whatever reason, they were not greatly affected by the change.

It also seems that many of the vegetated bends that do not exhibit erosion on the aerial photographs show some level of cutting when viewed in the field. The upper two maps in Figure 49 are of erosion at a bend in the Racetrack study reach. Reviews of sequential aerial photography, both in this study (left) and the 1997 R2 Resources, Inc. study (right), failed to find erosion at this bend. However, a field visit revealed that the bank at the outside of the meander bend is quite unstable (lower photographs, Figure 49). Woody vegetation at or near the banks is often unhealthy or dead, old roots and trunks are in the channel, and the banks are undercut and exposed along the whole bend, including numerous block failures. In a few places, willows and birches are part of shallow cantilevers that hang out from the bank by 0.8m. This situation was also found at other banks, farther upstream, that revealed no erosion in previous studies utilizing air photographs (R2 Resources, Inc. 1997; Dively 2001, unpublished data). This shows the limitations of only using aerial photographs to determine erosion sites.

Despite appearances, it is possible that this bank erosion is within the limit of detection on the photographs. There seem to be more roots along the bank to help keep

the soil in place, and the heavy vegetation and large overhangs may hide the amount being removed. If the banks actually are eroding as much as they appear, then the erosion could have happened after the 1997 photographs were taken. Considering the small amount of erosion that occurred between 1997 and 2001 at Grant Kohrs Ranch, this scenario seems unlikely, unless an ice flow or ice dam flood occurred in the reach during this time. Problems with the photographic rectification or alignment processes may also be at fault. These bends should be monitored after the next large discharge event, for even if they have not moved in the recent past, they seem to be relatively unstable now.

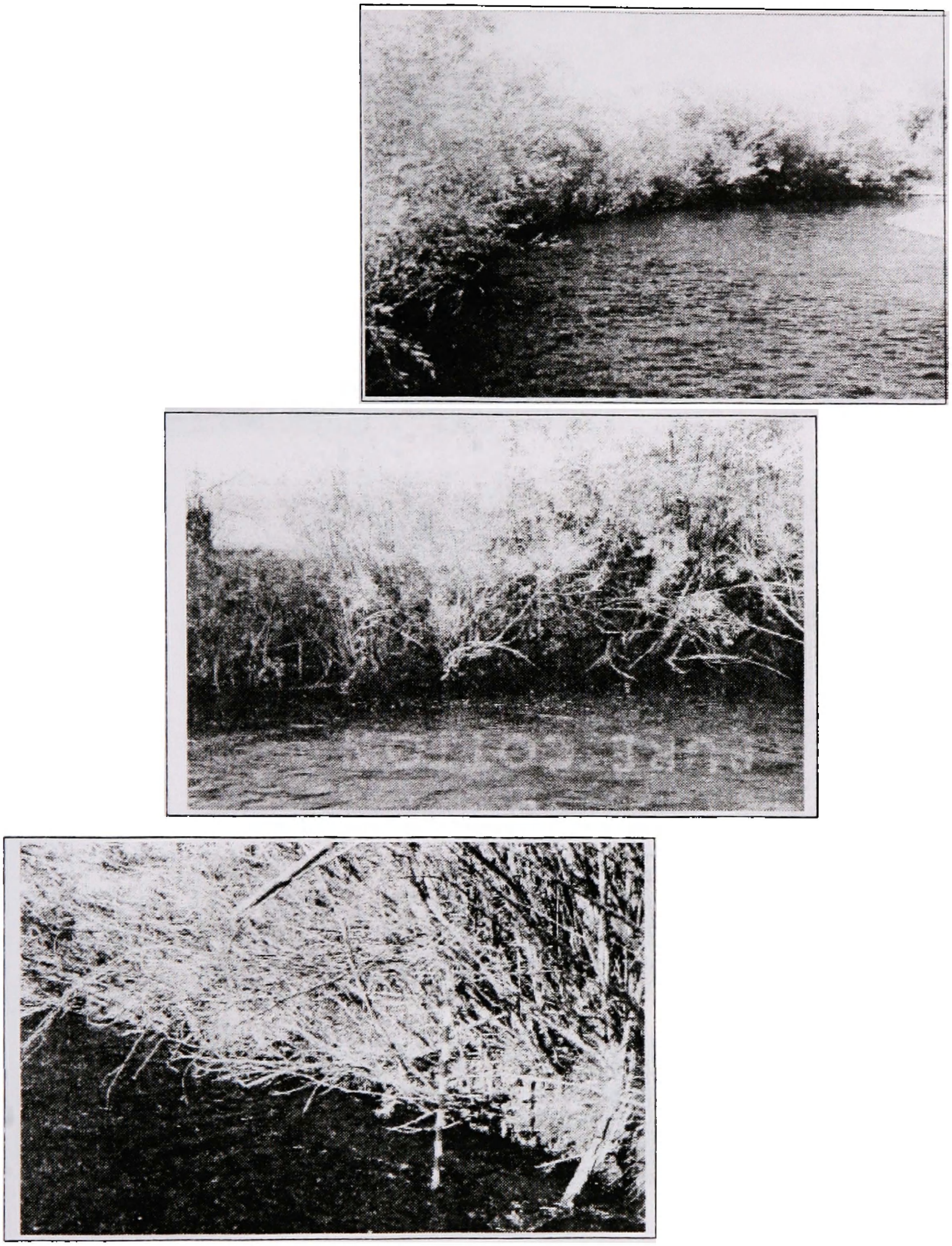

Figure 47. Examples of woody vegetation that limits bank erosion. Willows are taller and healthier. They also grow out of the lower half of the bank, near the river at medium flows. The top two photographs are taken just downstream from Warm Springs Ponds. The bottom picture was taken at a bend in the Racetrack reach (southern most point on the site map, Figure 48). The USGS streamgage at Galen, MT was at 80 cfs during the day these sites were visited.

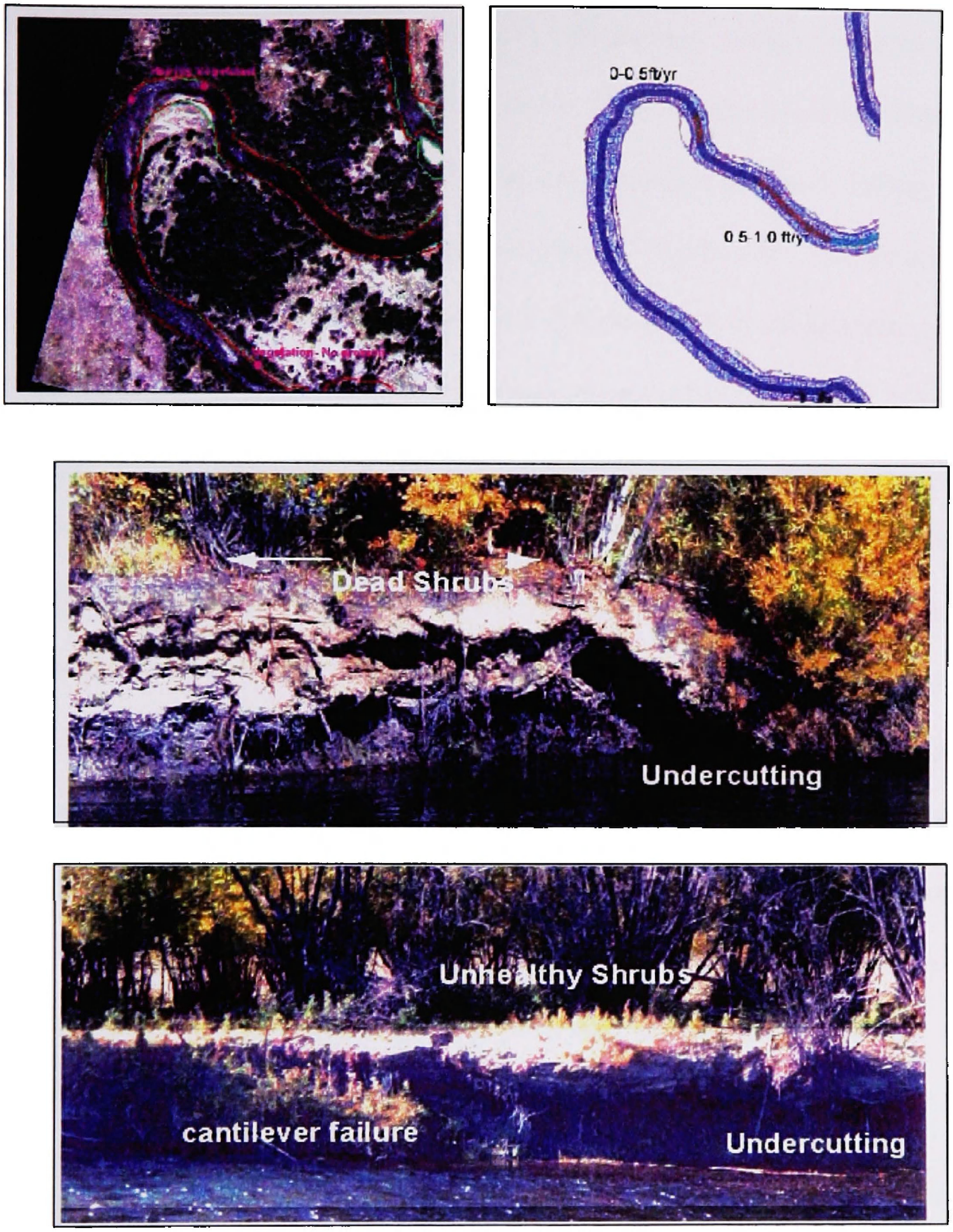

Figure 48. Erosion at bends that have undetectable erosion in the aerial photograph analysis. Upper two maps show that no erosion was detected at this bend in this study or in the one conducted by R2 Resources (1979). The lower two pictures were taken at the northern points on the study site map. They depict the bank conditions throughout the bend. Shrubs along the bank are unhealthy and being undercut, and overhanging banks are failing. The dark area over "undercutting" in the upper of the two bank photographs is a 0.8m gap between the overhanging shrub and the bank.

Slickens Dynamics

Besides being indicators of the phytotoxicity of the tailings' metals, slickens are also important to erosion and metals loading to the river. Salts composed of the metals can form on slicken surfaces, where they can subsequently dissolve in runoff during floods or large precipitation events and flow into the channel (Figure 49). This process makes slickens a direct contributor to metal loading to the river and the floodplain. However, they also have the potential to be indirect contributors through surface erosion. If water in the river exceeds flood stage, then the excess water will flow across the floodplain. Vegetation and other obstructions will slow down and direct the flow to areas with less resistance, which should include the barren slickens. If there is enough water and velocity gradients are high, the concentrated flow will erode through the unprotected slickens, which in turn creates a small channel which "attracts" more water, causing more incision. If this process continues, the new channel will be deep enough to undercut the floodplain vegetation, widen, and move even more contaminated material to the channel and other areas of the floodplain. Finally, because the eroded material is derived from the surface sediments, it will be comprised mostly of tailings material instead of the combination of tailings and pre-tailings material that erodes from the banks.

Figure 49. Example of a slicken. Lighter colored areas at the center of the photograph are salts that form on the surface. Short spikes above the salts are the remnants of willows.

Changes in slicken size and extent were investigated along with the changes in vegetation. It was difficult to quantify changes due to problems with image resolution, quality, color, et cetera, as well as the irregular shapes of the slickens and vegetation. However, slicken dynamics could be tracked on the aerial photographs. The 1947 photos were used to examine slickens changes over a long time period, but poor photograph quality made this task difficult. Lengths and widths of a few selected slickens were measured and compared to the same slickens on the 2001 photographs (Figure 50). Although the barren areas in Box A of the "Northbend" images and Box B of the "North

Bridge" images seem to slightly decrease in size, this is partly due to image resolution, and overall, there appears to be little significant change (Figure 50). Detectable differences are subtle, such as two new bushes on the east side of Box A in "Northbend" in 2001. Comparing the slickens at "Northbend" from 1983 to 2001 (Boxes A,C, and D in Figure 40) also reveals only slight alterations of the size, shape, and location of the slickens.

However, the slickens are not static. Barren areas and areas of stressed vegetation appear to change as they respond to disturbances. Perturbations, such as droughts, have similar effects on slickens extent as they do on general vegetation coverage. As with the shrubs, moisture levels seem to be a major control with the changes in slickens seen in Figures 40 and 50. In Boxes A, C, and D of the 1983 and 1994 pictures (Figure 40), there appears to be a mix of flourishing and senescent/dead vegetation around the slickens, and the slickens themselves appear to be the same basic size and shape. The 1997 aerial photographs exhibit larger shrub canopies and more grass coverage at and adjacent to the slickens. Finally, the 2001 coverage reverts back to large areas of senescent/dead vegetation with slightly larger slickens areas. Therefore, it seems that changes in climate (Figure 41), over both the short and long-term, can effect the slickens' size, and in turn, potentially influence the amount of metal loading.

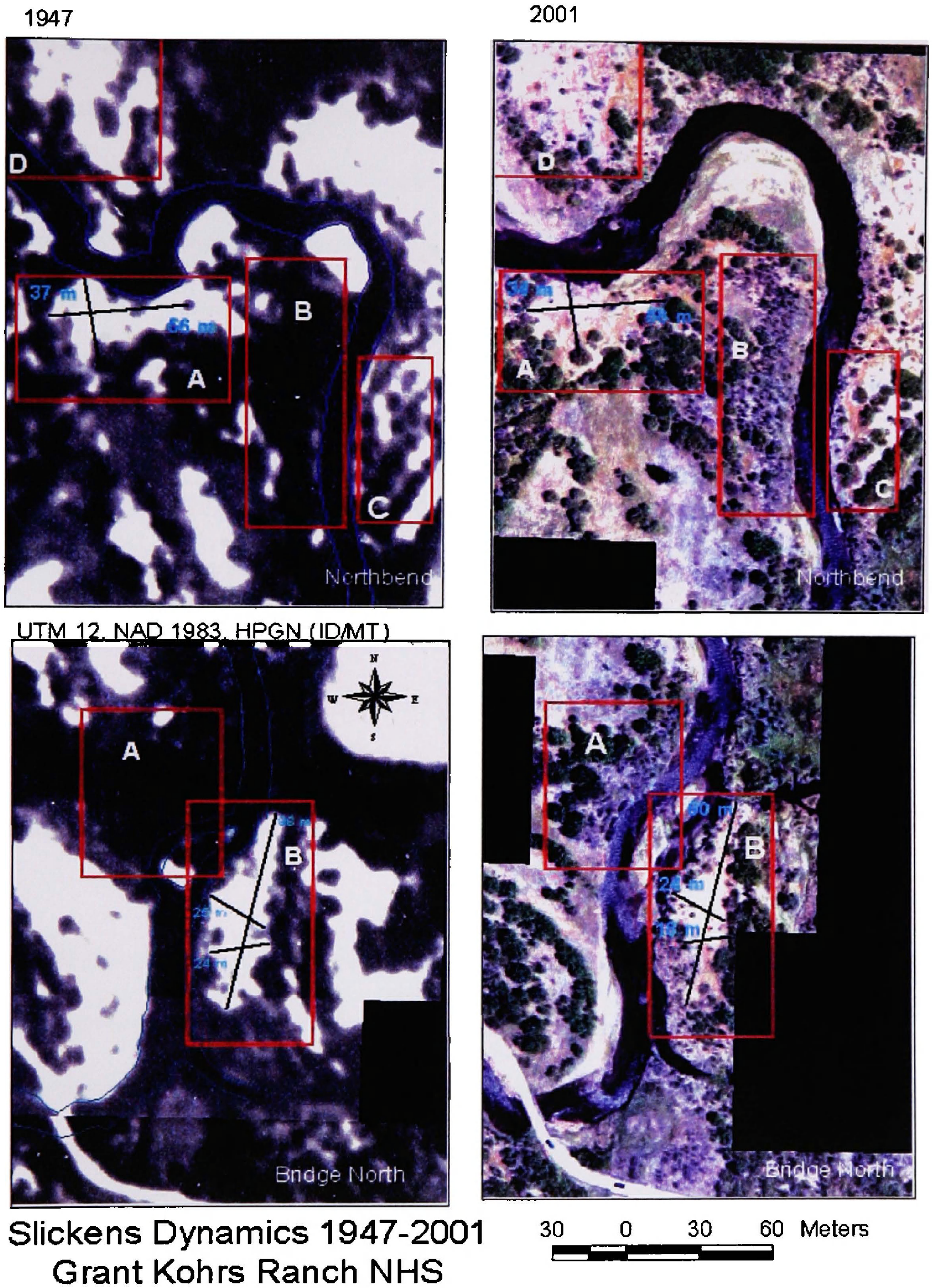

Figure 50. Changes in slickens extent and location from 1947-2001. 1947 photographs have poor resolution, but it appears that the size and shape of the slickens at both Northbend and Bridge North have not changed significantly over this period.

SUMMARY AND CONCLUSIONS

Responses to changes in sediment and water loads in a channel are often complex, and without good data on longitudinal profile, channel cross-section changes, or sediment deposition it is difficult to predict how the Clark Fork River has adjusted or will continue to adjust to changes in sediment and water discharges induced by mining and other land-use practices. Currently, the channel through the study reach is widening, increasing its sinuosity, and may be experiencing nickpoint migration. These adjustments indicate that the river is not in equilibrium, but it is not clear how far out of equilibrium it is, or what exactly it is responding to. For example, widening is a common response to an increased influence of bedload, which is often the result of elevated sediment loads (Miller 1997; Knighton 1998). However, increased bedload is usually accompanied by an increase in slope (Miller 1997; Knighton 1998), which is the opposite of what occurs at the study site. In addition, when comparing the erosion data in the upper Clark Fork River to other rivers, it seems that many of the observed changes are within the natural variability of most channels.

In the end, these changes may be due to the massive deposition that occurred in the floodplain during the mining period. Large changes seem to occur during higher flows. These flows probably regularly topped the banks under pre-tailings conditions, but now the flows are contained between higher banks. This "entrenchment" results in higher flow capacity, resulting in higher shear stress along the banks and the bed during large flows, which in turn, results in widening, more space for channel deposition, and increased sinuosity (Lecce 1997). Overall, the river may be cutting a new floodplain

capable of handling these high flows out of the current contaminated floodplain defined by the tailings terrace (Lecce 1997: Figure 51).

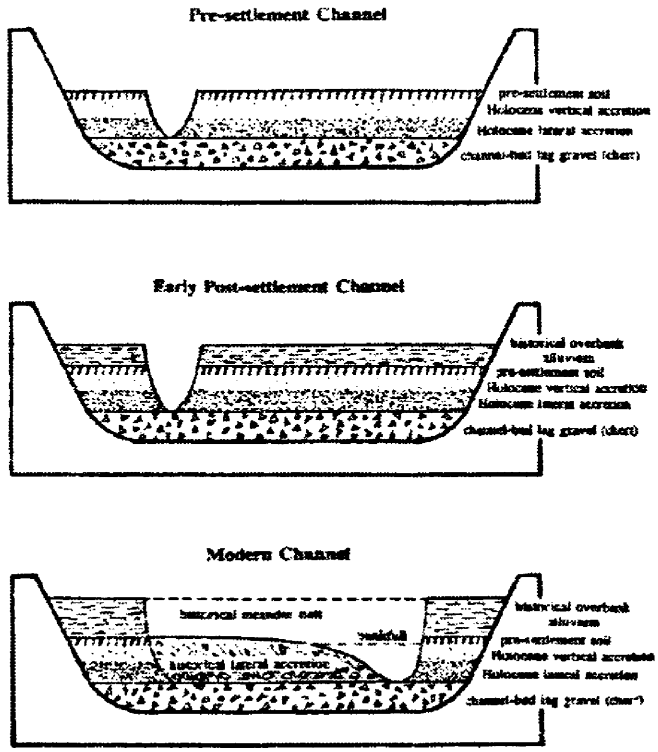

Figure 51. Establishment of a new floodplain within a floodplain affected by historical overbank deposition (from Lecce 1997).

Due to the presence of metal-contaminated floodplain soils, and their potential effects on human and environmental health, an effort is being made to restore the Clark Fork River floodplain within the Deer Lodge Valley. The main goal of this undertaking is to reduce the metal loading to the river by removing some exposed tailings (slickens), and stabilizing banks through treating soil with chemical amendments (lime) and planting woody vegetation. In addition, a 50-foot buffer zone is proposed on both sides of the river that will be managed using "Best Management Practices" (EPA 2002). The river,

however, is a dynamic system that may not conform to these recommendations. The extent of the tailings' impacts, and the complex relationships between vegetation, water availability, metals concentrations, and channel morphology could greatly impede any attempts at restoring a natural system along the upper Clark Fork River. Managing this system to minimize the effects of metal-contaminated floodplain soils requires that these relationships be taken into account.

Most rivers are dynamic. They continually erode banks, cut off bends, and cut new channels according to numerous hydrologic and climactic factors, especially the amount of water and sediment they are carrying. The Clark Fork River in the Deer Lodge Valley is no exception. The channel in the study reach is migrating significantly, with the outside of meanders eroding at approximately 0.5 m/yr. The net migration rate is 0.19 m^2/m of river/yr. However, these rates do not appear to be abnormal compared to other migrating rivers. In addition to altering the floodplain, bank erosion also provides a mechanism for metal loading to the river channel. Within Grant-Kohrs Ranch NHS, the river erodes approximately 740 m^2/yr, which amounts to several tons of excess arsenic, copper, and lead loaded to the channel per year as well.

Like most migrating channels, the location of eroding banks is controlled dominantly by the morphology of the river channel. The coincidence of riffles on meander bends is associated with the largest amount of bank erosion and cutbank formation. Unexpectedly, the presence of vegetation and excess metals along the banks in Grant-Kohrs Ranch seem to have little direct affect on the position and amount of erosion. Instead, cutbank formation appears to be a combination of undercutting of the bank by large flows, such as those in 1981 and 1997, and some shallow slumping along

less cohesive bank faces. The unconsolidated/non-cohesive gravel and pre-tailings deposits at the base of these banks are easily eroded at these high flows, leaving cantilevered banks that can cave into the river channel either during or after the flood event. In addition to the mechanisms of erosion, a lack of deep-penetrating roots in the lower bank layers also contributes to bank instability. The deposition of tailings on the floodplain has elevated the floodplain surface, increasing the distance to groundwater, and exacerbating the effects from metal loading and low streamflow, thus preventing vegetation from reaching moisture and stabilizing the lower levels of the banks.

Vegetation cover and slicken size appear to be mostly controlled by water availability (streamflow and precipitation). The major dimension of slickens were relatively stable over the time interval studied (1947-2001). However, vegetation cover definitely changes over time in response to wetter or dryer conditions. During dry years, woody vegetation is senescent/dead in many areas of the floodplain, but grows again during wet years. Many areas that are bare slickens in the dry years appear to be covered with grass when moisture increases. These observations show that the overall dimensions of the slickens are fairly static, but their vegetation characteristics and margin positions change due to short-term differences in climate. These responses suggest that slickens have the potential to grow or shrink substantially due to forcing by climatic conditions.

The main obstacle to re-establishing deep-rooted woody vegetation in the floodplain, and especially along the banks, is maintaining their health. Unfortunately, barring total removal of the contaminated soil and reconstructing the floodplain, countering the effects of the metals on the growth of shrubs will be difficult. Adding

lime amendments to the soil may locally diminish the bioavailability of metals, but liming the whole floodplain to the full depth of contamination is an unlikely scenario. The current recommendations call for a limit to the depth of lime emplacement and tailings removal (EPA 2002). Unfortunately, in many reaches of the river the pre-tailings soil layers, which will not be treated, are highly contaminated with metals as well (Moore and Woessner 2001).

Besides metal contamination, restoration planners also need to consider water availability. Willows will have a higher rate of survival if planted during a period of wet years (Moynahan 1999). More importantly, it seems a few dry years, even after establishment, may decrease shrub vigor or even kill newly planted shrubs. To increase the viability of new plantings or established vegetation, managing stream flow is essential. This likely will require integrated water management throughout, including establishing instream flow criteria, to keep both the river and the groundwater levels elevated. Unfortunately, increasing the amount of water in the channel also exposes bank plantings to a higher risk of removal due to bank erosion. However, it seems that significant erosion occurs only during relatively large peak flows. The increase in water during low flow periods probably will not be enough to cause increased erosion. On the other hand, during the larger peaks, the flows should be above the required instream flow. The amount of water during these peak discharges will probably dampen the effects of any water kept in the channel as part of a management scheme.

As far as stabilizing banks, the effectiveness of woody vegetation not only depends on maintaining plant health, but also the location in which they are planted. Most of the vegetation that currently holds the banks together along the river grows from

the base of the bank and on newly deposited bars, not the top of the tailings terrace. Therefore, willows and birches planted for the expressed purpose of bank stabilization should be added to the lower bank. They also should be "punched" through any contaminated floodplain soils and as close to, if not in, the basal sands and gravels. In addition, the lower bank position increases the access to the water table. However, this placement also leaves them vulnerable to high flows and erosion, and if the bank is unstable to begin with, it seems probable that the shrubs will be lost. Therefore, some degree of bank stabilization (coir, bank toe protection, etc.) should be implemented at most of these sites, at least until the vegetation is well rooted.

The use of vegetation and other "soft" approaches will probably not provide much long term stability along much of the upper Clark Fork River. Other, more traditional or creative approaches, should be implemented at sites where willows and birches will not, or do not, keep the banks in place. The river is currently adjusting its width and slope to its present water and sediment conditions. Keeping water levels up and controlling the slope with low head dams and/or drop structures at some of the present riffle locations may slow the adjustments as much as, or more than, vegetative bank protection. Increased water levels behind these structures would also benefit floodplain vegetation, new and old, by increasing groundwater levels.

Due to the erosion mechanisms, effects of water availability and metals, and the variability in geochemistry, geochemical processes, stratigraphy, morphology, and water (groundwater and surface water) throughout the Deer Lodge Valley, it seems that eliminating bank erosion along the entire floodplain will be difficult at best. The river is going to continue to migrate. Unfortunately, even if some level of erosion control is

reached, it will still result in large amounts of metal loading. For example, reducing the current rate by 75% still results in approximately 2 metric tons of excess Arsenic, .02 metric tons of excess Cadmium, 13 metric tons of excess Copper, 2 metric tons of excess Lead, and 7 metric tons of excess Zinc being eroded into the river in the Deer Lodge Valley per year.

If the river continues to move, then the whole floodplain continues to be at risk, not just the 50-foot portion currently lying along either riverbank. Meander migration will leave some areas of the buffer less prone to erosion, whereas other locations, not included in the present buffer, may be left exposed. In addition, the narrow buffer also leaves areas of the floodplain vulnerable to surface erosion during high water events. The distribution of tailings deposits shows that floods can spread through the floodplain much further than 50 feet. Also, although avulsions are extremely rare in the upper reach of the Clark Fork River, the one that occurred at Grant-Kohrs Ranch between 1868 and 1914, moved the channel around 200 m to the west. For these reasons, it is critical that the entire meander belt be protected and managed. To insure long-term river and floodplain health, stakeholders need to embrace this broader management concept, which may include accepting limits on agriculture, grazing, and water use.

If reducing the metal loading to the river is the overall goal, then the current level of bank erosion must be diminished. Metal loading and erosion limits should be set, and measures should be taken to reach them. However, the upper Clark Fork River and its floodplain are dynamic and extremely variable systems. Management and restoration plans for the floodplain must recognize this dynamism and adapt these plans to the various physical and biological processes that affect it.

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Appendices

Appendix A: RMS Error
Appendix B: Bend Locations
Appendix C: Bank Segment Data
Appendix E: Erosion Error

Appendix A

Root Mean Square Error Data for Floodplain Mosaics

Larger images of entire aerial photographs were "clipped" into smaller pieces centered on the river, and then the smaller images were referenced to the 1997 photo. Most of the obvious fixed points (fences, buildings, etc.) were cut from the smaller images or were difficult to see, so each image was georeferenced by matching the centers of approximately 30 shrubs or trees per image. The Root Mean Square (RMS) error returned after linking the shrubs is for the pixel (error is 1.62 pixels). To get the error in distance units, the RMS error was multiplied by the pixel size in the image. The final error for a mosaic was obtained by averaging the RMS error for each image used in constructing the mosaic.

Appendix A:
Root Mean Square Error Data for Floodplain Mosaics

image		*tot rms*	*pixel size*	*error (m)*
2001-1		1.62	0.13	0.21
	2	2.31	0.13	0.30
	3	1.41	0.13	0.18
	4	2.04	0.13	0.27
	5	1.70	0.13	0.22
	6	1.92	0.13	0.25
	7	1.68	0.13	0.22
	8	1.97	0.13	0.26
	9	1.57	0.13	0.20
	10	1.72	0.13	0.22
	11	1.87	0.13	0.24
	12	2.11	0.13	0.27
	13	2.18	0.13	0.28
	14	1.66	0.13	0.22
average		1.84	0.13	0.24
1994-1		0.93	0.57	0.53
	2	0.76	0.57	0.44
	3	0.69	0.57	0.39
	4	0.76	0.57	0.44
	5	0.71	0.57	0.41
	6	0.67	0.57	0.38
	7	0.68	0.57	0.39
	8	0.82	0.57	0.47
	9	0.64	0.57	0.36
	10	0.63	0.57	0.36
	11	0.84	0.57	0.48
	12	0.83	0.57	0.47
average		0.75	0.57	0.43
1983-1		1.00	0.36	0.36
	2	1.00	0.36	0.36
	3	0.95	0.36	0.34
	4	1.09	0.36	0.39
	5	1.26	0.36	0.45
	6	1.02	0.36	0.37
	7	1.07	0.36	0.38
	8	1.51	0.36	0.54
	9	1.19	0.36	0.43
	10	1.03	0.36	0.37
	11	0.95	0.36	0.34
	12	0.90	0.36	0.32
	13	1.17	0.36	0.42
	14	0.96	0.36	0.35
average		1.08	0.36	0.39

image		*tot rms*	*pixel size*	*error (m)*
1979-1		0.60	0.69	0.41
	2	0.73	0.69	0.51
	3	0.54	0.69	0.37
	4	0.61	0.69	0.42
	5	0.57	0.69	0.39
	6	0.51	0.69	0.35
	7	0.62	0.69	0.42
	8	0.48	0.69	0.33
	9	0.90	0.69	0.62
	10	0.67	0.69	0.46
	11	0.70	0.69	0.48
	12	0.70	0.69	0.48
	13	0.71	0.69	0.49
	14	0.71	0.69	0.49
average		0.64	0.69	0.44
1960-1		0.64	0.97	0.62
	2	0.52	0.97	0.51
	3	0.88	0.97	0.86
	4	0.39	0.97	0.38
	5	0.69	0.97	0.67
	6	0.57	0.97	0.55
	7	0.54	0.97	0.52
	8	0.75	0.97	0.73
	9	0.48	0.97	0.46
	10	0.52	0.97	0.50
	11	0.56	0.97	0.54
average		0.59	0.97	0.58
1947-1		1.59	0.35	0.56
	2	1.31	0.35	0.46
	3	1.22	0.35	0.43
	4	1.19	0.35	0.42
	5	1.29	0.35	0.45
	6	1.15	0.35	0.40
	7	1.12	0.35	0.39
	8	0.87	0.35	0.30
	9	1.12	0.35	0.39
	10	1.44	0.35	0.50
	11	1.33	0.35	0.47
average		1.24	0.35	0.43

image		*tot rms*	*pixel size*	*error (m)*
Garrison-1		0.86	0.39	0.34
	2	0.84	0.39	0.33
	3	0.91	0.39	0.36
	4	0.73	0.39	0.29
	5	0.67	0.39	0.26
average		0.80	0.39	0.31
Racetrack(140)-1		0.70	0.36	0.25
	2	0.76	0.36	0.27
	3	0.82	0.36	0.30
	4	0.88	0.36	0.32
	5	0.89	0.36	0.32
	6	0.91	0.36	0.33
average		0.83	0.36	0.30
Racetrack(142)-1		0.85	0.36	0.30
	2	0.86	0.36	0.31
	3	0.73	0.36	0.26
	4	0.80	0.36	0.29
	5	0.59	0.36	0.21
	6	0.77	0.36	0.28
	7	0.80	0.36	0.29
	8	0.70	0.36	0.25
	9	0.88	0 36	0.32
average		0.78	0.36	0.28

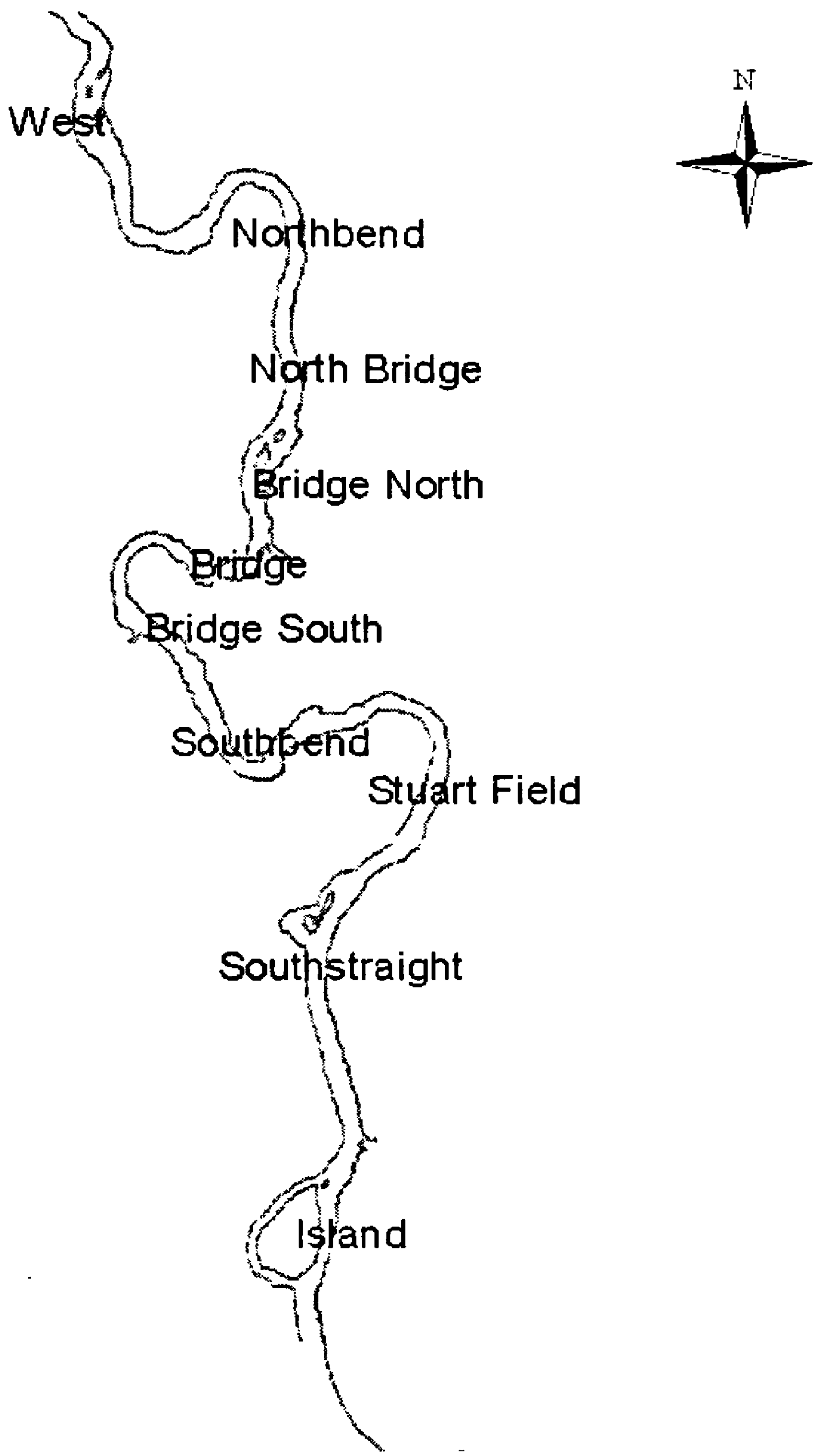
OVERALL TOTALS

average	0.39 meters
max	0.86 meters
min	0.18 meters

Appendix B

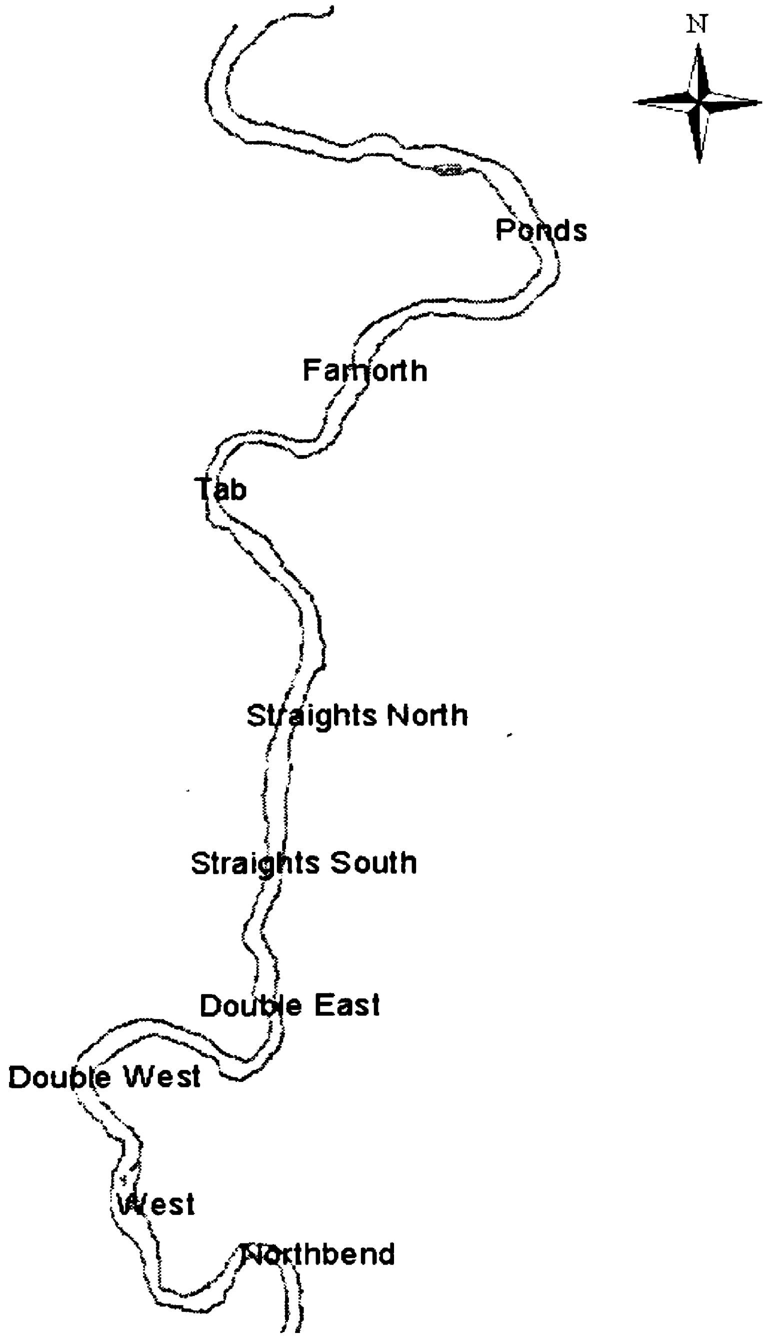
Bend Locations, Grant Kohrs Ranch NHS

Appendix B: Bend Locations, Grant Kohrs Ranch NHS



Appendix B.1. Bend Locations, Grant Kohrs Ranch NHS. South of bridge.

Appendix B: Bend Locations, Grant Kohrs Ranch NHS



Appendix B.2. Bend Locations, Grant Kohrs Ranch NHS. North of bridge.

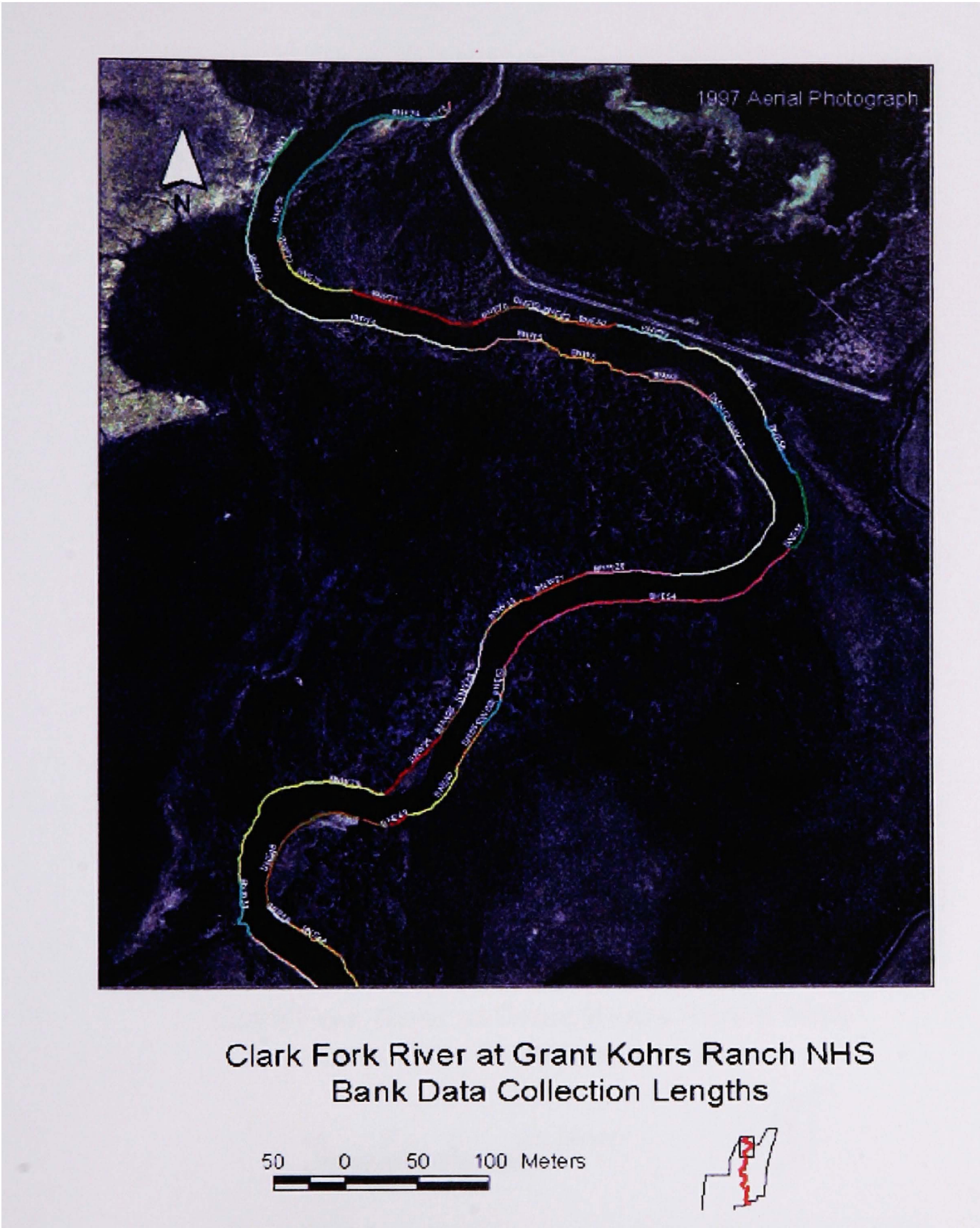
Appendix C

Survey Bank Segment Data, Grant Kohrs Ranch NHS

Riverbanks were mapped with a Trimble Pathfinder Global Positioning System (GPS) with a resolution of +/- 1 meter. While carrying the GPS, the researcher walked the top of the banks as close to the edge as possible (within about 0.5 m). The final GPS readings for the west banks were consistently offset around 4 meters from the banks on the georeferenced 1997 Environmental Protection Agency (EPA) aerial photographs, and were later corrected to the 2001 aerial photographs taken specifically for this study (Map, Inc., 1613 South Ave. West, Missoula, MT).

For each segment, bank shape, percentages of slumping, overhanging, and woody vegetation cover within 2 meters of the bank were visually estimated. Measurements of undercutting depth and tailings thickness were made with a Jacob's staff divided into 10 cm intervals, and the averages over the bank segment were noted. Types of vegetation (shrubs, grass, forbs, etc.), evidence of tailings (salts, adjacent slickens, senescent/dead vegetation), and other attributes of each bank segment were also noted. Although ocular surveys are inherently difficult to reproduce, data was gathered and mapped primarily for reconnaissance and to generally estimate the magnitude of slumping and the amount of shrubs along the banks. Methods were borrowed from the RWRP (Hansen, et al 1998) and the USGS (1998), and mapping and visual estimates were made by the same investigator (Benjamin Swanson) to minimize the variability introduced by using different observers. The estimated error is listed in Table 5.

Appendix C: Survey Bank Segment Data, Grant Kohrs Ranch NHS

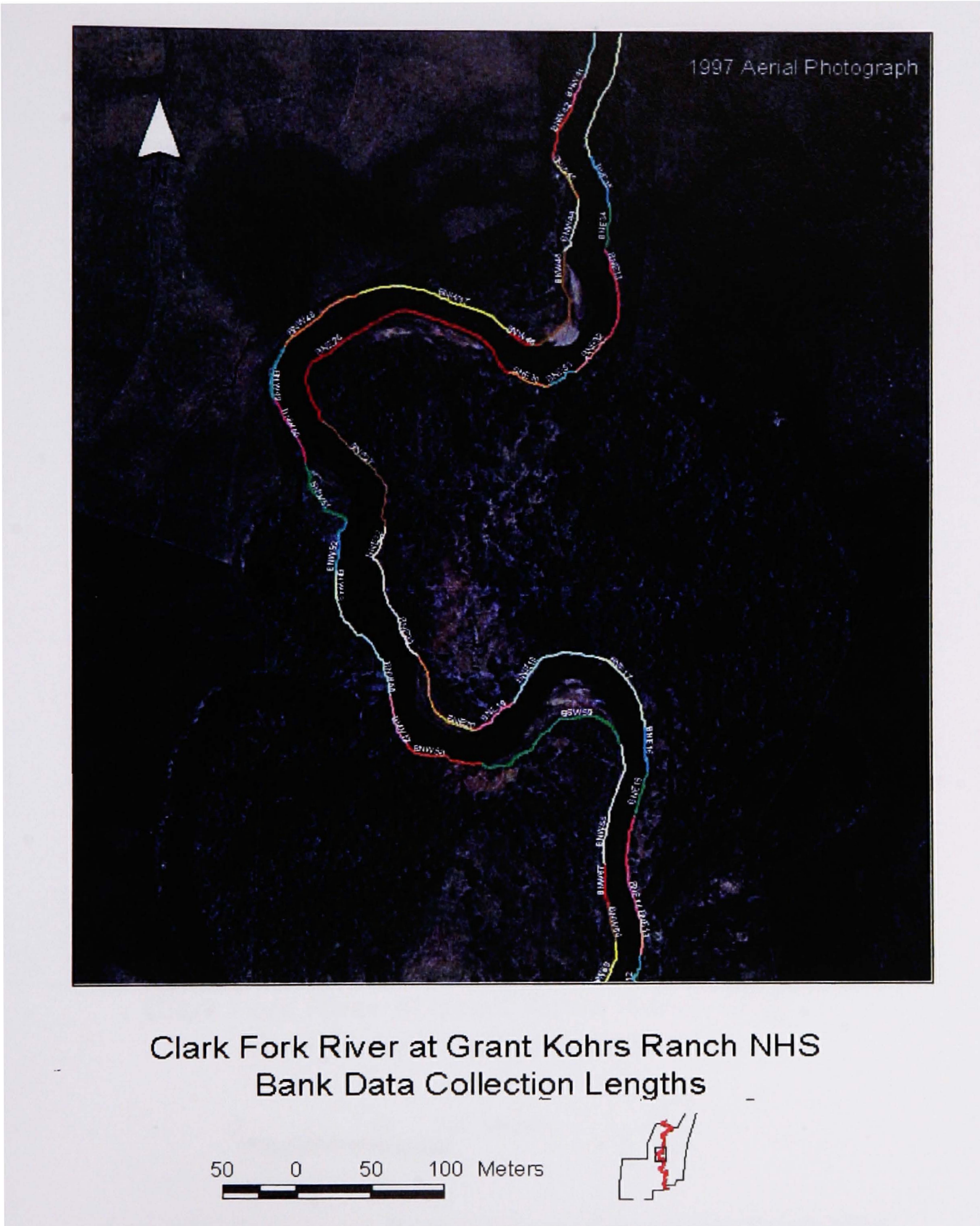


Appendix C.1- Survey Bank Segments, Grant Kohrs Ranch NHS.

Appendix C: Survey Bank Segment Data, Grant Kohrs Ranch NHS

Appendix C.2- Survey Bank Segments, Grant Kohrs Ranch NHS.

Appendix C: Survey Bank Segment Data, Grant Kohrs Ranch NHS

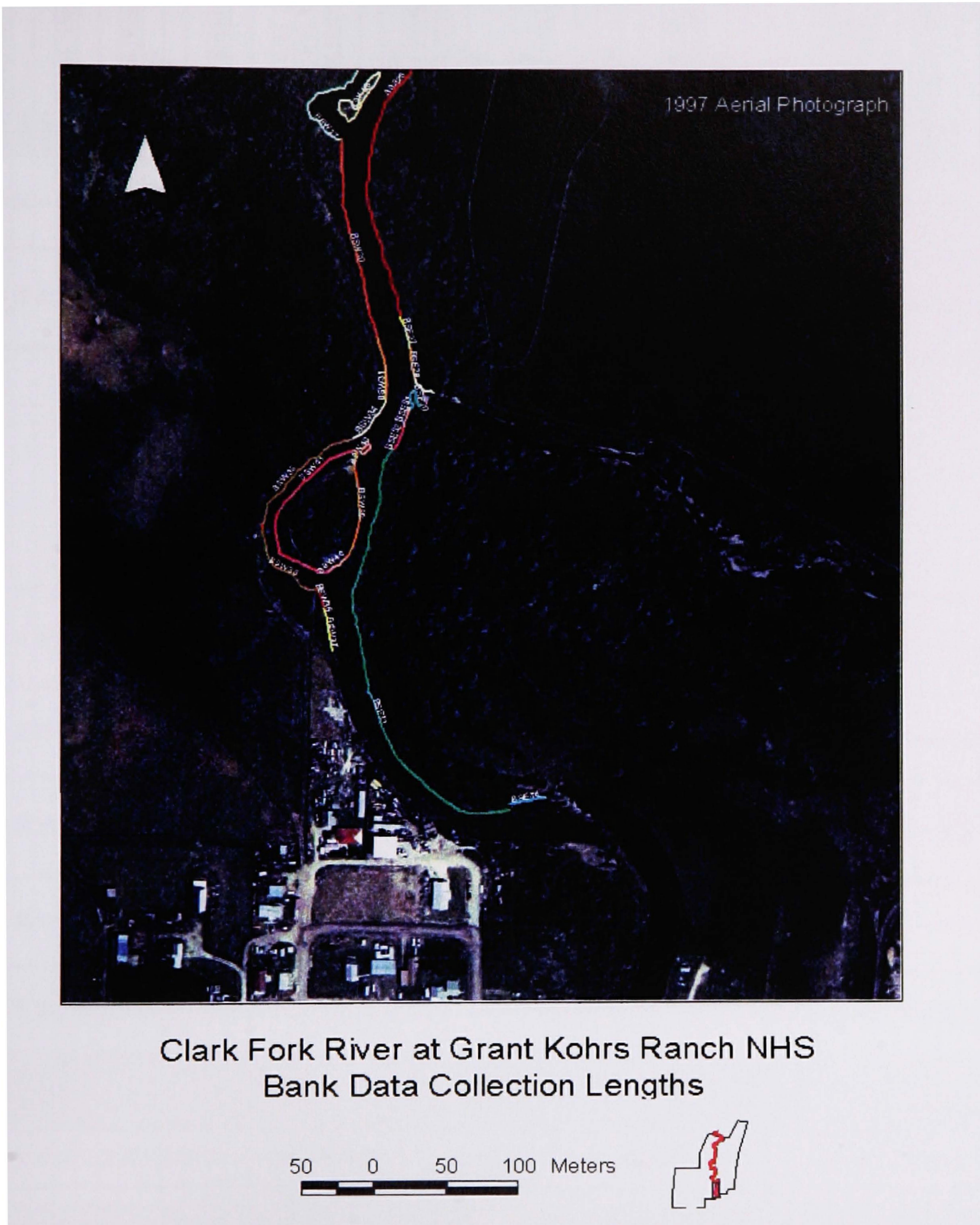


Appendix C.3- Survey Bank Segments, Grant Kohrs Ranch NHS.

Appendix C: Survey Bank Segment Data, Grant Kohrs Ranch NHS

Appendix C.4- Survey Bank Segments, Grant Kohrs Ranch NHS.

Appendix C: Survey Bank Segment Data, Grant Kohrs Ranch NHS



Appendix C.5- Survey Bank Segments, Grant Kohrs Ranch NHS.

Appendix C. Bank Inventory Data													
	Date	Max	Unfilt	Bank		Slumps	Overhangs	Undercut	Tailings	Tailings	Vegetation	Woody	
BOOK_ID	Surveyed	PDOP	Pos	Shape	Length	% of bank	% of bank	cm	cm	Evidence	% of bank	Veg	Bank Vegetation Type
BNE1	6/21/2001	2.7	6	Convex	13	0	0	0	0		0	0	riprap (10-65 cm) quartzite
BNE10	6/20/2001	2.0	20	Convex	34	60	60	25	0		75	30	grass
BNE11	6/20/2001	3.2	31	Convex	68	0	60	25	0		75	0	grass
BNE12	6/20/2001	3.6	33	Concave	54	40	10	0	45		60	30	grass, shrubs, rush
BNE13	6/20/2001	5.6	21	Concave	36	50	40	0	40		50	50	grass
BNE14	6/20/2001	3.6	40	Concave	73	60	40	0	60	slickens, dead vegetation	10	50	grass
BNE15	6/20/2001	1.9	21	Convex	33	0	100	40	30	salts, slickens	80	40	grass, shrubs (scraggly)
BNE16	6/20/2001	2.3	22	Concave	33	30	60	20	40	slickens	50	20	grass, shrubs
BNE17	6/20/2001	2.5	27	Concave	65	50	30	20	50	slickens	10	10	grass
BNE18	6/20/2001	2.2	36	Concave	76	40	40	0	30	dead vegetaion	20	30	grass
BNE19	6/21/2001	2.9	21	Convex	34	10	10	0	35	salts	20	50	grass, dead shrubs
BNE2	6/20/2001	2.5	8	Concave	6	95	0	0	20	slickens	80	10	grass
BNE20	19000100	0.0	0	Convex	77	0	0	0	0		90	0	grass
BNE22	6/21/2001	2.9	26	Convex	55	0	90	30	0	slickens	90	30	grass, rush, forbs, shrubs
BNE22	6/21/2001	2.6	24	Convex	52	0	90	30	0	slickens	90	30	grass, rush, forbs, shrubs
BNE27	6/21/2001	2.5	40	Concave	96	50	50	0	50	dead vegetation	10	10	grass (tops of slumps)
BNE28	6/21/2001	2.5	62	Convex	207	0	0	20	0	gravel slickens	85	10	grass, forbs
BNE3	6/20/2001	3.6	33	Concave	45	80	70	0	50		0	10	
BNE30	6/21/2001	6.4	13	Concave	32	90	10	0	15		40	0	grass (slumps)
BNE31	6/21/2001	3.0	12	Concave	19	20	20	0	40		40	40	grass, shrubs, dead shrubs
BNE32	6/21/2001	5.9	17	Concave	36	20	20	0	10		40	40	grass, shrubs, dead shrubs
BNE33	6/21/2001	2.9	29	Concave	73	70	10	0	0		20	0	grass (slumps)
BNE34	6/21/2001	5.0	19	Convex	32	0	0	0	0		80	50	shrubs, grass
BNE35	6/21/2001	1.7	20	Concave	39	50	20	0	30		30	0	
BNE37	6/21/2001	2.0	96	Convex	350	0	95	30	0		90	0	grass, shrubs
BNE4	6/20/2001	2.1	30	Convex	46	0	80	30	0	slickens	80	30	grass, rushes, shrubs
BNE46	7/3/2001	2.3	13	Convex	45	10	80	15	0		85	0	grass, rush
BNE47	7/3/2001	2.3	9	Concave	26	80	0	0	50		0	0	grass
BNE49	7/3/2001	2.6	7	Concave	18	85	10	10	50		30	0	grass (slumps)
BNE49	7/3/2001	2.6	39	Concave	58	70	25	40	60	dead vegetation	10	10	grass
BNE50	7/3/2001	2.6	39	Concave	89	40	30	0	65		40	15	grass
BNE52	7/3/2001	2.6	22	Convex	112	0	0	0	0		90	70	grass, rush, shrubs
BNE52	19000100	0.0	0	Convex	18	0	0	0	0		90	70	grass, rush, shrubs
BNE54	7/3/2001	1.9	10	Concave	18	75	0	0	50		20	10	grass (slumps)
BNE55	7/3/2001	1.9	14	Convex	54	0	85	0	0		90	70	shrubs
BNE56	7/3/2001	2.2	11	Concave	36	70	60	30	20		0	0	iris
BNE57	7/3/2001	1.9	7	Convex	22	30	70	30	0		90	0	grass, rush
BNE58	7/3/2001	1.9	11	Concave	27	50	25	20	55	slickens, dead veg	50	20	dead shrubs
BNE6	6/20/2001	2.6	30	Convex	33	30	10	0	45	slickens, dead shrubs	90	40	shrubs, dead shrubs, grass
BNE63	7/3/2001	2.0	58	Convex	208	0	80	0	0		85	60	rush, grass, shrubs
BNE64	7/3/2001	2.0	58	Convex	28	0	80	0	0		85	60	rush, grass, shrubs
BNE65	7/3/2001	2.0	15	Concave	65	40	80	20	0		20	0	grass (slumps)
BNE66	7/3/2001	2.0	15	Convex	46	0	90	25	0		90	50	grass, shrubs
BNE67	7/3/2001	2.0	22	Convex	85	0	0	0	0		0	0	riprap (10-65cm, quartzite)
BNE68	7/3/2001	2.0	18	Concave	50	0	25	25	0		75	15	grass
BNE69	7/3/2001	2.0	12	Convex	29	25	90	50	0		80	40	
BNE69	7/3/2001	2.0	9	Convex	24	25	90	50	0		80	40	

Appendix C. Bank Inventory Data

BOOK_ID	Date Surveyed	Max PDOP	Unfilt Pos	Bank Shape	Length	Slumps % of bank	Overhangs % of bank	Undercut cm	Tailings cm	Tailings Evidence	Vegetation % of bank	Woody Veg	Bank Vegetation Type
BNE69	7/3/2001	2.0	5	Convex	14	25	90	50	0		80	40	
BNE70	7/3/2001	3.3	13	Concave	32	10	80	30	0		20	50	grass
BNE71	7/3/2001	3.3	23	Convex	99	0	75	30	50		60	15	grass, spurge, rush, shrubs
BNE72	7/3/2001	3.3	13	Concave	53	5	50	35	0		60	60	grass, shrubs
BNE73	7/3/2001	3.3	6	Convex	17	0	0	0	0		100	40	grass, rush
BNE74	7/3/2001	3.3	22	Convex	112	0	10	35	0		85	15	grass, rush
BNE74	7/3/2001	3.3	10	Convex	54	0	0	0	0		50	0	grass, sedge, rush
BNE75	7/3/2001	3.3	7	Convex	14	0	90	45	0		85	20	grass, shrubs
BNE8	6/20/2001	2.5	32	Convex	34	0	90	30	0	slickens, dead shrubs	80	40	grass, shrubs, rush
BNW	19000100	2.3	20	Convex	120	0	0	0	0	slickens behind shrubs	100	80	shrubs, grass
BNW1	7/6/2001	2.6	8	Concave	32	0	0	0	0		50	5	grass, forbes, 1 shrub
BNW12	7/6/2001	3.6	8	Convex	16	0	100	30	0		85	75	waist high shrubs, grass
BNW13	7/6/2001	3.6	19	Convex	85	0	0	0	0		100	85	
BNW17	7/6/2001	3.6	19	Convex	88	0	90	30	50	slickens in beaver slides	90	20	rush, shrubs
BNW2	7/6/2001	2.6	9	Concave	25	0	0	0	0		0	80	shrubs (.5-2.5m)
BNW2	7/6/2001	5.7	19	Concave	63	0	0	0	0		0	80	shrubs
BNW20	7/6/2001	1.9	20	Concave	62	50	25	40	40	slickens, dead trees	30	10	rush, shrubs
BNW21	7/6/2001	2.7	11	Concave	33	50	25	40	40	slickens, dead trees	30	10	rush, shrubs
BNW21	7/6/2001	1.8	5	Concave	18	50	25	40	40	slickens, dead trees	30	10	rush, shrubs
BNW22	7/6/2001	2.7	6	Concave	39	20	0	0	50	dead vegetation behind	70	0	grass, forbes, dead shrubs
BNW23	7/6/2001	2.3	16	Convex	56	0	0	0	0		100	50	rush, shrubs
BNW25	7/6/2001	2.2	12	Convex	26	0	100	50	0	dead shrubs	80	30	waist high shrubs, rush
BNW26	7/6/2001	2.7	12	Convex	59	0	0	0	0		100	80	grass
BNW28	7/6/2001	2.5	37	Concave	156	70	50	20	50	slickens vegetation	20	10	grass (slumps)
BNW3	7/6/2001	2.2	4	Convex	13	15	70	50	0		85	80	grass, shrubs
BNW3	7/6/2001	2.8	34	Convex	149	15	70	50	0		85	80	grass, shrubs
BNW30	7/9/2001	2.1	17	Convex	48	0	70	30	0		75	30	grass, forbs, shrubs
BNW31	7/9/2001	2.1	32	Convex	66	0	0	0	0		100	10	grass, rush, shrubs
BNW31	7/9/2001	2.1	32	Convex	75	0	0	0	0		100	10	grass, rush, shrub
BNW34	7/9/2001	2.1	32	Convex	35	0	90	30	0	salts	85	0	grass, rush, forbs
BNW37	7/9/2001	2.6	17	Convex	44	0	75	35	0	salts	85	30	waist high shrubs, rush, forbs
BNW38	7/9/2001	2.6	13	Concave	38	0	0	0	60		60	0	
BNW39	7/9/2001	2.5	15	Concave	61	40	0	0	35	50 cm at DS end by birch tree	40	5	grass
BNW4	7/6/2001	3.5	12	Convex	57	0	40	15	0		100	20	rush, shrubs
BNW40	7/9/2001	3.7	40	Convex	165	0	70	35	0	slickens, salts	70	10	grass, waist high shrubs
BNW41	7/9/2001	2.2	8	Convex	22	50	40	45	40		70	0	
BNW42	7/9/2001	2.2	14	Convex	43	90	0	0	0		85	0	grass
BNW43	7/9/2001	2.0	7	Convex	33	0	0	0	0		100	20	grass, rush, waist high shrubs
BNW44	7/9/2001	3.3	12	Concave	41	80	20	20	50		60	0	grass (slumps)
BNW45	19000100	0.0	0	Convex	83	0	0	0	0		90	0	grass
BNW46	7/9/2001	3.6	8	Convex	17	10	100	25	0		90	0	grass
BNW47	7/9/2001	4.0	25	Concave	111	70	70	0	40		70	0	grass
BNW48	7/9/2001	3.6	17	Concave	66	0	50	30	30		80	0	grass
BNW49	7/9/2001	3.5	10	Concave	40	0	0	0	0		70	0	grass, forbs
BNW50	7/9/2001	1.8	11	Convex	52	0	0	0	0		100	90	shrubs, grass
BNW51	19000100	0.0	0	Convex	55	0	0	0	0		90	0	grass
BNW52	7/9/2001	1.6	12	Concave	39	0	10	0	50		70	40	shrubs, grass

Appendix C. Bank Inventory Data

BOOK_ID	Date Surveyed	Max PDOP	Unfilt Pos	Bank Shape	Length	Slumps % of bank	Overhangs % of bank	Undercut cm	Tailings cm	Tailings Evidence	Vegetation % of bank	Woody Veg	Bank Vegetation Type
BNW53	7/9/2001	2.7	19	Concave	51	0	10	0	50		70	40	shrubs, grass
BNW55	7/9/2001	2.0	16	Convex	54	0	70	20	0		0	10	grass, shrubs
BNW59	7/9/2001	2.2	15	Concave	39	50	50	30	40		20	15	grass (slumps)
BNW6	7/6/2001	2.0	12	Convex	65	80	0	0	40		60	40	grass (slumps)
BNW61	7/9/2001	2.2	24	Concave	55	80	10	20	45	slickens	10	5	
BNW64	7/9/2001	2.3	25	Concave	93	75	10	20	45	dead shrubs (6m back)	60	10	grass(slumps)
BNW65	7/9/2001	2 3	11	Concave	27	20	- 30	30	50	salts	50	70	grass, forbs
BNW67	7/9/2001	2.3	9	Convex	29	0	0	0	0		100	30	grass, rush, forbs
BNW70	7/9/2001	2.7	16	Concave	45	70	10	20	60		60	30	grass, forbs, thistle
BNW71	7/9/2001	2.1	3	Concave	34	20	0	0	50	dead woody veg	20	80	grass(slumps), shrubs
BNW72	7/9/2001	2.5	16	Concave	36	20	10	20	60		30	0	grass(slumps)
BNW73	7/9/2001	2.2	18	Convex	89	0	0	0	0	tailings in banks, slickens	85	50	grass, forbs
BNW8	7/6/2001	2.0	18	Convex	73	0	0	0	0		100	90	shrubs
BSE1	7/17/2001	2.5	14	Convex	33	0	0	0	0	slickens	80	40	grass, sedge, shrubs
BSE12	7/17/2001	3.1	13	Convex	60	0	0	0	0		100	40	grass, shrubs
BSE15	7/17/2001	2.9	17	Concave	53	40	40	40	50		70	40	grass, rush, shrubs
BSE16	7/17/2001	2.9	13	Convex	53	0	0	0	0		100	25	grass, rush, shrubs
BSE19	7/17/2001	3.3	7	Convex	9	0	0	0	0	salts, tailings	30	80	riprap, grass, forbs
BSE20	7/17/2001	3.4	11	Concave	31	15	70	40	40		30	10	grass, forbs
BSE21	7/17/2001	3.8	30	Concave	149	85	30	30	10	thin layers-top, chunks-lower	30	0	grass(slumps)
BSE22	7/17/2001	3.8	4	Convex	22	10	90	40	0	salts	70	75	grass, shrubs
BSE23	7/17/2001	3.6	9	Concave	31	40	0	0	50	salts	60	0	grass, forbs
BSE24	7/17/2001	3.6	12	Convex	49	0	0	0	0		100	0	forbs, grass
BSE26	7/17/2001	4.8	49	Convex	200	5	80	40	15	measured in beaver slide (??)	85	20	grass, rush, forbs
BSE27	7/17/2001	2.0	10	Concave	26	85	0	0	30		60	5	grass (slumps)
BSE28	7/17/2001	2.0	10	Concave	22	20	40	50	40		30	40	shrubs, grass
BSE29	7/17/2001	2.0	9	Concave	19	0	0	0	0		60	25	grass, forbs, shrubs
BSE30	7/17/2001	2.1	8	Convex	28	0	40	40	0		70	25	forbs, grass, shrub
BSE31	7/17/2001	2.6	6	Concave	15	40	0	0	40	thin in middle (15cm)	30	0	grass, forbs
BSE32	7/17/2001	2.6	6	Convex	19	0	0	0	20		85	25	small shrubs, grass, rush
BSE33	7/17/2001	3.2	72	Convex	335	5	80	40	0		80	25	rush, grass, shrubs
BSE34	7/17/2001	2.3	8	Convex	25	0	0	0	0		100	60	grass, forbs
BSE6	7/17/2001	2.2	13	Convex	74	0	0	0	0		100	15	grass, shrubs
BSE7	7/17/2001	2.4	20	Concave	61	50	30	70	50		30	50	grass, shrubs
BSE8	7/17/2001	2.2	12	Concave	37	15	20	40	40		50	75	grass, willows
BSE9	7/17/2001	2.2	14	Convex	48	0	0	0	0		90	80	grass, shrubs, forbs
BSW1	7/12/2001	1.9	14	Convex	29	0	0	0	0		0	0	riprap (20-80cm) quartzite
BSW10	7/12/2001	5.9	13	Convex	33	10	80	40	30	salts	75	70	shrubs, grass
BSW11	7/12/2001	2.8	18	Concave	47	50	30	45	60		30	20	willows, grass
BSW12	7/12/2001	2 2	15	Concave	44	30	10	25	40		30	10	grass, rush, thistle
BSW13	7/12/2001	3.2	10	Convex	38	0	0	0	0		100	10	grass, forbs, rush
BSW16	7/12/2001	3.2	10	Convex	34	10	80	35	0	salts, tailings	80	20	grass
BSW17	7/12/2001	3.5	29	Convex	152	0	0	0	0		100	80	shrubs, knapweed, grass
BSW2	7/12/2001	2.3	28	Concave	57	20	50	30	50		15	70	grass (slumps)
BSW23	7/12/2001	5.6	23	Convex	84	0	60	40	0		85	60	grass, rush
BSW24	7/12/2001	3 4	19	Concave	49	0	0	0	0	tailings	80	0	grass, rush
BSW26	7/12/2001	2.7	23	Convex	88	10	60	30	0		80	15	grass, forbs, shrubs

Appendix C. Bank Inventory Data

BOOK_ID	Date Surveyed	Max PDOP	Unfilt Pos	Bank Shape	Length	Slumps % of bank	Overhangs % of bank	Undercut cm	Tailings cm	Tailings Evidence	Vegetation % of bank	Woody Veg	Bank Vegetation Type
BSW28	7/12/2001	1.9	35	Convex	109	10	90	40	50		85	50	shrubs, grass, forbs
BSW3	7/12/2001	2.5	23	Concave	70	20	30	30	50		70	20	grass, forbs, sm wild rose
BSW30	7/12/2001	2.8	12	Concave	24	30	30	40	50		60	0	grass, forbs (slumps)
BSW31	7/12/2001	4.5	43	Convex	127	5	95	50	0	salts	80	40	shrubs, grass, rush
BSW32	7/12/2001	2.7	10	Convex	49	0	0	0	0		100	30	grass, rush
BSW35	7/12/2001	3.8	14	Convex	37	0	95	40	0		90	30	grass, rush
BSW36	7/12/2001	3.8	40	Convex	53	0	90	20	0		85	50	grass, rush, shrubs
BSW36	7/12/2001	3.8	40	Convex	78	20	0	0	0		75	0	grass
BSW36	7/12/2001	3.8	40	Convex	36	0	0	0	0		90	0	grass
BSW37	7/12/2001	2.8	8	Convex	32	0	0	0	0		85	0	grass
BSW38	7/12/2001	2.8	6	Convex	15	0	0	0	0		100	0	grass, sedge
BSW39	7/12/2001	2.1	23	Convex	86	0	90	40	0		90	20	grass, shrubs
BSW4	7/12/2001	2.1	16	Concave	38	20	0	0	50	salts, slickens	75	50	
BSW40	19000100	0.0	0	Convex	21	20	40	25	0		75	75	shrubs,grass
BSW40	7/12/2001	2.3	8	Concave	16	80	0	0	60		60	0	grass (slumps)
BSW41	7/12/2001	2.3	31	Convex	138	5	80	40	0		90	20	grass, forbs
BSW7	7/12/2001	2.2	15	Convex	48	0	0	0	0		95	30	rush, grass, shrubs
BSW9	7/12/2001	5.7	17	Convex	44	0	100	45	0		90	85	shrubs, grass

Appendix D

Erosion Error

Error analysis for erosion was also done using the average RMS error, 0.4 m, for each set of images. The RMS error is an absolute error, and therefore, a point in space can be off by the RMS error in any direction. Assuming that the erosion areas are rectangular, then the RMS error is 0.4 m for both the length and the width. Area for a rectangle equals the length multiplied by the width, so the error can be found with the following equation

$$A_e = \sqrt{(\Delta L / L)^2 + (\Delta w / w)^2} \quad \text{(Taylor 1982).}$$

A_e=Fractional error in erosion area
L=RMS error in length (.4m)
L=length
w=RMS error in width (.4m)
w=width

In the above equation, as the length increases the "*L/L*" approaches 0. Therefore, assuming a high length:width ratio, the "*L/L*" term becomes insignificant and the error equation becomes $A_e = \Delta w / w$.

Unfortunately, the erosion area shapes are not actually rectangular. Widths vary across the areas, and are usually thicker in the center and narrow at either end. Measurements of the length and average width were taken at random erosion areas from the 1983 data, and the calculated ratios ranged from 8:1 to 15:1, with a typical value of 11:1. To find the relationship between width and area in rectangles with a length:width ratio of 11:1, areas were calculated using theoretical pairs of length and width values, with each pair possessing this ratio. A power curve was fit to a plot of the theoretical

widths versus the calculated areas with the resulting equation being $w = .3015A^{0.5}$. where w=*width*, and A=*Area*. This equation was then used to calculate the representative widths of the erosion areas (average width assuming a length:width ratio of 11:1) measured on the aerial photographs . The final error for each area was calculated by dividing the average RMS error (.4 m) by its representative width ($A_e = \Delta w / w$). Using this method results in higher errors for smaller areas, so as the level of detection is approached for channel changes on the photographs the error increases dramatically. The median error value for all of the areas digitized for a photograph year was used to represent the error for that year's erosion.

Appendix D. Erosion Error

1947			
area (m^2)	*error (%)*	*max (m^2)*	*min (m^2)*
266	13.4	302	230
1190	11.4	1326	1054
714	11.9	800	629
468	12.4	527	410
125	15.2	144	106
266	13.4	302	231
278	13.3	315	241
159	14.5	182	136
4092	10.7	4530	3654
1621	11.2	1803	1440
900	11.7	1006	795
2267	11.0	2516	2018
429	12.6	483	375
85	16.5	98	71
1070	11.5	1194	947
690	12.0	772	607
330	13.0	372	287
3350	10.8	3712	2989
1787	11.1	1986	1588
1358	11.3	1512	1204
155	14.6	177	132
1510	11.2	1680	1341
2711	10.9	3006	2416
398	12.7	449	348
418	12.6	471	365
176	14.3	201	151
1215	11.4	1353	1076
239	13.6	271	206
550	12.2	617	483
394	12.7	444	344
1174	11.4	1308	1039
3259	10.8	3611	2907
708	11.9	792	623
131	15.1	151	111
152	14.7	174	130
1522	11.2	1693	1351
1277	11.4	1422	1132
1387	11.3	1544	1230

1960			
area (m^2)	*error (%)*	*max (m^2)*	*min (m^2)*
1552	3.4	1604	1500
484	6.0	513	455
141	11.2	156	125
1545	3.4	1597	1493
127	11.8	142	112
160	10.5	177	143
99	13.3	112	86
542	5.7	573	512
2585	2.6	2652	2518
819	4.6	857	781
141	11.2	157	125
685	5.1	720	650
708	5.0	743	673
31	23.8	39	24
319	7.4	343	296
2530	2.6	2597	2463
489	6.0	519	460
1270	3.7	1318	1223
120	12.1	134	105
47	19.3	57	38
1303	3.7	1351	1255
194	9.5	212	175
1695	3.2	1750	1640
3138	2.4	3212	3064
390	6.7	416	363
324	7.4	348	301
820	4.6	858	782
50	18.7	60	41
108	12.8	122	94
419	6.5	446	391
1796	3.1	1853	1740
71	15.7	83	60
33	23.0	41	26
627	5.3	660	594
47	19.4	56	38
1198	3.8	1244	1152
61	17.0	71	50
677	5.1	711	642

373	12.8	421	325
196	14.0	224	169
161	14.5	185	138
33	21.2	40	26
272	13.3	308	235
area (m^2)	*Median error*	*max (m^2)*	*min (m^2)*
39857	12.4	44424	35290

2936	2.4	3007	2864
48	19.2	57	39
135	11.4	150	120
583	5.5	615	551
238	8.6	259	218
441	6.3	469	413
134	11.5	149	118
235	8.7	255	215
222	8.9	242	203
46	19.5	55	37
317	7.5	341	293
358	7.0	383	332
259	8.2	280	238
area (m^2)	*Median error*	*max (m^2)*	*min (m^2)*
33298	7.4	34766	31831

Appendix D. Erosion Error

1979			
area (m^2)	error (%)	max (m^2)	min (m^2)
407	6.6	433	380
719	4.9	755	683
135	11.4	151	120
53	18.2	63	44
729	4.9	765	693
97	13.5	110	84
59	17.3	69	49
296	7.7	319	274
1712	3.2	1767	1657
471	6.1	500	442
17	32.6	22	11
332	7.3	356	308
447	6.3	475	419
75	15.3	86	63
243	8.5	264	223
160	10.5	177	143
139	11.2	155	124
1442	3.5	1492	1392
72	15.7	83	60
689	5.1	724	654
421	6.5	448	394
462	6.2	491	434
45	19.7	54	36
915	4.4	955	875
1098	4.0	1142	1054
101	13.2	115	88
1742	3.2	1797	1687
329	7.3	353	305
379	6.8	405	353
265	8.2	286	243
26	25.9	33	19
44	20.0	53	35
290	7.8	313	268
717	5.0	753	682
1325	3.6	1373	1277
269	8.1	290	247
45	19.8	54	36
9	45.1	13	5
42	20.5	51	33

1983			
area (m^2)	error (%)	max (m^2)	min (m^2)
726	4.9	762	690
249	8.4	270	228
501	5.9	530	471
975	4.2	1017	934
424	6.4	451	396
26	25.9	33	19
27	25.5	34	20
55	17.8	65	46
755	4.8	791	718
102	13.2	115	88
306	7.6	329	282
416	6.5	443	389
12	38.5	16	7
31	23.9	38	23
252	8.4	273	231
13	37.0	18	8
3	72.3	6	1
20	29.5	26	14
22	28.4	28	16
214	9.1	233	194
25	26.7	31	18
23	27.9	29	16
22	28.2	28	16
31	23.7	39	24
51	18.6	60	41
27	25.7	33	20
43	20.1	52	35
88	14.1	101	76
122	12.0	137	108
54	18.0	64	44
117	12.2	132	103
68	16.1	79	57
22	28.4	28	16
951	4.3	992	911
284	7.9	307	262
405	6.6	432	378
9	44.6	13	5
320	7.4	344	296
898	4.4	938	859

52	18.4	62	43
544	5.7	575	513
386	6.8	412	360
1136	3.9	1181	1091
282	7.9	305	260
66	16.3	77	55
181	9.8	199	164
314	7.5	337	290
144	11.1	159	128
257	8.3	278	235
88	14.2	100	75
366	6.9	391	341
112	12.5	126	98
140	11.2	155	124
530	5.8	560	499
138	11.3	153	122
1979			
area (m^2)	*Median error*	*max (m^2)*	*min (m^2)*
21554	8.1	22816	20292

504	5.9	534	474
162	10.4	179	145
47	19.3	56	38
565	5.6	597	534
3	72.5	6	1
80	14.9	92	68
1159	3.9	1204	1114
459	6.2	487	430
327	7.3	351	303
15	34.5	20	10
47	19.4	56	38
7	51.4	10	3
444	6.3	472	416
108	12.8	122	94
7	48.8	11	4
10	42.4	14	6
10	42.4	14	6
1983			
area (m^2)	*Median error*	*max (m^2)*	*min (m^2)*
12644	14.9	13542	11745

Appendix D. Erosion Error

1994			
area (m^2)	error (%)	max (m^2)	min (m^2)
125	11.9	139	110
206	9.2	225	187
43	20.3	51	34
602	5.4	634	569
221	8.9	240	201
148	10.9	164	132
615	5.3	648	582
19	30.4	25	13
17	32.6	22	11
205	9.3	223	186
377	6.8	403	351
53	18.3	62	43
18	31.0	24	13
21	29.2	27	15
92	13.8	105	80
11	40.5	15	6
8	45.6	12	5
18	30.9	24	13
48	19.2	57	38
25	26.6	31	18
119	12.2	133	104
89	14.1	101	76
13	36.7	18	8
48	19.1	58	39
15	34.3	20	10
20	30.0	25	14
36	22.0	44	28
10	42.9	14	5
107	12.8	121	94
328	7.3	352	304
149	10.9	165	132
225	8.8	245	205
336	7.2	360	312
8	46.9	12	4
242	8.5	263	222
4	66.1	7	1
373	6.9	398	347
308	7.6	332	285
61	17.0	71	50

1997			
area (m^2)	error (%)	max (m^2)	min (m^2)
75	15.3	86	63
36	22.0	44	28
63	16.7	74	53
33	23.2	40	25
7	51.8	10	3
3	78.7	5	1
16	33.2	21	11
11	40.7	15	6
57	17.6	67	47
3	76.1	5	1
21	28.8	27	15
3	74.7	6	1
8	47.1	12	4
13	36.1	18	9
3	72.2	6	1
12	38.2	17	7
8	46.0	12	5
12	38.5	16	7
22	28.2	28	16
8	48.0	11	4
6	55.0	9	3
31	23.8	39	24
31	23.9	38	24
24	27.0	31	18
36	22.0	44	28
3	73.1	6	1
57	17.5	67	47
10	42.4	14	6
35	22.4	43	27
17	32.5	22	11
9	43.2	14	5
5	57.4	8	2
7	49.4	11	4
34	22.8	41	26
12	38.6	16	7

1997			
area (m^2)	Median error	max (m^2)	min (m^2)
733	38.2	926	540

51	18.6	60	41
45	19.9	54	36
83	14.5	95	
233	8.7	253	212
4	70.0	6	1
54	18.0	64	44
724	4.9	760	688
6	52.7	10	3
14	35.2	19	9
36	22.0	44	28
8	48.2	11	4
4	68.9	6	1
43	20.2	52	34
21	28.8	27	15
21	28.9	27	15
10	41.9	14	6
9	43.6	13	5
17	32.5	22	11
40	20.9	49	32
84	14.5	96	72
55	17.9	65	45
12	39.0	16	7
39	21.2	47	31
1994			
area (m^2)	*Median error*	*max (m^2)*	*min (m^2)*
6974	20.0	7685	6263

Appendix D. Erosion Error

Racetrack			
area (m^2)	*error (%)*	*max (m^2)*	*min (m^2)*
221	8.919	241	202
60	17.064	71	50
764	4.800	801	727
94	13.671	107	81
56	17.801	65	46
42	20.443	51	34
932	4.347	972	891
30	24.273	37	23
154	10.675	171	138
754	4.832	790	717
88	14.104	101	76
26	25.941	33	19
122	12.020	136	107
256	8.290	277	235
38	21.476	46	30
33	22.977	41	26
99	13.345	112	86
75	15.340	86	63
163	10.396	180	146
19	30.404	25	13
74	15.408	86	63
43	20.263	52	34
559	5.610	591	528
357	7.020	382	332
536	5.730	567	505
1084	4.030	1128	1040
43	20.336	51	34
187	9.709	205	169
405	6.593	432	378
12	38.773	16	7
743	4.868	779	707
1196	3.837	1241	1150
273	8.025	295	251
141	11.158	157	126
1347	3.614	1396	1299
63	16.757	73	52
69	15.938	80	58
298	7.680	321	276
498	5.943	528	469
55	17.858	65	45
34	22.646	42	27

Garrison			
area (m^2)	*error (%)*	*max (m^2)*	*min (m^2)*
197	9.5	215	178
37	21.9	45	29
1401	3.5	1451	1351
318	7.4	342	294
42	20.4	51	34
42	20.4	51	34
26	25.9	33	19
79	15.0	90	67
654	5.2	688	620
31	24.0	38	23
33	23.0	41	26
93	13.7	106	80
10	41.1	15	6
88	14.1	101	76
142	11.1	158	126
391	6.7	417	365
845	4.6	883	806
36	22.2	43	28
340	7.2	364	315
777	4.8	814	740
69	15.9	80	58
400	6.6	426	373
15	34.5	20	10
121	12.1	135	106
40	21.0	48	32
42	20.6	50	33
217	9.0	236	197
39	21.2	47	31
23	27.6	29	17
Garrison			
area (m^2)	*Median error*	*max (m^2)*	*min (m^2)*
6547	15.0	7019	6074

524	5.796	554	494
493	5.974	523	464
465	6.153	493	436
1104	3.993	1148	1060
29	24.805	36	22
594	5.444	626	562
1361	3.596	1410	1312
70	15.837	81	59
74	15.397	86	63
325	7.356	349	301
796	4.703	833	758
209	9.167	229	190
179	9.903	197	162
185	9.752	203	167
62	16.810	73	52
21	28.848	27	15
99	13.357	112	85
115	12.378	129	101
64	16.535	75	54
8	45.798	12	5
33	23.007	41	26
34	22.789	42	26
25	26.566	32	18
138	11.304	153	122
60	17.100	70	50
114	12.442	128	100
77	15.164	88	65
422	6.456	450	395
35	22.520	43	27
331	7.296	355	307
1202	3.826	1248	1156
67	16.196	78	56
818	4.638	856	780
122	11.995	137	108
166	10.310	183	149
93	13.722	106	81
17	32.511	22	11
180	9.895	198	162
461	6.179	489	432
151	10.814	167	134
287	7.834	309	264
45	19.706	54	36
313	7.500	336	289
Racetrack			
area (m^2)	*Median error*	*max (m^2)*	*min (m^2)*
24014	11.6	25614	22414