GEOSPATIAL ANALYSIS OF GRAVEL BAR DEPOSITION AND CHANNEL MIGRATION WITHIN THE OZARK NATIONAL SCENIC RIVERWAYS, MISSOURI (1955-2003)

A Thesis
Presented To
The Graduate College Of
Southwest Missouri State University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science, Geospatial Sciences

By
Derek Joseph Martin
August 2005

GEOSPATIAL ANALYSIS OF GRAVEL BAR DEPOSITION AND CHANNEL MIGRATION WITHIN THE OZARK NATIONAL SCENIC RIVERWAYS, MISSOURI (1955-2003)

Geography, Geology and Planning

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ABSTRACT

Historical land clearing is believed to be responsible for present-day channel instability in main stem reaches in the Ozark National Scenic Riverways (ONSR) in south-central Missouri. The nature of instability is related to the delivery of excess amounts of gravel sediment to stream channels and higher rates of lateral bank erosion. These conditions are of concern to resource managers because of the potential damaging effects on recreational facilities and aquatic habitat. The purpose of this study is to develop a geographic information systems (GIS)/remote sensing (RS) based methodology to monitor spatial patterns of gravel deposition and lateral channel migration within the ONSR. Two study reaches, each several kilometers in length, on the Jacks Fork and Current Rivers were selected for evaluation based on their proximity to recreation areas and history of disturbance. Stream channel bank lines, centerlines and gravel bar features were digitized and analyzed in a GIS. A mean center of mass method was used to assess spatial patterns of gravel bar movement, and a meander apex method was used to assess spatial patterns of lateral channel migration within the study reaches. Results reveal that in disturbance reaches, channel migration rates typically occurred at 4 to 30 m/yr and bar centroids shifted 3 to 35 m/yr. While both sites appear to be presently at the end of a channel migration cycle, smaller-scale gravel wave pulses continue to push through the Current River system. Park managers may find it useful to classify channel reaches according to valley location and bar planform in order to better understand and predict the spatial distribution of disturbance zones.

KEYWORDS: Geomorphology, Geographic Information Systems, Remote Sensing, Channel Migration, Bar Deposition

This abstract is approved as to form and content

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Chairperson, Advisory Committee
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CHAPTER 1

INTRODUCTION

Over the past century the world has experienced a population surge that has severely affected the environment by placing stress on the world's natural resource demands (UNFPA, 2004). To fill these demands, land-use practices such as logging and agriculture were greatly intensified and, although needed, are responsible for the degradation of the quality of many of the world's rivers and water supplies. Impacts of human activities on the fluvial environment, however, are not always so apparent. Rivers are naturally dynamic systems, continually responding to local hydraulic and riparian changes and larger scale fluctuations in runoff and sediment load from upstream watershed areas (Leopold 1997, Knighton 1998). Thus, the key problem is to be able to effectively monitor river changes in a manner that allows the resolution of human-induced disturbance to be recognized within the natural variability of river behavior.

A very common result of anthropogenic changes to the fluvial environment is channel instability. As development or land-use changes take place in previously undeveloped watersheds, the rivers attempt to adjust to the new hydrologic regimes that in most cases mean accommodating higher and flashier discharges (Knighton, 1998). While attempting to adjust, beds and banks become unstable and large amounts of sediment are introduced to the river system. As a result, streams become more dynamic and higher rates of channel migration and sediment transport are induced by watershed disturbance.

Rivers are both agents and products of erosion and deposition, adjusting their channel dimensions to accommodate the sediment load demand from bed, banks and upland erosion. Continual adjustments are made in an attempt to develop a stable dimension in which the stream neither aggrades nor degrades (Rosgen, 1996). Factors affecting sediment load such as climate, land-use and population are constantly changing. Concurrent with these changes are changes in the levels of fluvial activity such as increased aggradation or erosion (Knighton, 1998). These are the changes that we seek to understand in order to manage a river system for the self- maintenance of natural form and stability.

As channel instability increases sediment load, needs for assessing and understanding these conditions becomes imperative. Many hydrologists have devoted much time and effort to understanding the fluvial system (Wolman and Miller, 1960; Leopold et al., 1964; Rosgen, 1996), paving the way for the current trend of incorporating a multidisciplinary approach to river systems analysis. Recent advances in technology have added yet another route for analysis. The sciences of remote sensing (RS) and Geographic Information Systems (GIS) have made it possible to make increasingly accurate photogrammetric measurements and analyses of the fluvial environment through advances in software development, as well as the increased availability of data sources such as aerial photography and satellite imagery (Campbell, 2002; Clark, 2001). These resources have also made it possible to assess a much larger area more efficiently, saving agencies valuable time and resources.

The aforementioned concerns have not only taken place in highly developed watersheds but also within more pristine and protected areas. These areas are of primary concern because their quasi-natural conditions are essential to wildlife habitat as well as sustainable tourism and recreation. One of the places such changes have occurred is within the Ozark Highlands region of Missouri, locally known as, “the Ozarks” (Figure

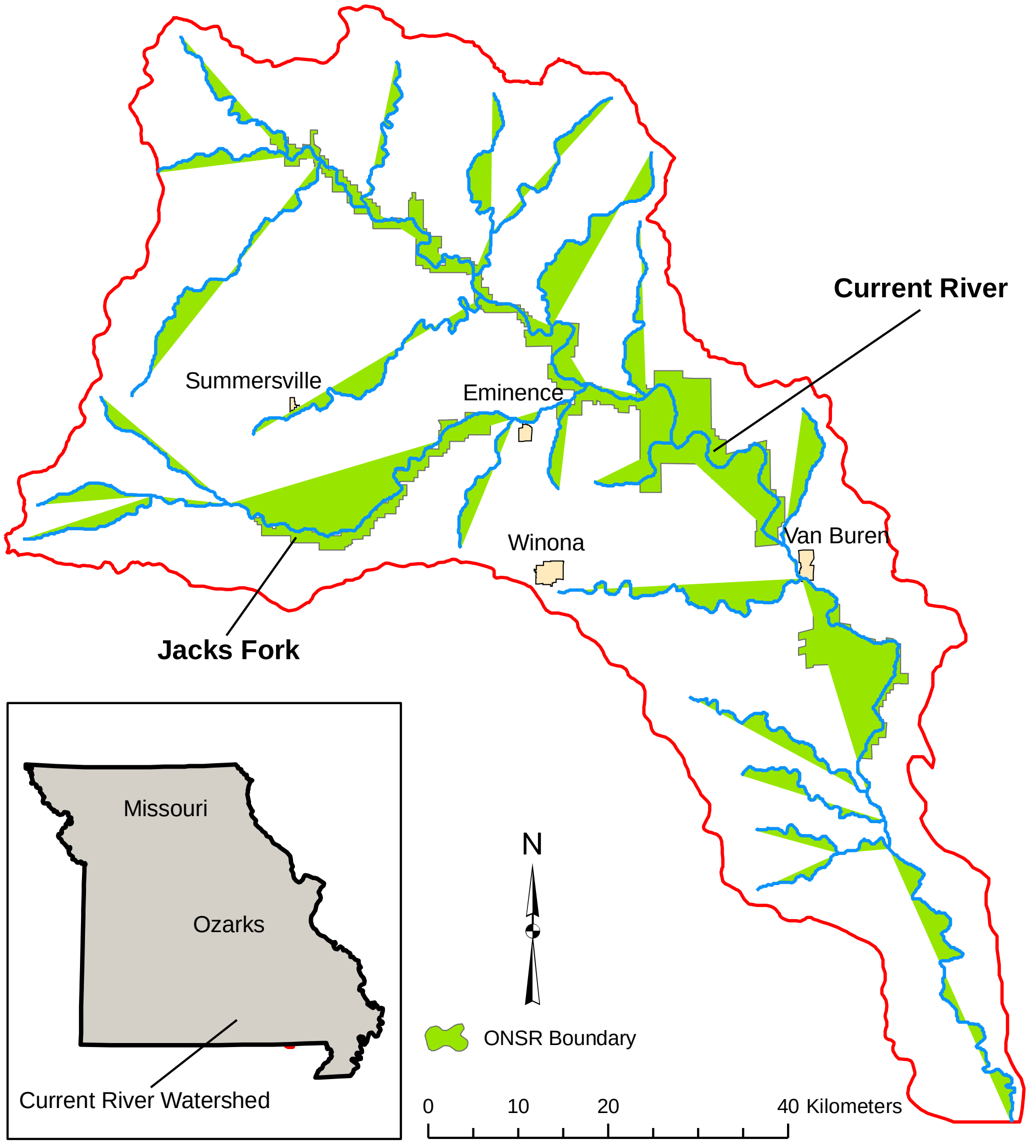


Figure 1. Location of the Current River within the Ozark National Scenic Riverways and the Ozarks of Missouri.

1). Census data have shown that human population growth has leveled off within the Current River watershed and the heavily logged landscape is re-growing (Jacobson and Primm, 1994). This provides a unique environment to study anthropogenic effects on Ozark Rivers because the land-use practices potentially responsible for mobilizing excess sediment such as logging, have substantially receded (Jacobson and Primm, 1994). Thus, anthropogenic effects on the river system can be studied, as well as the stages of recovery, given that current management practices maintain a critical level of environmental protection.

The Ozark National Scenic Riverways (ONSR) is a National Park that was created in 1964. Located in the southeastern portion of the Ozark highlands (Figure 1), the park includes 134 miles of the main stem of the Current and Jacks Fork rivers and entertains more than one million visitors per year. Land-use changes prior to and following the parks inception have led to management concerns regarding water quality and stream morphology (Jacobson and Primm, 1994; Grant 2004). A primary management concern is the possibility that late 19th century and early 20th century land-use practices, primarily logging and agriculture, are responsible for delivering excess amounts of gravel sized sediments to the stream channel (Jacobson and Gran, 1999). Excess gravel in the stream channel destabilizes recreation areas and structures within the park as well as perturbs the natural aquatic bio-habitat (Grant, 2004).

Previous longitudinal surveys within the ONSR revealed a watershed scale pattern of gravel-bar area indicating that a gravel wave is passing through the river system as a result of the intense, early 20th century land use practices (Jacobson and Gran, 1999). Park managers would benefit from knowing the characteristic spatial patterns of gravel movement as well as the rate at which the gravel is moving and how it is affecting stream morphology, especially in terms of lateral channel migration.

Innovative methods are needed to determine characteristics of gravel bar movement and lateral channel migration. One of the easiest ways to assess channel and gravel bar movement is with aerial photography. ONSR managers have access to almost 50 years of aerial photograph coverage of the Jacks Fork and Current rivers. GIS can be used to overlay multiple years of the digitized stream channels and gravel bars in order to quantify the stream’s lateral migration and the gravel bar’s migration downstream. The development of an innovative GIS/RS based methodology for studying and monitoring the movement of the stream and its gravel bars is of much importance to resource planners and park managers due to its time and cost efficiency.

Purpose and Objectives

This study uses 48 years of aerial photograph coverage to assess the patterns of lateral channel migration and gravel bar planform within two disturbed reaches within the Ozarks National Scenic Riverways in an attempt to understand long-term effects of historical land-use induced gravel accumulations. Although channel migration has been shown to be a spatially and temporally intermittent process (Hickin, 1974; Hickin and Nanson, 1984), generalizations can be made and will be beneficial in terms of resource management decision-making.

The four main objectives of this thesis are to:

1. Develop a geographic information systems/remote sensing approach to characterize the movement of gravel features as well as channel migration within the river system of the Ozark National Scenic Riverways;
2. Determine the relationship between gravel bar sedimentation and channel migration;
3. Determine the influence of riparian land cover on channel migration; and
4. Use this information to make predictions of future channel migration as well as help understand the process of fluvial geomorphic aspects of gravel bed streams in the Ozarks.

The purpose of this thesis is to apply geospatial technologies to the investigation of the effects of the migration of excess gravel within the Current River system. Results indicate: (1) gravel wave translation and sedimentation controls the migration rate of the channel; (2) channel and bar migration patterns may be linked to specific to channel disturbance type; and (3) valley location and morphology plays an important role in the type of channel disturbance that occurs. This information suggests that channels should be classified according to valley location and bar behavior in order to understand the spatial distribution of disturbance zones for management purposes.

CHAPTER 2

LITERATURE REVIEW

Resource management is currently experiencing an escalated need for geospatial information, such as land use information, population and demographic information, land cover change and in the case of this thesis, information on geomorphic change. There has recently been an increasing acknowledgement of the link between channel and sediment properties and aquatic biological habitat quality; however, little literature exists for the combination of geospatial analysis techniques with fluvial geomorphology. First, this chapter will discuss past and current trends in fluvial geomorphology relative to factors affecting gravel bar movement and lateral channel migration within the Ozarks of Missouri and second, trends in GIS and RS as they pertain to river systems analysis will be reviewed.

Channel Morphology of Ozark Streams

Channel Patterns. Rivers adjust their channel pattern in many ways to maintain or establish an equilibrium state. Channel patterns were originally classified into three groups: straight, meandering, or braided, by Leopold and Wolman (1957). This original classification scheme of patterns has served as the foundation from which more sophisticated classification schemes have branched (Figure 2). The channel forms shown in figure 2 are all considered part of a continuum of channel pattern evolution (Bridge, 2003). Bridge (2003) describes the general stages of channel pattern evolution to be the formation of alternate bars in a straight channel, followed by the increase in length and height of the bars which then induces bank erosion and channel widening, leading to the creation of braid bars and a braided or anastamosed channel. This type of channel evolution is shown in Figure 2(B). This study takes into account that the different study reaches fall within different stages of that channel pattern evolution, however, the focus remains on the meandering reaches. Although meandering is the most common type of channel pattern, it is understood the least due to its lack of sterile order and its undecipherable disorder (Ikeda and Parker, 1989).

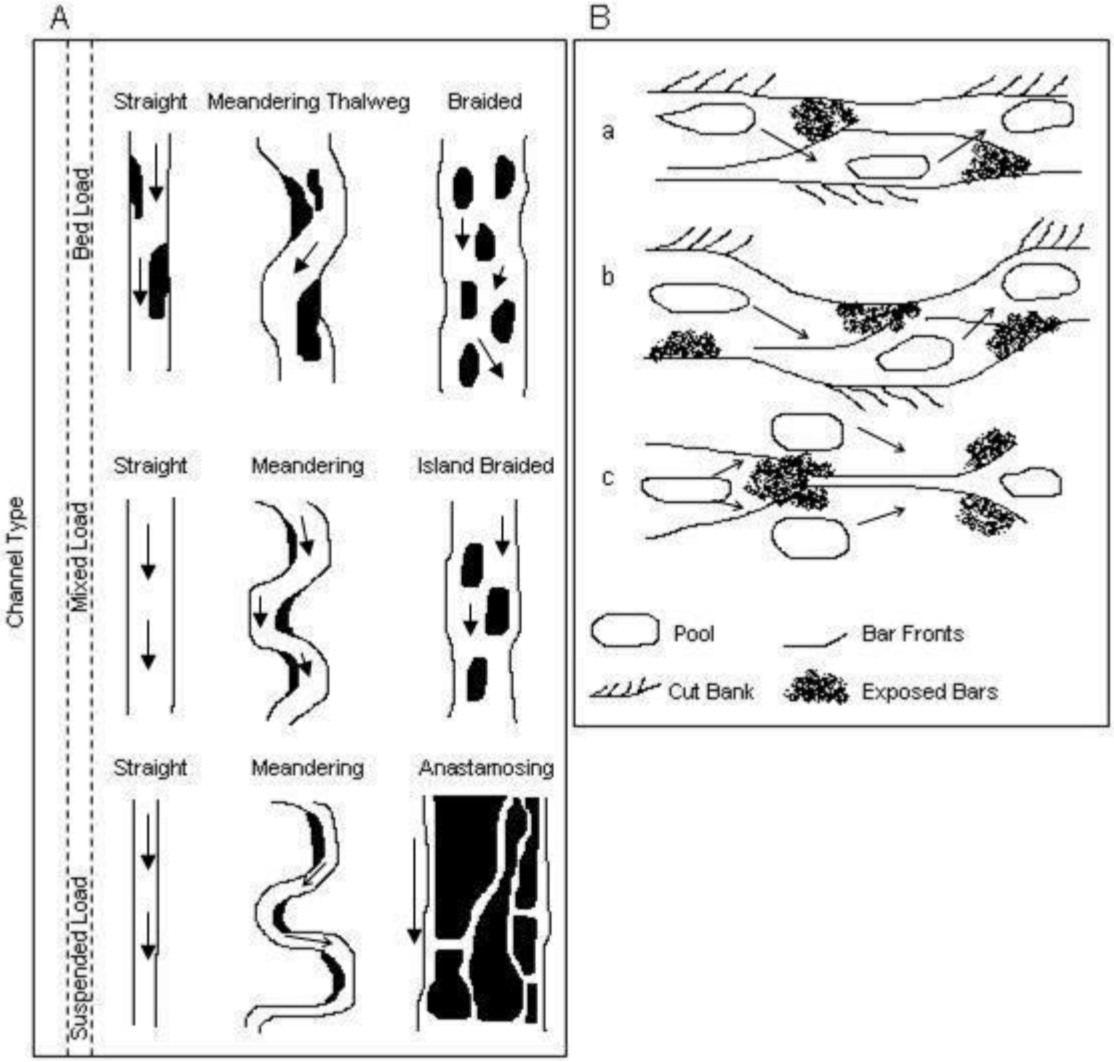


Figure 2. (A) Schumm's classification of channel patterns and (B) Overlapping pool-bar units in gravel-bed rivers of different channel patterns, modified from Knighton (1998).

The scope of this study, which involves understanding lateral channel migration and the accretion of gravel, is built upon the basic idea that channels adjust in width, depth and slope to handle the sediment that is received from the upstream river system (Leopold, 1997). Another foundational concept described by Leopold et al. (1964) is that alluvial streams in a state of natural, dynamic equilibrium migrate within their floodplains by eroding bank material from the outside of meander bends and depositing material on the inside of meander bends. Bank erosion occurs along straight channel reaches as well, but most commonly occurs slightly downstream from the axes of meander bends (Leopold, 1964). Given the above discussion one can state with confidence that the underlying processes controlling channel pattern are those of erosion and deposition.

A stream section that has a substantial amount of bed erosion taking place is said to be degrading and a stream section that has a substantial amount of deposition or alluviation taking place is said to be aggrading (Knighton, 1998). Degradation and aggradation can be heavily affected by anthropogenic activities within the watershed, thereby disrupting the streams equilibrium state. A stream in equilibrium with its environment is said to be stable. For a stream to be stable it must consistently transport its sediment load, both in size and type, associated with local deposition and scour (Rosgen, 1996). Following this definition, channel instability occurs when the scouring process leads to degradation, or excessive sediment deposition results in aggradation. Both of these conditions are currently occurring in Ozark streams (Jacobson, 1995; Jacobson and Gran, 1999; Jacobson and Primm, 1994; Jacobson and Pugh, 1995). Aggradation occurs where excess gravel is deposited within a reach, facilitating local flooding and bank erosion.

Degradation occurs where gravel bar deposits are being eroded and incised. The eroding gravel sediment is often transported and deposited in aggrading reaches downstream.

Channel patterns in Ozark streams are mostly dictated by the location of valley walls or the presence of a bedrock bed. Ozark streams were classified by Dury (1964) as manifestly underfit because modern streams meander at wavelengths much smaller than those of the valleys (Jacobson, 1995). Ozark streams are characterized by long, straight reaches separated by short, steeper, sinuous reaches, yielding a typically low average sinuosity. The long straight reaches are referred to by Jacobson (1995) as

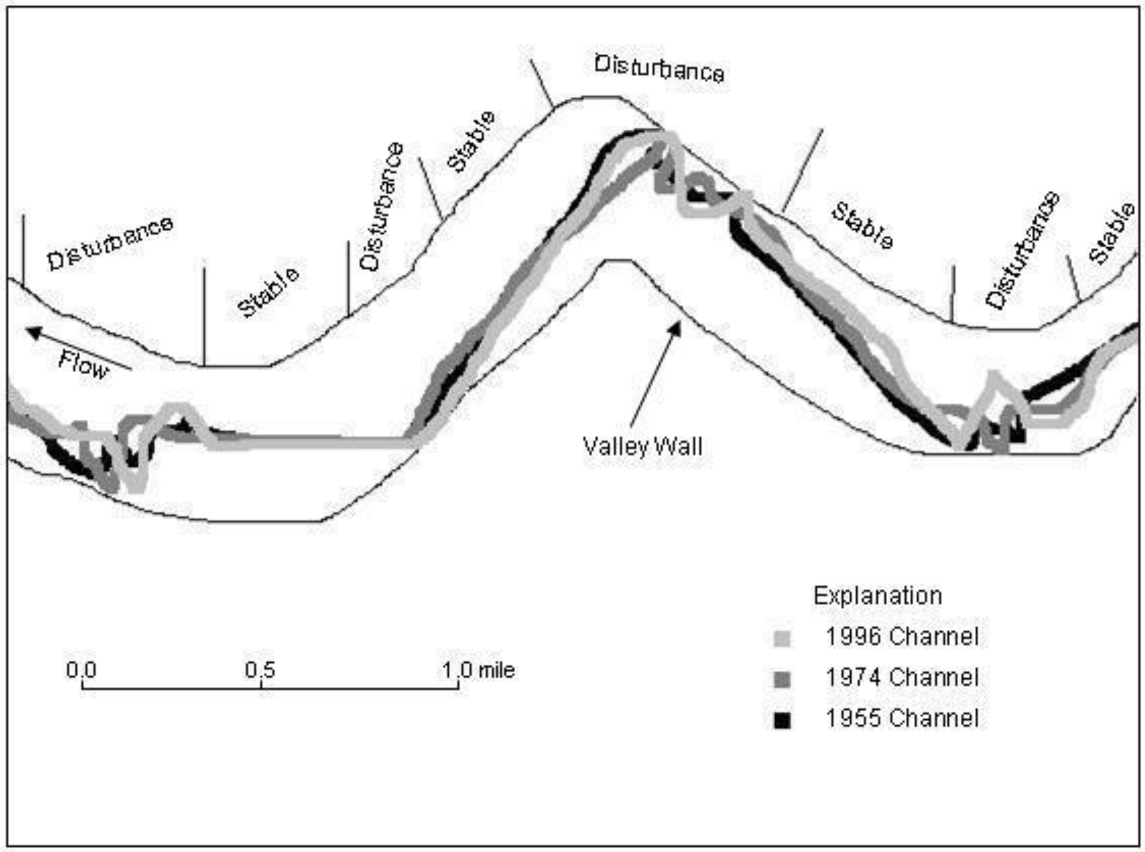


Figure 3. Example of common alternating disturbance and stable reach channel form found in the Ozarks (Modified From Jacobson and Gran, 1999).

stable reaches and the sinuous reaches, commonly displaying rapid rates of lateral migration, are referred to as disturbance reaches, emphasizing that accelerated rates of erosion and deposition are occurring there (Figure 3). Jacobson (1995) has also described disturbance as existing when channel conditions are outside of a normal or acceptable range of variation, using examples such as channel widening, channel incision, bed aggradation and changes in channel pattern. Accelerated changes in channel pattern within Ozark streams suggest that the streams are disturbed from their natural condition (Jacobson and Primm, 1994).

Channel Morphology.

Meandering. Natural channels have an inherent tendency to meander, irrespective of scale or boundary material, however, the definition of a meander remains somewhat arbitrary (Knighton, 1998). Knighton (1998) also explains that channel pattern depends not only on hydraulic factors but also on sedimentary ones. With respect to lateral channel migration; the ability of a stream to shift laterally depends on the resistivity of the banks (Hickin and Nanson, 1984). Bank resistivity is dependant on numerous factors including material composition and bank vegetation type and coverage.

The phenomenon of river meandering and lateral channel migration has been described in many publications (Ikeda, 1989; Nelson and Smith, 1989; Johannesson and Parker, 1989; Hasegawa, 1989; Burckhardt and Todd, 1998; Ellis-Sugai, 1999; Lancaster and Bras, 2002; Micheli et al., 2004). Through these publications it seems to be widely accepted that the process of meandering is neither random nor regular, but somewhere in between. It has been noted by Ferguson (1975) that meandering in a broad sense can be characterized by three planimetric properties: a scale variable, sinuosity, and degree of irregularity. River meandering has also been described by Stolum (1996) as a self-organizing process that oscillates in space and time between an ordered planform and a chaotic one. It is clear that the process of river meandering is still quite unclear.

Attempts to numerically model river meander patterns have been made with limited success due to the irregular, chaotic properties of river meandering (Lancaster and Bras, 2002; Edwards and Smith 2002). Although these models can not predict meander patterns with 100% accuracy, they, along with other less mathematically intense analyses of river meanders, can relate meander patterns to other factors such as land-use and hydrologic conditions (Hudson and Kessel, 2000; Ellis-Sugai, 1999; Lapointe and Carson, 1986).

It can be recognized that one of the simplest ways to monitor and assess channel meandering and the subsequent lateral migration is to note the depletion of the terrestrial environment on the outside of meander bends, or, essentially overlay the channel outline from multiple, consecutive years and note the existence of channel where, in the years previous, there was no channel (Ellis-Sugai, 1999; Jacobson and Pugh, 1995).

Gravel Bar Characteristics. Bar formation takes place simultaneously with the formation of meanders, a concept that still lacks a satisfactory explanation. As meanders form, so do alternate bars. These bars are not viewed as the cause of meandering, but as catalysts that accelerate the meandering process (Knighton, 1998). Given that spatiotemporal channel adjustment inevitably involves sediment redistribution, the supply and movement patterns of sediment are of primary concern to river managers (Knighton, 1998).

In the Ozarks, degradation in the upper watersheds, beginning sometime at or near the time of European settlement, is believed to be responsible for the aggradation of channels by gravel in the middle and lower sections of the watershed. Characteristic of this aggradation are the formation of large, sweeping gravel bars on the inside of meander bends throughout much of the watershed (McKenney and Jacobson, 1996; Jacobson and Primm, 1997). Bed aggradation of gravel sized sediment in the Current River has been related to land-use changes in the Ozark region over the past 160 years (Jacobson and Gran, 1999). Jacobson and Primm (1994) have identified likely mechanisms for gravel delivery to streams to be open-range grazing of cattle and hogs, widening and upstream extension of first order streams into previously unchannelled valleys, and channel incision due to runoff associated with the rural road network.

Jacobson (1995) assessed mean streambed elevation (MSBE) changes at gages throughout the Ozarks and found evidence of a wave of gravel sediment passing through Ozark River systems, possibly being responsible for the excess accumulations of gravel. He described four different MSBE response types: Depleted, Slightly Wavy, Extremely Wavy and Stable/Degrading. These response types are descriptive of the wave patterns observed in the MSBE changes.

The gage on the Jacks Fork at Eminence, Missouri displayed a depleted MSBE response type. The response showed a rapid initiation of a sediment wave around 1940 followed by a steady depletion of the wave until present. The timing of this wave strongly supports a connection to land-use (Jacobson, 1995).

The gage on the Current River at Van Buren, Missouri displayed an extremely wavy MSBE response type. This response showed multiple, high amplitude waves which have persisted to current times. The multiple waves may be a result of the gages location downstream of the Jacks Fork and many other tributaries. The many waves of sediment induced upstream may be passing the Van Buren gage at different times, displaying multiple MSBE changes (Jacobson, 1995).

Riparian Vegetation. Riparian vegetation has been said to maintain stream ecology, stabilize stream banks, shade streams, remove pollutants, create wildlife habitats and protect wetlands (Schueler and Holland, 2000). Riparian vegetation is also a known, controlling factor in the migration of stream channels (Ellis-Sugai, 1999; Jacobson and Pugh, 1995; Burckhardt and Todd, 1998). Beeson and Doyle (1995) have found that unforested stream bends are five times more likely to experience significant erosion during high flow events than forested stream bends and Micheli et al. (2004) has found that agricultural floodplains are 80 to 150% more erodible than riparian forest floodplains. Micheli et al.'s (2004) results also showed much higher migration rates through agricultural land. These findings make it well known that riparian vegetation has a major effect on migration rates and patterns of rivers.

In Ozark streams, and contrary to many other regions, vegetation has different potential effects on channel stability depending on size of the channel and whether vegetation is growing on an accreting, gravel point bar or on an eroding cutbank (Jacobson and Pugh, 1995). Jacobson also notes that geomorphic changes in Ozark streams may result from changes in riparian land use in the extensive tributary areas. For example, Jacobson and Primm (1994) found that headward extension of the channel network into areas where vegetation was disturbed or removed may have resulted in the delivery of gravel to the main stem. These findings underscore the belief that riparian vegetation may control the spatial pattern of stream channel instability in the Ozarks.

Historical Disturbance and Channel Change. Historical accounts of the pre-settlement Ozarks describe a somewhat different environment than what we see today. According to Jacobson and Primm (1994), the landscape which was encountered by settlers moving into the Ozarks in the early 1800's was not static and may have been going through a discrete shift in climate. This natural variability in the pre-settlement landscape made it difficult to determine whether changes induced by settlement were significantly different from the natural regime.

Descriptions of pre-settlement vegetation cover in the Current River basin also differed from what we see today. In Jacobson and Primm's (1994) analysis of historical land use changes in the Ozarks they cited accounts of explorers describing the uplands as mostly open prairie with scarce oak trees and no wood available for campfires. As they approached the Current River they described "forests of lofty pine" and abundant timber near the banks. The pine that they were referring to is the short-leaf pine (*Pinus echinata*) that is extremely scarce in this region today.

There is a lack of pre-settlement descriptions of streams in the Ozarks. However, the few accounts that do exist were again described by Jacobson and Primm (1994). These historical accounts make no mention of gravel or any other geomorphic features that might indicate channel instability or aggradation. Jacobson and Primm (1994) describe one explorer's account of camping on a "gravelly barren point" in the river. This is one of very few mentions of gravel, which leads one to believe that the pre-settlement fluvial environment was quite different than it is today.

The timber boom of the late 1800's and early 1900's is most often attributed to the current aggraded condition of Ozark streams. During this period of timber production there was once again no mention of excess gravel in the stream channels. However, following the timber boom oral accounts of "fishin holes" being filled in were common. Then by the mid-1940's it was popularly accepted that stream aggradation and instability were caused by upland land-use changes.

Jacobson has contributed a majority of the available literature on gravel-bed streams in the Ozarks, with a focus on the effects of land-use and the transport of sediment (Jacobson, 1995; McKenney and Jacobson, 1996; Jacobson and Primm, 1997; Jacobson and Gran, 1999; Jacobson and Pugh, 1995). Jacobson (1995) has noted that land-use induced disturbances at the drainage basin scale are of particular concern due to their broadly disseminated contributions over the landscape.

The geometry of alluvial rivers such as the Current and Jacks Fork, is controlled mainly by the flow and sedimentary processes that operate during seasonal floods (Wolman and Miller, 1960; Leopold et al., 1964; Carlston, 1965; Schumm, 1968; Daniel, 1971; Knighton, 1998). Over 80 years of flow data for the sites analyzed in this study are available from the United States Geological Survey (USGS 2005). The channel patterns and bar patterns in this study will be evaluated through the use of aerial photography and geographic information systems approaches. A review of the literature pertaining to these subjects will be discussed next.

Remote Sensing (RS) and Geographic Information Systems (GIS)

There is a growing number of available literature resources for RS and GIS research, however, very little has dealt with the use of RS and GIS for river systems research. This could be due to the relatively young age of the science itself. It could also be due to the complexity of analyzing linear features in an RS and GIS environment. RS and GIS are widely used in the areas of landscape ecology, forestry, natural disaster assessment and landcover assessment (Clarke, 2001). All of these applications have a common thread in that the entity being assessed (in most cases) is polygonal, or forms a broad enclosed shape such as a square or circle, in nature. Due to the available resolutions of remotely sensed imagery, it is much easier to assess polygonal, rather than linear entities. The development of methodologies by which we analyze thin, linear features such as rivers has displayed much slower progress then that of the analysis of polygonal features.

With increasing pressure on the use of natural resources, there is also an increasing demand for understanding the spatiotemporal patterns of resources and insight into the spatiotemporal processes governing their availability (Burrough and McDonnel, 1998). This is why RS and GIS are becoming a standard tool for the analysis of natural resources, however these types of analyses are dependant on the type and availability of the data source, whether it be aerial photographs, satellite images or radar images. There are an ever-increasing amount of data sources to choose from. These data sources are available in a broad range of spatial, spectral and temporal resolutions. The selection of the proper data source is very important.

The role of RS in river systems analysis has traditionally been diminutive. However, the past fifteen years have brought about progressions in the science that have made data much more accessible at a marginal cost. Most river systems studies utilizing remotely sensed imagery have focused on polygonal entities such as aquatic habitat units or riparian vegetation and land-use (Marcus et al., 2003; Marcus, 2002; Lattin et al., 2004; Schilling and Wolter, 2000; Lonard et al., 2000). In the study presented by Lattin et al. (2004), aerial photography was compared to Landsat Thematic Mapper (TM) imagery in an attempt to determine the influence of RS data sources on the quantification of land use/ land cover. They found that there was no significant difference between the aerial photographs and the Landsat TM imagery when relating riparian land use to stream ecological condition. From this they concluded that even though there are limitations, TM based assessments of riparian land use/land cover, when applied at the stream network scales, have potential to assist in estimating and describing the influence of riparian attributes on stream ecological condition. The conclusions of this work emphasized the contributions that remotely sensed imagery can have to the analysis of in-stream processes; however, the work did not make direct measurements of in-stream entities.

Analysis of in-stream entities via remotely sensed data sources requires a high spatial resolution image due to the thin, linear nature of streams. A typical Landsat TM image has a spatial resolution of 30 m, which in most cases is wider than the stream being studied. The use of high-resolution imagery is quite effective and has been demonstrated thoroughly by Marcus (2002) and Marcus et al. (2003) in studies performed to effectively map in-stream microhabitat. Both studies utilized 1 m resolution, 128 band hyperspectral imagery collected with a Probe1 sensor and were able to extract in-stream microhabitats at accuracies ranging from 67% to 99%. These numbers, although encouraging, were achieved through the use of imagery acquired at a monetary cost far beyond that available for the project discussed in this paper. However, the spatial resolutions of those data sources are also attainable through the use of standard aerial photographs, a data source with a much higher availability and economic feasibility.

Eidse (2005) described a project being undertaken by the Northwest Florida Water Management District and the USGS in which historical aerial photographs were used to digitize surface water features and analyze changes in morphology of the Apalachicola River in Florida. In the study they were able to determine that the river has changed substantially due to certain engineering practices. Eidse (2005) was also able to use the historical information as a restoration reference to know what the dimension and profile were like before alteration.

The use of aerial photography to monitor river systems in the Ozarks has been highly effective as demonstrated by Jacobson and Pugh (1995) and Legleiter (1999). Both used aerial photography to map instream features such as gravel bars and channel planform. Jacobson extracted these features in order to determine the locations of disturbance reaches as well as monitor the movement of gravel features. Legleiter extracted these features in order to determine stream disturbance as a result of a dam.

Jacobson and Pugh (1995) used low altitude aerial photography to map channel features in the Ozarks. The study conducted by Jacobson and Pugh sought to develop a synoptic overview of gravel in transport in the Current River Basin by mapping gravel features over a 160 km stretch of the mainstem of the Current River. Although effective, this study merely gave a basic snapshot of gravel transport at one point in time, rather than using multiple photo dates to assess temporal change.

Jacobson and Gran (1999) also used low altitude aerial photography to map channel features in the Ozarks, however, this study focused on changes in riparian land use and its relationship to channel instability. This study created a map of riparian land use change including location of gravel features, however, the presence of gravel features were only used to note areas of disturbance.

Sources of Error. There are certain limitations that come with the use of remotely sensed data, most notably data availability and spatial and temporal resolution (Campbell, 2002). Besides these limitations, there are also many ways in which error can be introduced into the analysis process.

Data of known accuracy is needed to make sound decisions using remotely sensed data (Congalton and Green, 1999). To evaluate that accuracy, the errors associated the data must be known. There are many possibilities to introduce error when using aerial photography. The error associated with older aerial photographs can be attributed to optical distortions and tilt. Optical distortion is caused by an inferior camera lens or camera malfunction. Tilt is caused by displacement of the focal plane from a truly horizontal position by aircraft motion. These sources of error just mentioned are commonly associated with older aerial photographs and the cameras that took them. The most important source of positional error currently is relief displacement meaning that only the tops of the objects located directly below the camera lens will be visible and objects not directly under the lens will appear to lean outward from the central perspective of the camera (Campbell, 2002). Since this form of error is associated with the height of an object, it does not apply with as much importance when using aerial photos to study rivers, however these types of errors may need to be considered during the selection of ground control points (GCP's). Jacobson and Pugh (1995) have noted that absolute locations are no more accurate than the control source.

Summary. Geographic information systems and remote sensing are emerging as a valuable tool for the analysis of natural resources. There are a broad range of applications for these tools and more are being realized every day. The science of fluvial geomorphology is one of the areas in which the application of GIS and RS could be extremely valuable.

With its history of land use and its unique karst geology, the Jacks Fork and Current River are experiencing geomorphic changes that need to be assessed and understood. GIS and RS will play an important role in the process of understanding these changes. This thesis takes advantage of those tools to monitor lateral channel migration and gravel deposition in order to understand how their relationships with each other as well as with land cover and hydrologic variables affect one another.

CHAPTER 3

STUDY AREA

The study region is located about 120 miles southwest of St. Louis, Missouri within the Ozark National Scenic Riverways. The ONSR is located within the Current River watershed (Figure 1), encompassing a majority of the Current River and its largest tributary, the Jacks Fork. These rivers join to help drain the southern portion of the Ozark Plateau, eventually connecting with the White River and the finally the Mississippi River. ONSR's primary attractions are its rivers, playing host to roughly 120 million recreationists each year. The Jacks Fork and Current River are lined with many limestone bluffs, one of the determinant factors of planform morphology in the Ozarks. A majority of the base flow in these rivers is provided by the many springs throughout the region. The springs are a result of the karst topography that is typical to the Ozark region, providing beautiful clear, blue, cold flowing water throughout much of the year.

Physical Description

The Ozarks are a broad geologic uplift with its medial axis oriented approximately southwest to northeast. This uplift is known as the Ozark highlands physiographic province. Sauer (1968) has noted that there are three distinguishing surficial characteristics of the Ozark Highlands; (1) Higher elevation than surrounding areas, (2) Greater relief and (3) A general accordance of summits. The apex of this uplift is formed by igneous rock outcroppings in the St. Francois Mountains and surrounding counties. These igneous formations help dictate drainage patterns in the region due to their high resistance to erosion. The Ozark highlands province has been broken down into four physiographic regions; the Boston Mountains, the Springfield Plateau, the St. Francois Mountains and the Salem Plateau by Panfil and Jacobson (2001). The Jacks Fork and Current Rivers join to drain part of the Salem Plateau.

The Salem Plateau is underlain mostly by flat-lying, Paleozoic, sedimentary rocks that are dominated by cherty limestone and dolomite (Figure 4). The Ozarks contain probably more chert than any other similar area. The chert ranges from small nodules to massive beds. In most places it has weathered into flattened fragments of conchoidal fracture.

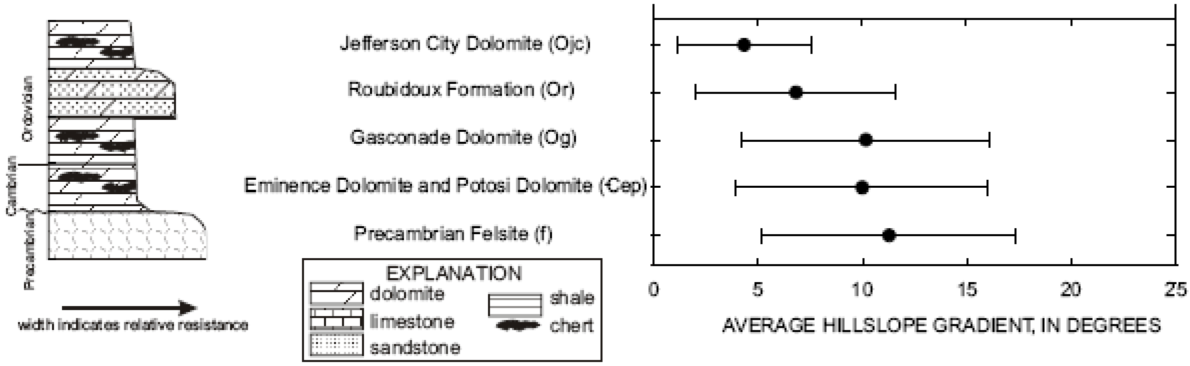


Figure 4. Stratigraphic section and average hillslope gradient for the Current river drainage basin (Panfil and Jacobson, 2001).

The carbonate limestone is also responsible for the distinct karst drainage system that has developed over much of the Ozark region. Much of the precipitation in this region infiltrates into the subsurface karst drainage and emerges in springs in the valley bottoms. The karst drainage system is responsible for the unique hydrologic characteristics of Ozark streams, such as losing sections, springs and sinkholes.

Ozark streams have distinctive characteristics as a result of the regions unique geology. Most Ozark streams are floored with a thick bed of chert fragments that extend the width of the channel. The stream beds are often much more resistant to erosion than its margins. This induces a tendency to cut laterally and accounts for (1) the relatively great width of Ozark valley floors and (2) the extraordinary degree to which Ozark streams have developed meandering habits (1968). It is characteristic of Ozark drainages to find a rapid succession of riffles and pools, with the pools flanked by wide white “gravel bars”.

Soil. Most Ozark soils are residual soils formed by the decay of the local rock formations. On upland flats and gentle slopes the surface materials are mostly derived from the underlying rock. Contacts of rock formations are commonly marked by sharp differences in soils. On steep slopes more resistant beds of rock dominate the soils.

Similar soil characteristics are found at both of the study sites; however there are some minute, local differences. Figures 5, 6 and tables 1 and 2 display the primary soil series associated with the areas surrounding the study reaches. The floodplain soils at the Burnt Cabin site consist mainly of the excessively drained Relfe series which is formed in sandy, gravelly alluvium under grassy/herbaceous cover and tame pasteurlands. The uplands are predominantly composed of the Gasconade and Alred series soils. The Gasconade series is formed in gravelly residuum weathered from dolomite located on hills, hillslopes under tree cover and other grassy/herbaceous cover. The Alred series is formed in colluvium over residuum weathered from cherty limestone located on hillslope, plateaus under tree cover and intermixed conifers and hardwoods.

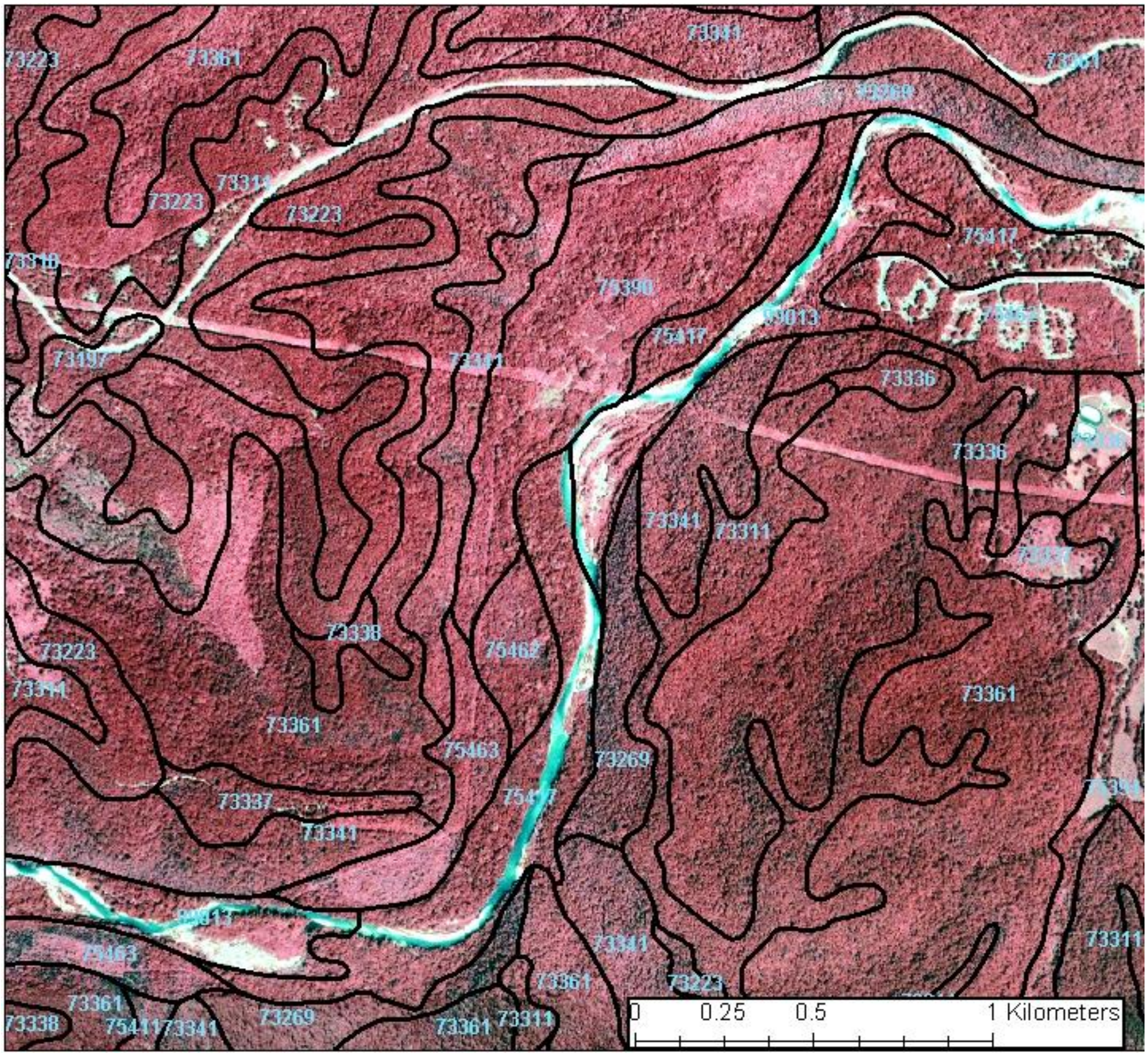


Figure 5. Soil map of the soil types surrounding the Burnt Cabin site.

Table 1. Explanation of map unit symbols used in Figure 5.

Map Unit Symbol	Map Unit Name
99013	Riverwash, Frequently Flooded
75417	Relfe-Sandbur Complex, 0 to 3 Percent Slopes, Frequently Flooded
75394	Relfe Gravelly Sandy Loam, 0 to 3 Percent Slopes, Rarely Flooded
75390	Razort Silt Loam, 0 to 3 Percent Slopes, Rarely Flooded
73361	Coulstone-Alred Complex, 15 to 50 Percent Slopes, Very Stony
73341	Gepp-Arkana Complex, 15 to 55 Percent Slopes, Rocky
73269	Brussels-Gasconade-Rock Outcrop Complex, 30 to 90 Percent Slopes, Very Bouldery
73223	Coulstone-Bender Complex, 15 to 50 Percent Slopes, Very Stony
73197	Viburnum Silt Loam, 3 to 8 Percent Slopes

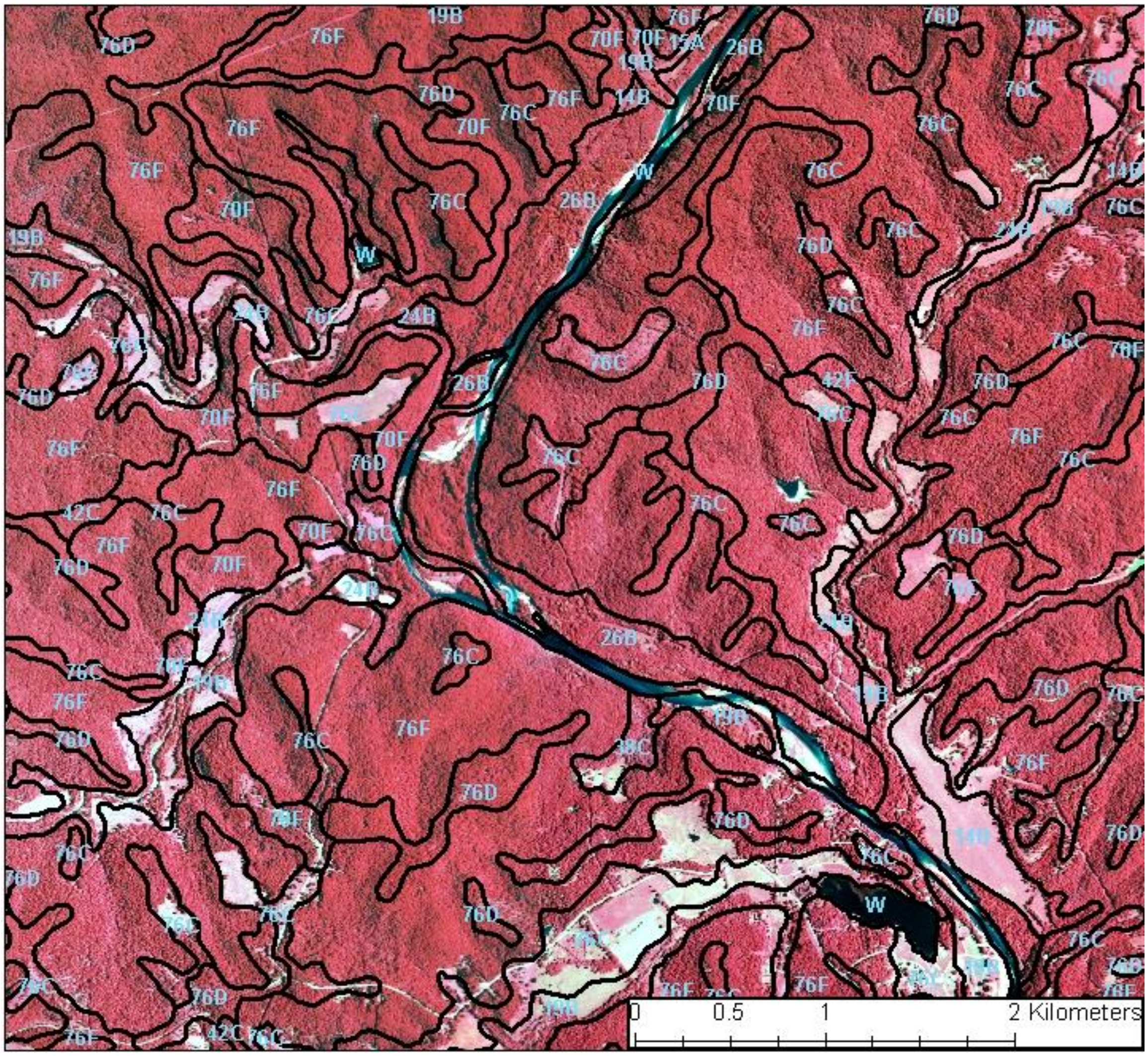


Figure 6. Soil map of the soil types surrounding the Lower site.

Table 2. Explanation of map unit symbols occurring in Figure 6.

Map Unit Symbol	Map Unit Name
15A	Gladden Sandy Loam, Sandy Substratum, 0 to 3 Percent Slopes
70F	Gasconade-Rock Outcrop Complex, 14 to 50 Percent Slopes
76F	Poynor Very Gravelly Silt Loam, 14 to 40 Percent Slopes
19B	Midco Very Cherty Loam, 1 to 4
24B	Secesh Silt Loam, 1 to 4 Percent
26B	Wideman Fine Sandy Loam, 1 to 4 Percent Slopes
38C	Captina Silt Loam, 5 to 9 Percent
42F	Clarksville Very Cherty Silt Loam, 14 to 40 Percent Slopes
76C	Poynor Very Gravelly Silt Loam, 3 to 9 Percent Slopes
76D	Poynor Very Gravelly Silt Loam, 9 to 14 Percent Slopes

The floodplain soils at the lower site consist mainly of the excessively drained Wideman series which is primarily composed of sand and forms under tree cover. Upland areas are predominantly composed of the Poynor series which is formed in gravelly colluvium over residuum weathered from cherty limestone located on hills on uplands under tree cover.

Climate. The Ozarks are generally humid with an average relative humidity of about 73%. Climate in the Ozarks is predominantly affected by east moving storm systems that often include thunderstorms with short bursts of intense rainfall (2001). The mean annual precipitation for the region is 1000 to 1200mm at Rolla, MO. The mean annual temperature is between 15 and 18 °C (Jacobson and Pugh, 1995). The humid climate dictates much of the regions vegetation and provides moisture to the constantly dissolving karst system.

History and Culture

The Ozarks have a long and somewhat controversial land-use history that has been influenced by the coming and going of different cultures. The first people on record to have settled the Ozark region were mound builders, of which there were at least two known cultures – Cliff dwellers and Woodland. Little is known about these people other than they inhabited the region for a number of centuries. Many Indian tribes have passed through the Current River region but the Osage Indians were dominant in this region for several hundred years. The region is also believed to have been penetrated by the Spaniards under the leadership of the famed explorer Hernando De Soto in the late

1500's, followed by the French *couriers dubois* or "runners of the woods" in the late 1600's who gave the Current river its first name –*La Riviere Courante***,** or, "Running River".

Some of the first known land disturbances in the Current River region were man-made fire. The Osage Indians set fire to the prairies because they believed it would improve grazing for large game. They also set fires to drive game towards hunters. This practice killed sprouts and tree seedlings, extending grassland areas at the expense of forests. The most serious retrogression of the Ozark environment began in the years that followed the civil war when inhabitants continued to "burn the woods to make the grass grow". Until this point, fire was one of the most harmful historical practices in terms of the quantity and quality of Ozark timberlands.

The arrival of the timber industry only enhanced the environmental retrogression that had begun with the burning of prairies and woodlands. The first commercial timber cutting was done in the late 1800's. After the St. Louis watersheds were depleted of good lumber, logging moved to the Ozarks with the mill at West Eminence being rated for many years as the largest in the nation. The commercial harvesting method at this time was to skim the cream of the crop to make a quick profit. In the case of the Ozarks the cream of the crop was the virgin stands of short leaf pine and hardwoods. Any remaining tree growth was slashed clean to make charcoal. The hill people would then set fire to the remaining brush to use for livestock grazing.

Stripping the land of timber and the grazing that followed is believed to be one of the primary causes of the mobilization of the cherty, gravel sediments to the stream channels. On the burned out land the humus layer of the forest floor soon disappeared, causing the thin topsoil to wash down the hollows, exposing the rocky chert. The grazing of animals on this land no longer stabilized by large woody vegetation induced high rates of surface erosion, washing the cherty gravel into the streams. Following these occurrences wildlife largely disappeared, and fewer game fish grew in the now gravel-choked streams.

CHAPTER 4

METHODOLOGY

The analysis of channel migration and gravel migration with the use of RS and a GIS can be broken down into six parts; (1)Site selection, (2)aerial photo acquisition, (3)photo rectification, (4)feature digitization (5)field verification and (6)geostatistical analysis.

Site Selection

ONSR is located in Southeastern Missouri on what is known as the Ozark Highlands. The park covers 126 square miles containing 134 miles of the Current and Jacks Fork Rivers. The Current and Jacks Fork Rivers combine to drain part of the Ozark Highlands. They eventually join with the Black and White Rivers in Arkansas and flow southward to the Mississippi River.

The ONSR has published numerous reports and papers concerning water quality and river geomorphology. This was partially a determining factor in the selection of the two study sites. Sites with preexisting data were favored, as well as sites that NPS managers believed posed possible structural threats due to a seemingly rapid rate of erosion and/or deposition. Sites were also chosen based on location within the park in an attempt to characterize channel and bar migration at sites representative of all areas of the park. The availability of aerial photograph coverage and rectification capabilities played a final role in the selection of sites.

Two sites located within the ONSR were evaluated for this study. The first site, the Burnt Cabin reach, is located on the Jacks Fork about ten miles west of Eminence, Missouri (Fig. 7, photo A). The Burnt Cabin study reach contains within it a broad, sweeping meander bend roughly 800 meters in length with a high cut-bank at the meanders apex and a large gravel bar at the inside of the bend. The nearest USGS gage station is located on the Jacks Fork in Eminence, Missouri (Table 3). The second site, the Lower reach, is located on the Current River about ten miles north of Van Buren, Missouri (Fig. 7, photo B). The Lower reach exemplifies a very dynamic meander bend with multiple channels, confined on either side by valley walls. The nearest USGS gage station is located on the Current River in Van Buren, Missouri (Table 3).

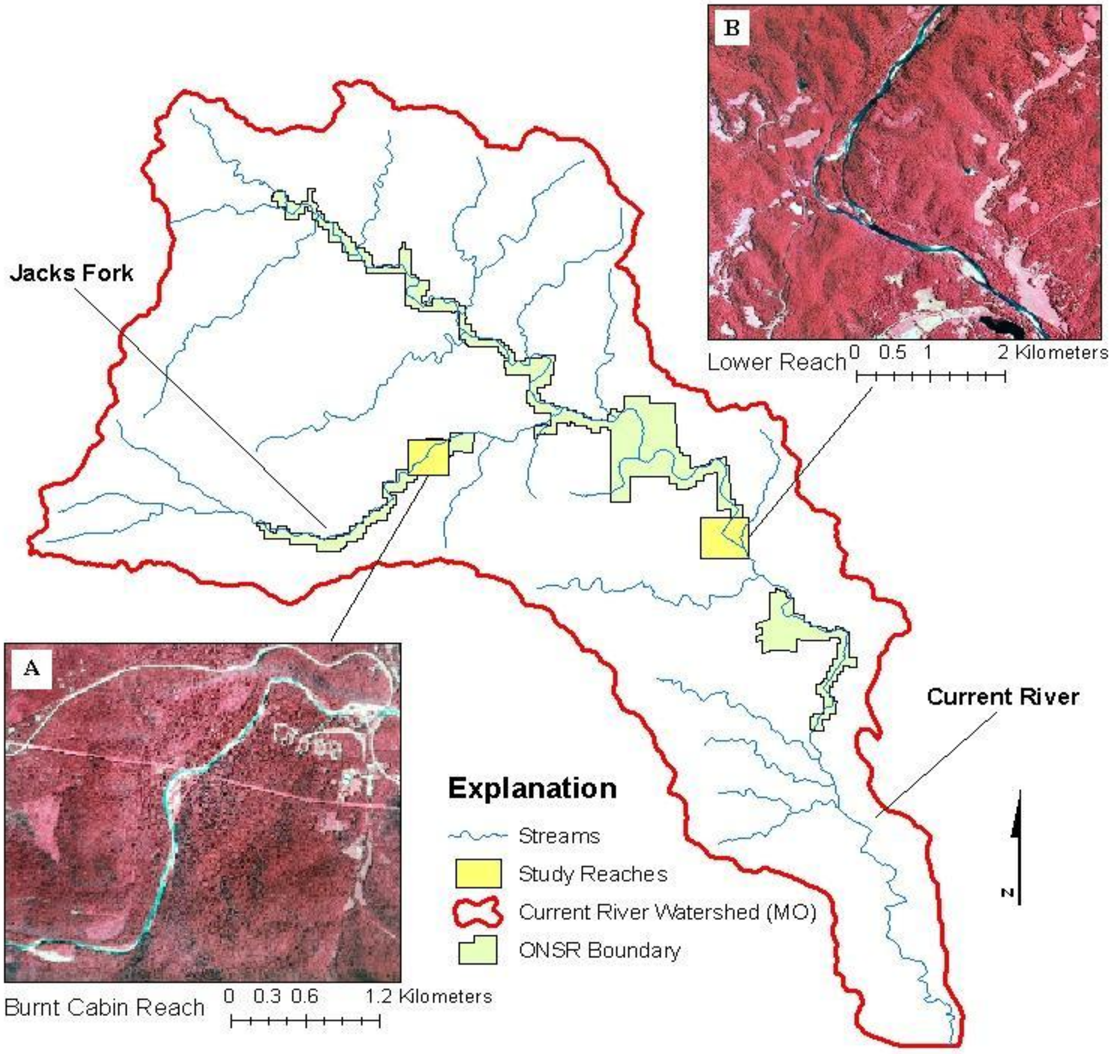


Figure 7. Location of the study reaches: Burnt Cabin reach (A) and Lower Reach (B).

Table 3. Gage information for the two gages used to retrieve discharge information.

Gage #	Gage Name	Latitude	Longitude	Drainage Area
7066000	Jacks Fork at Eminence, MO	37˚09’14.69”	91˚21'29.38"	398mi^2
7067000	Current River at Van Buren, MO	36˚59’28.96”	91˚00’48.64”	1667mi^2

The length of reach studied at each site varied. The length was based on reach classifications as either stable or disturbed, previously described by Jacobson. Also noted by Jacobson (1995), streams in the Ozarks display a common alternating pattern of “stable” reach followed by “disturbance” reach. Stable reaches are defined by their lack of erosion and deposition, whereas disturbance reaches are defined by the much larger amounts of erosion and deposition. Based on these descriptions, the length of reach studied was at least one cycle of stable-disturbance-stable. This reach length was chosen to capture gravel features on their way into and out of the disturbance reach of interest, rather than focusing primarily on the changes within the disturbance reach itself.

Photo Acquisition

Aerial photography was provided by the NPS, ONSR and the United States Geological Survey’s (USGS) Regional Mapping Center, Rolla, Missouri. Photos acquired from the ONSR were original contact prints and hence required georectification. Photos acquired from the USGS were in digital format and also required georectification. The ONSR provided photos from 1955, 1966, 1992 and 1996 for the Burnt Cabin reach (Fig. 8), and 1955, 1992 and 1996 for the Lower reach (Fig. 9). A 2003 Digital Ortho Quarter Quad (DOQQ) for each site was also acquired from the National Agricultural Imagery Program (NAIP), downloadable in Mr. SID format from the Missouri Spatial

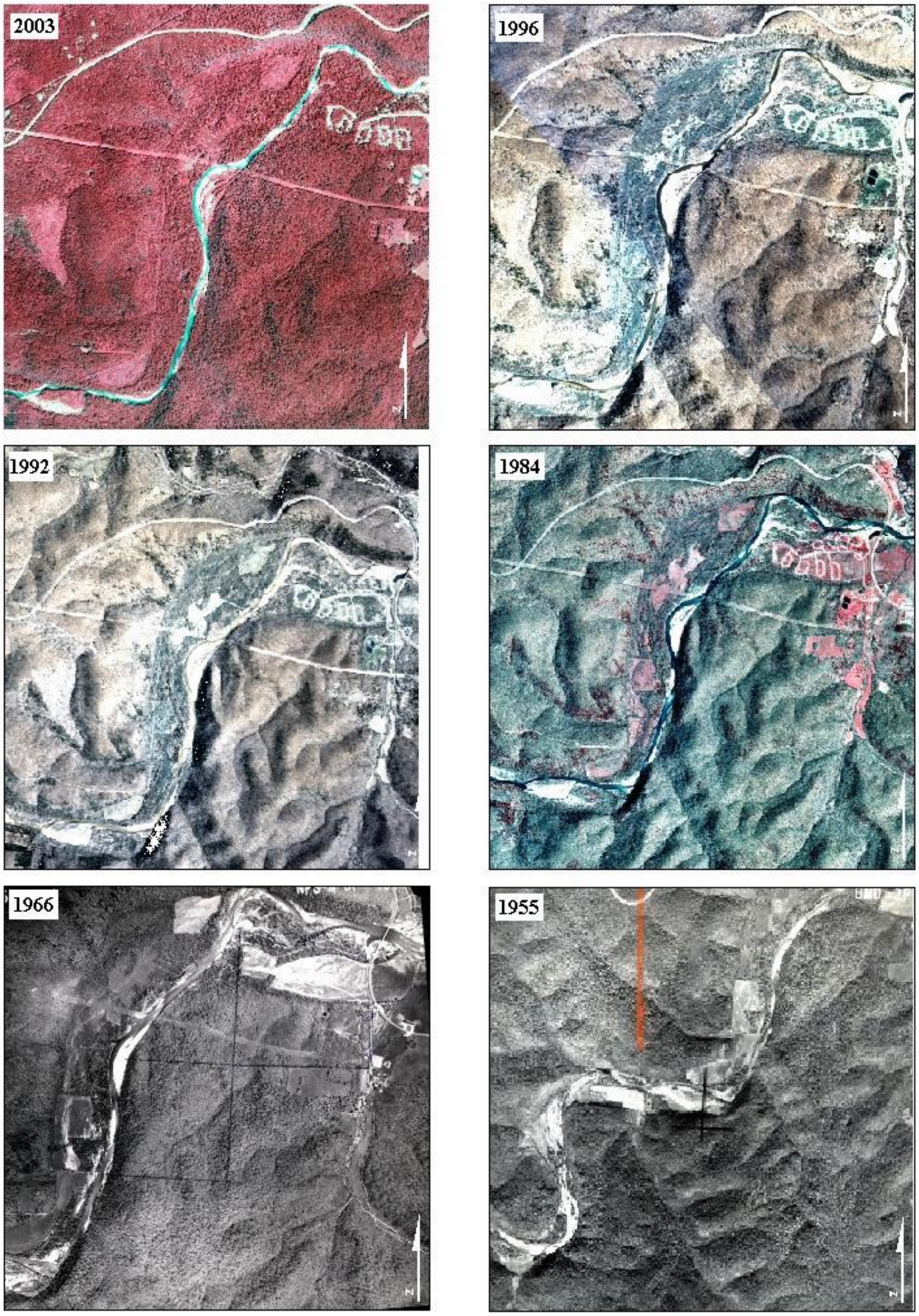


Figure 8. Photos of the Burnt Cabin reach.

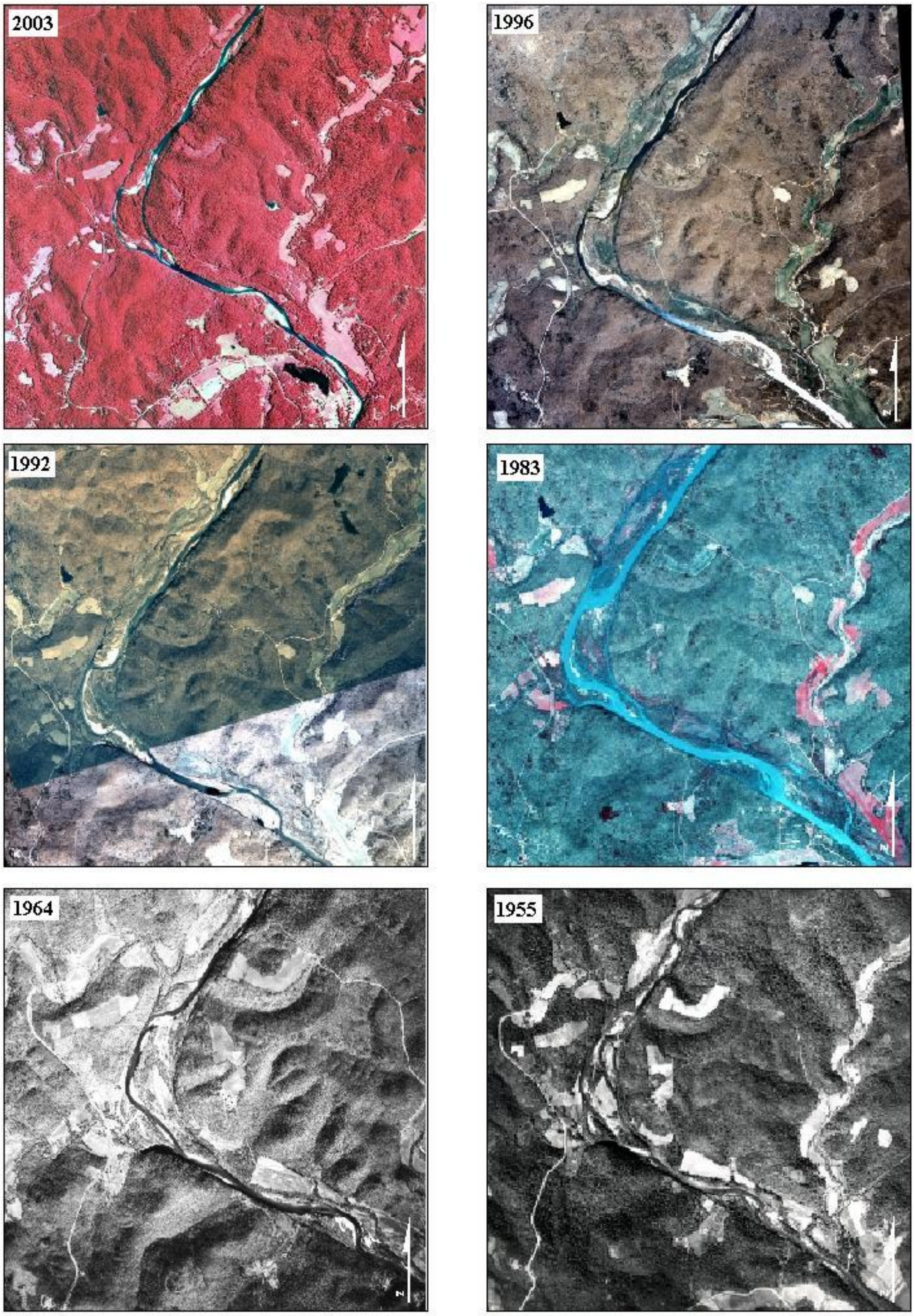


Figure 9. Photos of the Lower reach.

Table 4. Aerial photographs that were used to perform the channel and gravel bar migration study.

Site	Year	Scale	Type	Date of Photo	# of Photos	Source
Lower Current	2003	1:24000	CIR	20-Jun-03	DOQ Mosaic	NAIP, MSDIS
	1996	1:24000	True Color	16-Apr-96	1	NPS, ONSR
	1992	1:24000	True Color	8-Mar-92	2	NPS, ONSR
	1983	1:24000	True Color	15-Apr-83	1	USGS
	1964	1:24000	B&W	28-Jan-64	1	USGS
	1955	1:18000	B&W	26-Oct-55	2	NPS, ONSR
Burnt Cabin	2003	1:24000	CIR	24-Jun-03	DOQ Mosaic	NAIP, MSDIS
	1996	1:24000	True Color	16-Apr-96	2	NPS, ONSR
	1992	1:24000	True Color	5-Apr-92	1	NPS, ONSR
	1984	1:28000	True Color	6-Apr-84	1	USGS
	1966	1:18000	B&W	3-May-66	1	NPS, ONSR
	1955	1:18000	B&W	25-Oct-55	1	NPS, ONSR

Data Information Service (MSDIS). Table 4 provides a list of the aerial photos and their attributes used for this research.

Photo Rectification

All acquired air photos, except those from MSDIS and the USGS, were in hardcopy format and therefore required scanning and/or rectification. This was perhaps one of the most important, yet tedious and time consuming tasks undertaken for this project. Rectification accuracy is extremely important since change over time is analyzed by overlaying multiple years of air photos. If there is any error in the rectification, the overlaid photo could yield a false identification of lateral channel movement or gravel bar migration.

Contact prints were first scanned into digital format (.jpg) using a UMAX Powerlook 2100XL scanner. Photos were scanned at 600dpi to maximize resolution at a reasonable storage size (~5-9MB). Air photos were then rectified using the remote sensing software program, ENVI (© Research Systems Inc.). All photos were rectified by choosing known ground control points (GCP's) from the pre-rectified DOQQ's and in some cases from the 7.5 minute Digital Raster Graphics (DRG's) of those regions. The best GCP's proved to be road intersections and building corners. However, there were very few of these features due to the remote locations of the sites. In many cases individual trees and corners of fields were the best possible GCP's to use. About thirty GCP's were chosen for each photo however; this produced very high Root Mean Square (RMS) errors. The RMS error is measured as the standard deviation of the differences between actual positions of GCP's and their calculated positions after registration. Between ten and fifteen GCP's were used for each photo after turning GCP's on and off to find the best possible combination to yield the lowest RMS error. All RMS errors were 3.0 meters or below at the time of rectification. Some study areas were covered by two photos for certain years and therefore needed to be mosaiced to create a single image for the site for that year.

Feature Digitzation

Digitizing is the act of taking anything that is originally in hard copy format, such as maps or air photos, and recording them in a digital format in order to be viewed and analyzed in a computer environment. For this project four features were digitized in order to perform the analysis: (1) stream channel outline (wetted channel at time of photo), (2) stream channel centerline, (3) mobile gravel features and (4) riparian vegetation.

First, the stream channel outlines were digitized for each site. Since the scale at which the analysis is taking place is quite large (about 1:5000) a heads-up digitizing technique was utilized rather than an automated classification algorithm. This was done under the assumption that the digitizing accuracy would be higher using this method. Also, using an automated classification algorithm increases the risk of excluding pixels near the stream channel that may display a different reflectance due to the shading effect of bluffs and riparian vegetation (mixed pixel effect). Each digitized channel for each year was composed of one shape file, named as follows: channel_03.shp, channel_98.shp etc. and saved within either the Burnt_Cabin folder or the Lower folder.

After digitizing the channel outlines, the stream channel shape files from the multiple years were overlaid on one another for an initial visual analysis of change. The reaches within each stream channel shapefile were then classified based on Jacobson's definition of stable and disturbance reaches. Sections of the stream channel that exhibited a substantial amount of lateral movement or apparent sinuousity were classified as disturbance reaches. These reaches were easily discernable because the channel outlines for each year could be seen, which meant that the channel had moved from one year to the next. The stable reaches on the up and downstream ends of the disturbance reaches were also easily recognizable. At these reaches not all of the channel outlines could be seen because they were displayed on top of one another, which meant that the channel had not moved from one year to the next (Figure 10 and 11).

Second, the mobile gravel bar features were digitized (Figure 12 and 13). "Mobile" refers to those features that are completely void of vegetation and are therefore more readily available for transport. Only the mobile features were digitized since it is the movement of the gravel that is being examined. Mobile gravel features were easily recognizable on the air photos as they displayed a bright white

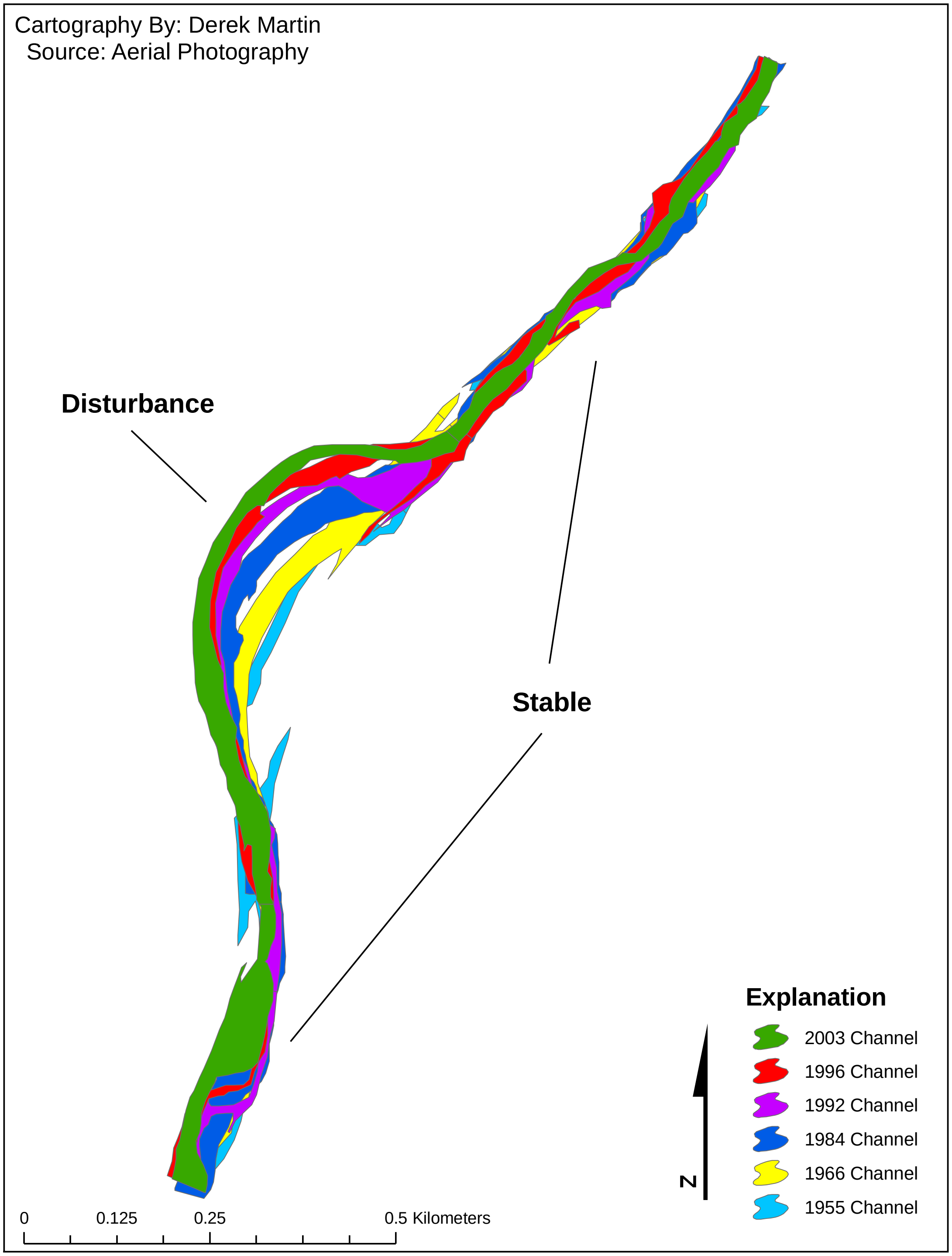


Figure 10. Recognition of disturbance and stable reaches within the Burnt Cabin site.

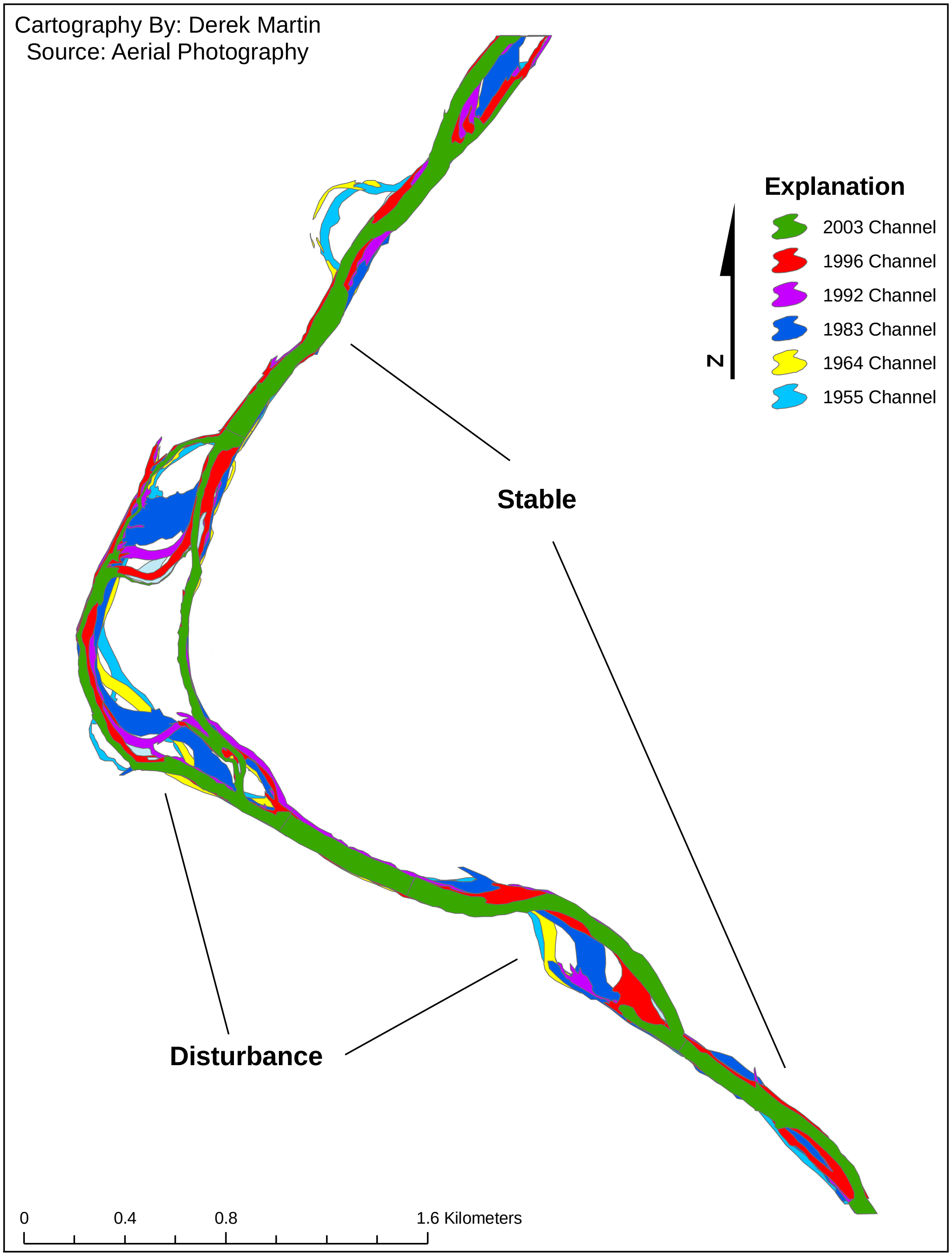


Figure 11. Recognition of disturbance and stable reaches within the Lower site.

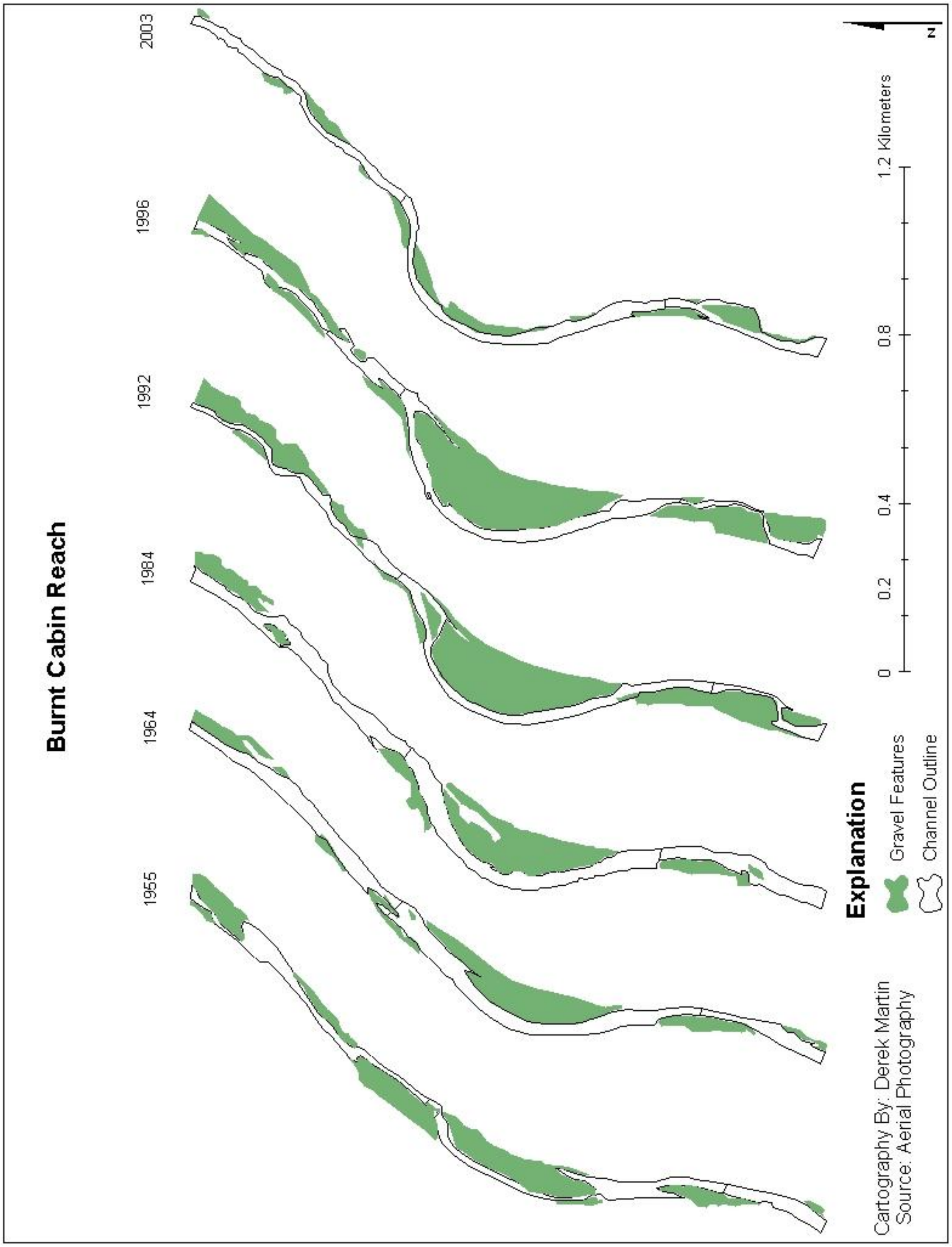
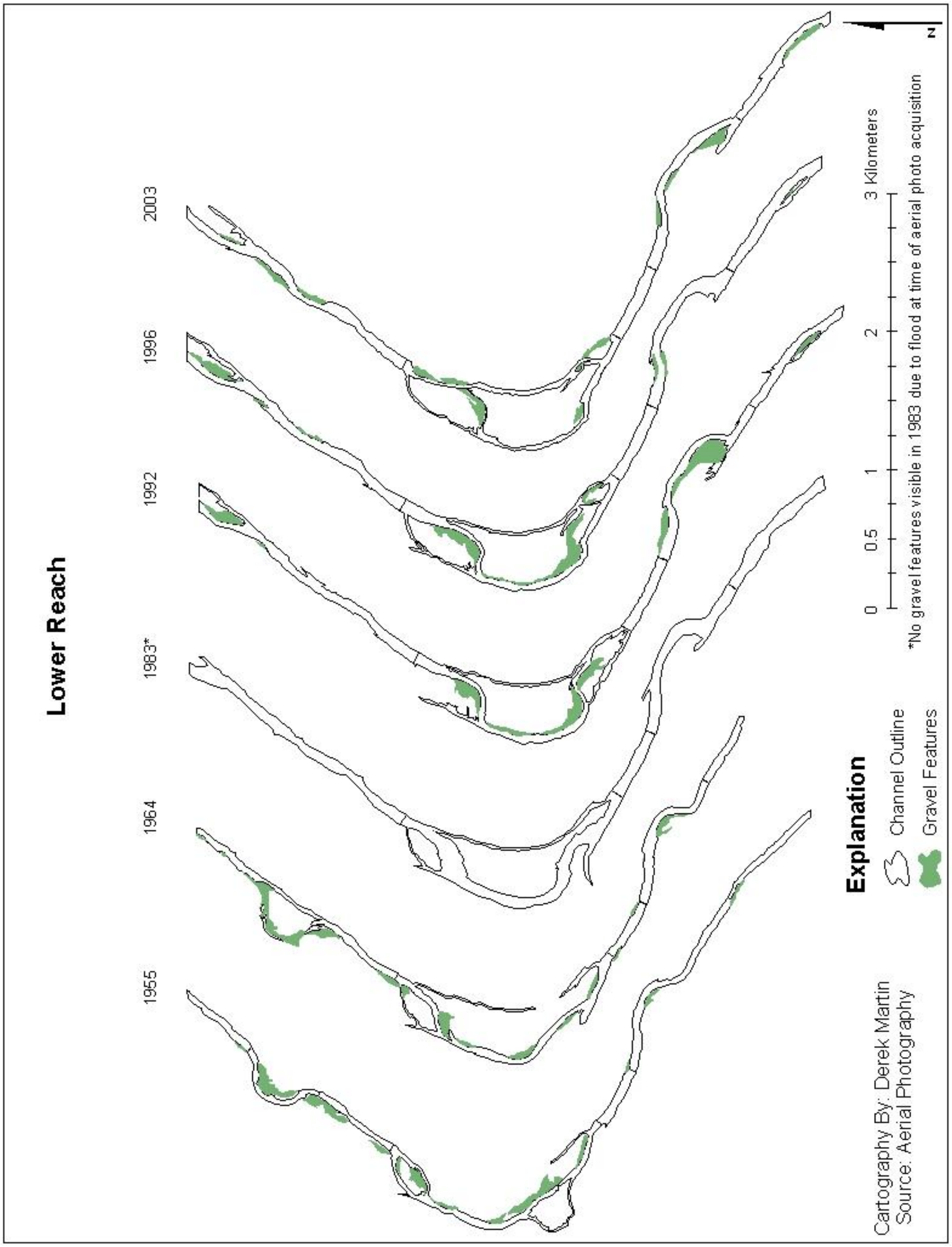


Figure 12. Digitized gravel features from each photograph of the Burnt Cabin site.



Lower Reach

*No gravel features visible in 1983 due to flood at time of aerial photo acquisition

Cartography By: Derek Martin
Source: Aerial Photography

Figure 13. Digitized gravel features from each photograph year for the Lower site.

reflectance among the water within the channel which reflected black or blue. The mobile gravel features for each year were saved as one shape file, named as follows: Bar_03.shp, Bar_98.shp etc. and saved within either the Burnt_Cabin folder or the Lower folder.

After digitizing the gravel features, they were displayed in the GIS along with their subsequent channels and given a classification attribute, stable or disturbed, depending on the reach in which they occurred (Figure 14 and 15). At this time the area (m^2) of the mobile gravel features was calculated. The calculation of area was done using the Field Calculator and the Visual Basic (VBA) Script Code shown in Appendix B.This area calculation required the formation of new shape files for each of the “Bar” shapefiles. The new shape files were named as follows: Bar_03Area, Bar_98Area etc. and saved within the site corresponding folder.

Third, the stream centerline was digitized. In order to determine the centerline of the stream, the previously digitized stream channel outlines were converted from vector format to raster format. Once converted to raster format, centerlines were determined using the centerline function of ArcToolbox by dragging the pointer down the raster image with a 5 pixel snap tolerance.

The next step was to digitize the riparian vegetation. Once again, due to the scale at which this analysis was being performed (~1:5,000) and the relative homogeneity of the landscape, it was not necessary to use an automated classification algorithm in order to extract vegetation. First, a 200 meter buffer was placed around the stream channel. A 200 meter buffer was used because throughout the

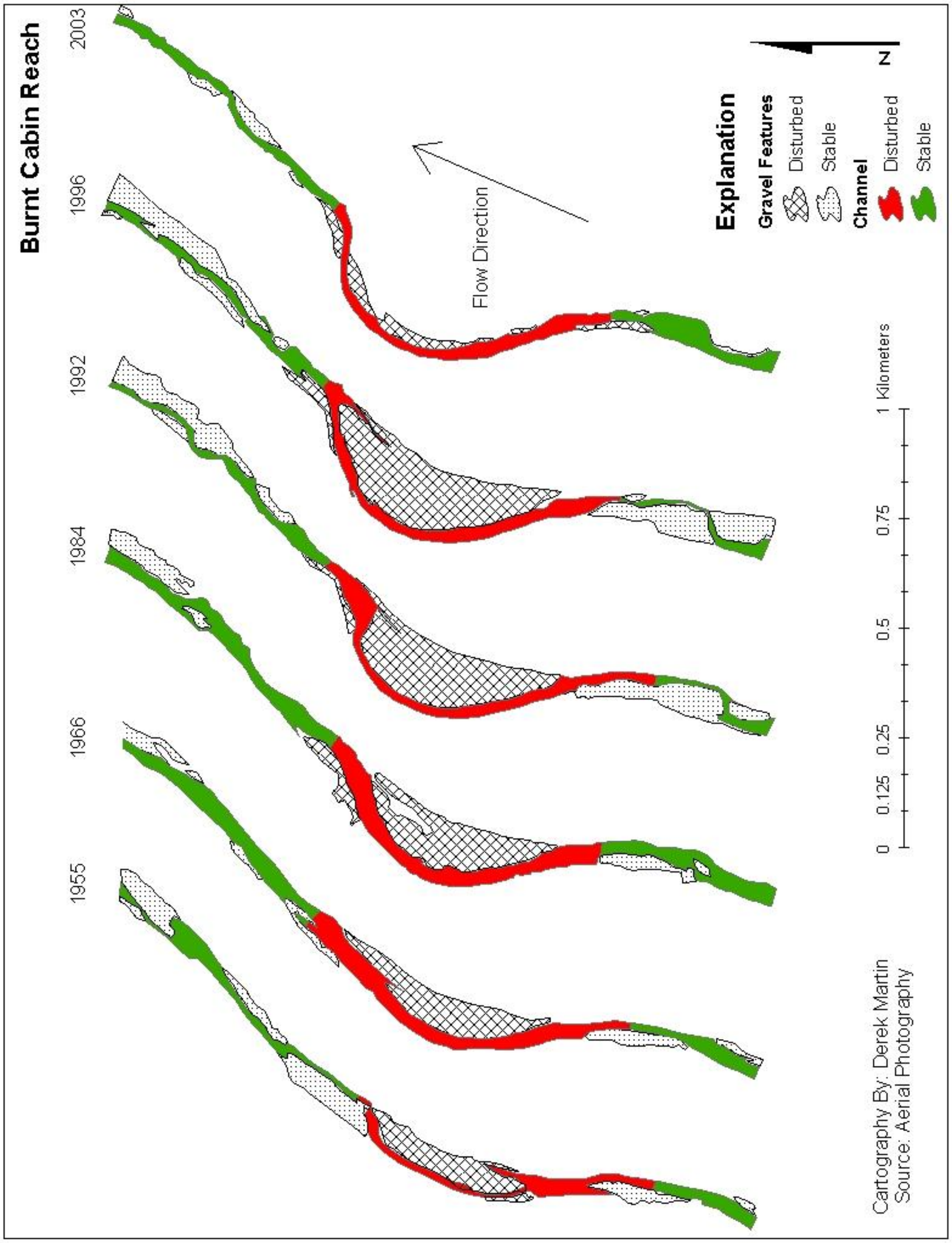
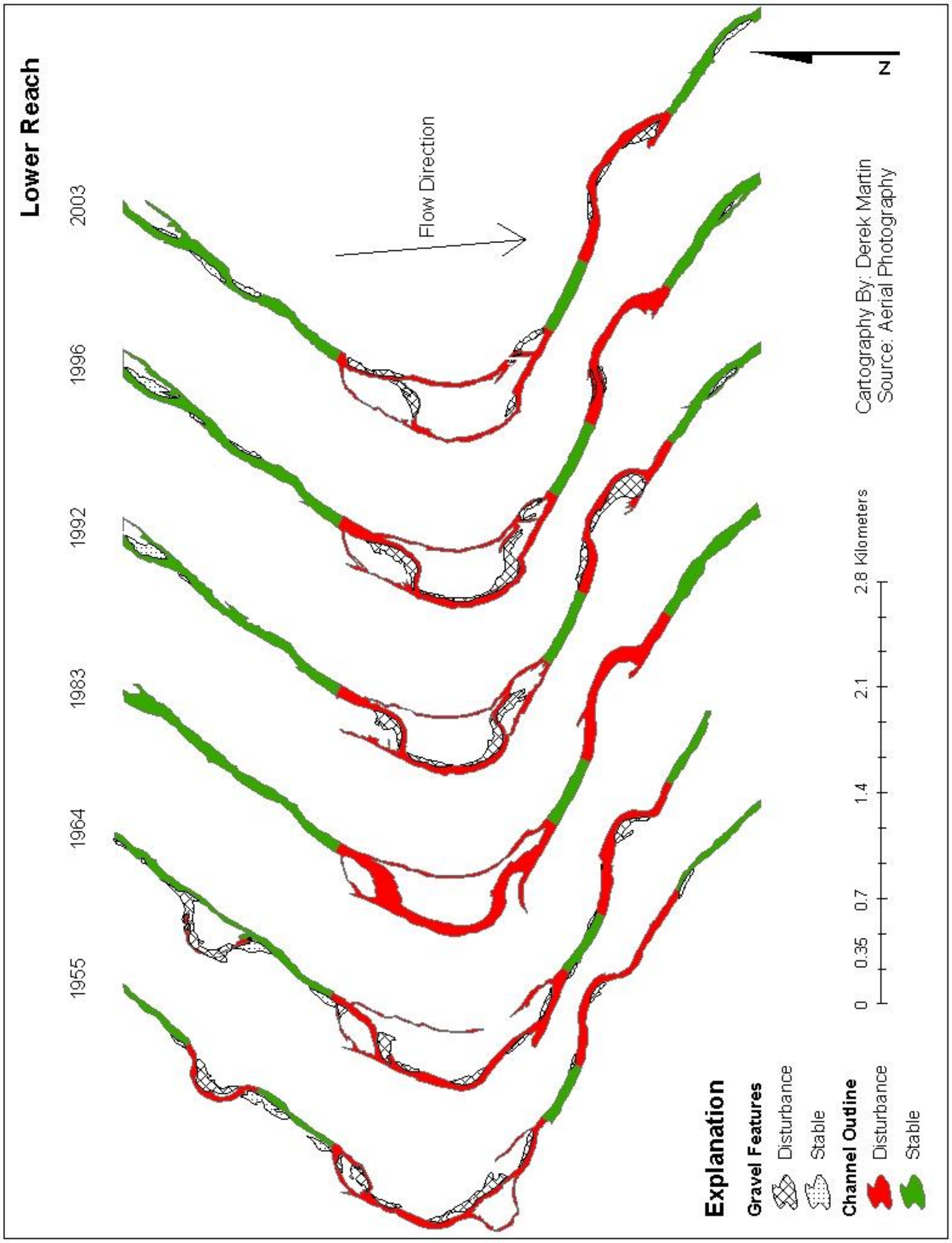


Figure 14. Gravel features of the Burnt Cabin reach were classified as stable or disturbance depending on the classification of the reach in which they occur.



Cartography By: Derek Martin
Source: Aerial Photography

Figure 15. Gravel features of the Lower reach were classified as stable or disturbance depending on the classification of the reach in which they occur.

study reaches the valley width averages about 400 meters. After applying the buffer, heads up digitizing was used to extract land cover polygons. The land cover classes were labeled according to these classes: Bar, Forest, Grass/Ag, Grass/Shrub, Mixed, Pavement/Road and Water. These classes were used because these are generally the classes that will affect erosion processes. For example: at this broad scale, erosion is controlled equally by coniferous riparian areas as it is with deciduous riparian areas, therefore, the classification "Forest" is used instead of splitting it into two classifications.

Before analyzing channel migration or bar migration, hydrologic factors must be taken into consideration. The most important consideration when using aerial photography to monitor channel and bar change is that river stages are different for each photo date. This will affect the reflectance of the aerial imagery. During times of high flow it will appear that there is less gravel bar area due to the amount of gravel submerged by the high flow. It will also make the channel appear wider, and vice versa when the flow levels are low. In order to fully consider and quantify these effects, the nearest USGS gage station data was acquired (USGS, 2005) and plotted for comparison (Appendix A). The data showed that stream discharge (Q) was relatively close to the mean annual discharge during the time of photo capture for each of the photos at the Burnt Cabin site. At the Lower site, the 1983 photograph was taken during one of the highest flows of the year and thus, was excluded from analysis. The 1996 photo was also taken during a high flow event but was retained for the analysis because the exclusion of another photo would result in too little data to perform the analysis.

Analysis of Bar Movement

Past studies of gravel bar movement have generally applied a methodology in which the movement of individual gravel bars was monitored or the presence or absence was noted. The extremely dynamic nature of the Current River and the Jacks Fork make the former method difficult to perform because the bar that is being monitored may completely wash downstream over the course of a photo interval. The latter method would seem more appropriate, however, the presence or absence of the bar reveals little about the properties of movement of the gravel. This paper proposes a different methodology for analyzing the movement of gravel.

Since single bars are much too difficult to monitor in the Current River and the Jacks Fork, a "grouped" mean center of mass approach has been proposed. Not only has this approach been suggested to overcome the dynamic nature of the river system, but it may also be useful for identifying spatial patterns of movement that may otherwise not be evident.

The Grouped Approach. Gravel features were classified according to the stable or disturbed reach in which they were located. The digitizing and classification of gravel features resulted in three groups of gravel features for the Burnt Cabin site (Stable_1, Dist_1, Stable_2) and four groups of gravel features for the Lower site (Stable_1, Dist_1, Dist_2, Stable_3) (Fig. 16). The geostatistical analysis was then performed on each group of gravel features at each site for each year. The geostatistical functions were performed in ArcGIS (©ESRI) as a function of ArcToolbox's Geostatistics tool. The first step was to calculate the mean

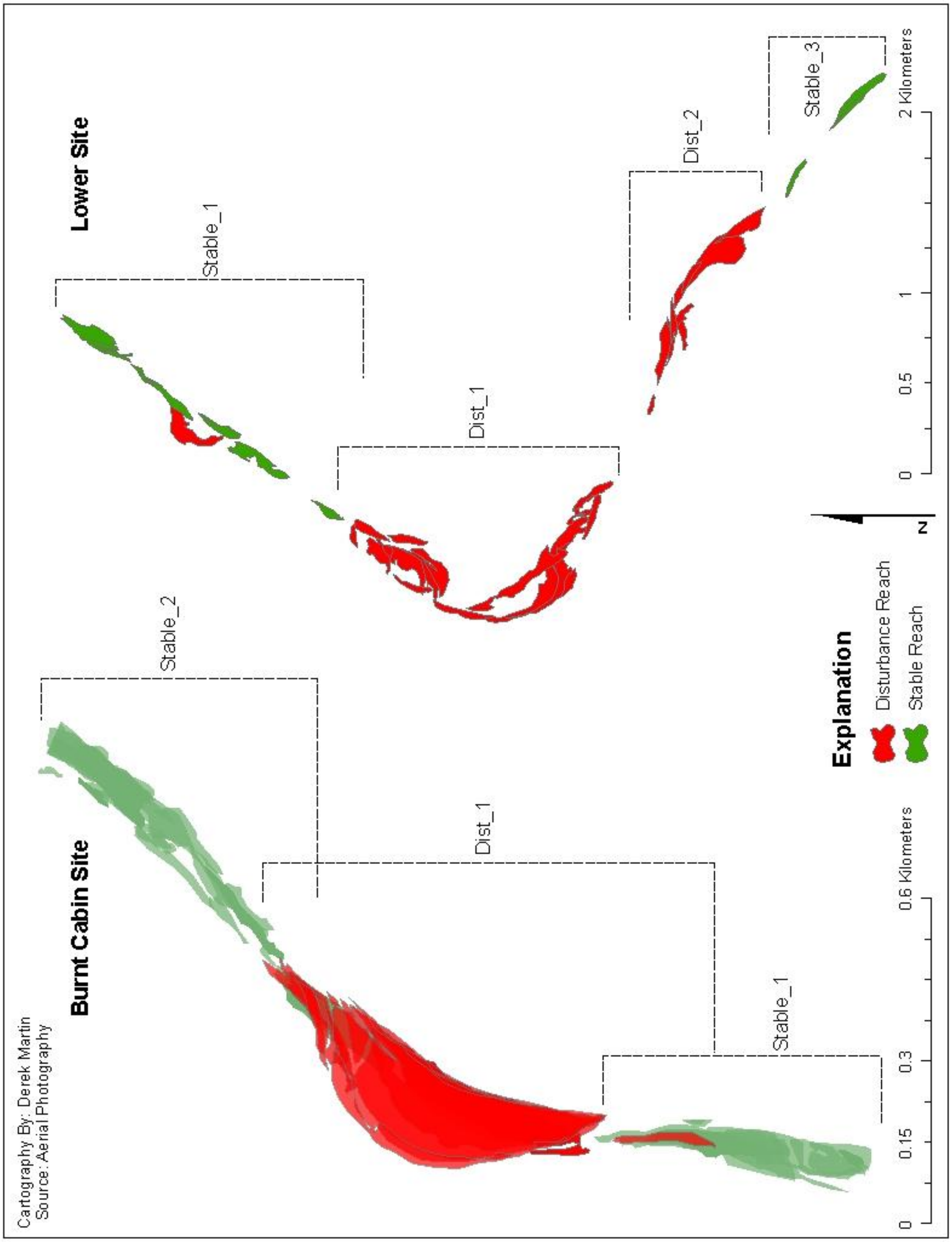


Figure 16. Groups of gravel features were classified according to the disturbance or stable reach in which they occurred.

Center of mass for each group of gravel features. This involved selecting one group of gravel features (Stable_1, Dist_1, etc.) from within each shape file (Bar_03area, Bar_98area etc.) and performing the mean center of mass calculation from the Geostatistics toolbox. The calculation that the mean center of mass tool performs is as follows: The exact x, y center is determined for each polygon within the group of polygons, then the center of those centers are determined (Fig. 17). This was done for each group of gravel features from each gravel feature shape file, for each year, for both sites. The next step was to measure the movement of the mean center of mass. This was done by simply measuring the distance between mean centers of mass of each consecutive year. The final step was to measure the azimuth direction of movement. This was done by entering a VBA Script Code in the Field Calculator in ArcMap. The script code can be found in Appendix B. The VBA script was downloaded free of charge from the ET Spatial Techniques website (http://www.ian-ko.com/, 2005). The azimuth direction of movement was calculated relative to the flow direction for that reach. The azimuth direction of flow was the zero azimuth. Based on these calculations, migration was determined to be in the downstream direction if the azimuth was between 315˚ and 45˚, laterally migrating if the azimuth was between 45˚ and 135˚, migrating in the upstream direction if the azimuth was between 135˚ and 225˚, and again, migrating laterally if the azimuth was between 225˚ and 315˚ (Figure 18).

Analysis of Channel Migration

In order to assess channel migration, a centerline approach was exercised. Stream centerlines were digitized using the previously developed channel outlines. Since

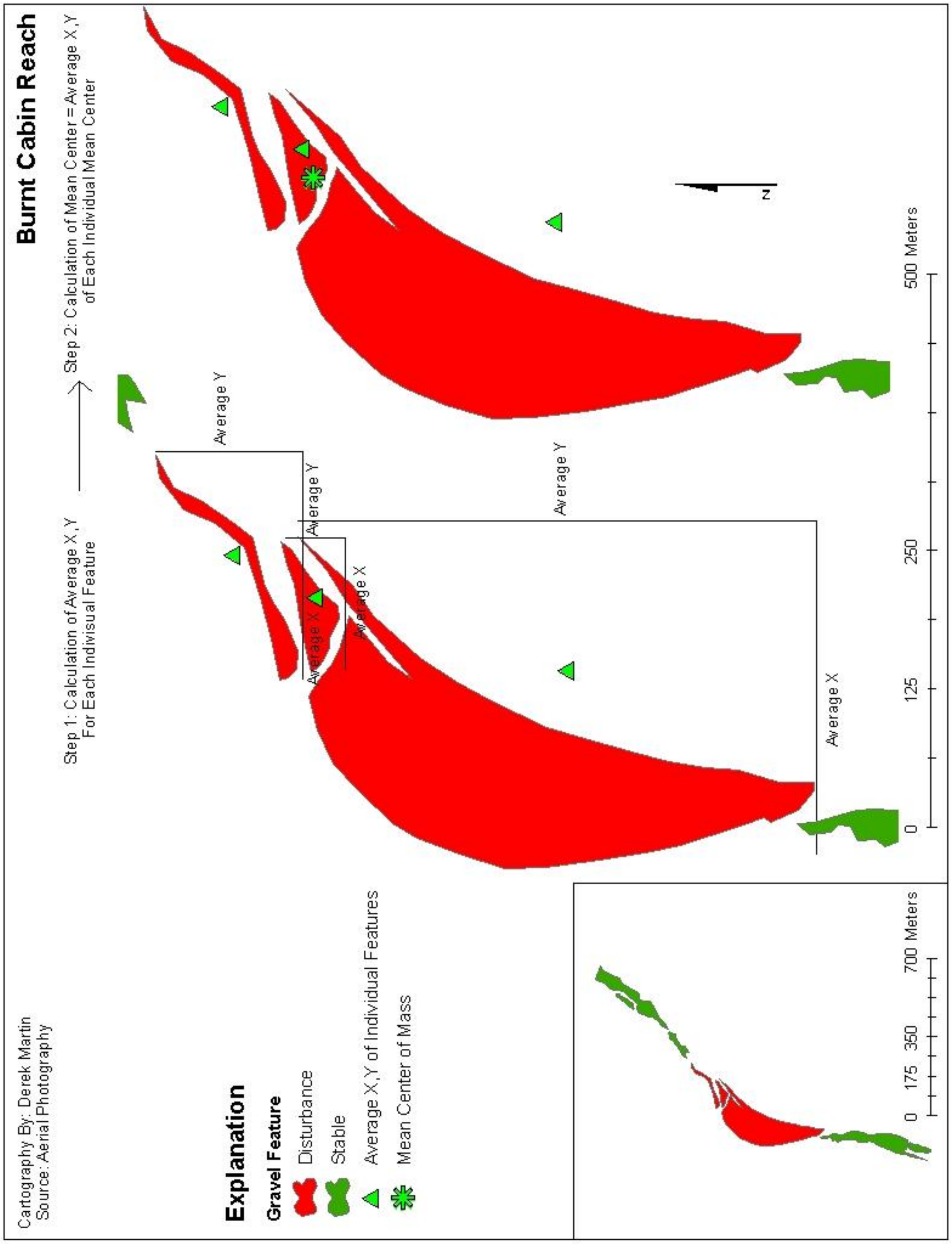


Figure 17. Determination of mean center of mass for gravel features grouped by reach classification.

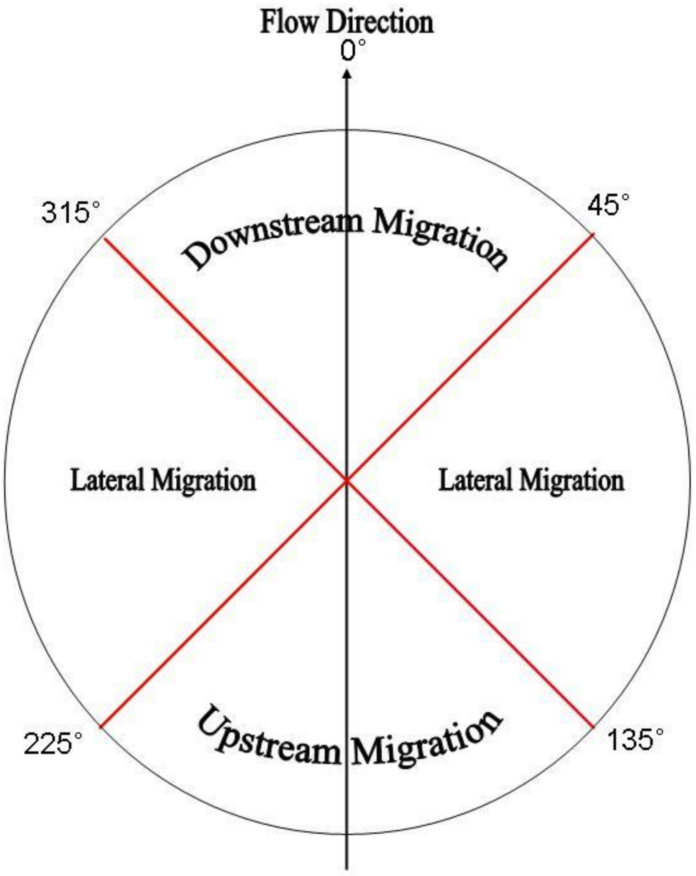


Figure 18. Azimuth quadrants that represent migration direction.

migration only takes place, according to definition, in disturbance reaches, migration was calculated at disturbance reaches only. Once digitized, the centerlines were overlaid. Then, based on the approach taken by Passmore (1997), point files were created where stream centerlines diverged from the stable reach or intersected the centerline from the previous photo. This resulted in the creation of a point shape file for each year-to-year interval. These point shape files were named as follows: diverge98_03.shp, diverge92_98.shp etc. and saved within the corresponding site folder. Then, to determine the meander's apex, a line was drawn between the two intersection points and a line was drawn perpendicular to that line at the exact center. The meander apex is located where the perpendicular line intersects that year’s channel centerline (Fig. 19).

After meander apices were determined, migration rates were calculated. First, migration distance was measured using the distance tool in ArcMap. Distances were then divided by the photo period (number of years between photos) to result in a migration rate of meters per year. Next, the azimuth direction of meander apex movement was calculated using the previously described method for calculating azimuth direction of bar mean center migration.

The centerline approach to assessing channel migration is often criticized due to its vulnerability to errors. Its most frequent criticism is that centerlines are not truly representative of the center of the river because higher flows will skew the centerline location. Although true, this type of error is of little concern for this project because the mean center of mass measurements for the gravel bars produce bar migration rates representative of general, reach-scale movement and not exact location and movement of bar materials. The same sort of result is sought with the channel migration rate calculations. If assessing something more local such as stream microhabitat dynamics, then the error induced by stream centerline calculations would be of concern.

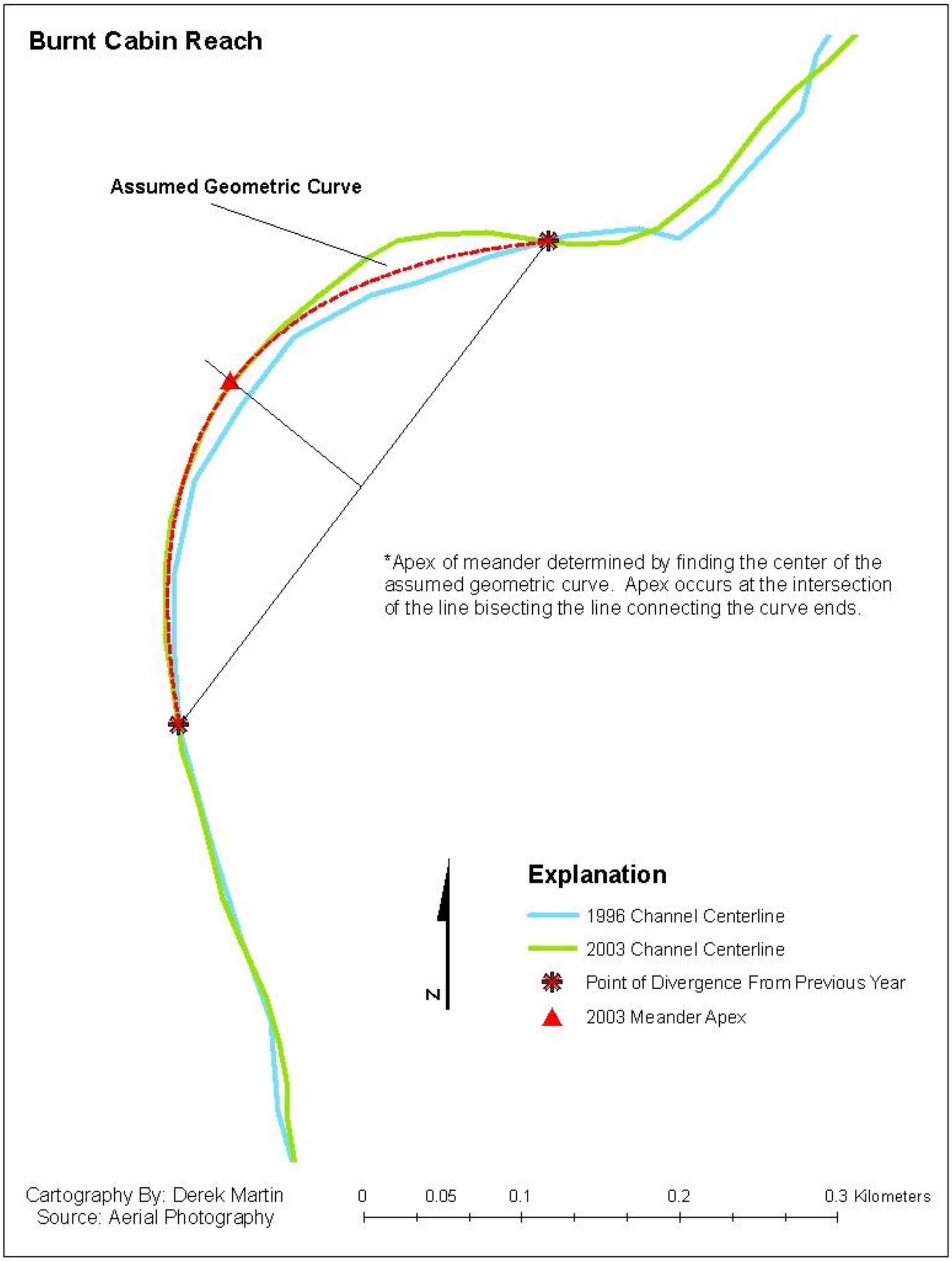


Figure 19. Example of determination of the meander apex.

Analysis of Riparian Land Cover

Riparian vegetation is believed to be a contributing factor to channel stability and hence, partial determinants in lateral channel migration rates. Riparian land cover area was quantified for the land cover classes: Bar, Forest, Grass/Ag, Grass/Shrub, Mixed, Pavement/Road and Water at both of the study reaches within a 200 meter buffer around the study reach (Fig. 20 and 21).

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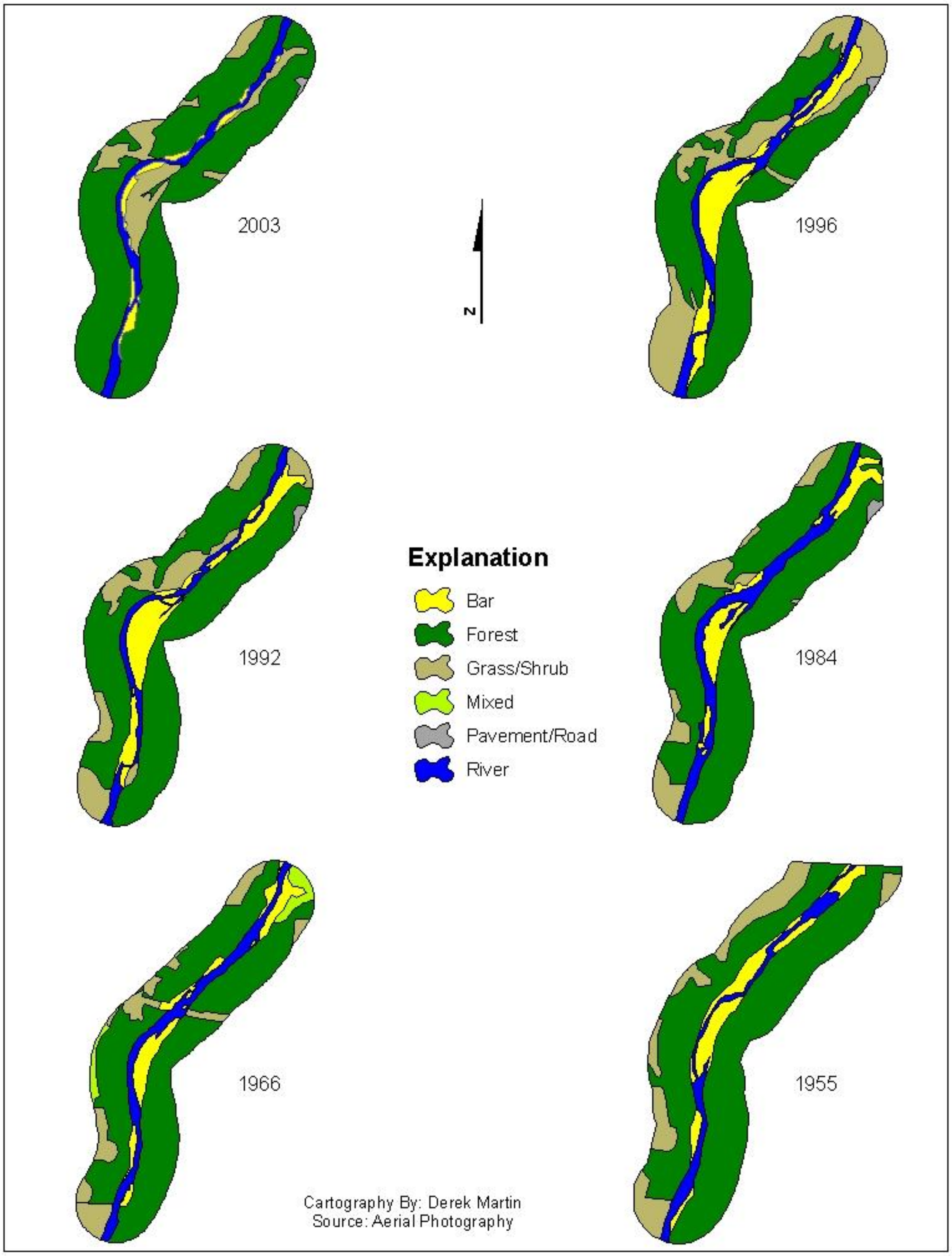
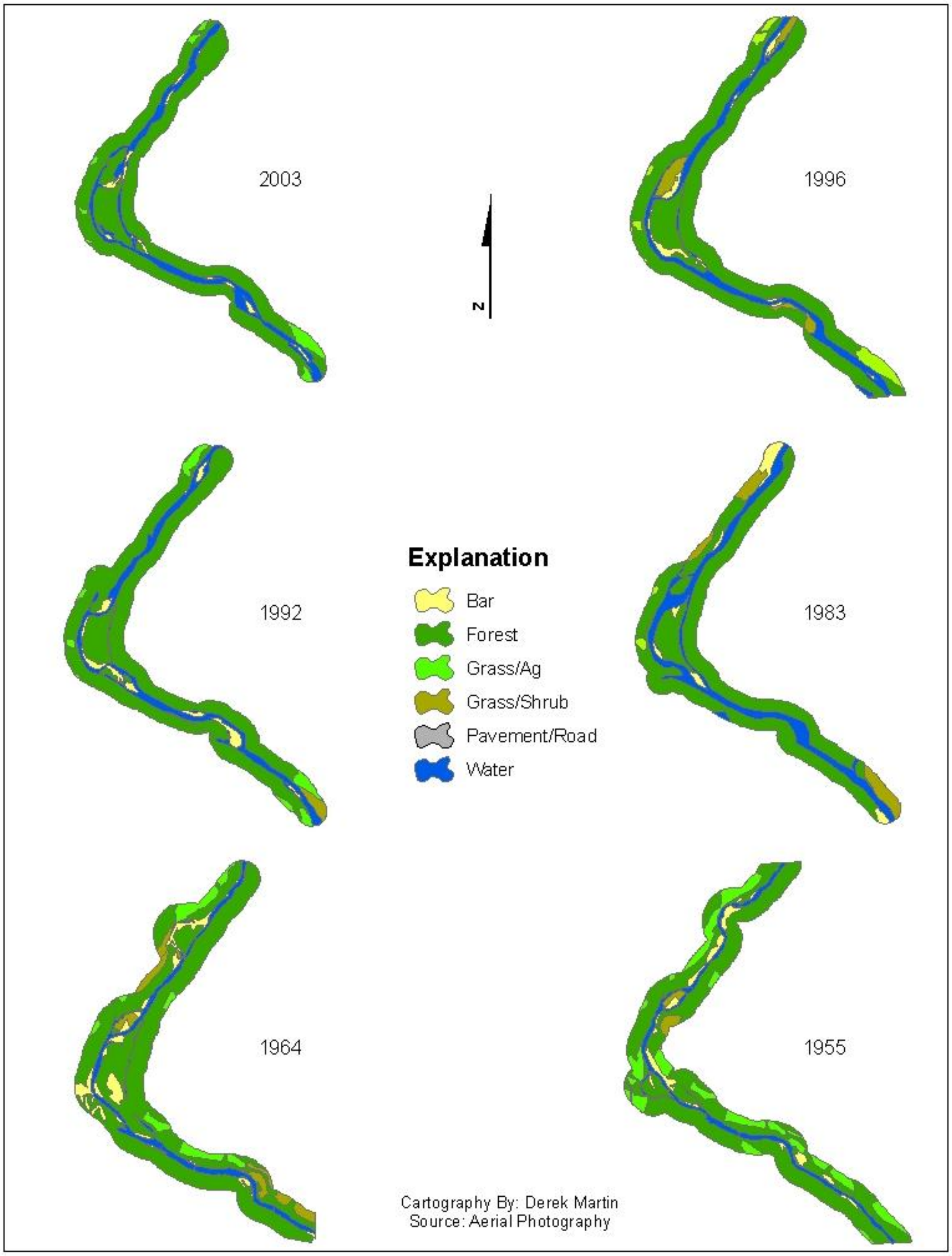


Figure 20. Land cover classifications for each photo year within the 200 meter buffer at the Burnt Cabin site.



Cartography By: Derek Martin
Source: Aerial Photography

Figure 21. Land cover classifications for each photo year within the 200 meter buffer at the Lower site.

Field Verification

During the month of March 2005, field verification was performed at both of the study locations in order to ensure classification accuracy for the land cover classifications. Points were chosen randomly at each study site until at least one point fell within each land cover classification type. Coordinates of those points were uploaded to a GPS. The GPS was used to navigate to the randomly selected points and the land cover type was verified or corrected. A digital photograph was taken at each of the different land cover types. Valley wall locations were also recorded at this time with the GPS. The location of the valley wall is important for determining the extent to which the river can meander.

CHAPTER 5

RESULTS AND DISCUSSION

GIS and remote sensing are used to quantify gravel bar deposition patterns, channel migration patterns, and riparian land cover over a 48 year period. Mean centers of mass are used to track gravel bar deposition and meander apex locations are used to measure channel migration rates. Azimuth direction of change is used to record the directon of channel and bar change through time. Riparian land cover classifications were determined using a 200 meter buffer from the stream centerline at each site. Appendix A contains the mean monthly discharge (Q) associated with the year in which each of the aerial photographs were taken. Appendix B contains the Visual Basic (VBA) script codes used to perform area calculations and azimuth measurements. Appendix C contains the raw data developed from the gravel deposition and channel migration analysis and Appendix D contains the S+ statistical output from the regression analysis. This chapter will discuss the relationships and trends found amongst the bar deposition patterns, channel migration patterns, riparian land cover and flow data.

Bar Deposition and Channel Migration

The mean center of mass method, used for measuring the migration of gravel features, and the meander apex method, used for measuring the migration of the channel, each allow three different types of migration assessment. First, movement can be assessed by visually analyzing the spatial patterns that they create. Second, movement can be quantified by measuring the distance that they have moved during certain time periods and third, the azimuth direction can be calculated.

Burnt Cabin Site. Gravel Bar Deposition. At the Burnt Cabin disturbance reach (Dist_1), the movement of the mean center of mass over the course of the photo periods was in a counter-clockwise, circular pattern (Figure 22). The azimuth direction of movement between each period for Dist_1 is given in Table 4. Azimuth direction is only given for disturbance reaches for the purpose of comparison to the channel migration which was only calculated at the disturbance reaches. This circular motion is indicative of the passing of a gravel wave, supporting the previous research presented by Jacobson (1995). As gravel is coming into the system, the mean center of mass for that reach occurs at the up-stream portion of the reach. As time passes and the gravel translates down-stream and accumulates in the disturbed area, the mean center of mass moves accordingly. As the gravel accumulations continue downstream, exiting the disturbed reach and another wave begins to make its way into the reach, the mean center returns to the up-stream end of the reach. Due to the lateral migration over this time period, the mean center of mass moves in a circular motion.

Table 5. Azimuth direction, distance, and interpretation of bar migration for Dist_1 at the Burnt Cabin site.

Period	Azimuth	Az Relative to Flow	Migration Description
55-66	35	15	Downstream
66-84	243	223	Upstream
84-92	37	17	Downstream
92-96	300	280	Lateral - Left
96-03	205	185	Upstream

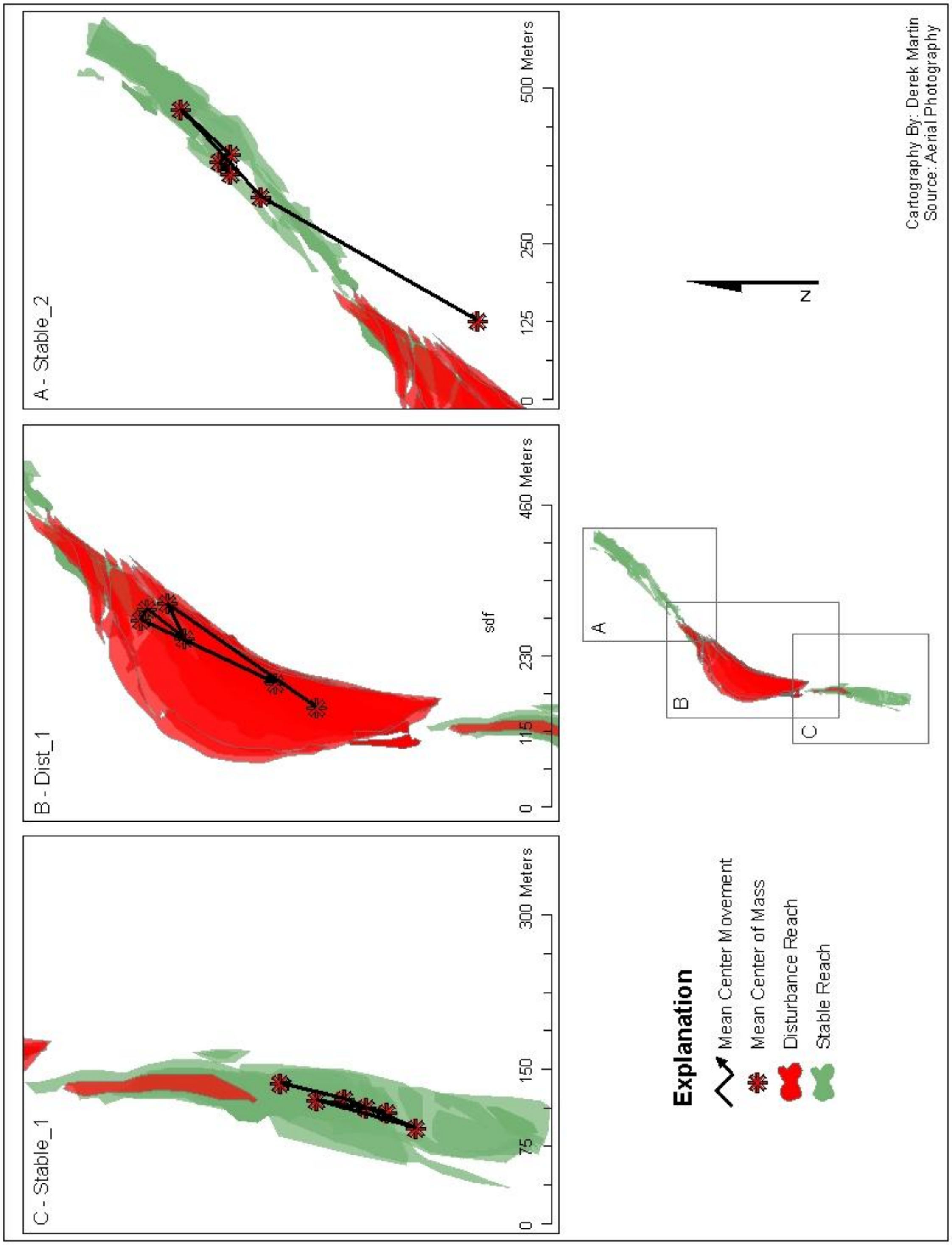


Figure 22. Spatial patterns of movement displayed by the mean center of mass within each reach of the Burnt Cabin site.

The stable reaches within the Burnt Cabin reach exhibited a laterally constrained pattern, indicating that there is very little channel migration taking place. If channel migration was occurring within these reaches, more lateral movement would be exhibited by the gravel features within these reaches. These patterns can also be seen in Figure 22.

Spatial trends in gravel migration rates are also evident. Figure 23 shows an increase in gravel bar area in Dist_1 from 2.1 to 6.2 hectares from1955 to 1996 and an increase in Stable_1 from .6 to 2.2 from 1984 to 1996. Stable_2 shows an immediate decrease from its peak, about 2.3 hectares, in 1955 while the upstream Dist_1 was accumulating. Following another small peak in 1992, Stable_2 began to decrease gravel area as the two upstream reaches approached their peak. This shows that the gravel accumulates rapidly at the disturbance site, reducing gravel storage downstream.

Figure 24 shows that in the time periods from 1966-84 to 1992-96 gravel migration rates steadily increased in Stable_1 from about three to nineteen meters per year. It then shows a sharp increase in migration rates from about five to thirty-three meters per year between the time periods 92-96 and 96-03 in Dist_1, while Stable_1 begins a decline. These data indicate the passing of a gravel wave near the end of the photo record and shows the capturing of the end of one wave and the beginning of another. Gravel storage (gravel bar area) reaches its highest point within the disturbance reach in 1996 (Fig. 23) and gravel migration rates are nearing their lowest points in the periods around 1996 (Fig. 24). If the gravel is being stored, it is not being transported.

Channel Migration. At the Burnt Cabin disturbance reach the lateral channel movement occurred in a pattern similar to the gravel movement, in a circular pattern. This movement is quantified by the changes in azimuth direction displayed in Table 5.

Lateral movement occurs in a clockwise circular pattern relative to the direction of flow (Figure 25). This coincides well with the counter-clockwise rotation of the gravel migration. As gravel migrates in the counter-clockwise direction it induces erosion, or, channel migration in the direction opposing that of the gravel.

Table 6. Azimuth direction, distance, and interpretation of channel migration for Dist_1 at the Burnt Cabin site.

Period	Azimuth	Az Relative to Flow	Migration Description
55-66	225	205	Upstream
66-84	259	239	Lateral - Left
84-92	8	348	Downstream
92-96	9	349	Downstream
96-03	312	292	Lateral - Left

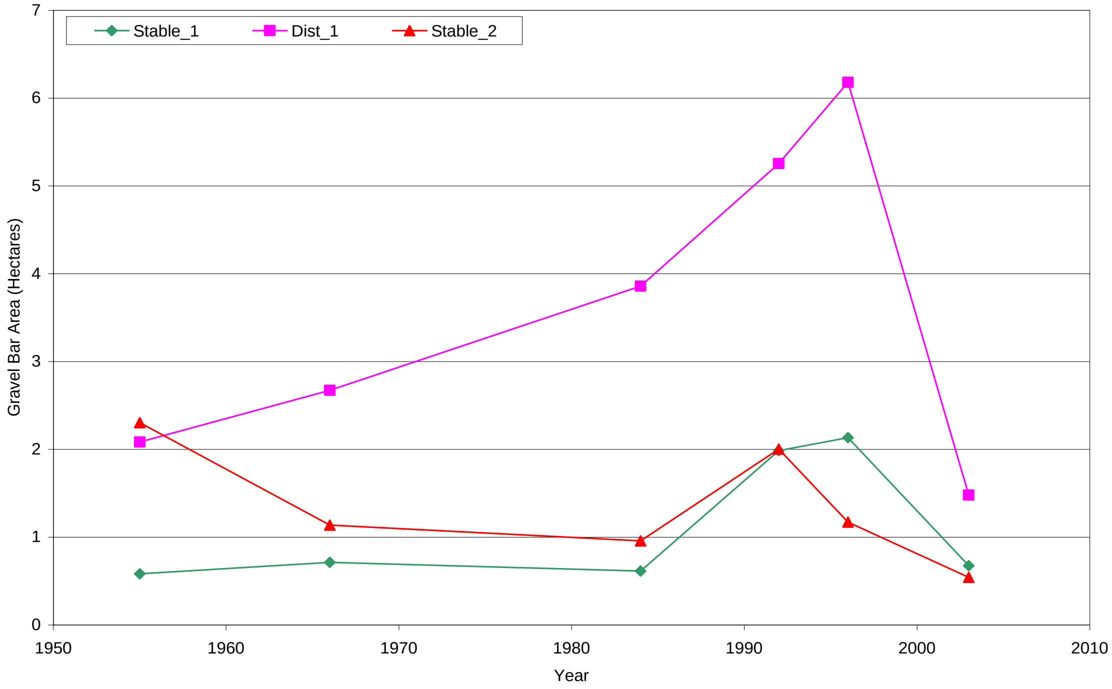


Figure 23. Changes in gravel bar area over time for the Burnt Cabin reach**.**

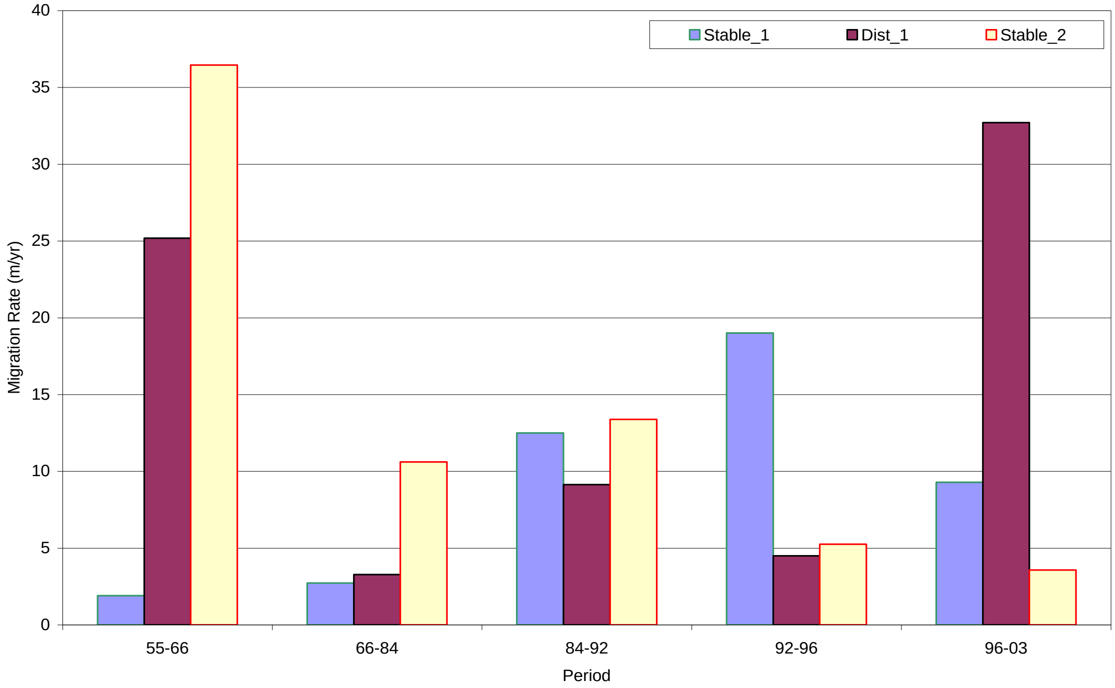


Figure 24. Changes in gravel migration rate over time for the Burnt Cabin reach.

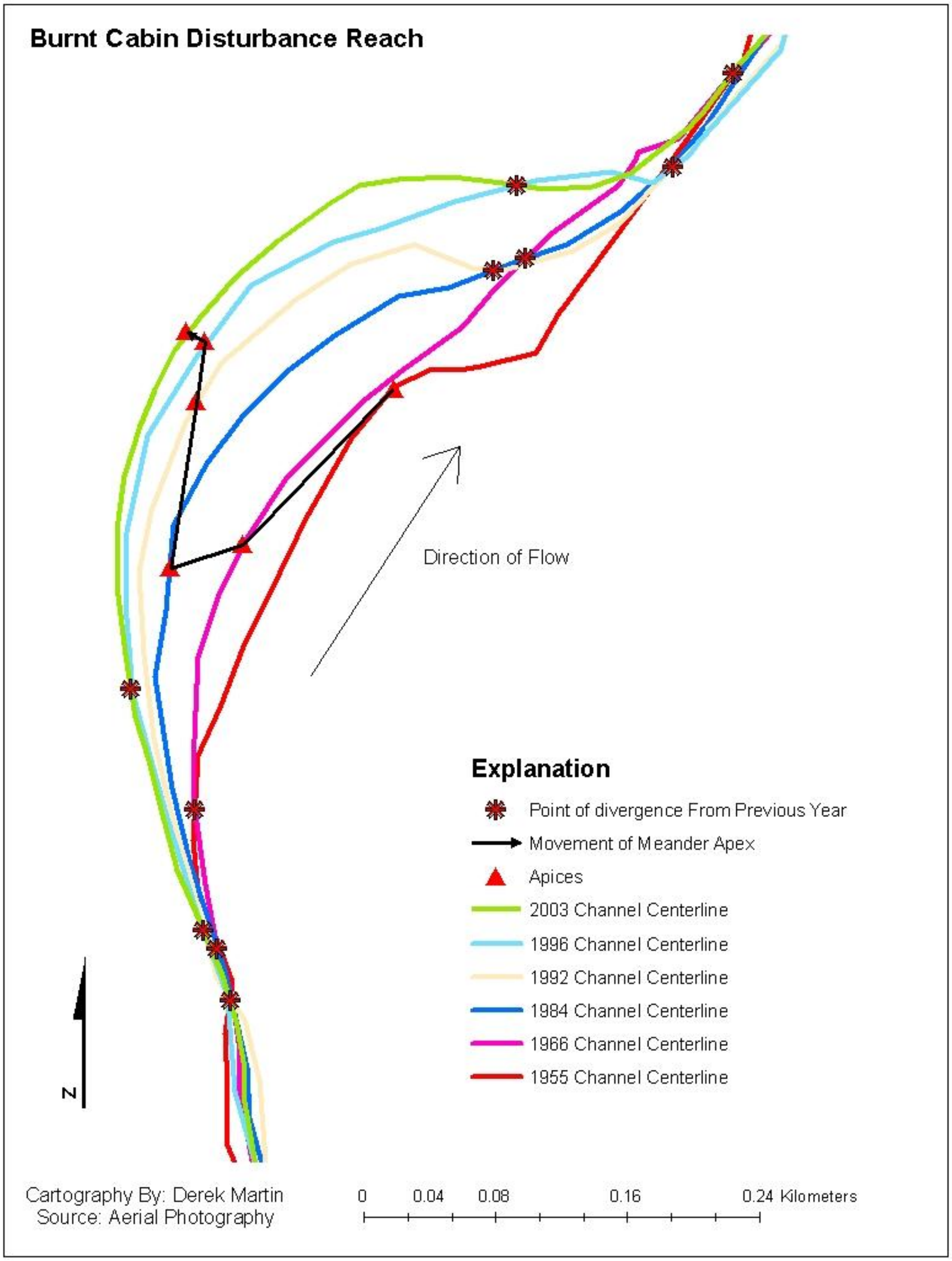


Figure 25. Movement of meander apex at the Burnt Cabin disturbance reach.

Bar/Channel Comparisons. Figure 26 displays channel and bar migration rate, area and azimuth direction for the Burnt Cabin site. The comparisons are made only at the disturbance reach because channel migration was only assessed at the disturbance reach.

The migration rates of the meander apex at Dist_1 appear to display a wave pattern throughout the course of the study period. Migration rates alternate, low to high to low, between three and ten meters per year. The alternating pattern is consistent over the course of the study period and occurs inversely to the mean center migration rates of the gravel bar. The consistency of the alternating migration rates support research by Jacobson (1995) that suggests this section of the Current River may be experiencing a post-gravel wave period, in which the river may be attempting to re-establish a pseudo-equilibrium state.

Channel area remains somewhat constant relative to the change in gravel bar area. This also supports the re-establishment of a pseudo-equilibrium state for this section of the Current River system. The comparisons of migration rates at the disturbance reach reveal a causal relationship. Following the 55-66 period where bar migration rates far exceed channel migration rates, channel migration rates increase. Following the periods in which channel migration rates exceed bar migration rates (66-96), bar migration rates increase. This supports the idea that small scale gravel waves are continuing to push through the river system.

The comparison of azimuth direction of migration shows that the largest changes in direction for mean centers, relative to the flow direction, took place in the 96-03 period. The largest changes in channel migration direction took place in the 66-84 period.

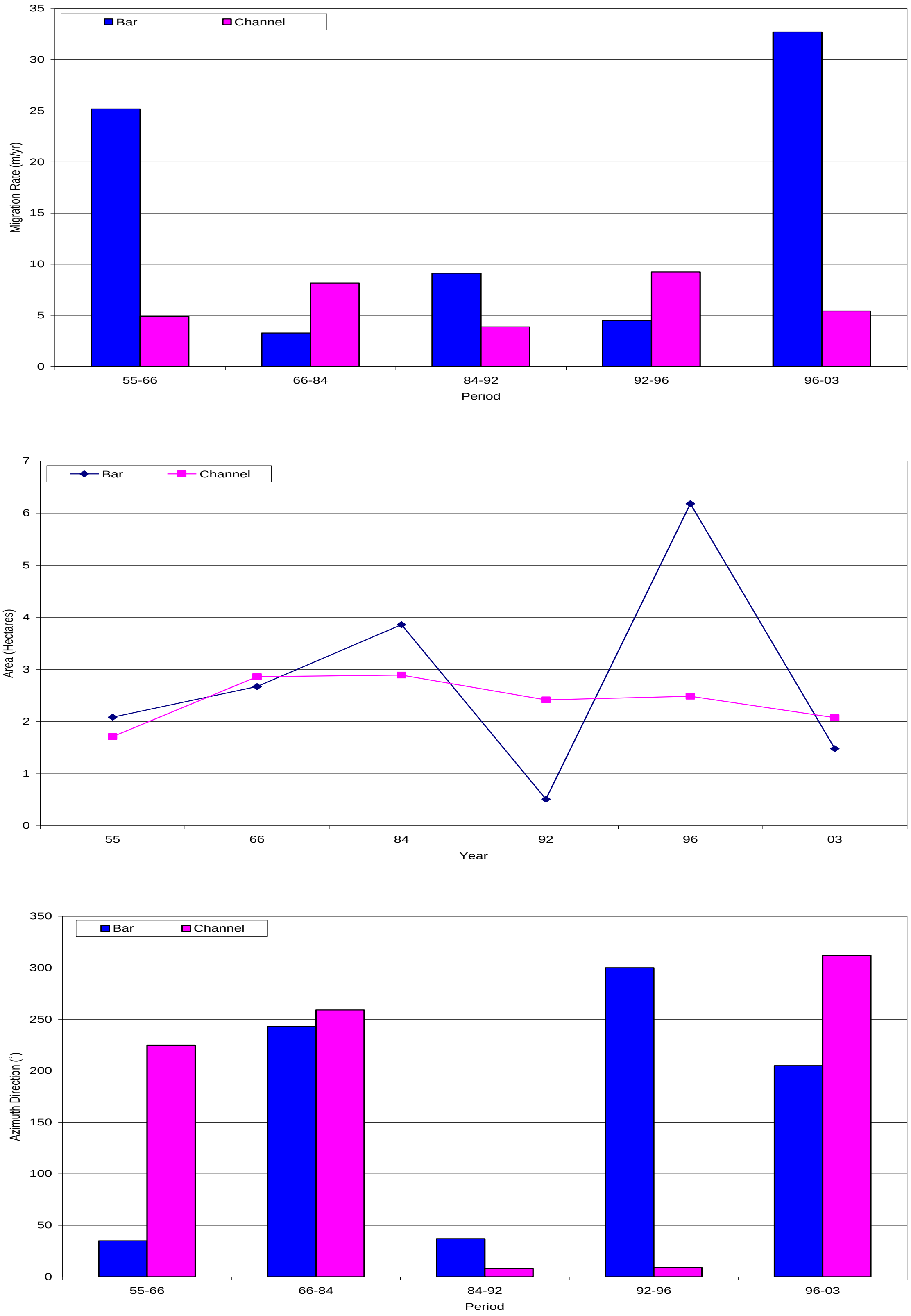


Figure 26. Changes in area, migration and azimuth for bar and channel at Dist_1.

Lower Site. **Gravel Bar Deposition.** The Lower site contained two disturbance reaches. The first, Dist_1, exhibited a pattern similar to that of the Burnt Cabin disturbance reach: a counter clockwise rotational pattern relative to the flow direction, possibly representing the pulse of a passing gravel wave. The second disturbance reach, Dist_2, downstream of Dist_1, exhibited a straight line pattern with migration occurring in the direction of flow (Fig. 27). Although the Dist_2 reach was classified as a disturbance reach, the straight line pattern exhibited by the mean center of mass movements suggests that there is a lack of lateral movement in terms of the gravel features and unlike the other disturbance reaches, does not display a pattern indicative of the passing of a gravel wave. Table 7 displays the azimuth direction of movement for both Dist_1 and Dist_2.

The gravel features within the stable reaches of the Lower site exhibited patterns similar to the stable reaches of the Burnt Cabin site. The mean center of mass movements occurred in a linear fashion. The longitudinal locations of the mean centers of mass indicate the passing of a gravel wave in Stable_1. The first mean center of mass occurs at the upstream end of the reach, the next at the downstream end of the reach and then moves back to the upstream end and are currently moving back downstream (Fig. 27). Stable_3 exhibits a linear movement in the downstream direction indicating little to no lateral movement.

Migration rates at the Lower site exhibit similar patterns to those of the Burnt Cabin reach, though, not as clearly. The disturbance reaches display an almost identical pattern in migration rate changes. Similar to the Burnt Cabin site, when migration rates

Table 7. Azimuth direction, distance, and interpretation of bar migration at Dist_1 and Dist_2 at the Lower Site.

Dist_1

Period	Azimuth	Az Relative to Flow	Migration Description
55-64	190	17	Downstream
66-92	209	36	Downstream
92-96	140	327	Downstream
96-03	17	204	Upstream

Dist_2

Period	Azimuth	Az Relative to Flow	Migration Description
55-64	113	353	Downstream
66-92	290	170	Upstream
92-96	98	338	Downstream
96-03	121	1	Downstream

are highest in the disturbance reaches, they are lowest in the stable reach, Stable_3, downstream of the disturbance reaches (Fig. 29). However, unlike the Burnt Cabin site, this data is not complimented by the gravel bar area calculations (Fig. 28). At the Burnt Cabin site, gravel bar area was at its highest while migration rates were at their lowest (gravel is being stored and is not migrating). At the Lower site, gravel bar area (Fig. 28) is highest during the time period in which migration rates (Fig. 29) are the highest for Dist_1. Dist_2 is similar to the Burnt Cabin disturbance reach in that gravel bar area is near its lowest during the time period in which gravel migration rates are at their highest.

The difference between the gravel bar area/gravel migration rate relationships at the two disturbance reaches at the Lower site could be a result of the type of disturbance that is occurring at these two reaches. Although they are only a couple hundred meters apart, the channel is quite different at each site. The channel at Dist_1 is a braided channel with two main channels. It occurs at a location which is bounded by a wide valley with steep valley walls which is what causes the sharp bend in the river and hence, the channel disturbance. The location of the valley walls also prevents excessive lateral migration.

The complexity of this disturbance results in uncommon gravel accumulation and movement. Dist_2 is located within a straight section of the channel and is not braided. The disturbance at Dist_2 was most likely caused by some sort of channel obstruction such as a root wad, causing the accumulation of gravel and the subsequent migration of that gravel downstream, in a narrower valley situation.

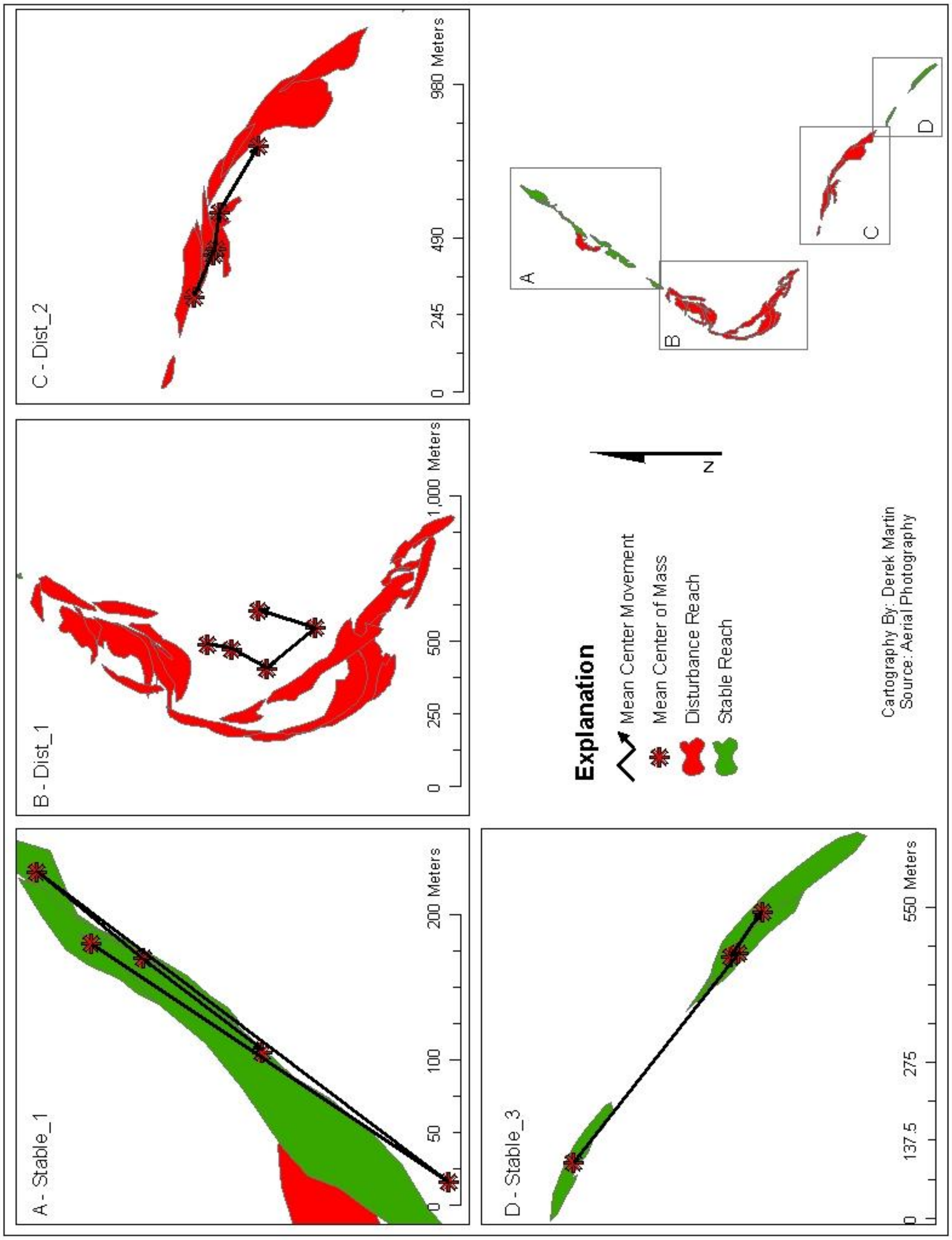


Figure 27. Spatial patterns of movement displayed by the mean center of mass within each reach of the Lower site.

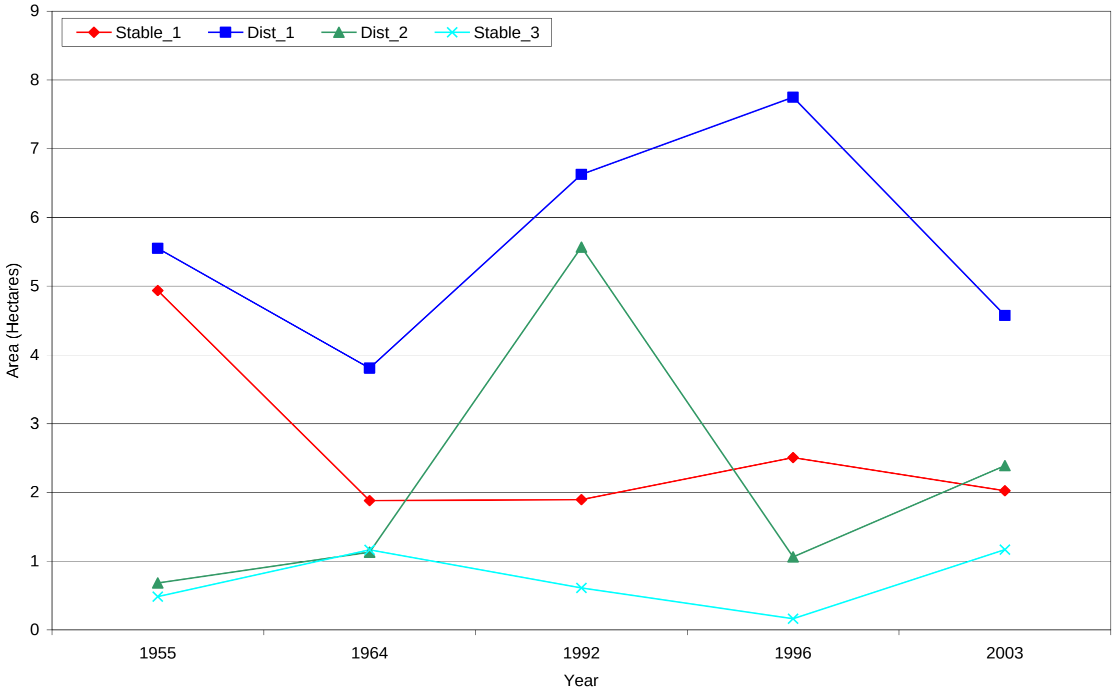


Figure 28. Changes in gravel bar area over time for the Lower reach.

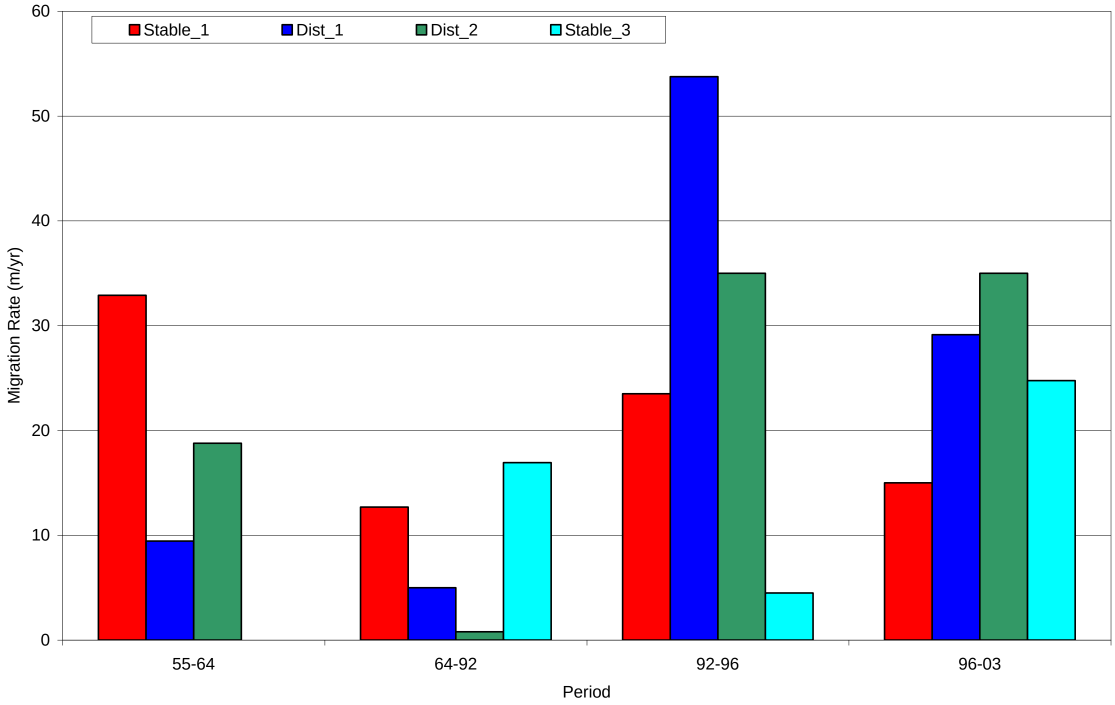


Figure 29. Changes in migration rate over time for the Lower reach.

Channel Migration. The spatial patterns exhibited by the meander apices at Dist_1 are sporadic and seemingly random (Fig. 30). This randomness is most likely attributed to the complexity of the topography which creates the confining valley walls and the braided channel type at this reach. The spatial pattern exhibited by Dist_2 at the Lower site exhibits a downstream translation of the meander apex as opposed to a lateral migration. As mentioned in the previous section, the disturbance at Dist_2 was most likely caused by a channel obstruction. Since that obstruction, the channel has maintained the meander bend but due to the narrower confines of the valley wall it cannot migrate laterally and hence, translates linearly in the downstream direction while maintaining its bend curvature. Table 8 displays the change in azimuth direction for each period.

The rates at which the meander apices are migrating are significantly different at both of the disturbance reaches. Dist_1 exhibits, much like the spatial movement pattern, sporadic changes in migration rates, showing no trend. Again, the sporadic change of migration rates in Dist_1 is most likely a result of the complexity of the topography and the braided channel. Dist_2 however, exhibits a steadily increasing migration rate throughout the course of the study period (Fig. 32).

Table 8. Azimuth direction, distance, and interpretation of channel migration at Dist_1 and Dist_2 at the Lower Site.

Dist_1

Period	Azimuth	Az Relative to Flow	Migration Description
55-64	250	77	Lateral - Right
66-92	245	72	Lateral - Right
92-96	155	342	Downstream
96-03	324	151	Upstream

Dist_2

Period	Azimuth	Az Relative to Flow	Migration Description
55-64	53	293	Lateral - Left
66-92	102	342	Downstream
92-96	289	169	Upstream
96-03	127	7	Downstream

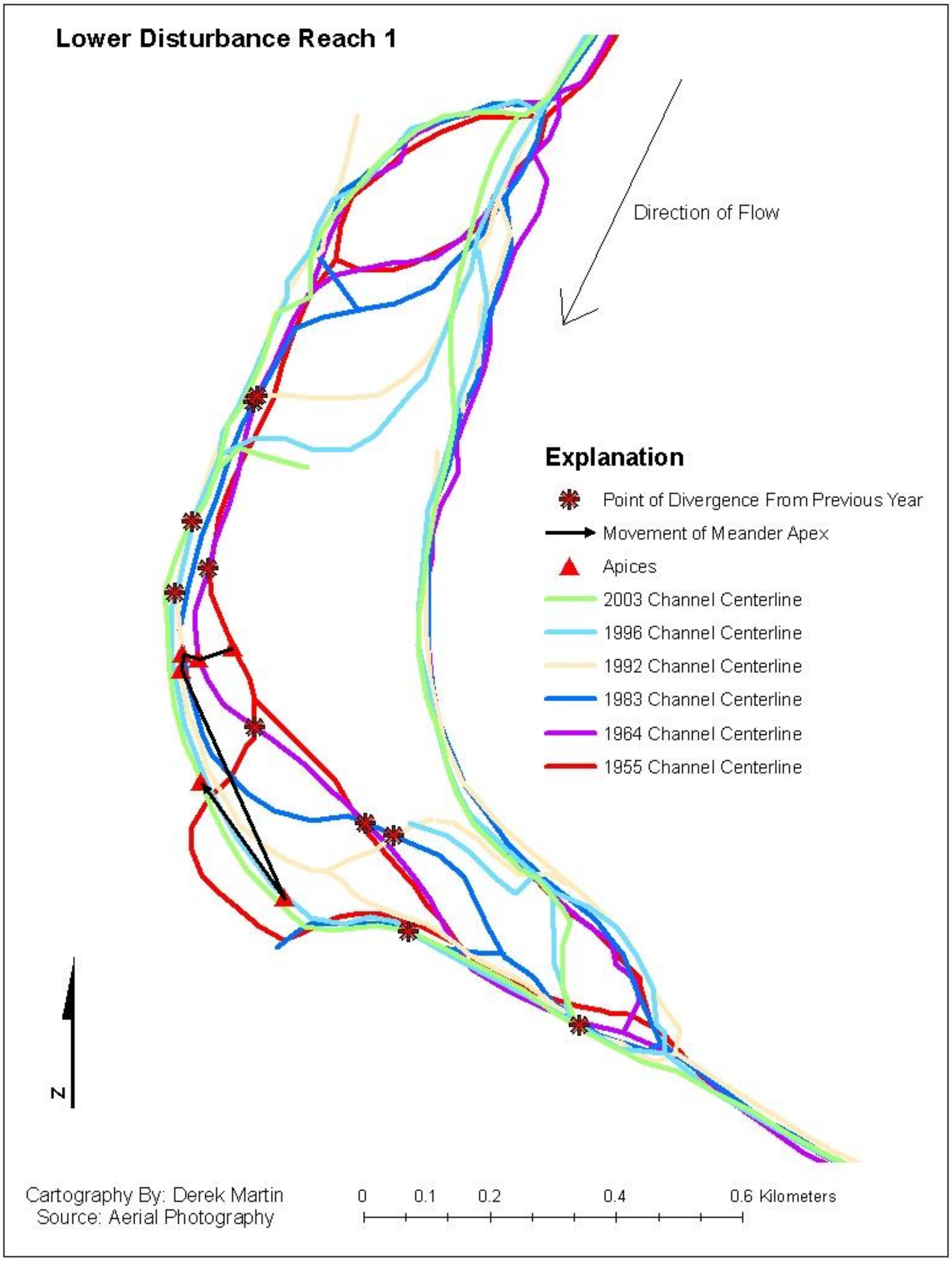
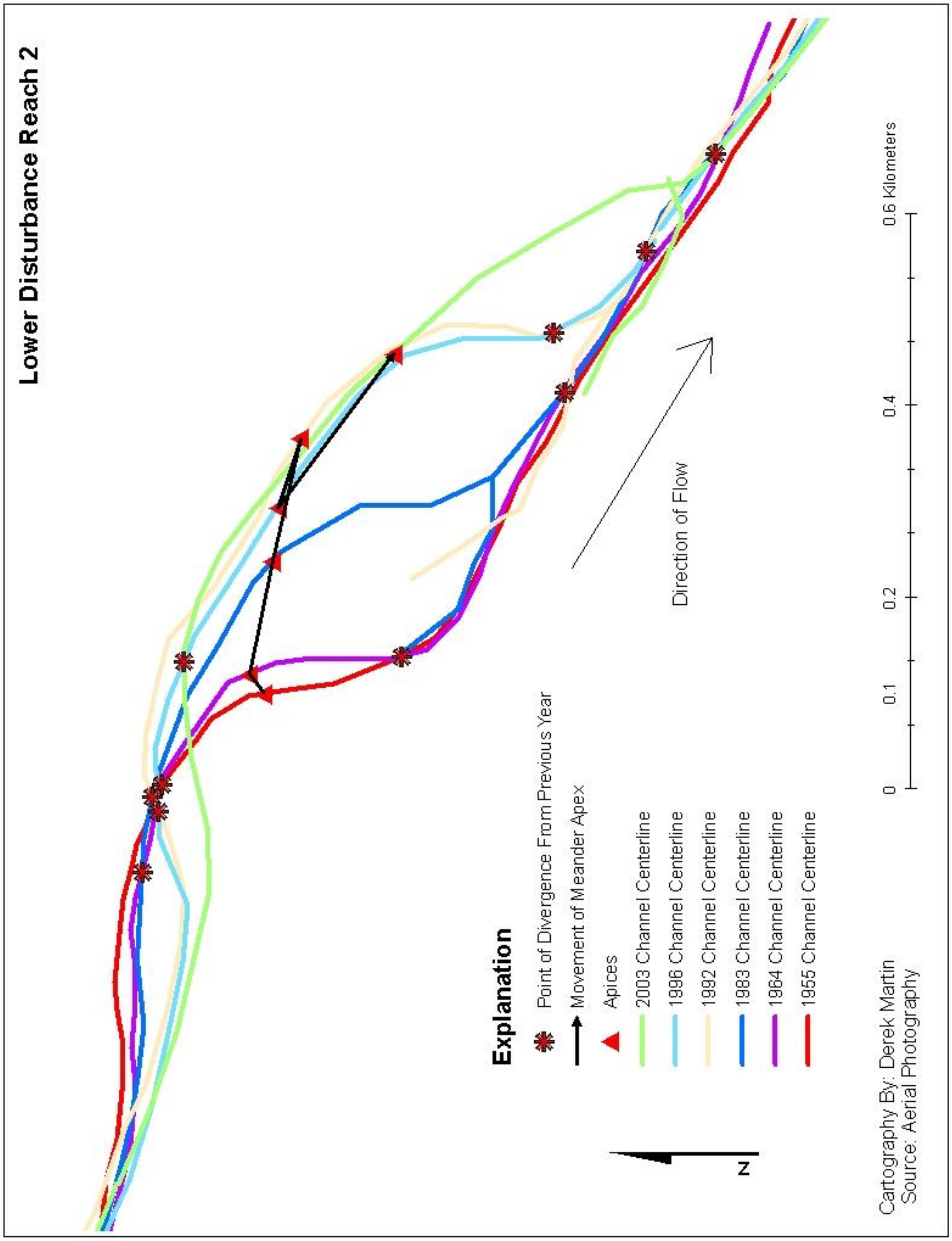


Figure 30. Movement of meander apex at the Lower Disturbance Reach 1.



Cartography By: Derek Martin
Source: Aerial Photography

Figure 31. Movement of meander apex at the Lower Disturbance Reach 2.

Bar/Channel Comparisons. Figure 32 displays channel and bar migration rate, area and azimuth for the Lower site. The migration rates at Dist_1 and Dist_2 at the Lower site, for both channel and bar, display similar patterns. For all but the channel migration rate at Dist_2, rates decrease from the periods 55-64 to 64-92 and then increase from 64-92 to 92-96 where they reach their peak, followed by declines in the bar and channel migration rates for Dist_1 and a leveling off of the bar migration rate at Dist_2. The channel migration rate at Dist_2 shows a steady, linear increase in migration rates from two to about thirty meters per year over the course of the study period. These results compare poorly to the channel and bar area calculations also displayed in Figure 32.

Bar and channel area show a fairly steady increase until 1996 for Dist_1. For Dist_2, channel area peaks in 1996 as well, but bar area peaks in 1992. Overall, bar area increases through 1996 except for the bar area for Dist_2. This could be a result of its downstream location. Bar accumulation upstream began limiting the amount of gravel transported and stored in the downstream Dist_2 reach. However, after 1996, when bar area begins to decrease in the upstream Dist_1, Dist_2 bar area begins an increase to 2003 indicating that the gravel stored in the upstream reach has been remobilized and has accumulated in the downstream Dist_2 reach.

The comparison of azimuth direction of migration, relative to the flow direction, shows that the largest changes in migration direction for gravel bar mean centers took place in the 66-92 period at Dist_1 and Dist_2. For the channel migration, the largest directional change at the Dist_1 reach occurred during the 96-03 period and the largest change at the Dist_2 reach occurred during the 96-03 period. These changes suggest a lag in period between migration activity of bars and migration activity of the channel.

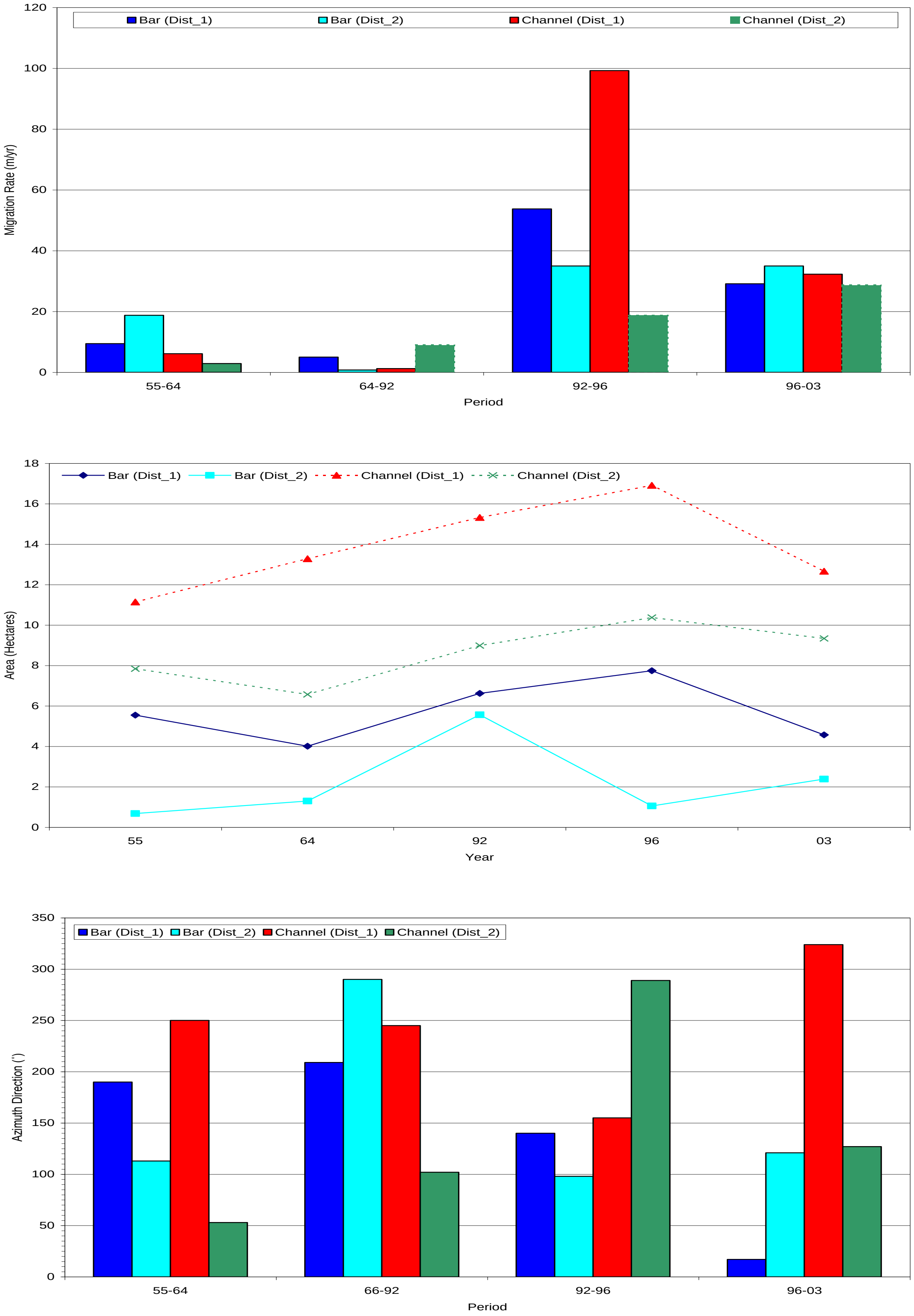


Figure 32. Changes in area, migration and azimuth at Dist_1 and Dist_2.

Land Cover

Land cover at both of the sites is dominated by forest. The earliest aerial photographs used for this analysis are from 1955, which is nearly thirty years after the end of the timber boom of the late 1800's and early 1900's. The lack of settlement after the timber boom resulted in little change in the landscape after the 1950's, especially in riparian areas. This lack of change is displayed in the following plots for both of the study sites. Figure 33 hows the land cover quantification within a 200 meter buffer of the stream channel for the Burnt Cabin site. There has been very little change within 200 meters of the stream channel. The most noticeable change is the slight increase in forest cover. Between 1984 and 1996, Grass/Shrub cover increases from 11 hectares to about 23 hectares. Then from 1996 to 2003 the Grass/Shrub cover decreases and Forest cover increases from 48 hectares to 66 hectares. This could be an indication of plant community establishment and evolution on the large gravel bar located in Dist_1. Also supporting this is the leveling off of the Bar cover type between 1992 and 1996, followed by a decrease in 2003, which is the same time that forest cover increase.

Figure 34 hows the land cover quantification for the Lower site. Little change has taken place at the Lower site as well. The most noticeable change is again, the slight the increase in forest cover. Also noteworthy is the increase in water cover. This indicates possible channel widening, which would occur to accommodate a higher sediment load. The area covered by water increases, however, the sharp increase from 1964 to 1983 is not a completely accurate representation of water cover for that year due to the high flow event that occurred at the time of photo acquisition (Appendix A).

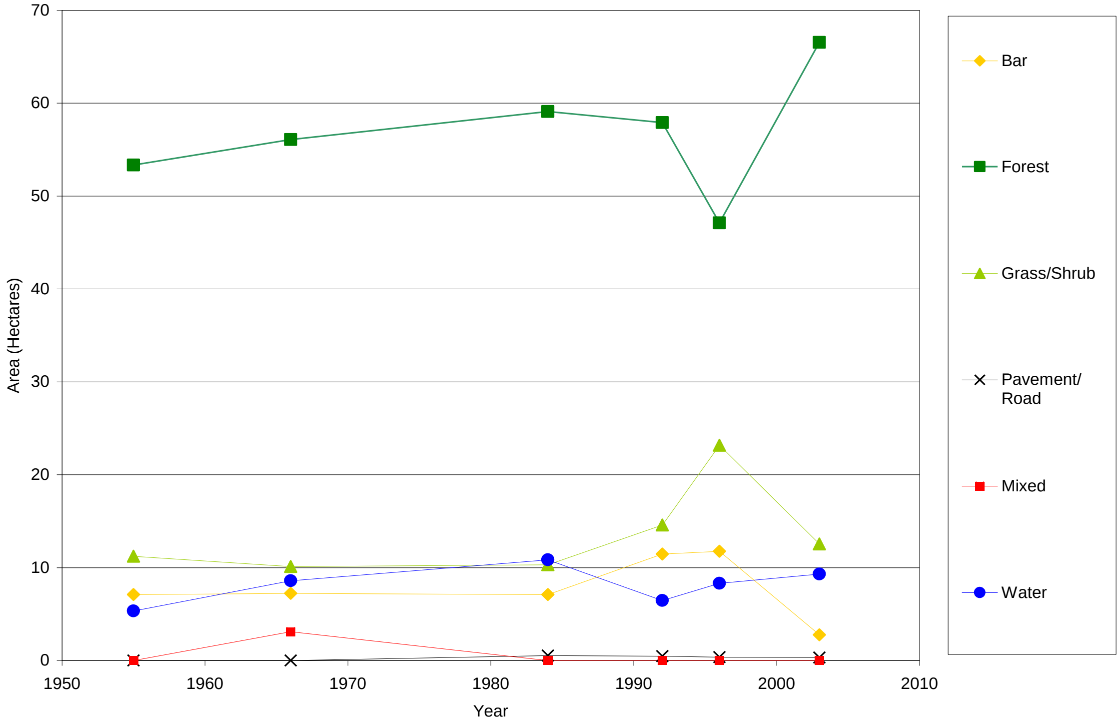


Figure 33 Land cover analysis within a 200 meter buffer of the Burnt Cabin reach.

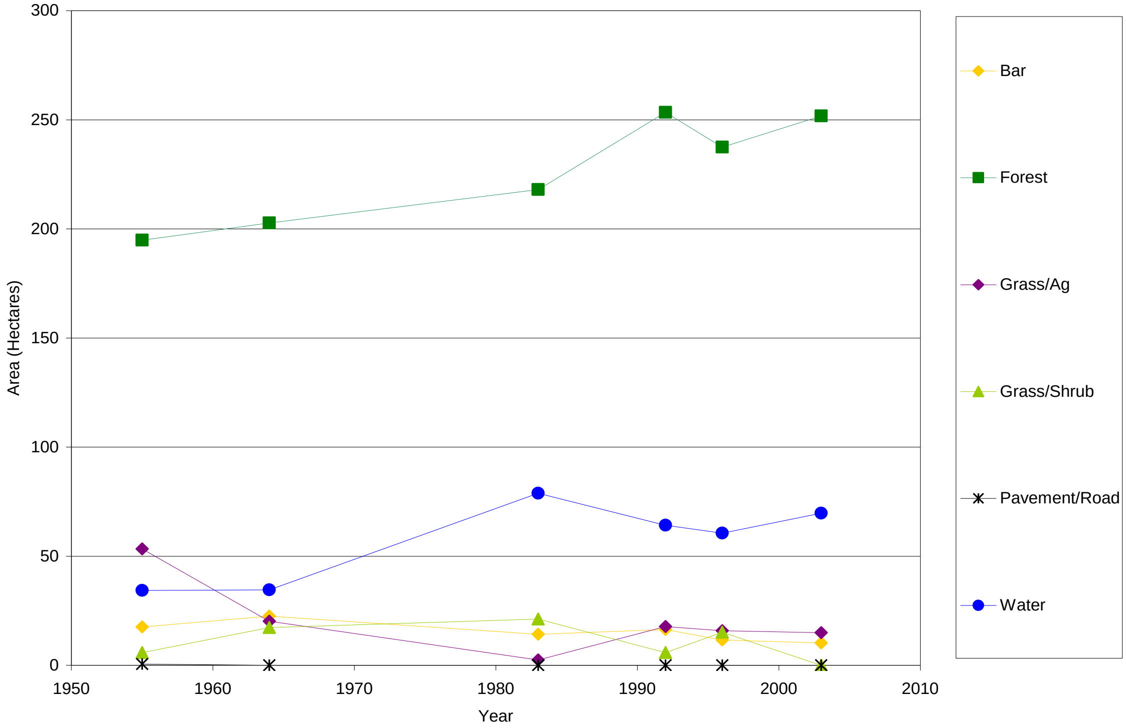


Figure 34 Land cover analysis within a 200 meter buffer of the Lower reach.

Valley Wall Influence

Perhaps the key component to the variability displayed between these two sites is the location of valley walls. As Jacobson and Gran (1999) observed, the alternating stable/disturbance pattern found in the Ozarks may be dictated by the location of valley walls. Also, Miller (1995) found that maximum boundary shear stress on the floodplain where a valley expansion coincides with a channel bend is as much as three times greater than the maximum channel shear stress along a canyon reach and 5-7 times greater than the maximum floodplain shear stress along a constant-width valley with a straight channel. This is the situation at the Burnt Cabin reach. At both of the sites, the location and width of the valley walls appears to play a key role in the channel patterns discovered throughout the analysis.

At the valley scale, both of these sites show similar valley characteristics: the average valley width at both of the sites is around 400 meters; both of the large meander bends occur at valley bends; both reaches go from a narrow valley into a wider valley; and both have an upstream tributary. However, variability occurs because the Burnt Cabin site is located on a tributary stream, the Jacks Fork, and is a much smaller stream. Two very different sized streams are flowing through valleys of nearly the same size. The Lower site is much smaller relative to its valley width and hence, has less room to migrate laterally, resulting in what we see in the downstream Dist_2 reach; translation of the gravel and channel in the downstream direction, rather than lateral migration. Also, there is more variability in the valley widths at the Burnt Cabin site. The valley ranges from 175 meters to 420 meters, whereas the Lower site’s valley ranges from 350 meters to 500 meters. Figures 35 and 36 display three-dimensional renderings of the study sites.

Of the three disturbance reaches evaluated in this study, they occur in two valley types. Dist_1 at the Burnt Cabin site and Dist_1 at the Lower site both occur on large valley bends. Dist_2 at the lower site occurs in what I will refer to as a mid-valley location, not on a bend, but in a straight section of the valley. Dist_2 revealed many differing spatial characteristics so it is therefore assumed that valley type (valley bend or mid-valley) plays an important role in the control of channel and bar migration.

Figure 35. A three dimensional rendering shows the location of the lateral migration-limiting valley walls at the Burnt Cabin site. The dist_1 reach is clearly visible.

Table 9. Average valley width per reach at the Burnt Cabin site.

Burnt Cabin Reaches	Avg. Valley Width (m)
Stable_1	425
Dist_1	476
Stable_2	585

Figure 36. A three dimensional rendering shows the location of the lateral migration-limiting valley walls at the two disturbance reaches at the Lower site.

Table 10. Average valley width per reach at the Lower site.

Lower Reaches	Avg. Valley Width (m)
Stable_1	374
Dist_1	378
Dist_2	324
Stable_3	655

Statistical Analysis

To fully understand the relationships between gravel bar mean center migration and channel migration, correlation analyses were performed. Also, in addition to these two variables, hydrologic variables were taken into account and included in the correlation analysis. The hydrologic variables included are mean annual discharge (cfs) and mean peak discharge (cfs).

First, a simple correlation matrix was calculated between the variables: mean annual discharge, mean peak discharge, migration rate of bars and migration rate of channels. Correlation coefficients were relatively low except between the variables: migration rate of bars and migration rate of channels, which produced a correlation coefficient of .743 (Table 11). Figure 37 displays the relationship between channel migration and bar migration.

Next, to confirm the existence of this relationship a simple analysis of variance (ANOVA) was performed. With migration rate of channel as the dependant variable and migration rate of bar as the independent variable, the ANOVA produced a critical F value of .004 and an F value of 13.55 at a confidence level of .95, thus rejecting the null hypothesis that there is no relationship. The result remains the same at a confidence level of .99. This confirms that the rate at which the gravel migrates is dependant on the rate at which the channel is migrating.

To assess the influence of valley width, average valley width was plotted for each reach (Fig. 38). The plot shows that the valley widens in the downstream direction at each site. It also shows that the disturbance areas occur within the mid-range of reach valley width with the exception of dist_2 at the Lower site.

Table 11. Correlation table for migration analysis.

	Mean Ann Q	*Mean Peak Q*	*Mig Rate Bar*	*Mig rate chan*
Mean Ann Q	1			
Mean Peak Q	0.868	1		
Mig Rate Bar	0.397	0.245	1	
Mig rate chan	0.508	0.416	0.743	1

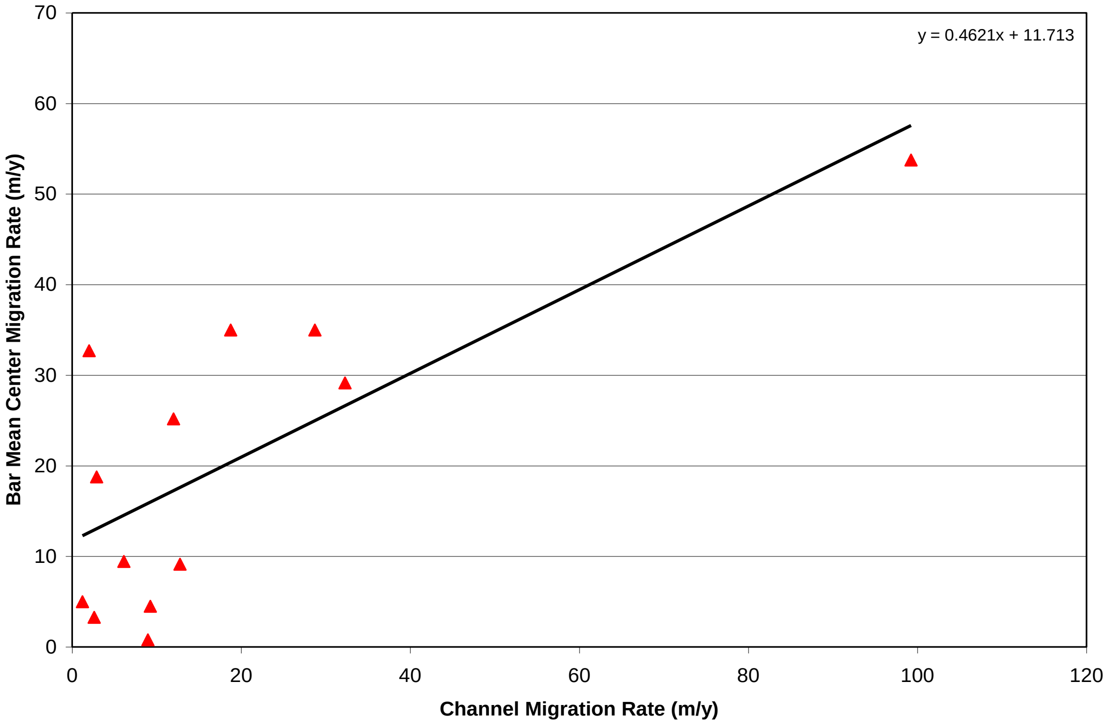


Figure 37. Regression relation between bar mean center migration rates and channel migration rates.

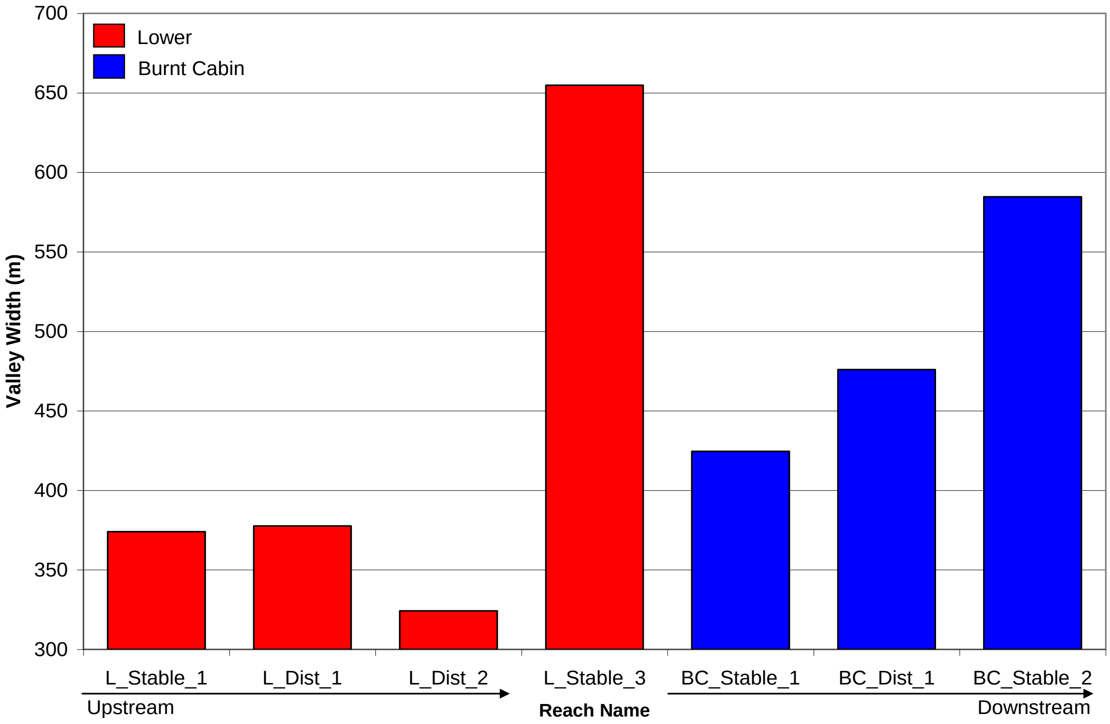


Figure 38. Average valley width per reach at each site.

Summary

The disturbance reaches analyzed in this study occur at two valley location types: valley bends and mid-valley. Dist_1 at the Lower site and Dist_1 at the Burnt Cabin site occur at a valley bend. Dist_2, at the lower site, occurs mid-valley. The valley bend disturbances occur within the mid range of valley widths at both sites and the mid-valley disturbance, Dist_2 at the Lower site, occurs where the valley width is the smallest. This helps explain the disturbance response that occurs at these reaches. The Burnt Cabin Dist_1 reach displays a laterally migrating response, which is allowed by the nearly 470 meter wide valley at this location. Dist_1, at the Lower site, displays more of a translating response due to the much narrower valley width as does the Dist_2 reach, which also displays a downstream translating response. This downstream translation is induced by the extremely confining valley at Dist_2, disallowing lateral movement.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The purpose of this study was to analyze 48 years of aerial photography to help determine relationships between gravel deposition and lateral channel migration within the Jacks Fork and Current River, Missouri. In addition, this study aimed to highlight the advantages of applying geospatial technologies, such as remote sensing (RS) and geographic information systems (GIS), to watershed management issues, such as the gravel wave issue that is currently of concern to National Park Service resource managers. This was done by (1) acquiring and rectifying aerial photographs from 1955 through 2003, (2) digitizing the channel, gravel features, and riparian land cover and, (3) applying geostatistical analysis methods, such as mean center of mass and meander apex to assess spatial movement patterns and quantify migration rates

In summary, the study areas showed two types of disturbance response in terms of channel migration and gravel deposition: lateral migration and downstream translation. These response types occurred in one of two valley locations: mid-valley and at valley bends. Other disturbance response controls appear to be valley width, tributary location, valley floor soils and vegetative resistance.

Results show that (1) migration patterns and rates of both gravel features and the channel are dependant on the disturbance response, i.e. whether it is migrating or translating; (2) the type of disturbance is dependant on the local topography, i.e. whether the disturbance exists mid-valley or at a valley bend and; (3) lateral migration rates of the channel are dependant on the migration rates of the gravel within the channel. Therefore, the excessive amount of gravel that was introduced to the Current River system in the late

1800’s to early 1900’s is currently affecting the rates at which the channels are migrating, the release of sediment and habitat destruction in the river system. These results support previous findings by Jacobson (1995) that parts of the river may be experiencing the tail end of this human-induced gravel and are currently re-establishing a pseudo-equilibrium state. The findings that support these conclusions are described following.

Gravel Migration.

The mean center of mass analysis revealed that spatial patterns of gravel migration at disturbance reaches display a counter-clockwise rotation pattern relative to the direction of flow, which involves lateral adjustment and bank erosion. Spatial patterns of gravel migration at stable reaches display an upstream and downstream linear migration pattern in the direction of flow. Although spatial patterns are different, the same type of migration process is taking place in both disturbance and stable reaches. When the gravel has migrated out of the reach, the mean center of mass reverts back to the upstream end where new gravel is entering the reach, starting the process over again. The difference is that lateral migration occurs in the disturbance reaches and to a much lesser extent in the stable reaches.

Gravel migration rate calculations support evidence that gravel is migrating through the system in wave form. Results show that gravel wave passage rates are relatively higher in upstream reaches and are lower in downstream reaches, indicating a “cyclic” wave of gravel movement. The passage of a single wave through a disturbance reach appears to be occurring on about a 50 year cycle at the Burnt Cabin site and a >50 year cycle at the Lower site.

Channel Migration

At the Burnt Cabin site, meander apex migration occurs in a clockwise rotation relative to the direction of flow. This is contrary to the counter clockwise rotation of the bar migration. At the Lower site, meander apex migration occurred both sporadically, showing no noticeable pattern, and linearly, translating in the downstream direction.

Lateral migration rate calculations show a consistent pattern at the Burnt Cabin site. At the Lower site, lateral migration rate calculations show a sporadic pattern at Dist_1 and a steadily increasing pattern at Dist_2. The differences in migration rates are attributed to the differences in local topography. At the Burnt Cabin site, the rate of channel migration appears to be controlled by the amount of gravel and the rate at which it migrates. At the Lower sites, where the stream is much larger in relation to the valley width, migration rates are more controlled by the location of the valley walls and are less dependant on gravel migration. Overall, excess gravel clogs the channel and directs water flow against the outer banks, causing lateral migration.

Land Cover Analysis

The land cover area calculations revealed that since 1955 very little has changed within the two hundred meter buffer around the stream channels. However, the changes that have taken place are consistent with the changes that have taken place within the channel. At the Burnt Cabin site, increases in Bar area followed by Grass/Shrub area followed by Forest area suggest that gravel that has been deposited has now been colonized by vegetation and has evolved to forest cover. The Lower site also showed an increase in forest cover as well as water area, suggesting that the channel has widened to accommodate the increased sediment load.

Recommendations

This study provides a methodology by which one can monitor and assess river changes as well as learn more about the properties of gravel and channel migration within the Current River system. This study has revealed that different types of channel disturbance (migrating vs. translating) display different types of channel migration and are highly influenced by valley type (valley bend vs. mid-valley). Research should now focus on the different types of channel disturbance in the Current River system by selecting numerous disturbance reaches throughout the watershed for analysis. These disturbance reaches can then be compared to other disturbance reaches located in similar valley and network settings. Disturbances of like valley type can then be compared in terms of their channel migration and gravel deposition features. This can help us understand the spatiotemporal characteristics of channel disturbance and bar deposition within each type of valley situation. This knowledge will be very useful to resource managers in terms of environmental management as well as resource and recreation planning and will also be useful to scientists studying geomorphic aspects of gravel bed streams.

In terms of environmental management, resource managers can develop assessment and/or remediation strategies based on their knowledge of the disturbance characteristics. For example, long term assessment study sites could be chosen based on valley location in order to monitor the long term migration of gravel in the system. Based on that information, the best possible aquatic bio-habitat monitoring sites could be chosen at the locations revealing habitat characteristics suitable, or expected to be suitable in the future, for species of interest.

In terms of a recreation planning tool, park managers can use the knowledge gained from this study to help in the location selection for new park facilities such as camp grounds, boat ramps as well as other recreational facilities. It will also aid in the maintenance of preexisting facilities that may be affected by the spatiotemporal changes that have taken place throughout the park.

This study also contributes valuable information to the growing knowledge base for gravel bed streams in the Ozarks. In addition to the collection of information on land use impacts, habitat scale gravel sediment routing, and vegetation influences, this study provides a spatiotemporal analysis of gravel deposition and channel migration characteristics that can be further studied to provide needed information on fluvial geomorphic characteristics of gravel bed streams in the Ozarks.

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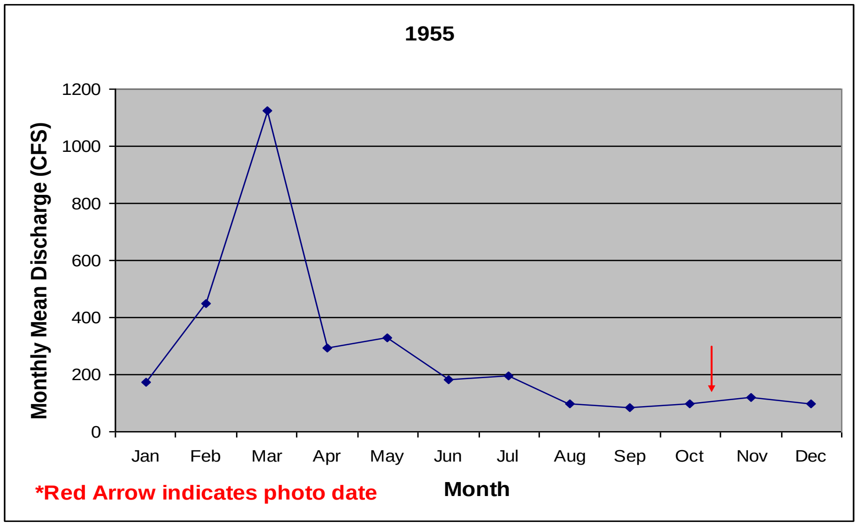
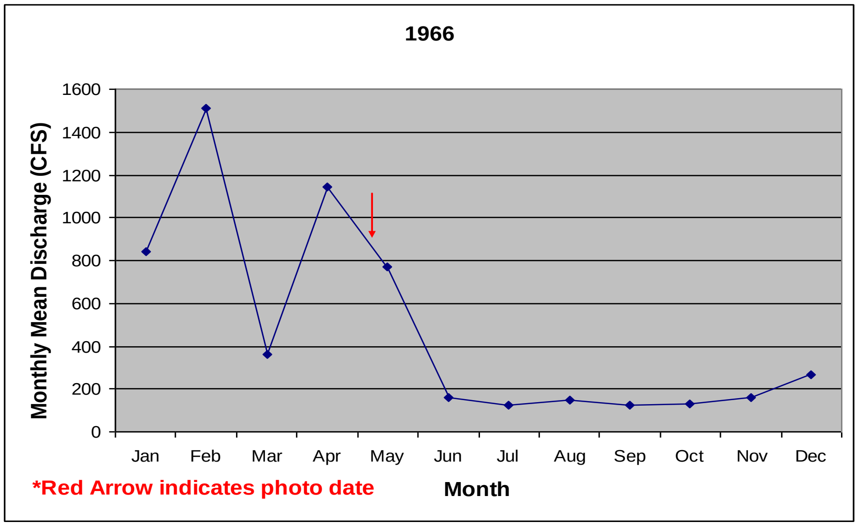
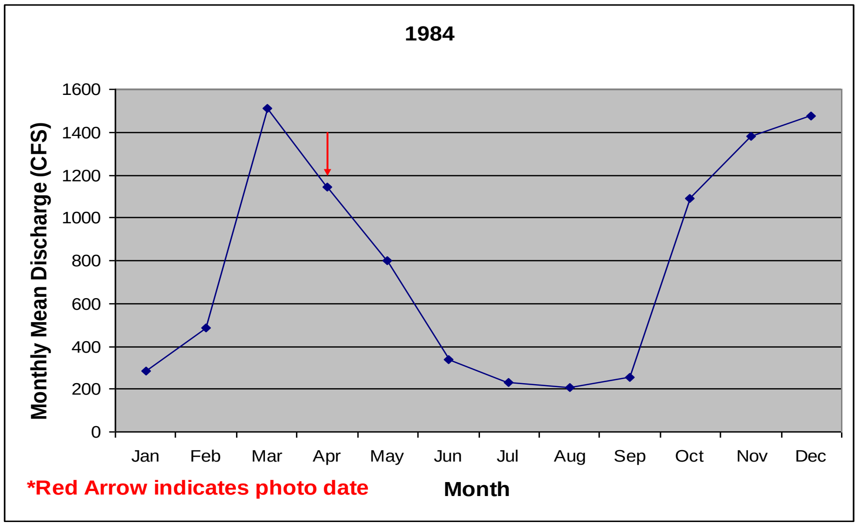
Appendix A

Photo Date Flow Data

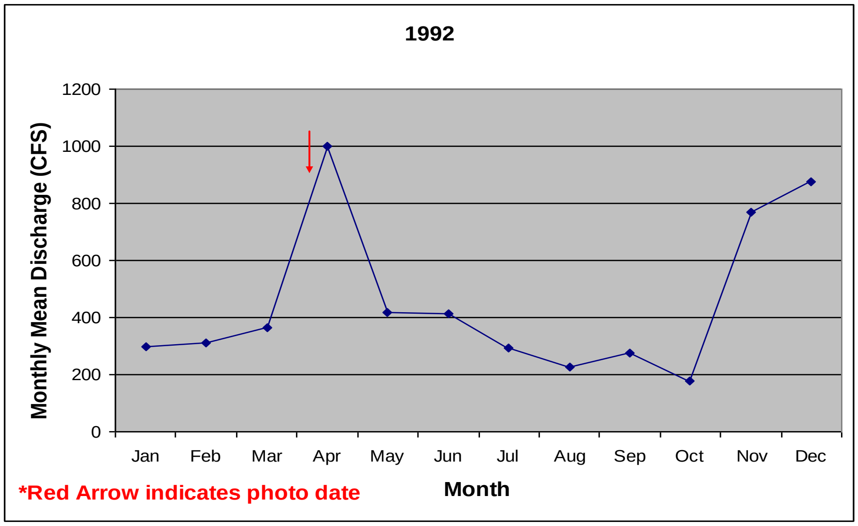
Burnt Cabin Site – USGS Gage 07066000, Jacks Fork at Eminence, MO

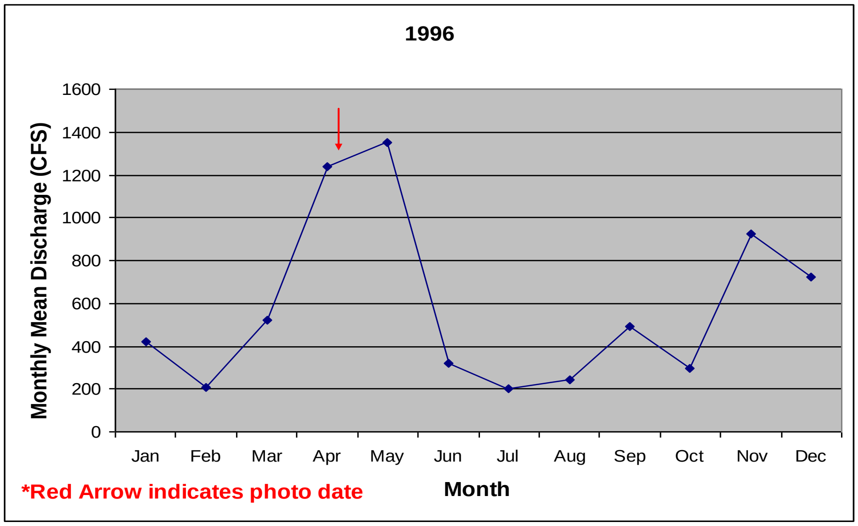


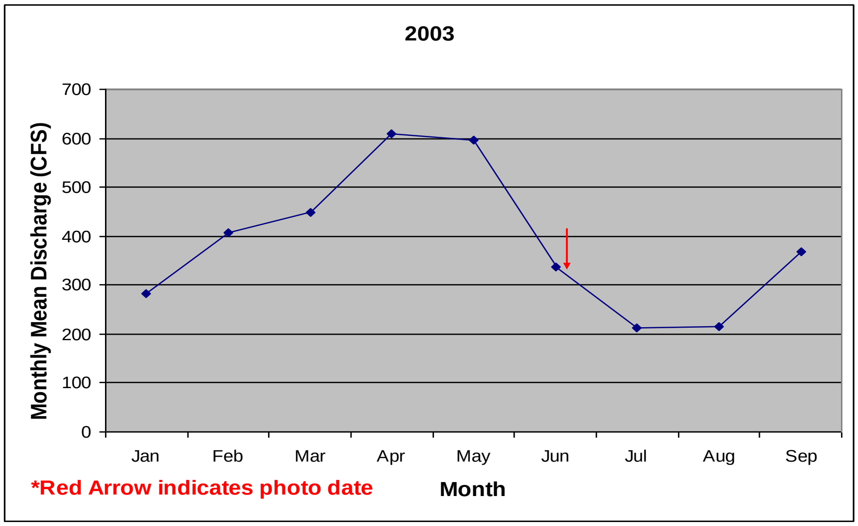




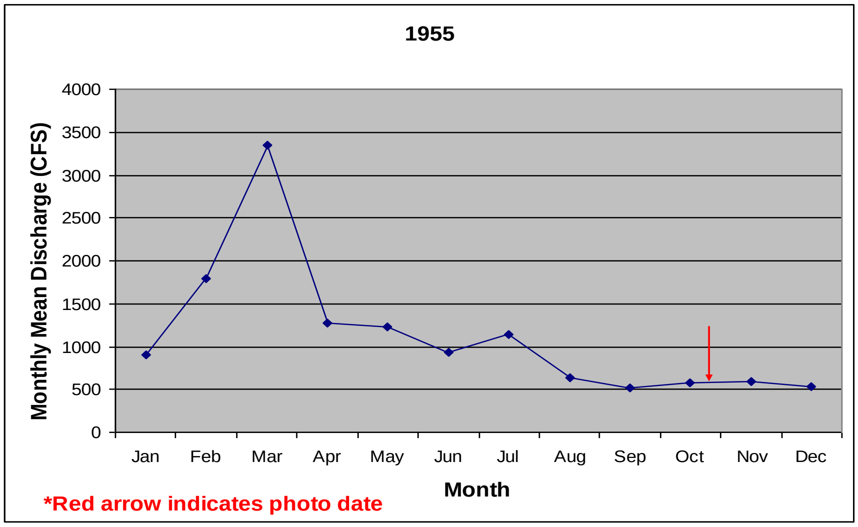
Burnt Cabin Site (cont'd)



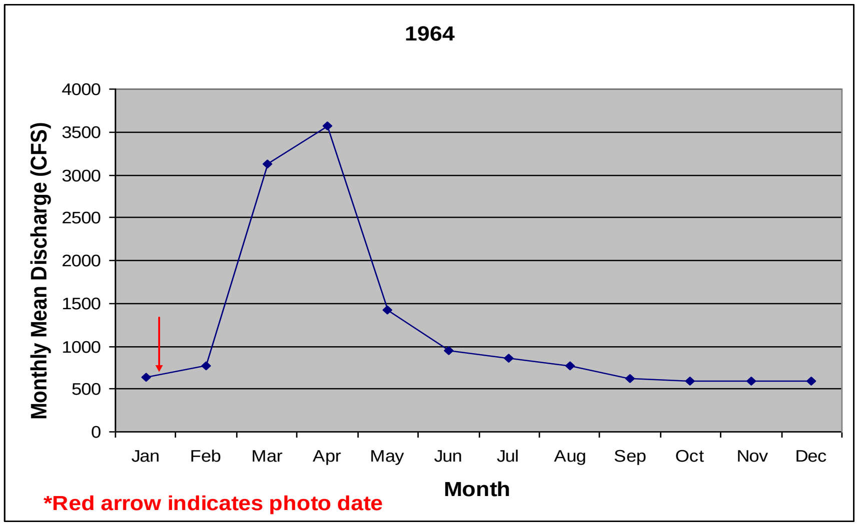




Lower Site – USGS Gage 07067000, Current River at Van Buren


1955

*Red arrow indicates photo date


1964

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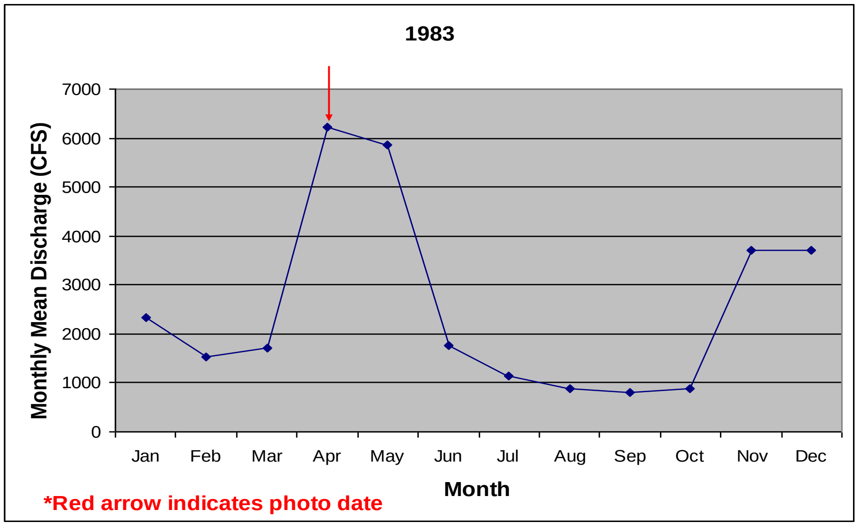
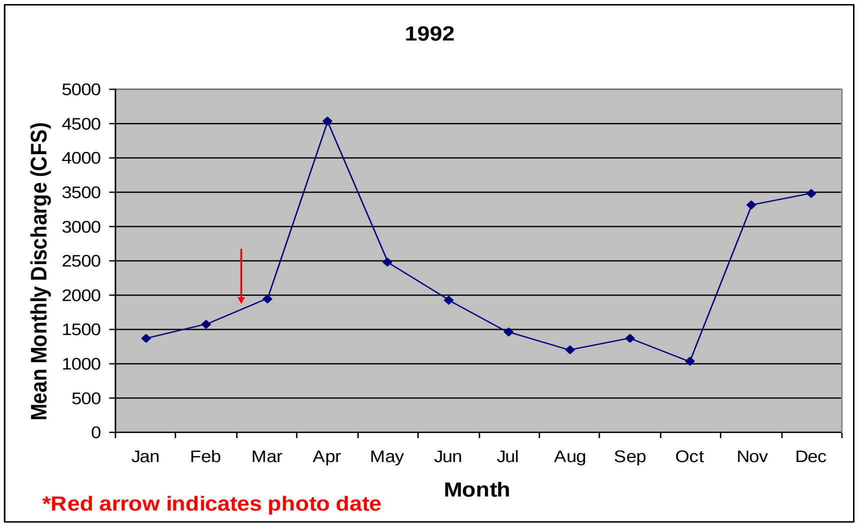
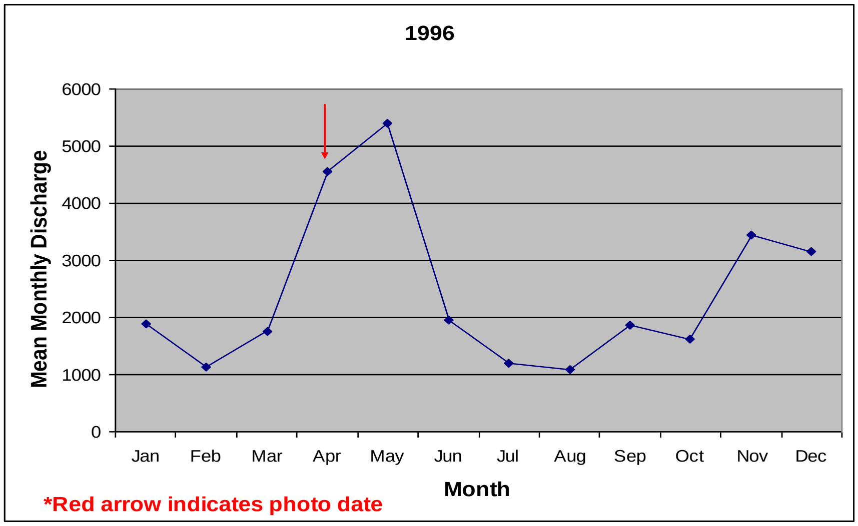
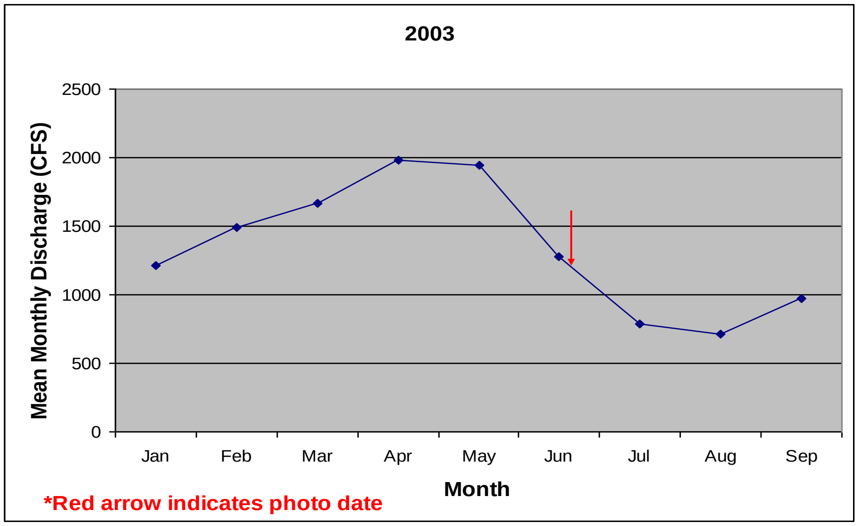

1983

*Red arrow indicates photo date

Lower Site (cont'd)







Appendix B

VBA Script Codes

Area Calculation

```
Dim dblArea as double
Dim pArea as IArea
Set pArea = [Shape]
dblArea = pArea.area
```

Azimuth Calculation

```
'=========================
'polyline_Get_Azimuth_9x.cal
'Author: Ianko Tchoukanski
'http://www.ian-ko.com
'=========================
On Error Resume Next
Dim pCurve As ICurve
Dim pLine As ILine
Dim dLength As Double
Dim dAngle As Double
Dim dDistance As Double
Dim bAsRatio As Boolean
Dim Pi As Double
'=======================
'adjust the parameters bellow
dDistance = 0.5
bAsRatio = True
'========================
Pi = 4 * Atn(1)
If (Not IsNull([Shape])) Then
  Set pCurve = [Shape]
  If (Not pCurve.IsEmpty) Then
    Set pLine = New esriGeometry.Line
    dLength = pCurve.Length
    pCurve.QueryTangent 0, dDistance, bAsRatio, dLength, pLine
    dAngle = pLine.Angle * 360 / (2 * Pi)
    if (dAngle < 90)then
      dAngle = 90 - dAngle
    else
      dAngle = 450 - dAngle
    end if
  End If
End If
```

Appendix C

Raw Data

Migration of Mean Center of Gravel Bars (m)
Burnt Cabin

	55-66	66-84	84-92	92-96	96-03
stable_1	21	49	100	76	65
dist_1	277	59	73	18	229
stable_2	401	191	107	21	25

Migration of Mean Center of Gravel Bars
Lower

	55-64	64-92	92-96	96-03
stable_1	296	355	94	105
dist_1	85	140	215	204
dist_2	169	22	140	245
stable_3	n/a	474	18	99

Migration Rate of Mean Center (m/yr)
Burnt Cabin

	55-66	66-84	84-92	92-96	96-03
stable_1	1.90	2.72	12.50	19.00	9.29
dist_1	25.18	3.28	9.13	4.50	32.71
stable_2	36.45	10.61	13.38	5.25	3.57

Migration Rate of Mean Center (m/yr)
Lower

	55-64	64-92	92-96	96-03
stable_1	32.89	12.68	23.50	15.00
dist_1	9.44	5.00	53.75	29.14
dist_2	18.78	0.79	35.00	35.00
stable_3	n/a	16.93	4.50	24.75

Channel Migration at Meander Bend
Burnt Cabin

	Distance (m)	Rate (m/yr)
55-66	54.00	4.91
66-84	147.00	8.17
84-92	31.00	3.88
92-96	101.00	9.25
96-03	38.00	5.43

Channel Migration at Meander Bend
Lower dist_1

	Distance (m)	Rate (m/yr)
55-64	55.00	6.11
64-92	34.00	1.21
92-96	397.00	99.25
96-03	226.00	32.29

Lower dist_2

	Distance (m)	Rate (m/yr)
55-64	26.00	2.89
64-92	251.00	8.96
92-96	75.00	18.75
96-03	201.00	28.71

Hydrologic Characteristics
Burnt Cabin

	Mean annual discharge (cfs)	Mean peak discharge (cfs)
1955-1966	384.75	18576.67
1966-1984	478.63	2069.43
1984-1992	549.00	21511.11
1992-1996	597.20	26206.00
1996-2002	449.14	9513.75

Hydrologic Characteristics
Lower

	Mean Annual Discharge (cfs)	Mean Peak Discharge (cfs)
1955-1964	1616.60	33860.00
1964-1992	2068.93	37053.79
1992-1996	2593.20	42520.00
1996-2002	1953.71	28405.71

Land Cover Classification Area (m^2)
Burnt Cabin

	1955	1966	1984	1992	1996	2003
Bar	6586.10	6712.81	6599.84	10646.23	10918.13	2570.46
Forest	49541.66	52089.91	54901.20	53790.53	43761.43	61803.27
Grass/Shrub	10430.59	9393.50	9570.67	13538.91	21519.48	11651.18
Pavement/Road	0.00	0.00	485.04	428.18	326.86	286.64
Mixed	0.00	2884.12	0.00	0.00	0.00	0.00
Water	4949.76	7976.38	10077.37	6000.02	7729.49	8642.33

Land Cover Classification Area (m^2)
Lower

	1955	1964	1983	1992	1996	2003
Bar	16286.28	20958.04	13218.54	15189.57	10780.50	9481.70
Forest	180968.41	188319.17	202505.57	235369.11	220577.23	233906.99
Grass/Ag	49506.36	18734.83	2271.69	16476.54	14726.40	13881.09
Grass/Shrub	5360.46	16031.34	19687.82	5396.29	14015.74	0.00
Pavement/Road	484.68	0.00	0.00	0.00	0.00	0.00
Water	31863.96	32105.30	73231.30	59598.30	56231.42	64699.55

Appendix D

Statistical Output

S+ Output For Linear Regression Analysis

```
*** Linear Model ***

Call: lm(formula = Chan.Mig.Rate ~ Bar.Mig.Rate, data = SDF7, na.action =
na.exclude
       )
Residuals:
    Min     1Q Median    3Q   Max
 -31.24 -12.25  1.071 7.677 40.88

Coefficients:
               Value Std. Error t value Pr(>|t|)
 (Intercept) -5.8333  8.2839    -0.7042  0.4960
Bar.Mig.Rate  1.1945  0.3245     3.6816  0.0036

Residual standard error: 18.37 on 11 degrees of freedom
Multiple R-Squared: 0.552
F-statistic: 13.55 on 1 and 11 degrees of freedom, the p-value is 0.003616


Analysis of Variance Table

Response: Chan.Mig.Rate

Terms added sequentially (first to last)
             Df  Sum of Sq  Mean Sq  F Value       Pr(F)
Bar.Mig.Rate  1   4574.400 4574.400 13.55441 0.003615518
   Residuals 11   3712.326  337.484
```