Lateral Stream Migration Rates in the Blue River Watershed, Wisconsin

by

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Lateral channel migration is a naturally occurring process within meandering rivers when adjusting to a relatively stable state. Factors like stream power, soil, and streambank vegetation can influence the rate of migration along a channel. Understanding the processes controlling channel migration can be used to determine locations susceptible to nutrient and metal contaminant release and sources of suspended sediment. Many of the recent studies on bank erosion have worked at the small scale of individual sites or reaches, therefore, it is important to examine the spatial patterns and controlling processes at the watershed scale to gather new perspectives and determine the strength of relationships on a larger scale. The purpose of this study was to determine whether migration rates have varied temporally and spatially within the Blue River watershed of southwestern Wisconsin. Furthermore, the effect of changing land use and land management practices on bank erosion were determined using historic survey data from 1830 and aerial imagery from 1940, 1968, 1995, and 2010 with geographic information science (GIS). Potential controlling factors were also determined by statistically comparing stream power and exanimating spatial links between stream power and geomorphic data. Results showed that changes in land management practices have impacted the watershed and the individual reaches within the watershed, wherein there was a general decline of migration rates within two of the reaches as land management practices improved, whereas relatively constant rates were observed

within the other reaches. The individual reaches mostly experienced low migration rates within the headwater streams where valleys were narrow and underlain with resistant dolomites, either increased or were consistent throughout mid-reach locations, and generally decreased farther downstream as valleys widened in exposed friable Cambrian sandstones. Stream power was a not a strong, singular explanatory variable, however, there were several reaches where high stream power was associated with high migration rates. Changes in lithology, slope, and sections of channel confinement explain some of the spatial variability in downstream trends. These results can be used in future studies estimating suspended sediment volumes and metal contaminant release from bank erosion within the Blue River watershed. This study also provides evidence of the importance of conducting studies at the watershed scale to better understand the spatial variability of geomorphic process and therefore potentially provide more organized and time-efficient approaches to watershed management.

LATERAL STREAM MIGRATION RATES IN THE BLUE RIVER WATERSHED, WISCONSIN

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CHAPTER 1: INTRODUCTION

Rivers are dynamic systems that tend to adjust to a relatively stable state in response to the imposed discharge and sediment supply (Knighton, 1998). Lateral channel migration is just one of the many adjustments that take place in meandering rivers (Nanson and Hickin, 1986; Palmer et al., 2014; Donovan et al., 2015). The erosion of streambanks that occurs when a channel migrate laterally is accomplished by two dominant processes, fluvial entrainment and mass wasting (Thorne, 1982; Lawler et al., 1999; Couper and Maddock, 2001; Davis and Harden, 2014). Potential controlling factors include stream power and soil and vegetation properties that increase the resistance of banks to erosion (Hooke, 1980, Lawler, 1993, 1995; Jacobson, 1995; Jacobson and Pugh, 1997).

Suspended sediment is a principal water quality problem in streams in the U.S. with 15% of stream length having excess streambed sediments impairing aquatic organisms (U.S. EPA, 2016). This sediment may be derived from soil particles eroded by overland flow on upland surfaces and transported to stream channels, or as sediment introduced as channel banks erode and remobilize channel and floodplain deposits (Smith and Wilcock, 2015). In many cases bank erosion has been shown to supply over 50% of the total sediment load of rivers (Knighton, 1998; Davis and Harden, 2014). Whether sediment is derived from upland erosion or streambank retreat, this sediment remains a significant non-point source pollutant that contributes to excessive sedimentation and the degradation of the ecological health of streams (Nietch et al., 2005; Bilotta and Brazier, 2008). Because recent studies have suggested that the source of sediment in streams subjected to significant hydrologic alterations has shifted from uplands to stream channels (e.g., Simon and Rinaldi, 2000; Simon and Klimetz, 2008; Palmer et al., 2014), it is important to assess and understand variations in rates of bank erosion in order to improve management strategies designed to reduce sediment loads.

Nutrients and heavy metal contaminants can be stored within-channel and in floodplains for many years (Costa, 1975). Streambank and floodplain erosion can reintroduce previously stored metal contaminants from historic mining into the fluvial system to be transported downstream sorbed to suspended sediment (Lecce and Pavlowsky, 1997; Walling et al., 2003; Rhoades et al., 2009). These reintroduced metals cause problems with assessing the impact of upstream pollution sources on downstream water quality as nonpoint sources of pollution (Novotny and Chesters, 1989; Rhoades et al., 2009). Past studies have shown that understanding spatial trends of geomorphic processes provides an understanding on how contaminated sediments will be deposited and stored (Lecce and Pavlowsky, 1997). It makes sense that similar principles could be used to assess how contaminants that have accumulated over time will be reintroduced as streambanks erode (Smith and Owens, 2014). Understanding rates of bank erosion can aid in managing for heavy metal contaminant release into the fluvial system.

Many studies addressing bank erosion work are limited by the time and spatial scales they work with. It is not uncommon for bank erosion studies to be conducted at the site or reach scale and over shorter time scales (seasonal to <3 years) as mass-movement processes attract more immediate interest to environmental management (Lawler, 1993; Couper, 2004; Piegay et al., 2005; Harden et al.; 2009). Some studies are conducted over long time scales (>30 years) and at watershed scales (Brierley and Murn, 1997; Fonstad and Marcus, 2003), however recent studies at this scale are limited. Recently there has been a move to integrate a range of scales (at site, reach, and watershed scales) in order to efficiently address management issues and a network's inner sensitivity (Piegay et al., 2005; Henshaw et al., 2012). Couper (2004) reiterates

Thorne's (1982) concern that working at only the smallest scales will reduce the understanding of process upstream and downstream and therefore system-wide instability, when often times in channel instability has been spurred by changes of poor land management practices at the watershed scale.

The primary objective of this research is to improve our understanding of spatial and temporal variations in lateral channel migration in an agricultural watershed in southwestern Wisconsin. The following research questions were addressed:

1. How do rates of lateral channel migration vary through time? Are these temporal variations explained by changes in land use practices?
2. Do rates of lateral channel migration vary spatially through the watershed?
3. Do hydraulic (e.g., stream power) and geomorphic variables explain spatial patterns of channel migration?

A watershed within southwestern Wisconsin was chosen for the study area because this region experienced an expansion in agriculture from the early 1800s to the 1900s. In the 1930s and 1940s improved land management practices were implemented throughout the region making a watershed within the region an ideal study site to determine the impacts of land use on channel migration. Data on channel position was available from 1830 from original General Land Office survey notes, and aerial imagery was also available for detecting channel movement. The earliest available imagery dated back to 1940, when improved land management practices were first being established. Finally, a previous study (Lecce, 1997a) was conducted in this watershed provided hydraulic and geomorphic data that allowed the third research question to be addressed.

Study Area

The Blue River watershed (208 km^2) is located within the Driftless Area in southwestern Wisconsin (Figure 1.1). This watershed was protected from Pleistocene glaciations by resistant crystalline bedrock in northern Wisconsin and the diversion of ice lobes into low lands in the east and west. Beneath the watershed lies the Ordovician and Cambrian sedimentary units made up of resistant dolomites and erodible sandstones. Uplands are underlain by dolomites of the Platteville Formation and the tributary valley walls by erodible sandstones of the St. Peter formation. Mid-basin locations are underlain by dolomites of the Prairie du Chien Group and downstream portions of the watershed have friable Cambrian sandstones of the Jordan Formation. These varying lithologies influenced different valley morphologies; narrow and steep valleys are found in the resistant dolomites while low gradient, wide valleys are found in the erodible sandstones (Lecce, 2013).

The sediments in tributary channels in the Blue River watershed contain gravel and boulder-size material while downstream reaches are dominated by sand-sized bedload (Lecce, 2013). As a whole, stream power values in the Blue River are highest in mid-basin locations, varying between about 10 and 100 Wm^{-2} (Lecce, 1997a) with trends and magnitudes varying with each tributary.

Along with the area's geology, land use change has spurred much of the area's geomorphic variations over time and space. Southwestern Wisconsin's land cover was once dominated by oak forest, wet and northern mesic forests, and savannas (Finely, 1976, 1978; White and Mladenoff, 1994; Cole et al., 1999). From 1820 to 1860, land cover transitioned to mostly row crops and pasture fields as settlement occurred (Knox, 1977; Knox and Hudson,

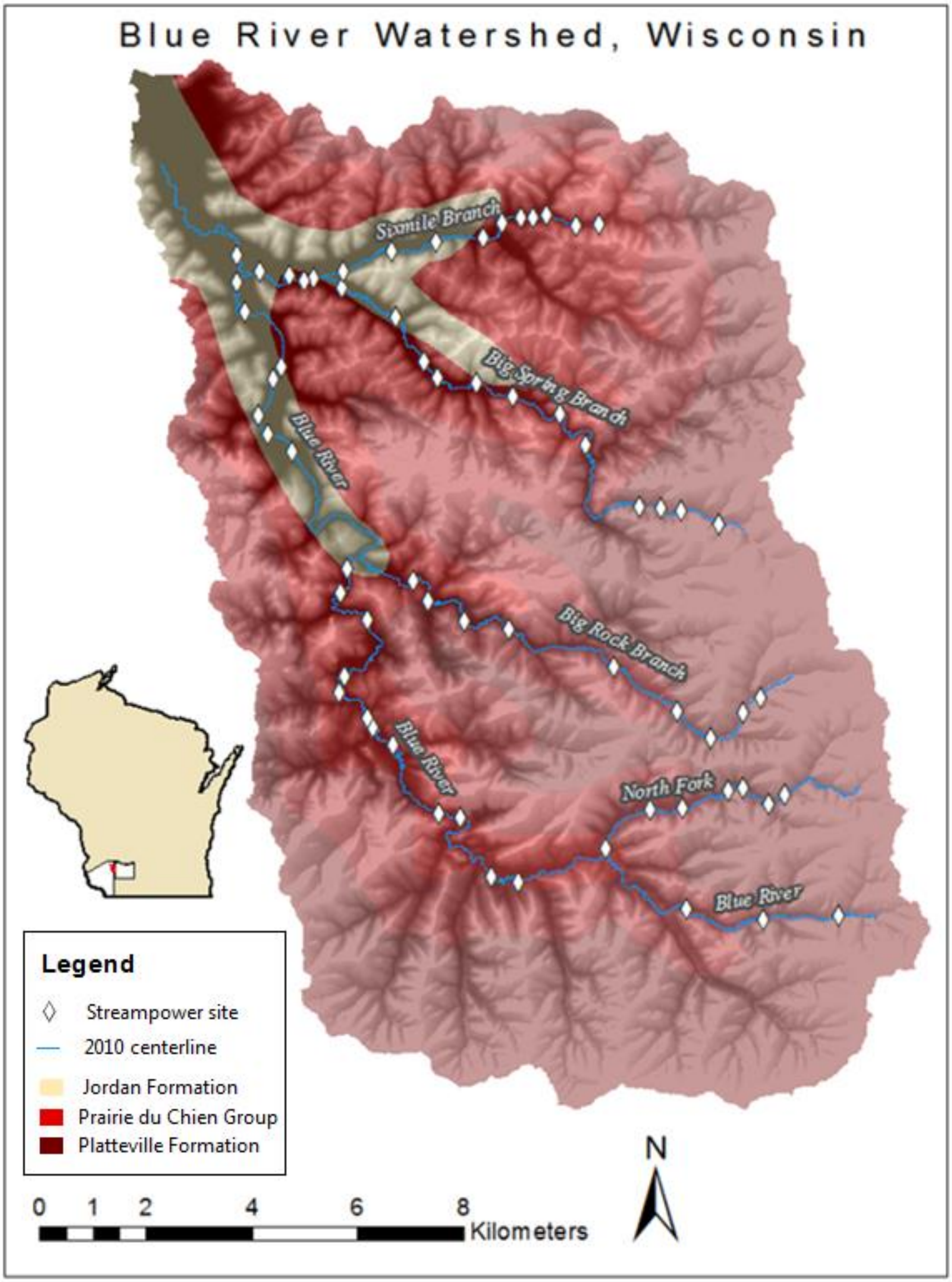

Figure 1.1. Map of Blue River watershed in southwestern Wisconsin displaying the 2010 stream center line of the Blue River and major tributaries and the channel study sites used for comparing 1831 stream positions.

1995; Cole et al., 1999). During this time, mining of zinc and lead also occurred, peaking between 1900 and 1920, and continuing until 1940 when only a few smaller mines remained active (Lecce and Pavlowsky, 2001). Knox and Hudson (1995) reported that channel adjustments in southwestern Wisconsin were rapid from the 1890s to the 1940s, when improved land management practices were implemented.

These changes in land use have great implications on infiltration rates and overland flows, which in turn affect bank erosion and floodplain alluviation (Chow, 1964; Knox, 1977). These changes also lead to long term effects on daily discharge deviations and the frequency of peak floods. Previous studies in the region have observed a more recent decrease in peak flows and variance in daily flows (Knox, 1977; Potter, 1991). After 1970, peak floods steadily declined and the standard deviation in daily flows decreased by 25% (Potter, 1991), which could be connected to stability in land use.

The effects of poor land-use practices on fluvial systems has been widely investigated for the Driftless Area of Wisconsin (Knox, 1977; Trimble and Lund, 1982; Magilligan, 1985, 1992; Woltemade, 1994; Lecce, 1997b; Faulkner, 1998). The Blue River watershed (Figure 1.1) in Wisconsin's Driftless Area has been long affected by changes in land use and improvements in land management practice. Beginning in the mid-1800s, land cover within Blue River changed from forest to agricultural activities associated with dairy farms. Following the implementation of land conservation practices in the 1930s, soil erosion, sedimentation rates, and discharge values began to decrease significantly (Trimble and Lund, 1982; Potter, 1991). These improved land use practices included contour plowing and strip-cropping, longer rotations, crop-residue management, and controlled grazing (Trimble and Lund, 1982).

The hydrology of the area is closely linked to these adjustments in land use and practices (Potter, 1991). While the Blue River is ungaged, surrounding drainage basins of similar size display a decrease and stabilization of discharge values around after the 1950s, the same time farming practices had improved. These observed changes in hydrology and recorded changes in sedimentation rates in nearby areas have spurred this study on lateral channel migration within the Blue River watershed.

CHAPTER 2: LITERATURE REVIEW

There is a large and growing literature that addresses human impacts on floodplains and stream channels (James and Lecce, 2013; Gellis et al., 2009). These impacts may vary temporally and spatially throughout a watershed (Donovan et al., 2015; Smith and Wilcock, 2015). The natural characteristics of the watershed can vary downstream along with land use practices and rates of agricultural or urban development, which leads to variations in a channel's stability over time and space. A channel's stability can be assessed by monitoring lateral channel migration rates and sediment supply to channels or floodplains. This can be difficult with temporal data limitations, yet important for linking channel instability to various land-use practices (Donovan et al., 2015). Within the last twenty years the use of aerial photographs and GIS to measure changes in watersheds and smaller reaches has been extensively investigated and applied with success (Jacobson and Pugh, 1997). This chapter will review the literature associated with lateral channel migration and the techniques used to measure it.

Lateral Channel Migration

Meandering is the dominant stream channel pattern throughout the Driftless Area (Judson and Andrews, 1955). While meanders are easily identified, they are generally characterized by three basic properties: wavelength, sinuosity, and degree of irregularity (Ferguson, 1979). Stolum (1996) has described meandering as a self-organizing process in space and time in order to achieve a state of equilibrium. The meandering process involves erosion of the cut bank on the outside of a meander bend, which is balanced by deposition of a point bar on the inside of the meander bend. As such, meandering channels migrate laterally back and forth across their floodplains. Undisturbed channels tend to meander in neither a regular nor a random fashion, but rather consist of a form based on a balance between hydrologic and sedimentary factors

(Ferguson, 1979; Knighton, 1998). As one of these factors changes over space or time, meandering (and subsequently lateral migration) will begin (Bagnold, 1960; Hickin and Nanson, 1984).

The erosion of streambanks associated with lateral channel migration occurs by the processes of fluvial entrainment and mass wasting, both of which are preceded by subaerial weathering and weakening such as soil desiccation and freeze-thaw (Thorne, 1982; Lawler, 1995; Lawler et al., 1999; Couper and Maddock, 2001; Davis and Harden, 2014). Although many studies have focused on the ability of stream flows to entrain bank materials and the resistance of bank materials to erosion (Couper, 2004; Rinaldi et al., 2004; Julian and Torres, 2006), bank erosion can be influenced by a variety of factors that include flow properties, bank material composition, subaerial erosion processes, climate, subsurface conditions, channel geometry, vegetation and animal burrows, and anthropogenic factors (Knighton, 1998; Harden et al., 2009). Wolman (1959) showed that there can be substantial differences in erosion rates in different seasons, with little erosion in extreme summer events when banks were dry, but higher during smaller flows in winter when banks were wet. Relationships between flow characteristics and erosion rates tend to be weak, although Nanson and Hickin (1986) found that cross-sectional stream power explained 48% of the variance in the migration rate in meandering channels in Canada. Lawler (1993) found that the highest rates of bank erosion were found in mid-basin reaches where stream power was maximized. At the watershed scale, Lawler (1993) suggested that (1) subaerial processes dominate in the headwaters where stream power is low, (2) fluvial entrainment dominates in mid-basin reaches where stream power peaks, and (3) mass wasting dominates farther downstream where bank heights and bank resistance increase and stream power is low.

A thorough review of the techniques used to measure bank erosion was completed by Lawler (1993) and since his review some of the techniques have been slightly updated with current technology, but many remained the same. Photogrammetric techniques (e.g., aerial images, LIDAR) are some of the most common methods for measuring erosion over the range of time and spatial scales due to its relative ease of availability and convenience. Photogrammetric methods were most commonly used for intermediate and long time scales (Hughes et al., 2006; Urban and Rhoads, 2003; Rhoades et al., 2009) until advances in remote sensing techniques and rapid data availability have improved the use of photogrammetric techniques at short and intermediate time scales (Micheli and Kirchner, 2002; Hughes et al., 2006; Kessler et al., 2013; Lea and Legleiter, 2016). Short time scale (e.g., hours to a few years) and small spatial scale measures can also be collected using traditional surveys (O'Neal and Pizzuto, 2011), erosion pins (Couper and Maddock, 2001; Henshaw et al., 2012; Palmer et al., 2014), or Photo-Electric Erosion Pins (PEEP) (Lawler, 1991, 2005) and PEEP-3T which includes Thermal Consonance Timing (TCT) (Lawler, 2008). Methods for measuring erosion over longer time scales and larger spatial scales (reach to watershed) also include traditional surveys and dendrogeomorphic analysis using exposed riparian tree roots (Stotts et al., 2014). One or more appropriate techniques can be used depending on a combination of the dominating processes driving erosion (Lawler, 1999), time and spatial scales (Couper, 2004), and data availability or site accessibility.

While there are complex interacting forces that drive channel migration, one can generally view channel adjustments as resulting from the relationship between the energy available for erosion and bank resistance (Graf, 1988). Erosional energy may be quantified by measures such as stream power (Nanson and Croke, 1992; Knighton, 1998), while bank resistance may be influenced by sediment properties (Hickin and Nanson, 1984) and vegetation and root characteristics (Thorne, 1982; Bendix and Stella, 2013). When erosional forces exceed channel boundary resistance, the channel may begin to migrate. Depending on the overall stability of the banks and floodplain based on land cover and sediment type, the rates of migration can vary through time and space.

Erosion from flow. Discharge has long been considered an important variable influencing changes in channel geometry (e.g., Leopold and Maddock, 1953), although Knighton (1987) suggested that discharge may have less influence on channel form than the capacity of the flow to accomplish geomorphic work. This implies that cross-sectional stream power may better express that ability of stream flow to modify the channel boundary:

$$\Omega = \gamma QS \tag{1}$$

where Ω is cross-sectional stream power (W/m), γ is the specific weight of water (9810 N/m^3), Q is stream discharge (m^3/s), and S is the energy gradient (m/m). Another frequently used measure of energy expenditure is mean stream power:

$$\omega = \gamma RSV = \Omega/w \tag{2}$$

where ω is the power per unit area of the channel bed (W/m^2), R is the hydraulic radius (m), and V is the mean flow velocity (m/s), and w is the channel width (m). Nanson and Hickin (1986) have shown that mean stream power is related to channel migration. Nanson and Croke (1992) suggested that actively meandering streams tend to have a mean stream power range of 10-60 W/m^2 and laterally stable streams are associated with stream powers values less than 10 W/m^2.

Bank resistance. Bank resistance can be quantified by evaluating the vegetation and sediment characteristics of the channel and floodplain. There are other factors that contribute to channel stability as well, including valley orientation, bank slopes, bend geometry, and drainage size (Langbein and Leopold, 1966; Hickin and Nanson 1975; Hickin and Nanson, 1984; Jacobson and Pugh, 1997). Jacobson and Pugh's 1997 study found that the channel stability of Little Piney Creek in the Ozarks was controlled more by these variables than by riparian vegetation. However, riparian vegetation still contributes to bank resistivity in smaller drainage basins, especially if it consists of woody vegetation (Thorne et al., 1990; Hupp, 1992; Hession et al., 2003; Kondolf and Piégay, 2003).

Cohesive sediments and resistant rocks result in channels that are narrow and deep while erodible sediments are associated with channels that are wide and shallow (Schumm, 1977). Shallow and wide channels also tend to have lower flow velocities as slope is generally small, allowing the cross-sectional form to influence secondary flow patterns. The interaction between primary and secondary flow patterns leads to shoaling and outer bank erosion naturally, and eventual channel migration (Hickin and Nanson, 1984; Markham and Thorne, 1992; Knighton, 1998).

Rates of lateral channel migration. Although rates of lateral channel migration will vary between watersheds depending on geology, land use, and topography, measurements from previous studies are useful for identifying average or accelerated rates. Donovan et al. (2015) compiled many studies' results from Piedmont channels, but noted that time scale can have an effect on results where measurements taken from imagery or maps over longer time periods will produce lower and smoother migration rates (Hooke, 1980). Comparatively, migration rates calculated from field measurements, over shorter time scales, and at smaller scales (i.e., single channel, section of channel) will produce larger values as mass failures from freeze-thaw periods (Wolman, 1959; Leopold, 1973) or seasonal floods will be captured in the data. In a review of bank erosion studies, Couper (2004) found that most focused on individual sites or reaches, while only about 10% examined bank erosion at the watershed scale.

Palmer et al. (2014) conducted field measurements using erosion pins over a 7-year time period along Walnut Creek, an agricultural watershed in Iowa that has similar topography to the Blue River watershed. They determined an average migration rate of 0.188 m/yr, which could be used to compare results from Blue River collected in later years when agricultural practices have improved. Magilligan (1985) reported that the nearby Galena drainage basin experienced a shift in floodplain sedimentation from 1.9 cm/yr during the 1820-1940 time period to 0.75 cm/yr from 1940-1979. He contributed this change to improved land management practices (Trimble and Lund, 1982). Knox and Hudson (1995) completed an extensive study of a few tributaries to the Galena River and found a shift in lateral migration rates of 0.06 m/yr from 1820-1890, 0.53 m/yr from 1890-1925, 0.70 m/yr from 1925-1940, and 0.12 m/yr from 1940-1990. They attributed the high rate from 1890-1925 to the expansion of agriculture, the higher rate from 1925-1940 as an adjustment period, and the lower rate from 1940-1990 to the improved practices of land management that started in the 1940s. It would be expected that lateral channel migration rates within the Blue River watershed would respond similarly and decrease as land management practices became more sustainable.

Historical disturbances. The introduction of anthropogenic land use change is known to be the cause of many changes in fluvial systems (Knox, 1977, 2001; Hession et al., 2003; Brierley, 2010; James and Lecce, 2013). As cultivation and settlement increase, run-off and erosion rates also increase. This can result in channel widening and an increase in bedload transport. However, the response is dependent on the topography and sediment characteristics as there have also been cases of channels becoming deeper and narrower from increased floodplain alluviation (Knox, 1977).

When land clearing and cultivation began in southwestern Wisconsin around 1820, the sediment supply and overland flow into streams increased (Knox, 1977), both of which can lead to changes in cross-sectional form. The increase in overland flow into streams contributed to an increase of floods with a recurrence interval of less than five years (Knox, 1977; Potter, 1991; Knighton, 1998). The increase in floods produced an increase in discharge and higher erosion rates upstream. Because these streams were not competent to incise into coarse channel bed lag gravels, the excess energy led to bank erosion and lateral channel migration (Lecce, 1997a). Moreover, downstream deposition along the floodplain accelerated from the increase in sediment yield (Knox, 1977).

Before the 1830s, most settlers came to southwestern Wisconsin to work in mines and fur trading posts (Knox, 1977). It can be difficult to discern whether increased sedimentation rates were directly caused by mining or from land clearing for settlement, as the two practices occurred within overlapping time periods. There have been documented increases in sedimentation along floodplains and within channels related to the presence of mines (Knox, 1977; Lecce and Pavlowsky, 1997, 2001). Noticeable sedimentation in channels tends to occur near the headwaters, where the channels are narrower and the drainage area is smaller, therefore being more easily influenced by slight changes in sediment inputs.

In the beginning of the 1930s, the Soil Conservation Service initiated many watershed projects to demonstrate management practices to improve watershed health (Potter, 1991). After improved agricultural practices were implemented an increase in bank stability and a decrease in soil erosion and floodplain sedimentation was recorded (Trimble and Lund, 1982). The local discharge values became less variable and there was a notable decrease in annual peak flood values over time (Potter, 1991).

Historical aerial imagery has long been used for detecting lateral channel change over a variety of time scales (Hooke, 1979; Lawler, 1993; Hughes et al., 2006). Using aerial imagery is especially popular when considering long time scales (10-100 yr) and larger spatial scales (reach to drainage basin) (Lawler, 1993), therefore linear measurements of migration are not the best representation as they likely do not capture the true direction of migration and introduce more subjectivity. Instead, measuring in terms of areas and standardizing for length and time period most accurately and objectively characterizes migration patterns (Lawler, 1993; Leeks et al., 1988).

Geographic Information System (GIS) Techniques

Aerial imagery has been used to map channel planform change for decades and the general process is well understood. Fluvial geomorphologists like Ferguson and Werritty (1983), Lapointe and Carson (1986) and many others have used aerial images to identify and measure channel movement, particularly in larger channels (20 m to over 200 m wide). However, issues arise when addressing smaller channels, a river system of varying channel sizes, or areas with thick canopy along banks (Jacobson and Pugh, 1997; Kondolf and Piégay, 2003).

Georectifying imagery. Most historic aerial images must be co-registered by converting the scanned images to a common projection and coordinate system usually by using digital orthophotographs or topographic maps (Hughes et al., 2006). It is important to be aware of the images' resolution to minimize the amount of data lost during rectification. It would be ideal to have the highest, yet suitable, resolution possible for the reference image. This would reduce information loss in the georectified images as they are likely captured in lower resolutions.

Scanned images are co-registered by choosing multiple ground control points (GCPs). There are different opinions on how the GCPs should be distributed and where they should be located. For measuring channel movement, it is best to choose GCPs close to the channel to avoid warping the channel itself (Hughes et al., 2006). GCPs should be placed on objects that are not likely to move through time and have clear edges, like a building, road intersection, or a survey marker. This type of control point is referred to as a 'hard point' by Hughes et al. (2006). However, exclusively selecting hard points is not always possible, especially if a uniform spatial distribution of GCPs is desired. Therefore, 'soft points' (Hughes et al., 2006) are also selected, which consist of features like centers of boulders or trees. Once an adequate number of GCPs has been selected and their presence has been confirmed throughout the aerial images being referenced, the images can be georectified.

When an image is georectified, it goes through a user-specified transformation to project the image to a common coordinate system. There are three main methods of transformation: aerotriangulation, orthorectification, and polynomial transformation. The first two methods are not ideal for most channel migration studies as aerotriangulation requires many GCPs and involves a complicated error analysis, and orthorectification requires advanced software and is a labor-intensive technique (Hughes, 2008). The most commonly used technique is the polynomial transformation. While large order polynomial transformations tend to result in lower georectification error, it is best to use lower order polynomial transformations (e.g., first or second order) to avoid extreme warping within photographs during rectification. Its benefits include the ability to be applied to a large set of photographs, its availability in common GIS packages, and being thoroughly investigated as it is most commonly used (Campbell, 2002; Hughes et al., 2006). To account for the subjectivity of manual digitizing, Micheli and Kirchner (2002) have suggested adding an uncertainty of 2 m (for 1:20,000 scale images) to the final feature error.

Detecting stream channels. Heads-up digitizing is most commonly used when delineating channel banks and a channel centerline. Recently, the availability of multispectral imagery has made detecting river channels relatively quick and accurate by identifying specific spectral signatures of in-channel flow and extracting the shape (Dillabaugh et al., 2002; Micheli and Kirchner, 2002). While this data source removes some of the subjective error associated with manual digitizing, it has limitations and may not be best suited for most fluvial geomorphology studies.

The most recent satellite data from Landsat 8 has a fairly low resolution of 30 meters in most locations which limits the feature size it can detect. Streams that are narrow and have small channel migration distances make it essential to have high resolution remotely sensed data (Dillabaugh et al., 2002; Martin and Pavlowsky, 2011). In addition, because rivers are curved features, shape extraction from a grid format source is not ideal when measuring discrete movement. These issues with satellite data make aerial imagery from low lying aircraft the preferred data source when delineating bank lines and stream centerlines.

Channel bank lines can usually be identified easily due to a visual break in vegetation, which can be enhanced by adjusting contrast and brightness (Micheli and Kirchner, 2002; Hughes et al., 2006; Legleiter, 2014). There are, however, cases where a bank line may not be clearly visible due to significant canopy cover or thick riparian vegetation. The user is then left to choose whether to visually interpolate the bank line or omit a section of the channel. Using tools in a GIS, a stream centerline can be digitized (or interpolated from bank lines) from multiple time series and then overlaid to detect lateral migration (Lauer, 2006; Legleiter, 2014; Frias et al., 2015).

Sources of error. Sources of error will arise in the georectifying and digitizing process. There have been many recent studies dissecting methods for calculating and applying error to measures (Micheli and Kirchner, 2002; Mount and Louis, 2005; Hughes et al. 2006; Martin and Pavlowsky, 2011; Legleiter, 2014). Many studies have applied buffers to stream centerlines to account for the error when measuring migration (Urban and Rhoads, 2003; Rhoades et al., 2009; Martin and Pavlowsky, 2011). Sections where the buffers overlap are considered stable and sections where they do not overlap are considered areas of significant movement (Jacobson and Pugh, 1997; Martin and Pavlowsky, 2011). While it is important to include error, the use of buffers can introduce bias. The method for reporting error should be considered with the scope and objective of the study. Some studies use the most inner boundary of the buffer, therefore all movement is at a minimal and small movements are removed (Martin and Pavlowsky, 2011) where others have used the outer most buffer boundary and potentially overestimate migration areas (Hughes et al. 2006; Hughes, 2008).

There have been recent studies that do not implement buffers and just report the geospatial error with measured rates (Micheli and Kirchner, 2002; Legleiter, 2014; Donovan et al., 2015; Lea and Legleiter, 2016). Legleiter (2014), who was working with small migration rates (<1 m/yr), reported the raw data along with the interquartile range (IQR), 95^{th} percentile, and the geospatial error. This method does not exclude small values nor add bias, but it still provides sufficient information to understand what magnitude of migration rates dominant in the study area and the distribution of the data.

The root mean square error (RMSE) is frequently used to measure georectification error for its convenience. However, Hughes et al. (2006) tested a variety of error measurement methods (i.e., mean, median) using different numbers of GCPs and types of transformations measures of error that show the RMSE is not the most appropriate for adjusting lateral movement measurements when the number of GCPs is limited. It was found that having over 30 GCPs resulted in minimal differences between error measures. Using first and second order transformations results in the lowest amount of error with the least amount of warping, which is essential in detecting movement (Lea and Legleiter, 2016).

CHAPTER 3: METHODS

The methods to determine lateral migration rates and trends included the use of GIS to measure channel movement and basic statistics. After collecting data in the form of land surveys and aerial images, GIS was used to digitize bank lines, interpolate centerlines, and collect migration rates. Averages and basic statistics of the migration rates were calculated for the watershed and individual reaches to determine variations over time. Using migration rates from the individual reaches, the rates were plotted downstream to determine spatial trends. Finally, the individual reaches' migration rates were plotted against hydraulic variables and downstream trends of hydraulic and geomorphic variables were compared to downstream stream trends in migration rates.

Data Sources

Channel positions for 1830 were determined using survey notes from the General Land Office (GLO) using the Public Land Survey System (PLSS). The surveys were completed from 1830 to the end of 1832 for the study area (Figure 3.1). These surveys recorded the location of the stream channel along township section lines, the direction of flow, and the channel width. The channel locations for 1830 were determined at 54 sites and were used to measure migration distances from 1830-1940.

Having records of channel position from 1830 is a valuable source because it can provide knowledge of how the channel has moved over a time period associated with the expansion of agriculture and unsustainable land use practices. However, these surveys have a certain amount of error and bias associated with them. Calculating the geospatial error of the GLO surveys is a difficult task, especially when representing the location of a continuous feature with a single

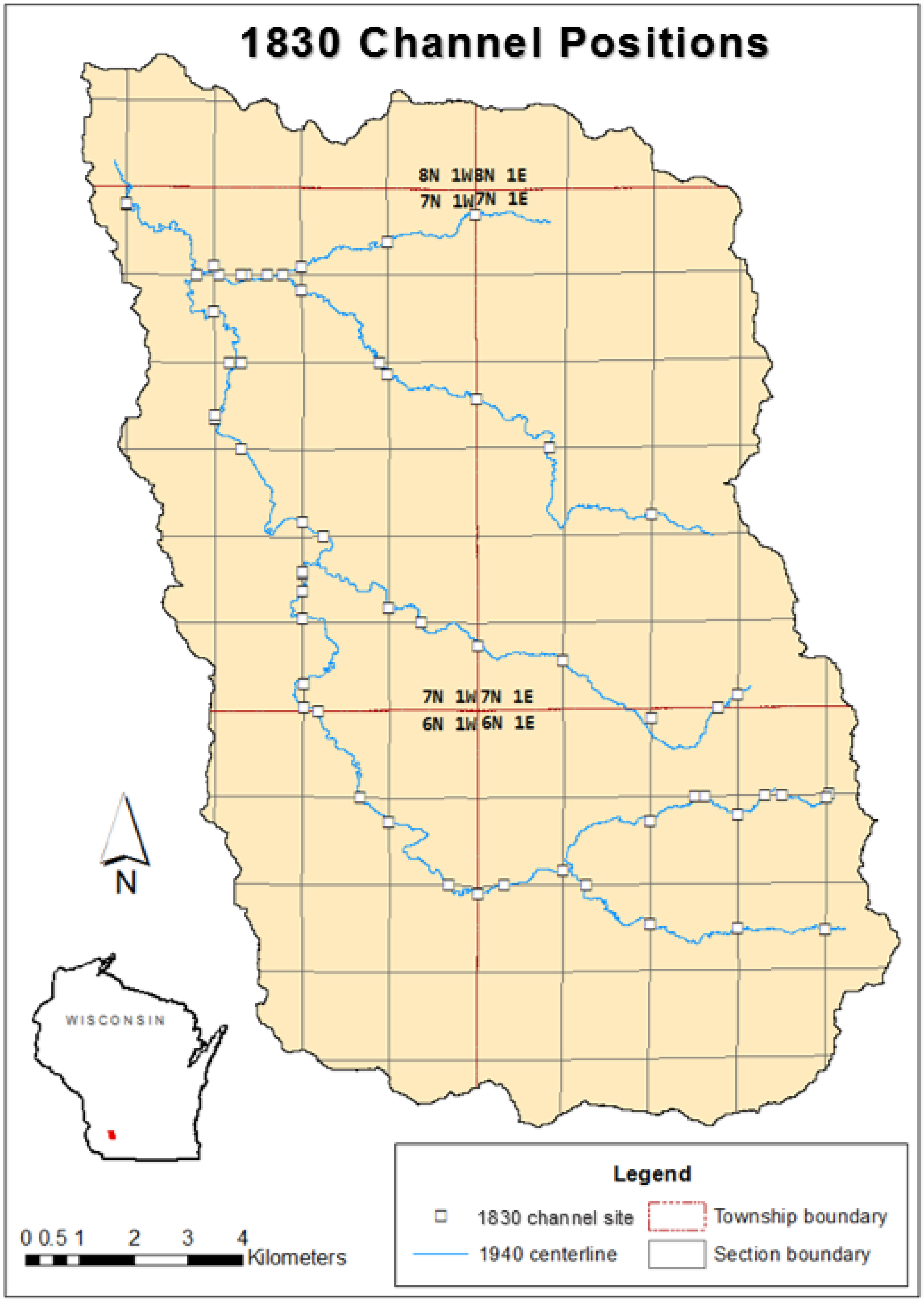

Figure 3.1. Map of 1830 channel sites from GLO survey notes with the 1940 stream centerlines of the Blue River watershed.

point (i.e., where the stream crosses a section line). A handful of studies have addressed this issue (Bourdo, 1956; Delcourt and Delcourt, 1996), however, they were working with tree and forest identification and location and often returned to the site of the surveys to record current tree species and forest boundaries to compare to the GLO land surveys. They bring up valuable points for consideration, for example, measurements were taken using chains and links, so bias could result from surveyors rounding to the nearest chain or link. Error was also likely introduced because the surveyors were probably not able to walk in a perfectly straight line due to equipment availability for the time, field conditions, or inclement weather. However, this data source is still an excellent record for reconstructing historical land settings considering the equipment availability and work conditions. The measures collected from the GLO surveys should be viewed as a general representation of stream position in 1830.

Recent changes within the watershed were measured using aerial imagery from the years 1940, 1968, 1995, and 2010. Single frame aerial images were collected for 1940 and 1968, while digital orthophoto quarter quads (DOQQs) were collected for 1995 and 2010 from various sources (noted in table 3.1).

Stream power data used in this study was previously collected by Lecce (1997a) for the Blue River watershed. Geomorphic variables were collected from topographic maps, digital elevation models, and geologic maps provided by the USGS.

Photo Georectification

The aerial images from 1995 and 2010 were DOQQs, which already have a spatial reference. However, the images from 1940 and 1968 required georeferencing and rectification. The 2010 imagery was used as the reference image because it had the highest spatial resolution

(0.46 m). A minimum of 30 GCPs were chosen that were in close proximity to the channel to minimize warping of the individual still images. The selected GCPs were visible throughout each set of imagery and consisted of both hard and soft points. Once the GCPs were selected, the 1940 and 1968 imagery was georectified using first and second order polynomial transformations and the georectification error was calculated using the RMSE (Table 3.1). The total geospatial error included the original horizontal resolution of the image, the georectification error, and an additional 2 m to account for digitizing error (Micheli and Kirchner, 2002).

Table 3.1. Time series of data and aerial photographs used to record channel positions throughout the Blue River watershed

Year	Data source	Format	Geo-referencing RMSE (m)	Total Error (m)
1830	GLO Survey	Points	N/A	N/A
1937 & 1940	WHAI Finder	BW	2.74	4.74
1967 & 1968	USDA	BW	2.18	4.18
1995	USGS	BW	N/A	3
2010	USGS	TC	N/A	2.46

All images are georeferenced to the 2010 USGS dataset (pixel size of 0.46 m). 1995 USGS imagery has resolution of 1 m. GLO= General Land Office; WHAI= Wisconsin Historic Aerial Imagery; USDA= United States Department of Agriculture; USGS= United States Geological Survey; BW= black and white; TC= true color.

Bank and Centerline Extraction

The distances between two consecutive stream centerlines were used to measure channel migration. The 1830 centerline position was designated by points and was determined by adding half the channel's width to the overall distance along the township section lines. For centerlines from 1940, 1968, 1995, and 2010, centerlines were interpolated from bank lines that were traced using heads-up digitization in a GIS. Bank lines were defined by breaks in vegetation and the beginning of a flowing channel visible in the aerial imagery. Some of the images had shadows or bright spots which made it difficult to discern bank edges. Image contrast and brightness were adjusted to clarify the channels' boundaries. The adjustments varied between photograph, where the contrast was increased to a maximum of 40% in some, and the brightness was either lowered or increased from -15% to 20%. To interpolate a centerline between the bank lines, continuous line segments were required, however, this became an issue along some sections with significant canopy cover that made channel visibility difficult or impossible. In these cases, the bank lines were estimated based on channel position before and after visibility was lost in order to create continuous bank lines, however, any channel migration within these sections was removed from the dataset.

The Planform Statistics Toolbox from the National Center for Earth Surface Dynamics (Lauer, 2006) (available online at http://www.nced.umn.edu/content/stream-restoration-toolbox) was used to interpolate stream centerlines between the bank lines. This was done by developing vertices downstream every 3 m, to ensure the curvature of the channel was preserved. The position of each vertex was placed an equidistance from each bank line by adjusting the angle from one vertex to another (Figure 3.2). A line was then drawn connecting each vertex, creating the stream centerline.

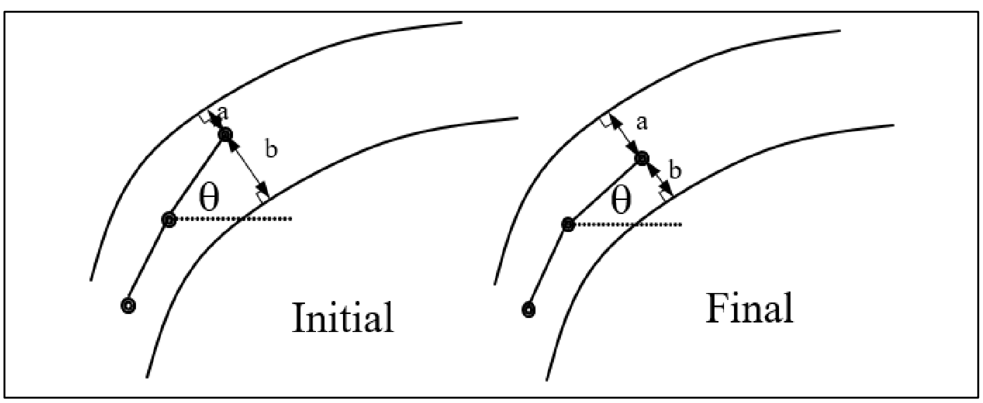

Figure 3.2. An example figure from Lauer's (2006) Planform Statistics Toolbox depicting how a vertex's position in the center of a channel was determined by adjusting angle theta.

Measuring Lateral Migration

Lateral migration rates were calculated by finding migration distances between each time period and dividing the distance by the years elapsed during that time period. The methods for calculating migration distances were different for time period 1830-1940 and the other time periods between 1940 and 2010 because the 1830 data consisted of points where the stream centerline crossed township sections lines whereas the other years were continuous centerlines.

1830-1940. The near function in ArcGIS was used to measure the nearest linear distance from each point representing the 1830 stream centerline to the 1940 stream centerline. In some instances the direction of the nearest linear distance was unlikely (Figure 3.3) based on lateral accretion deposits and the migration direction from 1830 channel locations up and downstream. In these cases an alternative migration distance was measured based on a more likely direction of migration. Once the migration distances were recorded they were divided by 110 years to get migration rates.

1940-2010. Stream centerlines from each time period were overlaid and the area between the centerlines was calculated to represent the area of migration (Figure 3.4). All meander cutoffs, avulsions, or sections of human modification were identified as “anomalies” and removed from the dataset (Figure 3.5) (see Appendix A for images of each anomaly). Anomalies were removed because they consisted of processes that were not likely to be explained by hydraulic or geomorphic variables, and a main objective of this study was to determine if a link between stream power and bank erosion acts as a control for lateral migration. Once all anomalies were removed, the areas of movement were summed every 100 m down valley from

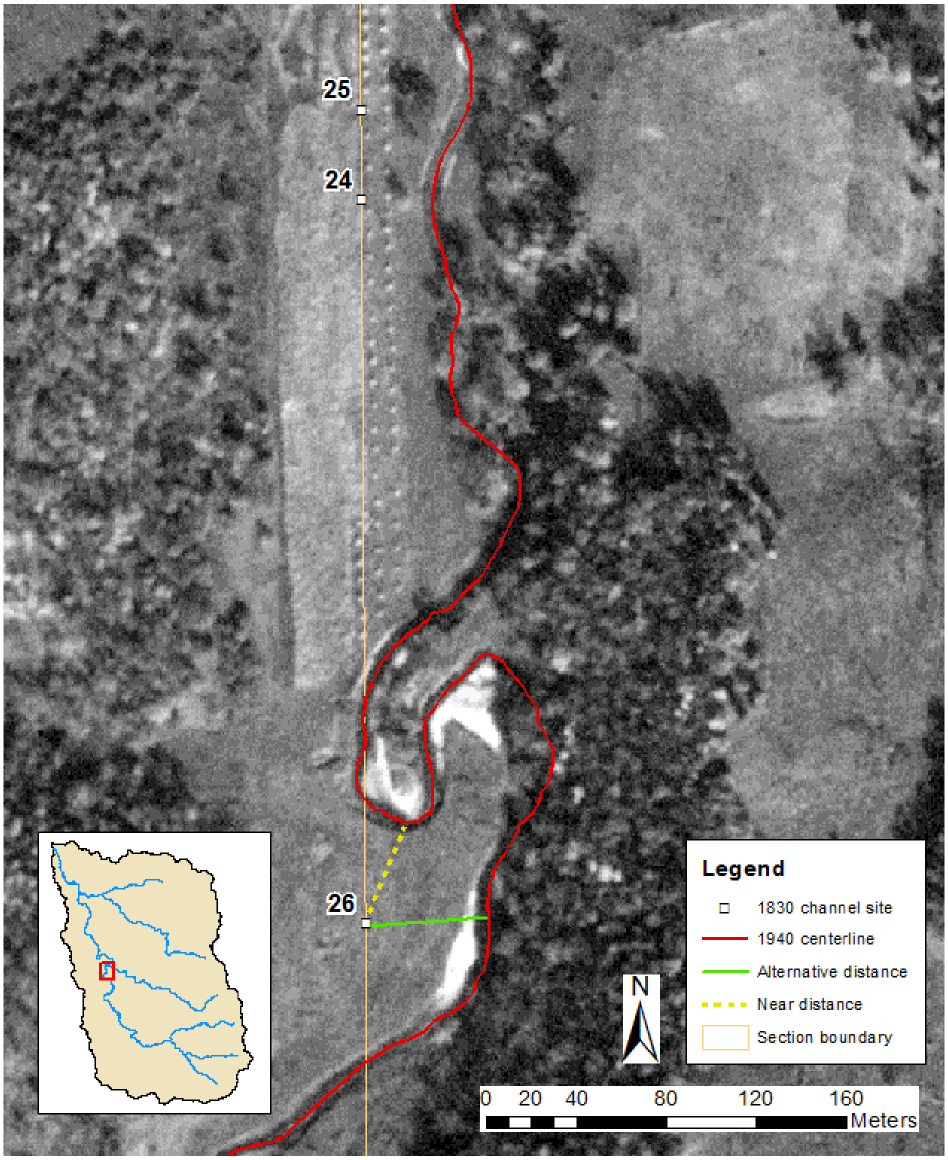

Figure 3.3. 1830 stream positions overlain 1940 imagery. Compared to the direction of the alternative distance, the calculated near distance for site 26 is less representative of lateral migration rate trends based on potential lateral migration direction seen at sites 24 and 25 (moving east).

the head waters for the individual reaches for each time period. Distance down valley was used as the downstream measure because it was consistent throughout the time periods. The summed areas were divided by 100 m (or when anomalies were removed, the appropriate downstream distance) to get lateral migration distance. The distance were then divided by years of the associated time period to get rates.

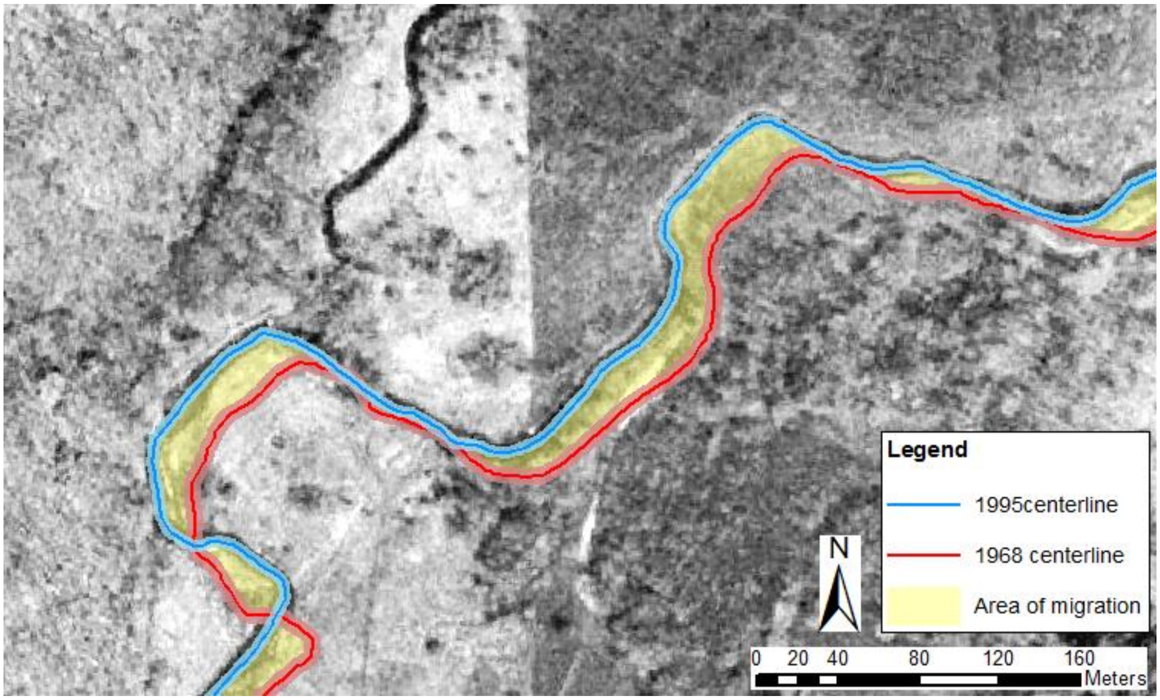

Figure 3.4. Example of how migration area was calculated. 1995 imagery with 1995 and 1968 centerlines overlain and polygons (in yellow) formed between the two centerlines. The light blue and pink underneath the centerlines represent the total geospatial error of each year's dataset.

Migration rates were considered significant if the lateral migration distance was larger than the total error associated with that time period. For example, the total error for the 1968-1995 time period was 7.18 m (Table 3.1), therefore any movements smaller than this were labeled "insignificant". All values are still reported and included in calculations as the insignificant movements are characteristic of the watershed. When reporting downstream trends, different symbols are used to distinguish significant and insignificant values. When calculating statistics of the migration rates for each time period all values are included and plotted with the IQR, 95th percentile, and geospatial error. Migration areas from 1940-1968, 1968-1995, and 1995-2010 were summed, divided by 100 m to get lateral migration distances, and then divided by 70 years to get migration rates for the 1940-2010 time period.

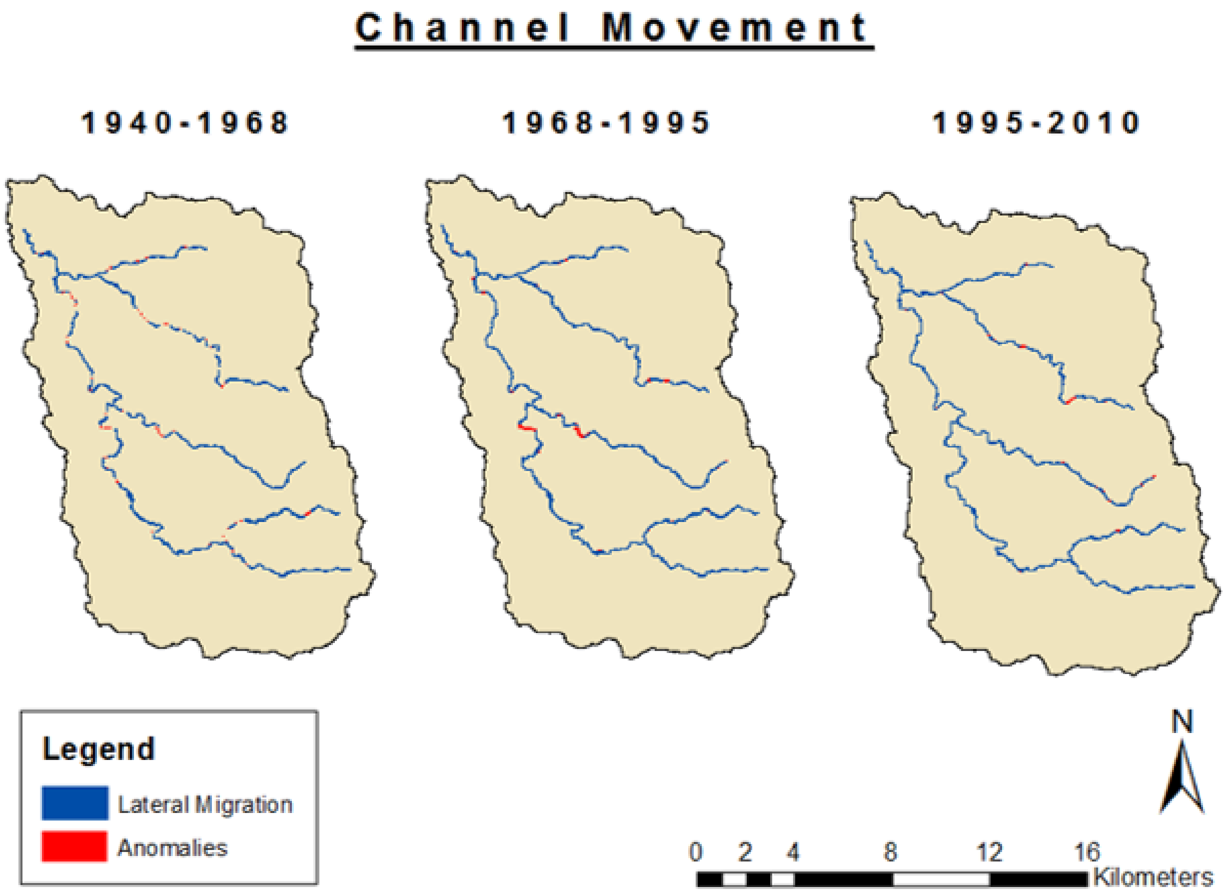

Figure 3.5. Maps of Blue River watershed depicting areas of lateral channel migration in blue and anomalies, i.e. cutoffs, avulsions, human modification, in red for each time series using aerial imagery for centerline extraction.

Determining Drivers of Migration

Temporal variations in migration rates were linked with changes in land use and land management practices by gathering dates of the expansion of agriculture and establishment of improved land management practices within the region (Trimble and Lund, 1982; Potter, 1991; Knox and Hudson, 1995). The areas of land that transitioned to strip cropping or contour plowing was digitized using the aerial imagery from 1940, 1968, 1995, and 2010 in order to calculate the percent of land changed within each time period. The boundaries of changed land were fairly easy to detect during the digitization process because fields are usually bordered by ditches or forests creating a visible break in land cover type.

The migration rates for the 1940-2010 time period were used to determine relationships between stream power and geomorphic variables. Stream power data from 62 sites provided by Lecce (1997a, 2013) were plotted against lateral migration rates to determine if any explanatory relationship exists between the variables. Downstream trends of stream power was overlaid downstream trends of migration rates to observe similarities in spatial patterns.

No exact coordinates are associated with the sites obtained from Lecce (1997a, 2013), therefore, their location is an approximation obtained from topographic maps. To avoid introducing bias, an average migration rate was calculated for each of the 62 sites. The rates were averaged from a 500 m section within which the site fell in the middle. The area of movement was summed within each 500 m section, divided by its downstream length to get distance, and then divided by years to get a rate (Figure 3.6).

The decision to use 500 m was determined by comparing average migration rates from 300 m, 500 m, and 700 m long sections. When average migration rates for these three sections were plotted against the sites' drainage areas (Lecce, 1997a), there was little difference in the trends (Figure 3.7). Using 300 m averages resulted in removing four sites because no movement occurred within 300 m of those sites. One site was removed using 500 m sections (site 10b), however there were sites immediately upstream and downstream from it, therefore no data was lost. Although using 700 m sections resulted in retaining all the sites, there was much overlap between neighboring sites, diminishing the downstream change in migration rates.

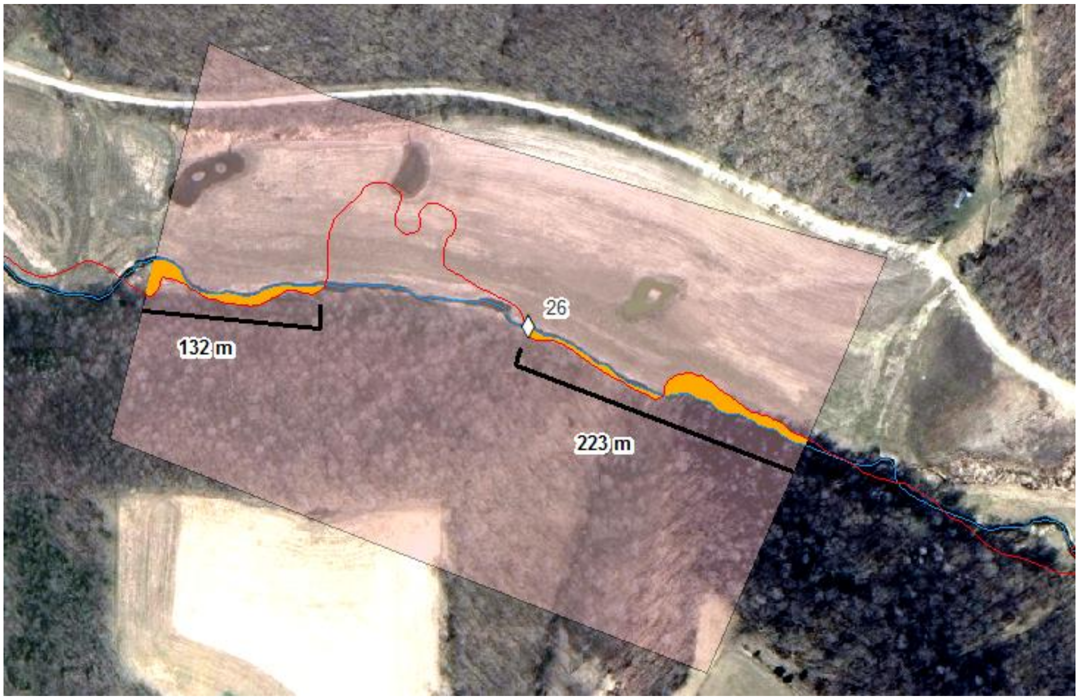

Figure 3.6. Example of a 500 m section (in pink) for site 26 depicted by the white diamond. Migration distance was determined by dividing the migration area (in orange) by its downstream length (black lines). In this case, the summed area of movement was divided by the total downstream length of 355 m, as 145 m of the section were removed due to an anomaly (artificial straightening). Red line is 1940 centerline, blue is 2010.

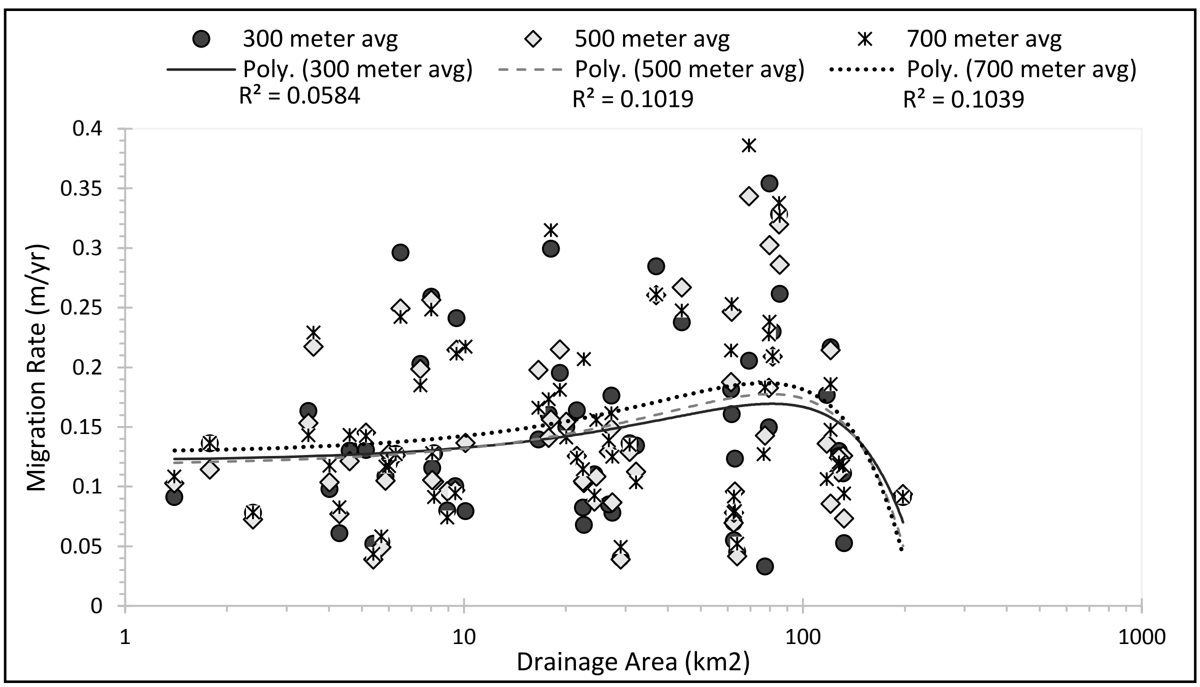

Figure 3.7. Migration rates averaged using 300 m, 500 m, and 700 m sections of data at each site from Lecce's (1997a) study fitted with second order polynomial curves.

Downstream migration rates were also plotted with the underlying geology shown and sections of localized confinement were overlaid on the plots to compare downstream patterns. Localized confinement was defined as sections of channel located up against a valley wall so that lateral movement becomes restricted on one bank side. This definition was based on Rapp and Abbe's (2003) definition of channel confinement.

CHAPTER 4: RESULTS AND DISCUSSION

This chapter discusses (1) temporal changes in lateral migration rates and relationships with land use trends, (2) spatial variations in lateral migration rates within each reach and for the entire watershed, and (3) potential hydraulic and geomorphic controls of migration rates. GIS was used to quantify lateral migration rates from 1830-1940 and 1940-2010, as well as three shorter time periods between 1940 and 2010. Anomalies such as cutoffs, avulsions, and human modified sections are removed from these datasets in order to best explain the link between stream power and bank erosion as a control for lateral migration. An average migration rate for each reach was used to express temporal trends as well as general spatial trends throughout the watershed. Migration rates calculated every 100 m were used to observe downstream trends at a finer scale. When analyzing relationships between migration rates and stream power, an average migration rate was calculated for a 500 m longitudinal distance surrounding each site. The 100 m averages were used when assessing relationships between geomorphic data and migration rates.

Temporal Trends

1830-1940 vs. 1940-2010. Average lateral migration rates for the Blue River watershed increased from 1830-1940 (0.188 m/yr) to 1940-2010 (0.351 m/yr) (Table 4.1). From 1830-1940, the average migration rates for individual reaches within the watershed varied from 0.181 m/yr (Big Spring Branch) to 0.211 m/yr (Big Rock Branch), while 1940-2010 migration rates varied from 0.223 m/yr (Sixmile Branch) to 0.390 m/yr (Blue River (north fork)). However, these datasets are not normally distributed, where most are heavily skewed to the right, which makes the median a better measure of central tendency. Similarly, median migration rates for the Blue River watershed also displayed an increase from the 1830-1940 period (0.151 m/yr) to the 1940-

2010 period (0.290 m/yr). The range of median migration rates within the watershed was slightly different, where the 1830-1940 rates varied from 0.111 m/yr (Big Rock Branch) to 0.174 m/yr

Table 4.1. Descriptive statistics of lateral migration rates (m/yr) for each time series for the whole watershed and for each reach

Watershed		
	1830-1940	**1940-2010**
Mean	0.188	0.351
Median	0.151	0.290
Standard Dev.	0.190	0.225
CV (%)	100.8	64.0
N	54	549

	1830-1940	**1940-2010**	**1940-1968**	**1968-1995**	**1995-2010**
Sixmile Branch					
Mean	0.202	0.223	0.236	0.216	0.246
Median	0.174	0.199	0.193	0.193	0.213
Standard Dev.	0.175	0.121	0.169	0.140	0.158
CV (%)	86.9	54.2	71.7	64.9	64.2
N	10	95	91	94	93
Big Spring Branch					
Mean	0.181	0.262	0.257	0.288	0.326
Median	0.141	0.246	0.217	0.265	0.281
Standard Dev.	0.144	0.130	0.186	0.164	0.186
CV (%)	79.6	49.6	72.5	56.9	57.0
N	14	153	132	150	145
Big Rock Branch					
Mean	0.211	0.358	0.468	0.385	0.243
Median	0.111	0.302	0.389	0.308	0.216
Standard Dev.	0.295	0.224	0.320	0.269	0.146
CV (%)	140.0	62.7	68.4	69.9	60.3
N	16	206	178	202	206
Blue River (north fork)					
Mean	0.187	0.390	0.559	0.398	0.240
Median	0.151	0.335	0.458	0.312	0.211
Standard Dev.	0.218	0.254	0.421	0.293	0.154
CV (%)	116.7	65.1	75.3	73.6	64.2
N	29	276	234	269	276

(Sixmile Branch), and the 1940-2010 rates varied from 0.199 m/yr (Sixmile Branch) to 0.335 m/yr (Blue River (north fork)). Median migration rates increased in each individual reach during the 1940-2010 time period.

The increase in migration rates throughout the watershed and in each reach is likely due to a limited number of data points from 1830 that cause a misrepresentation of the reaches' overall movements (N=54 in 1830-1940 versus N=549 in 1940-2010 for the whole watershed). The limited number of data points from 1830-1940 along with representing such a long time period (110 years) likely results in the underestimation of migration rates because it is possible that channels migrate back and forth rather than in one direction. Another disadvantage associated with long timer periods between channel position dates is that migration rates can vary significantly within those time periods. Variability in channel migration rates would probably have been large during the 1830-1940 period, as suggested by Knox and Hudson's (1995) study in the Galena River where small migration rates occurred from 1820-1890 (0.06 m/yr) followed by a large increase from 1925-1940 (0.7 m/yr). It is likely that migration rates within the Blue River would have been higher from 1920-1940 due to poor land management practices. Standard deviations and coefficients of variation are higher for all the 1830-1940 datasets, indicating that data are much more dispersed and could potentially misrepresent the general trend within the reaches or watershed. The actual migration rates between 1830 and 1940 were probably larger than the calculated rate because the channel could have been actively moving back and forth during that 110-yr period. Migration rates during the three shorter time periods between 1940 and 2010 provide evidence for this because the sum of the three migration distances is greater than the migration distance between the channel positions in 1940 and 2010. Although all migration rates were underestimated (i.e., lacking information on channel positions every year), the post-1940 migration rates will tend to be more accurate than the 1830-1940 rates.

The increase in migration rates during 1940-2010 from 1830-1940 could also indicate that the Blue River watershed did not have the same response to agricultural expansion or changes in land management practices as other watersheds within the region. There is no hydrologic record for the Blue River, therefore, the trend in peak flows is unknown. Frequent and high peak flows result in more runoff and high sediment loads, often leading to channel instability and movement through channel adjustment. Although it is likely that the Blue River did respond similarly to the Galena River and other nearby rivers (i.e. the Pecatonica River studied by Potter (1991)) since these watersheds have similar topography, geology, and land use type. However, there is not enough hydrologic or field evidence to definitively say trends of erosion rates would be the same throughout the Blue River watershed during the 1830-1940 and 1940-2010 time periods.

1940-1968; 1968-1995; 1995-2010. The 1940-2010 time period was broken up into shorter time periods using available aerial images to observe finer scale temporal change throughout the watershed. Post-1940 trends varied between the four reaches within the watershed (Figure 4.1). Sixmile Branch showed little change in median migration rates, while lateral migration rates for Big Spring Branch increased slightly over time. Median migration rates in both the Big Rock Branch and the Blue River (north fork) declined from 1940 to 2010, although the Blue River (north fork) displayed a larger magnitude of change.

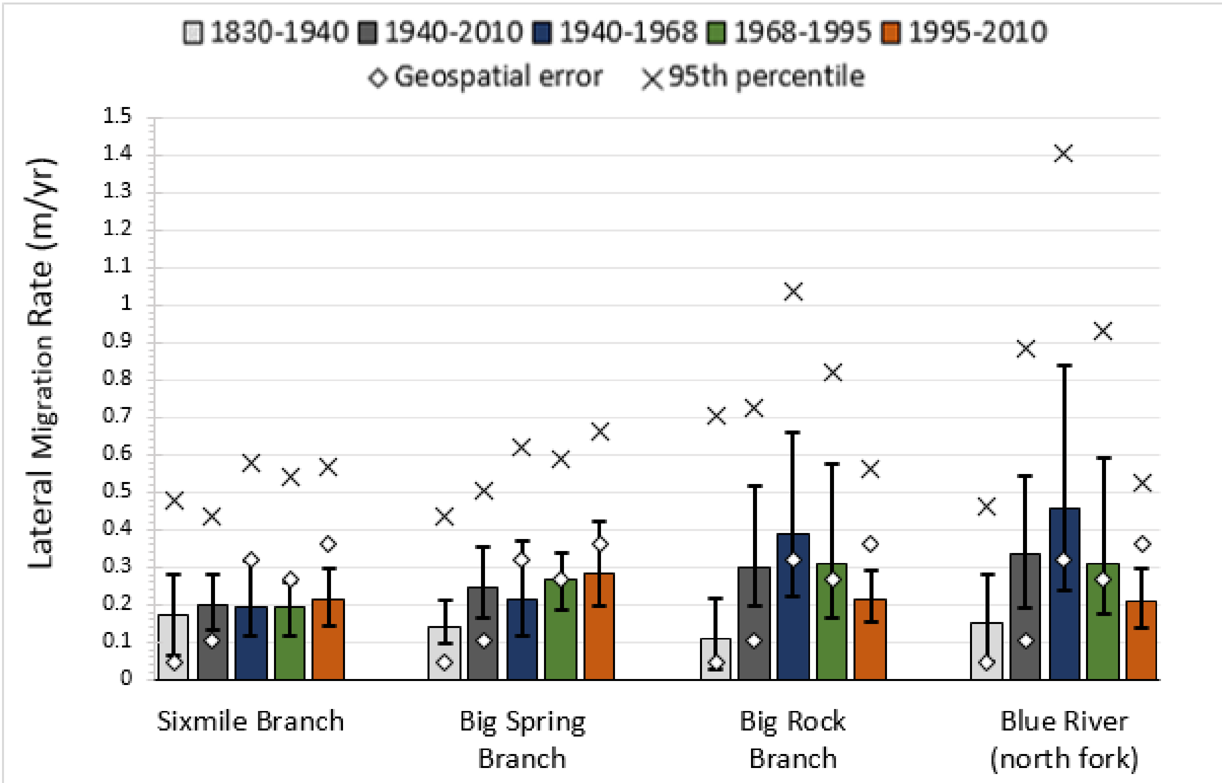

Figure 4.1. Median migration rates for each time period. Error bars represent the IQR.

Like other watersheds in this region, the Blue River watershed experienced an increase in agriculture and settlement from the early 1800s to the 1860s (Knox, 1977; Potter, 1991; Lecce and Pavlowsky, 1997). It has been demonstrated that channel size, migration rates (Knox, 1977; Knox and Hudson, 1995), and floodplain sedimentation (Trimble and Lund, 1982) increased in the region from the 1890s to the 1940s due to poor land management and rapid land use change. Peak flow hydrographs from nearby watersheds show a reduction in flow magnitude and variance from the late 1950s to early 1970s (Figure 4.2), which is likely explained by a combination of improved land management established in the 1940s and maintained land use types (Potter, 1991). Although there is not any discharge data for the Blue River watershed, it is

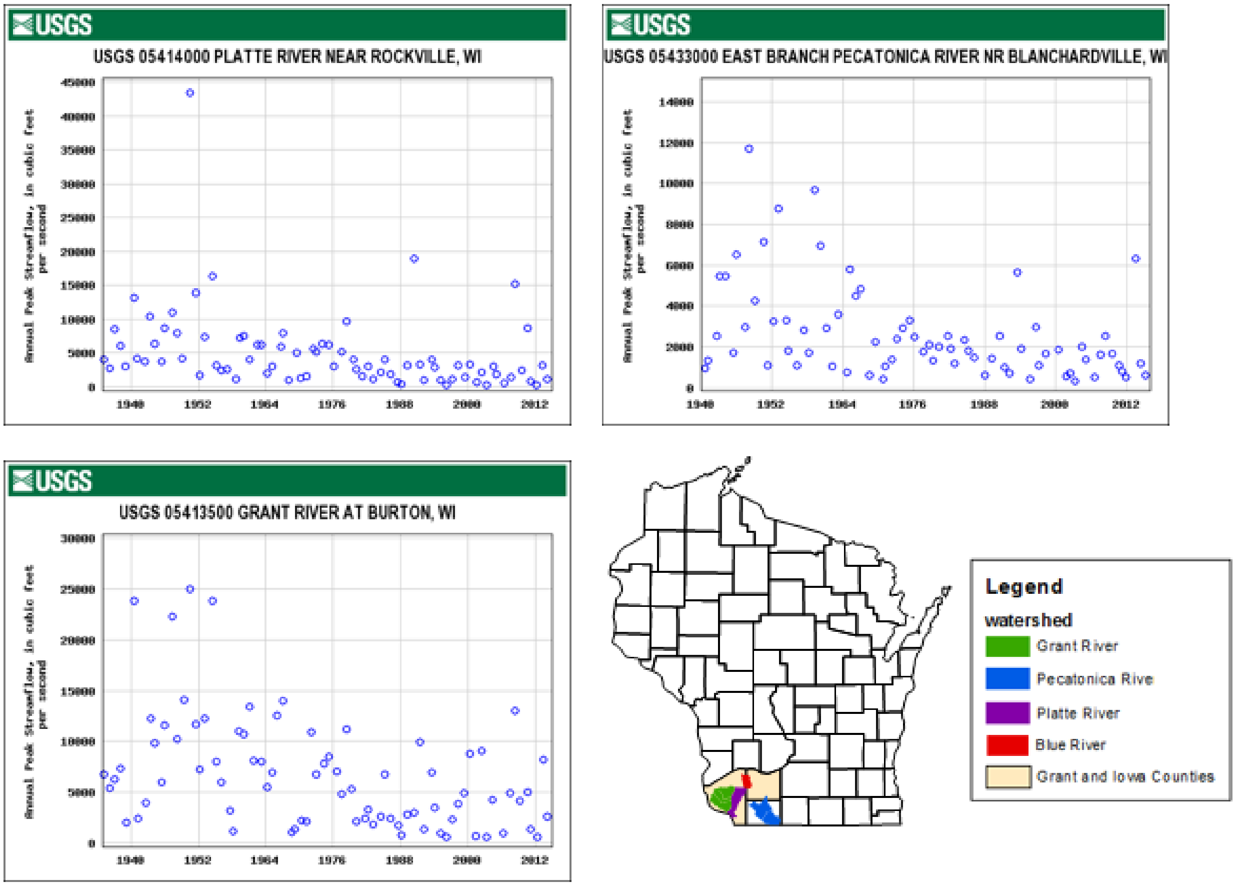

Figure 4.2. Hydrographs from nearby watersheds that are comparable to the Blue River watershed. Peak hydrographs provided by the USGS at: http://waterdata.usgs.gov/wi/nwis/rt

likely that the Blue River generally behaved similarly in terms of the post-1950s decrease in peak flow. This may help explain the overall tendency for lower channel migration rates observed in Big Rock Branch and Blue River (north fork) (Table 4.1).

Much of the change observed during the three time periods between 1940 and 2010 may be explained by changes in land use and improved land management practices (Trimble and Lund, 1982). The first time period (1940-1968) represents a transition to improved land management practices, but had not yet produced the hydrologic effect of reducing peak discharges (Figure 4.2; Potter, 1991). Based on aerial imagery from this study, in 1940 only 0.10% of the watershed practiced strip cropping, but by 1968 approximately 12% of the

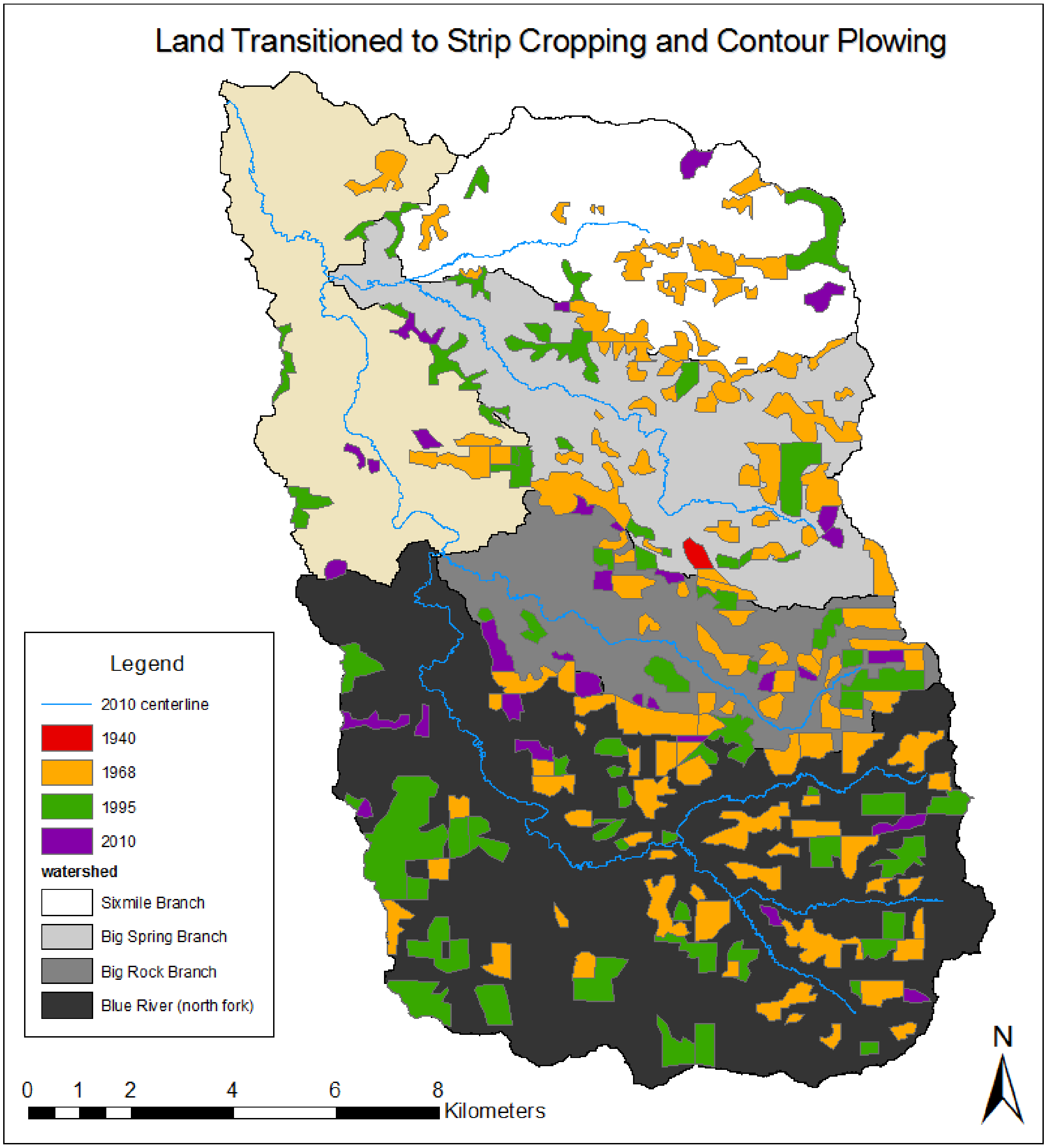

Figure 4.3. Land area that transitioned to strip cropping and contour plowing by the designated year based on aerial imagery analysis.

Table 4.2. Area of land changed to strip cropping and contour plowing by the designated year within the entire watershed and smaller catchments. See Figure 4.3 for catchment boundaries.

	Watershed	1940	1968	1995	2010
Blue River					
Area (km^2)	207.81	0.22	25.76	18.14	4.05
Percent change (%)		0.10	12	9	2
Cumulative change (%)		0.10	13	21	23
Sixmile Branch					
Area (km^2)	29.95	0	3.33	1.31	0.47
Percent change (%)		0	11	4	2
Cumulative change (%)		0	11	15	17
Big Spring Branch					
Area (km^2)	34.01	0.22	5.14	2.81	0.41
Percent change (%)		0.64	15	8	1
Cumulative change (%)		0.64	16	24	25
Big Rock Branch					
Area (km^2)	25.67	0	5.15	2.43	0.98
Percent change (%)		0	20	9	4
Cumulative change (%)		0	20	30	33
Blue River (north fork)					
Area (km^2)	85.35	0	10.49	10.32	1.72
Percent change (%)		0	12	12	2
Cumulative change (%)		0	12	24	26

watershed transitioned to strip cropping and contour plowing (Figure 4.3; Table 4.2). This trend continued so that by 1995 about 21% of the watershed was using strip cropping and contour plowing and by 2010 that percentage increased to 23%. The greatest percent change to improved farming methods occurred from 1940-1968 within the individual reach's catchments, too, with the largest area of change occurring in Big Rock Branch (20%) and Big Spring Branch (15%). The largest cumulative change from 1940-2010 occurred within Big Rock Branch (33%) and Blue River (north fork) (26%). The trends in Figure 4.1 showing declining migration rates in the Big Rock Branch and the Blue River (north fork) generally agree with these improved hydrological conditions in the watershed. The lowest cumulative change (17%) in farming practices occurred in Sixmile Branch (Table 4.2), which may help explain this reach's lack of post-1940 change in migration rates.

Changes in land management practices had a large scale effect on the watershed's hydrology and channel stability, however, there were localized changes that also could have impacted the channels. Some roads had been built or modified between the three time periods. During 1940-1968, there were five road modifications that were located near the stream channels and two that happened during 1968-1995 (Figure 4.4). Although there is no imagery of the road construction taking place, construction has commonly lead to excessive runoff and increased sediment loads, which can alter flow regimes and disturb the fluvial system (Eng et al., 2013). These road modification sites would likely have caused some disturbance downstream, which may contribute to the higher migration rates within Big Rock Branch and Blue River (north fork).

Sixmile Branch and Big Spring Branch do not display the declining trend displayed in the other two reaches to the south. Sixmile Branch has fairly consistent median migration rates and Big Spring Branch's migration rates increased slightly over the three time periods. However, the main difference between the Sixmile Branch and Big Spring Branch and the two other reaches are their much lower migration rates from 1940-1968. Sixmile Branch is in a wider valley where the slope drops off very quickly in the headwaters. Much of its floodplain is used for agriculture which was established early on (Figure 4.5) and many of the farms have continued old farming practices compared to farms within the other catchments (Figure 4.3; Table 4.2). Also, much of the channel along Sixmile Branch is confined against valley walls, restricting channel movement (top image of Figure 4.5). This phenomenon will be explained below in the section on geomorphic controls.

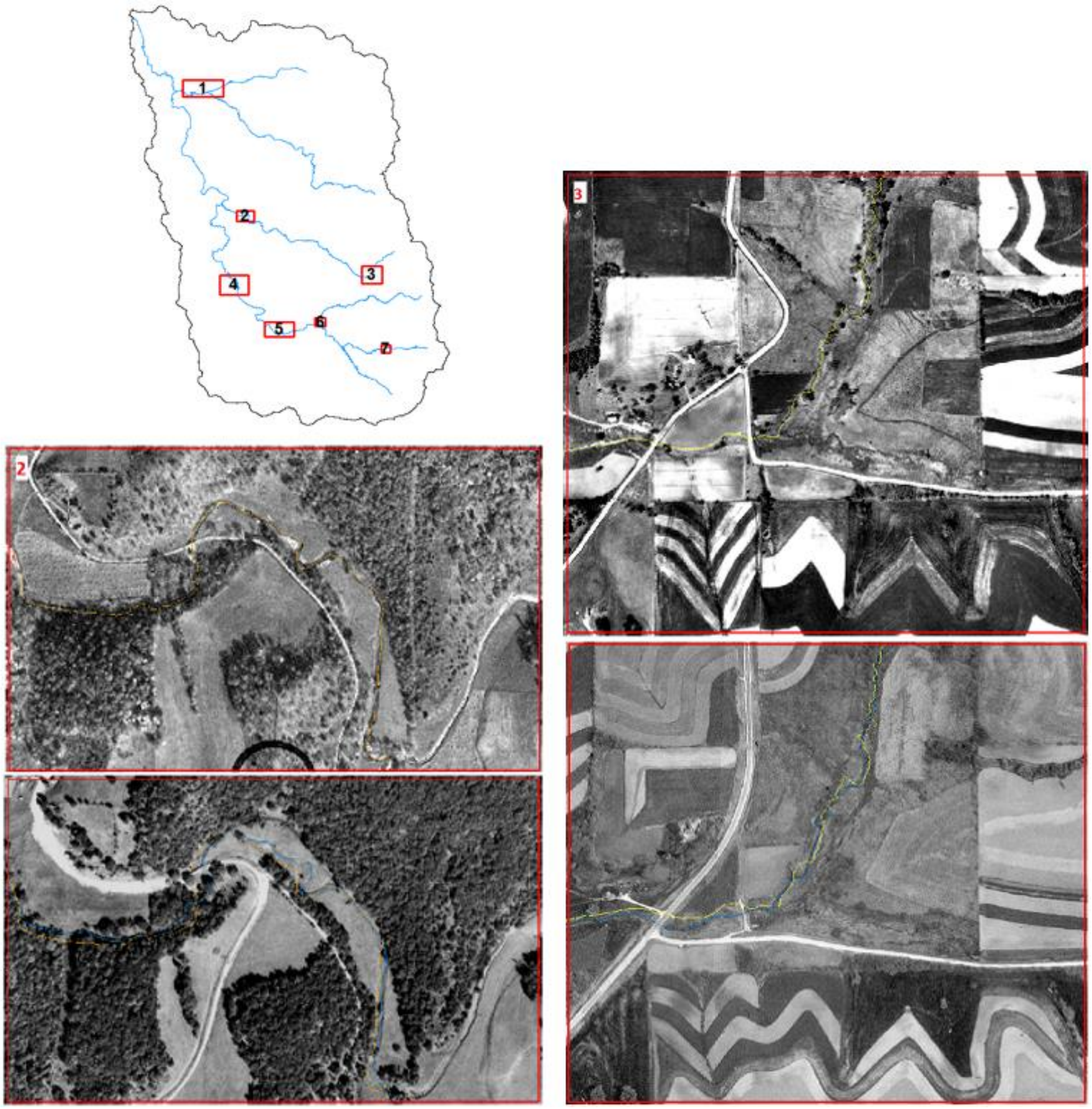

Figure 4.4. Map of locations where road modification occurred and two examples. Road modification #2 occurred during 1940-1968 and modification #3 occurred during 1968-1995. The top images of each example are the older of the two years. Pictures of all seven road modifications are provided in Appendix B.

Median migration rates for Big Spring Branch increase modestly between the three time periods, but again the rates are relatively low during the 1940-1968 time period compared to other reaches within the watershed. In contrast, the 1995-2010 rates are higher than any of the other reaches. The low rates from 1940-1968 are probably related to a large amount of artificial channel straightening along the Big Spring Branch. These straightened sections were removed

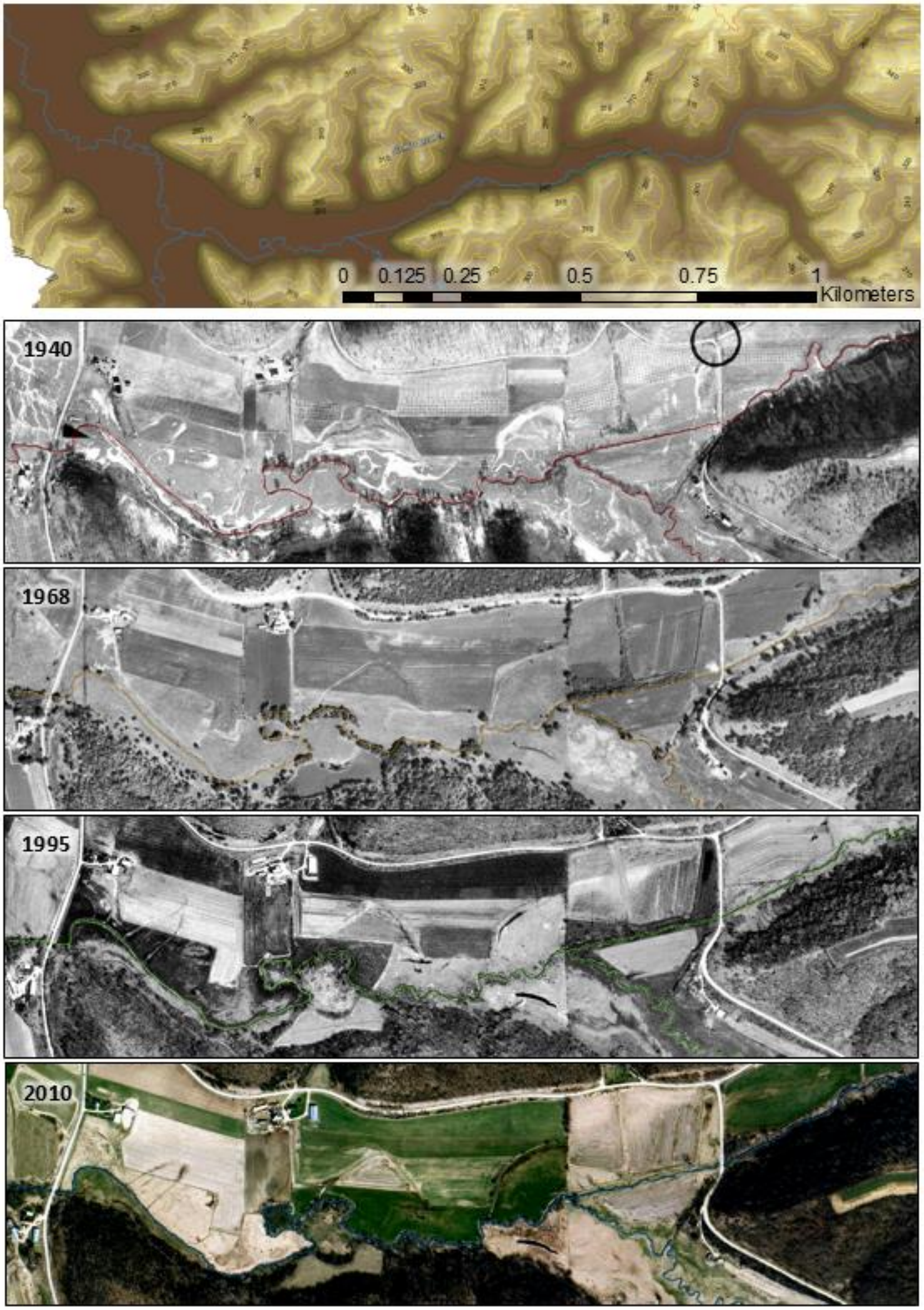

Figure 4.5. Top image: 2010 Sixmile Branch stream centerline overlain an elevation model with contours. Bottom four images: Imagery of a section of Sixmile Branch at 1:6,000 m scale from designated year overlain with associated stream centerline.

from this dataset. However, during 1968-1995 and 1995-2010, sections of channel began to develop small meanders via lateral migration (Figure 4.6). Some sections were experiencing migration rates up to 1 m/yr and there are almost twice as many sections with migration rates greater than 0.6 m/yr from 1995-2010 than during the previous time periods (see Figure 4.8 in next section).

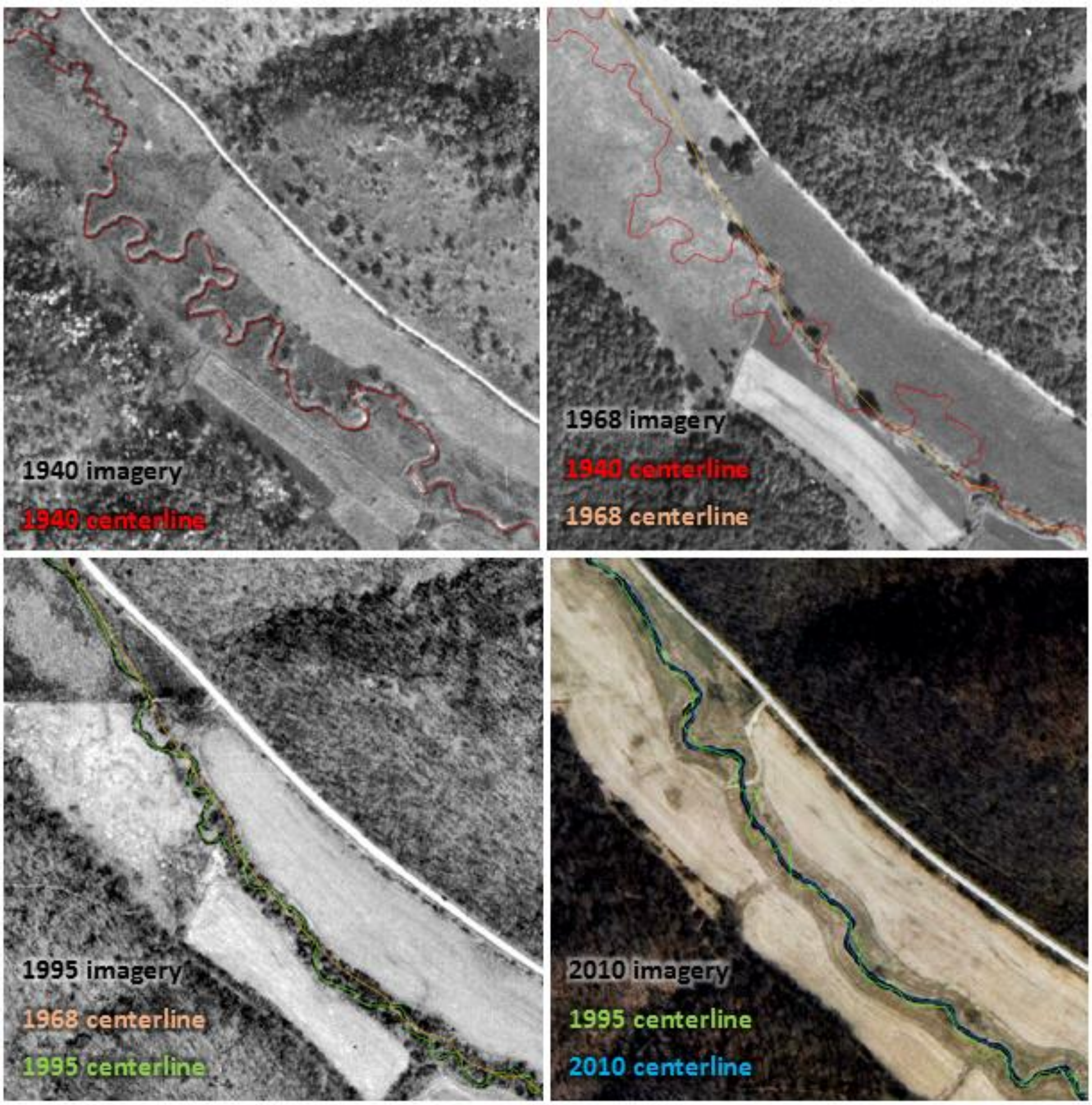

Figure 4.6. Example of artificial channel straightening from 1940-1968, then natural meander development during 1968-1995 and 1995-2010 along Big Spring Branch (1:4,000 m scale).

Full understanding of temporal variations in migration rates throughout the watershed and within individual reaches is limited because the Blue River is ungaged. There is no hydrologic record to observe the intensity and frequency of storm events, or the watershed's response to different storms, therefore, changes in migration rates over time cannot be linked to storm events. Hydrographs and precipitation records from nearby watersheds could be used to identify high precipitation periods, however, this information could not be used as a direct measure for the Blue River watershed as storms can be localized and the Blue River may respond differently based on differences in land use, topography, and relative recent weather conditions.

Spatial Trends

Spatial trends were evaluated by plotting lateral migration rates every 100 m against down valley distance. Downstream trends in migration rates were analyzed using all of the data, but separate trends were also plotted for just significant values (i.e., 'significant values' are those rates greater than the total error; see Table 3.1 for individual values). Downstream trends in migration rates within Sixmile Branch are fairly constant upstream (ranging between 0.03 m/yr and 0.63 m/yr) before increasing downstream from the confluence with Blue River. Big Spring Branch migration rates peak in the upstream portion of the reach between 1 km and 5 km down valley, before decreasing farther downstream. The highest migration rates in the Big Rock Branch are located in mid-reach locations between about 3 km and 13 km down valley. Maximum migration rates along the Blue River also occur in mid-reach locations between about 4 km and 20 km down valley. Relationships between lateral migration rates and distance down valley were fitted with quadratic functions and only the functions for Big Rock Branch and Blue River (north fork) tested significant at the 95% confidence level, however, the strength of the relationships as indicated by R^2 values showed that they were weak (Table 4.3, Figure 4.7).

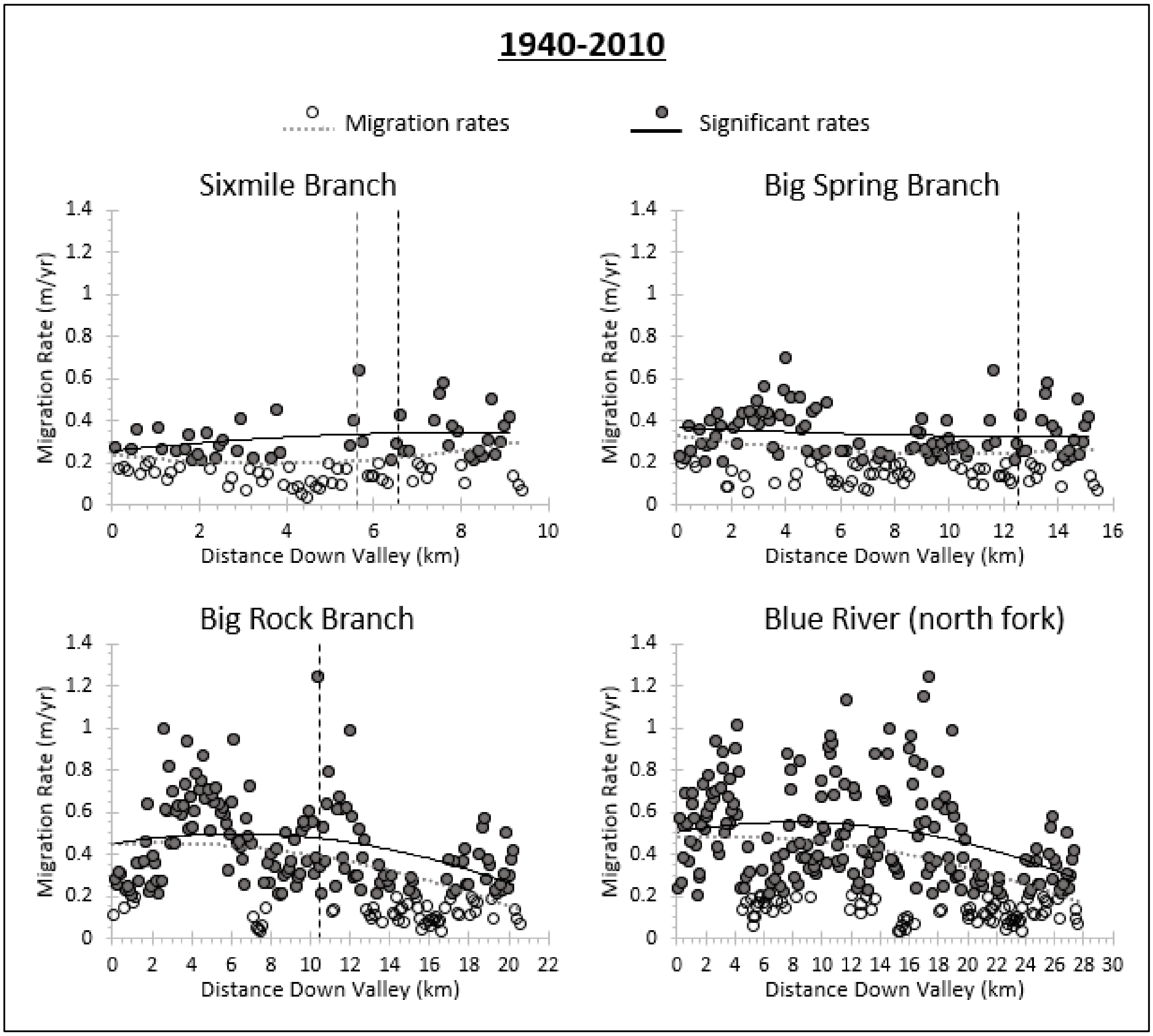

Figure 4.7. Downstream trends of lateral migration rates for the 1940-2010 time period fit with quadratic functions. In Sixmile Branch, the confluence with Big Spring Branch is designated with the grey vertical line, and the black vertical line designates the confluence with Blue River in all the plots.

Table 4.3. Equations, R^2 values, and significance values for the trends in Figure 4.7. Significant relationships at the 95% confidence level are marked with *.

1940-2010						
Reach	Significant Rates Eq.	R^2	P-value	All Rates Eq.	R^2	P-value
Sixmile Branch	$y = 0.2542 + 0.0222x - 0.0014x^2$	0.0693	0.2136	$y = 0.2358 - 0.0222x + 0.0031x^2$	0.0537	0.0788
Big Spring Branch	$y = 0.3634 - 0.0049x + 0.0001x^2$	0.0153	0.4916	$y = 0.3236 - 0.0156x + 0.0007x^2$	0.0294	0.1069
Big Rock Branch	$y = 0.4477 + 0.0155x - 0.0012x^2$	0.1216	7.4E-5*	$y = 0.4471 + 0.0045x - 0.0010x^2$	0.1826	1.3E-9*
Blue River (north fork)	$y = 0.5052 + 0.0115x - 0.0007x^2$	0.1017	2.9E-5*	$y = 0.4792 + 0.0028x - 0.0005x^2$	0.1342	2.9E-9*

Migration rates were also plotted against down valley distance for the three shorter time periods between 1940 and 2010 (Figures 4.8 and 4.9). Sixmile Branch had migration rates ranging up to 0.95 m/yr during the shorter time periods with the highest rates occurring from 1995-2010 (Figure 4.8). Migration rates in the upstream portion continually decrease throughout the time periods while migration rates downstream of the Big Spring Branch confluence increase. The downstream trends along Big Spring Branch are similar throughout the time periods with an upstream peak occurring from 1 km to 6 km and another peak near the confluence with Blue River. Migration rates also had a similar range in all three time periods where each time period displaying sections with migration rates of almost 1 m/yr.

Big Rock Branch displayed high rates in upstream and midbasin locations from 1940-1968 with one migration rate reaching up to 2.1 m/yr (Figure 4.9). The overall pattern during the 1968-1995 period was similar, but by 1995-2010 migration rates were consistently low throughout the entire reach, ranging from 0.07 m/yr to 0.82 m/yr and lacking the upstream and mid-basin peaks noted during the earlier time periods. Migration rates along the Blue River (north fork) were highest mid-reach during the 1940-1968 period with several values exceeding 2 m/yr. Maximum rates were lower (maximum = 1.45 m/yr) during the 1968-1995 period. Migration rates display a sharp decrease during the 1995-2010 period with only one value (1.3 m/yr at 8 km) exceeding 1 m/yr., with a fairly constant downstream pattern of rates ranging from 0.03 m/yr to 0.7 m/yr. Downstream trends were fitted with quadratic functions for each reach (Table 4.4).

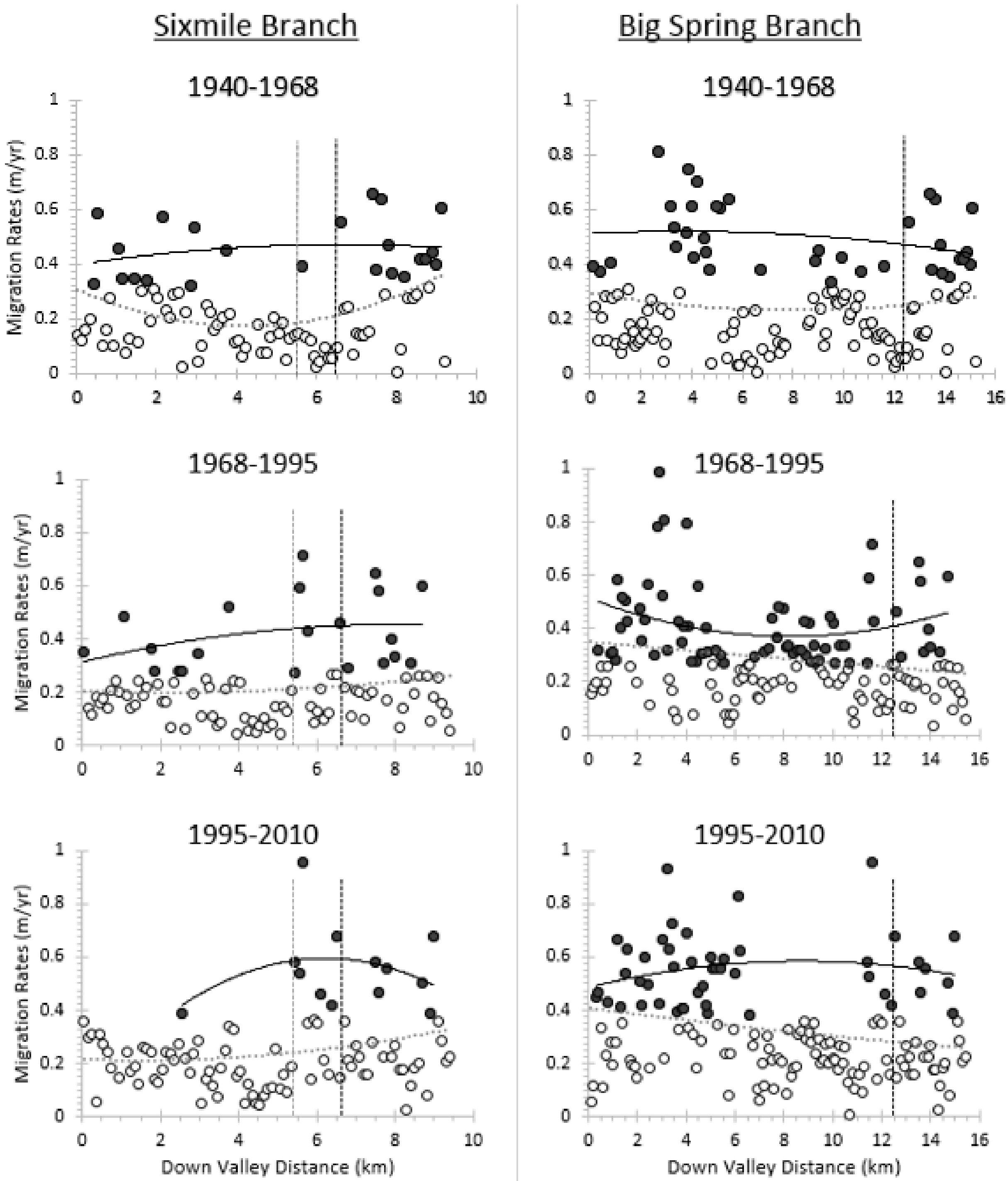

Figure 4.8. Downstream trends of lateral migration rates for Sixmile Branch and Big Spring Branch for time periods 1940-1968, 1968-1995, 1995-2010. Filled in circles indicate significant values (greater than total geospatial error). The grey vertical line designates the confluence with Big Spring Branch, and the black vertical line confluences with Blue River.

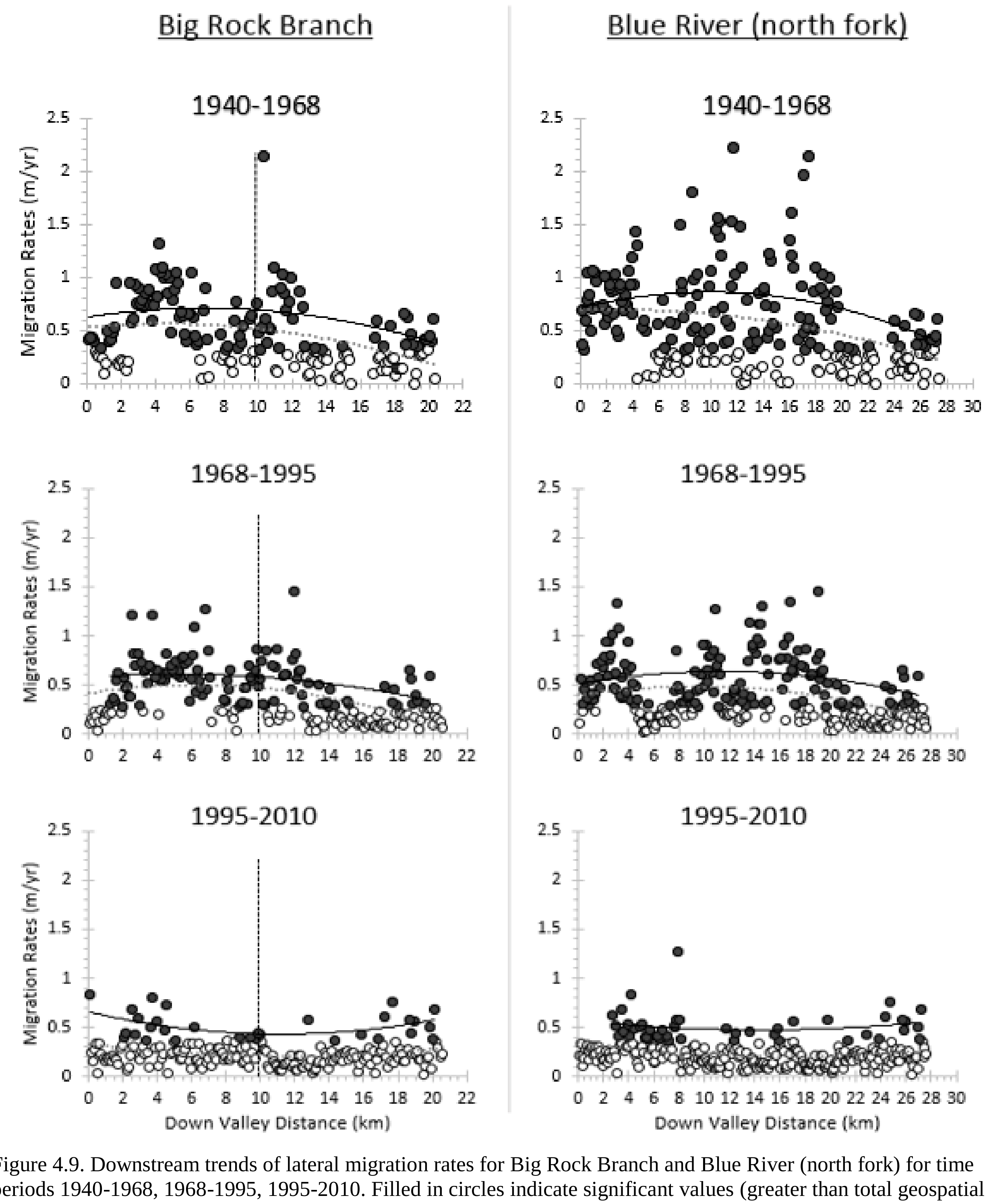

Figure 4.9. Downstream trends of lateral migration rates for Big Rock Branch and Blue River (north fork) for time periods 1940-1968, 1968-1995, 1995-2010. Filled in circles indicate significant values (greater than total geospatial error). The black vertical line designates confluences with Blue River.

Table 4.4. Equations, R^2 values, and significance values for the trends in Figures 4.8 and 4.9. Significant relationships at the 95% confidence level are marked with **, and at the 90% confidence level with * next to their p-values.

1940-1968						
Reach	Significant Rates Eq.	R^2	P-value	All Data Eq.	R^2	P-value
Sixmile Branch	$y = 0.002x^2 - 0.0064x + 0.4296$	0.0962	0.1653	$y = 0.009x^2 - 0.0741x + 0.3202$	0.1380	0.1605
Big Spring Branch	$y = 0.0002x^2 - 0.0052x + 0.532$	0.0084	0.5991	$y = 0.0013x^2 - 0.0198x + 0.3031$	0.0151	0.9477
Big Rock Branch	$y = -0.0015x^2 + 0.021x + 0.6372$	0.0727	0.0350**	$y = -0.0014x^2 + 0.0121x + 0.5385$	0.1255	1.0E-05**
Blue River (north fork)	$y = -0.0014x^2 + 0.0282x + 0.7182$	0.0751	0.0535*	$y = -0.0007x^2 + 0.0027x + 0.6978$	0.1133	4.9E-07**
1968-1995						
Reach	Significant Rates Eq.	R^2	P-value	All Data Eq.	R^2	P-value
Sixmile Branch	$y = -0.0022x^2 + 0.0353x + 0.3137$	0.0907	0.2070	$y = 0.0021x^2 - 0.0349x + 0.5136$	0.0594	0.2526
Big Spring Branch	$y = 0.0012x^2 - 0.0051x + 0.2046$	0.0174	0.3530	$y = 4E-05x^2 - 0.0082x + 0.3491$	0.0425	0.0114**
Big Rock Branch	$y = -0.0012x^2 + 0.0123x + 0.578$	0.086	0.0058**	$y = -0.0022x^2 + 0.0271x + 0.4154$	0.2188	8.4E-09**
Blue River (north fork)	$y = -0.001x^2 + 0.0227x + 0.5094$	0.0466	0.5278	$y = -0.001x^2 + 0.0189x + 0.3949$	0.1015	3.0E-05**
1995-2010						
Reach	Significant Rates Eq.	R^2	P-value	All Data Eq.	R^2	P-value
Sixmile Branch	$y = -0.0131x^2 + 0.1634x + 0.0873$	0.1240	0.9218	$y = 0.0019x^2 - 0.0055x + 0.216$	0.0501	0.0439**
Big Spring Branch	$y = -0.0013x^2 + 0.0227x + 0.4857$	0.0295	0.6005	$y = 0.0002x^2 - 0.0124x + 0.4095$	0.0569	0.0039**
Big Rock Branch	$y = 0.0018x^2 - 0.0408x + 0.6585$	0.1679	0.6573	$y = 0.001x^2 - 0.0221x + 0.3331$	0.0516	0.2249
Blue River (north fork)	$y = 0.0005x^2 - 0.013x + 0.568$	0.0186	0.8912	$y = 0.0005x^2 - 0.0177x + 0.3478$	0.0599	0.0174**

Sixmile Branch and Big Spring Branch are in the northern portion of the basin where the bedrock consists of mostly friable sandstones. Valleys are narrow in the headwaters, but widen quickly and display little change in slope along a majority of the reach. The headwaters to mid-reach portions of Big Rock Branch and Blue River (north fork) have valleys that have not incised as deeply into the stratigraphic sequence, therefore, the bedrock consists mostly of resistant dolomites. Many of the upstream valleys are very narrow and widen gradually downstream. At approximately the confluence of the Big Rock Branch and the Blue River (north fork), the main valleys incise into friable Cambrian sandstones and the valleys widen abruptly (Figure 1.1). The effects of the differences in lower basin and upbasin reaches have been reported in previous studies by Lecce (1997a, 1997b, 2013). Sixmile Branch and Big Spring Branch showed higher stream power values in the headwaters and continually decrease downstream as drainage area increases, while Big Rock Branch and Blue River (north fork) showed a distinct mid-basin peak in stream power. Similar responses to local geology and other smaller scale variations (e.g., variations in land use, channel position relative to valley walls, or channel slope) can be observed in downstream trends of lateral migration rates. However, despite the geomorphic differences upstream, data recorded downstream of confluences are shared by at least two or more of the reaches. Therefore all the reaches are viewed as spatially interconnected stream pathways that conveys water and sediment downstream (Lecce, 1997a).

Hydraulic and Geomorphic Controls

Stream power. Previous studies have suggested that stream power is linked to bank erosion rates (Nanson and Hickin, 1986; Nanson and Croke, 1992; Lawler, 1995). Stream power data used from Lecce's (1997a) study were measured at sites located on 7.5 minute topographic quadrangles (i.e., not using GPS), and as such lack exact coordinates. Therefore, when evaluating relationships between migration rates and stream power and other geomorphic variables, migration rates (from the 1940-2010 dataset) were averaged over a 500 m section around the approximate location of the sites. Mean stream power represents the ability of water to do geomorphic work per a unit area, therefore, it should theoretically represent a good index of the erosion potential near a site. Relationships between migration rates and mean stream power were fitted with power functions in log-log space and generally migration rates increased with mean stream power (Figure 4.10). None of the reaches, however, displayed strong or significant relationships (Table 4.5). Lateral migration rates of all of the reaches have weak relationships with mean stream power, indicating that stream power does not provide a single variable that explains the variation in migration rates. Mean stream power and cross-sectional stream power displayed very similar downstream trends within the Blue River watershed (Lecce, 1997a), therefore, there was no significant change in relationships when plotting lateral migration rates against cross-sectional stream power.

It should be recognized that stream power measures from Lecce's (1997a) study were collected in 1993 assuming bankfull flow, therefore, it is possible that these stream power values are not representative of migration rates over the 1940-2010 time period, because channel shape and slope could change. However, there was no improvement in the strength or statistical significance of relationships when migration rates from other time periods (i.e., 1995-2010) were plotted against stream power. The lack of strong relationships between stream power and migration rates from the different time periods indicates channel migration is not solely dependent on stream power within the Blue River watershed. However, stream power and bank erosion are likely controlled by a common variables.

Within the Blue River watershed, when Lecce (1997a) plotted stream power against drainage area for each reach it showed that variations of power were dominantly controlled by downstream changes in slope that were influenced by lithology. This relationship was nonlinear as slope and discharge had inverse relationships downstream. When both mean stream power and

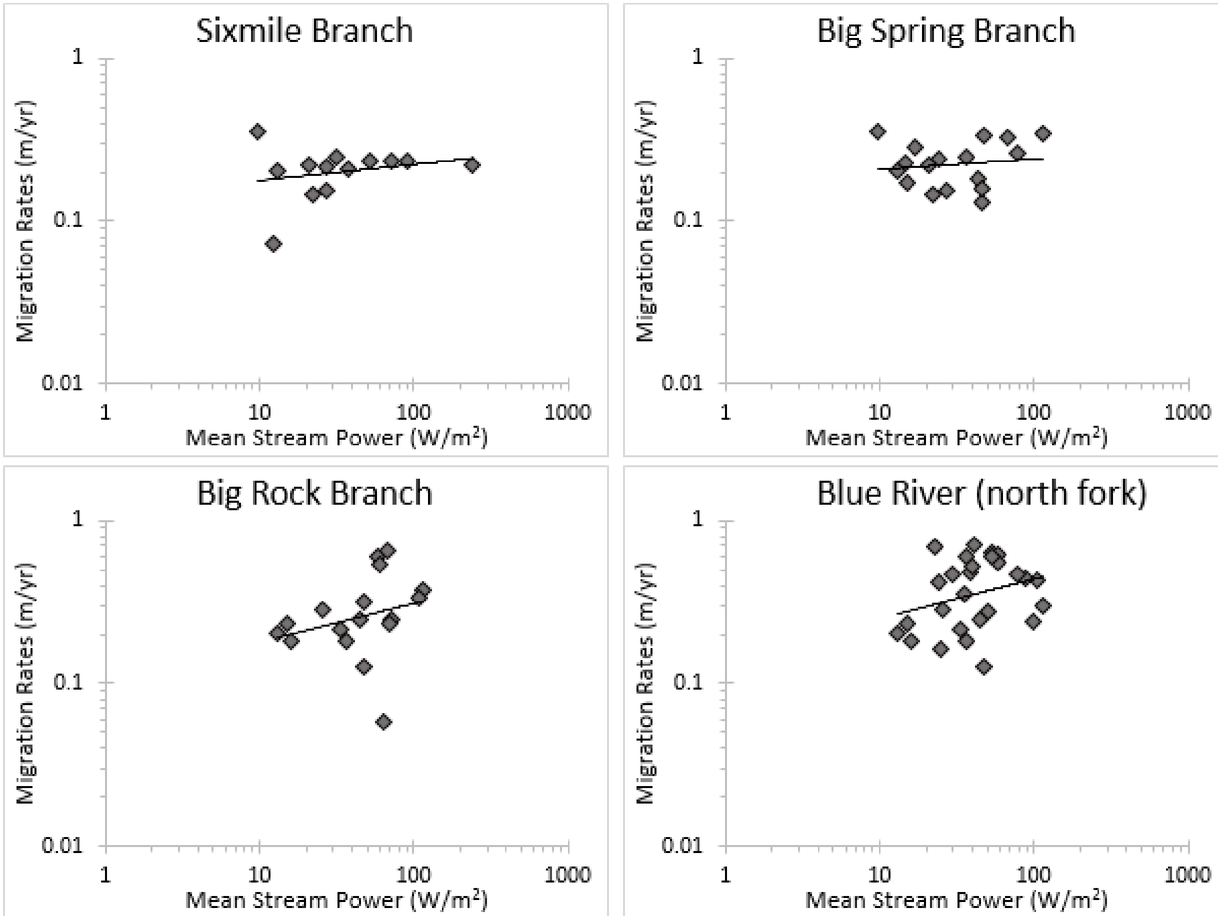

Figure 4.10. Average lateral migration rates from 1940-2010 plotted against mean stream power for each reach.

Table 4.5. Equations, R^2 values, and significance values for the trends in Figure 4.10.

Mean Stream Power			
Reach	Equation	R^2	P-value
Sixmile Branch	$y = 0.142x^{0.098}$	0.055	0.4411
Big Spring Branch	$y = 0.179x^{0.065}$	0.020	0.5928
Big Rock Branch	$y = 0.104x^{0.236}$	0.069	0.3086
Blue River (north fork)	$y = 0.143x^{0.243}$	0.079	0.1564

lateral migration rates are plotted against down valley distance (Figure 4.11), some similarities in downstream trends can be observed in Big Rock Branch and Blue River (north fork). Big Rock Branch experiences higher migration rates and mean steam power in upstream to mid-reach locations, while Blue River (north fork) displayed a mid-reach peak in both stream power and migration rates. Big Spring Branch displayed higher stream power values in upstream reaches where migration rates were high, while Sixmile Branch showed little similarity in downstream trends between the two variables.

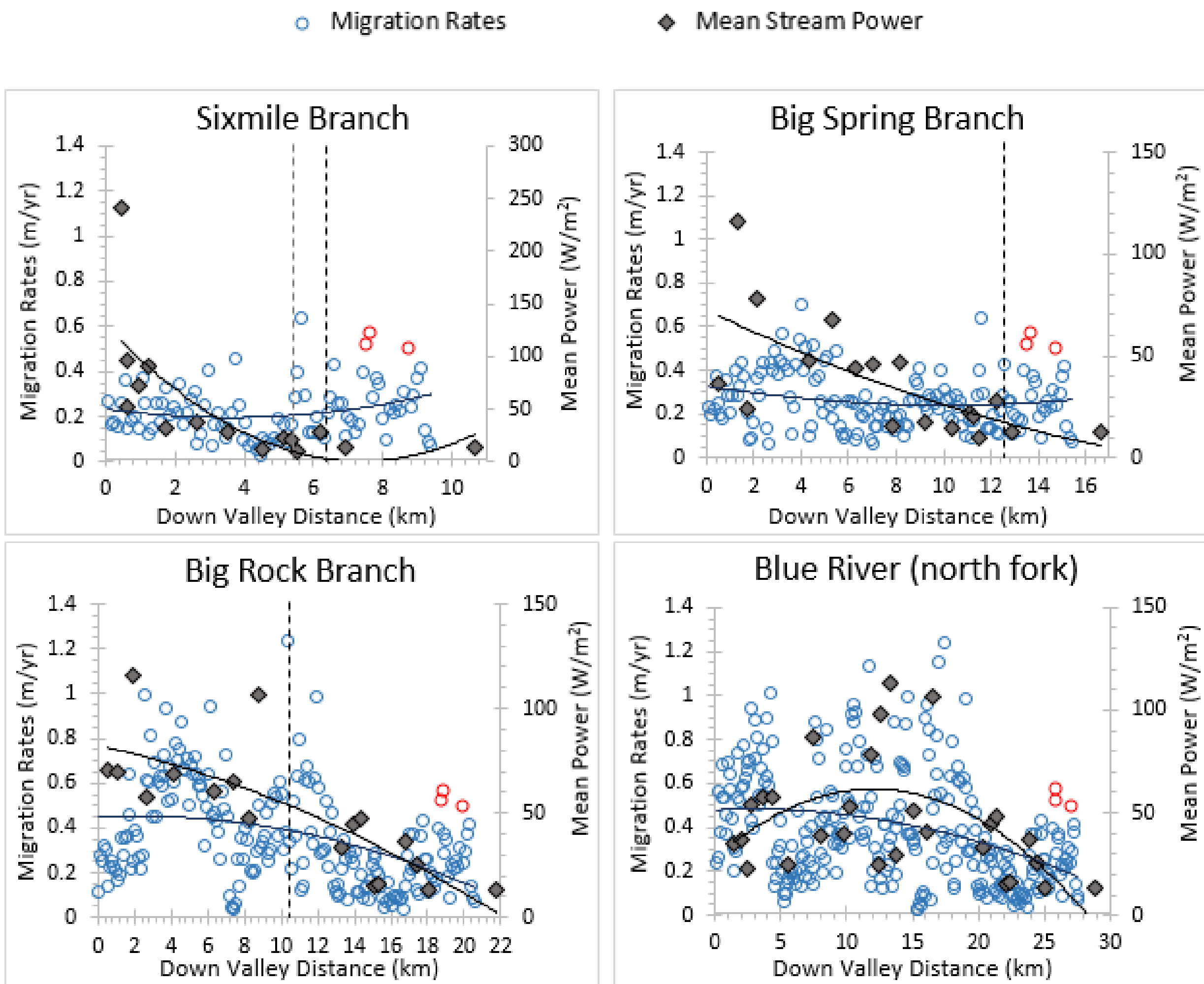

Figure 4.11. Mean stream power and average lateral migration rates from 1940-2010 plotted against down valley distance to compare downstream trends. Note that Sixmile Branch has a different vertical axis scale for stream power. See Figure 4.12 for explanation of red circles.

Figure 4.11 shows that there are three 100 m sections (identified by red symbols) with high migration rates (>0.5 m/yr) located downstream from the confluence of the Blue River and Sixmile Branch. However, upon closer inspection (Figure 4.12), the majority of the individual sections in this downstream portion are characterized by lower migration rates (<0.4 m/yr). This result would be more in keeping with the expectation that the low stream power, wide valleys, and low channel slopes characteristic of the downstream portion of the watershed would be

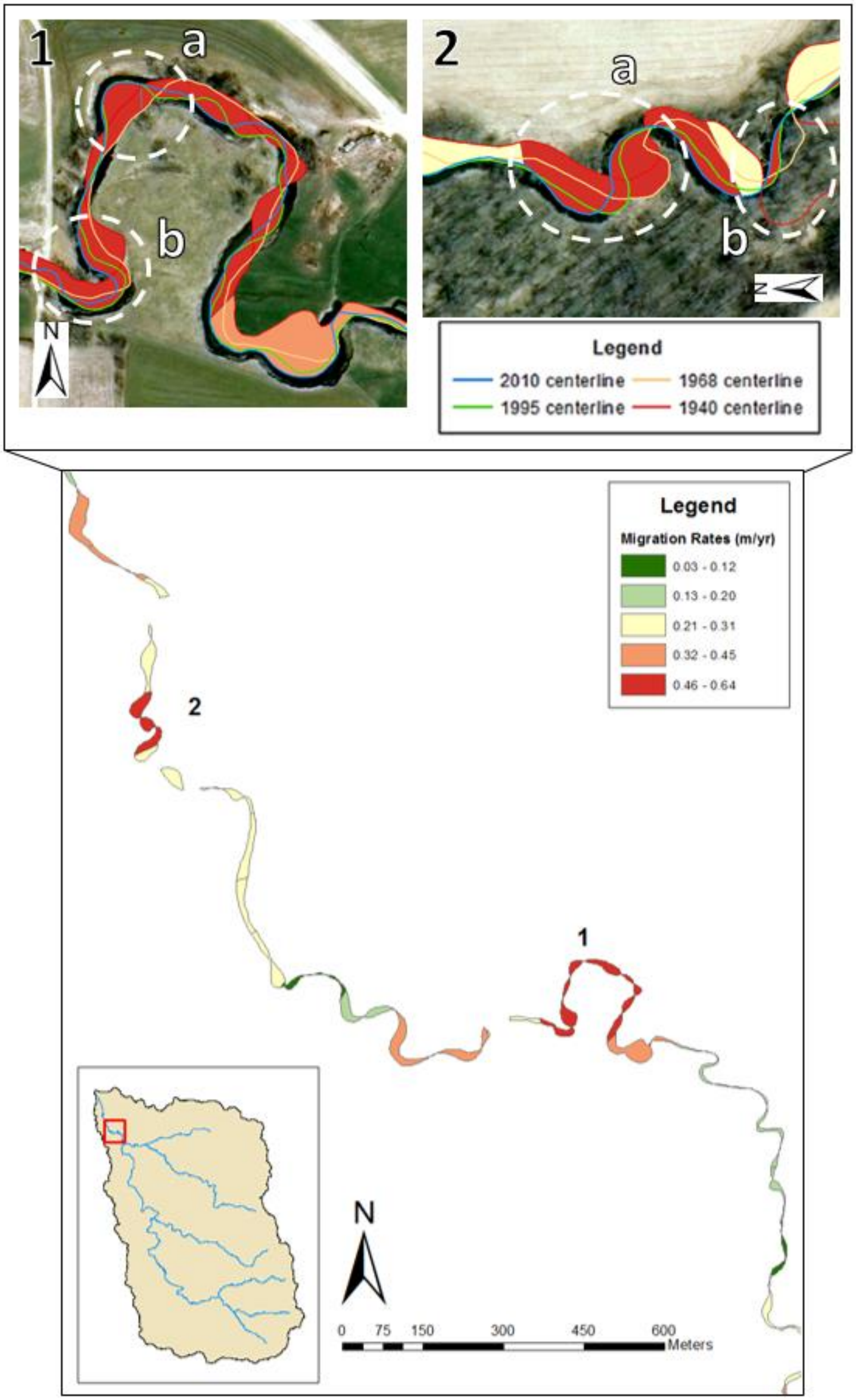

Figure 4.12. Downstream portion of Blue River showing magnitudes of average migration rates along 100 m sections. The high migration rates sections are magnified to 1:2,000 m scale and are labeled “1” and “2” with 2010 imagery. Channel flows north.

associated with low rates of lateral channel migration. The sections that do have high migration rates, however, could be associated with limitations in the identification of avulsions, data resolution, and potential undetected human disturbance.

The first two sections of high migration rates are located along a meander bend (“1” in Figure 4.12) near pastures, a road, and a farm house. Movement “a” is characterized by erosion on the left bank from 1940 to 1968, then by a large movement to the right bank from 1968 to 1995. The movement from 1968 to 1995 could result from an avulsion, however, there is not sufficient visual evidence and no field data to confirm the process. The second large movement along the meander bend, “b”, is from 1940 to 1968. There is potential this is downstream translation, however, one could also argue that the channel avulsed. Because these sections are also located near a farm house there is a possibility that channel positions were influenced human activities of trampling of banks by dairy cows that are not evident in the imagery. However, due to the lack of evidence to that effect the data were not considered anomalies during the filtering process.

The last section of high migration rates (“2” in Figure 4.12) includes one event of downstream translation labeled “a” where the largest movement occurs from 1968 to 1995. The channel could have avulsed in this section, though there was no obvious evidence of this process (i.e. old channel scar, alluvium near banks, clear movement opposite of cut bank). This particular section also had thick canopy cover along the channel banks, unlike most of the watershed where thick tree cover was located primarily on valley side slopes. The combination of black and white imagery, low resolution, and thick canopy made the banks difficult to detect even after photo enhancement. Therefore, the high migration rate associated with this section could be the consequence of inaccuracies in locating the channel position. Note the movement labeled “b” is an example where there was a clear cutoff (1940-1968) that was considered an anomaly and removed from the dataset. When these larger movements are redefined as anomalies and removed from the dataset, the migration rates in these sections decrease and more closely resemble the rates in this downstream portion of the watershed (Figure 4.13). Each measure drops below 0.4 m/yr which is characteristic of downstream migration rates (Table 4.6). However, these anomalies will not be adjusted values will not be used in later analysis regardless of the improvements in downstream trends to avoid introducing bias.

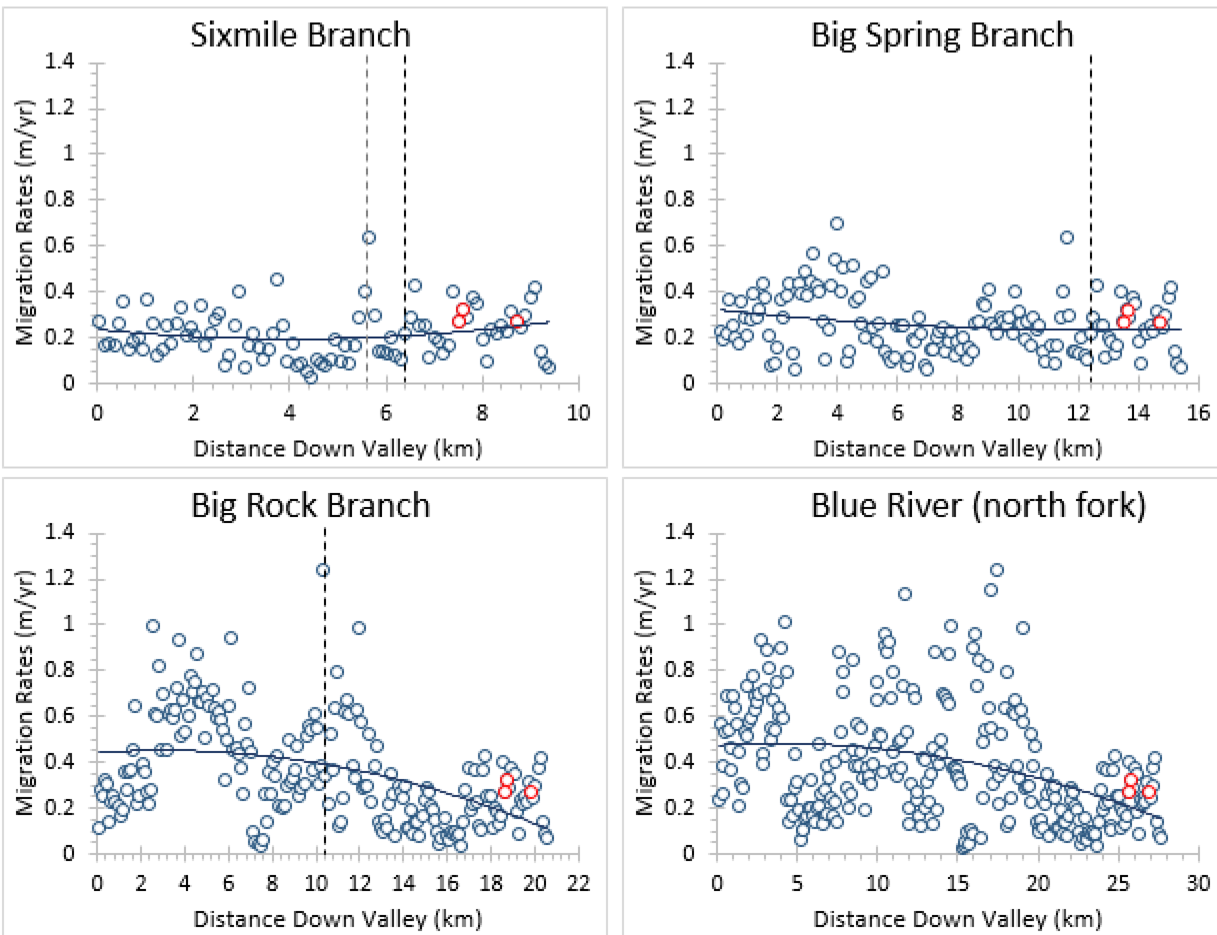

Figure 4.13. Plots of updated downstream migration rates from 1940-2010 after the five potential anomalies downstream of the Blue River and Sixmile Branch confluence were removed (shown in red). The grey vertical line designates the confluence with Big Spring Branch, and the black vertical line confluences with Blue River.

Table 4.6. Migration rates of the five 100 m sections downstream of the Blue River and Sixmile Branch confluence before and after the potential anomalies were removed.

Movement Label	Migration rate with anomaly (m/yr)	Migration rate after removal (m/yr)
1a	0.53	0.27
1b	0.58	0.32
2a	0.51	0.27

Cross-sectional stream power was also plotted against down valley distance to compare downstream trends with lateral migration rates (Figure 4.14). Sixmile Branch displays the same inverse downstream trends between the two variables. Cross-sectional stream power along Big Spring Branch displays the highest values from 4 km to 7 km with values decrease slightly downstream. The peak in migration rates along Big Spring Branch from 1 km to 6 km could be explained by a steeper slopes and higher cross-sectional power. Big Rock Branch shows a higher values for cross-sectional power from 2 km to 9 km downstream that coincide with high migration rates, and Blue River (north fork) displays a mid-reach peak in both migration rates and cross-sectional power. Within the Blue River watershed, downstream trends in cross-sectional stream power are influenced by downstream changes in slope (Lecce, 1997a). Although stream power is high at headwaters within Sixmile Branch, Big Spring Branch, and Big Rock Branch due to steep slopes, migration rates in the smallest headwater channels are low because of narrow valley floors and resistant bedrock that limits lateral movement.

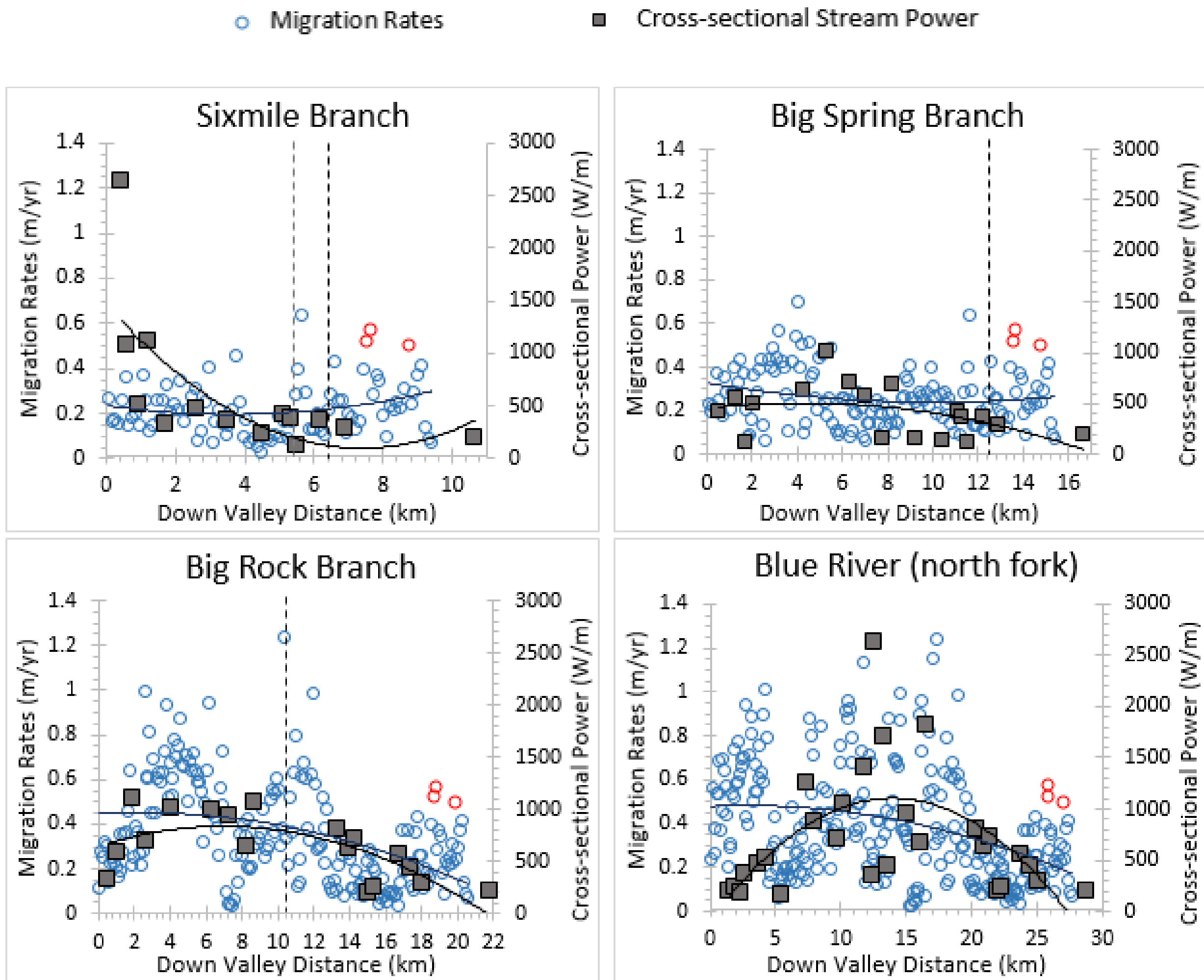

Figure 4.14. Cross-sectional stream power and average lateral migration rates from 1940-2010 plotted against down valley distance to compare downstream trends. The grey vertical line designates the confluence with Big Spring Branch, and the black vertical line confluences with Blue River. See Figure 4.12 for reference for red circles.

Geomorphic variables. Migration rates were also plotted down valley with the underlying lithology indicated and sections where the channel experiences localized confinement (Figure 4.15). Localized confinement is defined as a section of channel is located up against a valley wall and lateral movement becomes restricted on one bank. This definition of channel confinement is based on the study by Rapp and Abbe (2003) where channel confinement may be used to describe how much a channel can potentially move within a valley. The restricted ability of the channel to move once it is confined against a valley wall may reduce lateral channel migration rates measured in this study.

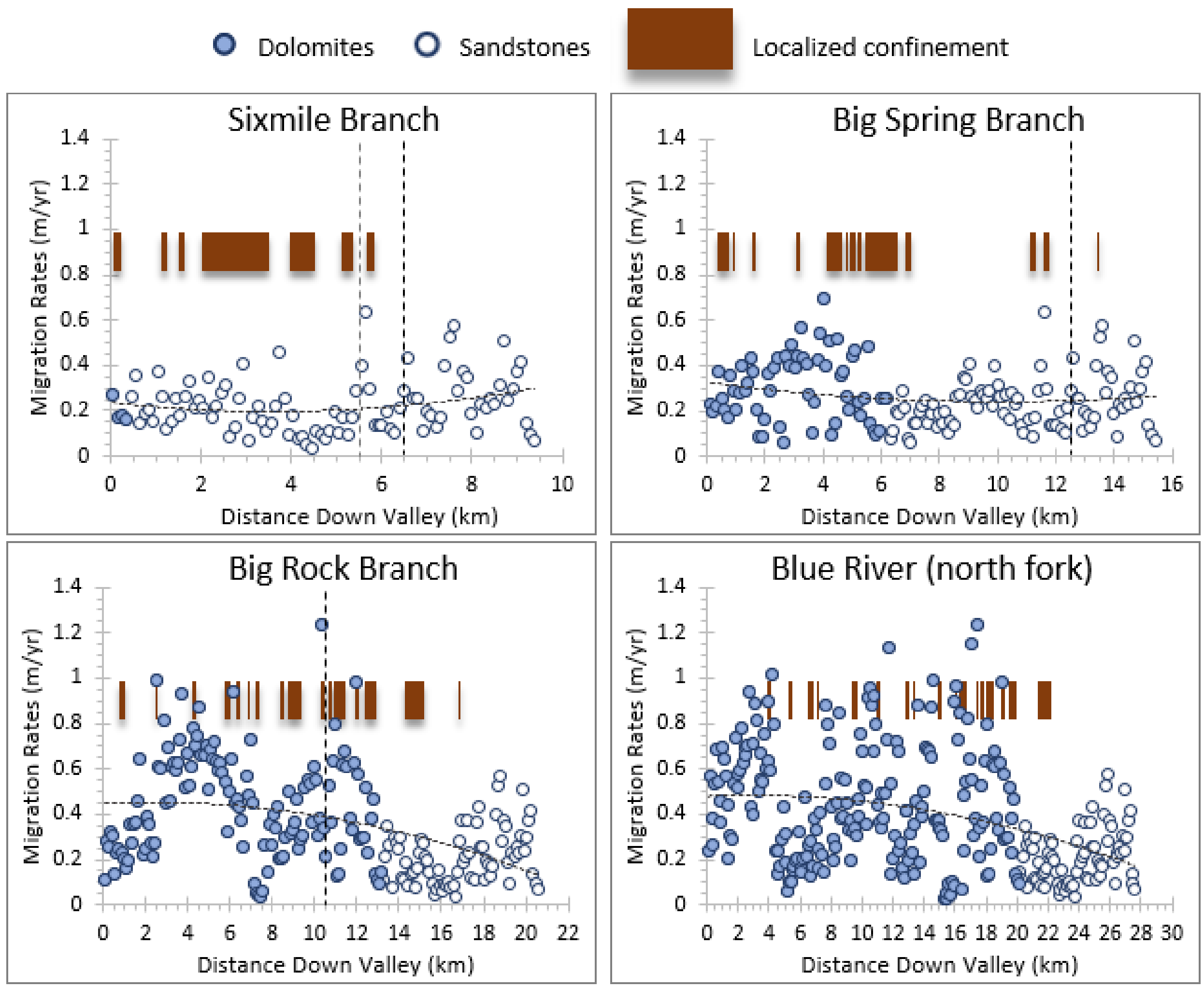

Figure 4.15. Downstream trends of lateral migration rates for the 1940-2010 time period. Sections underlain with dolomites are filled in circles and sections underlain with sandstones are hollow. Sections of localized confinement are shown with brown bars. The grey vertical line designates the confluence with Big Spring Branch, and the black vertical line confluences with Blue River.

The majority of Sixmile Branch is underlain with Cambrian sandstones, but about 31% of the reach is locally confined in relatively continuous sections (e.g., 2 km to 3.5 km down valley) where migration rates are low and fairly constant downstream. Within Big Spring Branch, the lithology changes from resistant dolomites to friable sandstones at 6 km down valley. Migration rates decrease rapidly upstream from this lithological transition, where they then begin to slowly increase downstream. About 23% of the channel is locally confined and most of those sections are upstream of 7 km down valley. The rapidly decreasing migration rates occur between about 3 km and 7 km, coinciding with a reach dominated by localized channel confinement.

The lithology along Big Rock Branch changes at 13 km down valley, just after the mid-reach peak in migration rates. About 23% of this reach experiences localized confinement, however, the sections are not as continuous as they were within Sixmile Branch and Big Spring Branch. In Blue River (north fork), the lithology changes from dolomites to sandstones at 21 km down valley after the mid-reach peak in migration rates occurs. About 20% of the reach is locally confined and the sections were discontinuous, similar to the sections in Big Rock Branch. Big Rock Branch and Blue River (north fork) do not demonstrate any obvious connection between reaches where the channel is confined and migration rates are low.

It would be reasonable to assume that migration rates should increase within this watershed where slopes are steep and valleys are narrow because these are places where stream power is generally high. The data presented thus far, however, show that the relationship between migration rates and stream power is weak in most cases. This may suggest that additional local factors such as land use and cover or localized confinement can also influence downstream variations in migration rates. As illustrated in Figure 4.15, localized confinement against valley walls could limit lateral movement because the flow cannot erode into the valley wall, and lateral movement in the other direction may be limited by channel banks composed of coarser gravels deposited by lateral accretion.

Another potential factor that may increase bank stability is farmers who prevent channel movement across their fields by methods not detectable in aerial imagery. It is likely a combination of these factors explain some of the low migration rates along Sixmile Branch. For example, it is clear from the imagery that a section along Sixmile Branch was artificially straightened from 1940-1968, and therefore, this “movement” was removed from the dataset (Figure 4.16). This portion of channel has remained fairly stable in the latter two time periods because it was confined against the southern valley wall and potentially prevented from moving across the fields to the north by farmers.

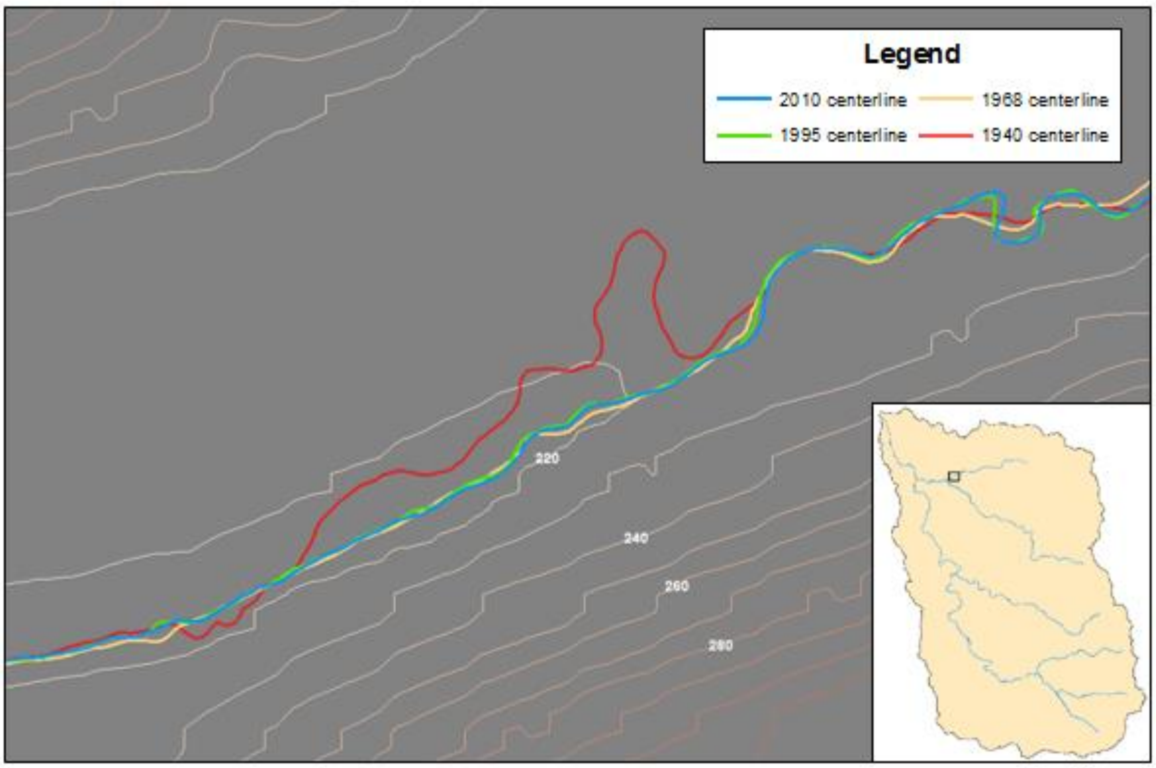

Figure 4.16. Example of a section along Sixmile Branch (4-4.5 km down valley) that was partially channelized by farmers between 1940 and 1968 and has remained fairly stable.

Another example of the lack of an association between stream power and migration rates is observed where migration rates are low in the smallest, headwater locations (i.e., first to third order streams; down valley distances < 1 km) along Sixmile Branch, Big Spring Branch, and Big Rock Branch (Figure 4.11). These locations are, paradoxically, associated with relatively steep channel slopes, and thus, high stream power. However, these locations are also characterized by narrow valleys, thin accumulations of floodplain alluvium, coarse channel materials. As such, there are limited opportunities for significant lateral channel migration even though stream power is high. Changes in lithology, valley width, and stream power were best linked with downstream variations in migration rates for Blue River (north fork) and Big Rock Branch. Although stream power did not act as a strong explanatory variable (Figure 4.10, Table 4.5), the downstream trends showed similar mid-reach peaks to those observed in migration rates.

Limitations

The discussion above highlights some of the potential limitations of this study mainly resulting from spatial and temporal data resolution and the difficulty of identifying anomalies (i.e., avulsions, cutoffs, and artificial straightening). The aerial imagery from 1940, 1968, and 1995 were in black and white, had lower resolution compared to 2010, occasional noise within the photo, and sometimes visible edge distortion from the camera lens that could impair the accuracy of bank line delineation (Figure 4.17). These conflicts were minimized by enhancing the photos through the adjustment of brightness and contrast, double checking features through the use of overlapped images, and avoiding digitizing features that were located along the photograph's edge. Sections where the photo quality was an obvious interference were removed, however, this required some user bias and final decisions could vary based on the user's judgement. While this error was accounted for by adding 2 m of horizontal error (Micheli and Kirchner, 2002), it does bring into question the reliability of some migration measures.

There were also sections of channel where determining an avulsion or human modification from lateral migration was difficult as there was no sufficient evidence to confirm the dominating process. For example, a section along Blue River shown in Figure 4.18 flows through a farmed section of land. The movement from 1940-1968 was most likely either an avulsion or artificial straightening based on the visible floodplain deposits in 1940 and the channel's proximity to roads, houses, and fields. However, it is unclear whether the movement was influenced by humans from 1968 to 2010, or if it was naturally migrating, therefore, these movements were not removed. There are other sections in similar scenarios throughout the watershed (see Figure 4.12 and corresponding discussion), emphasizing the limitation of only conducting aerial analysis for identifying lateral channel migration.

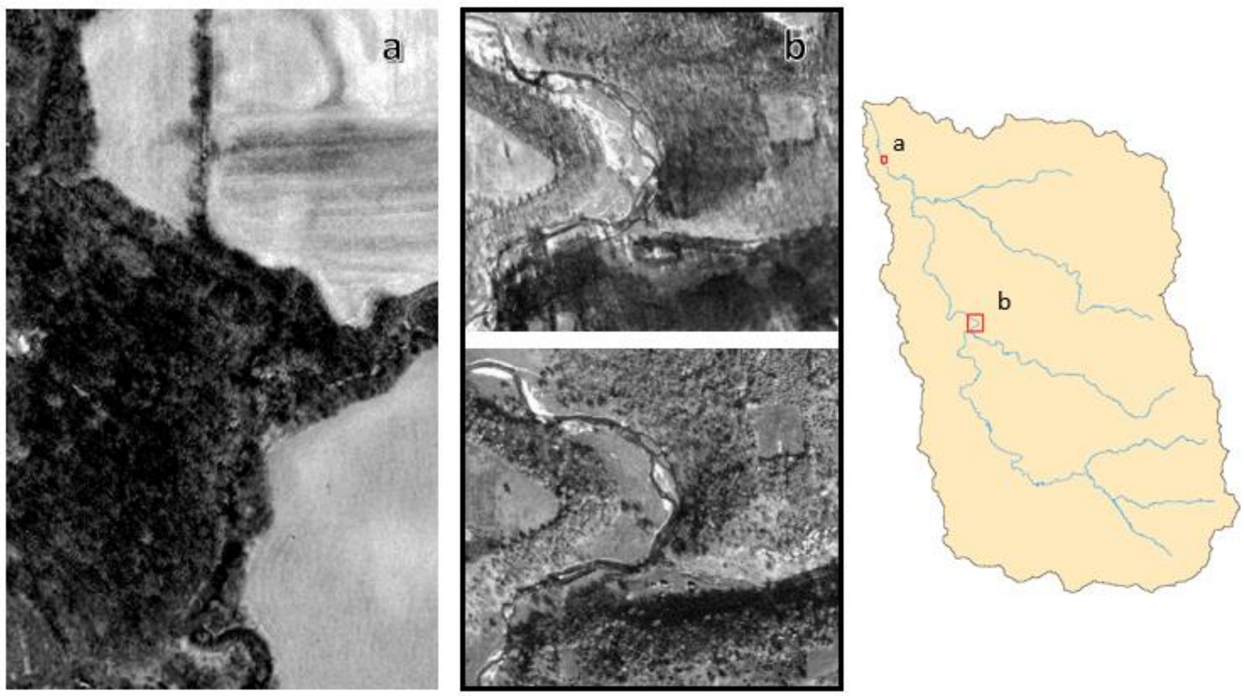

Figure 4.17. Example of limitations in image quality. Image "a" is from 1995 and shows low resolution and thick canopy cover that hinder stream bank delineation. Image "b" is two different photos from 1940 of the same location showing edge distortion in the top photo and a clear capture in the bottom photo.

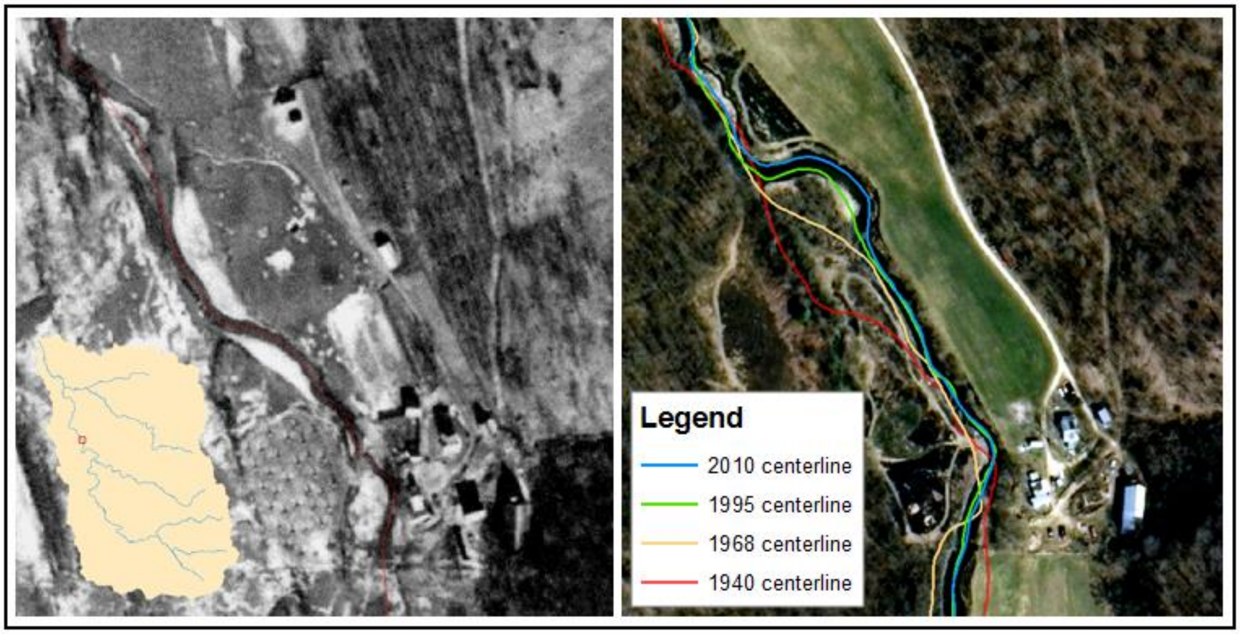

Figure 4.18. Example of limitation in accurately identifying anomalies within the dataset.

Despite these limitations, one of the objectives of this study was to determine how migration rates varied throughout time and the potential impacts land use may have had on the watershed. There were an adequate amount of channel sections where the bank lines could be clearly identified and lateral movement was apparent that make the average migration rates accurate representations of lateral channel migration within the watershed. Also, a major motivation driving this study was to determine assess the linkage between stream power and lateral migration that was caused by the process of bank erosion (i.e., not avulsions, cutoffs, or artificial manipulations). Therefore, a time-consuming and sometimes subjective effort was made to eliminate reaches that were affected by processes that influence channel relocation unrelated to gradual, progressive bank Therefore, this study allows a better understanding of the geomorphic processes driving lateral migration than if avulsions and other anomalies were included.

CHAPTER 5: CONCLUSION

The purpose of this study was to improve our understanding of spatial and temporal variations in lateral channel migration in the Blue River watershed, an agricultural watershed in southwestern Wisconsin. Using historical data from land surveys conducted in the 1830s and aerial imagery from the years 1940, 1968, 1995, and 2010, migration rates were determined using GIS throughout the watershed. The measured migration rates were used to (1) determine variations through time and compare variations to changes in land use practices, (2) determine spatial variability throughout the watershed, and (3) determine if stream power or geomorphic variables explain the spatial patterns of channel migration.

Although it was expected that lateral migration rates would generally be lower during the more recent 1940-2010 period (i.e., due to lower discharges associated with improved land management practices), the results showed that migration rates were lower during the earlier 1830-1940 period throughout the entire watershed and within each reach. This increase may be explained by a lack of data during the 110 year long 1830-1940 period, and by the high temporal variability in channel migration during this early period as suggested by previous studies in the surrounding region (Knox and Hudson, 1995). In other words, it may be that most of the lateral channel migration took place during a relatively short time span within this long 110 year period. For example, it is possible that migration rates were very low until 1900, and then were very high between 1900 and 1940. However, because of the lack of additional snapshots of channel location, averaging over this 110 year period would produce a low overall rate. In addition, if the Blue River migrated back and forth across its floodplain rather than in one direction, the lack of additional data on channel position may cause these reversals to be missed, resulting in the underestimation of total channel movement. During the shorter post-1940 time periods, two of the reaches displayed a declining trend over time, one showed an increase over time, and one remained constant. The two reaches that displayed declining trends (Big Rock Branch and Blue River (north fork)) correlate to changes in land management practices which were established in the 1940s. The hydrologic impact of improved land management is supported by peak hydrographs from surrounding watersheds, which show higher peaks and higher variance in peak flows until the late 1950s when peak flows declined and were stabilized due to reduced runoff. However, the other two reaches (Sixmile Branch and Big Spring Branch) did not display declining trends in migration rates over time. There was little change in land use practices within the Sixmile Branch catchment, which along with other factors may explain the consistently low migration rates. The Big Spring Branch watershed experienced the largest change in land use practices from 1940 to 1968, indicating that localized factors may play a larger role in driving channel movement. This also indicates that a watershed scale assessment of channel stability is not completely effective in addressing management strategies because of spatial and temporal variability within the watershed.

Spatial patterns of migration rates from 1940-2010 varied within each reach. Rates along Sixmile Branch were constant downstream, while in Big Spring Branch they peaked in upstream reaches. The Big Rock Branch and the Blue River (north fork) showed a mid-reach peak in migration rates. These trends were similar during the shorter time periods of 1940-1968 and 1968-1995, but then diminished during the 1995-2010 period which is likely due to stability in land use practices and the lack of extreme flows (as indicated by hydrographs from nearby watersheds). Although the spatial patterns vary in individual reaches, the factors driving the variations are fairly consistent.

Overall, stream power was a weak explanatory variable for migration rates, however, downstream trends in stream power displayed some similarities to downstream trends in migration rates in three of the reaches. Big Spring Branch displayed higher mean stream power values in upstream reaches where migration rates were high. Within Big Rock Branch and Blue River (north fork), high values for mean stream power in upstream and mid-basin reaches tended to correlate with reaches that displayed the highest migration rates. A similar pattern was observed with cross-sectional stream power. This provides some support for previous research by Lawler (1993) indicating that the highest rates of bank erosion occur in mid-basin reaches where stream power was maximized. Downstream changes in stream power are related to lithology, longitudinal gradient, and valley width (Lecce, 1997a). Resistant lithologies tend to be associated with narrow valleys and steep slopes. Therefore, general approximations of the relative magnitude of lateral channel migration may be obtained using slope as a surrogate for stream power. The overall weak association between stream power and migration rates was linked to additional local factors such as undetected human interference, methodological issues with the imagery, and the confinement of channels against valley walls where lateral movement in the other direction may be limited by channel banks composed of coarser gravels deposited by lateral accretion.

As many studies on bank erosion have been conducted at the smaller scale of individual sites or small reaches over short time periods, this study provides evidence for the importance of studies at the watershed scale to better understanding of the variability of spatial trends of geomorphic processes. Understanding spatial trends at the watershed scale could provide a more organized approach to watershed management and therefore more time-efficient planning when developing site-specific studies. For example, watershed-scale studies of sites associated with high migration rates could identify reaches worthy of more intensive investigation of the release of nutrients or heavy metal contaminants through bank retreat. Knowledge about the influence of lithology, channel confinement, and stream power and how these factors are related can improve the site selection process making environmental management more efficient. Lateral migration rates from this study and additional field data could also be used in future studies to estimate downstream suspended sediment loads from bank retreat and the release of nutrients and heavy metal contaminants within the Blue River watershed.

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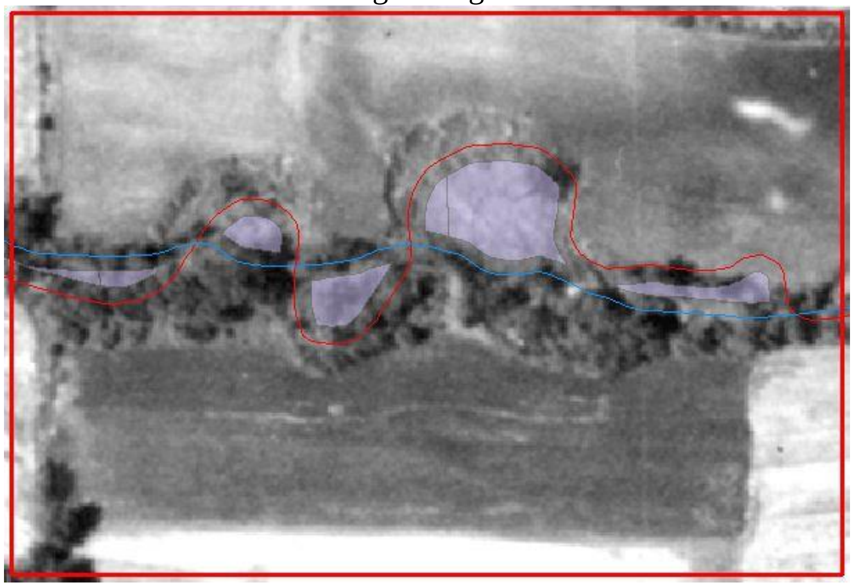
APPENDIX A: REMOVED ANOMALIES

1940-1968

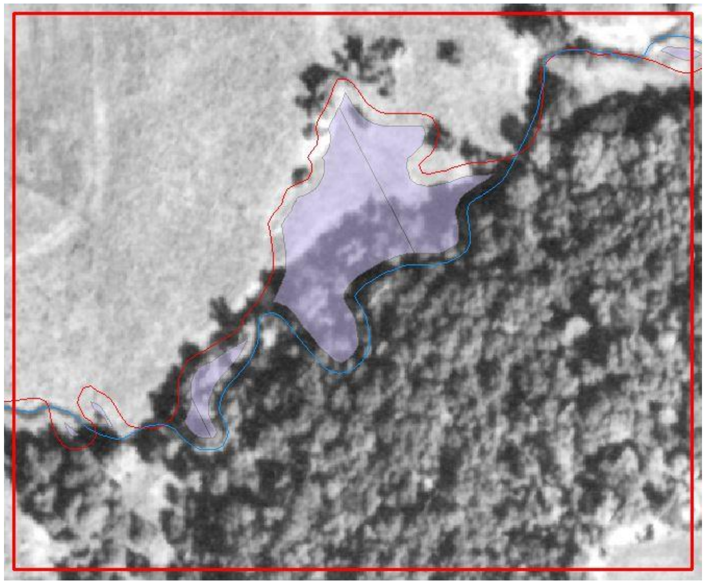
Listed by reach then distance downstream with type of anomaly noted

- Sixmile Branch

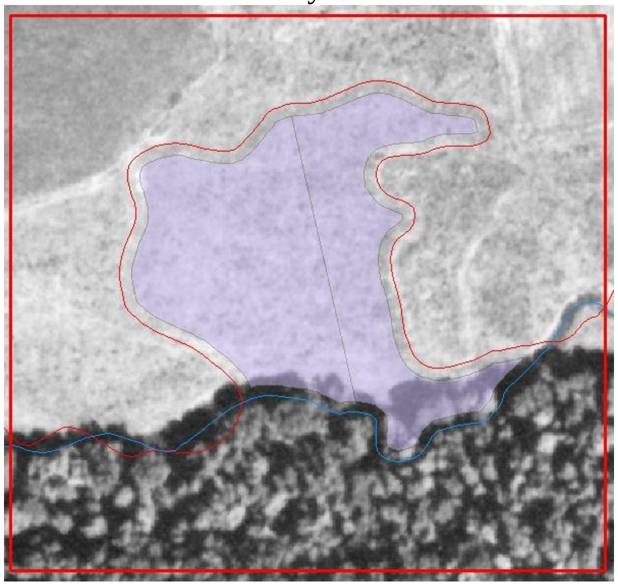
0.85-0.95 km: Artificial straightening



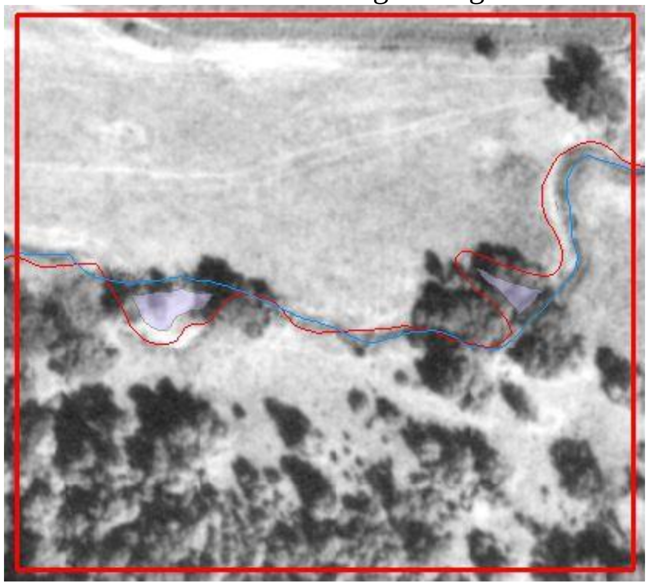
2.67-2.75 km: Moved by humans and canopy cover interference



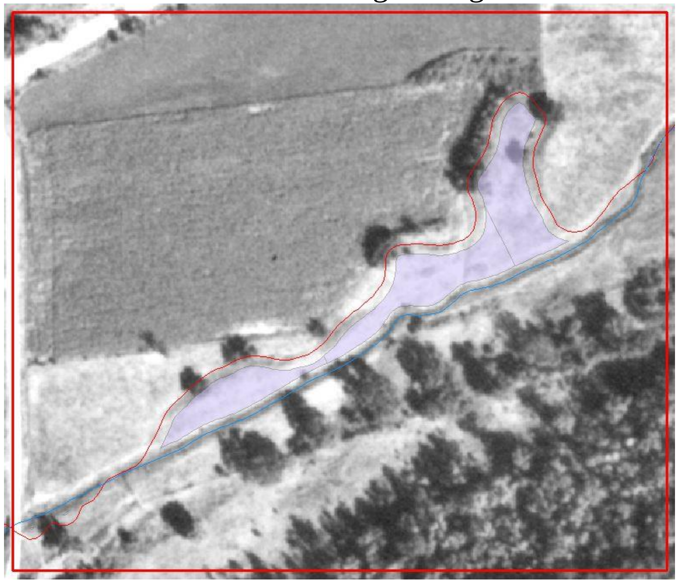
3.05-3.15 km: Moved by humans



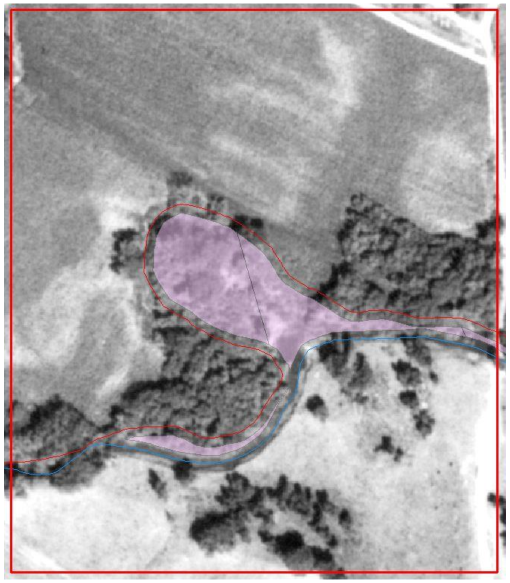
5.25-5.35 km: Artificial straightening or avulsion



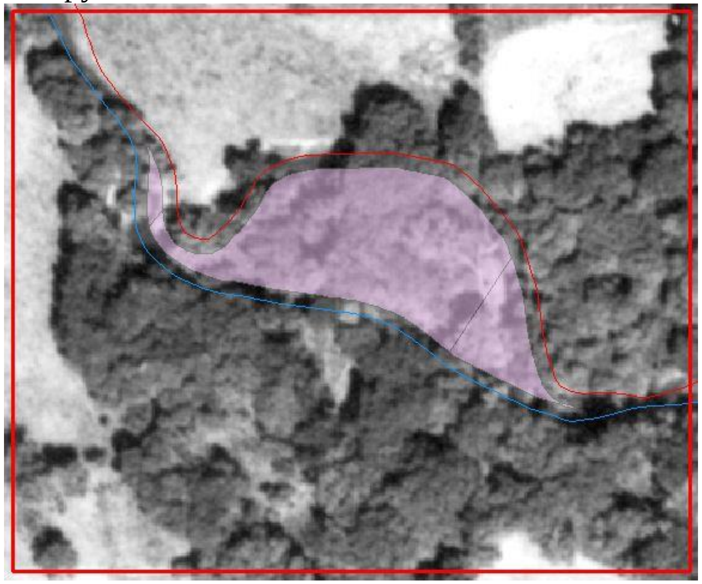
4.25-4.55 km: Artificial straightening



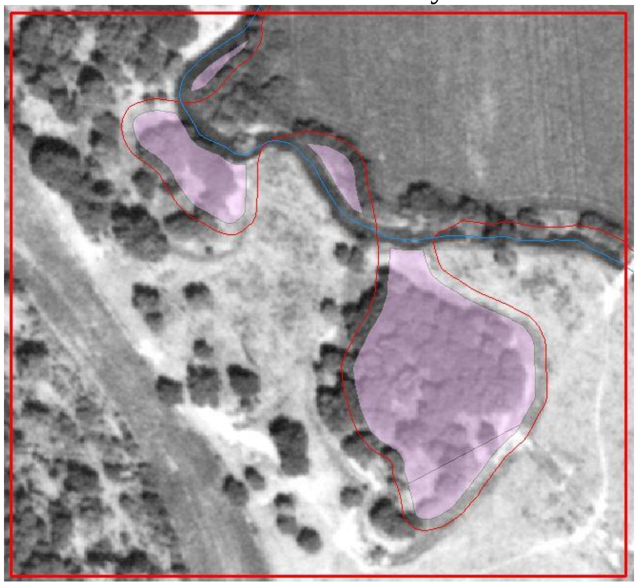
775-7.95 km: Cutoff



8.05 km: Combination of moved by humans and canopy cover interference

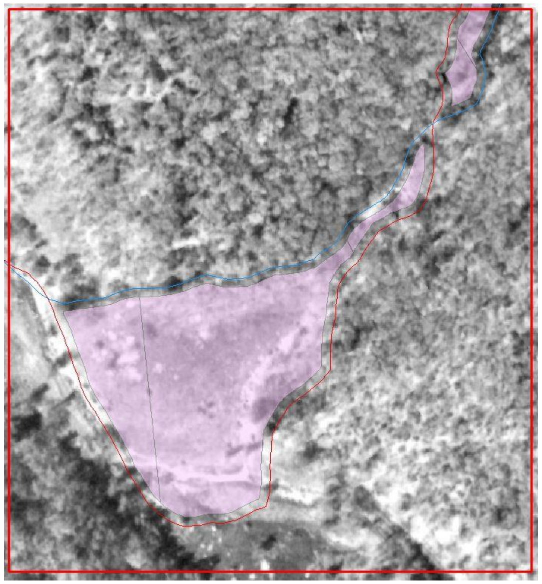


- 8.35-8.55 km: Cutoff or moved by humans

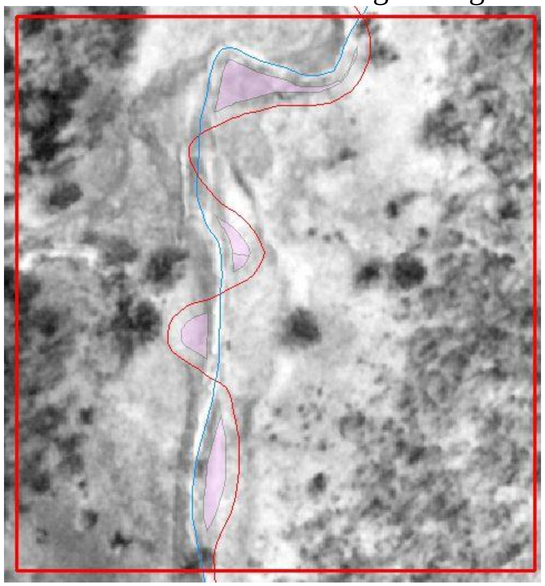


- Big Spring Branch

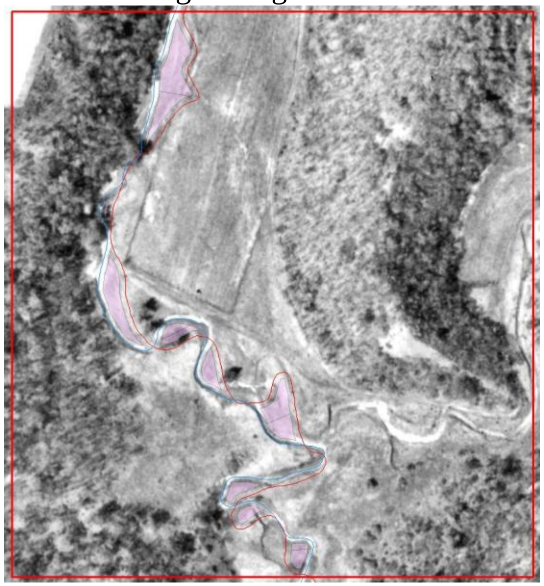
  2.85-3.05 km: Either moved by humans or avulsion



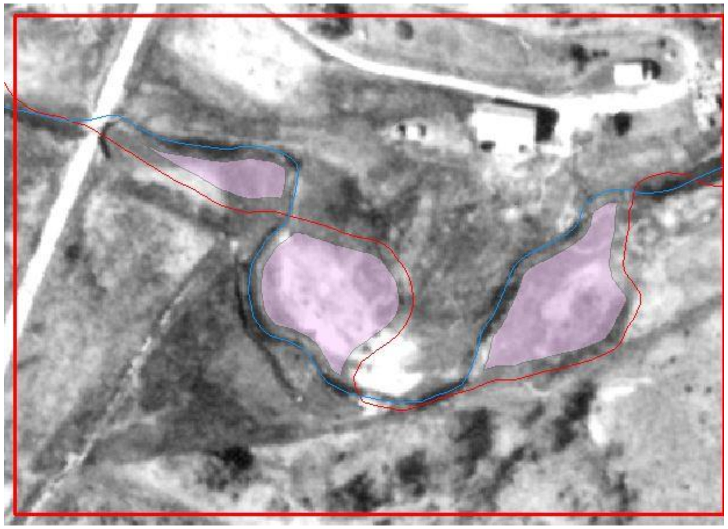
3.75-3.85 km: Artificial straightening



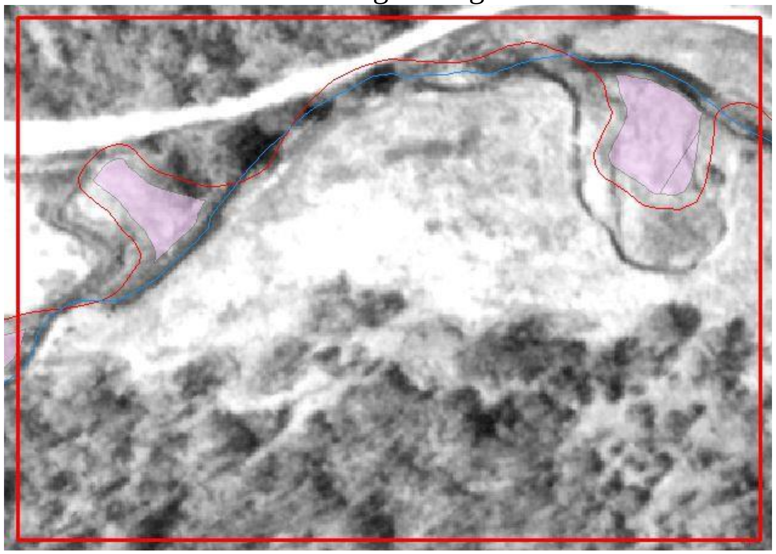
4.15-4.25 km and 4.45-4.55 km: Portions are artificial straightening



4.95-5.05 km: Avulsion

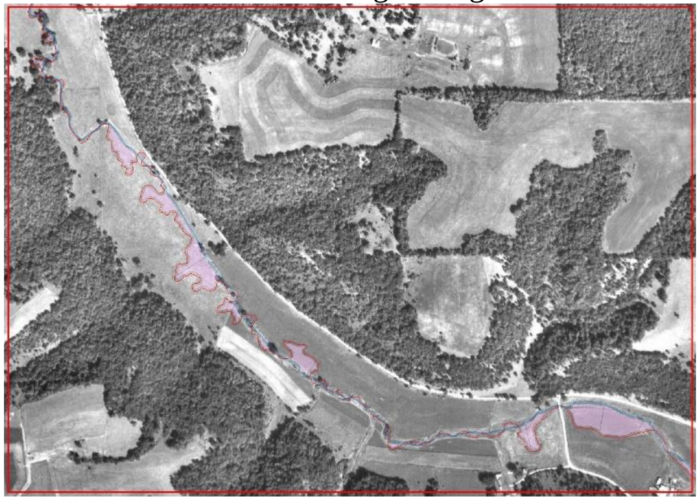


5.35-5.55 km: Artificial straightening

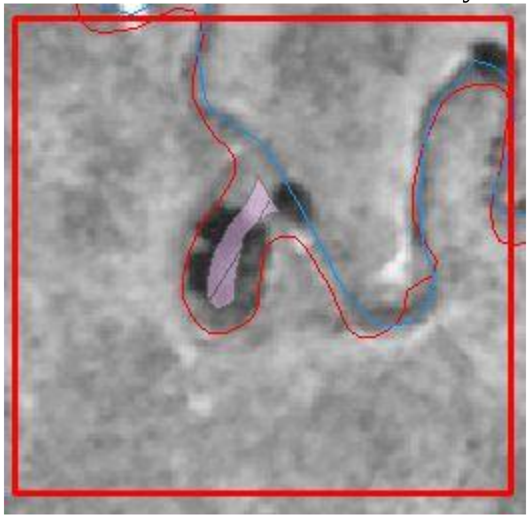


5.95-6.75 km: Artificial straightening

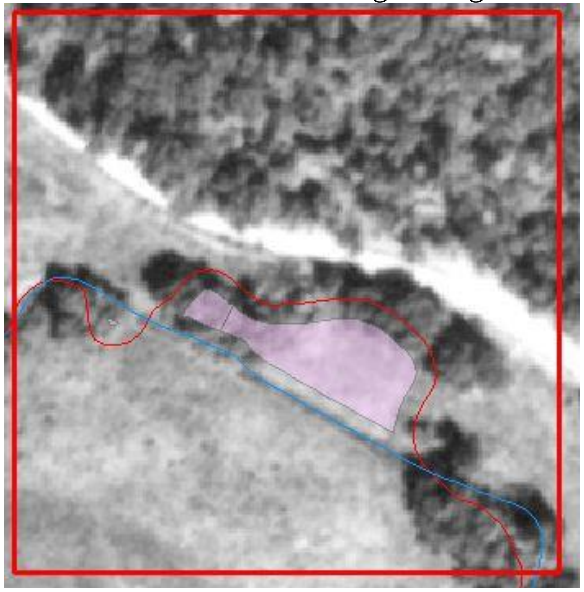
6.95-8.95 km: Artificial straightening



10.45-10.55 km: Cutoff or moved by humans

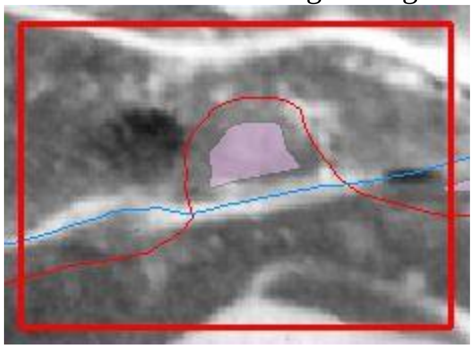


9.35-9.45 km: Artificial straightening

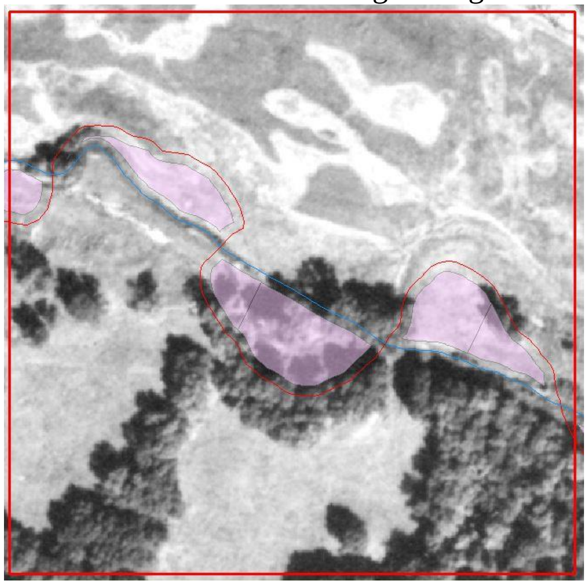


- Big Rock Branch

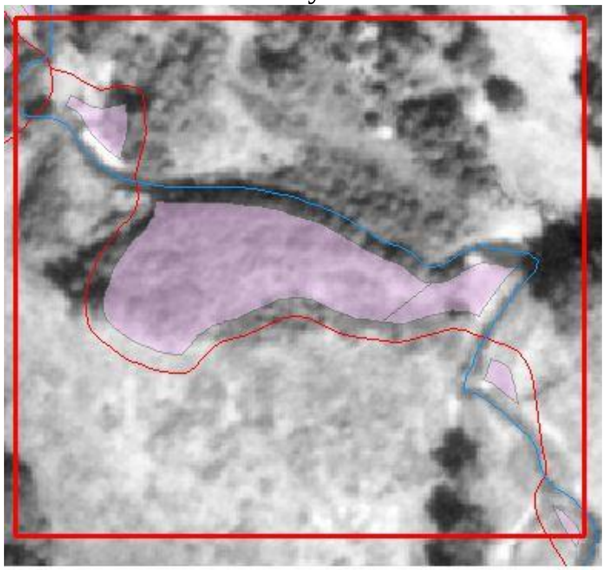
1.85 km: Artificial straightening



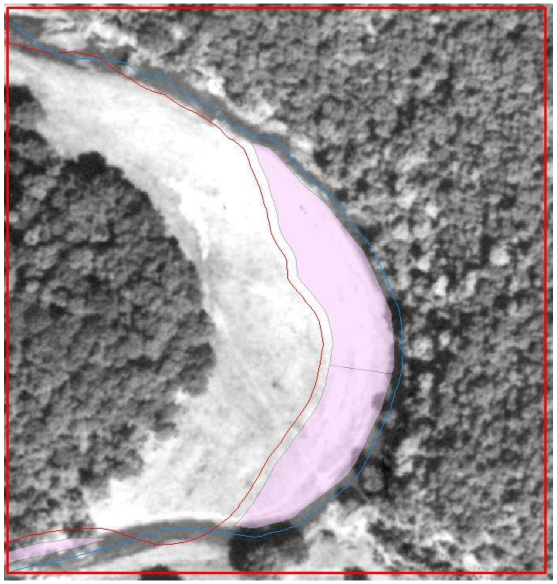
9.35-9.55 km: Artificial straightening



9.85-9.95 km: Moved by humans

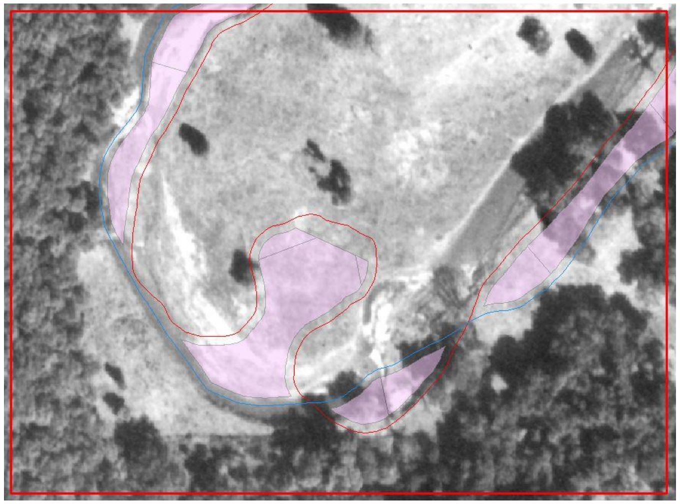


10.35-10.45 km: Avulsion

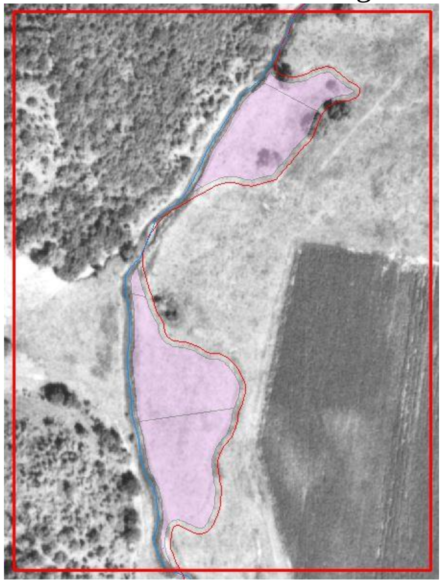


12.25-12.45 km: Avulsion

11.75-11.85 km: Cutoff and avulsion



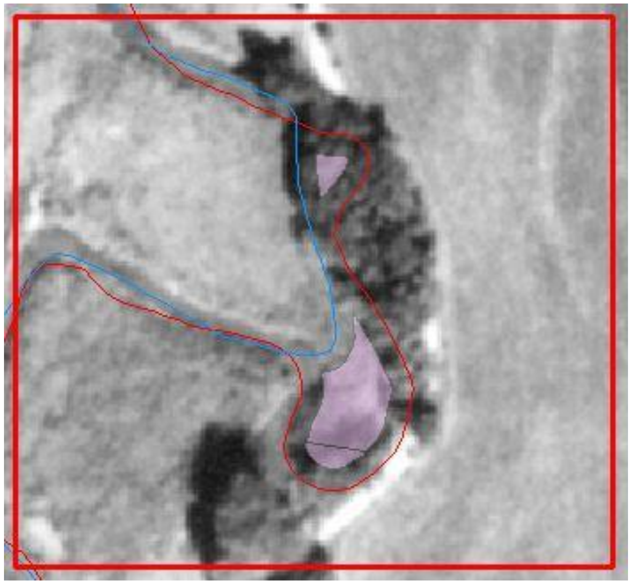
14.15-14.55: Artificial straightening



15.45-15.95: Artificial straightening

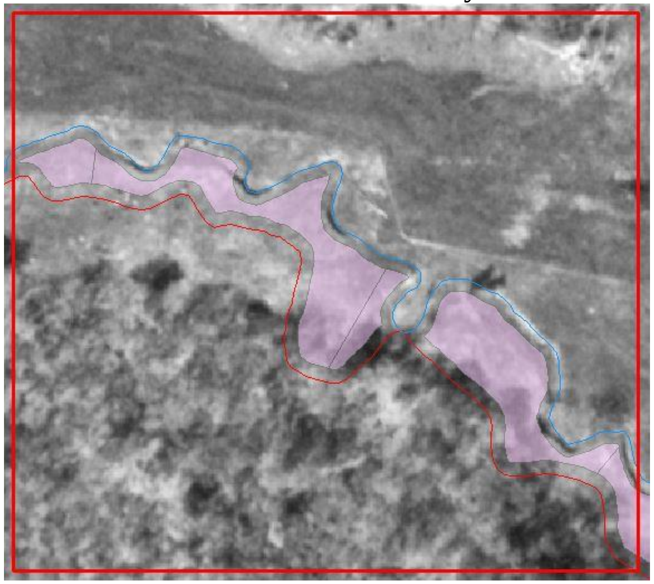
16.05-16.85 km: Artificial straightening and portions of canopy cover interference

17.25-17.35 km: Cutoff

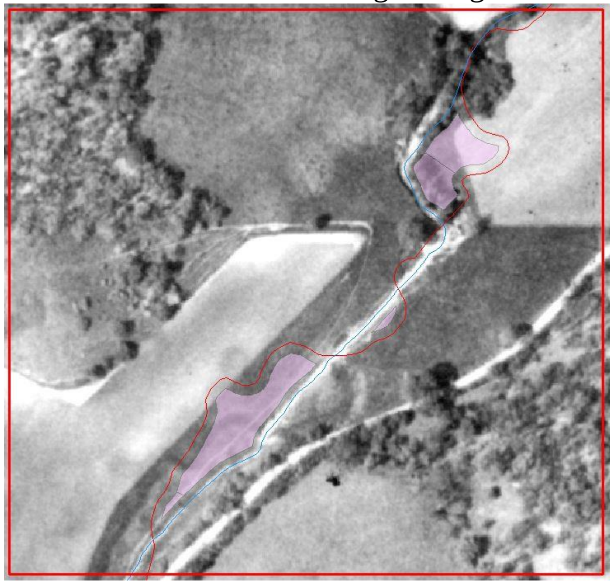


- Blue River (north fork)

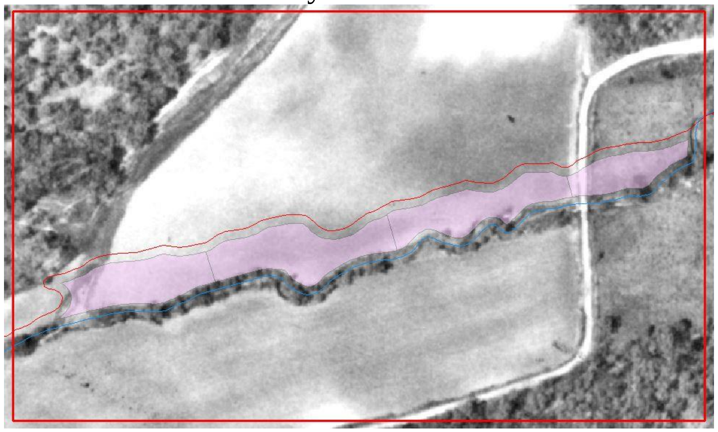
2.35-2.45 km: Avulsion or moved by humans



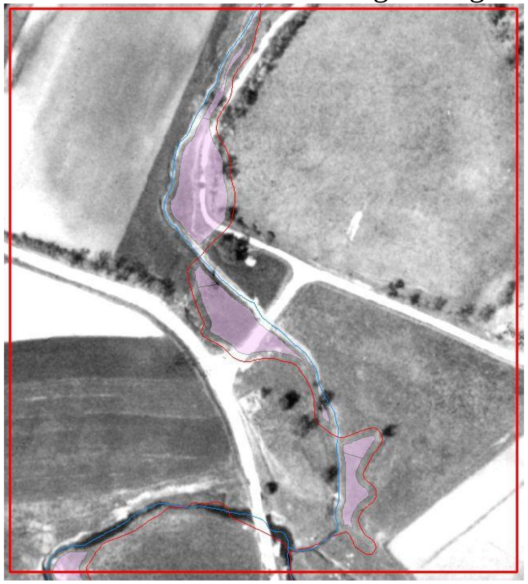
5.05-5.15 km: Artificial straightening



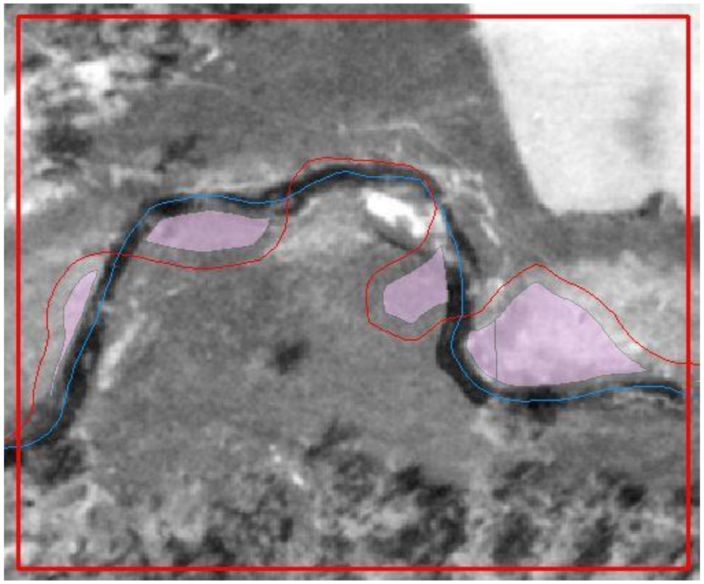
4.35-4.65 km: Moved by humans



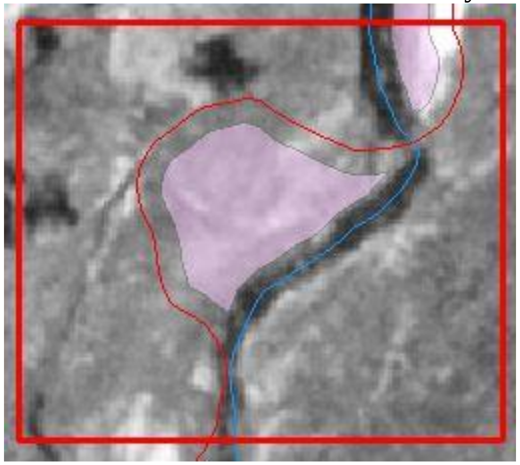
5.35-5.65 km: Artificial straightening



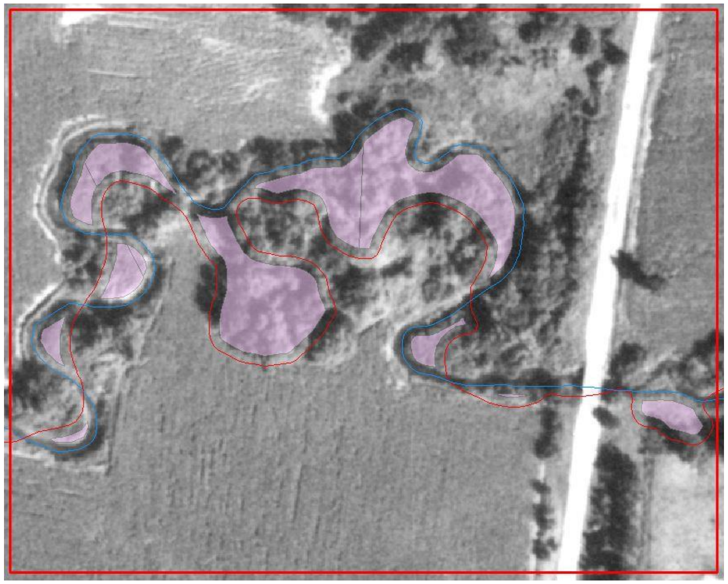
6.85 km: Avulsions



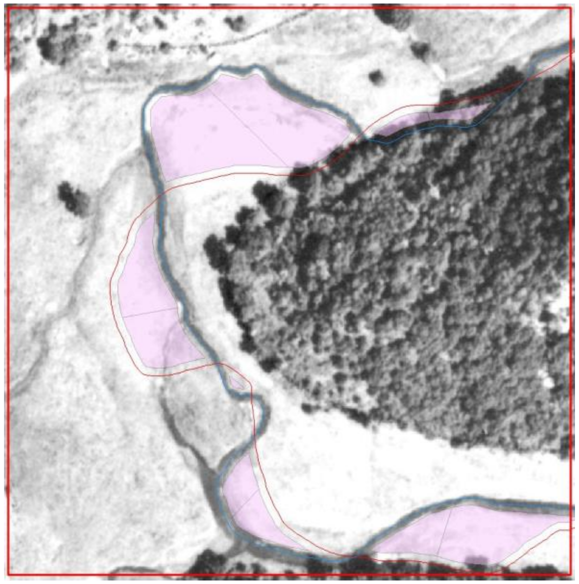
6.25-6.35 km: Avulsion or moved by humans



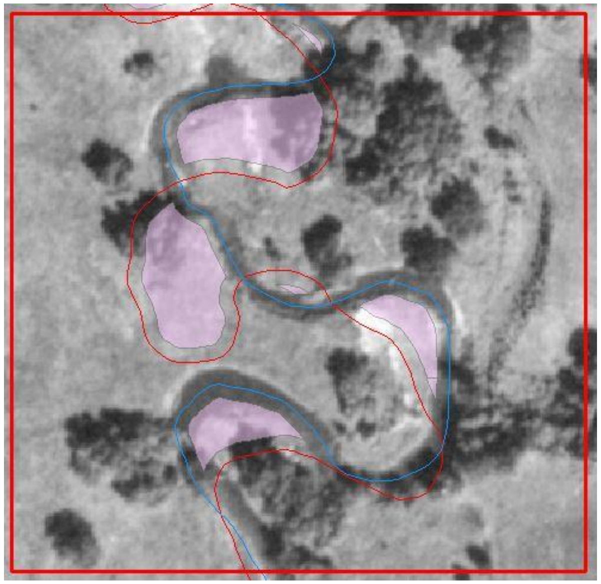
7.45-7.65 km: Portions of avulsions and canopy cover interference



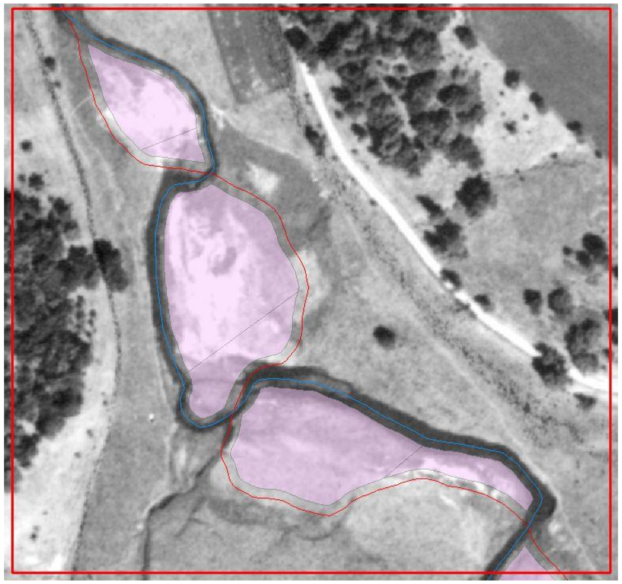
9.15-9.25 km: Avulsion



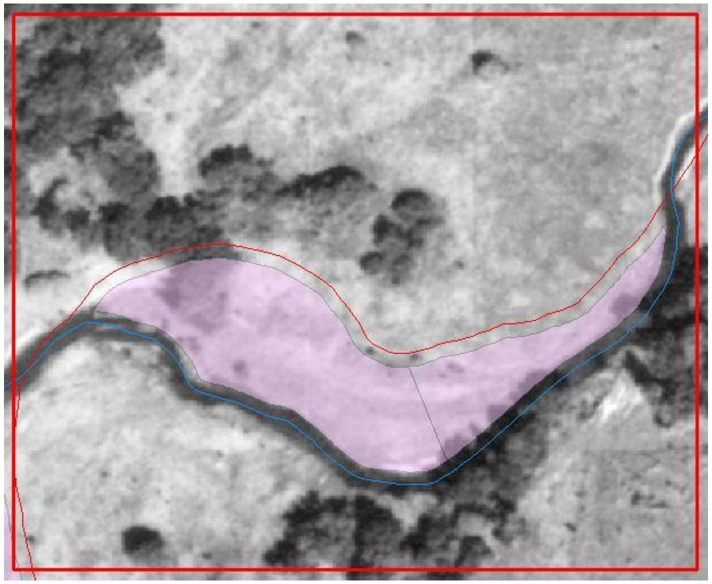
11.45-11.55 km: Avulsion



12.25-12.75 km: Avulsion

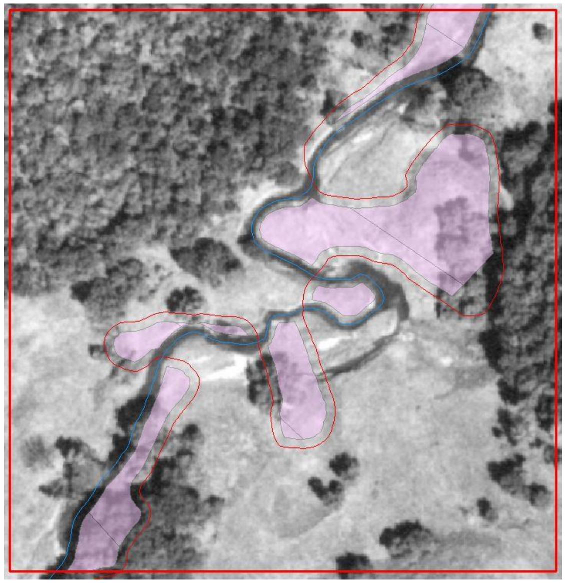


13.65-13.85 km: Avulsion

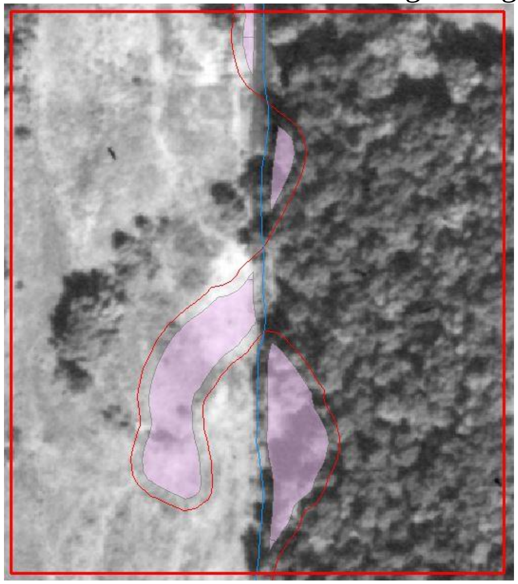


13.15 km: Artificial straightening

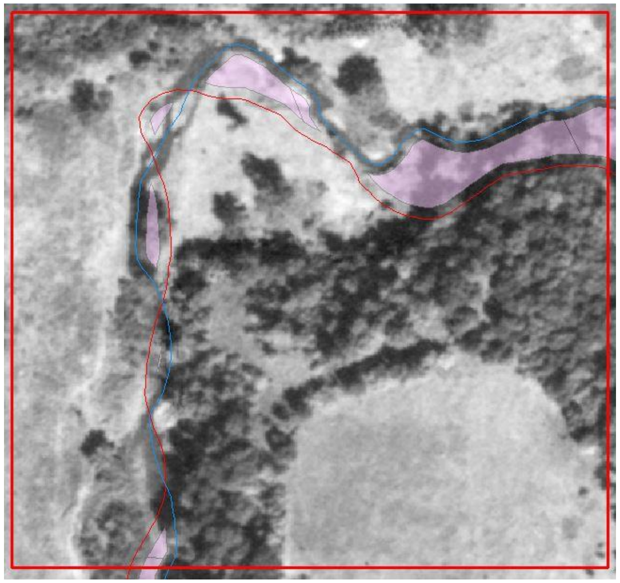
14.25-14.45 km: Avulsions and cutoffs



16.35-16.45 km: Artificial straightening



16.75 km: Avulsion

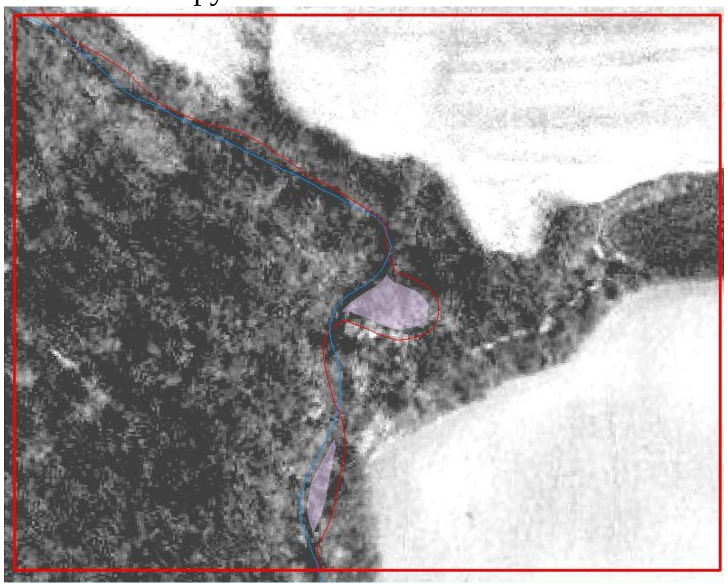


1968-1995

Listed by reach then distance downstream with type of anomaly noted

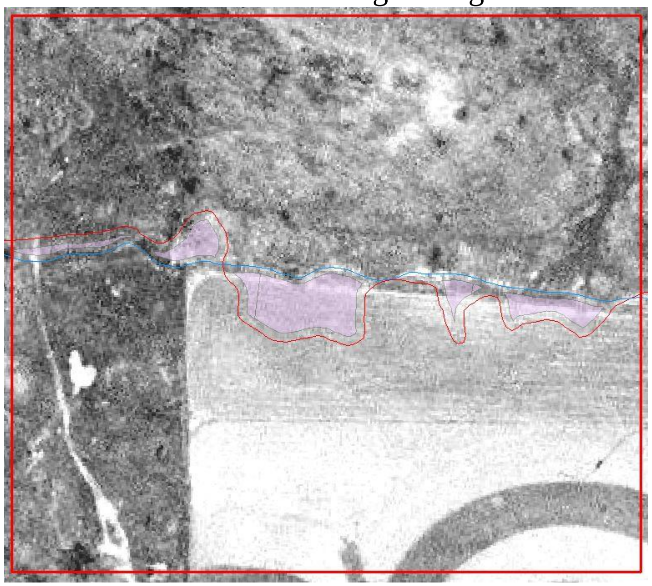
- Sixmile Branch

8.85 km: Canopy cover interference

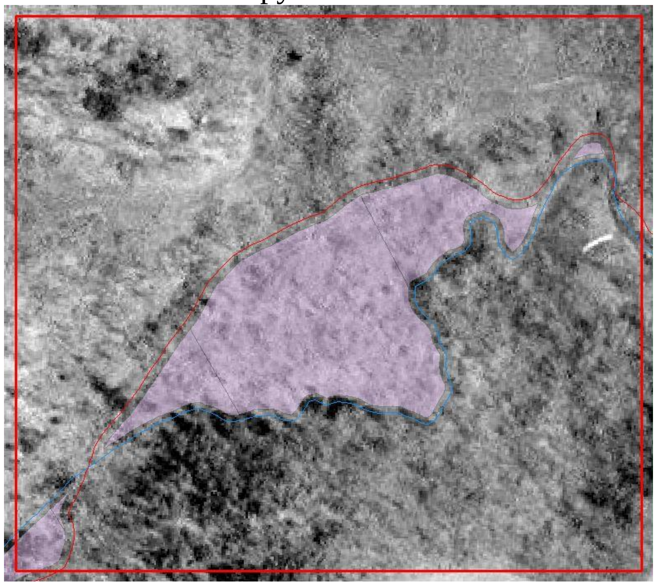


- Big Spring Branch

1.85-2.05 km: Artificial straightening

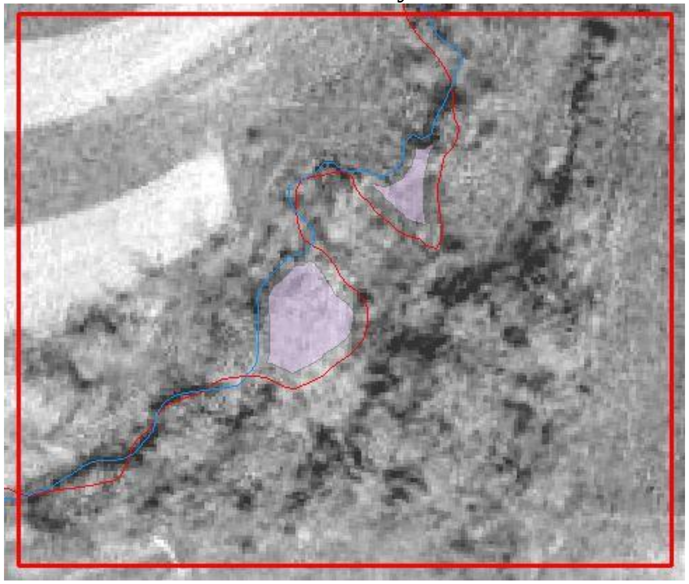


2.55-2.75 km: Canopy cover interference

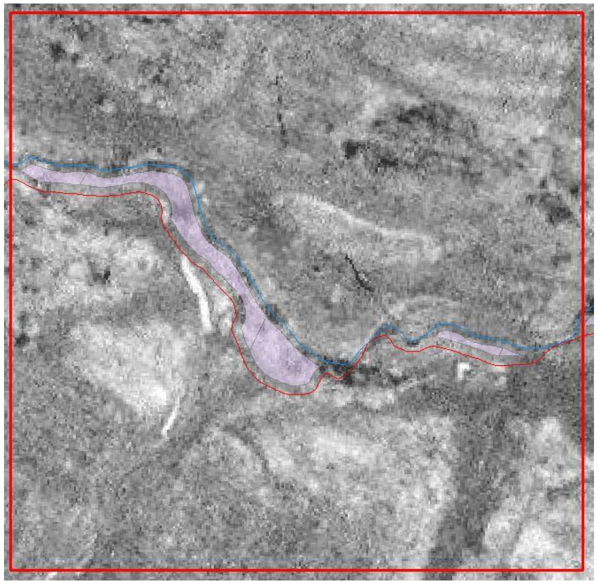


- Big Rock Branch

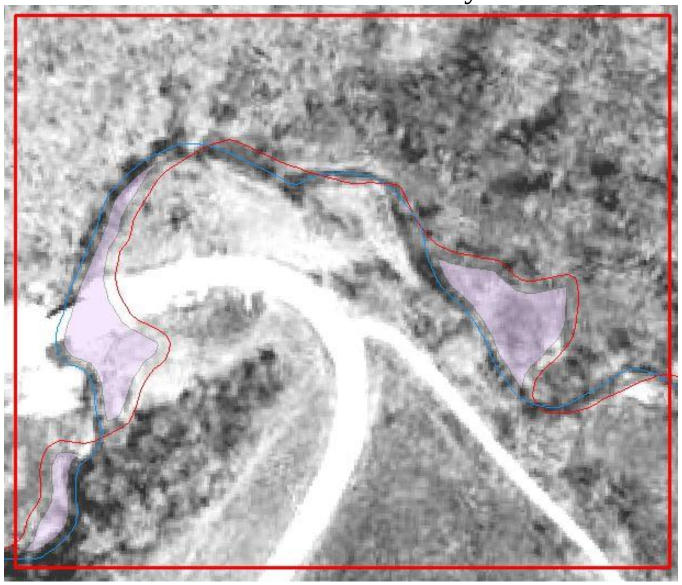
0.55 km: Avulsion or moved by humans



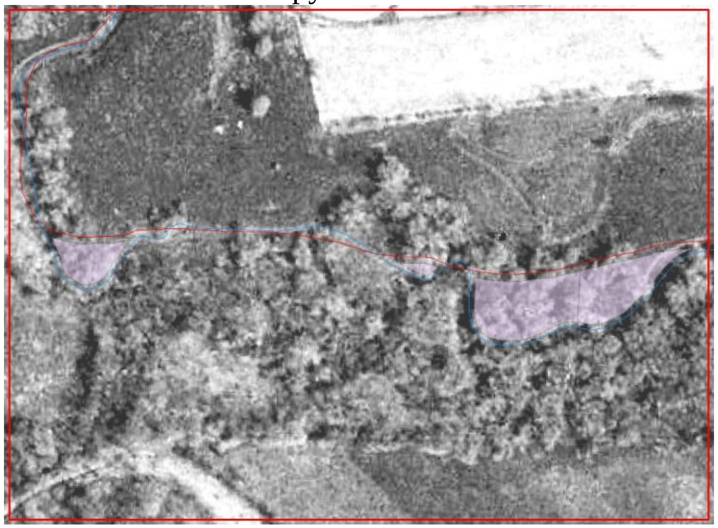
4.15-4.25 km: Avulsion



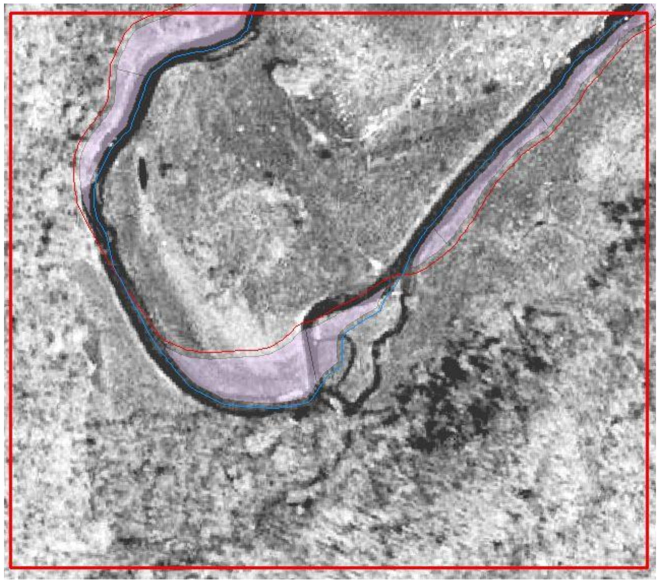
8.75-8.85 km: Avulsion or moved by humans



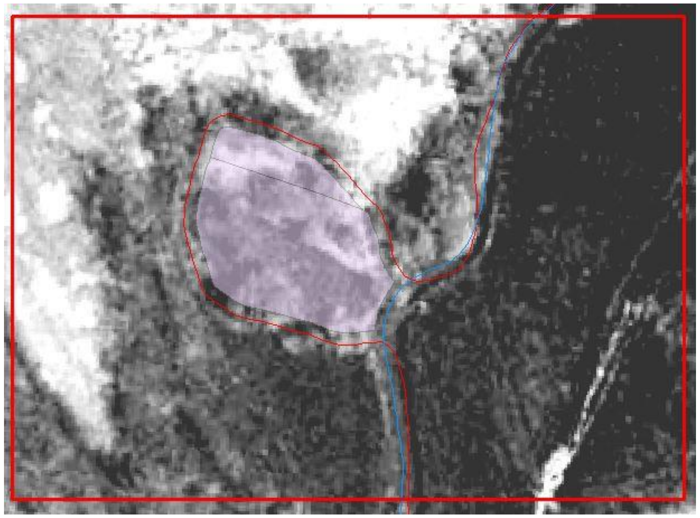
16.65-16.95 km: Canopy cover interference



11.75: Avulsion

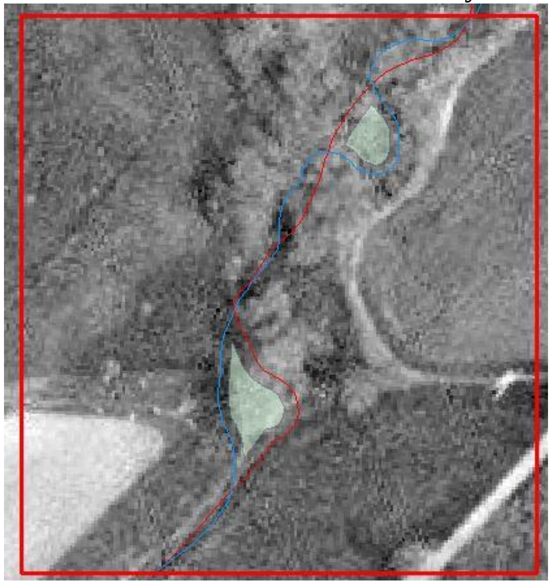


17.45 km: Cutoff

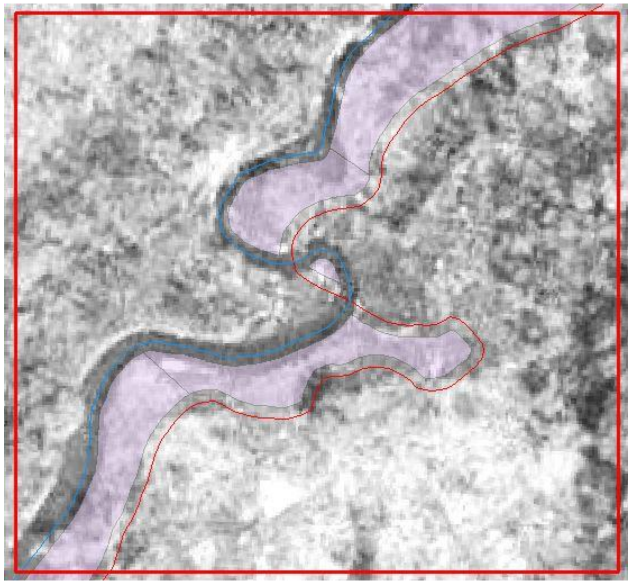


- Blue River (north fork)

5.05-5.15 km: Avulsion or moved by humans



14.25 km: Avulsion

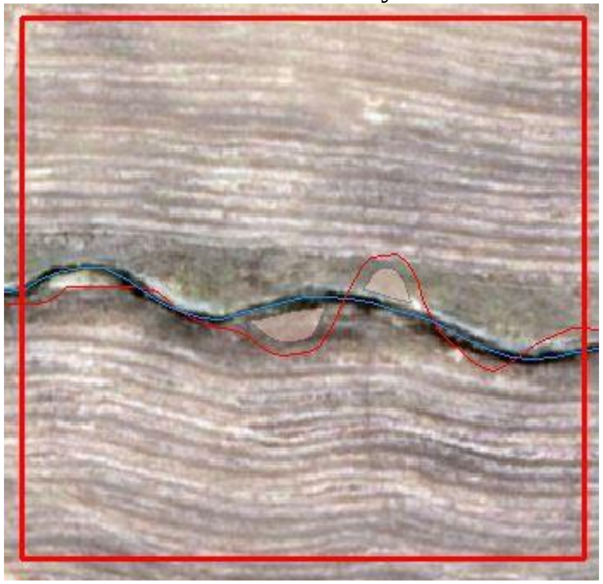


<u>1995-2010</u>

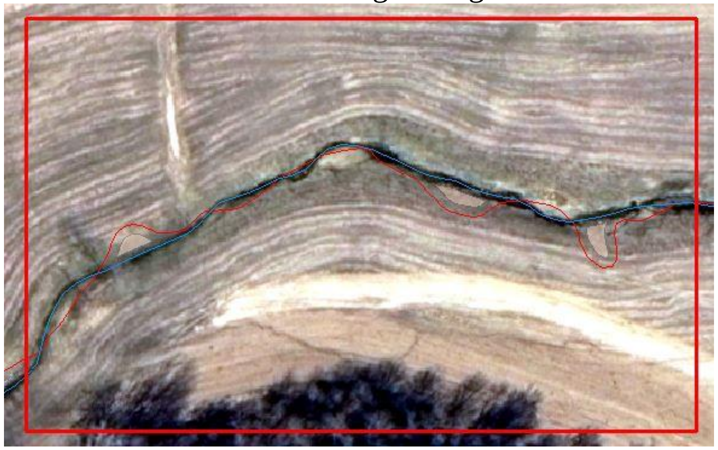
Listed by reach then distance downstream with type of anomaly noted

- Sixmile Branch

0.85 km: Avulsion of move by humans



1.05-1.15 km: Artificial straightening



2.85-3.05 km: Avulsion

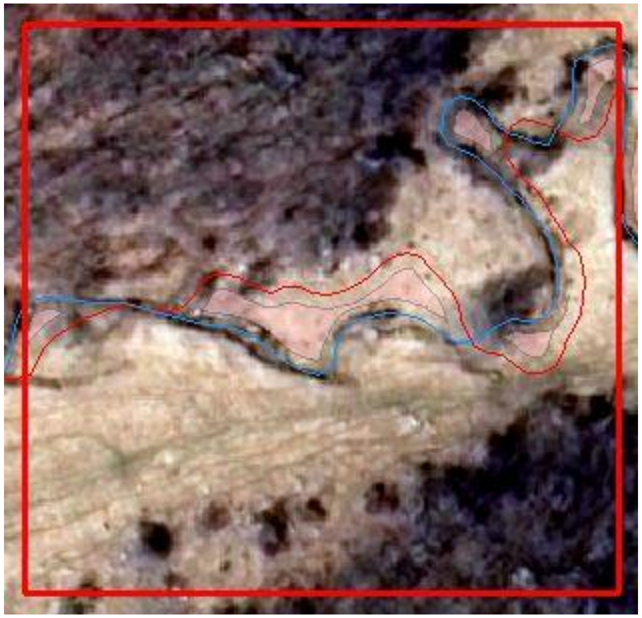
5.65 km: Avulsion

- Big Spring Branch

0.35 km: Avulsion

0.65 km: Avulsion

1.35 km: Avulsion

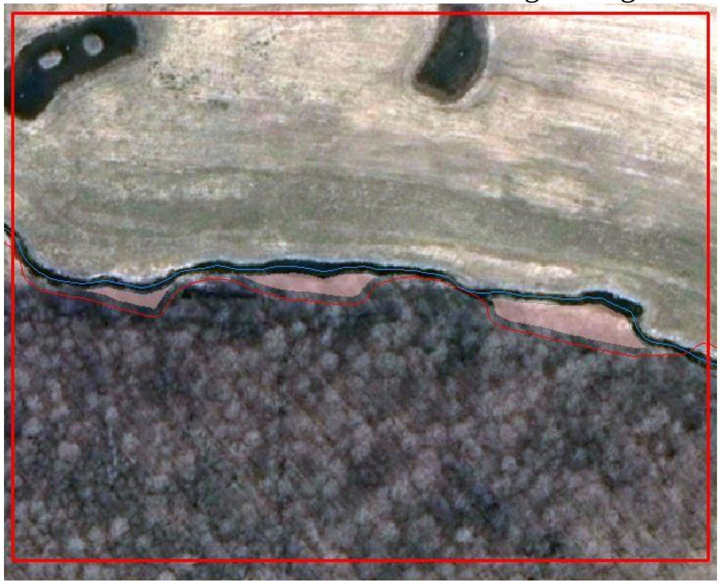


2.55-3.05 km: Canopy cover interference

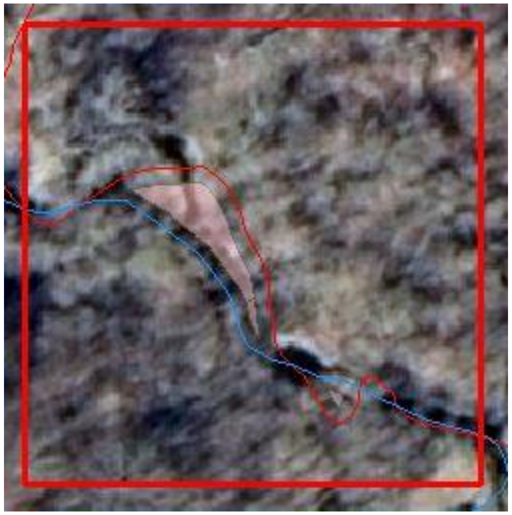
3.45 km: Avulsion

3.85 km: Avulsion

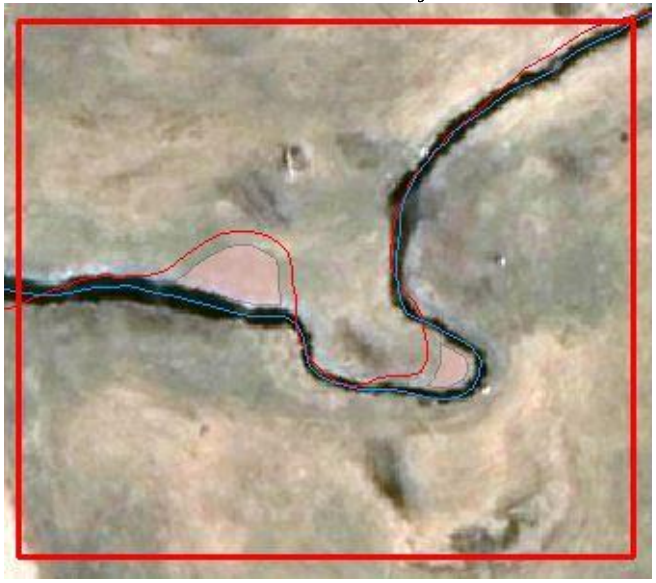
6.45-6.65 km: Avulsion or artificial straightening



4.25 km: Avulsion



7.35 km: Avulsion and moved by humans



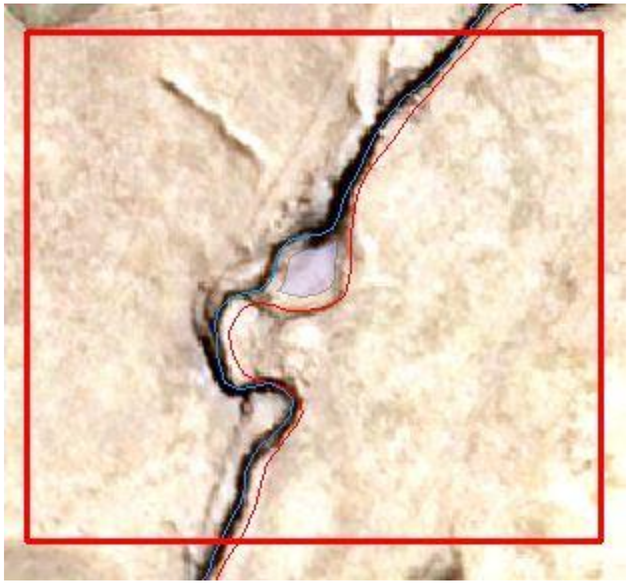
7.65-7.85 km: Avulsion

8.18-8.25 km: Artificial straightening

10.85 km: Avulsion

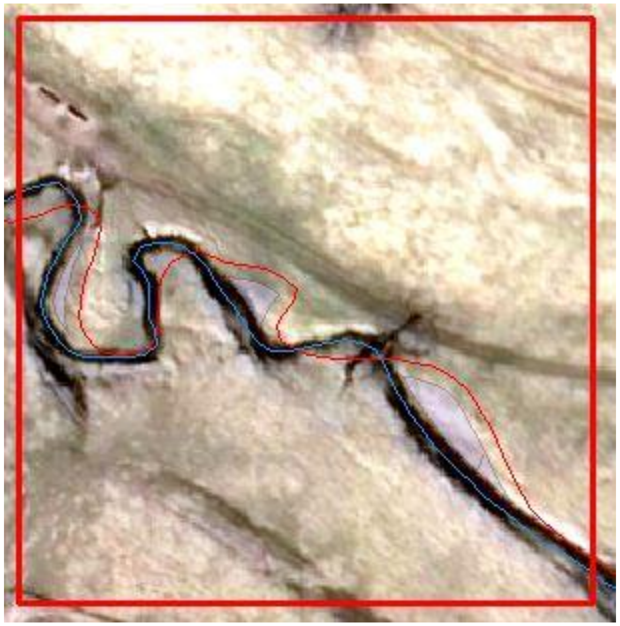
- Big Rock Branch

1.35 km: Avulsion



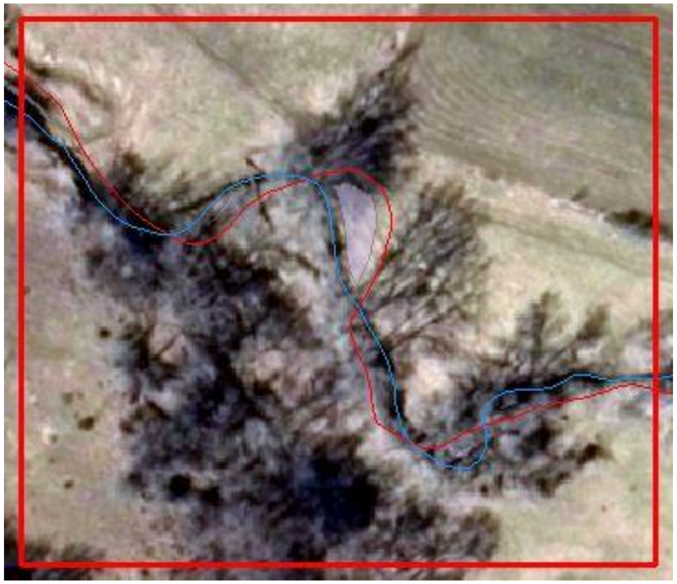
1.85 km: Artificial straitening

2.05 km: Avulsion



2.25-2.45 km: Avulsion or moved by humans, and canopy cover interference

3.35 km: Avulsion



4.75 km: Avulsion or canopy cover interference

3.65-3.75 km: Avulsion or canopy cover interference

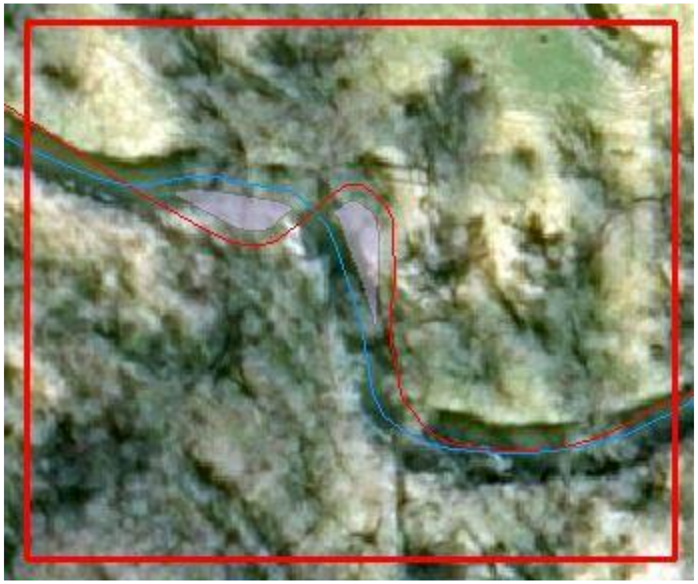
6.95 km: Avulsion

7.95 km: Avulsion

11.75 km: Avulsion

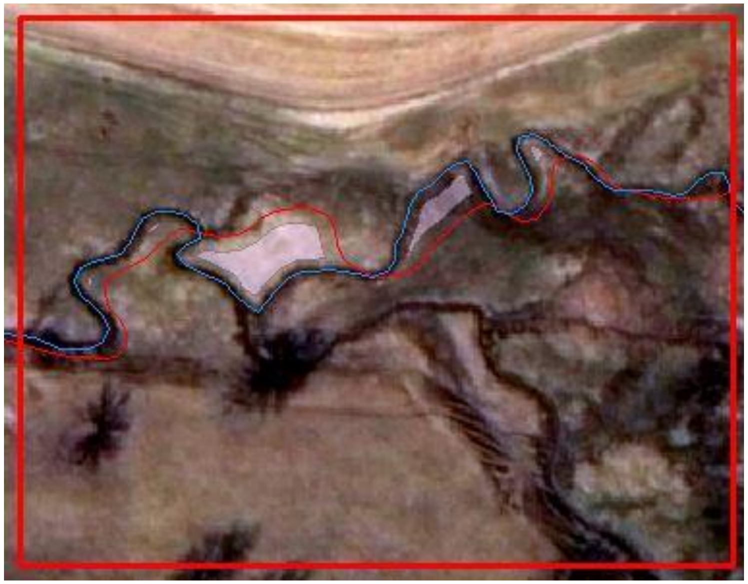
9.45 km: Avulsion or artificial straightening

16.75 km: Avulsion



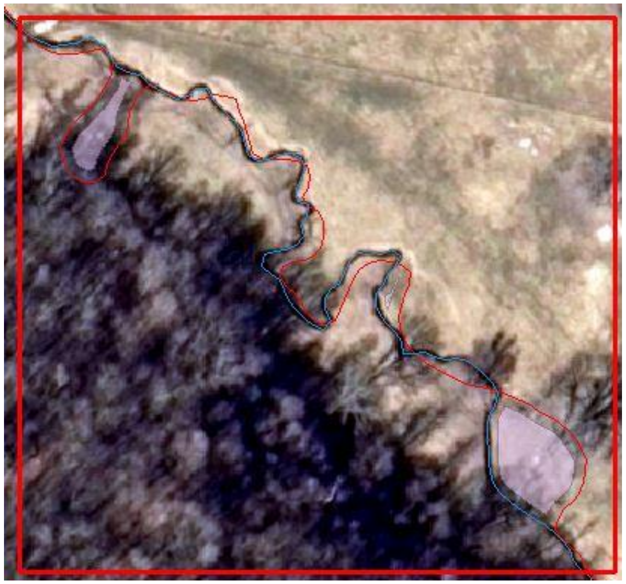
- Blue River (north fork)

0.15 km: Avulsion



1.65-2.05 km: Avulsion and canopy cover interference

2.25-2.35 km: Avulsion and cutoff



2.75 km: Avulsion

3.05-3.15 km: Avulsion

5.15 km: Avulsion

4.45-4.65 km: Avulsion and canopy cover interference

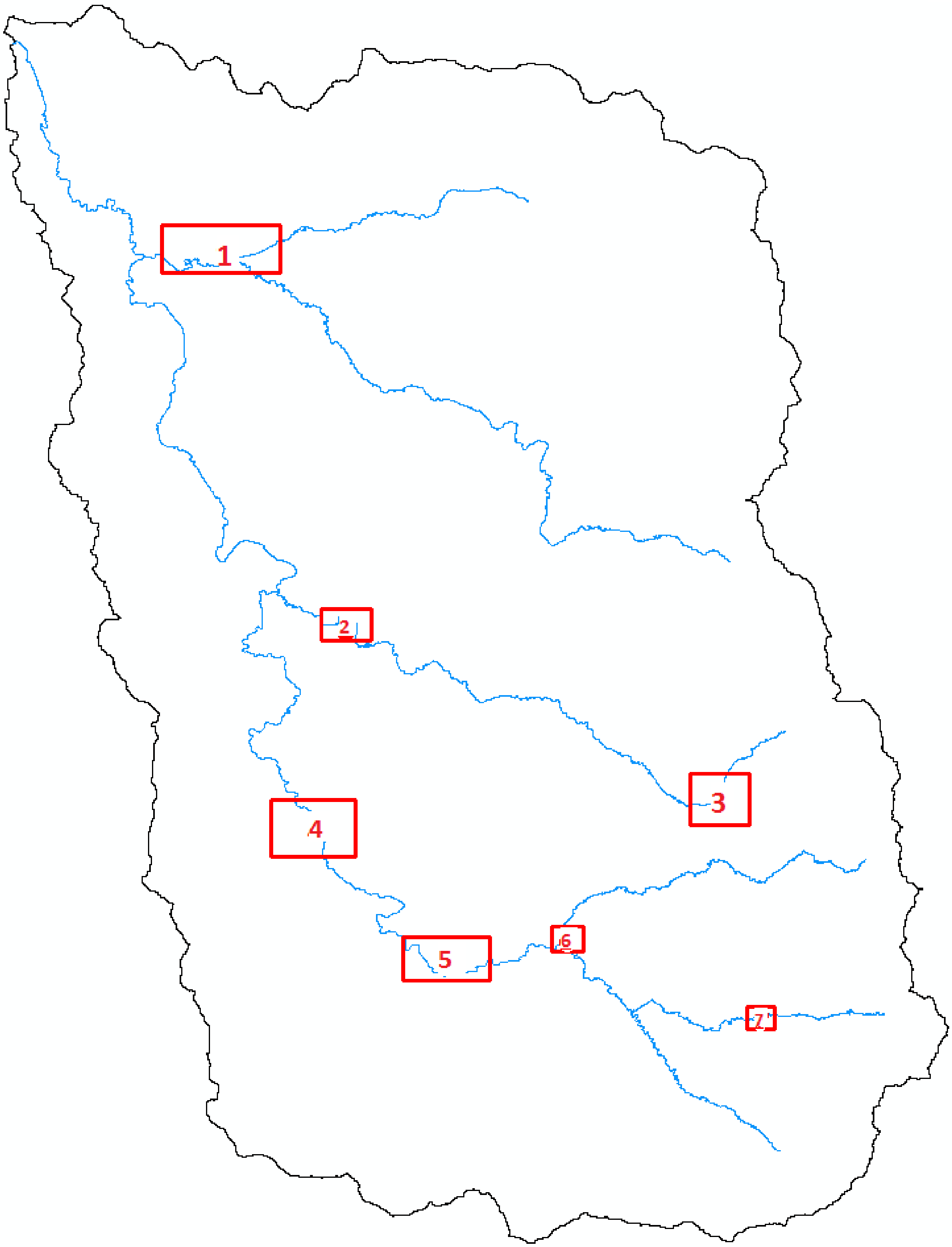
7.75 km: Avulsion or moved by humans

8.75 km: Avulsion

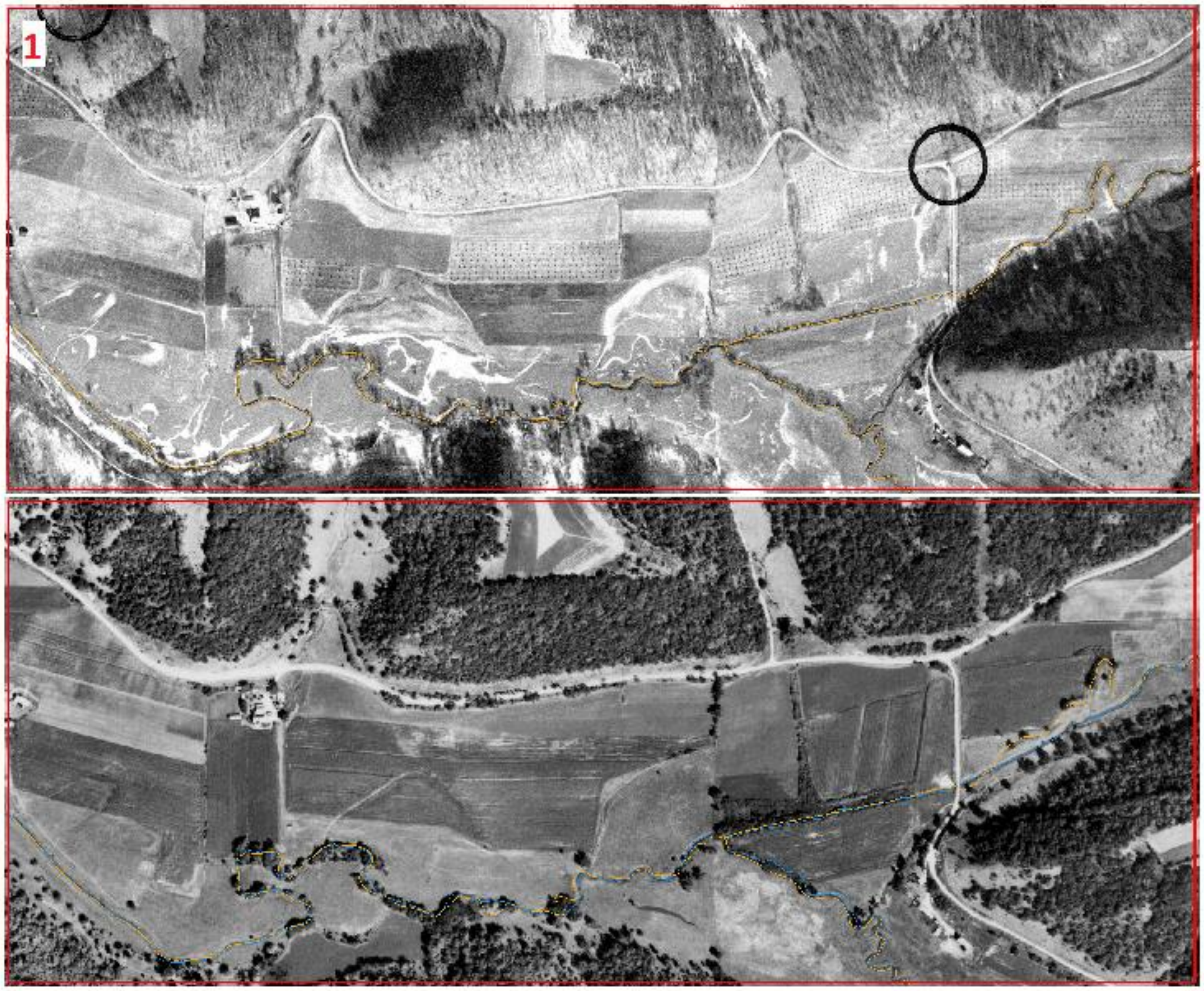
9.15 km: Artificial straightening

13.15 km: Avulsion

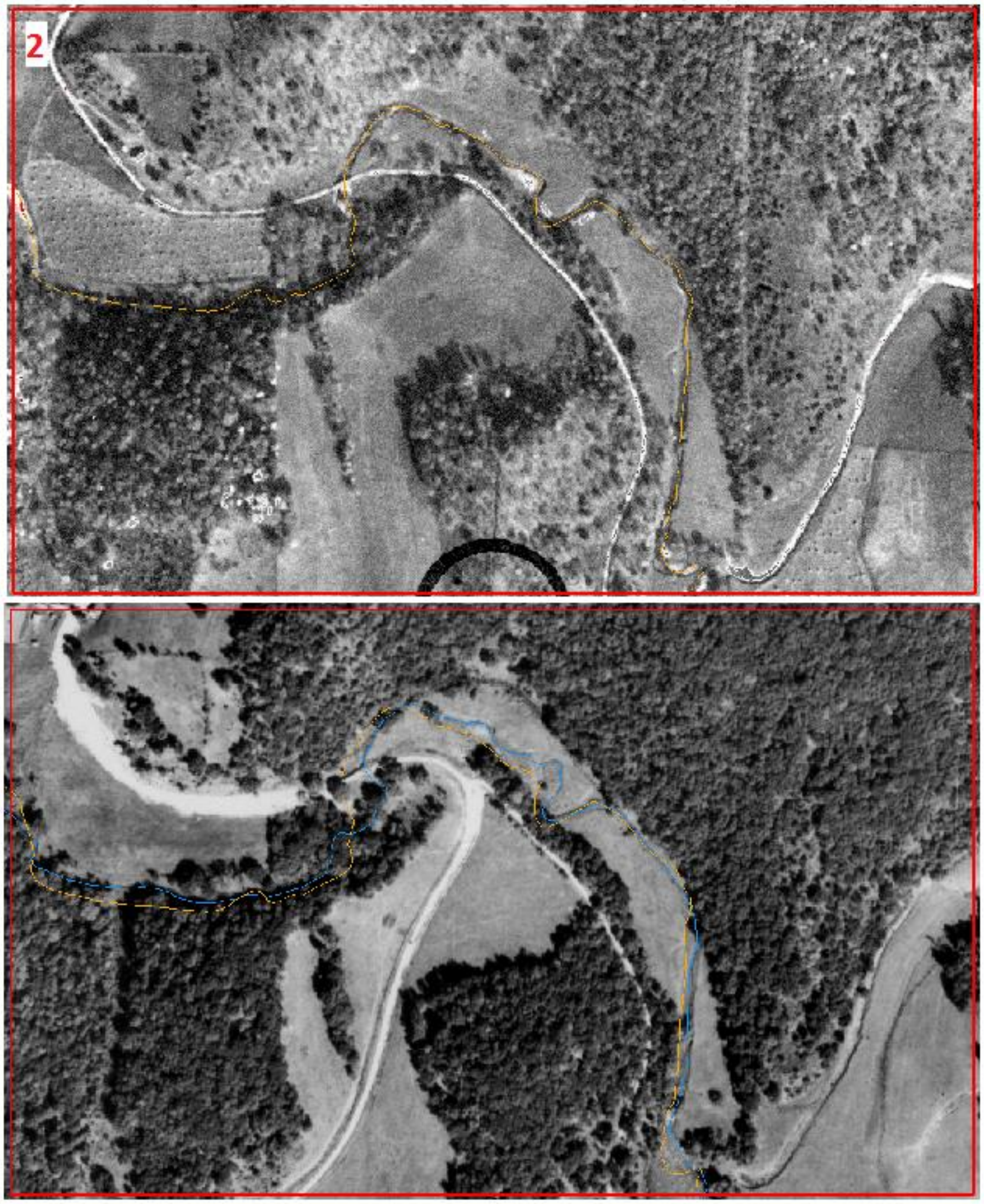
APPENDIX B: ROAD MODIFICATIONS



1. 1940 to 1968

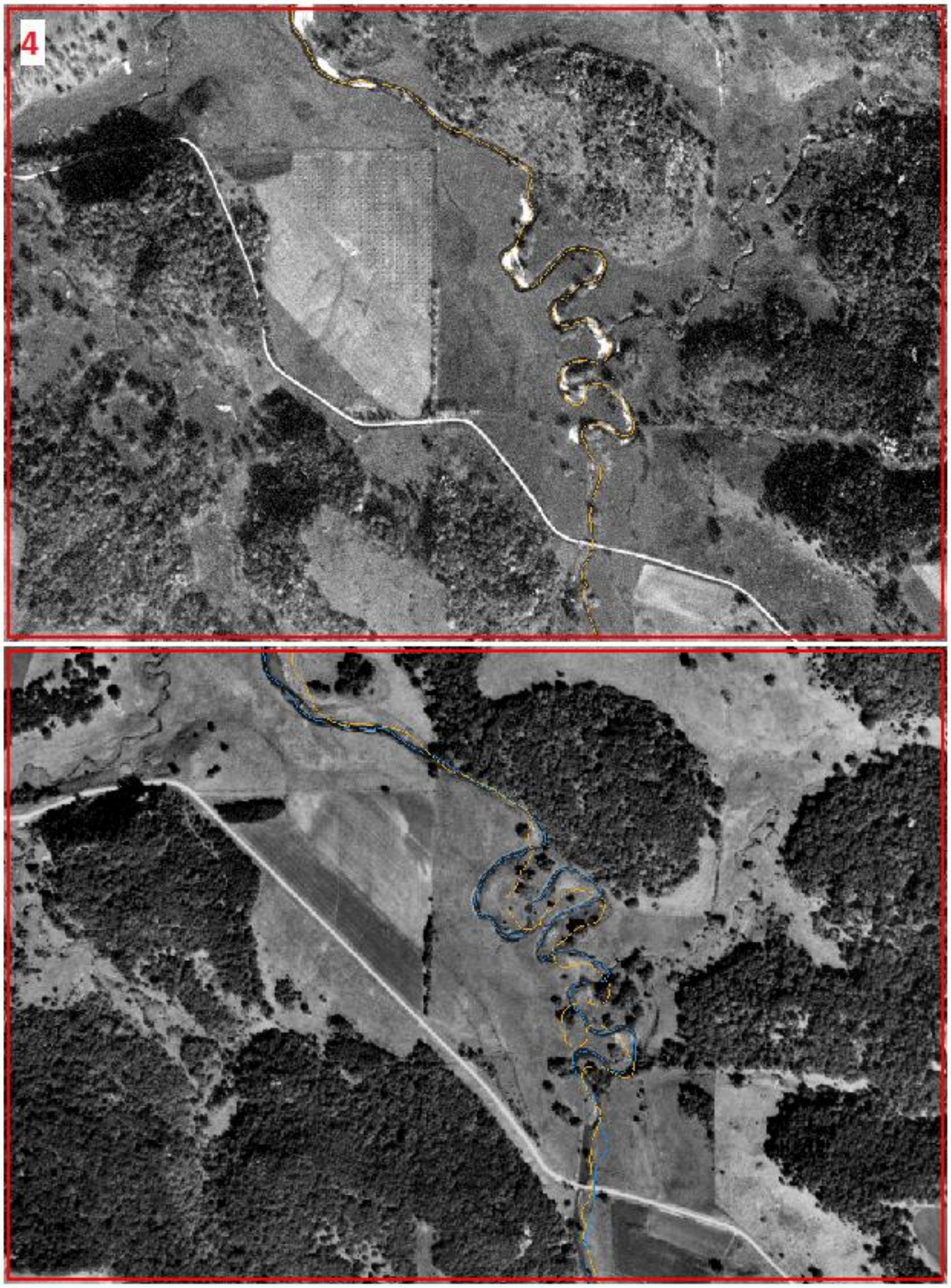


2. 1940 to 1968

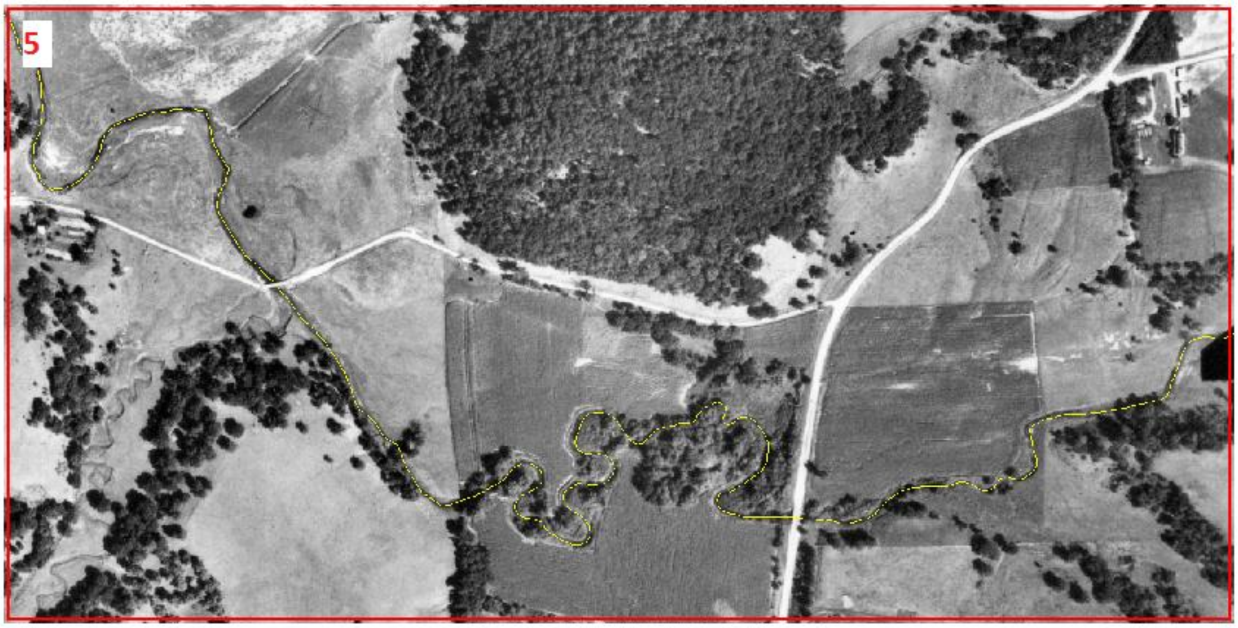


3. 1968 to 1995

4. 1940 to 1968



5. 1968 to 1995



6. 1940 to 1968

7. 1940 to 1968