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MEANDER MIGRATION PREDICTION OF THE CLARK FORK RIVER
AT GRANT-KOHRS RANCH, MONTANA

by

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Date
Intense base metals, gold and silver mining and smelting operations in the vicinity of Butte and Anaconda for more than a century generated huge volumes of potentially toxic tailings that were dumped in the headwaters of the Clark Fork River, Montana. The metal-contaminated sediments were deposited along the river transforming the region in one of the most hazardous waste sites in the United States. This fact led the Environmental Protection Agency to identify the area as the largest Superfund complex in the United States.

The problem is not limited to the specific location of the mining and smelting operations since the ongoing meander migration of the Clark Fork River channel causes the gradual removal of floodplain sediments which are then redeposited downstream. Due to this natural process, metal-contaminated sediments lying on the floodplain become a continuous source of contamination long after mining operations have ceased.

A four-kilometer reach of the Clark Fork River located at Grant-Kohrs Ranch was analyzed using a GIS-based methodology to predict the time that will take the river to remove the metal-contaminated floodplain by natural processes. River banklines were digitized from aerial photographs dated 1960 and 2001 and used as data to predict the position of the channel fifty years later (year 2050). The position of the predicted channel was then used as input data to predict the position of the stream for year 2100. Each newly predicted bankline was subsequently used to predict the location of the river in fifty years interval until year 2200; then one hundred-year interval were used to predict the position of the channel until year 2500.

This methodology had previously been used mainly by engineers to predict meander migration of bends that are a threat to civil structures. It is the first time that the method is used for long-term meander migration predictions. Results suggest that the river will need at least 1000 years to remove once the sediments deposited on the floodplain at Grant Kohrs Ranch by natural fluvial processes.
To Rafaela, the sun of my life
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<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. INTRODUCTION</td>
<td>History</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Literature review</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Area of Study</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Objective</td>
<td></td>
</tr>
<tr>
<td>II. STREAM CHARACTERISTICS – MEANDERING STREAMS</td>
<td>Channel planform characteristics and classifications</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Meandering streams</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Geometry of Meanders</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flow pattern in meanders</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Evolution of meanders – Migration</td>
<td></td>
</tr>
<tr>
<td>III. METHODOLOGY</td>
<td>Introduction</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Basic concepts for applying the method</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Measuring meander migration</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Migration prediction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Meander classification</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Application of the method in the study area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Historical rivers banks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Testing the software</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Data Logger</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Channel Migration Predictor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Error evaluation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Short term versus long term prediction</td>
<td></td>
</tr>
</tbody>
</table>
IV. RESULTS AND DISCUSSION ................................................................. 52
   Introduction
   Approach
   Description of results
V. SUMMARY AND CONCLUSIONS ...................................................... 64
   Advantages and Disadvantages of the Methodology
   Migration Patterns
   Future Research Opportunities Using this Methodology
   Conclusions
REFERENCES .............................................................................................. 71
LIST OF FIGURES

Figure 1.1. Clark Fork River Superfund Site Location Map (from EPA, 2004) ......................... 3

Figure 1.2. A. Layer of contaminated sediments along the banks of the Clark Fork River in the Grant Kohrs Ranch. B. Animal bone found in the margins of the Clark Fork River in the Grant-Kohrs Ranch area. Copper minerals from mine tailings have deposited on the bone surface (green material) .......................................................... 6

Figure 1.3. Study Area Location Map .................................................................................. 8

Figure 2.1. Planforms and cross sections showing the three main types of channel patterns (Modified from Rosgen et al. (1998) ................................................................. 10

Figure 2.2. Sinuosity and channel patterns (from Schumm, 1963) ........................................ 11

Figure 2.3. Channel patterns classification (after Rust, 1978) ............................................ 12

Figure 2.4. Alluvial channel patterns (after Schumm, 1981) ............................................... 13

Figure 2.5. Channel classification based on pattern and type of sediment load, with indication of relative stability (from Schumm and Meyer, 1979) ........................................... 14

Figure 2.6. Classification of alluvial channels based on the degree and character of sinuosity, braiding, and anabranching (from Brice et al., 1978) ........................................... 15

Figure 2.7. Major planform properties of rivers (Brice, 1984) ............................................ 16

Figure 2.8. Major types of rivers (Brice, 1984) ................................................................ 16

Figure 2.9. Stream classification delineation showing longitudinal, cross-sectional and plan views of major stream types (from Rosgen, 1994) .................................................. 17

Figure 2.10. Classification key for natural rivers (from Rosgen, 1994) ................................. 18

Figure 2.11. Planform schematic view of a meander pair showing main morphological features (from Legasse et al., 2003) ................................................................. 19

Figure 2.12. Meander planform parameters ....................................................................... 20

Figure 2.13. Relation of meander length to width (left); and to radius of curvature in channels (right) (from Leopold and Wolman, 1960) ......................................................... 21

Figure 2.14. Flow pattern in meanders. A. i). Location of maximum boundary shear stress (tb), and ii) flow field in a bend with a well-developed bar (after Dietrich, 1987). B. Secondary flow at a bend apex showing the outer bank cell and the shoaling-induced outward flow over the point bar (after Markham and Thorne, 1992). C. Model of the flow structure in meandering channels (after Thompson, 1986). Black lines indicate surface currents and white lines near-bed currents. (from Kinghton, 1998) .... 22

Figure 2.15. Evolution of meander loops and classification scheme. Flow direction is left to right (from Brice, 1974) ................................................................. 24


Figure 2.17. Types of meander growth and shift (from Knighton, 1998) ............................ 25
Figure 2.18. Relationship between migration rate and bend curvature (from Hooke, 1991) ................................................................. 26

Figure 3.1. Measuring different types of meander migration (from Legasse et al., 2003) .... 30

Figure 3.2. Meander bend movement (from Legasse et al., 2003) ........................................ 31

Figure 3.3. A. Amount and direction of centroid movement for two time intervals defined by three hypothetical historical records (DA and DB). B. Best-fit circles and banklines drawn along the outer bank of the hypothetical channel for the three historical records (from Legasse et al. 2003) ................................................................................................................... 32

Figure 3.4. A. Circles inscribing the position of the outer bank for the historical records 1, 2, and 3 and circle inscribing the predicted position of the bankline for year 4. B. Banklines for historical records 1, 2, and 3 and predicted position of the channel for year 4 derived from the position of the inscribing circle shown in sketch A (from Legasse et al., 2003) ................................................................................................................... 34

Figure 3.5. Some of the parameters measured using the Data Logger extension (from Legasse et al., 2003) .............................................................................................................................................. 36

Figure 3.6. Modified Brice Classification (from Legasse et al., 2003) ........................................ 38

Figure 3.7. Digitized banklines on aerial photographs of the study area for four different historical records ................................................................................................................................... 39

Figure 3.8. Data Logger extension dialog box showing the information that must be entered ...................................................................................................................................................... 40

Figure 3.9. Example of bend delineation (A), best-fit circle (B), and parameters measured (C) using the Data Logger extension ........................................................................................................... 41

Figure 3.10. Actual position of channel for historical records 1960, 1983, and 2001. Circles inscribing outer bank of bends for channels of years 1960 and 1983, and predicted circle for year 2001 .......................................................................................................................................... 42

Figure 3.11. Example of an “unconventional” meander with bars interfering the measurements (upper right). Two “conventional” bends are shown in lower left. Real and predicted best-fit circles for year 2001 are also shown ........................................................................................................................................... 43

Figure 3.12. Comparison of real and predicted circles for the year 2001 historical record..... 44

Figure 3.13. Evaluation of error in the prediction based on the differences in lengths of the radius of curvature between the real and predicted circles ................................................................................................................................... 45

Figure 3.14. Radius of curvature orientation comparison between the real and the predicted circles ................................................................................................................................................... 46

Figure 3.15. Representation of the error vector and its components ...................................... 47

Figure 3.16. Total prediction error represented by the extension, translation and rotation differences between the real and predicted circle positions ................................................................................................................................... 48

Figure 3.17. Long term channel migration prediction ...................................................................... 49

Figure 4.1. Channel migration prediction for year 2050, using years 1960 and 2001 as historical records ................................................................................................................................................... 54
Figure 4.2. Channel migration prediction for years 2100 and 2150.................................55
Figure 4.3. Channel migration prediction for years 2200 and 2300.................................56
Figure 4.4. Channel migration prediction for years 2400 and 2500.................................57
Figure 4.5. Zones of the study reach characterized by different levels of activity as demonstrated by the variation of sinuosity through time..........................................................58
Figure 4.6. Variations in sinuosity through time for Zones A, B, and C shown in Figure 4.5.............................................................................................................................................59
Figure 4.7. Variation of sinuosity values through time for the study reach.......................59
Figure 4.8. Position of the Clark Fork River channel at Grant Kohrs Ranch for historic records 1960 – 2001 and predicted position for the years 2050 to 2500..............................61
Figure 4.9. The red outline shows the area covered by tailings in year 2001. The yellow line indicates the area that will be removed by year 2500 according to the results of the predictions, and the green area represents the portions of the floodplain that will not have been removed by the path of the stream by year 2500....................................................62
Figure 4.10. Historical and predicted channel positions at Grant Kohrs Ranch. Original floodplain represented with red outline, the yellow line enclosed the area that will have been removed by the year 2500, and the green area symbolizes the sectors of the original floodplain that will have not been reworked by year 2500 according to the predictions..............................................................63
Figure 5.1. Comparison of resulting predicted channel for year 2500 using short-term intervals (left) and a long-term interval (right).................................................................65
Figure 5.2. Migration pattern for a straight subreach within the study area. Short term vs. Long term migration (Zone A) ........................................................................................................68
Figure 5.3. Migration pattern for a subreach of moderate sinuosity within the study area (Zone B). Short term vs. Long term migration.................................................................68
Figure 5.4. Migration pattern for a high sinuosity subreach within the study area (Zone C). Short term vs. Long term migration.................................................................69
LIST OF TABLES

Table I. Classification of stable alluvial channels (After Schumm, 1977).......................12
Table II. Variation of Sinuosity through time for the study reach.................................60
CHAPTER I

INTRODUCTION

History

Large-scale mining and milling operations started during the late 1800s, continued during the 1900s, and are still active today near Butte and Anaconda, Montana producing large amounts of base metals, gold and silver. The removal and treatment of the host rock in order to yield the ore, generated high volumes of tailings that were disposed in the headwater tributaries of the Clark Fork River (Moore and Luoma, 1990a; Moore and Luoma, 1990b; Axtmann, 1991).

From 1887 to 1896, 450 metric tons (mT) of silver were processed per day (Moore and Luoma, 1990a). By 1896, 4,500 mT of copper were smelted per day, and in 1910 the world's largest smelter plants were producing 11,500 mT of copper a day in Anaconda. Mining companies were disposing mining and milling waste directly into the Silver Bow Creek, in the Butte area. The mine tailings, together with the other sediments transported by the stream, were carried away during high seasonal flow events reaching the Clark Fork River and then were redeposited downstream. During late winter of 1908, the largest flood event on record for the Clark Fork drainage occurred, resulting in the removal, transport, and redeposition on the floodplain of extensive volumes of mining waste, contaminated soils and sediments (EPA, 2004).

The production of metals continued until 1980, when the Anaconda smelter closed due to a depression in copper prices. By then, over 1 billion metric Tons of ore and waste rock had been removed from the Butte mining district (Moore and Luoma, 1990a). Continuous discharge of contaminated material over extended periods of time produced high concentration of hazardous metals in the stream bed as well as in the floodplain sediments. According to Moore and Luoma (1990b), the more than 300 million m$^3$ of rock removed from Berkeley pit, the largest open pit mine in the district, and the tens of millions
of m$^3$ of mine tailings that came from various underground mining operations would cover a land area of approximately 10 km$^2$.

It the early 1980s scientists realized the magnitude of the metal-contaminated hazardous material lying on the floodplain and riparian zones of the Clark Fork River (Moore and Luoma, 1990a), and in 1992 the Clark Fork River was designated as a Superfund site (US Environmental Protection Agency, 2002). The Superfund Program was established in 1980 by the U.S. Congress in response to growing concern over health and environmental risks caused by numerous contaminated sites all over the US.

Due to its nomination as a superfund site, and even before that, the Clark Fork River has been extensively examined and numerous studies have been carried out to assess the magnitude of the contamination and find solutions to the problem (Moore and Luoma, 1990; Axtmann and Luoma, 1991; Butler, 2003; Schafer et al., 1993). Different aspects of the consequences of mine tailings have been considered and studied, such as the effects of metal contamination on the riparian vegetation and aquatic biota (Lejeune et al., 1996; Kaputska, 2002; Phillips and Spoon, 1990); distribution, stratigraphy and geochemistry of tailings (Rice and Ray, 1985); and geomorphologic variations due to the input of mining tailings (Brooks and Moore, 1989). Most of these studies have focused on the evaluation of the damage and the human and environment implications as well as the examination of fluvial processes.

In August 2002, the Environmental Protection Agency (EPA) in conjunction with the Montana Department of Environmental Quality (DEQ) presented a Clean-up proposal plan (US Environmental Protection Agency, 2002). In April 2004, the EPA and DEQ officially signed the documents describing the clean up plan for the Clark Fork River Superfund site, from Warm Spring Ponds to the Milltown Reservoir (Figure 1.1), about 120 river miles of the Clark Fork River (EPA, 2004). The cleanup plan cost estimation is $120 million and it is supposed to take about 10 years to accomplish. The cleanup plan will take place mostly in Reach A, the most highly contaminated area between Warm Springs Ponds to Garrison, in the Deer Lodge Valley (Figure 1.1), limited cleanup in Reach B and no proposed clean up in Reach C.

The amount and extent of hazardous material distributed along a river, especially with primarily agricultural and recreational land use, is a great concern. However, it is even more important to realize that all this material is part of a dynamic system that is constantly
redistributing contaminated sediments and consequently producing changes in the metal concentrations and in the input of contaminants within the river. The highly contaminated floodplain of the Clark Fork River represents a long-term source of metals to the river channel directly affecting the aquatic ecosystem as well as stressing the riparian/floodplain vegetation in the area. For this reason, it is imperative to understand how fluvial systems work and what role the many variables (vegetation, channel migration, erosion-deposition, time) play in contributing to the natural recycle of the contaminated area.

Figure 1.1. Clark Fork River Superfund Site Location Map (from EPA, 2004)

Literature Review

The Clark Fork River has been a subject of numerous studies by individual researchers, interdisciplinary teams and government agencies interested in a wide variety of aspects related to mine tailings, metal contamination, hazardous waste, and fluvial processes such as bank erosion.
Many investigators (Rice and Ray, 1985; Lejeune et al., 1996; CH2M Hill, 1987; RWRP 1996, 1996; Kaputska, 2002) have examined the effects of metal-contaminated soils in the riparian vegetation and concluded that metals in the floodplain sediments decrease the vigor of many plants, although some species, such as willows, seem to tolerate a high metal content in the soil.

Much attention has also been paid to the consequences of water contamination from mine tailings on fish communities. According to Phillips and Spoon (1990), frequent fish kills in the upper Clark Fork River occur during spring runoff and summer thunderstorms, when metals such as copper, arsenic, cadmium, zinc, and iron are washed out from the mine tailings, deposited in the floodplain sediments, and incorporated in the river.

Studies on the distribution, geochemistry, and stratigraphy of mine tailings and contaminated river sediments have been conducted by many researchers (Brooks, 1988; Moore and Luoma, 1990; Nimick, 1990; Axtmann and Luoma, 1991; and Schafer 1997), who observed that mine tailings are distributed throughout the floodplain, with the thickness and metal content varying from site to site.

Brooks (1988) reported variations or changes in the geomorphology of the floodplain attributed to a period of aggradation followed by degradation caused by a sudden increase of the sediment load during the mining stage (mine tailings) and a subsequent decrease of sediment input once mining ceased. R2 Consultants (1998) calculated erosion rates over the entire upper Clark Fork River basin, based on 1960 and 1989 air photos. Using a similar methodology of photo comparison, Swanson (2002) carried out a detailed analysis of three river reaches within the Deer Lodge Valley. Swanson calculated erosion rates by comparing multiyear sets of aerial photographs, in an attempt to describe floodplain variations through time and evaluate the processes driving the changes. After extensive and detailed analysis of aerial photographs combined with field work, he concluded that the outside of meanders in the study area erode at approximately 0.5m/year and that the net migration rate is 0.19 m²/m of river/year; this means that the river erodes approximately 740m²/year. Therefore, the amount of material that had been removed by meander bend erosion over the 54 year period covered by his research (between years 1947 and 2001) was 39,850 m². Swanson (2002) also used geochemical results from previously collected sediment samples (Moore and Woessner, 2001) to calculate the mass of excess metals being
added to the channel in the study area, and geochemistry data from another site (Brook, 1988) to estimate the metal load upstream of his study site.

No previous references for the area of study have been found so far that concern the analysis of planform dynamics aiming to model or predict future stream geometry and contaminated sediment recycling. This thesis addresses that topic.

Various approaches have been used in different study areas in order to address meander migration patterns. Many researchers have used mathematical and computational models to calculate stream migration in meandering systems (Duan et al., 1999; Duan et al., 2001; Wang and Jia, 2000; Guneralp and Rhoads, 2004). Yang et al. (1999) integrated remote sensing information and GIS to analyze channel migration in the Yellow River Delta, China; Viet et al. (2002) examined riverbank changes of the Mekong River, Vietnam, using similar techniques.

GIS has also been extensively used to model fluvial dynamics. Quantitative channel morphology studies were performed by Miller et al. (2000), combining extensive fieldwork with GIS. Agnella et al. (2003) defined potential channel migration areas by processing GIS data obtained from historical maps and aerial photographs. Haluska and O’Connors (2002) used GIS in order to determine temporal and spatial rates of channel migration for several rivers in western Washington. A methodology to predict channel migration using ArcView was introduced by Lagasse et al. (2003). Lortie et al. (2002) conducted a project in the Housatonic River, Massachusetts, investigating riverbank meandering using topographic maps and aerial photographs, to illustrate patterns, rates of erosion, and predict future rates in contaminated banks. Mainly studies have focused on changes of river geometry over short time periods, but little attention has been paid to long term migration prediction or the redistribution of contaminated floodplain sediments. Furthermore, no research addressing this matter has been specifically applied to the Clark Fork River and its contaminated floodplain.

As part of the remediation plan, the EPA (US Environmental Protection Agency, 2002) suggested planting vegetation both along the cutbanks and on the floodplain to decrease channel migration rates. However, according to Swanson’s (2002) research, erosion rates are already very low, only an average of 0.19m/year. Thus, vegetation will likely not have a great impact on retarding erosion. Furthermore, bank erosion will continue anyway at some rate; channels will migrate even when slowed by vegetation. Therefore, it is more
crucial to understand how the channel migrates and how long it will take to migrate while accounting for all the variables that might retard or accelerate this process (vegetation, time, floods, etc.).

**Area of Study**

The Clark Fork River begins on the western slopes of the Continental Divide near Butte, Montana, and flows north and northwest for about 320 miles ending in Lake Pend Oreille, Idaho. The 140-mile reach of the river between Butte and Missoula is known as the Upper Clark Fork River (UCFR) and constitutes the largest Superfund Site in the United States (US Environmental Protection Agency, 2002). Billions of tons of contaminated sediments lie along the banks and floodplains of this segment of the river (Moore and Luoma, 1990a), have turned this site into one of the worst environmental threats in the country (Figure 1.2).

The area of study is included within the Superfund site of the Upper Clark Fork River, in Grant-Kohrs Ranch National Historic Site, north of Deer Lodge, Montana (Figure 1.2).

*Figure 1.2. A. Layer of contaminated sediments along the banks of the Clark Fork River in the Grant Kohrs Ranch. B. Animal bone found in the margins of the Clark Fork River in the Grant-Kohrs Ranch area. Copper minerals from mine tailings have been deposited on the bone surface (green material).*
1.3). The Clark Fork River traverses the ranch from south to north, then turns to the west after Garrison, and continues to flow in a southeast-northwest direction toward Lake Pend Oreille in Idaho.

The 4-km-long reach of the Clark Fork River within Grant-Kohrs Ranch was the primary reach of concern in Swanson's thesis. He conducted a detailed study of the riverbank determining the erosion rate for that area. Swanson also used data collected from two other reaches located north and south of his main study area (Swanson, 2002), Garrison to the north and Racetrack reach to the south. Data and results obtained by Swanson were used in this study. The river channel in the Grant-Kohrs Ranch area has a low gradient (0.0020) and a meandering pattern with a sinuosity of 1.62 (Swanson, 2002). It is mainly composed of gravels and sand deposits (point bars, riffles, and pools). The floodplain occupies a large portion of the ranch.

**Objective**

Channel migration is a complex process that occurs when a stream moves or migrates across or within its channel bottom (Leopold et al., 1964). This involves lateral channel shift (horizontal movement) or vertical channel movement which takes place as the channel bed raises or lowers. Lateral channel migration is the result of erosion of the floodplain along one of the bank sides and consequent deposition of material along the other bank. This migration generally occurs gradually but it can also take place abruptly (usually during a flood episode) when the river abandons its channel and relocates taking a completely new path. Many variables control channel migration, and according to Lagasse and others (2003), these include: stream discharge, sediment load, longitudinal valley shape, bank and bed resistance to erosion, vegetation, geology, and human activity.

Meander migration is the major process that controls the redistribution of mine tailings in the study area, transferring the contaminated soil from the floodplain into the channel, contributing in that way to clean up the system by creating new point bars and floodplain with sediment from clean tributaries thus diluting the metal content. Understanding the dynamic of the meandering systems is therefore essential to predict not only the geometry and relocation of the stream in the future, but most importantly, the transport and redistribution of the contaminated soils.
The available data for the study area, including erosion rates, aerial photographs and current distribution of mine tailings, are analyzed and extrapolated using GIS in an attempt to predict the position that the river will have in the future and assess the effect of erosion and deposition in the redistribution of contaminated sediments. The main objective of this...
thesis is to predict how long it will take the Clark Fork River to remobilize the contaminated sediments that lay in the floodplain at Grant Kohrs Ranch by natural processes, and produce maps that show the potential future position of the channel within the Ranch.
Rivers are rarely straight for distances greater than ten times the width of the channel (Leopold et al., 1957). They tend to gain sinuosity in the horizontal plane as a mechanism of channel adjustment to different factors such as gradient and type and amount of load moved resulting in the development of very distinguishable channel patterns. Based on the sinuosity of the stream, Leopold et al. (1957) established a simple classification, recognizing three main types of channel patterns: meandering, straight, and braided or anastomosing (Fig. 2.1).

Figure 2.1. Planforms and cross sections showing the three main types of channel patterns (Modified from Rosgen et al. (1998).
This classification is based on the sinuosity of the stream, defined as the ratio between the channel length and the straight-line valley length. According to Leopold et al. (1964) a stream is classified as meandering if the sinuosity is greater than 1.5; if the sinuosity is less than 1.5, the stream is classified as straight. However, Schumm (1977) pointed out that a stream with a sinuosity as low as 1.2 can be considered meandering if the channel displays a repeating pattern of bends (Fig. 2.2). Brice (1984) considered as meandering streams those with a sinuosity value higher than 1.25. Braided streams are characterized by the presence of many channels that successively meet and re-divide leaving alluvial islands between the anastomosing channels (Fig. 2.1).

These well-defined categories are good to describe stream patterns at a reach scale rather than at the scale of fluvial systems, where drainage patterns (such as dendritic, parallel, radial, trellis, annular, etc.) are described. Channel patterns may change from reach to reach, gradually evolving from one category into another in response to changes in the channel conditions or processes such as gradient or sediment supply. This concept, first introduced by Leopold and Wolman (1957) and then confirmed by many other authors (e.g. Thorne, 1997; Knighton, 1998), postulated that natural channels form a continuous spectrum of patterns varying from single-channel straight, through multi-channel braided systems. The vast diversity of stream patterns that can be generated in between the three original categories (straight, meandering, and braided) led various authors to develop different classifications to describe the many types of channel patterns that can be observed in natural streams. Rust (1978) used the sinuosity and degree of channel division as factors to present a classification where four types of patterns are recognized (Figure 2.3).

Figure 2.2. Sinuosity and channel patterns (from Schumm, 1963).
Broader classifications differentiate subcategories derived from the original three types of channels taking into account not only sinuosity and division of channels but many other variables such as channel gradient, discharge, sediment size, degree of regularity, or load supply (Church, 1992; Brice, 1975; Brice et al., 1978; Schumm, 1977, 1981, 1985; Rosgen, 1994). Table 1 summarizes a classification of alluvial rivers by Schumm (1977) based on sediment transport, channel stability, and measured channel dimensions of rivers in the Great Plains of the United States.

Table 1. Classification of stable alluvial channels (after Schumm, 1977)

<table>
<thead>
<tr>
<th>Mode of sediment transport and type of channel</th>
<th>Bed Load (% of total Load)</th>
<th>Stable (graded stream)</th>
<th>Depositing (excess load)</th>
<th>Eroding (deficiency of load)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended Load</td>
<td>&lt;3</td>
<td>Stable suspended-load channel. Width-depth ratio &lt;10; sinuosity &gt;2.0; gradient relatively gentle</td>
<td>Depositing suspended load channel. Major deposition on banks cause narrowing of channel; initial streambed deposition minor</td>
<td>Eroding suspended-load channel. Streambed erosion predominant; initial channel widening minor</td>
</tr>
<tr>
<td>Mixed load</td>
<td>3-11</td>
<td>Stable mixed-load channel. Width-depth ratio &gt;10, &lt;40; sinuosity &lt;2.0, &gt;1.3; gradient moderate.</td>
<td>Depositing mixed-load channel. Initial major deposition on banks followed by streambed deposition.</td>
<td>Eroding mixed-load channel. Initial streambed erosion followed by channel widening</td>
</tr>
<tr>
<td>Bed load</td>
<td>&gt;11</td>
<td>Stable bed-load channel. Width-depth ratio &gt;40; sinuosity &lt;1.3; gradient relatively steep.</td>
<td>Depositing bed-load channel. Streambed deposition and island formation</td>
<td>Eroding bed-load channel. Little streambed erosion; channel widening predominant</td>
</tr>
</tbody>
</table>
A more exhaustive classification, also developed by Schumm (1981), is presented in Figure 2.4. He described fourteen patterns within three categories based on the type of load: suspended, mixed, or bed load. A simplified version of this classification is shown in Figure 2.5, where channel patterns are grouped in five basic patterns based on the type of sediment load, flow velocity, stream power and other variables that influence channel morphology (Schumm, 1985).

![Figure 2.4. Alluvial channel patterns (after Schumm, 1981)]
Brice et al. (1978) developed a classification based on the degree and character of three factors: *sinuosity* (Fig. 2.6 A, B), *braiding* (Fig. 2.6 C, D), and *anabranching* (Fig. 2.6 E, F). Sinuosity values range from 1.0 (straight) to approximately 3.0. The degree of braiding is expressed as the percentage of channel length that is divided by islands or bars. If a stream is divided by islands whose width is greater than three times water width at average discharge, the river is defined as anabranching (Brice et al., 1978). The degree of anabranching is measured as the percentage of reach length that is occupied by large islands. Later, Brice (1984) presented a classification scheme where four major planform properties are considered: sinuosity, point bars, braiding and anabraching (Fig 2.7). Figure 2.8 illustrates four major types of rivers presenting an association of the most common planform properties.

*Figure 2.5. Channel classification based on pattern and type of sediment load, with indication of relative stability (from Schumm and Meyer, 1979)*
A. **Degree of Sinuosity**

| 1. | 1-1.05 |
| 2. | 1.06-1.25 |
| 3. | >1.26 |

C. **Degree of Braiding**

| 0. | <5% |
| 1. | 5-34% |
| 2. | 35-65% |
| 3. | >65% |

E. **Degree of Anabranching**

| 0. | <5% |
| 1. | 5-34% |
| 2. | 35-65% |
| 3. | >65% |

B. **Character of Sinuosity**

1. Single Phase, Equiwidth Channel, Deep
2. Single Phase, Equiwidth Channel
3. Single Phase, Wider at Bends, Chutes Rare
4. Single Phase, Wider at Bends, Chutes Common
5. Single Phase, Irregular Width Variation
6. Two Phase Underfit, Low-water Sinuosity
7. Two Phase, Bimodal Bankfull Sinuosity

D. **Character of Braiding**

1. Mostly Bars
2. Bars and Islands
3. Mostly Islands, Diverse Shape
4. Mostly Islands, Long and Narrow

F. **Character of Anabranching**

1. Sinuous Side Channels Mainly
2. Cutoff Loops Mainly
3. Split Channels, Sinuous Anabranches
4. Split Channel, Sub-parallel Anabranches
5. Composite

---

*Figure 2.6. Classification of alluvial channels based on the degree and character of sinuosity, braiding, and anabranching (from Brice et al., 1978)*
Figure 2.7. Major planform properties of rivers (Brice, 1984)

Figure 2.8. Major types of rivers (Brice, 1984)
Rosgen (1994) proposed another classification that is widely used to describe natural streams. He presented a geomorphic characterization of streams types by describing their longitudinal profiles, valley and channel cross-sections, and planform patterns, delineating seven major stream types (A to G, Figure 2.9). Categories A, B, C, E, F, and G are single-thread channels, D includes multiple channels. Rosgen (1994) also proposed a morphological description and classification scheme based on entrenchment, gradient, width/depth ratio, and sinuosity of the streams. Within the broad stream categories A-G shown in Figure 2.9, there are six additional types defined by the type of material, grading from bedrock to silt/clay (Figure 2.10).

The stream reach of the Clark Fork in the area of Grant Kohrs Ranch has a sinuosity of 1.62 (Swanson, 2002), thus it falls within the category of a meandering stream and therefore this chapter will mainly deal with the characteristics of meanders.

![Figure 2.9. Stream classification delineation showing longitudinal, cross-sectional and plan views of major stream types (from Rosgen, 1994)](image-url)
MEANDERING STREAMS

It has been extensively demonstrated that straight channels tend to deviate naturally from their original path to follow a winding and turning course. Leopold et al. (1966) stated: "The striking geometric regularity of a winding river is no accident. Meanders appear to be the form in which a river does the least work in turning; hence they are the most probable form a river can take."

According to the Encyclopedia of Geomorphology (2004), "meandering refers to the spontaneous evolution of a single channel to high values of sinuosity." Strahler et al. (1978) define an alluvial meander as the "sinuous bends of a graded stream flowing in the alluvial deposit of a floodplain", while Whitlow (1984) describes a meander as "a loop-like bend in a river characterized by a river cliff on the outside and a gently shelving point bar on the inner side of the bend."

Geometry of Meanders

The characteristics of meanders have been the focus of study of many researchers who have not only described the morphology of the bends but also have tried to address

Meander bends have often been described qualitatively by identifying the different geomorphological aspects that are present. But, they have also been described quantitatively through the measurement of basic parameters (such as meander length, channel width, sinuosity, and radius of curvature) to identify the main attributes that characterize meander loops. Some of the most common descriptive morphological features in meanders are shown in Figure 2.11. Sediment accumulation occurs in the inner banks developing crescent-shaped depositional features called point bars (Fig. 2.11). The size and rate of development of the point bars may provide an indication of the intensity of bend growth and migration. The point bars are sometimes cut across by channels known as chutes. Chute channels are generally formed as a mechanism of short-circuiting during periods of overbank flooding or because of discharge fluctuations (Stolum, 1998). Pools are deep, flat areas created by scour and located in the outside of a meander bend. They generally contain fine-grained material like silt and sand. In contrast, riffles are formed with coarser-grained materials, such as gravel or larger bed sediments, that are accumulated during high flows. Both, pools and riffles generally form under turbulent flow conditions.

![Figure 2.11. Planform schematic view of a meander pair showing main morphological features (from Lagasse et al., 2003)](image-url)
Quantitatively, the characteristics of meander bends can be defined through the parameters shown in Figure 2.12. Although the idealized symmetrical planview of a meander as presented in figure 2.12 is hardly found in nature, the proportions between three fundamental dimensions such as repeating distance of the bend (either wavelength or channel length), channel width, and radius of curvature are very useful measurements to characterize meanders. Leopold et al. (1957) pointed out that meander length and channel width are empirically related to the discharge and therefore it can be postulated that there is an important relationship between both parameters, as there is also between channel width and radius of curvature. These correlations can be observed in Figure 2.13, which presents data from a large range of stream sizes, from one-ft-wide laboratory experiments to a one-mi-wide natural stream, the Mississippi river (Leopold et al., 1957; Leopold and Wolman, 1960). The exponents in the regression equations are so close to one that the relations between meander length (L) and channel width (w) and meander length and radius or curvature (R_c) can be considered linear.

\[ \begin{align*}
A & = \text{amplitude} \\
B & = \text{width of meander belt} \\
\lambda & = \text{wavelength} \\
L & = \text{length of channel} \\
R_c & = \text{radius of curvature}
\end{align*} \]

*Figure 2.12. Meander planform parameters*
Leopold and Langbein (1966) characterized the planform of meanders based on generalized geometric shapes finding that a sine-generated curve closely resembles the shape of an idealized river meander. However, they also pointed out that real meander curves are generally asymmetrical and considerably deviate from the idealized symmetry of the sine-generated curve due to the fact that meanders tend to migrate downvalley as they shift laterally. This has been also been proven after examining many models of bend shape, concluding that symmetrical models cannot reproduce the downvalley asymmetry that is characteristic of natural meanders (Ferguson, 1973; Carson and Lapointe, 1983).

**Flow Pattern in Meanders**

The pattern of flow in meanders varies with discharge, bend tightness, and cross-sectional form (Knighton, 1998). According to Knighton (1998), the main features of flow patterns in meanders reflect the interaction between a centrifugal force acting outwards on the water as it flows, and an inward-acting pressure gradient force driven by the cross-stream tilting of the water surface. The main flow patterns are shown in Figure 2.14 and are listed as follows:

a) superelevation of the water surface against the outer bank (Figure 2.14 B)
b) helicoidal or spiral flow directed towards the outer bank at the surface and towards the inner bank at the bed causing a strong secondary circulation superimposed to the main downstream flow (Fig. 2.14C)

c) a maximum velocity current that moves from near the inner bank at the bend entrance to near the outer bank at the bend exit, crossing the channel through the zone of greatest curvature (Fig. 2.14A(ii))

Markham and Thorne (1992) identified secondary currents located primarily in three regions of the channel cross-section:

a) mid-channel region. Approximately 90% of the flow passes through this region where helicoidal motion is well established (Fig. 2.14B and C).

b) outer bank region. Opposite circulation to the main helicoidal movement is developed in this region (Fig. 2.14B and C)

c) inner bank region. Outward transverse flow due to convective acceleration above the shoaling point bar (Fig. 2.14C)

Figure 2.14. Flow pattern in meanders. A. i). Location of maximum boundary shear stress ($\tau_{\text{b}}$), and ii) flow field in a bend with a well-developed bar (after Dietrich, 1987). B. Secondary flow at a bend apex showing the outer bank cell and the shoaling-induced outward flow over the point bar (after Markham and Thorne, 1992). C. Model of the flow structure in meandering channels (after Thompson, 1986). Black lines indicate surface currents and white lines near-bed currents. (from Kinghton, 1998)
Primary and secondary current patterns in meanders control the distribution of erosion and deposition. Erosion in a meander occurs in the outer bank downstream of the apex, where the currents are strongest, while deposition is concentrated in the opposite bank where building of point bars takes place. This erosion-deposition pattern contributes to downvalley meander migration (Knighton, 1998).

**Evolution of Meanders – Migration**

River meanders are very dynamic features that are constantly changing their planform and position as a consequence of the erosional-depositional processes that take place in their banks. This process, for which a stream channel moves across or within its valley bottom, is known as channel migration. As with bend geometry, there have been numerous attempts to describe the migration of meanders, both qualitatively and quantitatively. Qualitative descriptions try to depict the nature of movements and the changes in the bend position through time (Brice, 1974; Hooke, 1977; Knighton, 1998). Quantitative descriptions tend to quantify the movements observed by measuring some of the bend parameters, finding relationships between them, and comparing the results obtained in different sequences in time (Hickin, 1974; Hickin and Nanson, 1975; Larsen, 1995).

Channel migration can occur gradually due to continuous lateral shifting of the stream channel, or it can take place abruptly when the stream suddenly relocates as a result of a meander cutoff. The evolution of meander loops therefore involves downstream migration, increase in amplitude, and eventual cutoff at the neck (Brice, 1974). As Neill (1970) indicated, "free meanders enlarge laterally, then cutoff". The stream channel develops perpendicular to the valley axis incrementing the bend amplitude in a process known as meander growth and extension (Hooke, 1997). As the meander grows, the length of the stream is lengthened and the gradient is lowered. When the curvature of the loops becomes very high, short-circuiting due to cut-off occurs, the stream follows the shortest path and the loop is separated from the active stream and abandoned forming an oxbow. As a consequence, the river shortens and the gradient increases. This continuous process of lateral and downvalley relocation of the stream channel causes the floodplain to be constantly reworked by the natural river. Dune and Leopold (1978) asserted that river channels in alluvial plains have occupied every position in the valley floor at some point in the past due to lateral movement of the stream channel.
After analyzing the progressive development of meanders from sequential aerial photographs in 125 reaches of meandering streams in the United States, Brice (1974) illustrated and described the evolution of meander loops. Figure 2.15 schematizes the sequence of forms according to Brice, which are included in four main categories of loops: simple and compound symmetrical, and simple and compound asymmetrical. He arbitrarily defined a meander loop as an arc which has a length greater than its radius of curvature and does not exceed seven times its height (Fig. 2.15 A).

Modes of meander movement have been delineated and described by many researchers (Brice and Blodgett, 1978; Keller, 1972; Hooke, 1991; Hickin, 1974; Knighton, 1998). Brice and Blodgett (1978) examined the behavior of more than 200 sinuous and meandering stream reaches in order to analyze the mode of meander loop development. Results are shown in Figure 2.16.

Figure 2.15. Evolution of meander loops and classification scheme. Flow direction is left to right (from Brice, 1974)

The typical development of a low-amplitude loop, that decreases in radius while migrating downstream, is represented in Mode a. Mode b occurs where the stream is confined either by natural levees or by narrow valleys or floodplains. Mode c represents well developed meanders on streams that have moderately unstable banks. Larger loops on highly meandering streams are likely to follow mode d. Here, secondary meanders develop and the loop is converted in a compound bend because the meander has become too large in relation to stream size and flow. Meandering or highly meandering streams, usually of the equiwidth point-bar type, can also evolve in the pattern depicted in Mode e. The banks have been sufficiently stable for an elongated loop to form without being cut off, but the neck of the loop is gradually being closed and cutoff will eventually occur at the neck. Modes f and g apply mainly to locally braided, sinuous, or meandering streams having unstable banks. Loops are cut off by chutes that break diagonally or directly across the neck.

Knighton (1998) described four types of meander growth and shifting: translation, extension, rotation, and lobbing and compound growth (Figure 2.17). Translation occurs when the bend does not alter its basic shape but shifts position downstream; extension takes place when the bend moves mainly in the lateral direction, increasing its amplitude and path length; if the bend axis changes in orientation, rotation occurs.

Although these meander growth patterns exist in nature, it is not very common that bends translate downstream without any kind of deformation or that extension occurs without a downvalley component. Therefore, more complex meander growth patterns resulting from the combination of all these types of movements are more likely to be found in natural streams.

Figure 2.17. Types of meander growth and shift (from Knighton, 1998)
Some migration processes tend to occur during flooding events, such as avulsion and chute cutoffs, however, channel shift takes place regularly in most meandering streams and it is not related solely to periods of bankfull discharges. Neck cutoffs for example take place after a gradual increase of sinuosity of a single meander loop and after continued erosion in the bend apices. The complete sequence of meander development from initial bending to cut off is a process that can take from a few years to several centuries (Hooke, 1997).

Hikin and Nanson (1975) and Hickin (1978) suggested that a relationship exists between the bend geometry and the rate of migration. After an intense examination of more than 125 bends on 19 river reaches of the Beatton River in British Columbia, Canada, they demonstrated that the rate of migration reaches a maximum value when the ratio between the radius of curvature and the channel width is between 2 and 3. Further evidence confirmed the non-linear relationship between form and rate of change (Hickin and Nanson, 1984; Biedenharn et al., 1989; Hooke, 1987) as shown in Figure 2.18. Hooke (1997) stipulated that the rate of lateral movement is directly related to the size of the channel, the annual migration rate generally being 10% of the channel width, reaching sometimes up to 20%. Yet, other investigators have found no correlation between bend geometry and rate of migration (Parker, 1984; Furbish, 1988; Larsen, 1995)

![Figure 2.18. Relationship between migration rate and bend curvature (from Hooke, 1991)](image-url)
As observed in Figure 2.18, the migration rate decreases rapidly when the $R_c/w$ ratio becomes smaller than 2 or greater than 3. As the bend becomes tighter and the $R_c/w$ is less than 2, the migration decreases probably due to an increase in resistance or decrease in outer bank radial force (Knighton, 1998). If the $R_c/w$ is much less than 2, deposition might occur along the outer bank of the meander, the rate of lateral migration decreases sharply or migration stops and the bend cuts off or avulses. When the curvature is smaller ($R_c/w$ ratio greater than 3) shear stress induces a faster rate of migration in the upstream than in the downstream limb, causing a curvature increment. It can be deduced from these assertions that changes in the radius of curvature strongly influence the pattern of erosion-deposition and therefore the rate of migration of a stream.
CHAPTER III

METHODOLOGY

INTRODUCTION

Stream channels of meandering rivers are dynamic systems that are constantly modifying their planforms due to the erosion and depositional processes that take place in the margins of the channel as the water moves along the stream. In each meander bend, the water erodes the external bank while depositing material on the inner bank. As a result, the river channel wanders across the floodplain in a process that is imperceptible in the short term but is quite noticeable when it is observed over a longer geological time span.

Migration of river meanders has been the subject of numerous researchers and scientists, especially geomorphologists and engineers, since in many cases the movement of the bends can become a threat to man-made structures such as houses, bridges, buildings and other civil structures (Allmendiger et al., 2000; Booth, 1991; Lagasse, et al., 2001, Rapp and Abbe, 2003; Butler, 2004; Larsen, 1995; Brice, 1977, Hickin and Nanson, 1984; Ferguson, 1984; Hooke, 1984, 1997; Andrle, 1996; Downward et al., 1995).

Although much attention has been paid to meandering rivers, most of the studies have focused on understanding fluvial processes, delineating the morphology of meander loops, attempting to explain the reasons for meandering, and analyzing the mechanics of the migration process through modeling (Howard, 1996; Nagabhushanaiah, 1967; Sun et al., 1996), but not many studies have been conducted in order to predict the migration of meanders. Lagasse et al. (2003, 2004) developed a practical methodology to predict the rate and extent of channel migration in the proximity of transportation facilities, enabling engineers to evaluate the potential impacts of channel migration over the lifetime of bridges.
or highway river crossing. This methodology has been used to predict short-term migration of individual loops or reaches that might represent a hazard to bridges or other civil infrastructures, but it has not been previously used in long-term predictions. The present study attempts to apply this methodology in the Grant-Kohrs Ranch study area in order to predict the time that it will take the Clark Fork River to remove or rework the contaminated sediments along the banks of the river by natural processes of meander migration. The contaminated sediments cover the whole floodplain area and, therefore, that is the area that will be analyzed here.

The methodology makes predictions of potential future meander positions based on the behavior of the bend in the past, by comparing shapes and positions of meander loops in aerial photographs taken on at least two different dates. Lagasse et al. (2003, 2004) proposed the methodology using any of the three different techniques presented in their report: a) simple manual overlay to compare the position of banklines in two sequential aerial photographs or maps, b) photo comparison using the photo editing capabilities of computer-supported softwares such as Microsoft Word, Power Point, AutoCAD, ArcView or ArcINFO; and c) measurement and extrapolation techniques provided in two GIS-based ArcView extensions developed by Lagasse et al. (2004). These extensions are called Data Logger and Channel Migration Predictor and were especially developed to predict channel migration. The Data Logger extension is used to archive measurements and data from the bend that is being analyzed. The Channel Migration Predictor extension uses that data to predict the probable magnitude and direction of the bend migration at some specified time in the future. The present study used the Arc View extensions technique and, therefore, only details of this methodology are delineated in the following sections.

**BASIC CONCEPTS FOR APPLYING THE METHOD**

**Measuring Meander Migration**

Before attempting to predict channel migration it is important to define certain information that will be used to depict graphically the movement of a particular bend, and standardize the way the measurements will be taken. Each bend should be defined by:

- a starting point at the upstream end,
- an ending point at the downstream end,
the center of bend radius (bend centroid),
- an orientation with respect to a baseline (down valley direction), and
- an outside bank radius ($R_o$) (Fig. 3.1).

According to Lagasse et al. (2004), there are four modes of movement in meander migration: extension, translation, expansion, and rotation (Fig. 3.1). The outer bank of the meander will move to a new location resulting in a change of the meander position if any of these modes of movements affect the stream. Extension (Fig. 3.1a) can be measured at the bend centroid perpendicular to the downvalley direction and it represents across-valley migration; translation (Fig. 3.1b) is also measured at the bend centroid, but parallel to the valley direction since it represents a downvalley migration. If the bend expands (or contracts), the radius increases (or decreases) (Fig. 3.1c). Rotation occurs when the meander bend changes orientation with respect to the valley alignment (Fig. 3.1d). A combination of all these modes of movement is shown in Figure 3.1e.
The modes of movement can all be represented by vectors with magnitude and direction. By combining the vectors, a resultant can be obtained with a magnitude and orientation that symbolize the total movement of the outer bank. Figure 3.2 shows an example where the three vectors representing extension, translation and expansion have been computed to obtain the resultant vector termed "Apex Movement".

\[
\text{Extension} + \text{Translation} + \text{Expansion} = \text{Resultant Vector (Apex Movement)}
\]

\[R_{C_1} - R_{C_2} = \text{Expansion}\]

Figure 3.2. Meander bend movement (from Lagasse et al., 2003)

To find out the rate of movement of a bend in a certain period of time, it is necessary to locate the meander in two sequential aerial photographs for the desired time span, identify the valley orientation, find the bend centroid and measure the radius and its orientation relative to the downvalley direction. The bend centroid and the radius of curvature are defined after finding the circle that best fits the outer bank of the meander. The Handbook for Predicting Stream Meander Migration (Lagasse et al., 2004) provides in its Appendix B a detailed description for delineating banklines and best-fit circles in meander bends.

**Migration Prediction**

Trends of change in the direction and rate can be evaluated with more reliability if more than one period of analysis is used by examining more than two historical aerial photographs. For example, Figure 3.3 A depicts the banklines for three sequential years,
Year 1, Year 2, and Year 3. The amount and direction of movement during these periods of time must be calculated first in order to predict the amount and direction of migration in the future. The best-fit circles for the outer bank positions in Years 1, 2, 3 are shown in Figure 3.3B as well as the radius of curvature of each outer bank \((R_{c1}, R_{c2}, R_{c3})\) and the direction and amount of movement of the bend centroids, represented by the angles \(\theta_a\) and \(\theta_b\) and the distances \(D_A\) and \(D_B\) respectively. The subscripts A and B refer to the time period between two sequential years, in this case A is the time elapsed between Year1 and Year 2 and B is the intervening time between Year 2 and Year 3. C is the time period between Year 3 and Year 4 in the future, for which the bankline position will be predicted.

From Year 1 to Year 2, Period A, the radius of curvature of the outer bank will have changed and the ratio of change is defined by:

\[
\Delta R_{CA} = \frac{(R_{c2} - R_{c1})}{Y_A}
\]

where:

- \(\Delta R_{CA}\) = Rate of change in radius of curvature during Period A (m/yr)
- \(R_{c1}\) = Radius of curvature of outer bank in Year 1 (m)
- \(R_{c2}\) = Radius of curvature of outer bank in Year 2 (m)
- \(Y_A\) = Number of years in Period A
Likewise, for Period B (Year 2 to Year 3) the rate of change of the radius of curvature for the outer bank is defined by:

$$\Delta R_{CB} = \frac{(R_{C3} - R_{C2})}{Y_B}$$

where:

- $\Delta R_{CB}$ = Rate of change in radius of curvature during Period B (m/yr)
- $R_{C2}$ = Radius of curvature of outer bank in Year 2 (m)
- $R_{C3}$ = Radius of curvature of outer bank in Year 3 (m)
- $Y_B$ = Number of years in Period B

The position of the predicted radius of curvature of the outer bank in Year 4 is given by:

$$R_{C4} = R_{C3} + \left[ \frac{(R_{C3} - R_{C2})}{Y_B} \right] (Y_C)$$

where:

- $R_{C4}$ = Predicted radius of curvature in Year 4 (m)
- $R_{C3}$ = Radius of curvature of outer bank in Year 3 (m)
- $R_{C2}$ = Radius of curvature of outer banks in Year 2
- $Y_B$ = Number of years in Period B
- $Y_C$ = Number of Year in Period C

Figure 3.4 shows the direction and amount of movement of the centroid of the circle inscribing the outer bank given by the angle ($\theta$) and the distance ($D$) of migration for each time period. To define the angle of migration for Period C, two methods can be used, the first is to use the same migration angle for period B (i.e. $\theta_C = \theta_B$). The second method consists in using the rate of change of the migration angle from the previous period to define the rate of change for the period that is being predicted. For example:

$$\theta_C = \left[ \frac{(\theta_B - \theta_A)}{Y_B} \right] (Y_C) + \theta_B$$

where:

- $\theta_C$ = Predicted angle of outer bank migration for Period C
- $\theta_A$ = Angle of outer bank migration for Period A
- $\theta_B$ = Angle of outer bank migration fro Period B
\[ Y_B = \text{Number of years in Period B} \]
\[ Y_C = \text{Number of years in Period C} \]

For each period, the magnitude of migration for the bend centroid is \( D_A \) and \( D_B \). The rates of migration for periods A and B are calculated by dividing \( D_A \) and \( D_B \) by the number of years in the associated period. The amount of centroid migration for Period C is calculated more accurately using Period B, which is the most recent rate of centroid displacement by using the following relationship:

\[ D_C = (D_B/Y_B) \cdot Y_C \]

where:

- \( D_C \) = Magnitude of centroid migration for Period C (m)
- \( D_B \) = Magnitude of centroid migration for Period B (m)
- \( Y_B \) = Number of years in Period B
- \( Y_C \) = Number of years in Period C

Figure 3.4A shows the predicted radius of curvature, centroid, and predicted position of the circle that inscribe the outer margin of the stream for Year 4, while Figure 3.4B depicts the predicted margins of the river in Year 4.

---

**Figure 3.4.** A. Circles inscribing the position of the outer bank for the historical records 1, 2, and 3 and circle inscribing the predicted position of the bankline for year 4. B. Banklines for historical records 1, 2, and 3 and predicted position of the channel for year 4 derived from the position of the inscribing circle shown in sketch A (from Lagasse et al., 2003)
Data Logger and Channel Migration Predictor Extensions

The Data Logger and Channel Migration Predictor are ArcView extensions that were developed by Lagasse et al. (2004) of Ayres Associates for the NCHRP (National Cooperative Highway Research Program) Project 24-16 to simplify the measurement of bend migration data and assist with the prediction of meander migration. They were both created in Avenue, which is a programming language and development environment that comes with the ArcView software package. The extensions have not been updated for their use in the ESRI newer versions (ArcGIS 8.x or 9.x) and therefore they are only available for use in ArcView 3.x.

The Data Logger is used to gather data of the river planform for each bend and each historical record. That information is stored in a database file and then used by the Channel Migration Predictor extension to calculate the position of the river in a given future time. The bankline of the river reach to be analyzed must be digitized for at least two sequential years and saved in a shape file format prior to start using the Data Logger. For each bend to be examined and each historical record, the procedure using the Data Logger extension is as follows:

a. Registration of points outlining the bend along the external bank
b. Registered points are used to inscribe an arc of circle describing the bend radius of curvature ($R_c$) and orientation.
c. Measurement of certain bend planform parameters:
   - Channel width at three bend locations: upstream crossing and downstream crossing (ends of the bend), and bend apex.
   - Meander wavelength
   - Meander amplitude

All these dimensions are obtained using the GIS measurement tool provided in the ArcView software and registered in the Data Logger. Figure 3.5 depicts some of the measurements that are made and recorded with Data Logger. The parameters are defined as follows:

Radius of Curvature. Once 5 to 7 points are registered along the outer bank of the meander bend, from the beginning to the end of the meander (crossing points in Figure 3.5), a best-fit circle for the registered points is inscribed on the bend. The center point of that
circle represents the bend centroid and the radius of the inscribed circle describes the radius of curvature of the meander.

**Meander Bend Orientation.** The meander bend orientation is given by a line that extends from the bend centroid to a point in the outer bank arc halfway between the upstream and downstream crossing points (Fig. 3.5). The bend orientation angle is measured counterclockwise from a zero angle defined to be due east.

**Meander Wavelength and Amplitude.** The meander wavelength ($\lambda$) is represented by twice the length measured between the center point of the channel at the upstream end and the center point of the channel at the downstream end. The amplitude is represented by the distance along a line that extends from the wavelength line perpendicularly to the outer bank at the apex point. The apex point is defined as the point where the outer bank extends the farthest from the bend centroid.

**Channel Width.** Channel widths are measured from the top inner bank to the top outer bank at the end crossings and at the apex point. The channel width of the crossing in the data set is the average of the widths obtained in both end points.

![Figure 3.5. Some of the parameters measured using the Data Logger extension (from Lagasse et al., 2003)](image-url)
The Channel Migration Predictor uses the information that has been recorded in Data Logger to calculate and record the translation and extension rates for each bend and each historical period. If two historical banklines were registered, there will be one historical interval. Two historical periods result from using banklines of three historical records. The Channel Migration Predictor uses the extension and translation rates to estimate by extrapolation the position that each bend will have in a specified future date. In order to do so, some information must be provided, which includes: name of the file containing the data archived with Data Logger (.dbf file), number of historical records, bend number to analyze, date of desired bankline prediction, and site type. The site type refers to the category of meander the bend falls in within the classification developed by Lagasse and others (2003), which is outlined in the following section.

Meander Classification

As discussed in Chapter II, many classification systems have been proposed by various authors to categorize the geomorphological characteristics of river planforms. These classifications generally categorize rivers as straight, meandering, braided, or anabranching. However, none of the existing classifications completely met all the needs of the project for which the Data Logger and Channel Migration Prediction extensions were created. The objective of the NCHRP Project 24-16 was to develop a quantitative screening procedure to identify stable reaches (Lagasse et al., 2004) and classify sites by meander mode. After scrutinizing a broad range of classifications, Lagasse et al. (2003, 2004) concluded that the channel pattern classification originally developed by Brice (1975, reproduced in Figure 2.6, Chapter II) could provide the basis for the screening and classification they needed, and developed a new categorization by modifying Brice classification. The modified Brice classification proposed by Lagasse et al. (2004) is presented in Figure 3.6.

According to Lagasse et al. (2004) meandering rivers can be represented by a range of nine categories, which are depicted in Figure 3.6. They also stated that equiwidth rivers, such as those included in categories A, B₁, and G₁, could be considered as stable. River channels falling in the F category should be considered as potentially unstable and unpredictable, so the method could not be applied to this category. All the remaining classes, B₂, C, D, E, G₂, can be analyzed using the methodology proposed by Lagasse et al. (2004).
<table>
<thead>
<tr>
<th>A</th>
<th>SINGLE PHASE, EQUIWIDTH CHANNEL INCISED OR DEEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>B₁</td>
<td>SINGLE PHASE, EQUIWIDTH CHANNEL</td>
</tr>
<tr>
<td>B₂</td>
<td>SINGLE PHASE, WIDER AT BENDS, NO BARS</td>
</tr>
<tr>
<td>C</td>
<td>SINGLE PHASE, WIDER AT BENDS WITH POINT BARS</td>
</tr>
<tr>
<td>D</td>
<td>SINGLE PHASE, WIDER AT BENDS WITH POINT BARS, CHUTES COMMON</td>
</tr>
<tr>
<td>E</td>
<td>SINGLE PHASE, IRREGULAR WIDTH VARIATION</td>
</tr>
<tr>
<td>F</td>
<td>TWO PHASE UNDERFIT, LOW-WATER SINUOSITY (WANDERING)</td>
</tr>
<tr>
<td>G₁</td>
<td>TWO PHASE, BIMODAL BANKFULL SINUOSITY, EQUIWIDTH</td>
</tr>
<tr>
<td>G₂</td>
<td>TWO PHASE, BIMODAL BANKFULL SINUOSITY, WIDER AT BENDS WITH POINT BARS</td>
</tr>
</tbody>
</table>

*Figure 3.6. Modified Brice Classification (from Lagasse et al., 2003)*
APPLICATION OF THE METHOD IN THE STUDY AREA

Historical River Banklines

The first step in the process of predicting channel migration using Lagasse’s et al. (2004) methodology involves the collection of sequential historical aerial photographs of the area of interest, which are compared to evaluate the changes in the position of the river banks from year to year in order to calculate the rate and direction of migration.

The historical photographs used in this project correspond to years 1960, 1979, 1983, 1994, 1997, and 2001 and were collected from different sources, digitized and georeferenced by Swanson (2002). The 1960, 1979, 1983 and 1994 sets of aerial photos were provided by the Grant-Kohrs Ranch Park staff and the National Resource Conservation Service (NRCS) and were then digitized by Swanson at 600 dpi resolution. The 1997 photo was obtained from the EPA in digital georeferenced format, projected in UTM (Universal Traverse Mercator) coordinate system, Zone 12, NAD 27. The 2001 aerial photographs were specifically ordered for Swanson’s project; the area was flown and photographed by Map, Inc. in June 2001. The 2001 photographs were then digitized at a resolution of 1200 dpi. The digital versions of all images were uploaded in ArcView to be georeferenced by matching fixed points in the images (roads, fences, corners of structures, vegetation, etc.) to the same features in the 1997 photo using the ArcView Image Analyst extension (Swanson, 2002).

Once digital versions of all images were registered, the banklines were delineated and digitized in ArcView for each historical record. Some examples are shown in Figure 3.7.

Figure 3.7. Digitized banklines on aerial photographs of the study area for four different historical records.
Testing the Software

In order to evaluate the accuracy of the prediction, the software was tested by using two of the historical records available to predict the position of the banklines for a year coincident with the most recent historical record available (year 2001) and compare the predicted channel with the actual position of the banklines. The period of time involved between the oldest and most recent sets of aerial photographs available was 41 years (years 1960 and 2001 respectively), so the time interval between the two historical records used as data should be in the order of 20 years, therefore the historical records chosen to make a prediction for year 2001 were the years 1960 and 1983.

Data Logger

To start using Data Logger, the riverbank lines from the two different historical records, years 1960 and 1983, were loaded in ArcView. Additional data that must be entered in the dialog box when Data Logger is launched include the number of bends to be analyzed (24 in the study reach) and the date of the aerial photos used for the prediction (Figure 3.8).

Once the data is entered, the Data Logger creates two empty shape files per bend (one for each historical record) and a database file where the measurements will be registered. The shape files are filled when each bend is delineated with points along the outer margin of the meander (Fig.3.9A). A circle inscribing those points is subsequently created (Fig.3.9B), with demarcation of the bend centroid and direction of the radius of curvature. Measurements of the parameters can then be made. Figure 3.9C depicts some of the parameters that are measured. U-U indicates the place where the width of the channel has been measured at the upstream end of the
meander; D-D shows the point where channel width was measured at the downstream end; while the point where the channel width was measured at the apex is denoted by A-A. The length of line extending from the center of the channel at the upstream end to the center of the channel at the downstream end represents half the value of the wavelength (½ λ). The amplitude is the distance measured along a line extending perpendicular from the wavelength line to the point where the apex was measured in the outer bank. This procedure is repeated for the same bend in the second historical year, and then for all the bends in the reach.

Figure 3.9. Example of bend delineation (A), best-fit circle (B), and parameters measured (C) using the Data Logger extension.
Channel Migration Predictor

The Channel Migration Predictor extension is used when all the parameters for the bends that are to be analyzed have been recorded with the Data Logger extension. Also, it is necessary to provide information about the type of bend that is being analyzed according to the modified Brice Classification proposed by Lagasse et al (2003). For the study area, almost all the bends fall within category C of the classification (Figure 3.6), this is single phase, wider at the bend, with point bars.

This extension uses the data registered in the database file to calculate the translation and extension rates for each bend and each historical record, making each prediction one bend at the time. Once all the calculations and predictions are done, the Channel Migration Predictor creates three new shape files containing the circles that inscribe the banklines for the bends in each historical year and the circle inscribing the predicted bankline. Figure 3.10 shows the circles for two historical records, and the predicted circle for the year 2001. The position of the channels for the two historical records and the actual 2001 historical record are also shown.

The Channel Migration Predictor does not provide the actual position of the predicted channel; instead it presents the circles inscribing the predicted position of the bends. Each circle is defined by the magnitude and orientation of its radius of curvature. The position of the predicted channel can be inferred using this information.

For the study area, the methodology used to outline the position of the predicted channel was the following: Once the prediction for all the bends was done, the banklines for
the two historical records used as data, as well as the predicted circles for all the bends, were uploaded in ArcMap 9.0. A new empty shape file was created in ArcCatalog to contain the new predicted bankline. With the aid of the editing tools, the bankline was demarcated using as a reference the position, size, and orientation of the predicted circles, as well as the delineation of two historical banklines, trying to maintain the same channel width as the two original banklines. Periodically the position of the predicted channel was double-checked using as a reference the migration rates estimated by Swanson (2002). Some of the other tools needed for the delineation of the predicted channel are not provided with the software but were part of the user’s skills and they include: patience, art aptitude, and common sense.

Minor problems or errors were detected in the predictions for a few bends that have shapes that are not very “conventional”. These bends are not sinusoidal and contain bars in the channel, which interfered with the measurements, especially when measuring the channel widths, causing an error in the migration prediction. An example in Figure 3.11 depicts in the lower left corner two “conventional” bends and the real and predicted circles that are very similar in size and position, demonstrating that the method works without problems in those cases. In the center of the figure, a non-conventional bend is shown and an error is observed. The two historical records show that the bend is migrating mainly by extension (toward the west), but also with a smaller downvalley translation component. This is confirmed with the actual position of the channel in year 2001 (Figure 3.11). However the predicted circle suggests a movement in the opposite direction (to the east). As mentioned above, it is concluded that the error could be related to the geometry of the bend and to interference by the islands when measuring the channel width.

Figure 3.11. Example of an “unconventional” meander with bars interfering the measurements (upper right). Two “conventional” bends are shown in lower left. Real and predicted best-fit circles for year 2001 are also shown.
at different points. Apart from this problem in a few locations, no major errors were
detected with the prediction, and close coincidences between the real circles and the
predicted ones were observed (Figure 3.12). A more thorough assessment of the error is
discussed in the next section.

**Error Evaluation**

By visually comparing the size and position of the circles inscribing the outer banks
of the real channel and
the predicted channel it
is possible to estimate qualitatively the magnitude of the error. Figure 3.12 shows the outline of the real channel for year 2001 and the real and predicted circles. The main differences that can be observed at first glance are detected in the size of the circles, given by their radii of curvature, and in the position or orientation of the radii of curvature. These are the parameters used to make a quantitative evaluation of the error when applying the methodology of Lagasee et al. (2003). The first

![Figure 3.12. Comparison of real and predicted circles for the year 2001 historical record](image)
estimation of the error was done by comparing the length of the radius of curvature for the real circle against the length of the radius for the predicted circle for each bend. These values for the twenty-four bends are plotted in the diagram shown in Figure 3.13. A total coincidence in the length of the radius for both circles is represented by the red line. All values falling under that line represent an underestimation in the prediction. Values above the red line signify an overestimation in the length of the radius of curvature of the predicted circle. The dashed blue lines represent an error of 25% in the prediction, either under or over estimation. This means that the predicted circle has a radius that is 25% smaller or bigger than the real circle. All values falling within the area enclosed by those lines represent an error less than 25%. As depicted in Figure 3.13, seven of the predicted circles were estimated with an error larger than 25%, three of them by underestimation and four by overestimation; eight of the predicted circles were estimated with an error between 10 and 24%; and the rest had an error less than 10% with one total coincidence and four circles having an error of 1% only.

Comparing the length differences of the radii curvature between the real and predicted circles is not enough information to evaluate the error because two circles might have the same radii of curvature but they could be "facing" completely opposed directions. Therefore, the radius of curvature orientation of the real and predicted circles also needs to be compared. The angles where measured from 0° to 360° with the 0 in the North and increasing in a clockwise direction. The values of the radius of curvature orientation of the
real circle are plotted against the angle of the radius of curvature orientation for the predicted circle for each bend (Figure 3.14). Again, the red line represents 100% coincidence in the orientation of the radii of curvature for the real and predicted circles. However, in this case not all the points that lie above the red line indicate an overestimation in the prediction. For values of the real \( Rc \) less than 180°, the points located below the red line indicate an overestimation. This is because it is assumed that the bends tend to migrate across and/or down valley. Since the flow direction in the study area is from South to North that means that the bends would tend to migrate in the East-West direction and northward. If the angle of the radius of curvature of the real circle is less than 180°, a predicted circle with a radius of curvature orientation smaller than that of the real one, would signify an overestimation in the prediction. Contrarily, if the orientation of the real radius of curvature has an angle between 180° and 360°, a predicted circle with an angle of orientation of the radius of curvature larger than the one of the real circle signifies an overestimation in the prediction. Consequently, in the graph shown in Figure 3.14, values represented above the red line for \( Rc \) orientation (x-axis) less than 180° indicate overestimation. If the angle of orientation of the \( Rc \) is larger than 180°, values lying above the red line indicate underestimation.

![RADIUS OF CURVATURE ORIENTATION](image)

*Figure 3.14.* Radius of curvature orientation comparison between the real and the predicted circles.
The error for each of these values was also calculated, assuming that a 100% error would mean a radius of curvature for the predicted circle oriented in the opposite direction (a difference of 180°) than to the real circle. Figure 3.14 depicts the values for the 24 bends (Rc orientation of real circle against Rc orientation of predicted circle). Also the lines indicating errors of +/- 10% (dotted blue line) and +/- 25% (dashed-dotted yellow line) are represented in the diagram. Only one of the bends shows an error larger than 25%, and four bends show an error slightly over 10% (11 and 12%).

A comparison using exclusively radius of curvature lengths and orientation still does not define completely the error in the prediction, since two circles could have the same radius of curvature and same orientation but they could be parallel, so there could be a difference in the prediction of the extension or translation movements. For that reason, a third approach was taken to evaluate the prediction error. This was done by comparing the points of intersection of the perimeter of the circle with the radius of curvature for both circles (the real and the predicted) and tracing a vector joining the point of intersection in the predicted circle to the point of intersection in the real circle (Figure 3.15). The vector represents the total difference in movement between the real and the predicted circles. This vector can also be represented by its horizontal and vertical components, which symbolize the extension and translation movements, respectively, considering that the area of study has a flow direction from South to North and assuming that extension movement is in the East-West direction (across valley) and that the translation movement is in the down valley or north direction. The angle between the radii of curvature of the real and predicted circles would represent the difference in the rotation movement. A
vertical vector would represent an error in the translation prediction solely, while a horizontal vector represents error in the extension prediction. The magnitudes for the translation and extension components of the migration error vector for each bend were measured and plotted in Figure 3.16. The rotation error (angle between the radii of curvature of the real and predicted circles) is also shown in Figure 3.16. The bend numbers are represented in the x-axis, while the magnitude for the translation and extension components are plotted in the y-axis in meters, as well as the rotation error, which is plotted in degrees. The negative values symbolize underestimation errors, while positive values represent overestimation errors. As observed in the graph, twenty one of the twenty four bends have errors smaller than 25 meters or degrees, which is completely acceptable for the prediction.

![Figure 3.16. Total prediction error represented by the extension, translation and rotation differences between the real and predicted circle positions.](image)

**Short-Term versus Long-Term Prediction**

The Channel Migration Predictor extension was conceived to make short term predictions that would evaluate the threat of civil structures collapsing due to meander migration. The objective of the present study, however, was to make long term predictions to assess the amount of time that the Clark Fork River would need to remove or rework the contaminated floodplain by natural processes.
Initially, the extension was evaluated for a long-term prediction (year 2500) using as data the oldest and most recent historical records available, years 1960 and 2001 respectively. The results obtained were not satisfactory since the resulting planform was unrealistic and did not reflect how natural fluvial systems actually work, because the predictions are made bend by bend, ignoring how the neighbor bends behave. For this reason, cutoffs were not taken into account in the software and the meanders could evolve indefinitely without experiencing any cutoff. Figure 3.17 shows an example of a long term prediction. In the left diagram, the predicted circles are shown in red and the predicted channel according to the position of the circles has been sketched in light green.

Figure 3.17. Long term channel migration prediction

The diagram in the right depicts the predicted channel after the cutoffs and the abandoned meanders or oxbows drawn separately (shown in yellow). The path of the river
after the cutoffs observed in the almost 500-year prediction was unrealistic. This was probably because during the 500 year time period involved in the prediction there would have been many situations in which the river could take new paths due to cut offs, but these possibilities have not been considered by the program. For that reason it was concluded that the period of time involved between the last historical record used for the prediction and the prediction date should not be much larger than the period of time involved between the two historical records used for the prediction.

Thus, for this study the predictions were made for 50-year intervals. The first prediction was for year 2050; once the predicted channel for year 2050 was drawn using the predicted circles as a reference, that record and the previous historical record (in this case year 2001) were used for the next prediction and so on. Results are discussed in next chapter.
CHAPTER IV

RESULTS AND DISCUSSION

Introduction

Channel migration has been discussed by various authors who mainly studied meander shift qualitatively describing the changes in the geometry of bends due to meander shift (Brice, 1974; Hooke, 1987). Quantitative methods have also been used to measure meander migration (Hickin, 1974, Hickin and Nanson, 1975; Larsen, 1995) and many mathematical and computational models have been proposed to predict or analyze the migration of meanders (Guneralp and Rhoads, 2004, Duan et al., 1999; Duan et al., 2001, Johannesson and Parker, 1985, Larsen, 2005, Lancaster and Bras, 2002). Nevertheless none of these studies have considered long-term predictions.

Larsen (1995) studied the Mississippi River and concluded that meandering bends of this river need at least 1000 years for a complete evolution from straight channel to cutoff. He also pointed out that channel migration values greater than the channel width occur over a time span of decades or even centuries. In his study of the Clark Fork River at Grant Kohrs Ranch, Swanson (2002) estimated that the erosion rate of the meanders in that area is approximately 0.5 m/year and that the net migration rate is about 0.19 m²/m of river/year. However, it is clear that a long-term prediction is needed in the present study since the objective is to predict the time that will take the river to rework the floodplain by natural processes of channel migration.

Approach

Predictions for the study area were done ultimately by 50-year intervals, using the oldest and most recent historical records that were available as the initial data, years 1960 and 2001 respectively. The first prediction was for year 2050. The second prediction used the
historical record 2001 and the 2050 predicted channel as data to predict for year 2100. The next prediction used the predicted channels for years 2050 and 2100 to predict the position of the channel for the year 2150. The position of the channel for year 2200 was predicted using as data the predicted outline of the channel for year 2100 and 2150. After that, the following predictions were done for 100 year-intervals, using as data the two most recent predicted channels over a time span of 100. Thus, the prediction dates include years 2050, 2100, 2150, 2200, 2300 (using years 2100 and 2200 as records), 2400, and 2500.

Some assumptions were made in the prediction process:

- The Clark Fork River reach that is the subject of this study is not restricted by natural or man-made confinements, such as valley walls or levees that would contain or control the free migration of the meanders.
- All the meanders considered for the analysis fall within the category C of the modified Brice Classification proposed by Lagasse et al. (2004). This is not completely true for all the bends, especially the ones that have islands or bars. However, because that type is not contemplated in any of the categories proposed by Lagasse et al. (2004), for the purpose of this study all bends are regarded as being within category C.
- No major periods of flooding occurred during the prediction periods (2001-2500) that would short-circuit the meander process.
- The predicted channels have a similar channel width as the channels used for data.
- The area that will be used as reference to evaluate how long it will take the river to remove the contaminated sediments is the area occupied by the floodplain since it is assumed that is the zone covered with contaminated sediments.
- Although the sedimentation/erosion process occurs continuously, and it is known that contaminated sediments that are being eroded from banks upstream of the study reach could possibly be redeposited in areas of the floodplain at Grant Kohrs Ranch, it is assumed that when the floodplain was reworked by the stream at least once, no more contaminated sediments will be deposited on it.
Correlations of bend geometry with meander shift are not analyzed here since that is outside of the scope of the present study. The only characteristic of the channel that is used for comparison in the prediction is the relative position of the bends as compared to the positions observed in the historical records or predicted channels used as data.

Description of Results

As mentioned above, the first four predictions were done for a 50-year interval. Results obtained after analyzing these predictions showed that there were no sites in the reach where cutoffs could occur within the next 50 years or even more and therefore intervals of 100 years could be used for predictions after year 2200.

The predicted channels are depicted in figures 4.1, 4.2, 4.3, and 4.4. The floodplain is also shown to visualize how the migration of the meanders is progressively eroding the area occupied by the floodplain. The analysis began with the migration prediction for a total of 24 bends. However this number changed with time, since the stream was gradually modifying its length and shape, becoming more tortuous with time as sinuosity increased. By year 2200 the number of bends analyzed had increased to 28, but near the time of the first cutoff, which took place approximately in 2300, the number of bends considered for analysis decreased to 18.

Visually, one of the most obvious characteristics of the variations in the position of the channel through time, is that portions of the study reach are more active than others. This was indicated not only by the higher degree of sinuosity of the more active portions at a specific year, but also by a faster increment in the sinuosity through time in those areas as compared to the less active areas. According to the degree of sinuosity, three distinctive zones are differentiated: Zone A, Zone B, and Zone C. Figure 4.5 portrays the position of the channels in the three zones for the years 2001 and 2200 (before the first cutoff occurred).

Zone A has a low sinuosity and it may be included within the category of a straight channel according to the definition proposed by Leopold et al. (1964). The sinuosity for this portion in year 2001 was 1.084 and by 2200 it only increased 0.91% to 1.094. Zone B is composed of two portions of the study reach that were distinguished as having a similar
Figure 4.1. Channel migration prediction for year 2050, using years 1960 and 2001 as historical records.
Figure 4.2. Channel migration prediction for years 2100 and 2150
Figure 4.3. Channel migration prediction for years 2200 and 2300.
Figure 4.4. Channel migration prediction for years 2400 and 2500
behavior, with high sinuosity but not very intense activity as demonstrated by a moderate increase in sinuosity through time. The sinuosity for Zone B was 1.675 in 2001, combining the two portions shown in Figure 4.5 as Zone B, and increased to 1.918 in the predicted channel for year 2200, an increment in sinuosity of 14.47%. Finally Zone C, the most active portion of the study reach, is characterized by moderate to high sinuosity values and high increase in sinuosity through time. In year 2001 the sinuosity of the channel in portion C was 1.877 and by year 2200 the sinuosity had increased almost 62% to 3.038.

Sinuosity values for the three zones for years 2001 and 2200 are shown in Figure 4.6 where the increments in sinuosity through time can clearly be observed for the three different zones.

Variations in sinuosity though time have also been analyzed for the whole study reach. The study reach had a sinuosity of 1.52 in year 1960, but gradually increased as meander migration progressed (Figure 4.7)

Figure 4.5. Zones of the study reach characterized by different levels of activity as demonstrated by the variation of sinuosity through time.
In year 2001 the sinuosity was 1.62 and by year 2200 the predicted sinuosity reached the highest value, 2.24. In year 2300 or shortly before that the first cutoff occurred and the sinuosity value decreased considerably at 1.93 (Figure 4.7). Then the sinuosity continued increasing but in year 2500 or shortly before, another cutoff took place. In this case the sinuosity did not drop noticeably as it happened in year 2200. Although there is shortening of the stream due to cutoff, at the same time there was lengthening of the stream in other places as a result of meander migration and, therefore, the total length of the stream remained almost the same and the sinuosity had only increased 0.01. All the sinuosity values of the stream at the study reach for the different historical or predicted records are presented in Table 4.1.
Table II. Variation of Sinuosity through time for the study reach

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</tbody>
</table>

As the meandering stream migrates and the sinuosity increases, new paths are taken and the floodplain is gradually and continuously been remobilized. By comparing the different positions that the stream has taken through time and measuring the areas of the portions of the floodplain that have been affected at least once by the path of the stream, it is possible to calculate the time that will be needed for the channel to rework all of the contaminated floodplain. Figure 4.8 shows the position of the channel for all the historical records and the predicted years, as well as the area covered by the original floodplain (red outline). This area includes only parts of the original floodplain and also contains zones that are not part of it. In Figure 4.9, the yellow line enclosing the position of all channels from 1960 to 2500 (yellow outline) represents the area that has been affected by the path of the stream at least once by year 2500. Figure 4.10 shows the extent of the original floodplain (red dots), the area that has been predicted as being remobilized by the path of the stream from years 2001 to year 2500, and the portions of the original floodplain that have not been reworked by the stream by year 2500 (green). The total area of the original floodplain for the study reach is approximately 544,400 km². After the year 2500, 381,800 km² of sediments would be removed by the path of the meandering stream, however, only 261,100 km² will be part of the original floodplain as shown in Figure 4.8. This means that 47.95% of the total area covered by the floodplain would be removed by natural processes of meander migration, thus at least 540 more years would be needed to remove the whole floodplain.
Figure 4.8. Position of the Clark Fork River channel at Grant Kohrs Ranch for historic records 1960 – 2001 and predicted position for the years 2050 to 2500.
Figure 4.9. The red outline shows the area covered by tailings in year 2001. The yellow line indicates the area that will be removed by year 2500 according to the results of the predictions, and the green area represents the portions of the floodplain that will not have been removed by the path of the stream by year 2500.
Figure 4.10. Historical and predicted channel positions at Grant Korph Ranch. Original floodplain represented with red outline, the yellow line enclosed the area that will have been removed by the year 2500, and the green area symbolizes the sectors of the original floodplain that will have not been reworked by year 2500 according to the predictions.
CHAPTER V

SUMMARY AND CONCLUSIONS

The methodology introduced by Lagasse et al. (2003, 2004) was designed for predicting short-term meander migration and had never been used before for long-term predictions. For the present study, the methodology was first tested using two sets of aerial photographs of the area, dated 1960 and 1983, to obtain the digitized margins of the stream and use them as input data to predict the position of the channel for the year 2001, the most recent historical record available. The results obtained for this prediction were acceptable and the margins drawn using as reference the predicted circles inscribing the position of the bends matched quite closely with the real position of the bends for the year 2001.

When the method was applied in a long-term prediction, using as data the oldest and most recent historical records available for the Grant Kohrs area (1960-2001) to predict the position of the channel 500 year later, the results obtained were not realistic because the methodology does not contemplate situations in which the stream abandons meanders by cutoffs. For that reason, shorter term predictions were made and the resulting predicted channel was then used as data to predict the positions of the stream for later dates.

The application of the method in steps, using as input data the positions of the channel that had been obtained by prediction instead of real historical records, inevitably introduces errors that are carried to the ensuing predictions. However, the results obtained applying this methodology do not seem as unrealistic and are much more reliable than results obtained when using the method in one step. The input introduced by the user becomes essential when deciding that cutoffs should take place and that the channel would bypass the meander taking a completely new path; this fact would otherwise be ignored by the software. Figure 5.1 shows a comparison of the results obtained for predictions using short-term intervals with results obtained using a long-term interval.
Advantages and Disadvantages of the Methodology

Some of the advantages of the methodology developed by Lagasse et al. (2003) for predicting channel migration are listed below:
The best fit circle is inscribed by the software eliminating the biases introduced by the user when trying to find the size and position of the best-fit circle.

The extensions are simple and easy to use once the methodology is understood and the software learned.

Although the methodology is tedious when applying it to a reach with many bends and making many predictions, it is much faster than applying manual methods to calculate migration predictions.

Some of the problems encountered while using the software as well as some disadvantages of the methodology are pointed out below:

- The extensions were developed for ArcView 3.x and have not been updated for the newer versions of ArcGIS 9.
- Because the meanders are not perfectly shaped, sometimes it was difficult to decide where exactly take the measurements, such as upstream, downstream, and apex channel width.
- Slightly different values were obtained when taking the measurements twice in the same bend, even when done by the same user; thus some errors are introduced during the measurement stage.
- A default name is given for the empty shape files that will contain the outline of the bends and the best fit circles, as well as for the files containing the predicted circles (i.e. bend1-year1, predictedcircle_1). The program does not allow the user to rename the files or to choose the folder where to store them. When a new project is started, if the user did not create a new folder for that specific project, the files will be overwritten without previous warning.
- The product obtained after applying the methodology is the position and size of the circles inscribing the predicted bends. Therefore the actual outline of the channel need to be drawn by the user, whose common sense and ability to reproduce the margins of the channel as close to reality as possible become the crucial tool for obtaining acceptable results.
- Predictions are made individually for each bend, therefore the influences of the neighbor bends are not taken into account by the software.
Migration Patterns

The Clark Fork River is a typical meandering stream with a continuously changing planform due to meander shift. The reach in the Grant-Kohrs Ranch area is not an exception and has evolved in shape through natural processes of river channel migration that take place because the stream erodes the outer bank and deposits sediments in the opposite side. This process not only produces a change in the bend planform but most importantly, constantly changes the location of the channel within the valley. The pattern of meander migration is influenced by many factors such as the shape of the local bend, the planform shape upstream, flow characteristics, and bank erosion potential (Johannesson and Parker, 1985).

Unless constrained, all meanders naturally tend to migrate downstream and across valley gradually changing shape and location. The grade of sinuosity of the bend generally has a direct impact on the migration component that will prevail, as noted by Brice (1974), Hooke (1984) and Larsen (1995). Lower sinuosity bends tend to migrate more in the down-valley direction, while higher sinuosity bends tend to extend in the cross-stream direction. This pattern has been observed at Grant Kohrs Ranch, which is characterized by three distinctive zones defined by their sinuosity degree (Figure 4.5): Zones A, B, and C; where Zone A has the lowest sinuosity (straight channel) and Zone C has the highest sinuosity values, as discussed in Chapter IV. Migration in the short-term analysis is not very perceptible in Zone A, however, in longer-term observations it has been noticed that down-valley migration dominates over cross-stream movement (Figure 5.1). In Zone B, with moderate sinuosity, downvalley migration seems to dominate over crossvalley migration in the short term analysis, especially in the southern bend shown in Figure 5.2. The northern bend does not seem to be affected by migration in the short-term analysis, even when the bend has a high sinuosity. This is because the bend is constrained by a levee located in the north of the bend (Figure 5.2). For the long-term analysis, a cross-stream dominant migration component is observed. The presence of the levee was ignored for the prediction, since one of the assumptions was that the bends could freely meander without any human or natural interference.

In Zone C, where the sinuosity values are higher, cross-stream migration dominates, as shown in Figure 5.3. However, in this example there are two bends where migration has an upstream component as observed in Figure 5.3. The position of these bends influences
the migration pattern of the immediate contiguous bends, which have a strong downvalley migration component even when their sinuosity is high.

Figure 5.2. Migration pattern for a straight subreach within the study area. Short term vs. Long-term migration (Zone A).

Figure 5.3. Migration pattern for a subreach of moderate sinuosity within the study area (Zone B). Short-term vs. Long-term migration.
The changes in bend shape are manifested by the tendency of the meanders to increase the bend amplitude with the consequent increment in channel sinuosity. The meanders extend so far and eventually become so tight that cutoffs occur, producing an abrupt change of the channel location by bypassing the meander loop that is finally abandoned. During the 500-year period analyzed for prediction in the present study, a total of six meander loops were predicted as being abandoned by neck cutoff. The sinuosity of the predicted channel changes regularly with time, increasing gradually as migration progresses. The sinuosity curve shown in Figure 4.7 of the previous chapter shows several instances when cutoffs occur with a sudden drop of sinuosity or with no apparent increase in sinuosity (i.e. year 2500).

**Future Research Opportunities Using this Methodology**

As previously mentioned, the methodology developed by Lagasse et al. (2003) was created to be used by engineers to make short-term predictions of bends that might be a threat for civil structures, and it had never been used before for long-term predictions. As demonstrated in this project, the methodology works for long-term predictions if the predictions are made using short-term intervals. Applied in that way, this methodology would represent an excellent tool in planning since it could be used to predict the migration
pattern of streams that are close to cities or developments and help to decide where is the best place to construct a bridge or any other civil structure or where not to build.

Also it would be very interesting to test if the methodology could be used to make backward predictions and find out what was the path of the stream in the past. If the methodology works backwards, it would be very useful for prospecting gold, platinum, or other heavy metal placer deposits.

Conclusions

The continuous process of meander migration results in the constant removing and redispersing of sediments on the floodplain while the stream shifts its position along the valley. According to the estimated predictions for the present study, the Clark Fork River will need at least one thousand years to remove or redispersing the contaminated sediments deposited in the floodplain at the Grant Korhs Ranch site. This is assuming that no more contaminated sediments are being deposited on the floodplain while this process takes place. Nevertheless, it is well known that the source of contaminated sediments is still active, since upstream of the study area there are banks containing layers of mine tailings. These are being continuously eroded, adding to the stream certain amount of metal-contaminated load, which is later redeposited downstream reinitializing the process. Therefore, the stream will need to redispersing the floodplain sediments more than once in order to completely deplete the area of contaminated sediments.

The application of the methodology to predict channel migration of the Clark Fork River at Grant Korhs Ranch has demonstrated that it will take the stream thousands of years to rework the floodplain loaded with metal contaminated sediments. Evidently, the river natural process of channel migration is not the most efficient method to eliminate the mine tailings from the area. Other actions need to be taken in order to clean up the polluted system if quicker remediation is desired.
REFERENCES


Kohrs Ranch National Historic Site, U.S. National Park Service, Department of Interior, 36p.


