An Analysis of Planform Changes of the Upper Hocking River, Southeastern Ohio, 1939-2013

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ABSTRACT

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Channel planform change of the Hocking River was documented over 75 years between Sugar Grove and Athens, Ohio, to determine whether any significant changes were associated with major human activities or selected physiographic variables in the watershed. Channel planform change was mapped by acquiring and analyzing aerial photographs and digitizing the channel in GIS. Planform variables of sinuosity, width, asymmetry, and channel migration were calculated. Of the studied human and environmental variables, human-induced changes through the advent of transportation infrastructure, specifically US Route 33, and channelization to mitigate property damage within the floodplain were the leading causes of significant planimetric change of the upper Hocking River over the 75-year span. Significant changes in sinuosity, width, and channel migration occurred directly in the modified reaches as well as the reach immediately downstream from a modification. Historic floods triggering meander cut-offs was the second most important variable affecting planimetric change. Finally, the percent change in riparian vegetation was shown to have a moderately negative correlation with percent change in channel width, while a correlation between percent change in riparian vegetation and rate of change in channel position was not found. Overall, while the upper Hocking River displayed natural planimetric variability over the study interval, the greatest impacts, both directly and indirectly, upon channel planform were associated with human modifications.

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CHAPTER 1: INTRODUCTION

In the last 25 years human impacts on humid-region river systems have become a major topic in geomorphic research. Humans modify stream channels directly through dams and by artificial channelization, but people also impact stream channels indirectly by modifying the landscape beyond the channel. Logging, mining, urbanization, and transportation are important examples of human actions beyond the channel that can change a stream's flow and sediment regimes (Leopold, 1956; Strahler, 1957; Harden, 2004; Gregory, 2006). The primary impacts on perennial flow from landscape modification by these activities are increases in discharge and sediment load. For example, the installation of new industrial, commercial, residential, and transportation structures in a naturally forested area will increase the extent of impervious surfaces. This results in a decrease of infiltration of precipitation into the subsurface and an increase in surface runoff. Overland flow moves faster than groundwater, thus the increase in urbanization causes greater stream discharges and faster arrival of peak flows that occurred prior to development (Oglesby et al., 1972; Gregory and Walling, 1979). These increases, in turn, lead to greater channel width and depth, which are the most common channel adjustments to a new urbanized flow regime (Wolman, 1967; Leopold, 1968; Hollis and Luckett, 1976). One of the best statements summarizing the scope of human impacts on watersheds is by Black (1971, p. 71-78), who stated,

> Whatever the practice, and insofar as he is active on the land, man is a feature of watershed equilibrium himself, because he can modify one or more of the environmental factors which contribute to equilibrium. He may, of course, increase watershed stability; but, more frequently, he is a destructive force, rendering the watershed more susceptible to a change or changes which will upset equilibrium.

Human activities within a drainage basin can affect other parameters besides channel width and depth. Like channel width, many of these parameters are apparent from the channel planform, which is the two-dimensional appearance of the river in map view. Once the planimetric map of the river channel is created through digitization in GIS from georeferenced aerial photographs, measurements can be made to determine stream sinuosity, channel width, meander wavelength, and other meander geometry variables. How these variables change over time for a given stream segment requires creating multiple planimetric maps at the same scale from historic aerial photographs taken at different times. These sequential sets of aerial photographs also provide temporal data for determining meander migration rates.

Humans are becoming the dominant force influencing channel migration, but natural environmental factors also influence planform geometry. These environmental variables include climate, vegetation, flow regime, sediment regime, lithology, bedrock structure, and soils (Schumm and Lichty, 1965).

The Hocking River in southeastern Ohio is a fourth-order meandering stream that is a tributary to the Ohio River. Prior to being settled by Euro-Americans in the early 19th century, the Hocking River basin was primarily forested (USDA, 2014). Since that settlement, many parts of the drainage basin have undergone logging, mining, agriculture, and urbanization. The purpose of this study is to document how the planform of the Hocking River between Sugar Grove and Athens, OH, has varied over the 75 years spanned by available air photo sets (1938, 1951, 1966, 1976, 1988, 2004, and 2013) and to determine whether any significant changes are associated with major human activities or environmental factors in the watershed.

This research will contribute to an improved understanding of the nature and rates of stream planform change and channel migration, and it will lead to a better understanding of the sensitivities of the planform to an array of environmental and human variables. River systems are critical ecological resources which also provide transportation, attract settlement, draw industry, and offer numerous aesthetic and recreational pleasures. Knowing more about the pattern, magnitude, and frequency of planform changes and their sensitivity to human actions may help communities reduce their role in causing channel instability, which often leads to landscape and property damage.

Previous researchers have documented cases in which spatial or temporal trends in environmental variables or one type of human impact have affected channel width, migration rates, and meander geometry of the Hocking River (e.g., Engelman, 1996; Gregorio, 2008). In addition to spatial (e.g., soils, lithology) and temporal (e.g., precipitation) environmental variables, over the last 75 years the 73.2 km long portion of the Hocking River studied in this thesis has experienced a wide array of potentially disruptive human activities, each with their own spatiotemporal attributes. Comparing the spatiotemporal pattern of changes in the river's planform with the patterns of multiple environmental and land use variables will provide new information on the relative significance of these factors.

Finally, results will be directly applicable to the designated reach of the Hocking River, which, except for Engelman's (1996) work on the segment between Nelsonville and The Plains, OH, has gone largely unstudied for planform change. By assessing the amount of channel change over the last 75 years and the role of human impacts on it, this research will help communities understand the functionality of the upper Hocking River planform and the major drivers that cause significant change. Furthermore, results from this research should be applicable to other drainage basins with similar environmental and human impact variables. The following questions are addressed in order to gain such understanding:

1. What significant changes in planform of the Hocking River from Sugar Grove to Athens occurred over the past 75 years?
2. What significant changes in planform of the Hocking River are the result of human and environmental variables?

CHAPTER 2: LITERATURE REVIEW

Previous researchers have identified several important attributes of the planform of sinuous streams and have developed numerous techniques to measure those attributes and the change in channel position over time. Intrinsic and extrinsic natural environmental factors can lead to planimetric changes in meandering channels. So, too, can human action impacting the stream either directly or less directly through changes in land use and land cover in the drainage basin. Urbanization, mining, and deforestation are land use/land cover changes that can affect meandering stream planform. This discussion of the literature focuses on channel planform variables, natural environmental factors that can change stream planform, and land use and land cover changes that can affect stream planform.

2.1 Planimetric Analysis

Channel planform has been studied in some capacity since the late 19th century by such researchers as Fergusson (1863), Allen (1895), and Shillingford (1895). Aerial photography became the primary tool for studying spatial and temporal changes in channel planform beginning in the late 1930s (Lawler, 1993; Martin and Pavlowsky, 2011). Commonly studied stream planform variables are wavelength, radius of curvature, amplitude of meanders as well as inflection zone (point at which the curvature changes), channel width, stream length, and valley length. Using these measurements, stream sinuosity and meander asymmetry can be derived (Howard and Hemberger, 1991). Multiple years of photographic coverage allow the determination of how these variables have changed over time and the calculation of channel migration rates. When dealing with planform change it is important to determine if the system is free or confined, which is associated with the bedrock and topographic structure, as the amount of confinement in the river valley will inhibit or promote lateral migration (Nicoll and Hickin, 2010). Planimetric analyses expanded after Bagnold (1960) suggested that meander migration rates depend on planimetric attributes of meander bends.

Bagnold (1960) studied relationships between meander radius of curvature, channel diameter (width), and flow resistance (Figure 1). He determined that the optimum ratio of radius of curvature to channel diameter for minimum flow resistance is between 2 and 3. The radius of curvature affects flow asymmetry by influencing migration over the floodplain. The amount of migration is caused by the presence or absence of friction on the outer bank, which typically occurs when the ratio is below 2 and above 3, respectively. This also coincides with the zone of turbulence, which is the area of energy dissipation through eddying. Asymmetry is more pronounced in meander loops with a ratio close to 2 than in meander loops with ratios greater than 3. The smaller the ratio the higher the turbulence and potential for channel migration.

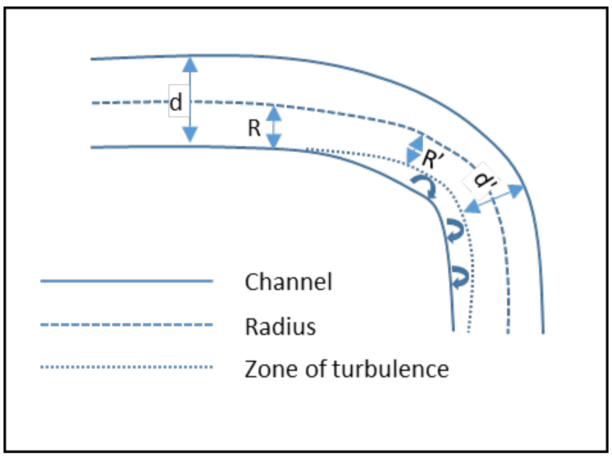

Figure 1. Radius of curvature adapted from Bagnold (1960, p. 137). The diameter and radius of a straight channel are annotated by (d) and (R), while the diameter and radius of a curved channel are (d′) and (R′), respectively.

Langbein and Leopold (1966) completed a crucial study of the planimetric form of stream meanders. Their theory of minimum variance asserts that meanders take the most efficient form for transporting the sediment load while keeping changes in various stream properties as small as possible. Langbein and Leopold (1966) postulated that the meandering pattern is the most common planimetric stream form, and they found good correlations between the form of natural stream meanders and sine-generated curves, which represent the most common random walk model, a stochastic path between two points. The authors noted, however, that streams with multiple similar (uniform) meanders match sine-generated curves better than do meanders from streams with high variability from one meander to the next. Langbein and Leopold's (1966) model was constructed under the assumption of uniform lithology, and the random walk model may not apply well to lithologically variable natural meanders.

Another important study was carried out by Keller (1972), who developed a five-stage model to show how channel pattern varies over time in an alluvial substrate. Given temporal and spatial adjustments, a channel planform can vary throughout the entire length of the system. The model begins with a meandering thalweg in a straight channel. Changes in the sediment, flow regime, and boundary conditions lead to channel meandering. As sinuosity increases so does the formation of pools, riffles, and point bars. This process continues until a threshold is reached, such as when a meander cut-off occurs, which will reset the system sequence.

Since the early 1970s, considerable work has further expanded the use of planform analysis. Howard and Hemberger (1991) completed a multivariate study of different planform metrics. Using multivariate statistics they were able to reduce their initial set of over 40 properties characterizing the planform of rivers to about 20. Some of the retained expressions are redundant and many share such basic variables as wavelength, amplitude, valley length, and inflection distance. The two equations most relevant to this thesis research are total sinuosity and meander loop asymmetry.

Before the advent of GIS, studies of channel planform were conducted from data derived manually from aerial photographs. Gurnell and Downward (1994) and Gurnell (1997a, 1997b) demonstrated the advantages of using GIS to analyze channel planform changes over time.

Compared to conventional manual methods, GIS allows for more efficient georeferencing of multiple maps or images to a common scale, provides the means for conducting a variety of spatial analyses with greater speed and accuracy, and offers numerous qualitative tools to change data symbology. Gurnell and Downward (1994) advised that aerial photographs used for planimetric studies should all be acquired at close to the same scale in order to reduce spatial error, time, and cost. They identified delineation of the channel under the tree canopy as a key problem when digitizing channels. Defining the channel when water levels fluctuate and vegetation obscures the bank can also be difficult, but these problems can be reduced by obtaining leaf-off aerial photography. Like Lawler (1993), Gurnell and Downward (1994) consider it important to dismiss the assumptions that change in river planform is continuous and linear between dates of photography; on the contrary, during photograph lapse times channels might stabilize or experience nonlinear rates of movement.

Similar variables have been used widely throughout the literature to describe the morphometrics of planform change. Numerous researchers have found that width, bend curvature, and asymmetry are all related. Using two- and three-dimensional computational hydrodynamic models, Chen and Duan (2006) confirmed the work of Bagnold (1960) and Langbein and Leopold (1966), that increasing the radius of curvature changes the flow dynamics of the channel, thus creating higher velocity on the outer bend resulting in lateral migration. Hickin and Nanson (1975) and Hooke (2007) found, in agreement with Bagnold (1960), that bend curvature plays a crucial part in the rate of migration.

Bend curvature also affects the shape of meander loops, which is typically asymmetrical. Nicoll and Hickin (2010) described meander asymmetry for several confined rivers on the Canadian prairie and concluded that asymmetry generally remained the same while migrating downstream in continuous waveforms. Using nonlinear simulation flow models, Frascati and Lanzoni (2009) studied long-term planform change and compared their data to natural meanders.

They found that the amount of asymmetry in the planform can be attributed to such factors as floodplain erodibilty and vegetation (Frascati and Lanzoni, 2009). Meander loops can also be compound as well as asymmetrical (Brice, 1973). In freely meandering streams, asymmetrical meanders tend to revert back to symmetrical once the meander loop is cut off (Hooke, 2004). Stolum (1996, 1998) found that the degree of asymmetry and sinuosity in a particular reach result from three stages of planform change. These stages are subcritical, critical, and supercritical, which is the severity of sinuosity for a given channel reach to change from a straight channel to a tortuous channel on the threshold of meander loop cutoff. Although these stages represent ordinal categories, they can happen along any segment of a stream channel, and can be out of sequence depending on the variables at particular locations. For example, one reach might be straight (subcritical), while another reach can be tortuous (supercritical). Furthermore, a change in stage in one segment can alter the next segment of stream, similar to a chain reaction. Hooke (2007) maintained that while measurements of these variables are important in understanding complexity of meanders and change in planform, what has yet to be explained is why some bends undergo an accelerated rate of change while the rate of change in others slows or ceases.

In summary, previous researchers have used theory and statistics to help explain why streams meander and why stream meanders tend to have a similar general form. Several variables have been established to characterize quantitatively how individual meanders, or groups of meanders, might differ from each other or vary over time. Some attempts have been made to associate different values of those parameters with specific circumstances within the drainage basin. In the last 20 years, digital techniques have allowed for improved efficiency and standardization in measuring meander attributes and in determining how they have changed over time using multi-date imagery.

2.2 Natural Controls of Channel Migration

Schumm and Lichty (1965) published a groundbreaking work on dependent and independent environmental variables that influence stream systems at three major temporal and spatial scales. Schumm and Lichty (1965) asserted that geology and climate remain independent variables across all time scales, while vegetation, topography, and hydrology, which are dependent variables over the longest time spans, become independent variables over shorter time spans (Table 1). Channel morphologic variables of width, depth, slope, and pattern that are

Table 1. Temporal and spatial independent and dependent variables in a drainage basin. The time periods of cyclic, graded, and steady represent long term, short term, and current time, which designate when drainage basin variables change status (Schumm and Lichty, 1965).

Drainage basin variables	Status of variables during designated time spans		
	Cyclic	Graded	Steady
1. Time	Independent	Not relevant	Not relevant
2. Initial relief	Independent	Not relevant	Not relevant
3. Geology (lithology, structure)	Independent	Independent	Independent
4. Climate	Independent	Independent	Independent
5. Vegetation (type and density)	Dependent	Independent	Independent
6. Relief or volume of system above base level	Dependent	Independent	Independent
7. Hydrology (runoff and sediment yield per unit area within system)	Dependent	Independent	Independent
8. Drainage network morphology	Dependent	Dependent	Independent
9. Hillslope morphology	Dependent	Dependent	Independent
10. Hydrology (discharge of water and sediment from system)	Dependent	Dependent	Dependent

dependent over moderate time spans, are independent over very short time spans. At small temporal and spatial scales a channel cross section can achieve a steady state, meaning no net erosion or deposition; at larger scales a stream segment can fluctuate around average values for channel size, slope, and position in dynamic equilibrium. It follows from the assumption of equilibrium that dependent channel morphologic variables will change in response to changes in the independent variables. However, this might not always be the case, which as previously mentioned introduces the concept of dynamic equilibrium of a system.

Schumm (1979) later provided an in-depth discussion of the concept of thresholds in geomorphic systems. A threshold is a limit that if crossed will bring about an abrupt change in the system. Geomorphic thresholds fall into two categories, extrinsic and intrinsic. When a geomorphic system, such as a stream, undergoes an abrupt change because of an influence outside the stream, such as climate or geology, it is responding to an extrinsic threshold. For example, a stream is responding to an extrinsic threshold when the channel is diverted because of an earthquake. An intrinsic threshold is at work when the system undergoes an abrupt change, such as a meander cut-off because of the stream's normal process of increasing sinuosity. In practical terms, understanding intrinsic thresholds for a meandering channel could enable researchers to predict when change is likely to occur. This prediction would be based on knowing the thresholds for slope, discharge, load, and meander loop curvature.

Schumm (1988) discussed five possible problems related to thresholds and environmental variables. First, data that are analyzed and applicable for one location may not be applicable to another. Second is the notion of geomorphic convergence, which refers to the same outcome produced by different mechanisms. Third, divergence occurs when a single process can create multiple outcomes, such as the case of an increase in slope causing one channel to meander and another to braid. Singularity, that each individual landform will respond to environmental variables differently, is Schumm's (1988) fourth point. Lastly, the sheer complexity of fluvial systems poses a problem for understanding all the variables involved and their independent or dependent roles.

In summary, the variables that influence river morphology can be broken into two general categories: intrinsic and extrinsic with their appropriate thresholds. Intrinsic variables are those that operate within the system, while extrinsic variable operate outside the system. Channel pattern, drainage density, channel slope, stream load, channel width, and channel depth are internal variables; these in turn influence each other because they are in the same system. External variables are climate, tectonics, base level changes, and human activities in the drainage basin; these are outside the stream system and act independently from the internal variables (Schumm and Lichty, 1965; Schumm, 1979). Combined, these variables are the building blocks of how a fluvial system functions. A noticeable factor affecting many fluvial systems today is the extensive landscape modification caused by human land use and land cover practices (Wolman, 1967; Leopold et al., 2005; Gregory, 2006; Price and Leigh, 2006; Klimek and Latocha, 2007).

2.3 Human Influences on Planform

Land use refers to human activity throughout the environment and is associated with land cover. Land cover designates mappable categories of landscape features whether natural or anthropogenic. Many human-induced changes in land use/land cover directly or indirectly affect aspects of the area's geomorphology. Geomorphic consequences of human use of the land have received some previous research, particularly in humid region settings.

Strahler (1957) studied the difference between natural and "induced" erosion and aggradation in watersheds. He noticed that changes in landscape morphology are becoming increasingly induced by people through deforestation, cultivation, and urbanization. In support of Strahler's (1957) summation, Leopold (1956) analyzed different land uses and their effects on sediment yields in streams. He found that of the land use practices, deforestation is extremely detrimental to stream channels because it leads to bank instability and rapid runoff and surface erosion of the unprotected topography. Though damaging, Leopold (1956) indicated that in time the system will try to establish a quasi-equilibrium or that vegetation would be reestablished and more stable conditions returned. Some systems, however, may never recover.

In 1967 Wolman published his view that with urbanization, a stream that is previously in dynamic equilibrium with the environmental conditions will experience large sedimentation fluxing as the result of an increase in the extent of impervious surfaces associated with urbanization. He studied the effects of urbanization on seven streams in the Baltimore, Maryland, metropolitan area. Using cross sections, photography, and sediment analyses, Wolman (1967) determined that prior to urbanization sediment yield for the forested basin was around 35 metric tons/km^2/yr, which is much lower than the 105-280 metric tons/km^2/yr caused by converting the land to agriculture. During the transfer from agriculture to an urban landscape sediment yields can approach 35,026 metric tons/km^2/yr or more. This huge increase in sediment yield is catastrophic to fluvial systems and can drastically alter channel networks permanently. The sheer amount of sediment resulting from landscape conversion can cause channel planform to change. Wolman noted that although this exponential increase in sediment flux is caused by construction, once urbanization has been completed sediment yields may be equal to or lower than that during forested conditions.

Leopold (1968) examined the effects of urbanization on hydrology in an effort to create a handbook for urban planning. He concluded that urbanization is by far the single most destructive land cover change for fluvial systems (Leopold, 1968). Urbanization causes changes in peak stream flow, amount of runoff, water quality, and aesthetics. Water quality changes through the presence in agricultural and urban areas of various chemicals and trash. These change the chemical and biological composition of the ecosystem (Klein, 1979). Besides the biological aspect, the physical effects of land use and land cover changes can consist of bed and bank instability and a decrease in flood reoccurrence intervals, which ultimately change the channel planform (Leopold, 1968). The characteristics of watershed topography, specifically slope and the location of urbanized areas within the basin, can play a major role in planform change. Steeper gradients, in conjunction with increased impervious surface, result in higher velocity which, in turn, increases stream power and the occurrence of bank instability (Hammer, 1972). Urban sprawl also increases the frequency of flooding (Hollis, 1975). Expanding on Leopold's (1968) work, Hollis (1975) concluded that river impairment caused by urbanization occurred at approximately 5% impervious surface coverage, while both Hollis (1975) and Klein (1979) determined that 30% impervious surface coverage resulted in a severely impaired watershed.

Gregory (2006) was also concerned with the effects of land use/land cover on fluvial systems through modification of the flow and sediment regimes. He advocates lifting the "paradigm lock" between scientists and manager/stakeholders in an attempt to understand the human role in changes to river channel planform. Themes needing attention include the prediction of channel change, feedback effects, global change, geomorphic design, and cultural dimensions (Gregory, 2006). Gregory (2006) also describes six effects of land use/land cover change on river systems in terms of hydrology and sediment regime (Table 2), and concludes that the main factor affecting channel planform is increased sediment. Six common indirect factors that influence channel planform are stream gravel extraction, basin water transfer, climate change, reservoir development, and urbanization.

Gravel pits located next to streams are detrimental because they can lead to bank instability, channel avulsions, and lateral migration. In-stream gravel extraction has caused accelerated degradation upstream and aggradation downstream by manipulating the longitudinal profile (Mossa and Marks, 2011). Artificial interbasin transfer of water increases discharge above normal levels in the receiving basin leading to channel instability, while streams in the supplying basin undergo a decrease in capacity and competence for transporting their load. Climate change

Table 2. Adopted from Gregory (2006). This tables represents the most common factors that contribute to the changes in discharge and sediment yield of a river system, whether that leads to an increase (+) or decrease (-) in response.

LULC Type	Discharge	Sediment Yield
Deforestation	+	+
Agriculture	+	+
Afforestation		-
Construction		+
Urbanization	+	-
Mining		+

has tremendous influence on rivers, particularly on the regional scale, by altering the temperature and precipitation, which in turn alter the flow and sediment regimes (Daisuke, 2006; Palmer, 2006; Arnell, 2013). Land use/land cover practices will only exacerbate future climate conditions, putting further strain on river systems (Park, 1981).

Dams and associated reservoirs are some of the most destructive river modifications and can completely alter the entire drainage basin ecosystem, such as creating a new base level and two completely new systems separated by the structure. This modification in hydrology induces a new equilibrium in the system, and can cause flooding, channel desiccation, decreased dissolved oxygen, bed scouring, impairments on aquatic species, and channel planform change unless a proper discharge-release plan is administered (Park, 1981; Heinz Center, 2002; Ma et al., 2012; Yuan et al., 2012).

Two other major land use/land cover practices that cause detrimental impacts on riverine systems are deforestation and mining. Particularly relevant papers on these have been published by Harden (2004), Price and Leigh (2006), and Ferrari et al. (2009).

Harden (2004) studied a century of land use/land cover influences on fluvial systems throughout the southern Appalachian region. Through an extensive literature review, Harden found that at the turn of the 20th century approximately 99% of the 2.2 million hectares of the region were converted to logging and mining operations. In as little as 30 years, the majority of the southern Appalachians was completely denuded. Since that time large portions of the region have been acquired by federal government as national park, monument, forest, wilderness, and recreation areas. While the region has recovered a little, urbanization now threatens the fluvial system, especially within the Blue Ridge Mountains.

Price and Leigh (2006) examined the morphology and sedimentology of watersheds that have been lightly impacted and moderately impacted by deforestation of the Little Tennessee River basin in the Blue Ridge Mountains, North Carolina. Land use impacts in mountain regions tend to be sporadic from agriculture and urbanization but high from logging. Forest cover was calculated by completing a supervised classification using Landsat imagery from 1950, 1970, 1990, and 1998 in GIS. Price and Leigh (2006) determined that while changes occurred in sediment output, channel morphology was not significantly altered, suggesting that sediment changes due to land use are more spatially and temporally sensitive than channel morphology. They concluded that alterations in channel morphology might be more evident on basin-wide scales than at the reach level.

Appalachia is even better known for its coal than its forest resources. Acquiring coal through surface mining causes widespread damage to the riverine system as Ferrari et al. (2009) discovered in western Maryland. Ferrari et al. (2009) found that surface mining and reclamation have effects on rivers similar to those caused by urbanization. By law only the return of original topography and revegetation are required in the reclamation process. Soils that are left compacted and barren of nutrients result in a high frequency of reclamation failures. The hydrologic regime is also often neglected and with the lack of any stormwater measures runoff mimics urban discharge with higher peak flooding frequencies. Ferrari et al. (2009) concluded that to mitigate this effect, in addition to returning topography and vegetation, hydrologic connectivity should be restored in a properly reclaimed surface mining operation.

One of the most significant human-induced factors contributing to channel migration is removal of the riparian corridor. Micheli et al. (2004) analyzed this problem on the Sacramento River in California. Using maps and aerial photography from 1896 to 1997, Micheli et al. (2004) digitized the river in GIS, overlaid the files, and completed an eroded-area polygon to calculate migration. They analyzed vegetation maps in relation to bank stability. Combining all data, they found channel planform change was greater in agricultural corridors versus riparian buffers by as much as 80%-150%. This result can be used directly not just in California but in other watersheds that have similar land cover/land use, such as the Hocking River; the Sacramento River flows in a basin comprised of 65% forest, 25% agriculture, and 10% urban land (Micheli et al., 2004), which is similar to the basin of the Hocking River.

2.3 Hocking River Research

2.3.1 Planimetric Analysis of the Hocking River

Engelman (1996) analyzed the channel planform of the Hocking River from Nelsonville to The Plains. She investigated whether the effects of surface mining within the Monday Creek tributary basin had resulted in channel changes in the Hocking River below or above their confluence. Using historical aerial photography from 1938, 1958, and 1995, digitizing the channel planform in GIS, and measuring wavelength, sinuosity, and asymmetry, Engelman (1996) determined that a significant change in channel width and asymmetry of meander bends occurred throughout this time span below the confluence with Monday Creek. She inferred that these changes were the result of bed load delivered to the Hocking River from the Monday Creek basin. Engelman (1996) concluded that the influx of sediment into the Hocking River from Monday Creek will continue to affect downstream planform until the sediment pulse has completely passed. However, she commented that much additional research is needed, primarily concerning land-use changes in the upper Hocking River.

Gregorio (2008) looked at the planimetric change of the Hocking River for approximately 24 km downstream from the channelized section in Athens to its confluence with the Ohio River at Hockingport. The purpose of his study was to determine whether downstream planform changes had occurred that could be attributed to channelization of the river through Athens by the Army Corps of Engineers in the early 1970s. Using historical aerial photography over a 67-year period, digitizing the Hocking River from these in GIS, and measuring channel planimetric attributes similar to those collected from the small upstream reach by Engelman (1996), Gregorio (2008) determined that while some segments increased in width, only limited changes occurred in channel form and position. Discharge increased after the channelization, but that was not surprising as the primary purpose of channelizing a river is to increase its capacity and throughflow to decrease flooding. The capacity to handle flooding is accomplished by straightening, widening, and increasing slope of the channel.

2.3.2 Land Use/Land Cover in the Hocking River Basin

In order to explain changes in river planform, in addition to natural variables, it is advantageous to have adequate knowledge of the land use/land cover history of the drainage basin. Several studies provide data relevant to the land use and land cover in the Hocking River basin.

Massey-Norton (1980) analyzed the Hocking River at six locations between Lancaster and Coolville, and all major tributaries, for natural radionuclides that initially resided in the strip-mined coal. He sampled stream sediment and water to calculate the concentration and migration path of the radionuclides. Concentrations of uranium, thorium, and potassium-40 were small but indicative of leaching from the mines. Massey-Norton (1980) indicated that people in the area should not use the groundwater as their only source of potable water.

Loss of riparian forest increases bank instability and the potential for exacerbated erosion. Wryst (1995) used aerial photography from 1939 to 1989 as well as GIS to analyze how the migration of the Hocking River modified the riparian corridor between Athens and the town of Guysville. Results showed an increase in the forest cover by 79% over the 60 yrs. Kelley (1999) compared the contributions to the Hocking River discharge from two small tributaries in Athens, one from a rural and the other from an urbanized area, to determine the effects of urbanization on small watersheds. Kelley found greater discharge from the small urbanized basin, but was not able to describe through his modelling efforts the relative importance of urbanization on increasing discharge.

Commonly associated with urbanization is the practice of channelizing river systems to help mitigate flood hazards. Hatton (1999) studied how the channelized segment of the Hocking River through Athens had changed since its construction in 1971. Hatton (1999) hypothesized that in trying to re-establish longitudinal-profile equilibrium the segment experienced a decrease in the capacity to transport sediment, which led to sedimentation, thereby increasing the likelihood of flooding. For the channelized reach, Hatton measured the amount of aggradation that had occurred between 1971 and 1999, found a 33% reduction in the river’s competence, corrected the USGS discharge rating curves, and predicted the segment’s future competence. He found the flood recurrence interval to have decreased to 9 years from the engineered expectancy of 40 to 50 yrs. Hatton concluded that better channel maintenance and floodplain zoning were needed to reduce the anticipated loss of life and property that would accompany future floods.

In order to analyze the effects of land-use changes along the entire length of the 19th century Hocking Canal, Wicks (2002) used maps of the original extent of the canal, air photo interpretation, USGS topographic quadrangles, and GIS. She found that approximately 50% of the Hocking Canal remained visible in the landscape, while the rest of its length had been affected by urban sprawl, converted into roads, ditches, and culverts, or completely backfilled.

Several kilometers have been designated as historic corridors for future appreciation. Wicks concluded that any future land-use modifications adjacent to the Hocking Canal should be planned in order to preserve as much of the existing canal as possible.

CHAPTER 3: STUDY AREA

The Hocking River (Figure 2) meanders for approximately 164 km within a drainage basin of approximately 3,093 km^2, which includes the counties of Athens, Fairfield, Hocking, Meigs, Morgan, Perry, and Washington. The main channel of the Hocking River originates approximately 4.7 km southeast of Lithopolis, OH, at an elevation of 320 meters above sea level (masl), and lies at 180 masl at the confluence with the Ohio River at Hockingport (OGRIP, 2006-2010). As of 2013, the average width of the Hocking River was 41 m and did not exceed 70 m. The Hocking drainage system consists of a dendritic pattern that dissects the topography with hundreds of tributaries. The largest tributaries are Rush Creek, Federal Creek, Sunday Creek, and Monday Creek. These tributaries make up approximately 53% of the Hocking River drainage basin, which was calculated from representative sub-watershed shapefiles acquired from the USGS National Map Viewer. The basin consists roughly of 62% forest, 27% agricultural land, and 10% urban (Ohio EPA, 2014).

The portion of the Hocking River investigated for this thesis, referred to in this thesis as the upper Hocking River, begins approximately 2.0 km downstream from the confluence of the Hocking River and Rush Creek. From that location the Hocking River flows approximately 73.2 river km to Athens over a valley aerial distance of 50 km. This particular length was selected because previous research by Gregorio (2008) was conducted on the lower Hocking River, which is the section between Athens and Hockingport, OH. The section of the river between Sugar Grove and Lithopolis, OH, upstream of the study reach, was not included in this research because that area was highly modified by late Pleistocene glaciation (Stout and Lamb, 1939) and has undergone reoccurring artificial channelization since 1939. For high spatial resolution, the total studied length was subdivided into 25 smaller reaches ranging between 746 m and 9 km in length, and displaying straight to highly sinuous channel patterns.

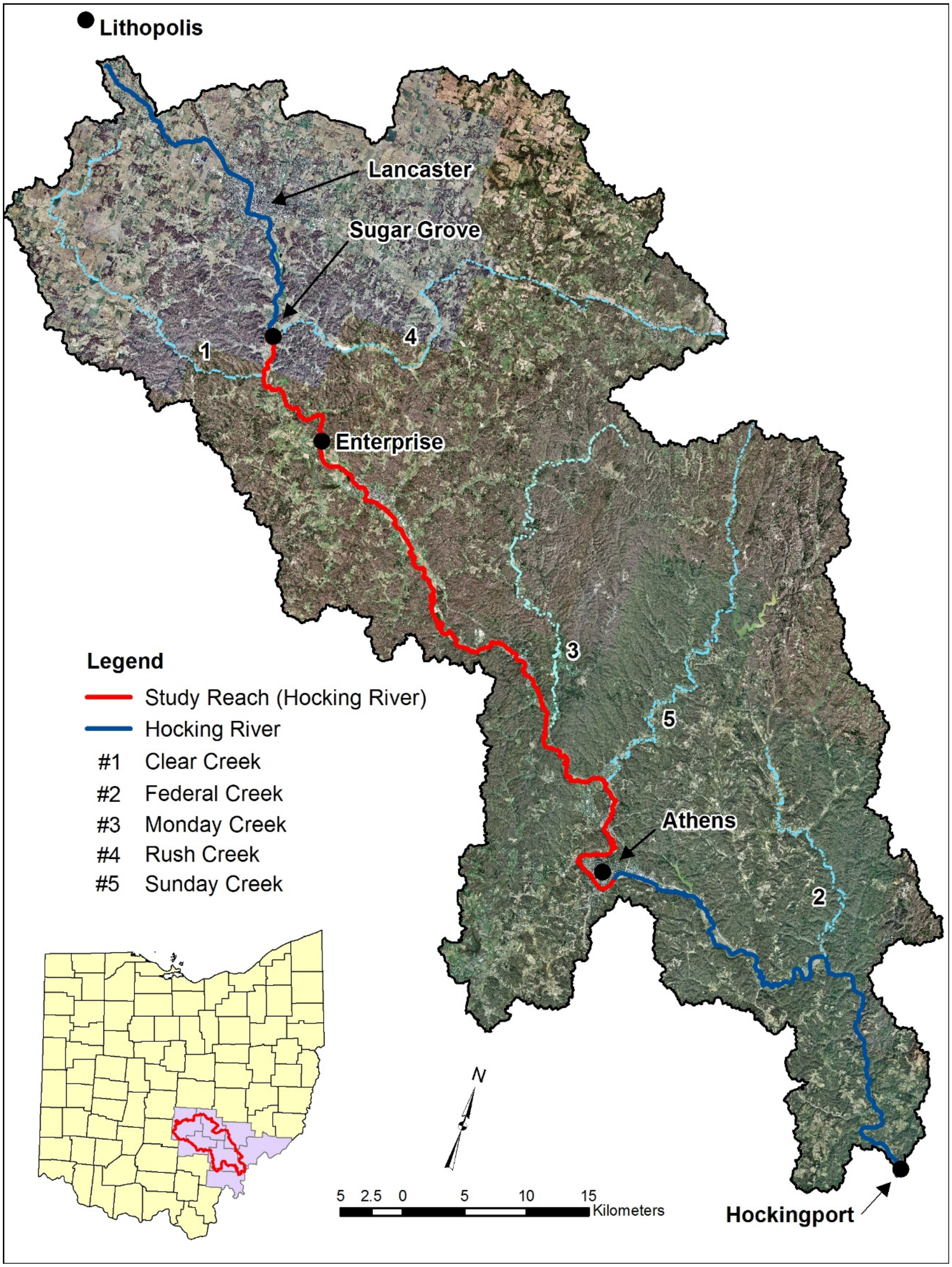

Figure 2. Study portion of the Hocking River. Base map source: 2013 digital aerial orthophoto (OGRIP, 2013).

Two USGS river gaging stations, one at Enterprise and the other at Athens, are located along the studied reach of the Hocking River. The Enterprise gage had a mean annual discharge from 1932 to 2012 of 16 m^3/sec from a basin of 1,188 km^2 (USGS NWIS, 2014). Downstream in Athens, the mean annual discharge from 1916 to 2011 was 43.5 m^3/sec from a drainage basin area of 2,442 km^2. The upper Hocking River basin represents approximately 79% of the river's total drainage basin (USGS NWIS, 2014).

Southeastern Ohio lies within the Allegheny Plateau section of the Appalachian Plateaus physiographic province. Bedrock in the region is dominated by Mississippian and Pennsylvanian sedimentary strata, especially shale, sandstone, mudstone, siltstone, limestone, and thin beds of coal (Ohio Division of Geological Survey, 2006). Iron, salt, and coal have been mined in southeastern Ohio since the early 19th century. By 1950, these mining operations had closed due to the high sulfur content and because the industries that used the material relocated to cities such as Cleveland, OH, and Pittsburgh, PA. Today, with the exception of a Buckingham Coal Company underground mine in Perry County, current mining consists of sand and gravel extractions from the floodplain along the Hocking River in Athens, Fairfield, and Hocking Counties (Ohio Division of Mineral Resources, 2014).

Landforms and surface sediments in the region were strongly influenced by the Pleistocene Epoch, particularly the Illinoian Glaciation and Wisconsinan Glaciation of the greater Laurentide Ice sheet. During both intervals, the glacial terminus reached as far south as Lancaster and resulted in downstream glacial outwash and proglacial lakes. Southeast of the present location of Haydenville lies Lick Run Col, which was a subbasin drainage divide in the pre-glacial Teays River system (Stout et al., 1943). This divide was breached and incised during the Illinoian Glaciation, resulting in the current configuration of the Hocking River (Stout et al., 1943). Further incision and terrace formation occurred along the Hocking River throughout the subsequent Wisconsinan Glaciation (Stout and Lamb, 1938; Stout et al., 1943; Camp, 2006).

The climate of the study area is humid continental, Dfa in the Köppen-Geiger climate classification system, having cold winters and hot summers. The region has a mean annual temperature of 11°C, mean January temperatures of -1.6° C, and mean July temperature of 23° C. Mean annual precipitation is approximately 100 cm (National Climate Data Center, 2014).

Natural vegetation in the study area consists predominantly of broadleaf deciduous forest, including ash, maple, oak, and hickory. Dominant riparian vegetation surveyed along the Hocking River is comprised of river birch, boxelder, American sycamore, musclewood, black willow, and green ash. Soil surveys carried out by the USDA show that the Hocking River floodplain consists predominantly of silt loam, silty clay loam, and gravel substrate in Fairfield County, loam and silt loam in Hocking County, and silt loam in Athens County (USDA: Web Soil Survey, 2013).

CHAPTER 4: METHODOLOGY

4.1 Aerial Photograph Acquisition

In order to study the channel planform of the Hocking River several sets of vertical aerial photographs were acquired (Table 3). The acquired aerial photographs consist of seven photo sets in intervals over 10 years, including 1938, 1951, 1966, 1976, 1988, 2004, and 2013. While the 1938 through 1988 images are digital scans, 2004 and 2013 were obtained as digital orthophotographs through the US Geological Survey's (USGS) EarthExplorer database and Ohio Geographically Referenced Information Program (OGRIP), respectively.

Table 3. Aerial Photograph Sources.

County	Year	Scale*	Type	Source	Foliage
Athens	1939	1:20,000	Black &White	ASCS	on
	1951	1:20,000	Black &White	ASCS	on
	1966	1:20,000	Black &White	FSA	on
	1976	1:38,000	Black &White	NRCS	off
	1988	1:40,000	Black &White	NAPP	off
	2004	1 m	Natural Color	USGS	on
	2013	0.3 m	Natural Color	OGRIP	off
Fairfield	1938/39	1:20,000	Black &White	ASCS	on
	1951	1:20,000	Black &White	ASCS	on
	2004	1 m	Natural Color	USGS	on
	2013	0.3 m	Natural Color	OGRIP	off
Hocking	1938/39	1:20,000	Black &White	ASCS	on
	1951	1:20,000	Black &White	ASCS	on
	1966	1:20,000	Black &White	FSA	on
	1976	1:40,000	Black &White	FSA	on/off
	1988	1:40,000	Color Infrared	NAPP	off
	2004	1 m	Natural Color	USGS	on
	2013	0.3 m	Natural Color	OGRIP	off

*Scales indicated by 1 m and 0.3 m represent the spatial resolution of the digital aerial orthophotographs.

The scanned aerial photographs were primarily obtained from the Soil and Water Conservation Districts of Athens, Hocking, and Fairfield Counties in Ohio. The aerial photographs were originally acquired by the U.S. Agricultural Stabilization and Conservation Service (ASCS), National Aerial Photography Program (NAPP), and Natural Resources Conservation Service (NRCS). Supplemental aerial photographs were ordered from the US Department of Agriculture’s Farm Service Agency (FSA) Aerial Photography Field Office. Photographs dating prior to 1950 were acquired through the National Archives and Records Administration. All photographs were collected at the highest resolution possible and scales larger than 1:60,000. Color, color infrared, and black and white photographs were used if they met the quality requirements. While working with leaf-off photography would have been ideal, the availability of appropriate seasonal photographs was limited.

4.2 Processing Aerial Photographs

Once the aerial photographs were acquired each was georeferenced. Georeferencing is the process of taking a photo that has no known coordinate system and referencing it to a source base map that has a coordinate system. Georeferencing was completed in ArcMap 10.2 using the 2nd order polynomial for the raster transformation, which was found to be more applicable than the 1st order polynomial due to the local topography. Using ground control points (GCPs) (e.g., road intersections, buildings, parking lot edges) found on both the photo and base map and linking them together resulted in the alignment of the working photo to the source photo. The primary base map used for georeferencing was the 2013 digital orthophotographs. Due to the temporal span of photo sets, georeferencing was completed in reverse chronological order. While the 2013 was the primary base map, those photo sets that were completely georeferenced were used as secondary base maps. This was deemed necessary given the large variability in land cover of 75 years along the upper Hocking River and availability of GCPs. The more GCPs, the more accurate the georeferencing, however a minimum of three GCPs was required. Hughes et al. (2006) suggest that GCPs should be established within close proximity of the floodplain to reduce displacement when mapping channel change. Digital aerial photos that already contain a coordinate system were checked to make sure it matched the desired coordinate system; those that did not were reprojected using ArcToolbox to the desired projection.

Verification of the accuracy of georeferencing was completed using the root mean square error (RMSE), which indicates the accuracy between the control photograph and the transformed photograph. The RMSE analyses were completed by looking at the residual error for each georeferenced location provided by the View Link Table in ArcGIS 10.2. The maximum error tolerance for each link was 1.0 m. The smaller the RMSE the more accurate the georeferencing. Below is the RSME equation used in ArcMap 10.2, where the subscripts S and R represent the base-map point and the georeferenced point, respectively:

$$RSME = [(X_S - X_R)^2 + (Y_S - Y_R)^2]^{1/2}$$

4.3 Digitizing Channel Planform

The planform of the Hocking River was digitized in ArcMap 10.1 using the Editor tool. For each aerial photograph a new line shapefile was created for the entire studied length of the Hocking River on both banks. Great care was taken to minimize errors of planform exaggeration and generalization (Downward et al., 1994). Using the Planform Statistics Toolbox (Lauer, 2012), the channel centerline was derived by generating the point equidistant between the digitized left and right banks every 6.09 meters along the channel. This interval was found to best create smooth curves in a variety of meander loops without truncating them.

4.4 Planform Variables

The planform change of the upper Hocking River was assessed quantitatively by measuring the sinuosity, meander asymmetry, channel width, and lateral migration for each successive photo year for the total study reach as well as the 25 study subsets. These 25 reaches were determined based on the activity of the centerline throughout the six photo sets. For this reason, little to no change in centerline marked the start and end of a reach in order to sufficiently capture changes in sinuosity, asymmetry, channel position change, and channel width change. Numbers for each reach increased in sequential order with downstream flow. Measurements of sinuosity and meander asymmetry used equations described by Howard and Hemberger (1991), while channel migration and width were obtained using the Planform Statistics Toolbox developed by Lauer (2012). Below are the descriptions of each equation and tool that was used. All completed measurements were exported as text files for analysis in Excel.

1. Total sinuosity: $S_T = \frac{TL}{D}$

   Total sinuosity is the total reach length (TL) divided by the total valley length (D). Total reach length was calculated for each study reach using the created centerline.

2. Channel width: During the creation of the centerline as described above, each 6.09 meter interval node extrapolated the width of the channel and populated the data into a GIS database file, which was later imported into Excel to determine the change in width.

3. Asymmetry index: $A = (\lambda_u - \lambda_d) / \lambda_h$

   For each meander loop, identified by an upstream (λ_u) and downstream (λ_d) inflection point, λ_u is the centerline length from the meander's point of maximum curvature, $[\xi]_{max}$, to the upstream inflection point, while λ_d is the centerline length from the point of maximum curvature to the downstream inflection point (Figure 3). λ_h is the total overland length between the two inflection points. Values after calculation are between -1 and +1 and designate whether the meander is asymmetrical to upstream or downstream, which suggests if the meander is migrating upstream or downstream, respectively (Nanson, 1980a, 1980b; Hooke, 1984, 2004; Nicoll and Hickin, 2010). In addition to the index, visual interpretation over successive photo years was used to determine whether asymmetrical meander loops were translating upstream or downstream. Given the sheer number of meander loops an ordinal system was created using two letters and a number in order to quantify the amount present in the upper Hocking River. The first letter is capitalized representing asymmetry, the second letter indicates the specific meander site, while a third number represents the particular meander loop if there are multiples. For example, Aa3 designates that this particular meander loop is the third loop in a series at the first site.

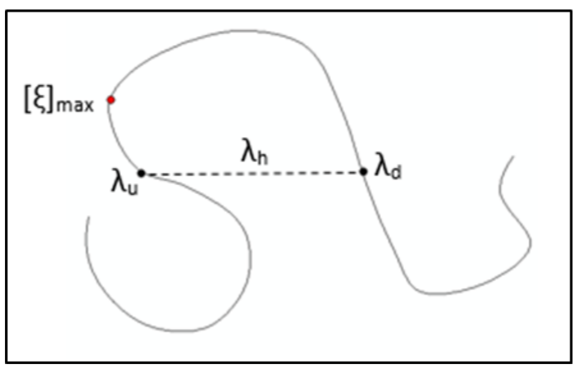

Figure 3. Meander loop attributes used in measuring meander asymmetry ($(\lambda_u - \lambda_d) / \lambda_h$), where λ_u and λ_d are the stream length from the point of maximum curvature to the upstream and downstream inflection points, respectively, and λ_h is the overland distance between λ_u and λ_d. This example has upstream (negative) asymmetry assuming that flow is left to right.

4. Channel position change: This measurement indicates how much a river channel has moved or migrated between two dates. Channel migration is typically through lateral movement of the cut-bank and point bar succession. The amount of channel migration

was determined by using the lateral migration tool of the Planform Statistics Toolbox (Lauer, 2012). The tool measures the channel position by identifying the changes in distance between centerlines of two photo sets for a set sample interval, which was kept at 6.09 meters to stay consistent with width measurements. For example, Figure 4 shows the output vector of the completed measurement of channel position between 1966 and 1976. As with channel width, all data were saved into text documents and imported into Excel for change analyses.

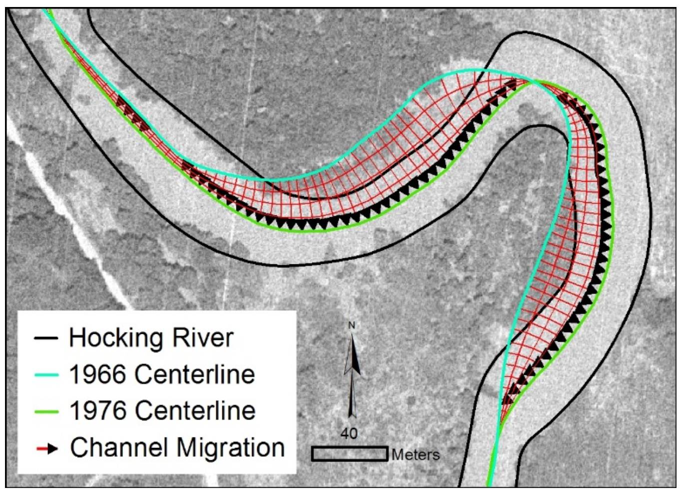

Figure 4. The lateral migration tool identifies the distance between two photo set centerlines. The tool then creates vectors at predetermined intervals, which contains the distance migrated. Base map source: FSA, 1976. River flow is north to south.

4.5 Environmental Variables

Some changes in the Hocking River planform may have been influenced by alterations in natural environmental variables. Data on discharge, flood records, soils, and vegetation were collected and analyzed for the entire study reach. These data were acquired through the USGS Surface Water Database, National Oceanic and Atmospheric Administration's Advanced Hydrological Prediction Center, USDA Web Soil Survey database, respectively.

Discharge data were collected from the Enterprise and Athens gaging stations. From these data, long-term mean monthly discharges were calculated for the 82 years of record between 1932 and 2013 from the Enterprise and the Athens gaging stations. In addition, an 82-year mean annual discharge was calculated for both the Enterprise and the Athens gaging stations using the same temporal span. Data were also acquired on historic flood crests for both Enterprise and Athens spanning 106 and 107 years, respectively. Using such a large temporal span insured that flood events prior to aerial reconisence of 1939 were represented. These data provided information on the frequency and magnitude of events throughout the study reach and time span. Frequency of events was determined annually, instead of monthly, because of the long span, approximately 10 years, between the photosets. The magnitude of flood events was classified by NOAA's Advanced Hydrologic Prediction Center, which includes an action stage, flood stage, moderate flood stage, and major flood stage. The designation between one stage to the next is a predetermined gage height threshold. The heights for each of these stages were different between the two gaging station due to differences in their channel geometry and gaging station datum.

In order to determine the effects that spatially heterogeneous soils may have on channel planform, information on soil name, texture, slope, and frequency of inundation was collected throughout the entire study length. Soil maps were created from GIS data acquired from the USDA Web Soil Survey in order to locate soil spatial variability throughout the study reaches. To adhere to vegetation shapefiles, soils were also constrained within Federal Emergency Management Agencies (FEMA) 2014 National Flood Hazard Layer (NFHL) 100 year flood zone.

Vegetation is well known to encourage infiltration and reduce surface and stream bank erosion. The existence of a riparian buffer was assessed spatially and temporally. Preliminary study had indicated that the riparian buffer was not continuous over space or time along the Hocking River. The extent of buffer continuity was observed to determine if it is associated with the planform variables. Quantifying the riparian buffer was completed in ArcGIS 10.2 through digitizing visible trees adjacent to either stream bank. The width of the riparian buffer zone was set to a maximum of 30 m from the digitized banks, which was selected according to the Virginia Department of Conservation and Recreation's Resource Protection Area Manual (Baird and Wetmore, 2006). The spatial extent of the 30-m wide buffer zones and the extent of the vegetated areas within them were then measured for each photoset. To study the change in channel-bordering vegetation over the 75-year study period, for each study reach, the amount of vegetation was expressed as a percentage of the buffer.

4.6 Statistical Analysis

The data collected on channel planform variables and the extent of vegetation in the buffer were analyzed statistically. Tests of comparison and tests of association were applied to different variables and sets of variables, in all cases with a 0.05 level of significance.

For each study reach, channel width and change in channel position were compared seperately between successive photoset years. For width, the comparison was between two photo averages (e.g., 1939 at 20.6 m and 1951 at 22.7 m) for each study reach. Channel position change was compared between two pairs of photosets and the positive or negative average position change (e.g., channel postion change was -0.1 m for 1939-1951 and 3.4 for 1951-1966). Finally, sinuosity was compared between each successive set of photo pairs for all 25 reaches. These analyses were conducted in Excel by using two-sample, one-tailed Student t-tests assuming samples of unequal variance for channel width and channel migration. The following hypotheses were tested:

1. Null Hypothesis ($H_{0:}\ \mu_1 = \mu_2$): There is no significant difference in sinuosity between successive photosets encompassing the 25 study reaches.
2. Research Hypothesis ($H_{0:}\ \mu_1 \neq \mu_2$): There is a significant increase or decrease in sinuosity between successive photosets encompassing the 25 study reaches.

3. Null Hypothesis ($H_{0:}\ \mu_1 = \mu_2$): There is no significant difference in the channel width between successive photosets for each reach.
4. Research Hypothesis (H_1: $\mu_1 > \mu_2$): There is a significant increase or decrease in the channel width between successive photosets for each reach.
5. Null Hypothesis ($H_{0:}\ \mu_1 = \mu_2$): There is no significant difference in the extent of channel migration between successive pairs of photosets for each reach.
6. Research Hypothesis (H_1: $\mu_1 > \mu_2$): There is a significant increase or decrease in the extent of channel migration between between successive paris of photosets for each reach.

Spearman's correlation was used to determine association between both the percent change in width, and separately rate of change in channel position, versus the percent change in vegetation in the riparian buffer. Spearman's correlation was used instead of Pearsons correlation because of outliers. Correlation analyses were completed for each of the 25 study reaches for each of the six pairs of successive years of photographs as well as for the entire dataset between percent change in vegetation and percent change in channel width, and percent change in vegetation and rate of change in channel position. Spearman values range between +1 and -1, with positive values indicating that both variables tend to increase and decrease together, and a negative correlation indicating that when one variable increases the other tends to decrease. The closer the coefficient is to +1 or -1 the stronger the correlation. Correlation coefficients (r_s) were tested for statistical significance at the 0.05 level using the following standard formula, where n = the sample size:

$$t_{calc} = r_s\sqrt{\frac{n-2}{1-r_s}}$$

1. Null Hypothesis ($H_{0:}\ \mu_1 = \mu_{2)}$: There is no significant correlation between the percent change in riparian vegetation and rate of change in channel position for each successive pair of photosets over the entire upper Hocking River.

2. Research Hypothesis (H_1: $\mu_1 > \mu_2$): There is a significant positive or negative correlation between the percent change in riparian vegetation and rate of change in channel position for each successive pair of photosets over the entire upper Hocking River.
3. Null Hypothesis (H_0: $\mu_1 = \mu_2$): There is no significant correlation between the percent change in riparian vegetation and percent change in channel width for each successive pair of photosets encompassing all 25 reaches.
4. Research Hypothesis (H_1: $\mu_1 > \mu_2$): There is a significant positive or negative correlation between the percent change in riparian vegetation and percent change in channel width for each successive pair of photosets encompassing all 25 reaches.

4.7 Land-Use History

Once river segments of minimal and greatest planform change and their period of change were identified, land use/land cover history was analyzed using the historical air photos. These photo sets were used to determine if the episodes of planimetric change were associated with major episodes of land use/land cover change directly in the floodplain or located in the tributaries of the upper Hocking River. Association was evidenced by spatial and temporal proximity of land use/land cover changes and planform changes. While transportation, agriculture, and urbanization were observed on the air photos, the spatial and temporal data on mining were obtained through the Ohio Department of Natural Resources (ODNR) Divisions of Geological Survey and Mineral Resources. Given the decadal gap between photo sets, documentation from the state agencies aided in assessing in a more qualitative way if modification of the landscape contributed to planform change. The amount of data collected was dependent on type, size, establishment, and abandonment of the particular land use/land cover. While the quantification of the change in land use/land cover is possible, it is not within the scope of this research to determine the exact percentages of change for the upper Hocking River basin.

CHAPTER 5: RESULTS

Over the 75 years considered in this study, the upper Hocking River as a whole has generally remained stable with respect to some variables while exhibiting significant changes in others. In general, urbanization changed little over 75 years. Air photo interpretation showed little increase of urban sprawl on the floodplain. During this time span, mining techniques changed from underground coal extraction to surface extraction of primarily sand and gravel. US Route 33 was constructed between 1951 and 1976. In addition, several historic flood events occurred over the 75-year span.

Different study reaches (Figure 5) showed varying amounts of planimetric activity. Among the 25 reaches, a total of 58 meander loops were identified within 11 of the reaches (Table 4). A total of 16 meander loop cut-offs occurred over the 75 years along the upper Hocking River. Of these, 12 were artificial, while three were natural. There was also one meander loop cut-off that was produced in combination between human (artificial) and environmental (natural) variables. As of 2013, the upper Hocking River had an average channel width of 37 m and a sinuosity index of 1.5. Temporally, the majority of the planimetric change occurred between 1951 and 1988.

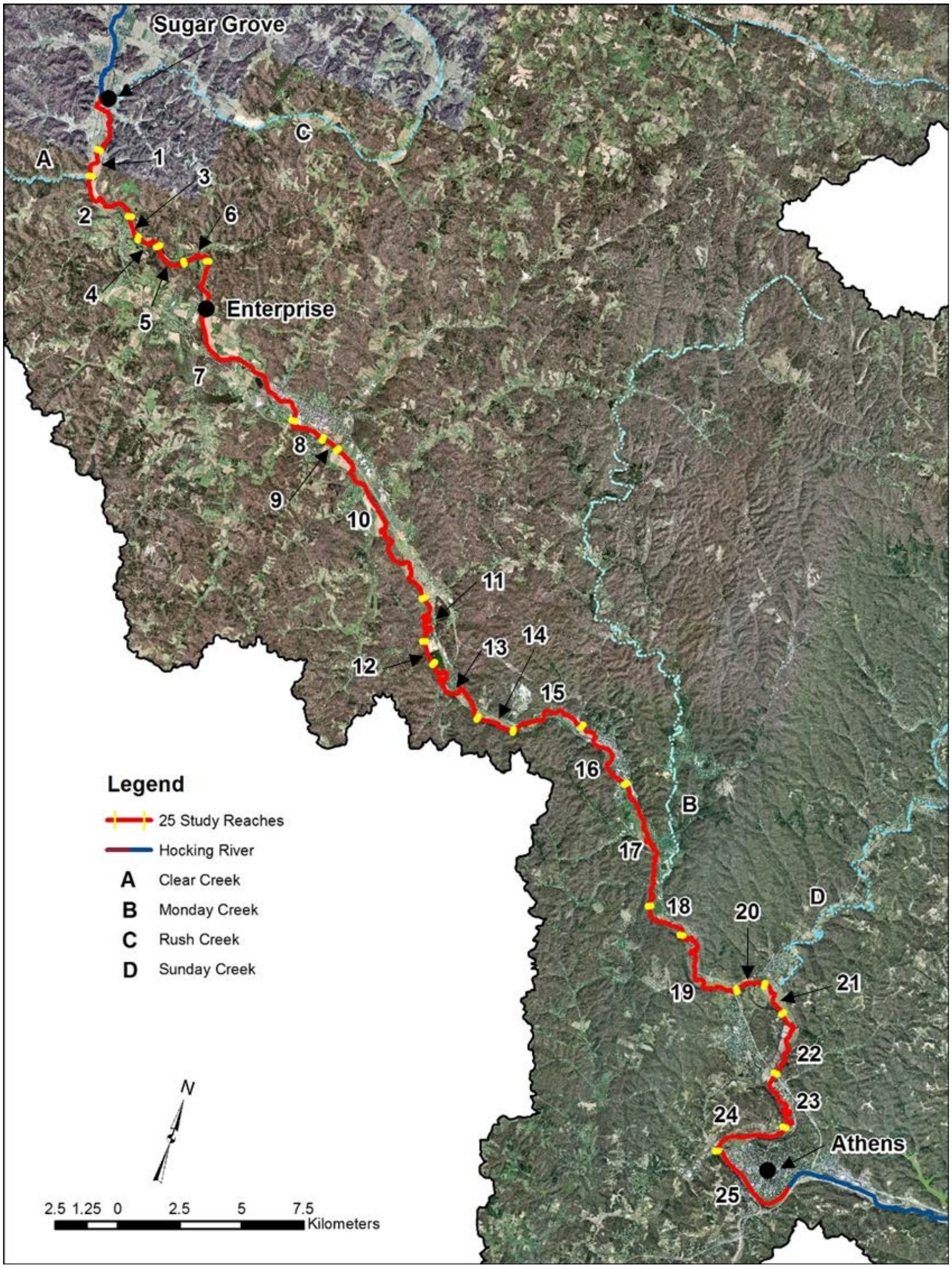

Figure 5. The red line represents the studied portion of the Hocking River, while the numbers annotate the locations of the 25 smaller study reaches. Base map source: 2013 digital orthophotographs (OGRIP, 2013). River flow is northwest to southeast.

Table 4. Location and name of the 58 meander loops.

Reach	Number	Meander loops
6	3	Aq-Aq2
10	7	Ag-Ag1, Af-Af3, Ai
11	4	Ae-Ae3
13	3	Ad, Ar-Ar1
15	3	Aj-Aj2
17	8	Ac-Ac6, Ab
19	9	Ak1, Al, Am-Am6
21	3	An-An2
22	5	Aa, Ao-Ao3
23	6	A-F
25	7	Ap-Ap6

5.1 Human Impact Variables

5.1.1 Coal and Mineral Industries

Between 1888 and 1990 714 mines were established and later abandoned within Athens, Perry, and Hocking Counties (Figure 6). The only currently active underground mines in the Hocking River basin are located at the intersection of Athens, Morgan, and Perry Counties and are owned by the Buckingham Coal Company of Glouster, Ohio (ODNR, 2013) (Figure 7). Coal extraction in Ohio between 1800 and 1948 was primarily accomplished through underground mining. Given the advancements in engineering during WWII, underground mining was transitioned towards surface mining, which accounted for more than half of Ohio's production in coal by 1948. Similarly to underground mining, the majority of surface mines that existed between 1914 and 1995 were located along a narrow swath running in a northeasterly direction between Athens County and Hocking County. Furthermore, the highest concentration in the swath was located in the Monday Creek watershed (Figure 8).

Currently, the only surface mining in progress along the study reach is industrial mineral extractions of sand and gravel occurring within the Hocking River floodplain (Figure 9).

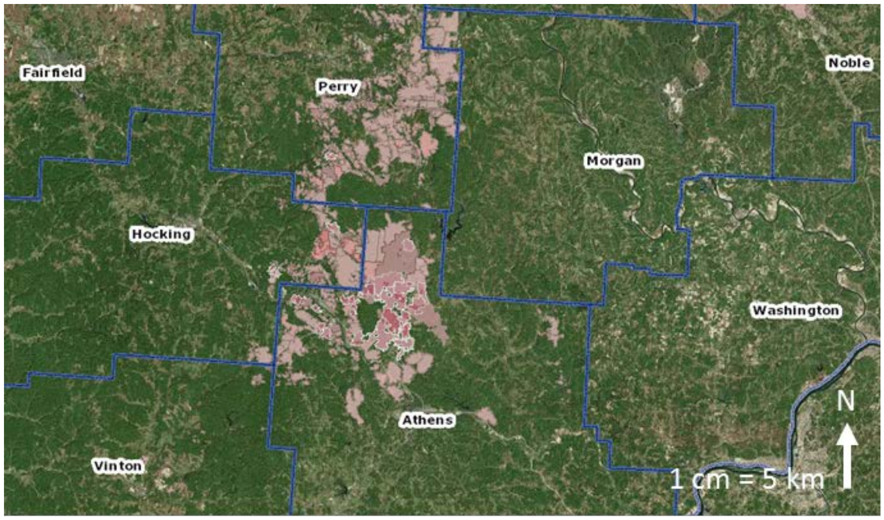

Figure 6. The pink polygons represent the location of all the underground coal mines abandoned between 1888 and 1990 (ODNR, 2013).

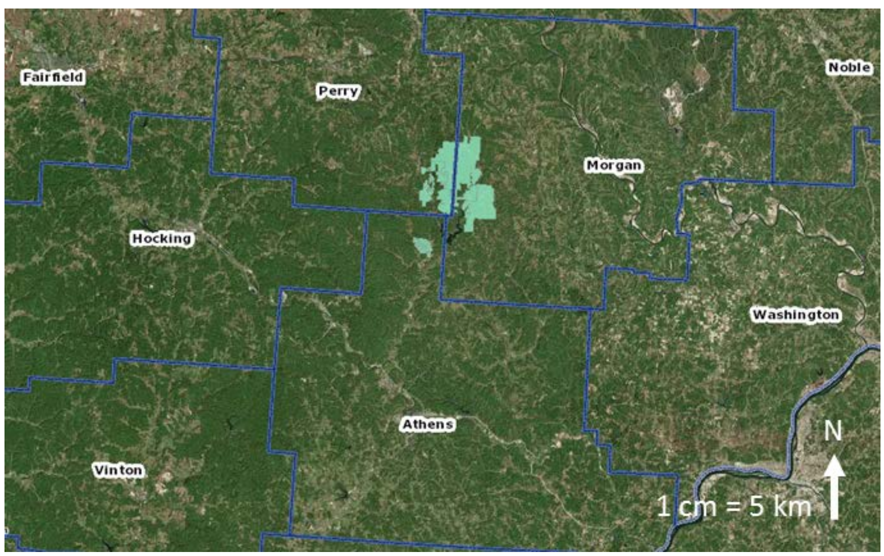

Figure 7. The turquoise polygon that straddles Perry, Morgan, and Athens Counties is the only active underground mine in the Hocking River drainage basin (ODNR, 2013).

Of these, the only ones in operation in 2015 are those labelled B, C, D, and F on Figure 9. These mines were established at different times along the floodplain. Mines D and G were established between 1951 and 1966, while mines A and E were established between 1966 and 1976; they are located in Study Reaches 15, 19, 10, and 15, respectively. Furthermore, mine C was established between 1976 and 1988, while mines B and F were established between 1988 and 2004, in Study Reaches 12, 10, and 17, respectively (ODNR, 2014).

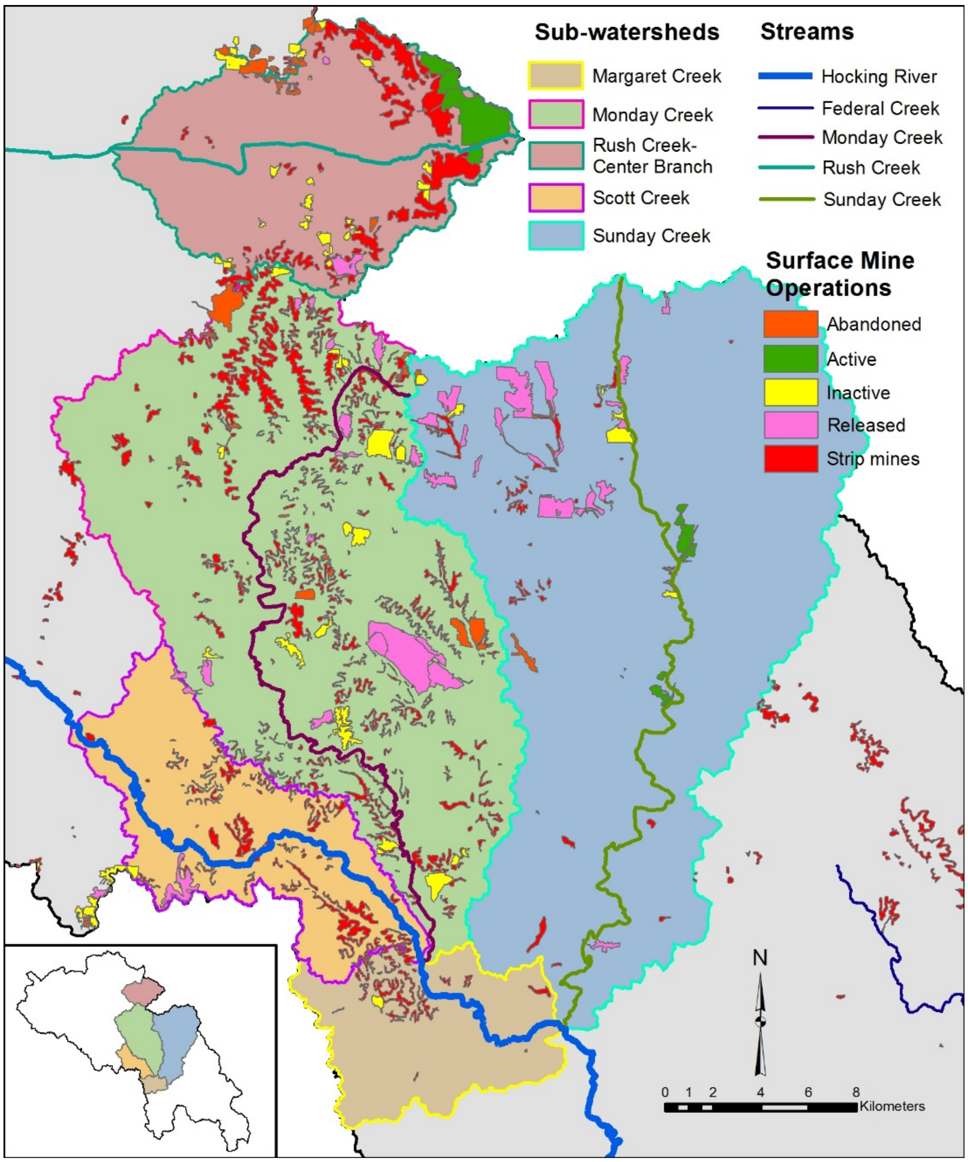

Figure 8. Location of the highest concentration of surface mines in the Hocking River drainage. Data were adapted from ORDNR (2013).

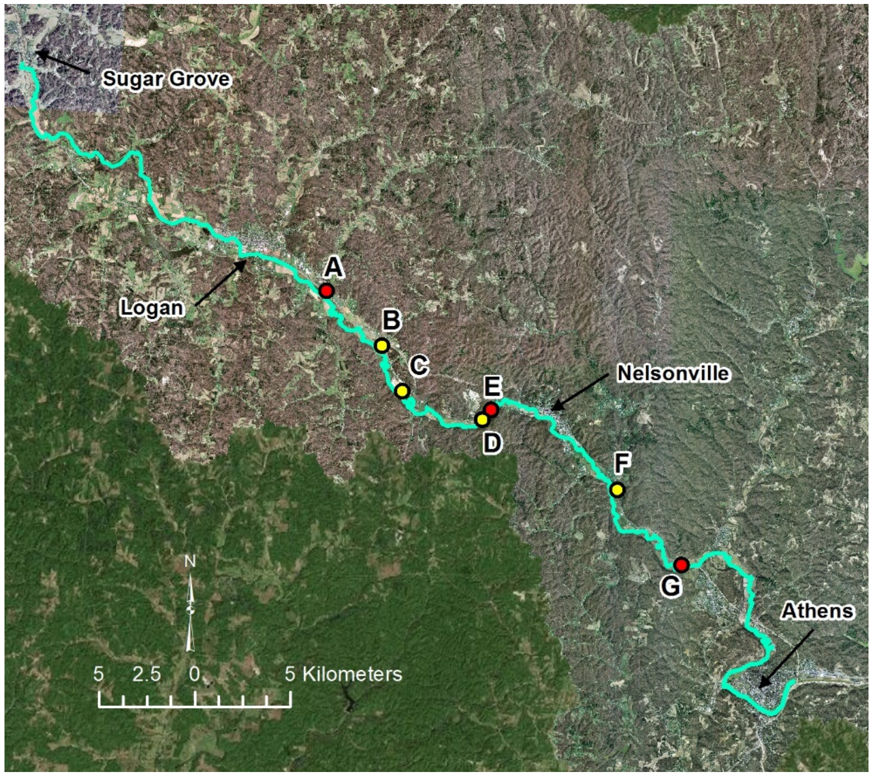

Figure 9. Industrial mineral operation on the Hocking River (blue line) floodplain. Yellow dots and red dots represent active and inactive sand and gravel extraction sites, respectively. River flow is northwest to southeast.

5.1.2 Channel Realignment and Channelization by US Route 33

Historically, transportation routes have been constructed along paths of least resistance, for which river valleys and associated floodplains are the ideal setting. While numerous roads weave through the topography of the Hocking River drainage basin, US Route 33 is the primary route that connects the major cities located along the Hocking River. However, the current US Route 33 configuration has been modified extensively from the existing location prior to 1951. The new configuration involved two phases of construction, which occurred between 1951 and 1966 and between 1966 and 1976, at various locations throughout the studied portion of the Hocking River.

Between 1951 and 1966 the construction of US Route 33 realigned the Hocking River at three locations. The first location occurred in Study Reach 1 above the confluence of the Hocking River and Clear Creek. This realignment decreased the length of the river by approximately 16 m and shifted an entire section to the left (directional shifts are viewed facing downstream) by a maximum of approximately 26 m (Figure 10). The second was located in Study Reach 2 below the confluence of the Hocking River and Clear Creek. This realignment decreased channel length approximately 50 m and shifted the channel a minimum of 22 m and maximum of 50 m to the left (Figure 11). The last realignment occurred in Study Reach 17 just south of Nelsonville above the confluence of the Hocking River and Monday Creek, and resulted in the termination of meander loops Ac5 and Ac6, which reduced the channel length by 514 m (Figure 12).

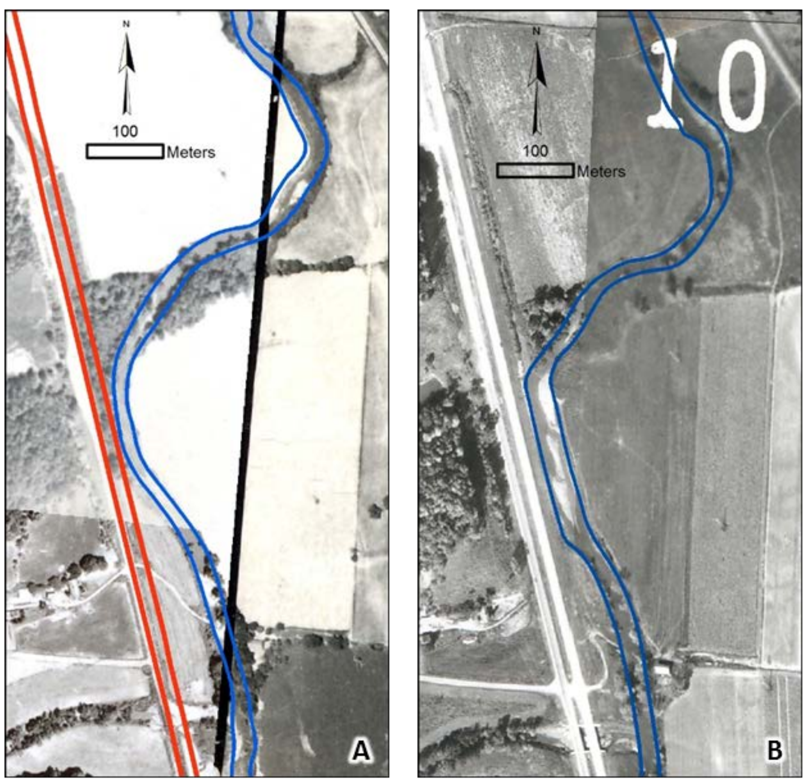

Figure 10. Channelization of the Hocking River (blue line) in Study Reach 1 as the result of US Route 33 between 1951 (A) and 1966 (B). The red lines indicate where future placement of the highway would have crossed the earlier photo. River flow is from north to south.

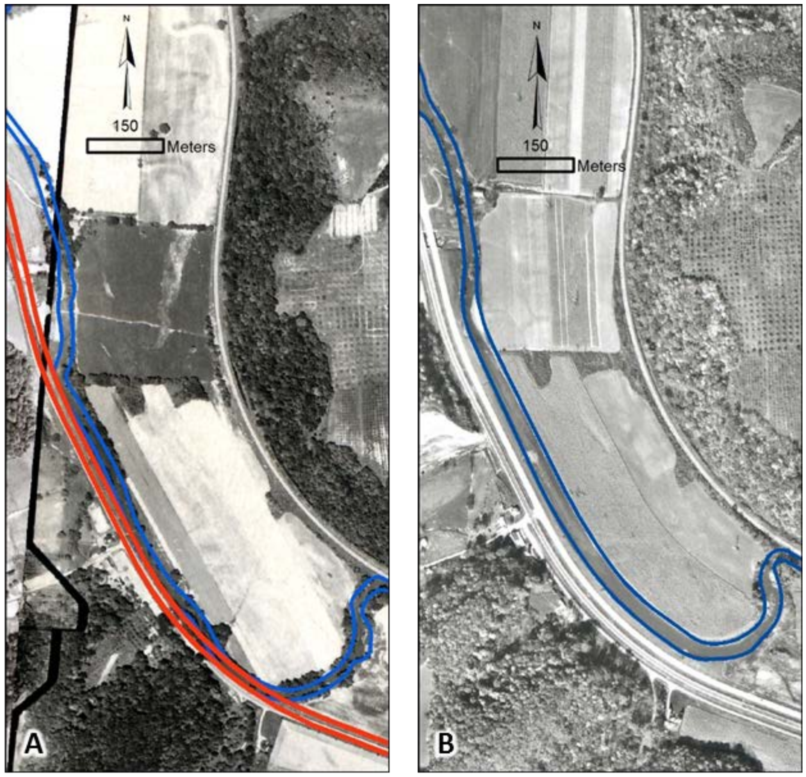

Figure 11. Channelization of the Hocking River (blue line) in Study Reach 2 as the result of US Route 33 between 1951 (A) and 1966 (B). The red lines indicate where future placement of the highway would have crossed the earlier photo. River flow is north to south.

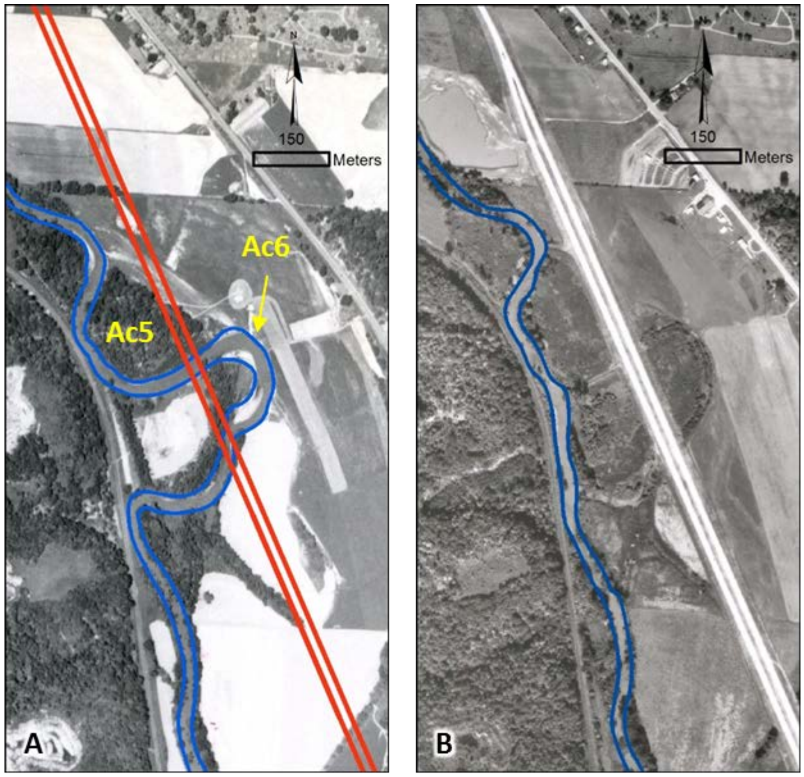

Figure 12. Channelization of the Hocking River (blue line) in Study Reach 17 as the result of US Route 33 between 1951 (A) and 1966 (B). The red lines indicate where future placement of the highway would have crossed the earlier photo. River flow is north to south.

Between 1966 and 1976, road construction of US Route 33 was completed resulting in two realignments of the Hocking River at Logan, OH. The realignment in western Logan (Study Reach 8) reduced channel length by approximately 92 m (Figure 13), while the realignment in eastern Logan (Study Reach 10) shifted the channel as much as 84 m to the right (Figure 14). The third realignment, also located in Study Reach 10, occurred between the Route 328 bridge and the confluence of the Hocking River and Threemile Creek. That project terminated meander loops Ag and Ag1. When combined, the two channelized sections in Study Reach 10 reduced the channel length by 346 m (Figure 15).

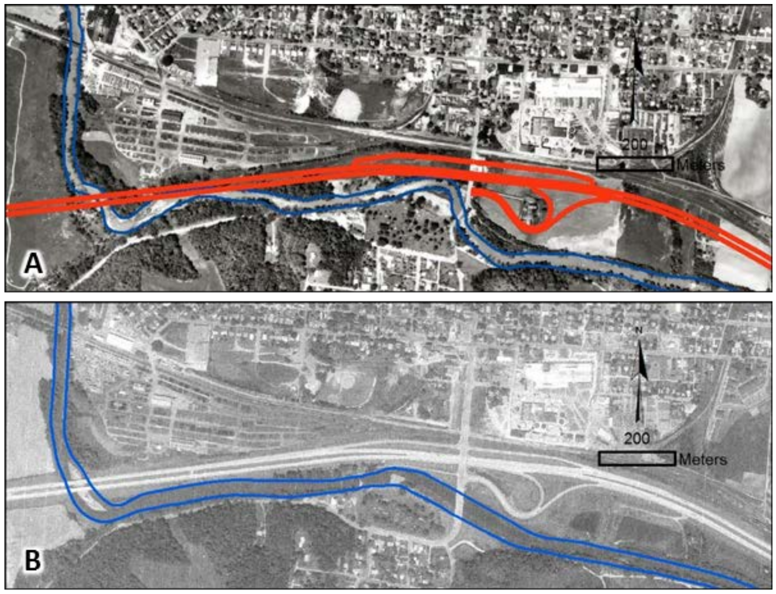

Figure 13. Channelization of the Hocking River (blue line) in Study Reach 8 as the result of US Route 33 between 1966 (A) and 1976 (B). The red lines indicate where future placement of the highway would have crossed the earlier photo. River flow is west to east.

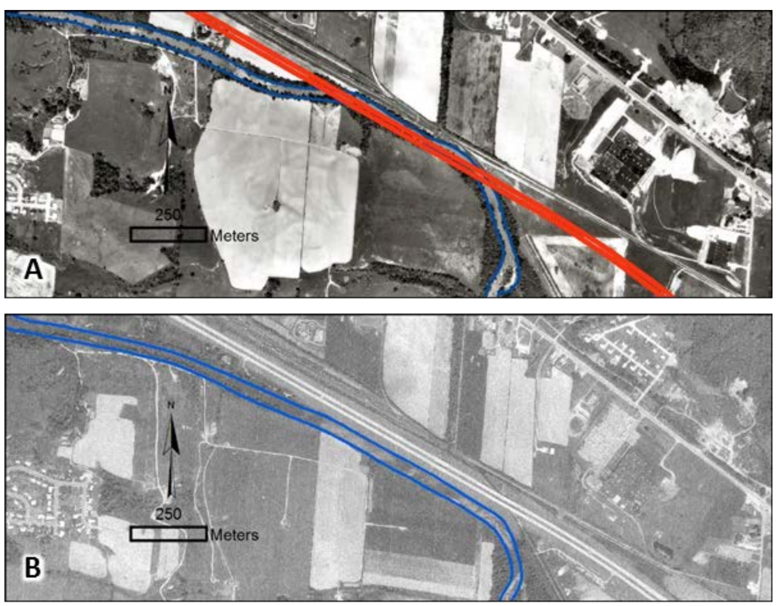

Figure 14. Channelization of the Hocking River (blue line) in Study Reach 10 as the result of US Route 33 between 1966 (A) and 1976 (B). The red lines indicate where future placement of the highway would have crossed the earlier photo. River flow is northwest to southeast.

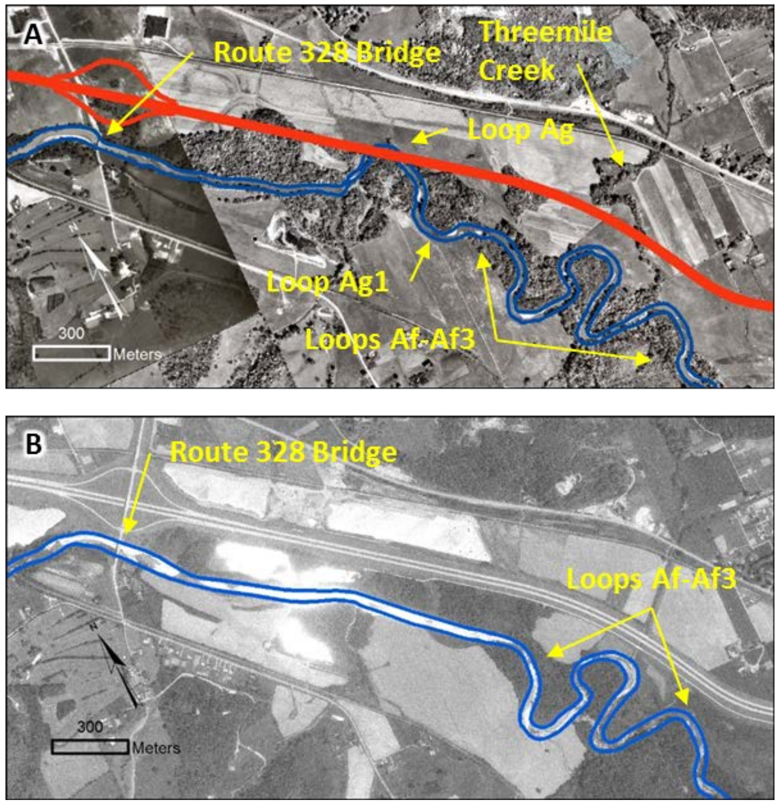

Figure 15. Channelization of the Hocking River (blue line) in Study Reach 10 as the result of US Route 33 terminating meander loops Ag and Ag1 between 1966 (A) and 1976 (B). The red lines indicate where future placement of the highway would have crossed the earlier photo. River flow is northwest to southeast.

5.1.3 Artificial Channelization Unrelated to US Route 33

While the aforementioned realignments were the direct results of construction related to US Route 33, three others were unrelated to the establishment of US Route 33, resulting instead from the mitigation of loss of property and further damage by lateral migration of the river. The first of these channelizations occurred between 1976 and 1988 in Study Reach 11 on meander loop Ae3, located near Haydenville, OH, (Figure 16). This channelization shortened Study Reach 11 by 185 m from its original length of more than 2.5 km. The second channelization occurred between 1939 and 1951 in Study Reach 19 approximately 1.7 km west of Chauncey. This event terminated meander loops Am3 and Am4, which were combined into Am2 for further analysis (Figure 17). This same construction decreased the length of Study Reach 19 by 77 m to

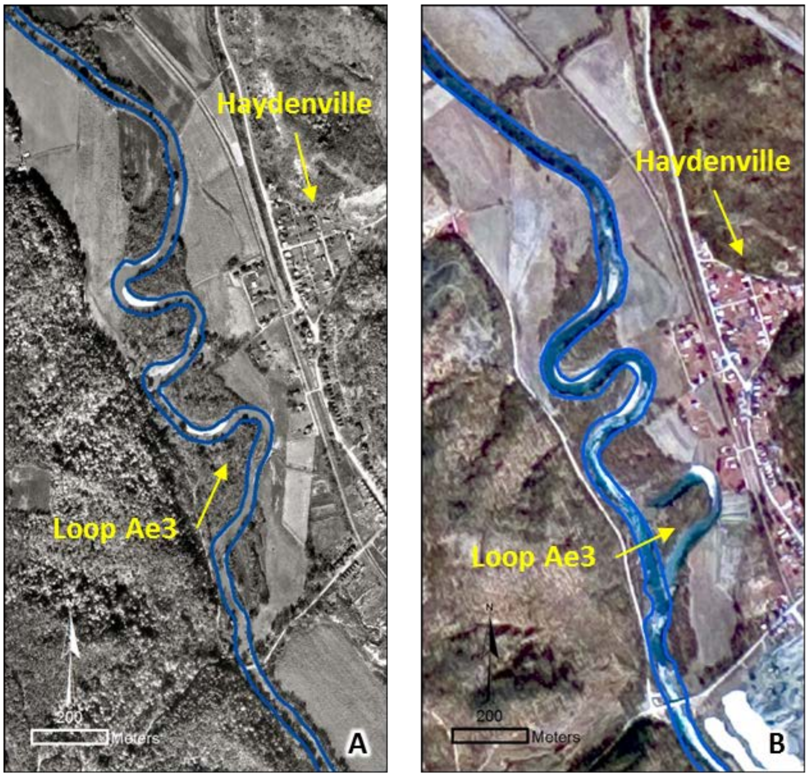

Figure 16. Channelization and termination of meander loop Ae3 in Study Reach 11 between 1976 (A) and 1988 (B) as a measure to mitigate further channel migration and property damage in Haydenville, OH. River flow is north to south.

approximately 5,028 m. The third and largest of the channelizations not related to US Route 33 is located in Study Reach 25 at Athens, OH. This work was undertaken between 1968 and 1971 by the US Army Corps of Engineers in response to the 1968 flood, which crested at 7.5 m and completely inundated the area encompassed by West and East Green of Ohio University (Hocking Conservancy District, 2012; NOAA-AHRS, 2014). The channelized reach extends from Whites Mill, at the intersection of Routes 56 and 682, downstream to approximately 3.3 km past the Stimson Avenue. bridge (Figure 18). The channelization reduced this study reach length by approximately 598 m to 5.1 km.

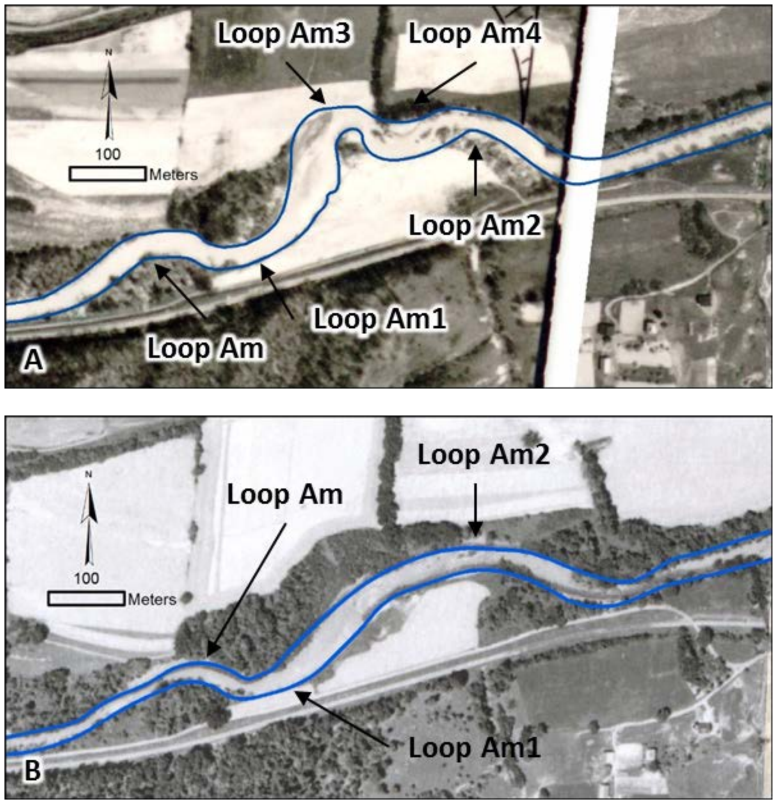

Figure 17. Channelization and termination of meander loops Am3 and Am4 in Study Reach 19 between 1939 (A) and 1951 (B) as a measure to prevent further channel migration into agricultural land. River flow is west to east.

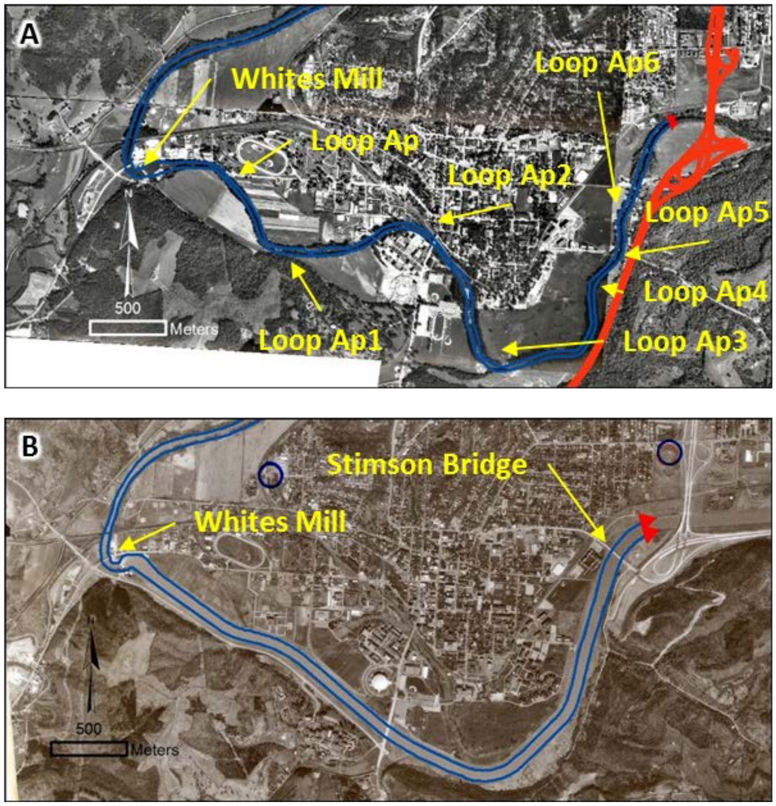

Figure 18. Channelization and termination of meander loops Ap-Ap5 in Study Reach 25 between 1966 (A) and 1976 (B) as flood mitigation due to the 1968 flood in Athens, OH. The red lines indicate where future placement of the highway would have crossed the earlier photo. River flow is west to east.

5.2 Environmental Variables

5.2.1 Discharge and Flood Events

Annual mean discharge data over 82 years for both the Enterprise (Figure 19) and Athens (Figure 20) gaging stations display similar sequences, which is indicative of gaging stations in consecutive locations within a drainage basin. This trend can be seen in the mean monthly discharge for the Enterprise and Athens gaging stations over 82 years of data. (Figure 21). This range of years selected for each gaging station's discharge data is based on the data available from the United States Geological Survey's National Water Information System (water.usgs.gov), and includes the date range of aerial imagery used in this thesis.

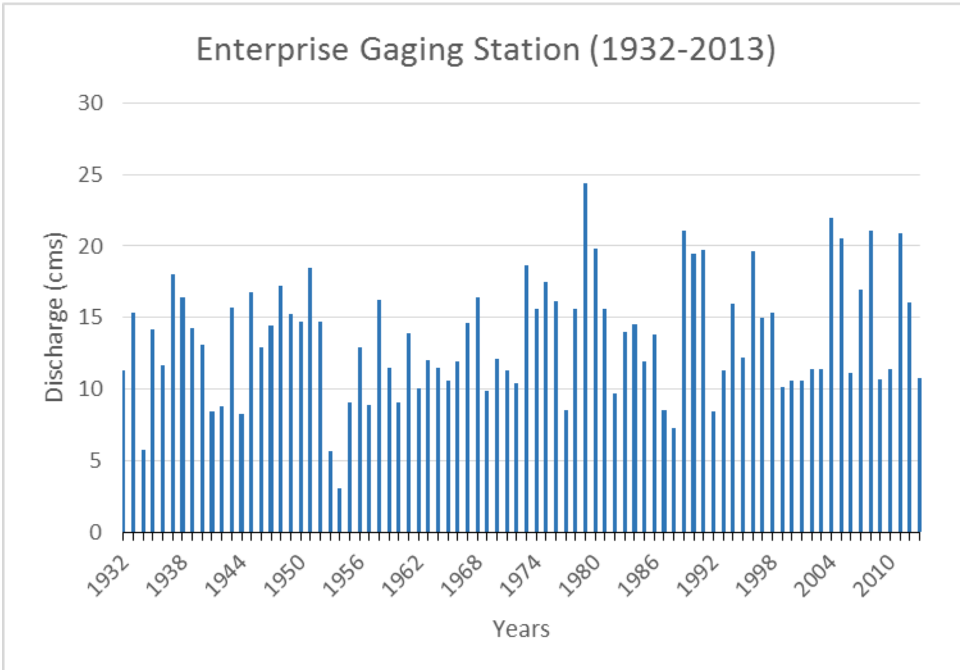

Figure 19. Mean annual discharges at the Enterprise gaging station.

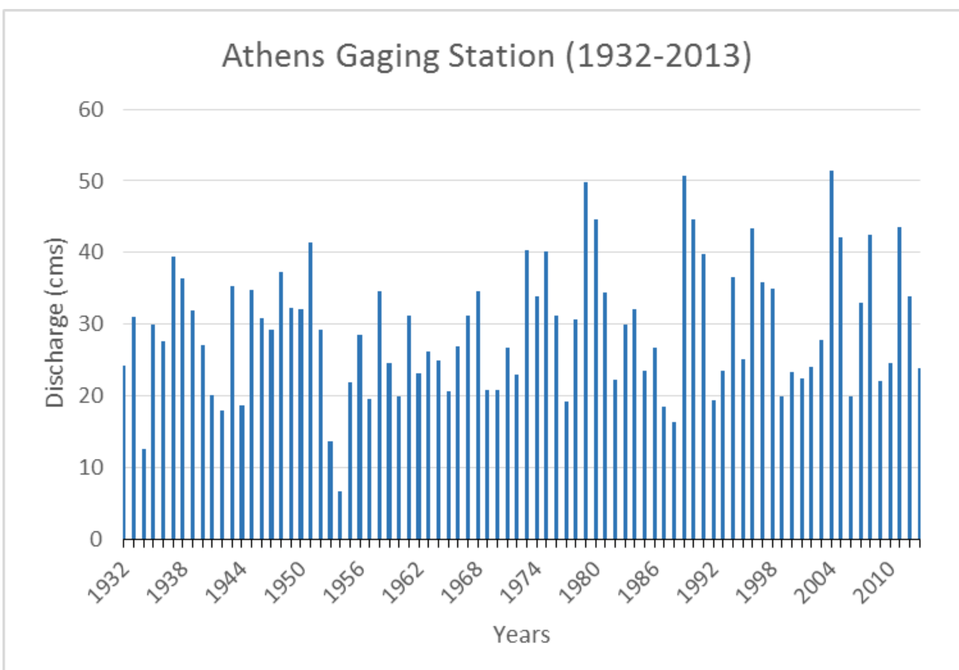

Figure 20. Mean annual discharges at the Athens gaging station.

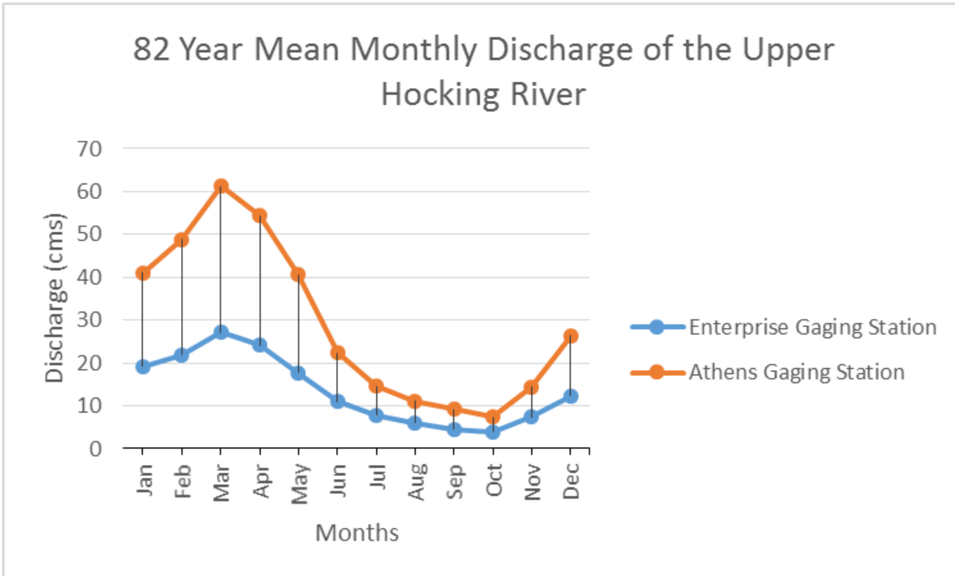

Figure 21. Long-term mean monthly discharge for the Enterprise and Athens gaging stations.

Thirty-three flood events occurred between 1907 and 2013 at the Enterprise gaging station. Four classes of events are distinguished by the National Weather Service (NOAA-AHPC, 2014) based on gage heights, and include action stage, flood stage, moderate flood stage, and major flood stage. For the Hocking River at Enterprise, the corresponding gage heights for the four types of high flow are 2.74 m, 3.65 m, 4.97 m, and 6.40 meters, respectively. Over the 75-year study span for this thesis, there were no action stage, 21 flood stage, eight moderate stage, and one major flood stage event. One moderate and one major flood stage event occurred prior to 1939 (Figure 22).

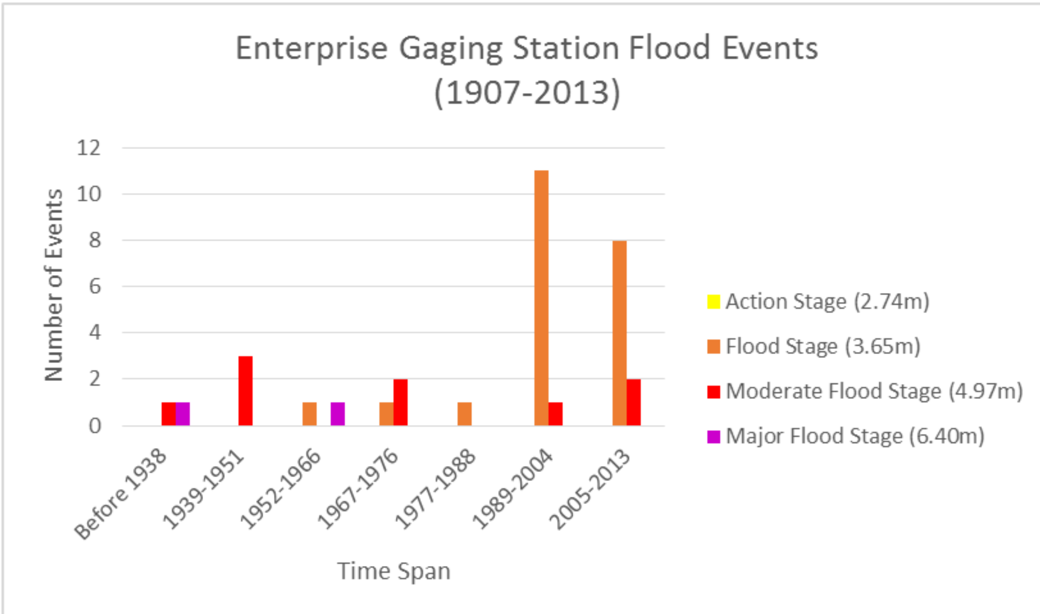

Figure 22. Flood events recorded at the Enterprise gaging station.

Analysis of data from the Athens gaging station revealed that 29 flood events occurred between 1907 and 2014. Given that the Athens gaging station is farther downstream and at a different datum than Enterprise, different gage heights were established, which included action stage (5.48 m), flood stage (6.09 m), moderate flood stage (6.70 m), and major flood stage (8.53 m). Over the course of the 75-year study span, Athens experienced five action stages, 12 flood stages, and nine moderate flood stage events. Three moderate stage events occurred prior to 1939 (Figure 23).

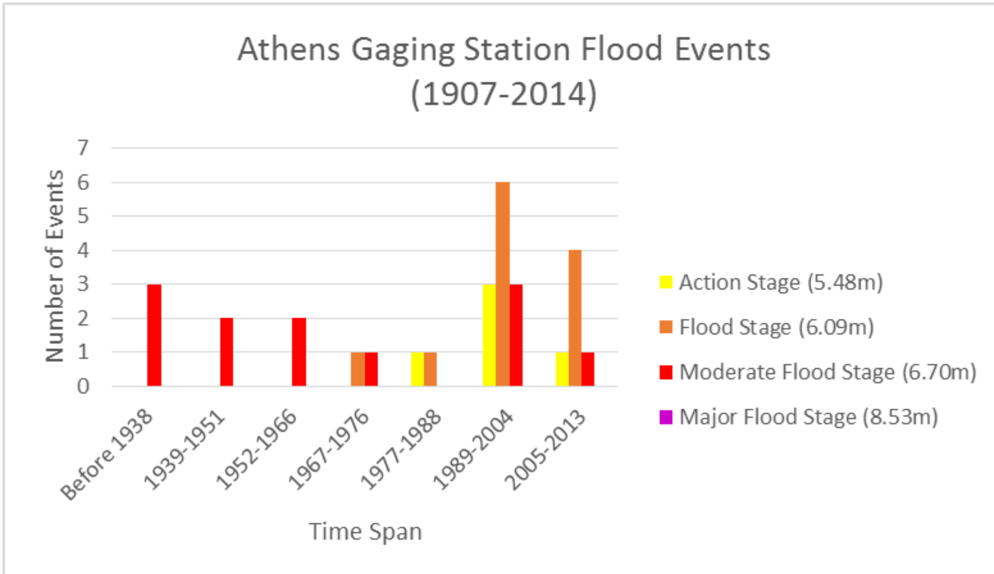

Figure 23. Flood events recorded at the Athens gaging station.

5.2.2 Vegetation

Varying amounts of woody deciduous vegetation grew along all 25 study reaches within the designated 30-m wide riparian buffer. The extent of tree cover in the riparian buffer exhibited an overall increasing trend between 1939 and 2013 (Figure 24). During this time span it was also determined that vegetation increased by 36%. All Study Reaches except 1, 3, 9, and 21 had an initial increase in riparian vegetation between 1939 and 1951. Of the 25 reaches, 21 exhibited a generally positive trend in vegetation growth in all photo years after 1951. While these overall trends were positive, all reaches experienced some fluctuation in the extent of vegetation from year to year (Table 5). For example, Study Reach 1 had a positive long-term trend, however the riparian vegetation decreased from 35% of the total buffer area in 1951 to 19% in 1966 before increasing again in later years.

Ten reaches exhibited general trends of no change or decreasing vegetation in the riparian buffer over the study period. Reaches 21, 22, and 25 displayed negative trends in vegetation within the riparian buffer. The largest of these reductions occurred in Study Reach 25, where vegetation decreased from 44% in 1939 to 6% in 2013 of the total buffer area. Study Reaches 5, 7, 13, 16, 17, and 18 experienced periods in which vegetation percentages did not change.

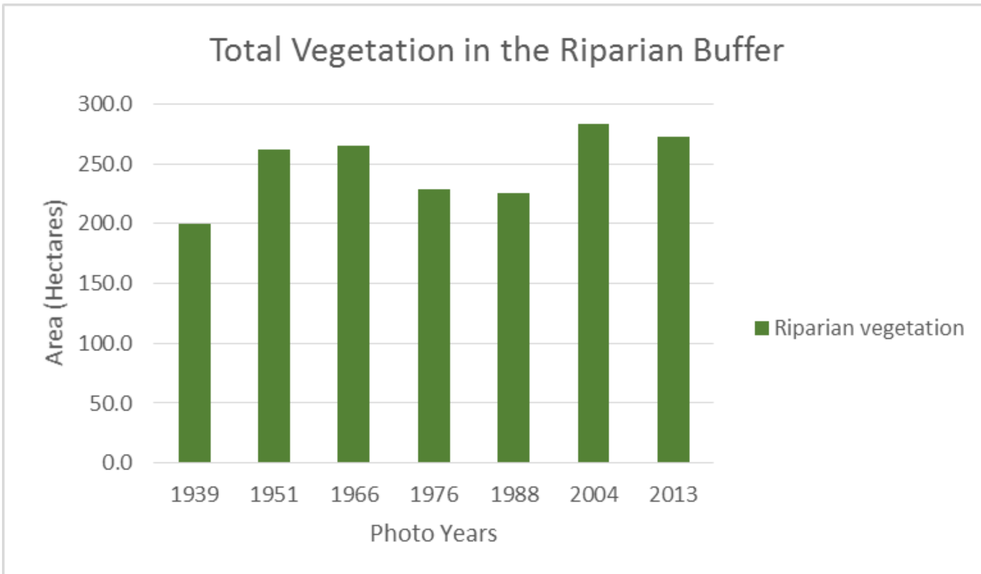

Figure 24. Total extent of riparian buffer within the 30 m.

Table 5. Total (hectares) and percentage vegetation in the riparian buffer by study year.

		1939	1951	1966	1976	1988	2004	2013
Reach 1	Total Buffer	8.1	8.1	8	8	8	8	8
	% of Buffer	37	35	19	40	35	52	47
Reach 2	Total Buffer	19.6	19.5	19.1	19.0	18.9	18.8	18.9
	% of Buffer	37	48	40	49	39	60	52
Reach 3	Total Buffer	6.1	6.0	6.0	6.1	6.1	6.1	6.1
	% of Buffer	25	38	32	42	27	43	32
Reach 4	Total Buffer	6.3	6.4	6.5	6.5	6.5	6.7	6.6
	% of Buffer	32	38	34	50	40	54	48
Reach 5	Total Buffer	9.5	9.5	9.4	9.4	9.5	9.4	9.5
	% of Buffer	53	68	73	71	64	62	62

Table 5. continued.

Reach 6	Total Buffer	7.7	7.7	7.7	7.6	7.5	7.3	7.2
	% of Buffer	51	58	66	63	57	67	60
Reach 7	Total Buffer	55.2	55.2	55.3	55.1	55.2	55.1	55.2
	% of Buffer	34	44	41	41	37	48	41
Reach 8	Total Buffer	10.2	10.0	10.2	9.6	9.8	9.6	9.7
	% of Buffer	50	55	43	20	28	57	48
Reach 9	Total Buffer	4.6	4.5	4.6	4.5	4.6	4.6	4.6
	% of Buffer	52	40	41	43	59	73	66
Reach 10	Total Buffer	53.1	56.5	56.1	53.8	50.7	52.0	52.0
	% of Buffer	53	65	67	57	61	75	66
Reach 11	Total Buffer	13.5	14.4	15.2	15.4	14.3	15.3	15.3
	% of Buffer	46	52	63	53	55	66	65
Reach 12	Total Buffer	6.2	6.2	6.1	6.1	6.1	6.0	6.1
	% of Buffer	70	80	87	73	66	97	87
Reach 13	Total Buffer	24.4	25.2	26.7	26.1	26.1	26.9	27.1
	% of Buffer	54	58	65	65	63	76	70
Reach 14	Total Buffer	9.8	9.9	9.9	9.8	9.8	9.8	9.8
	% of Buffer	43	50	46	58	62	66	68
Reach 15	Total Buffer	21.9	22.1	22.3	22.2	22.6	22.6	22.7
	% of Buffer	19	58	66	57	56	74	68
Reach 16	Total Buffer	21.5	21.6	21.6	21.6	21.6	21.6	21.6
	% of Buffer	14	40	44	38	42	55	55
Reach 17	Total Buffer	37.1	37.9	34.8	35.0	35.8	37.0	37.2
	% of Buffer	33	53	53	49	56	64	65
Reach 18	Total Buffer	12.6	12.7	12.7	12.6	12.7	12.7	12.8
	% of Buffer	46	65	64	64	61	68	71
Reach 19	Total Buffer	31.3	30.7	30.3	30.4	30.9	30.9	31.2
	% of Buffer	40	64	65	57	63	74	72
Reach 20	Total Buffer	7.4	7.4	7.4	7.4	7.5	7.4	7.4
	% of Buffer	34	43	42	36	43	56	50
Reach 21	Total Buffer	9.5	9.6	9.7	9.8	10.0	10.3	10.4
	% of Buffer	64	62	69	56	49	51	46
Reach 22	Total Buffer	19.3	19.5	19.8	19.6	19.2	18.5	18.6
	% of Buffer	64	73	63	64	48	61	69
Reach 23	Total Buffer	18.1	19.4	20.2	20.3	21.0	21.6	21.7
	% of Buffer	55	64	72	73	64	70	75

Table 5. continued.

Reach 24	Total Buffer	19.4	19.4	19.5	19.5	19.4	19.5	19.6
	% of Buffer	53	59	58	39	47	63	82
Reach 25	Total Buffer	35.0	34.8	35.0	31.4	31.3	31.4	31.4
	% of Buffer	44	50	51	2	1	5	6

5.2.3 Floodplain Soils

Sixteen soil series were identified within the 100-year inundation zone of the studied portion of the Hocking River (all 25 reaches) (Table 6). The Chagrin silt loam (Cg) is distributed in all 25 reaches, and is classified as a floodplain soil existing on frequently flooded, 0 to 3% slopes. Other floodplain soils identified were the Chagrin loam (Cd), Newark silt loam (Nn), and Orrville silt loam (Or). The Chagrin loam is located in Reach 24 on slopes between 0 and 3%. Newark silt loam is found on slopes between 0 and 2% in Study Reaches 7 and 23, whereas the Orrville silt loam was only found in Reach 7 on slopes between 0 and 3%. The remaining soils along the studied portion of the river, also silt loams and loams, are not floodplain soils but exist on slopes ranging between 0 and 70% in Study Reaches 15, 16, 20, 22, 23, 24, and 25, typically on river terraces above the active floodplain. The predominant soil that the Hocking River flows through is the Chagrin silt loam. Because all study reaches flow through a homogeneous soil class, soils were not included further in the analysis of variables influencing river planform.

Table 6. Soil types along the Hocking River.

Symbol	Map Unit Name	Reaches
BkF	Berks-Westmoreland silt loams, 40 to 70% slopes	24
Cd	Chagrin loam, rarely flooded	24
Cg	Chagrin silt loam, frequently flooded	1 to 25
DtF	Dekalb-Westmoreland complex, 40 to 70% slopes	20
GmC	Glenford silt loam, 8 to 15% slope	16
LkB	Licking silt loam, 3 to 8% slope	24
LkC	Licking silt loam, 8 to 15% slope	25
NeC	Negley loam, 8 to 15 slope	16
Nn	Newark silt loam, frequently flooded	7, 23
Or	Orrville silt loam, frequently flooded	7
Pg	Pits and gravel	15, 19
RcD	Richland loam, 15 to 25% slopes	16, 24
RcE	Richland loam, 25 to 40% slopes	15
Ud	Udorthents, loamy	16, 22, 23, 25
WhE	Westmoreland-Guernsey silt loams, 25 to 40% slopes	16
WhF	westmoreland-Guernsey silt loams, 40 to 70% slopes	20

5.3 Planimetric Variables

5.3.1 Asymmetry

Because asymmetry is measured at meander loops, this analysis used the 58 distinct meander loops found along the river, some of which existed for only part of the study period. In total, the 58 meander loops occurred in 11 study reaches along the river (Table 4). Calculations of the asymmetry index show that of the 58 meander loops, 56% exhibit upstream (negative) asymmetry; 42% have downstream (positive) asymmetry; and 2% are symmetrical (Appendix A) (Table 7). While the asymmetry index indicates the orientation of the maximum bend curvature of the meander loops, visual inspection of successive photo years reveals, with the exception of the above-mentioned loops for specific time period, that every meander loop along the upper Hocking River was translating downstream over the study period (Figure 25).

Table 7. Among the 58 meanders loops, these eight represent the only symmetrical loops.

Year	1939	1951	1966	1976	1988	2004	2013
Meander							
Ac2						X	
Ac3						X	
Ae		X				X	
Af1						X	
Af3					X		
Ai					X		
An				X	X		
Ao1					X		

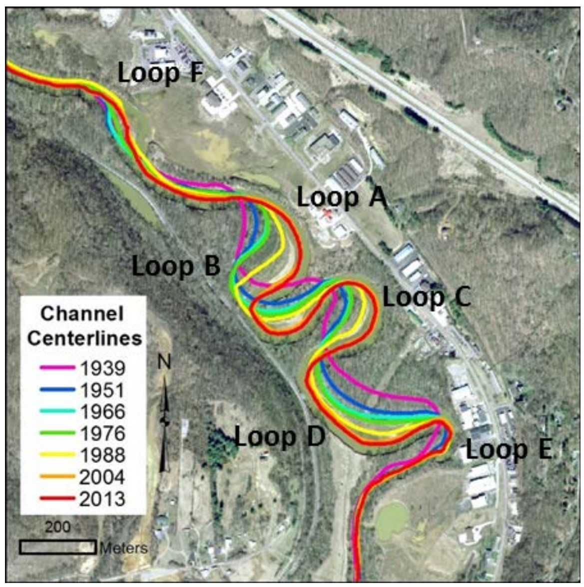

Figure 25. Asymmetry of meander loops A-F in Study Reach 23. River flow is northwest to south.

As previously mentioned in Section 5.1.2, specific meander loops were terminated either by channelization due to US Route 33 or through flood and property damage mitigation. These changes affected asymmetry in Study Reaches 10, 11, 17, 19, and 25. Accompanying road construction of US Route 33 between 1951 and 1976, meander loops Ag and Ag1 (Figure 26a) in Study Reach 10 and meander loops Ac5 and Ac6 (Figure 26b) in Study Reach 17 were eliminated. Meander loop Ae (Figure 26c) in Study Reach 11 was terminated between 1976 and 1988 in order to reduce further lateral migration towards houses in Haydenville, OH, whereas meander loops Am3 and Am4 in Study Reach 19 were terminated between 1939 and 1951 to prevent further lose in agricultural land (Figure 17). Lastly, meander loops Ap through Ap6 (Figure 27) in Study Reach 25 were eliminated by the channelization and relocation of the Hocking River after the 1968 flood in Athens. In these cases asymmetry was either permanently or temporarily reset.

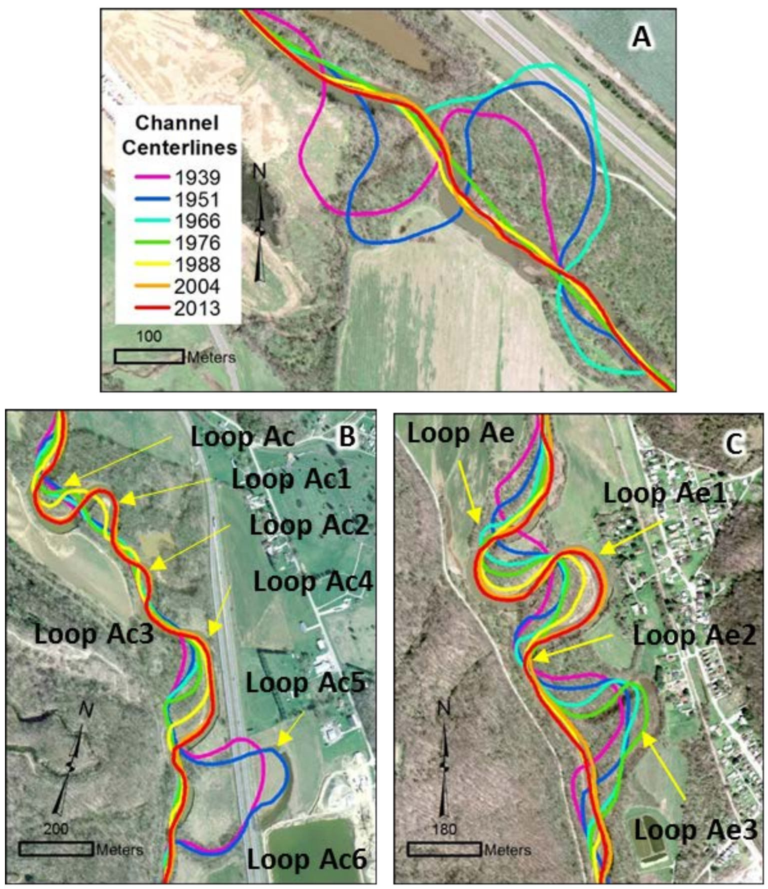

Figure 26. Asymmetrical meander loops Ag (A), Ac (B), and Ae (C) represent Study Reaches 10, 17, and 11, respectively. River flow is to the south.

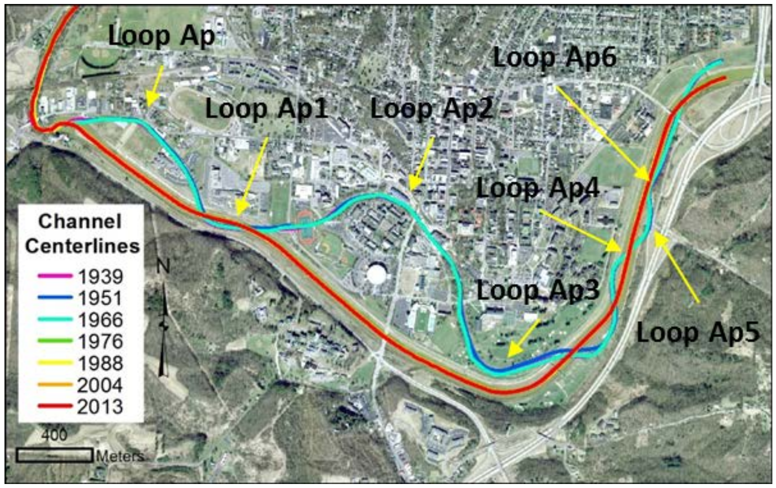

Figure 27. Asymmetrical meander loops Ap-Ap6 in Study Reach 25 in Athens depicting the location of channel pre- and post-1968 flood. River flow is west to east.

In addition to the artificial channelization of the Hocking River affecting asymmetry by reducing meander loops, three meanders, in Study Reaches 10, 13, and 19, experienced change in asymmetry due to natural cut-offs. The change in asymmetry can be seen in meander loops Af and Af1 (Figures 28a), meander loops Ar and Ar1 (Figure 28b), and meander loops Am5 and Am6 (Figure 28c). In all three reaches asymmetry appears to have terminated through flood-induced meander chute cut-offs and was either permanently or temporarily reset to a straighter channel. A more in-depth discussion of the effects of flood events on asymmetry is provided in Section 5.4.5. Several meander loops display large downstream translation asymmetry. These include meander loops An-A2 (Figure 29a) and Ao1-Ao3 (Figure 29b) located in Study Reaches 21, and 22, respectively. Of the 58 meander loops, Study Reach 13 is the only one that displays a compound meander loop (Ad), which developed after 1951 (Figure 29c). The remaining asymmetry sites exhibit change but not to the extent of the sites previously discussed, which include Study Reaches 22, 17, 10 in Figure 30, and Study Reaches 15, 19, and 6 in Figure 31.

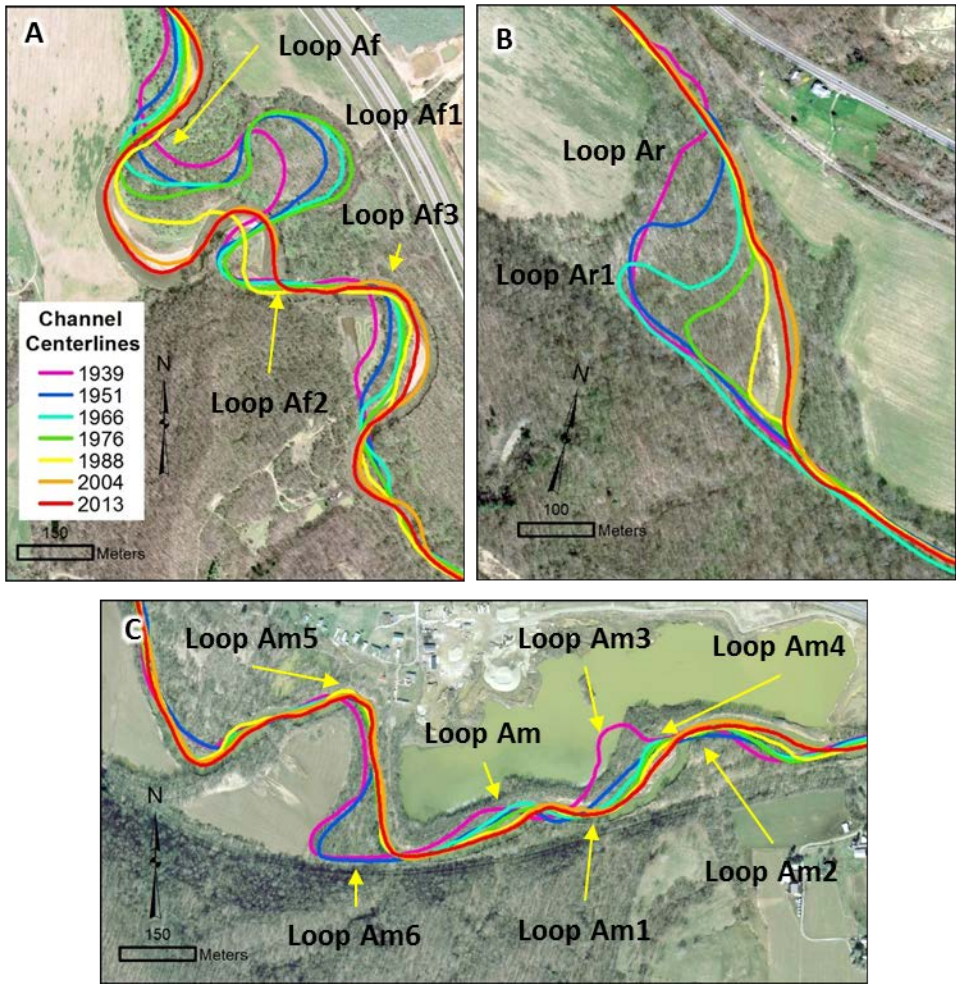

Figure 28. Flood-induced meander loop chute cut-offs of meander loops Af1 in Study Reach 10 (A); Ar and Ar1 in Study Reach 13 (B); and Am5 and Am6 in Study Reach 19 (C). River flow is north to south (A), northwest to southeast (B), and west to east (C).

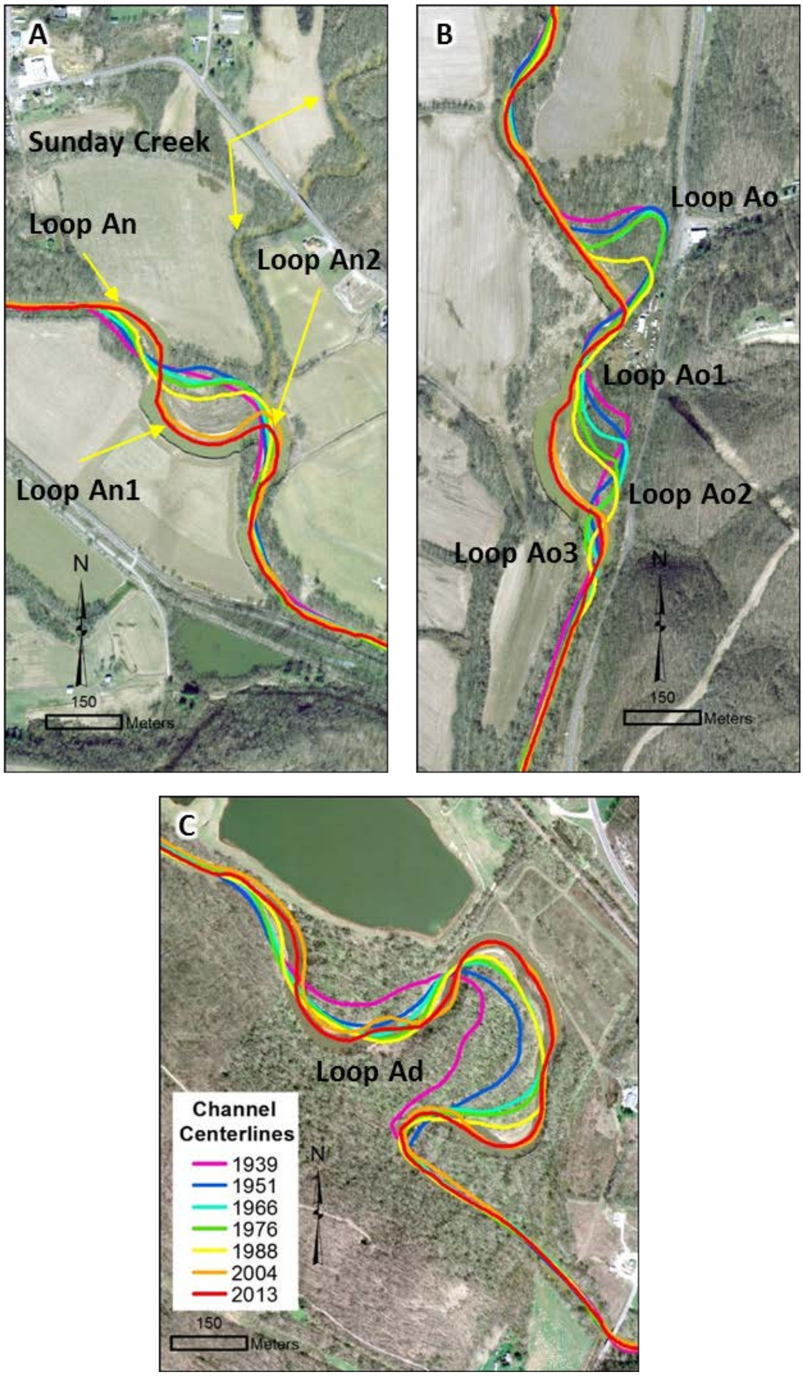

Figure 29. Large asymmetrical change was observed in meander loops An-An2, Ao-Ao3, and Ad, which are located in Study Reaches 21 (A), 22 (B), and 13 (C), respectively. River flow is west to southeast (A), north to south (B), and northwest to southeast (C).

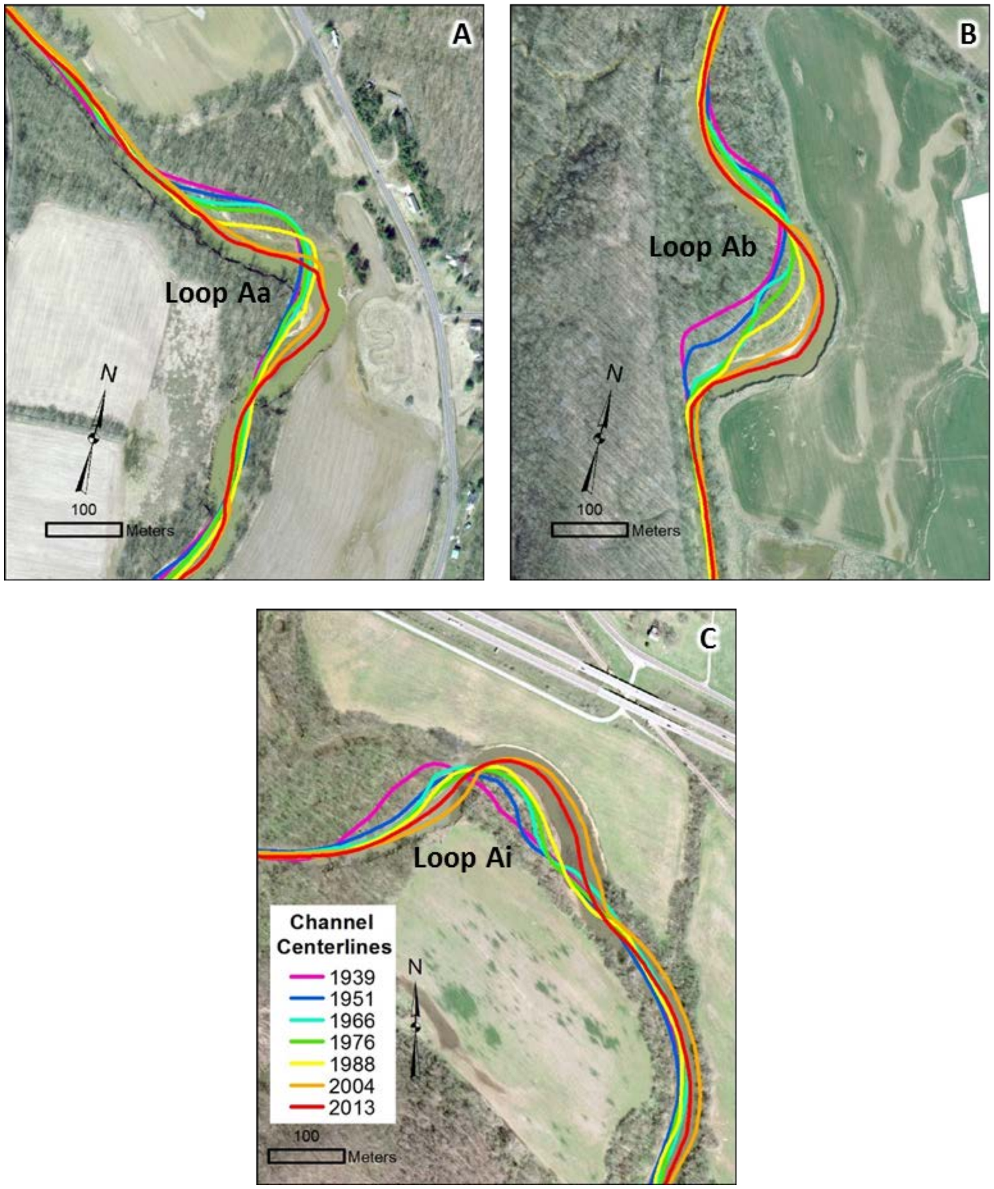

Figure 30. Asymmetrical downstream translating meander loops are seen in meander loops Aa, Ab, and Ai in Study Reaches 22 (A), 17 (B), and 10 (C). River flow is north to south in (A) and (B), while it is west to south in (C).

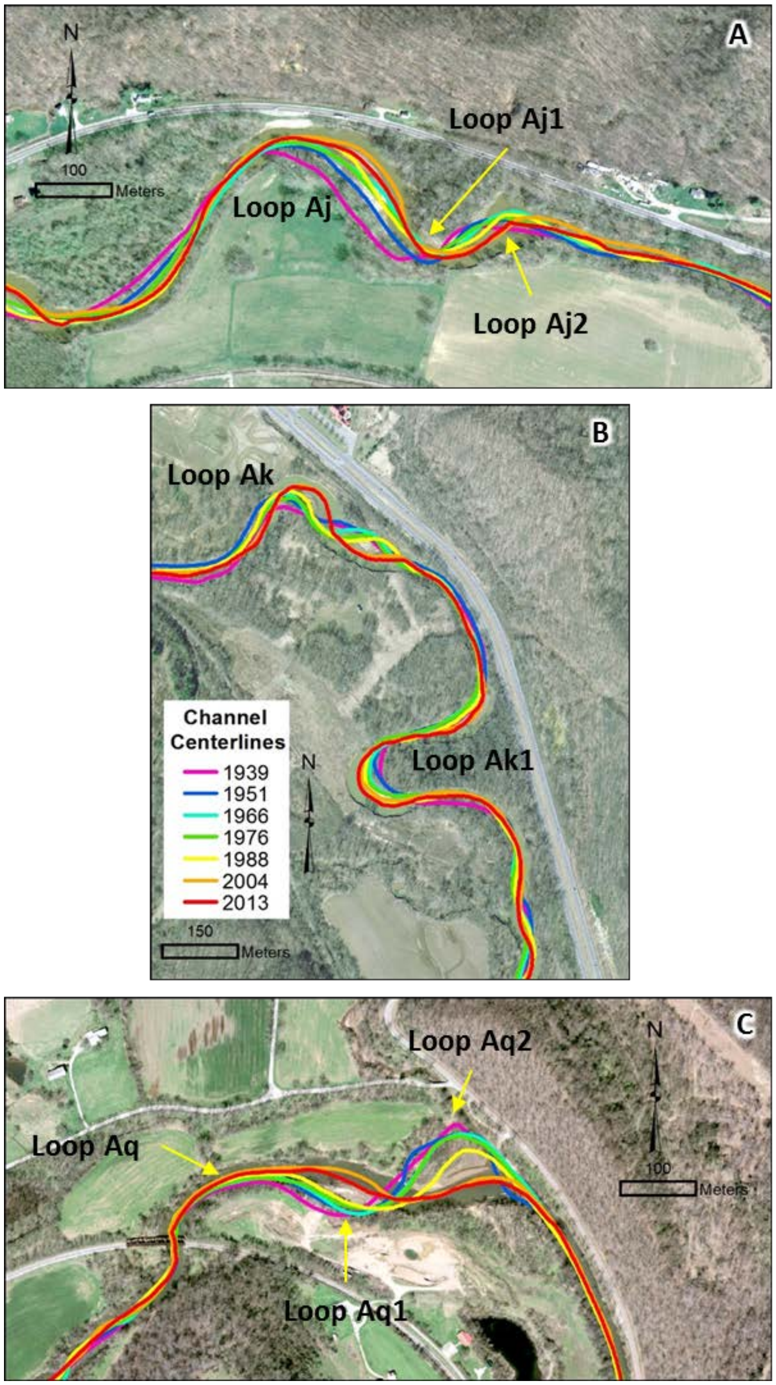

Figure 31. Asymmetrical downstream translating meander loops are seen in meander loops Aj-Aj2, Ak-Ak1, and Aq-Aq2 in Study Reaches 15 (A), 19 (B), and 6 (C). River flow is west to east in (A) and west to south in (B) and (C).

5.3.2 Sinuosity

Over the time span of the study, sinuosity displayed a minimum index value of 1.0 and a maximum index value of 1.7, which correspond to straight and meandering channels, respectively. As of 2013, the Hocking River has a sinuosity index of 1.5, and thus is designated as sinuous. This designation was determined by using the sinuosity index of Leopold and Wolman (1957), who stated that a sinuosity index of <1.1 is designated as straight, 1.1 to 1.5 is classified as sinuous, and >1.5 is classified as meandering. Sinuosity for the studied section of the Hocking River as a whole varied over the 75-year time span. While some reaches displayed relatively little change in sinuosity, others changed considerably (Appendix B). For the total studied stream length of approximately 73.2 km, the largest change in sinuosity over the 75-year span occurred between 1939 and 1976 (Figure 32). This period of 37 years marks the period in which the majority of channel planform modification occurred, whether artificial or natural. It was also determined that there is no significant ($\alpha = 0.05$) difference in the 25 reach means between successive photo years (Table 8). An important factor to take away is that results concerning sinuosity can vary with the scale of a study. This can be seen when comparing Figure 32 and Table 8. Sinuosity in terms of the entire 73-km length indicates that the upper Hocking River remained at or above an index of 1.5, which is meandering. However, when applying the mean sinuosity index for each photo year and encompassing all 25 reaches the upper Hocking River is designated as sinuous. The sinuosity index for each study reach provides a better indication of the overall sinuosity of the upper Hocking River as it incorporates spatial and temporal variations that are not captured with the total sinuosity. Some of the 25 reaches maintained a consistent sinuosity class whereas others changed classes over the study period. Six reaches remained straight, 15 sinuous, one meandering, while one reach transitioned from meandering to sinuous, and two reaches transitioned from sinuous to meandering during the study period. Additionally, out of the 25 reaches, 13 exhibited no change in their specific sinuosity index, while 12 exhibited change

(Table 9). Out of the 12 reaches with varying sinuosity, the largest shifts occurred in Study Reaches 11, 13, 23, and 25.

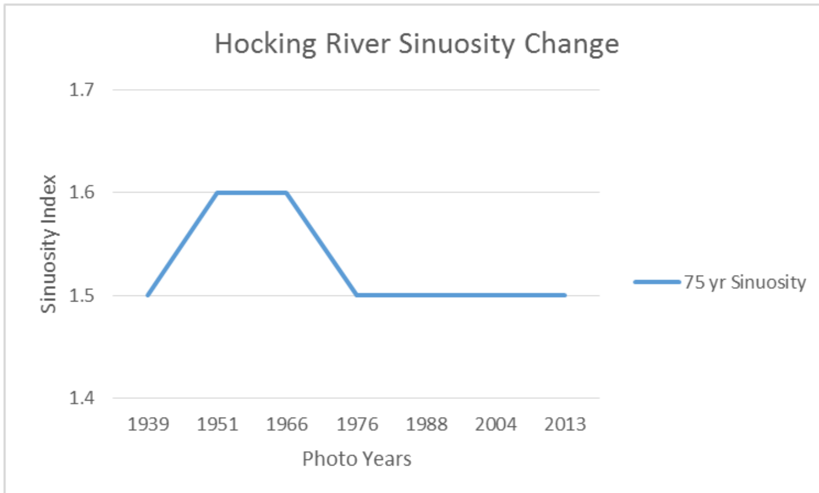

Figure 32. Total sinuosity along the 73.2 km study reach of the Hocking River.

Table 8. Mean sinuosity for all 25 reaches, and results of one-tailed t-test results comparing successive pairs of photo years.

Year	Mean	*p value*
1939	1.2	0.364
1951	1.3	
1951	1.3	0.468
1966	1.3	
1966	1.3	0.374
1976	1.2	
1976	1.2	0.5
1988	1.2	
1988	1.2	0.5
2004	1.2	
2004	1.2	0.5
2013	1.2	

Table 9. Change in sinuosity for 25 reaches, where (-), (+), and N designate decreases, increases, and no change in sinuosity, respectively.

Reach	Change Sinuosity	Type	Impact
1	N	Sinuous	Channelized
2	(-)	Sinuous	Channelized
3	N	Sinuous	
4	N	Sinuous	
5	(-) (+)	Sinuous	
6	(-)	Sinuous	
7	N	Sinuous	
8	(-)	Sinuous	Channelized
9	N	Straight	
10	(-)	Sinuous	Channelized/Historic flood
11	(-) (+)	Sinuous	Channelized
12	N	Straight	
13	(-) (+)	Sinuous to Meandering	Historic flood
14	N	Sinuous	
15	N	Sinuous	
16	N	Sinuous	
17	(-) (+)	Sinuous	Channelized
18	N	Sinuous	
19	N	Meandering	Channelized/Historic flood
20	N	Sinuous	
21	(+)	Sinuous	
22	(-)	Sinuous	
23	(+)	Sinuous to Meandering	
24	N	Sinuous	
25	(-)	Meandering to Sinuous	Channelized

Study Reach 11 experienced a gradual increase in sinuosity from 1.3 in 1939 to 1.5 in 1976. After 1976 sinuosity declined to 1.3 in 1988 as the result of termination of meander loop Ae3 in Haydenville through channelization to mitigate property damage by further lateral migration (Figure 33).

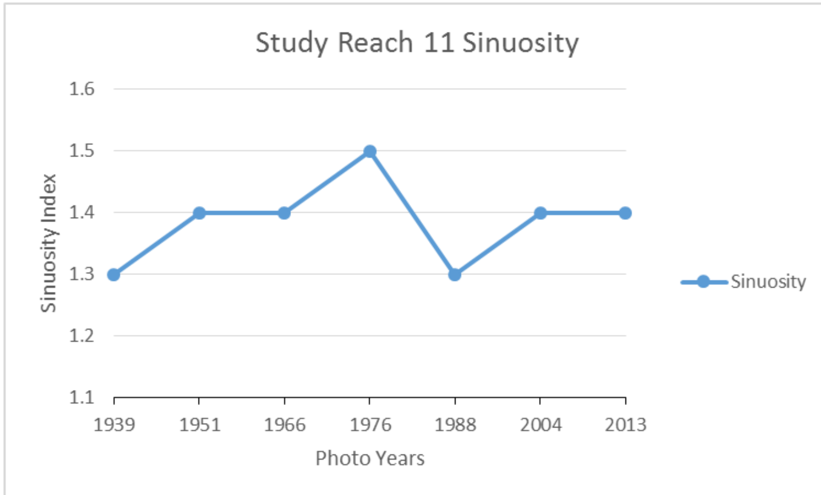

Figure 33. Change in sinuosity over time at Study Reach 11.

Study Reach 13 also underwent a sinuosity increase in the early part of the study period, in this case from 1.4 in 1939 to 1.6 in 1966 (Figure 34). The decrease in sinuosity between 1966 and 1976 is attributed to the termination of meander loops Ar and Ar1 through continuous meander loop chute cut-offs and new channel establishment not directly related to artificial channelization. The rebound seen after 1988 is the result of compound meander loop Ad, which is unique as it is the only one in the upper Hocking River.

Study Reach 23 is the only location that experienced a steady increase in sinuosity from 1.3 in 1939 to 1.7 in 2004 (Figure 35). This large continual increase in sinuosity can be seen in Figure 25, which shows the downstream translation of meander loops A-F.

Study Reach 25, on the other hand, underwent a large decrease in sinuosity between 1966 and 1976, but maintained uniform values before and after that decrease (Figure 36). The sinuosity reduction at this reach in Athens was accomplished artificially, by channelization and relocation of the Hocking River after the 1968 flood, which terminated meander loops Ap-Ap6.

The remaining reaches that exhibited some change in sinuosity over the study period are 2, 5, 6, 8, 10, 17, 21, and 22 (Table 9). After constant sinuosity, Study Reaches 2, 6, and 22 stepped down one value between 1988 and 2004 (Figure 37); Study Reaches 8 and 10 likewise decreased one value between 1966 to 1976 and 1976 to 1988, respectively (Figure 38). Study Reaches 5 and 17 oscillated one index value down and back up during the middle of the study period (Figure 39). In a very different pattern, Study Reach 21 underwent a small increase in sinuosity between 1939 and 1951, which thereafter remained constant (Figure 40). The

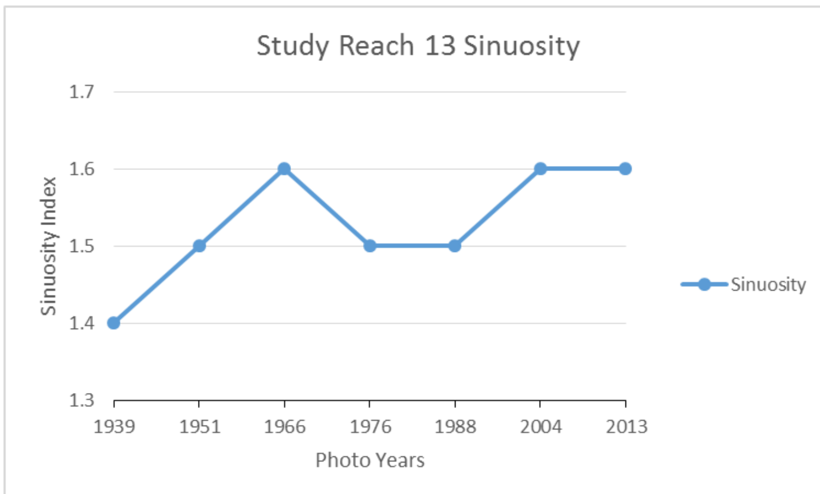

Figure 34. Change in sinuosity over time at Study Reach 13.

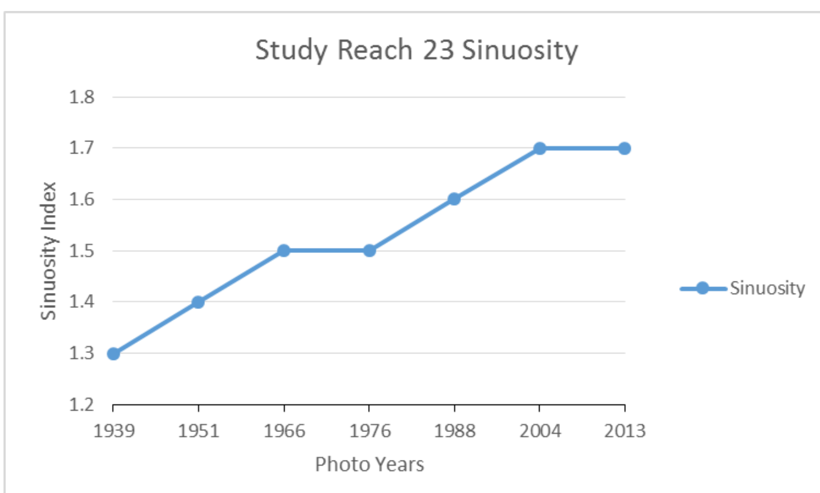

Figure 35. Change in sinuosity over time at Study Reach 23.

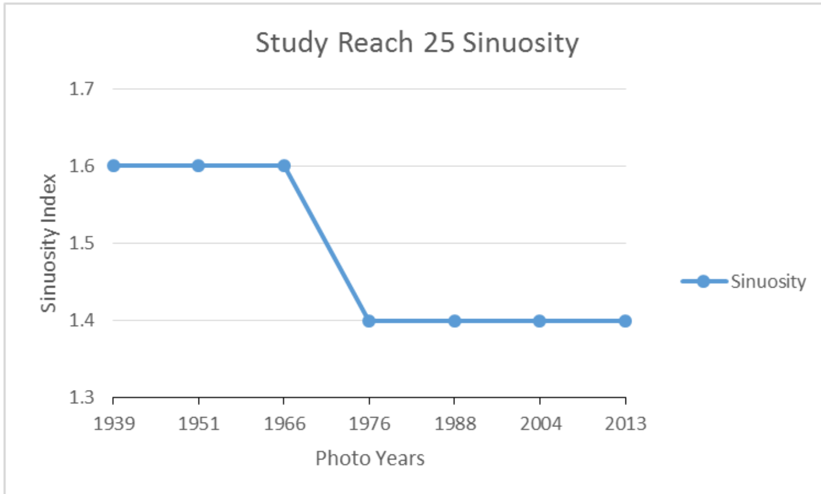

Figure 36. Change in sinuosity over time at Study Reach 25.

observed sinuosity variation in Study Reach 8 was the direct product of artificial channelization, whereas the variations in Study Reaches 10 and 22 were due to more natural meander cut-off and meander translation episodes. Sinuosity oscillation along Study Reach 17 coincided with channelization, followed by the river forming new meanders. No major changes in the river are observed to be associated with the slight to moderate sinuosity variations in Study Reaches 2, 5, 6, 10, and 21. No change in sinuosity occurred over the study period for Study Reaches 1, 3, 4, 7, 9, 12, 14-16, 18-20, and 24 (Appendix B). Sinuosity indices ranged between 1.0 and 1.6, with no observable spatial pattern in the distribution of the reaches with the various sinuosity values.

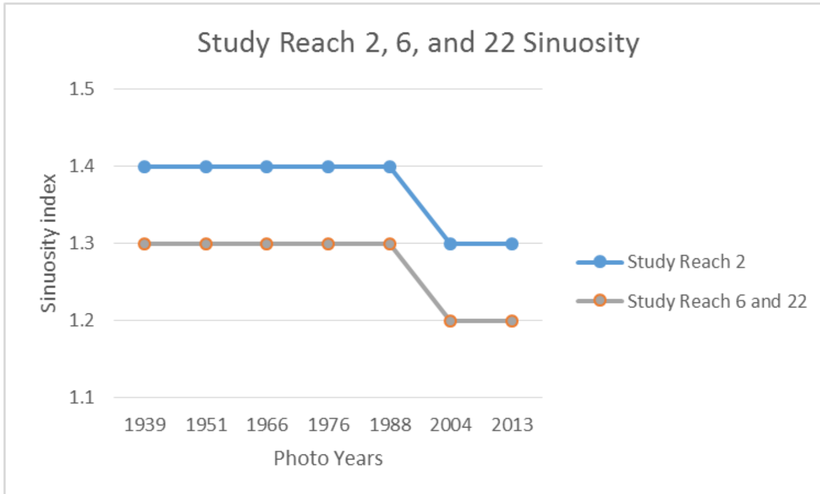

Figure 37. Change in sinuosity over time at Study Reach 2, 6, and 22.

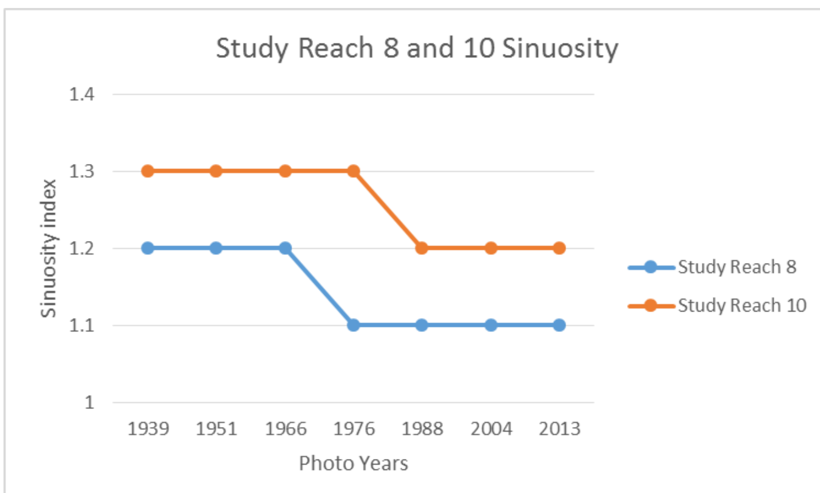

Figure 38. Change in sinuosity over time at Study Reach 8 and 10.

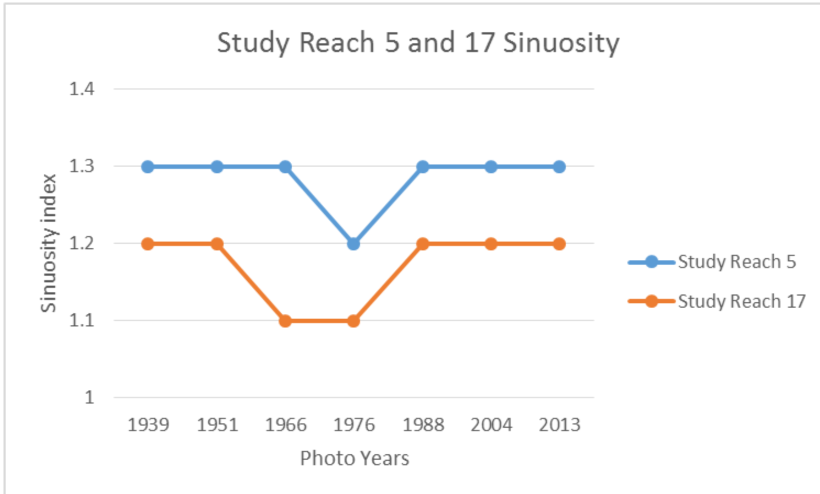

Figure 39. Change in sinuosity over time at Study Reach 5 and 17.

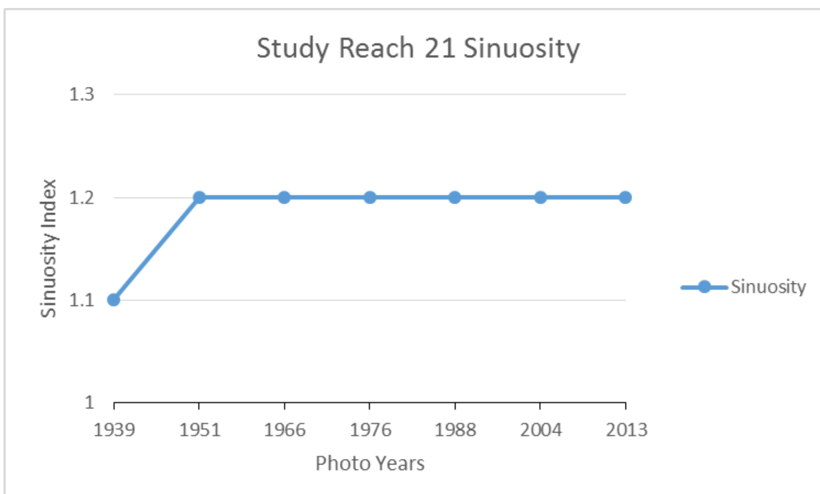

Figure 40. Change in sinuosity over time at Study Reach 21.

5.3.3 Channel Width

The upper Hocking River has a 75-year average channel width of 37 m. During this period the minimum channel width of 20 m was located in Study Reach 3 for 1951, while the maximum was in Study Reach 25 at 73 m for 1976. The averages for the individual seven photo sets were between 32 m and 42 m. As of 2013, the upper Hocking River has an average channel width of 41 m and does not exceed 70 m.

Most of the 25 reaches had statistically significant differences (α=0.05) in channel width between each successive pair of photosets. Although channel width fluctuated to some extent in each reach over the 75 years (Appendix C), the overall trend was an increase in width that propagated downstream over time (Table 10 and Figure 41). The overall trend of width increase downstream and through time, as well as the fluctuations in width, were confirmed by the statistical significance (α = 0.05) that was determined between photosets for the majority of the 25 reaches (Table 11). Study Reaches, 1, 2, 4, 7-10, 12-14, 17-20 experienced continual significant channel-width change throughout the study years. The remaining reaches, while having considerable significant change over some intervals, had one to three periods of no significant change in width. Reaches 11, 15, 16, 22, 24, and 25 each had one interval of no significant width changes, whereas reaches 3, 5, 6, 21, and 23 each had two intervals without a statistically significant change in width. Presence or absence of statistically significant change of width appears to have a relationship with the percentage of woody vegetation present in the riparian buffer. This point is discussed more fully in Section 5.4.4.

Statistically significant width change at Study Reaches 1, 2, 8, 10, 17, and 25, and the meander cut-offs at Reaches 10, 13, and 19 (Table 8) coincided with the periods of channelization during the construction of US Route 33 and historic flood events. For the sections in Reaches 1 and 2, channelized between 1951 and 1966, width increased by 3.6 m and 5.5 m, respectively. Reaches 8, 10, and 17 widened significantly between 1966 and 1976 by 12.4 m, 5.4 m, and 7.1 m, respectively, all directly influenced by artificial channelization. The largest change in width was artificial, occurring in Reach 25 at Athens between 1966 and 1976. This relocation and channelization of the Hocking River at Athens increased the channel width from 36.9 m to 73.1 m (Figure 42). Statistically significant changes in width occurred with the meander cut-offs

Table 10. Mean width trends in 25 reaches over the seven photo years. Brown shading designates periods of channelization, while blue shading designates periods of meander chute cut-off.

Reach	1939	1951	1966	1976	1988	2004	2013
1	20.6	22.7	26.3	27.5	34.7	29.3	31
2	25.9	24.9	30.4	32.3	40.3	30.2	36
3	24.9	19.8	23.2	24.7	30.7	30.8	31.5
4	24.1	23.1	21.3	28.9	37.5	31.7	35.5
5	26.9	20.8	25.5	31.3	34.7	35.5	36.1
6	26.9	26.9	24.8	31.3	34.9	34.1	35.7
7	31.9	29.7	29	32.7	37.7	33.4	35.4
8	34.6	29.2	32.1	44.5	34.6	35.3	39.6
9	28	37.2	38	40	38.6	34.7	40.3
10	38.3	35.9	33.7	39.1	42.4	37.9	45.9
11	38.1	37.4	34.1	38.9	48	37.4	44.4
12	32.5	31.7	37.8	43	53.4	39.5	41.5
13	37.9	34.1	31.9	39.7	47.9	39.4	42.1
14	30.3	29.7	31.2	35.6	38.4	41.6	38.4
15	35.8	30.4	33.7	37.8	39.5	40.3	40.8
16	33.1	28.9	31.5	36.1	38.1	38.1	36.3
17	34.1	27.3	30.3	37.4	43	40.4	41.1
18	32.9	26.3	29.5	45.2	33.3	38.1	33.5
19	33.1	27	29.3	36.9	38.6	45.4	40.4
20	35.6	33.4	32.1	41.2	39.1	43.9	41
21	35.3	38	32.4	39.4	43.3	43.7	44
22	38	36.2	35.6	40	45.3	48.8	47.1
23	47.4	43.2	40.9	47	53	52.1	52
24	45.1	41.8	43.8	49	49.3	50.5	47.7
25	44.1	41.4	36.9	73.1	72.9	68.7	69.9

in Reaches 10, 13, and 19. For Reach 10, width increased from 39.1 m to 42.2 m between 1976 and 1988, which was during the period when meander loop Af1 was terminated. In Reach 13, the termination of meander loops Ar and Ar1 between 1966 and 1976 was accompanied by an increase in width from 31.9 m to 39.7 m. Finally, Reach 19 increased significantly from 27 m to 29.3 m between 1951 and 1966.

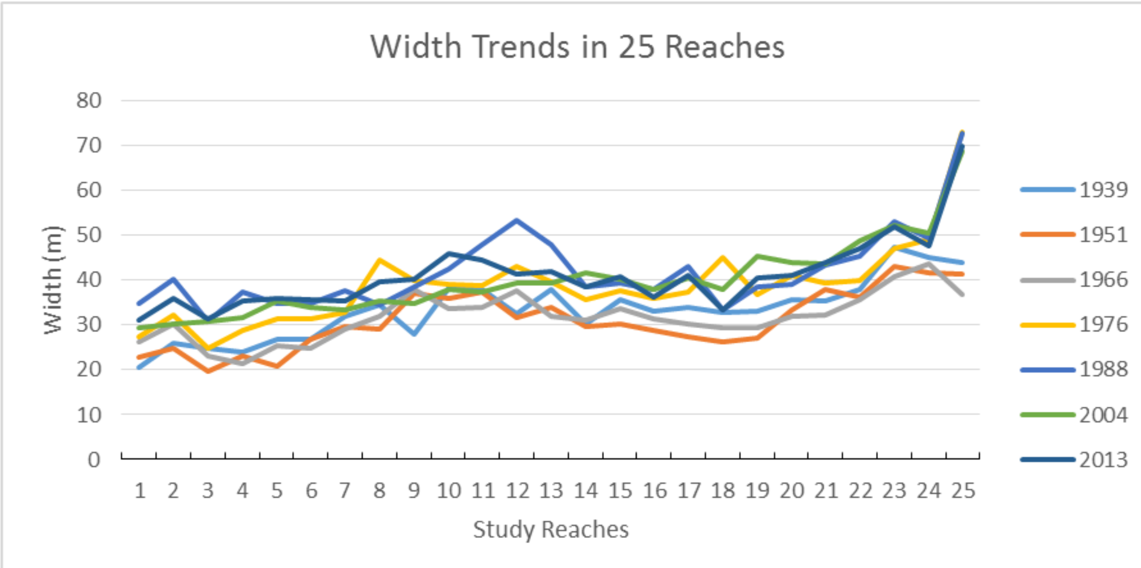

Figure 41. Spatial-temporal trends in mean channel width for the 25 reaches over the seven photo years.

Table 11. Mean channel width (in meters) for each study reach and photo year, and results of one-tailed t-test results comparing successive pairs of photo years.

SR 1			SR 2		SR 3		SR 4		SR 5	
Year	Mean	*p value*	Mean	*p*	Mean	*p*	Mean	*p*	Mean	*p*
1939	20.6	<.001	25.9	<.001	24.9	<.001	24.1	0.028	26.9	<.001
1951	22.7		24.9		19.8		23.1		20.8	
1951	22.7	<.001	24.9	<.001	19.8	<.001	23.1	<.001	20.8	<.001
1966	26.3		30.4		23.2		21.3		25.5	
1966	26.3	.002	30.4	<.001	23.2	<.001	21.3	<.001	25.5	<.001
1976	27.5		32.3		24.7		28.9		31.3	
1976	27.5	<.001	32.3	<.001	24.7	<.001	28.9	<.001	31.3	<.001
1988	34.7		40.3		30.7		37.5		34.7	
1988	34.7	<.001	40.3	<.001	30.7	0.339	37.5	<.001	34.7	0.052
2004	29.3		30.2		30.9		31.7		35.5	
2004	29.3	0.028	30.2	<.001	30.8	0.173	31.7	<.001	35.5	0.099
2013	31.0		36.0		31.5		35.5		36.1	

Table 11. continued.

SR 6			SR 7		SR 8		SR 9		SR 10	
Year	Mean	*p*	Mean	*p*	Mean	*p*	Mean	*p*	Mean	*p*
1939	26.9	0.483	31.9	<.001	34.6	<.001	28.0	<.001	38.3	<.001
1951	26.9		29.7		29.2		37.2		35.9	
1951	26.9	<.001	29.7	<.004	29.2	<.001	37.2	0.024	35.9	<.001
1966	24.8		29.0		32.1		38.0		33.7	
1966	24.8	<.001	29.0	<.001	32.1	<.001	38.0	<.001	33.7	<.001
1976	31.3		32.7		44.5		40.0		39.1	
1976	31.3	<.001	32.7	<.001	44.5	<.001	40.0	<.001	39.1	<.001
1988	34.9		37.7		34.6		38.6		42.4	
1988	34.9	0.128	37.7	<.004	34.6	0.011	38.6	<.001	42.4	<.001
2004	34.1		33.4		35.3		34.7		37.9	
2004	34.1	0.026	33.4	<.001	35.3	<.001	34.7	<.001	37.9	<.001
2013	35.7		35.4		39.6		40.3		45.9	

Table 11. continued.

SR 11			SR 12		SR 13		SR 14		SR 15	
Year	Mean	*p value*	Mean	*p*	Mean	*p*	Mean	*p*	Mean	*p*
1939	38.1	0.076	32.5	0.047	37.9	<.001	30.3	0.032	35.8	<.001
1951	37.4		31.7		34.1		29.7		30.4	
1951	37.4	<.001	31.7	<.001	34.1	<.001	29.7	<.001	30.4	<.001
1966	34.1		37.8		31.9		31.2		33.7	
1966	34.1	<.001	37.8	<.001	31.9	<.001	31.2	<.001	33.7	<.001
1976	38.9		43.0		39.7		35.6		37.8	
1976	38.9	<.001	43.0	<.001	39.7	<.001	35.6	<.001	37.8	<.001
1988	48.0		53.4		47.9		38.4		39.5	
1988	48.0	<.001	53.4	<.001	47.9	<.001	38.4	<.001	39.5	0.012
2004	37.4		39.5		39.4		41.5		40.3	
2004	37.4	<.001	39.5	<.001	39.4	<.001	41.6	<.001	40.3	0.129
2013	44.4		41.5		42.1		38.4		40.8	

Table 11. continued.

SR 16			SR 17		SR 18		SR 19		SR 20	
Year	Mean	*p value*	Mean	*p*	Mean	*p*	Mean	*p*	Mean	*p*
1939	33.1	<.001	34.1	<.001	32.9	<.001	33.1	<.001	35.6	<.001
1951	28.9		27.3		26.3		27.0		33.4	
1951	28.9	<.001	27.3	<.001	26.3	<.001	27.0	<.001	33.4	0.002
1966	31.5		30.3		29.5		29.3		32.1	
1966	31.5	<.001	30.3	<.001	29.5	<.001	29.3	<.001	32.1	<.001
1976	36.1		37.4		35.2		36.9		41.2	
1976	36.1	<.001	37.4	<.001	45.2	<.001	36.9	<.001	41.2	<.001
1988	38.1		43.0		33.3		38.6		39.1	
1988	38.1	0.452	43.0	<.001	33.3	<.001	38.6	<.001	39.1	<.001
2004	38.1		40.4		38.1		45.4		43.9	
2004	38.1	<.001	40.4	0.014	38.1	<.001	45.4	<.001	43.9	<.001
2013	36.3		41.1		33.5		40.4		41.0	

Table 11. continued.

SR 21			SR 22		SR 23		SR 24		SR 25	
Year	Mean	*p value*	Mean	*p*	Mean	*p*	Mean	*p*	Mean	*p*
1939	35.3	<.001	38.0	<.001	47.4	<.001	45.1	<.001	44.1	<.001
1951	38.0		36.2		43.2		41.8		41.4	
1951	38.0	<.001	36.2	0.084	43.2	<.001	41.8	<.001	41.4	<.001
1966	32.4		35.6		40.9		43.8		36.9	
1966	32.4	<.001	35.6	<.001	40.9	<.001	43.8	<.001	36.9	<.001
1976	39.4		40.0		47.0		49.0		73.1	
1976	39.4	<.001	40.0	<.001	47.0	<.001	49.0	0.297	73.1	0.337
1988	43.3		45.3		53.0		49.3		72.9	
1988	43.3	0.373	45.3	<.001	53.0	0.078	49.3	0.006	72.9	< .001
2004	43.7		48.8		52.1		50.5		68.7	
2004	43.7	0.37	48.8	0.003	52.1	0.424	50.5	<.001	68.7	< .001
2013	44.0		47.1		52.0		47.7		69.9	

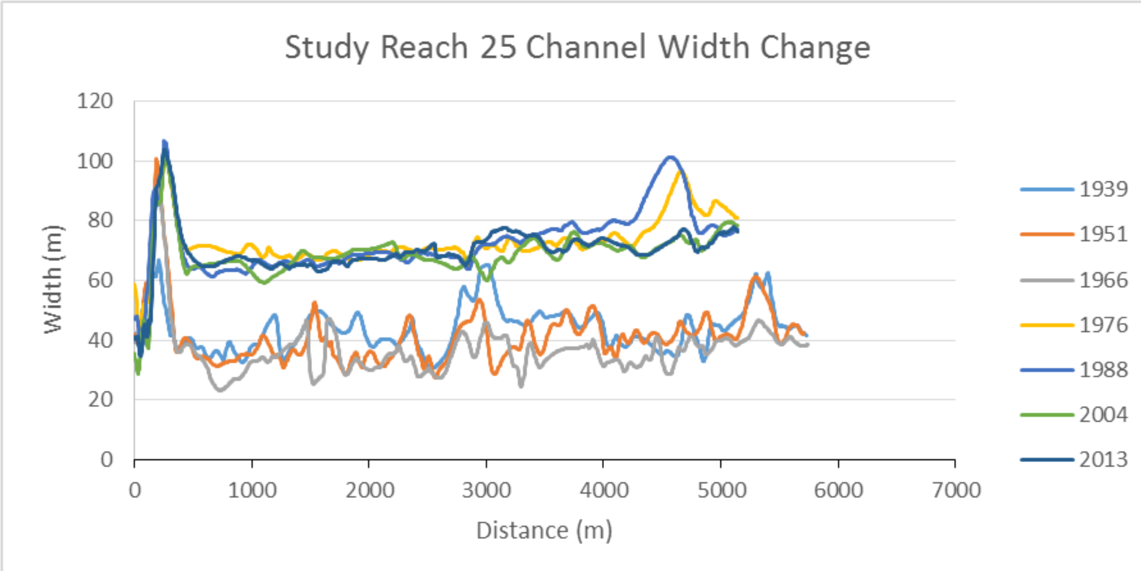

Figure 42. Significant width increase after the channelization and relocation of the Hocking River after the 1968 flood in Athens.

5.3.4 Channel Position Change

Statistical analysis of channel position between photo sets for each of the 25 study reaches confirms that significant change of channel position occurred along the upper Hocking River over the course of the 75 years under study (Table 12). Not all of the 25 reaches displayed large changes in channel position over all pairs of photo years; some sites had periods of stability in channel location between episodes of active channel position change. Study Reaches 3, 5, 7, 10, 12, 14, 17, and 25 consistently showed significant channel position change between each successive pair of air photographs. The other 17 reaches experienced significant channel position change between some photo years, but had one, two, or three sets of photo years in which channel position was not significantly different. For all the figures that depict channel position change in this section, each spike per photo set represents a change in the direction of the channel migration between two photo years, and the larger the spike the greater the amount of channel migration. Channel position was designated as positive if the channel shifted to stream left and negative if it shifted to stream right. Additionally, by creating a histogram of mean channel position change for the six photo sets in Table 10, it was determined that the upper Hocking River primarily fluctuated more to the left along the 73.2 km over the 75 year study span (Figure 43). Of the data analyzed, Study Reach 25 was an outlier and is not represented in the +/-12 m mean change in channel position shown in Figure 43.

Table 12. Statistical analysis of channel position change for the 25 reaches using one-tailed t-tests of comparison for samples of unequal variances.

SR 1			SR 2		SR 3		SR 4		SR 5	
Year	Mean	*p value*	Mean	*p*	Mean	*p*	Mean	*p*	Mean	*p*
1939-1951	-0.1	<.001	5.4	0.327	7.4	<.001	5.8	0.091	3.2	<.001
1951-1966	3.4		5.7		0.0		4.8		2.0	
1951-1966	3.4	<.001	5.7	<.001	0.0	<.001	4.8	<.001	2.0	<.001
1966-1976	-2.2		-1.5		-3.2		-3.4		-3.2	
1966-1976	-2.3	0.009	-1.5	<.001	-3.2	<.001	-3.4	<.001	-3.2	<.001
1976-1988	-1.0		1.5		-1.9		0.5		-2.1	
1976-1988	-1.0	0.005	1.5	<.001	-1.9	<.001	0.5	<.001	-2.1	<.001
1988-2004	0.1		-0.8		4.0		4.7		4.1	
1988-2004	0.1	0.233	-0.8	0.23	4.0	<.001	4.7	<.001	4.1	<.001
2004-2013	0.4		-1.3		-3.5		-0.5		-2.0	

Table 12. continued.

	SR 6		SR 7		SR 8		SR 9		SR 10	
Year	Mean	*p value*	Mean	*p*	Mean	*p*	Mean	*p*	Mean	*p*
1939-1951	0.1	0.071	-1.7	<.001	2.5	<.001	-3.1	<.001	2.3	<.001
1951-1966	1.1		-0.2		-0.3		2.9		5.2	
1951-1966	1.1	0.002	-0.2	<.001	-0.3	<.001	2.9	<.001	5.2	<.001
1966-1976	-0.4		-0.6		-7.2		-3.7		-8.4	
1966-1976	-0.4	0.438	-0.6	<.001	-7.2	<.001	-3.7	<.001	-8.4	<.001
1976-1988	-0.3		-1.5		1.9		2.8		-3.8	
1976-1988	-0.3	0.061	-1.5	<.001	1.9	0.007	2.8	0.137	-3.8	<.001
1988-2004	1.5		1.7		0.4		3.1		6.3	
1988-2004	1.5	<.001	1.7	<.001	0.4	<.001	3.1	<.001	6.3	<.001
2004-2013	-2.8		0.0		-1.7		-3.4		-4.3	

Table 12. continued.

	SR 11		SR 12		SR 13		SR 14		SR 15	
Year	Mean	*p value*	Mean	*p*	Mean	*p*	Mean	*p*	Mean	*p*
1939-1951	5.5	0.013	-2.9	<.001	9.6	<.001	-0.6	<.001	-1.6	<.001
1951-1966	2.1		5.8		5.0		-4.4		1.7	
1951-1966	2.1	0.057	5.8	<.001	5.0	<.001	-4.4	<.001	1.7	0.192
1966-1976	0.1		-2.4		2.4		2.1		1.4	
1966-1976	0.1	<.001	-2.4	<.001	2.4	0.383	2.1	<.001	1.4	<.001
1976-1988	-7.2		1.3		2.5		7.3		0.4	
1976-1988	-7.2	<.001	1.3	<.001	2.5	<.001	7.3	<.001	0.4	0.102
1988-2004	12.8		12.0		8.5		-6.3		1.0	
1988-2004	12.8	<.001	12.0	<.001	8.5	<.001	-6.3	<.001	1.0	<.001
2004-2013	-8.1		-12.4		-4.5		-2.3		-0.9	

Table 12. continued.

SR 16			SR 17		SR 18		SR 19		SR 20	
Year	Mean	*p value*	Mean	*p*	Mean	*p*	Mean	*p*	Mean	*p*
1939-1951	-0.1	0.019	6.9	<.001	6.3	<.001	1.7	<.001	-0.7	<.001
1951-1966	0.4		-9.2		-3.6		-2.1		2.7	
1951-1966	0.4	<.001	-9.2	<.001	-3.6	0.247	-2.1	<.001	2.7	<.001
1966-1976	-0.8		-0.6		-3.4		-3.5		0.4	
1966-1976	-0.8	0.46	-0.6	<.001	-3.4	<.001	-3.5	<.001	0.4	0.061
1976-1988	-0.9		1.6		3.6		2.4		-0.1	
1976-1988	-0.9	<.001	1.6	<.001	3.6	<.001	2.4	0.005	-0.1	0.004
1988-2004	3.5		6.1		1.4		1.3		1.0	
1988-2004	3.5	<.001	6.1	<.001	1.4	<.001	1.3	<.001	1.0	<.001
2004-2013	-2.1		-3.7		-2.6		-2.9		-2.6	

Table 12. continued.

SR 21			SR 22		SR 23		SR 24		SR 25	
Year	Mean	*p value*	Mean	*p*	Mean	*p*	Mean	*p*	Mean	*p*
1939-1951	2.9	<.001	-0.6	0.225	-5.8	<.001	3.9	<.001	4.1	<.001
1951-1966	-1.1		-0.1		-2.0		-1.8		-5.4	
1951-1966	-1.1	0.039	-0.1	<.001	-2.0	0.024	-1.8	0.201	-5.4	<.001
1966-1976	-2.0		-3.8		-1.0		-2.0		-111.7	
1966-1976	-2.0	0.038	-3.8	<.001	-1.0	<.001	-2.0	<.001	-111.7	<.001
1976-1988	-1.0		0.4		4.6		2.7		-3.4	
1976-1988	-1.0	0.06	0.4	<.001	4.6	<.001	2.7	<.001	-3.4	<.001
1988-2004	-3.5		-4.8		1.0		1.3		1.4	
1988-2004	-3.5	0.208	-4.8	0.089	1.0	<.001	1.3	<.001	1.4	<.001
2004-2013	-4.8		-3.5		-2.7		-0.1		-1.0	

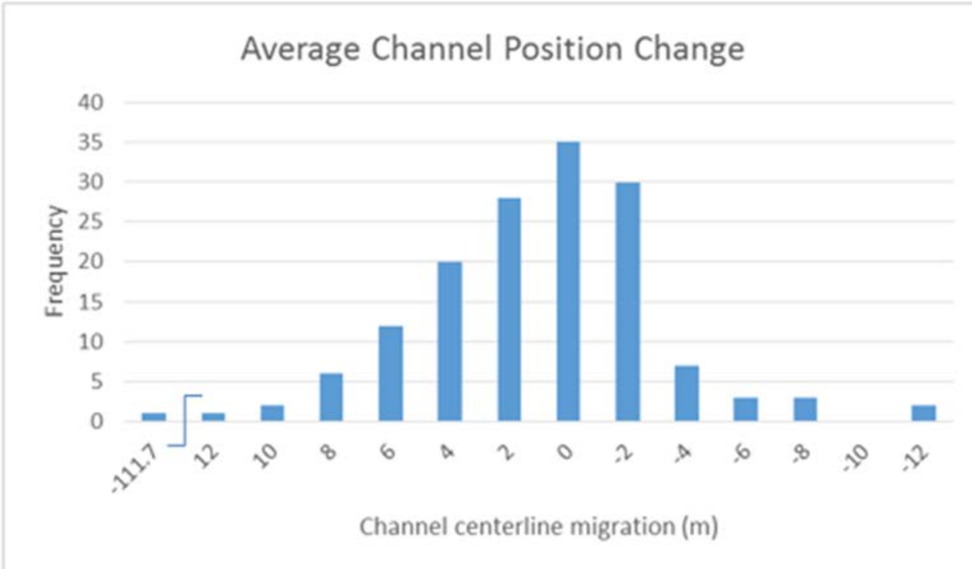

Figure 43. The histogram depicts the frequency of the mean change in channel position over the 75-year study span along the 73.2 km of the upper Hocking River. Study Reach 25 is represented by -111.7, which placed it as an outlier due to large change in channel position.

Channel migration occurred along all 25 reaches of the Hocking River in at least some periods between 1939 and 2013. The greatest changes in channel position accompanied major channel modification events, whether natural or artificial. These cut-off and artificial channelization events occurred in Study Reaches 1, 2, 8, 10, 11, 13, 17, 19, and 25. In addition, Study Reaches 4, 6, 15, 21, 22, and 23 experienced some significant changes in channel position even though they did not have channel modifications due to cut-offs or direct artificial restructuring.

5.3.4.1 Extensive Channel Position Change

Study Reach 1 experienced three periods of large channel migration between photosets 1951-1966, 1966-1976, and 1976-1988, which resulted in the channel migrating 24.2 m to the left, and 26 m and 19.5 m to the right, respectively (Figure 44). Change in channel position associated with the artificial realignment of the river to make way for the construction of US Route 33 occurred in the 1951-1966 photo set approximately 1 km downstream from the start of Reach 1.

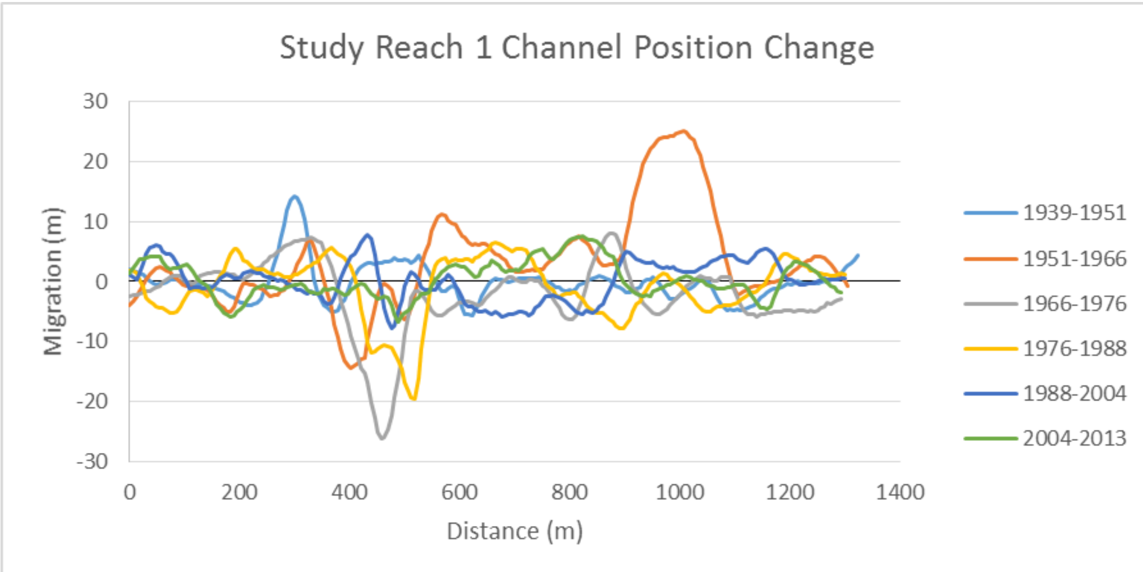

Figure 44. Change in channel position at Study Reach 1.

Study Reach 2 was also affected by channel realignment due to the establishment of US Route 33 between 1951 and 1966. This can been seen on Figure 45 as three spikes between 250 m and 1 km within the reach. Another large amount of channel migration occurred between 1988 and 2004 approximately 2.75 km downstream from the start of the reach, and shifted the channel.

Study Reach 8 exhibited four distinct locations of large channel migration between 1966 and 1976, which was the period of the construction of US Route 33 through Logan (Figure 46). Prior to channelization, lateral migration fluctuated between 0 and 20 m with the exception for photoset 1939-1951 and 1951-1966. Realignment between 1966 and 1976 occurred between 190 m and 1.5 km downstream from the start of Reach 8. These locations migrated 39.4 m, 44.1 m, and 55.4 m to the right, and 47.1 m to the left, respectively.

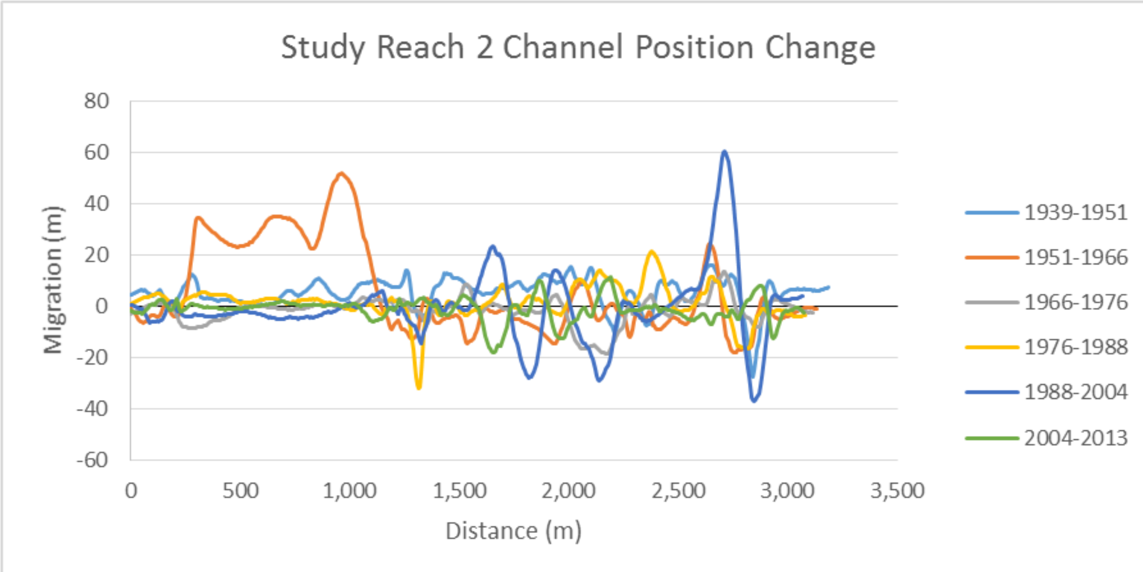

Figure 45. Change in channel position at Study Reach 2.

Study Reach 10 experienced four large lateral migration events between photosets 1939-1951 and 1976-1988 (Figure 47). Similar to Study Reach 8, Reach 10 had channel relocations with the advent of US Route 33 between 1966 and 1976. Prior to channelization the large lateral migration occurred between 3 km and 5 km downstream from the start of Reach 10. This stretch consisted of meander loops Ag, Ag1, Af-Af3, and Ai. During this time the largest channel position change in this reach was located 3.5 km downstream at meander loop Ag1, which between 1951 and 1966 shifted 162.4 m to the left. After this period channel realignment moved the Hocking River by approximately 80 m to the right between 330 m and 680 m downstream. The other location was 3.2 km downstream and shifted the channel about 200 m to the right, which effectively terminated meander loops Ag and Ag1. In addition, in the period immediately following realignment there was a large lateral shift of approximately 144 m to the right when meander loop Af1 was terminated through a chute cut-off.

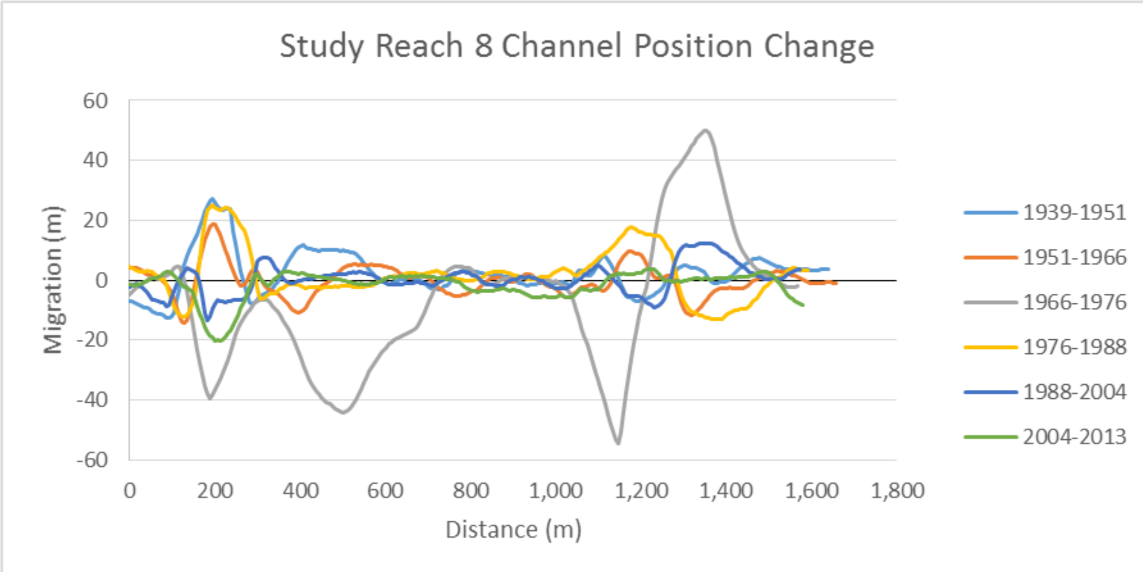

Figure 46. Change in channel position at Study Reach 8.

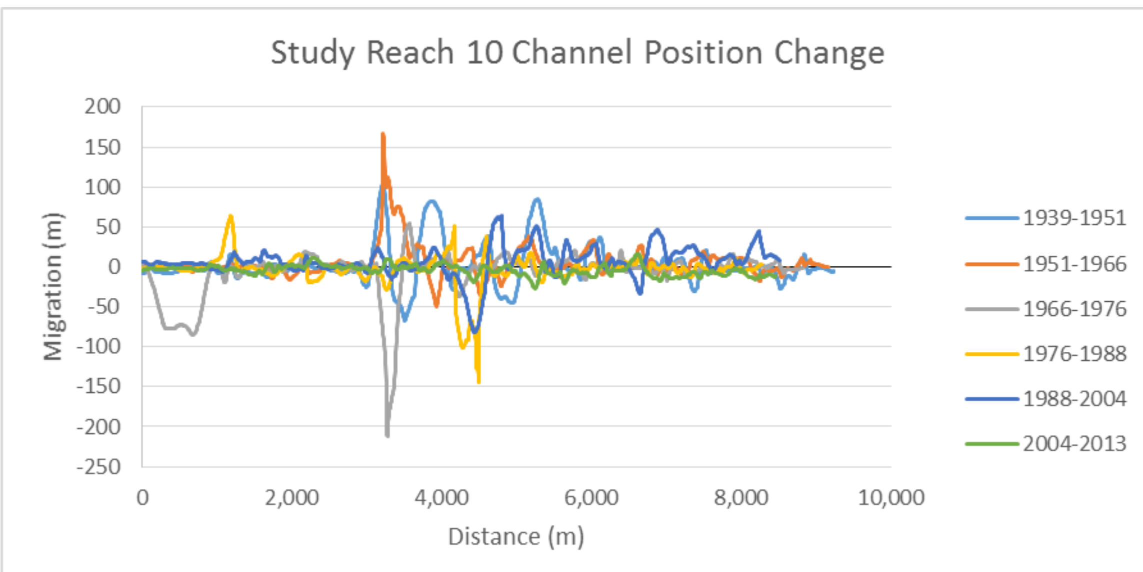

Figure 47. Change in channel position at Study Reach 10.

Study Reach 11 only experienced one large lateral shift of 175 m to the right in channel position, and this occurred between 1976 and 1988 (Figure 48). This shift represents meander loop Ae3, which was artificially terminated to mitigate further lateral migration and possible property damage in Haydenville. Prior to this event channel position fluctuated between 0 m and 50 m throughout meander loops Ae-Ae3, which are located between 730 m and 2 km downstream.

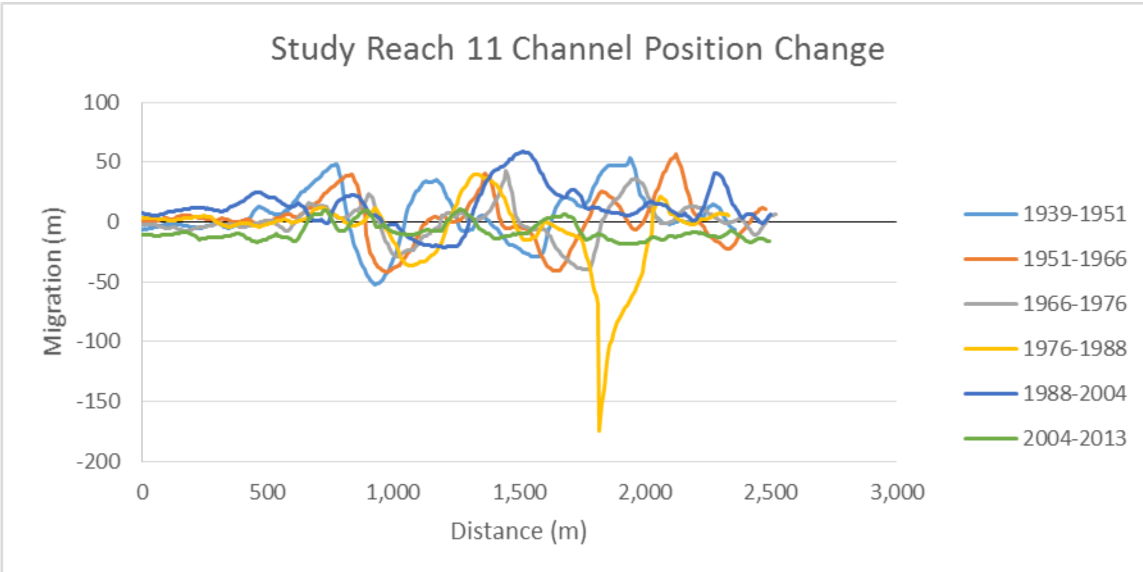

Figure 48. Change in channel position at Study Reach 11.

Study Reach 13 is unique in containing the only compound meander loop among the 25 reaches; it also has a chute cut-off farther downstream. The compound loop, Ad, is located approximately 1 km downstream from the start of the reach and experienced consistent channel position change throughout all photosets. The largest shifts, however, were between photosets 1939-1951, 1951-1966, and 1988-2004. The channel at Ad moved the most, approximately 115 m to the left, between 1939 and 1951. The other site having large channel position change within Study Reach 13 was located at meander loops Ar and Ar1 at approximately 3.75 km downstream of the start of the reach. For all sets of photo years through 2004, the channel shifted between 57 m and 84 m. Between 1976 and 1988 meander loops Ar and Ar1 appeared to be terminated through a natural process of continuous chute cut-off (Figure 49). However, as indicated by the spike representing 1988-2004, channel migration continued left until ceasing and reversing in direction between 2004 and 2013.

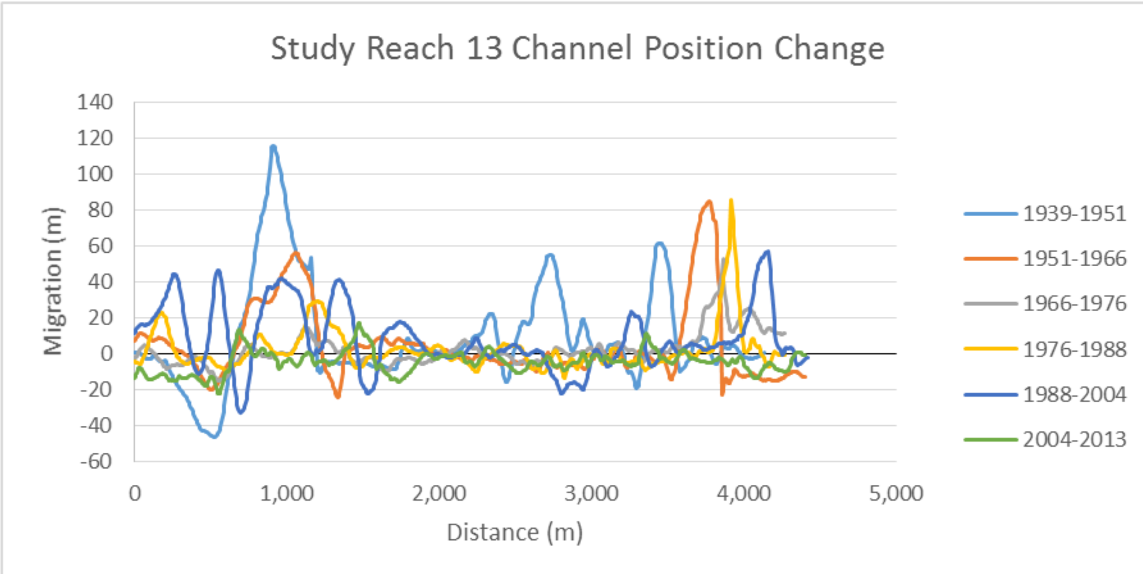

Figure 49. Change in channel position at Study Reach 13.

At various points along the 6 km long Study Reach 17, the river channel migrated naturally between 0 m and 65 m between photosets, except between 1951 and 1966 when a segment shifted approximately 216 m to the right (Figure 50). This large change in channel position was accomplished through channelization, which also terminated meander loops Ac5 and Ac6 about 3.75 km downstream from the start of the reach. Again, this was the direct result of the construction of US Route 33.

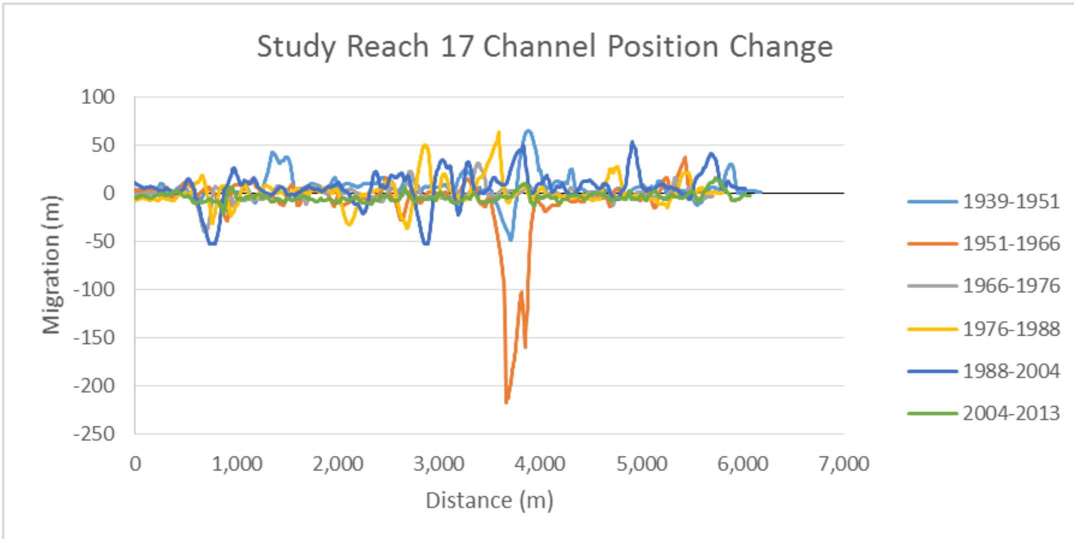

Figure 50. Change in channel position at Study Reach 17.

Study Reach 19 exhibited large channel position change during three photoset years, 1939-1951, 1951-1966, and 1988-2004 (Figure 51). Over the other photoset years, the channel in this 5 km long reach migrated only as much as 20 m. Of the periods that exhibited large migration, natural cut-offs and artificial channelization were influential. Along this study reach, the Hocking River migrated almost 80 m between 1951 and 1966 as the result of termination of meander loops Am5 and Am6. The other major change in channel position occurred approximately 4 km downstream from the start of the reach among meander loops Am through Am4. Specifically, the large lateral movement represents channelization that terminated meander loop Am3 and Am4 to restrict further property damage, and resulted in the Hocking River shifting 89 m to the right.

The largest change in channel position among the 25 reaches occurred at Study Reach 25 between 1966 and 1976 (Figure 52). This artificial movement of the river in Athens was accomplished by the Army Corps of Engineers for flood protection. Prior to this relocation the channel migrated laterally between 0 m and 33 m, with the largest channel shifts predominantly located between meander loops Ap and Ap3. By the completion of the channelization at Athens in 1971, the Hocking River had been relocated a maximum of 600 m to the right.

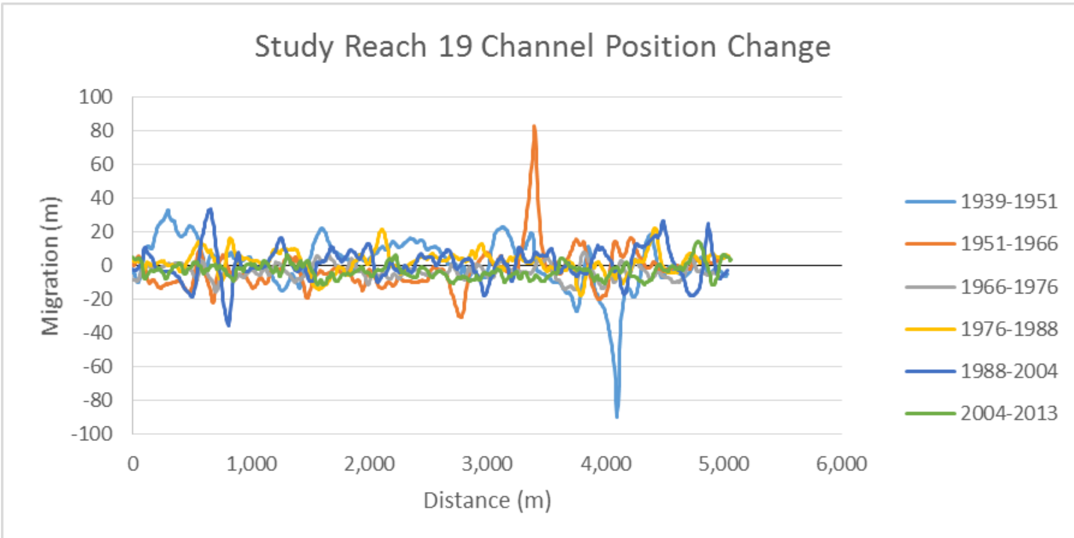

Figure 51. Change in channel position at Study Reach 19.

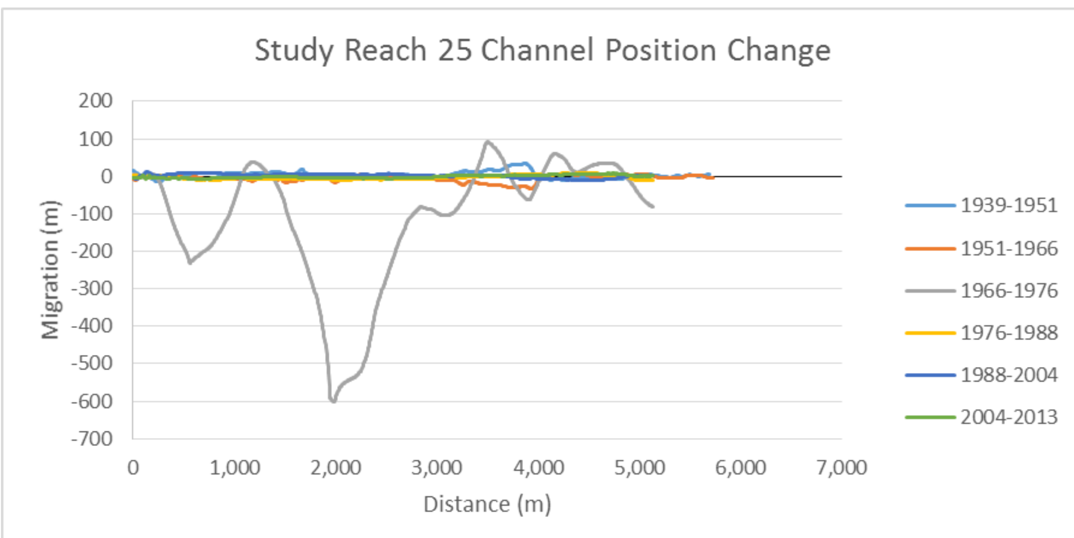

Figure 52. Change in channel position at Study Reach 25.

5.3.4.2 Moderate Channel Position Change

Channel migrations of the remaining reaches, 3-7, 9, 12, 14-16, 18, and 20-24, are not directly attributable to channelization or chute cut-off within those reaches. Of these reaches, 4, 6, 15, and 21-23, experienced the largest amounts of channel migration. The remaining reaches only fluctuated a maximum of +/- 25 m (Appendix D). Among these six study reaches the majority have the largest channel position change occurring during the 1988-2004 photo interval. Looking at the amount of change exhibited in these reaches it has become evident that channel position change has the ability to shift greatly without direct in-reach influence through apparent flood-induced meander chute cut-offs or by artificial channelizations. In general, Study Reaches 4, 6, and 15 stayed within 40 m of movement, while Study Reaches 21, 22, and 23 had the largest at 81 m, 87 m, and 62 m, respectively.

Study Reach 4 experienced two periods of large (> 25 m) channel position change at separate locations, which were between photosets 1988-2004 and 1951-1966. The 36 and 33 m movements occurred approximately 240 m and 740 m, respectively, downstream from the start of Reach 4. This amount of movement was the result of the erosion of two large cutbanks (Figure 53). Similar to Reach 4, Study Reach 15 also exhibited cutbanks that resulted in an approximate channel position change of 36.7 m to the right and 23 m to the left downstream approximately 175 m and 1 km, respectively, from the start of Reach 15 for photosets 1988-2004. The downstream translation of meander loops Aj-Aj2, located approximately 2 km downstream, also contributed to channel position change for photosets 1939-1951, 1951-1966, 1976-1988, and 1988-2004 (Figure 54). Study Reach 6 is the only reach that had a large amount of channel position change directly attributable to meander loops. These are meander loops Aq1 and Aq2, located approximately at 850 m and 1 km downstream of the start of Study Reach 6, respectively. The largest amount of change in channel position in Study Reach 6 was in photoset 1988-2004 at 40 m (Figure 55).

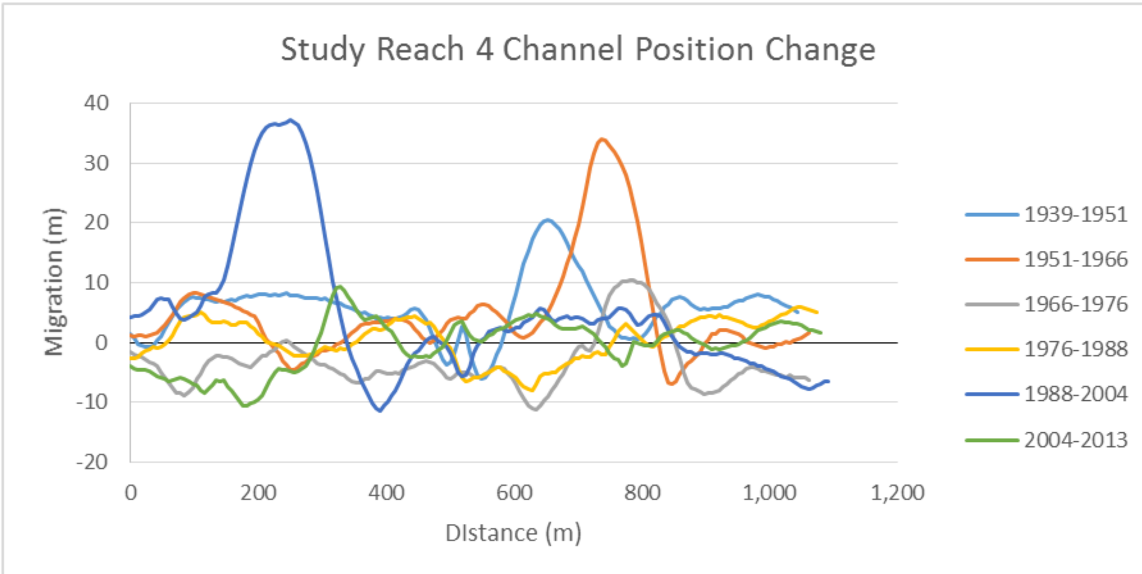

Figure 53. Change in channel position at Study Reach 4.

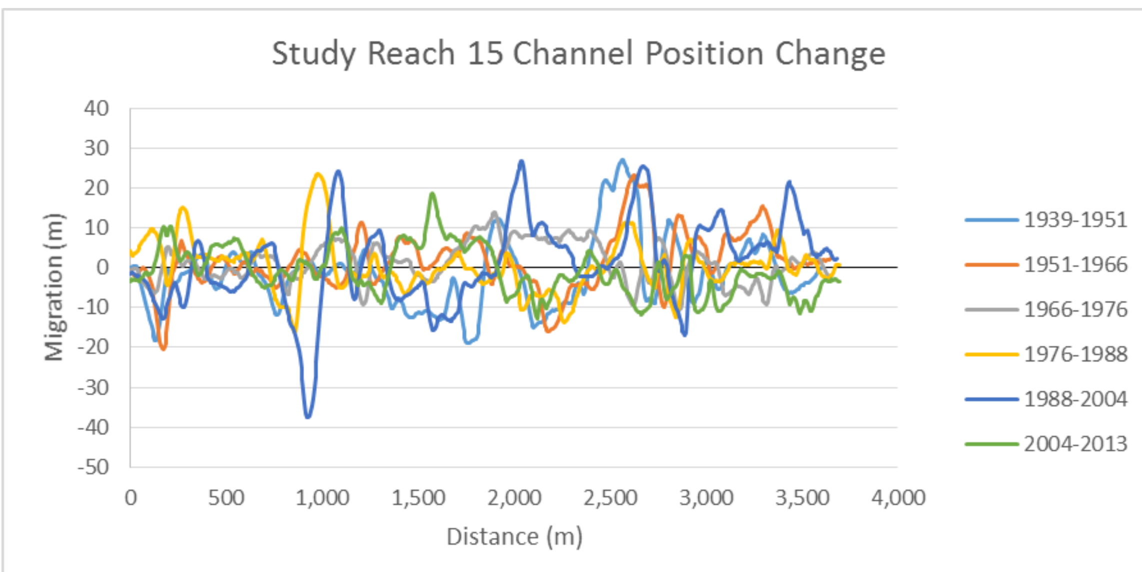

Figure 54. Change in channel position at Study Reach 15.

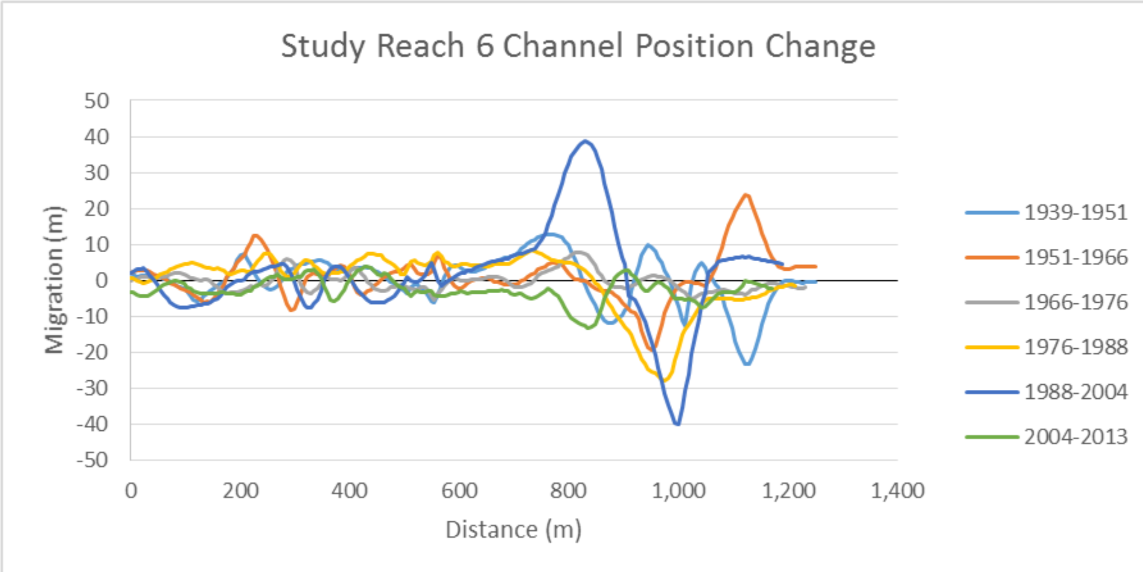

Figure 55. Change in channel position at Study Reach 6.

In Study Reach 21, while experiencing channel position change in all photoset years, exhibited its largest channel migration in meander loop An1 of 80 m to the right in photoset 1988-2004 between 275 m and 950 m downstream from the start of the reach, which encompasses the meander loops An-An2. In this zone, at 725 m downstream, lies the confluence of Sunday Creek with the Hocking River. Furthermore, meander loops An and An2 during this period migrated a maximum of 33.6 m and 19 m to the left, respectively (Figure 56). The amount of channel position change is astonishing when compared to the centerline location in photo set 1976-1988.

While meander loop Aa in Study Reach 22 displayed channel migration approximately 700 m downstream, it was small in comparison with the extent of channel position change that was exhibited by meander loops Ao-Ao3, which are located between 1.5 km and 2 km downstream from the start of Study Reach 22. On photosets 1976-1988 and 1988-2004, meander loop Ao moved laterally to the right by approximately 87 m and 80 m, respectively, and ultimately terminated, as seen in the 2004-2013 centerline. In addition, located 2 km downstream, Ao2 exhibited the most lateral movement between 1988 and 2004 by approximately 85 m. Finally, Ao3 underwent a consistent increase in channel migration between 2 km and 2.5 km up until photoset 2004-2013 (Figure 57).

Study Reach 23 is a unique section of the Hocking River as it is the only location that exhibits a meander wave train that has not been channelized nor has it had meander chute cut-offs. Channel migration of meander loops A-F, between photosets 1939-1951, 1976-1988, and 1988-2004, had a maximum amount of channel change of 62 m to the left and 47 m to the right. It is located between 1.5 km and 3.0 km downstream from the start of Study Reach 23 (Figure 58).

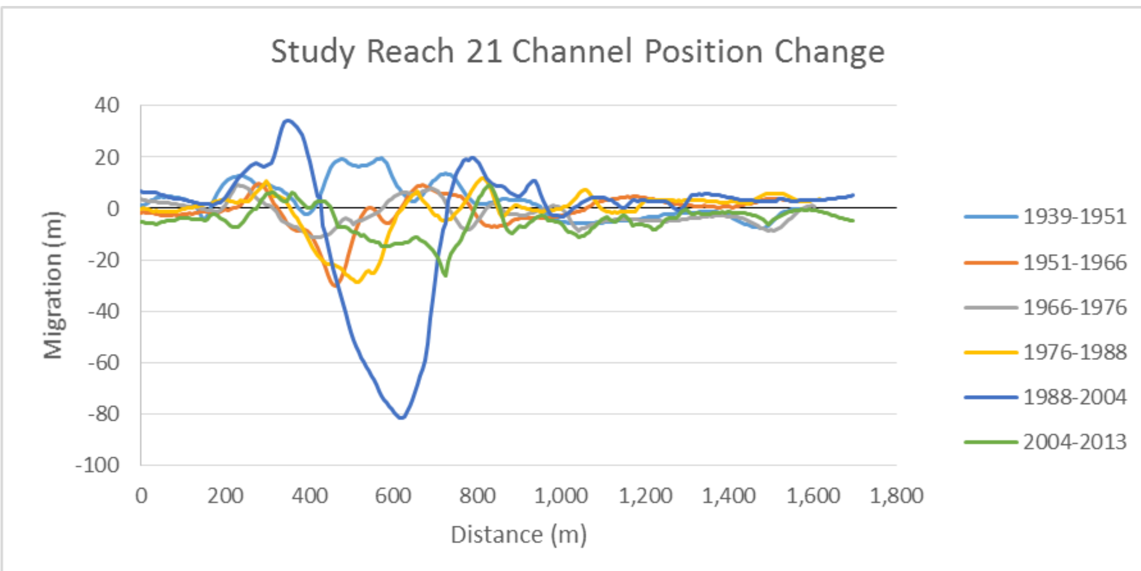

Figure 56. Change in channel position at Study Reach 21.

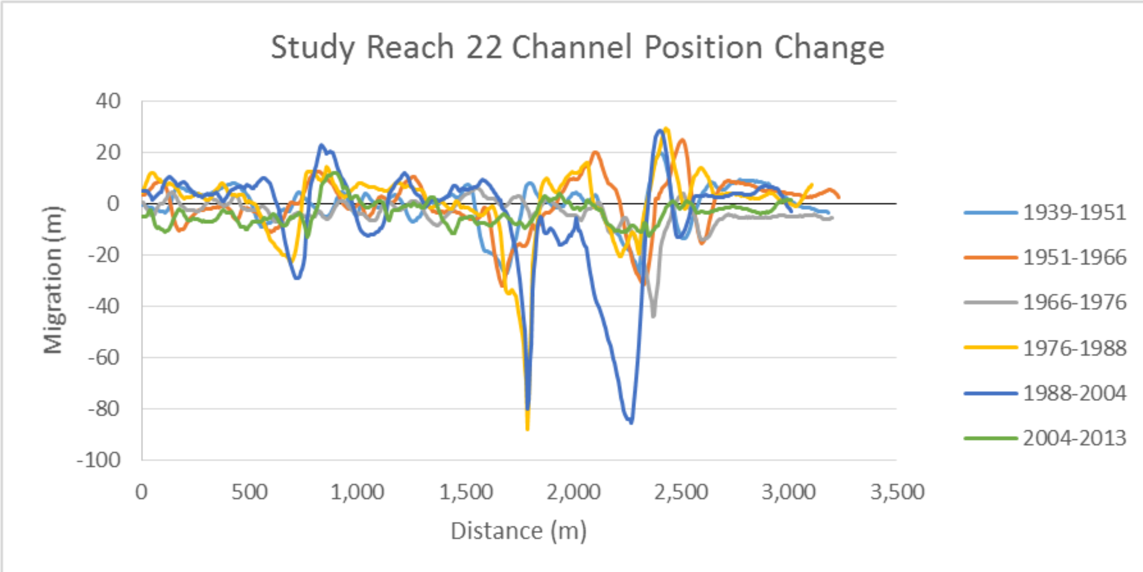

Figure 57. Change in channel position at Study Reach 22.

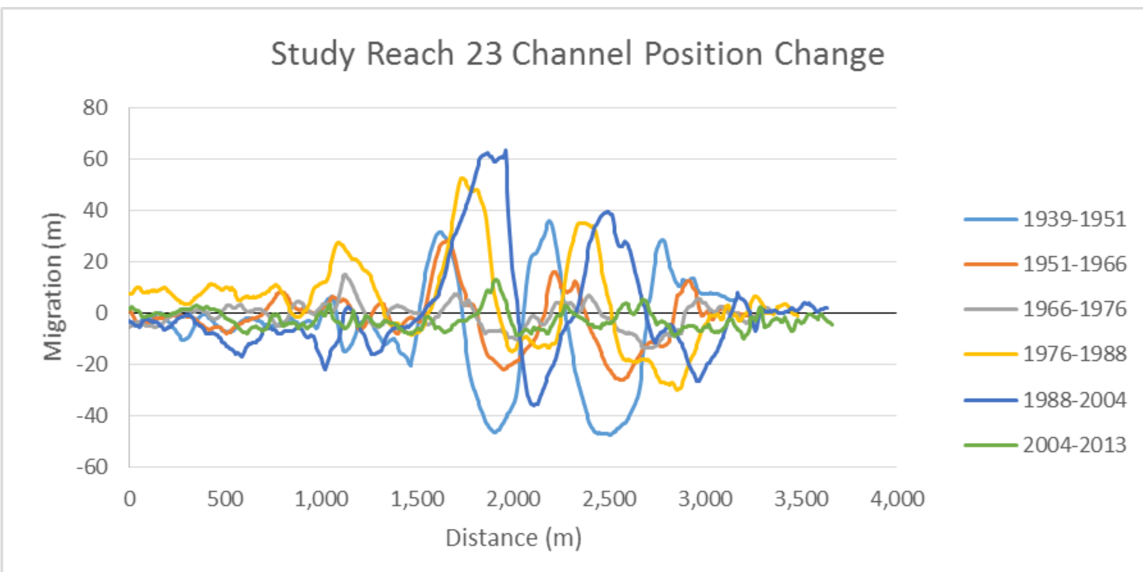

Figure 58. Change in channel position at Study Reach 23.

5.4 Human and Environmental Impacts on Channel Planform

Associations between planimetric variables and the human impact and environmental variables used the study reaches or individual meander loops, as cases. For some variables, it was not possible to perform statistical tests of association; those hypothesized relationships are evaluated on the basis of logic and coexistence in space and time. For quantitative variables, study reach averages were used in conducting statistical tests of association involving sinuosity, width, and lateral migration. Meander loops served as cases for analyses involving asymmetry.

5.4.1 Surface Mining Impacts on Planform Change

Industrial mineral mines B through H (Figure 7), although located in the floodplain, do not appear to have affected channel planform variables. Interpretation of aerial photosets indicates that the mines were either far removed from the river channel or separated from the channel by a vegetated riparian buffer that was left intact. This is supported by distances measured from channel bank to the edge of gravel mining ponds, which ranged between approximately 10 and 347 m. For these reasons, it was also concluded that the mining activities would not have affected values of sinuosity and asymmetry. However, large tracks of surface coal mining have existed throughout the tributary watersheds of Monday Creek, Scott Creek, and Margaret Creek (Figure 6). Without detailed, historic sediment budgets, planimetric change related to large sediment pulses from more distant coal mines is only suggestive, as Engelman (1996) pointed out in her research on the Hocking River planform change between The Plains and Athens in regards to surface mining in the Monday Creek subbasin.

5.4.2 Transportation Impacts on Planform Change

Transportation markedly impacted the Hocking River between 1951 and 1976 with the advent of the new US Route 33 that connected Lancaster to Athens. During this time period transportation-related channelization occurred in Study Reaches 1, 2, 8, 10, and 17, and directly modified planimetric variables in those reaches. It seems possible that these engineering projects impacted planform variables on the immediate downstream reaches of 3, 9, 11, and 18.

Transportation-related channelization between 1951 and 1966 left Study Reach 1, 2, and 17 with significantly wider channels. During this time Study Reach 1 shifted on average 3.4 m to the left, which had barely moved laterally in the pre-channelized interval (1939-1951). Study Reach 2 was not moved laterally during the channelization, while Study Reach 17 shifted on average 9.2 m to the right in 1951-1966. The second transportation-related channelization occurred between 1966 and 1976 and affected Study Reach 8, and 10. After channelization both Study Reach 8 and 10 had significantly wider channels. During this time Study Reach 8 exhibited an average shift of 7.2 m to the right in 1966-1976, while Study Reach 10 had an average shift of 8.4 m to the right in 1966-1976.

In terms of the effects of channelization on downstream reaches, it was determined that Study Reach 3, 9, 11, and 18 all had a significant increase in channel width. Study Reach 11 was the only one that did not undergo a significant change in channel position. Study Reach 3 went from a pre-channelized average shift of 7.4 m to the left in 1939-1951 to an average shift of zero in 1951-1966. Study Reach 9 shifted on average 3.7 m to the right between 1966 and 1976, while Study Reach 18 shifted on average 3.6 m to the right between 1951 and 1966.

5.4.3 Channelization Impacts on Planform Unrelated to US Route 33

As discussed in Section 5.1.3, three incidences of channelization occurred that were not related to US Route 33. These involved Study Reaches 11, 19, and 25 as mitigation steps to reduce property damage as the result of flooding and lateral migration. These channelizations had significant ($p < 0.001$) influence on channel planform within the reach and possibly on the immediate downstream reaches of 12 and 20.

As a result of channelizing between 1976 and 1988, Study Reach 11 saw a significant increase in channel width. However, Study Reach 19 underwent a decrease in channel width after the 1939-1951 channelization. In terms of channel position change, both Study Reach 11 and 19 had significant shifting. Study Reach 11 exhibited an average shift of 7.2 m to the right between 1976 and 1988, while Study Reach 19 shifted an average shift of 1.7 m to the left between 1939 and 1951.

In terms of downstream impacts, it was determined that Study Reach 12 and 20 performed like Study Reaches 11 and 19. While channel width increased in Study Reach 12, Study Reach 20 had decreased width. Regarding channel position change, Study Reach 12 had an average shift of 1.3 m to the left between 1976 and 1988, while Study Reach 20 had an average shift of .7 to the right between 1939 and 1951.

The largest change in width occurred in Study Reach 25 as the result of channelization. This reach also shifted to the right by 5.4 m between 1951 and 1966 before being relocated 111.7 m farther to the right between 1966 and 1976. Measurements downstream are unavailable as the study area ended at the Stimson Avenue bridge. However, Gregorio (2008) determined that, while there was statistically significant change in width directly below the channelized reach, little change was observed in sinuosity, asymmetry, and lateral migration. He also found that the effects of the channelization through Athens on downstream planimetric variables decreased with increasing distance downstream.

For both reasons of channelization, that is, road construction and flood mitigation, significant impacts to channel width and lateral migration have occurred. In addition to these planimetric variables, sinuosity and asymmetry were also impacted. As discussed in those previous sections, the primary impact of channelization on sinuosity and asymmetry was the shortening of channel length by means of channel realignments and/or meander loop cut-offs, which occurred in Study Reach 1, 2, 8, 10, 11, 17, 19, and 25. It would appear that the immediate impacts of modified reaches are the greatest and most readily seen in the immediate reach downstream.

5.4.4 Vegetation Correlation with Width and Channel Position Change

Spearman's correlation (r_s) revealed a strong negative association ($r_s = -.61$; $p<0.05$; n=150) between percent change in vegetation and percent change in channel width for the overall combined data set of all study reaches for all successive pairs of photosets. An increase in the extent of woody vegetation in the riparian buffer is associated with a decrease in channel width. Negative correlations were also found when comparing these variables for each pair of successive photo years. In terms of successive years of photos, 1939-1951 had the strongest negative correlation followed by 1976-1988 and 2003-2013 (Table 13, Figure 59).

A scattergram of percent change in channel width versus percent change in vegetation indicates that the point representing Study Reach 25 for 1966-1976 is an outlier. This is the reach at Athens, which had extensive artificial modification of the channel during this time interval. This outlier is evidence of how much human impacts can alter the planform of a river system. In order to see if this outlier affected the results, the point was omitted and the correlation re-calculated (Table 14 and Figure 60). This decreased the strength of the negative correlation in the 1966-1976 column by -0.09 and had an extremely small impact on the overall correlation, reducing it by 0.01.

Table 13. Spearman's correlation results between percent change in vegetation (riparian buffer) and percent change in channel width, with Study Reach 25 1966-1976 outlier included.

	1939-1951	1951-1966	1966-1976	1976-1988	1988-2004	2004-2013
r_s	-0.67	-0.38	-0.35	-0.66	-0.33	-0.64
t value	4.275	1.989	1.765	4.205	1.650	3.995
p value	<.05	<.05	<.05	<.05	>.05	<.05

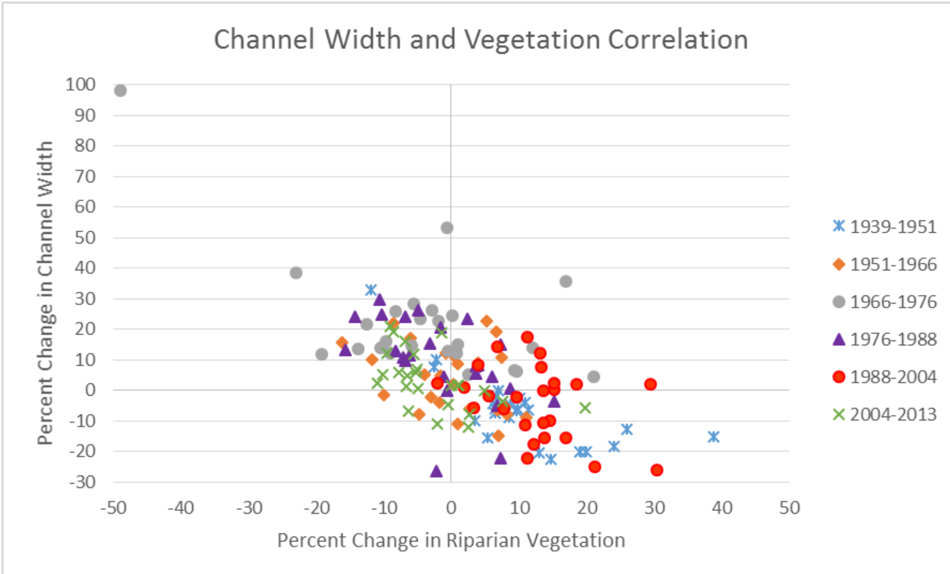

Figure 59. Scattergram of percent change in channel width vs. percent change in vegetation for all study reaches and all successive photosets.

Table 14. Spearman's correlation results between percent change in vegetation (riparian buffer) and percent change in channel width, with the Study Reach 25 1966-1976 outlier omitted.

	1939-1951	1951-1966	1966-1976	1976-1988	1988-2004	2004-2013
r_s	-0.67	-0.38	-0.26	-0.66	-0.33	-0.64
t value	4.275	1.989	1.263	4.205	1.650	3.995
p value	<.05	<.05	>.05	<.05	>.05	<.05

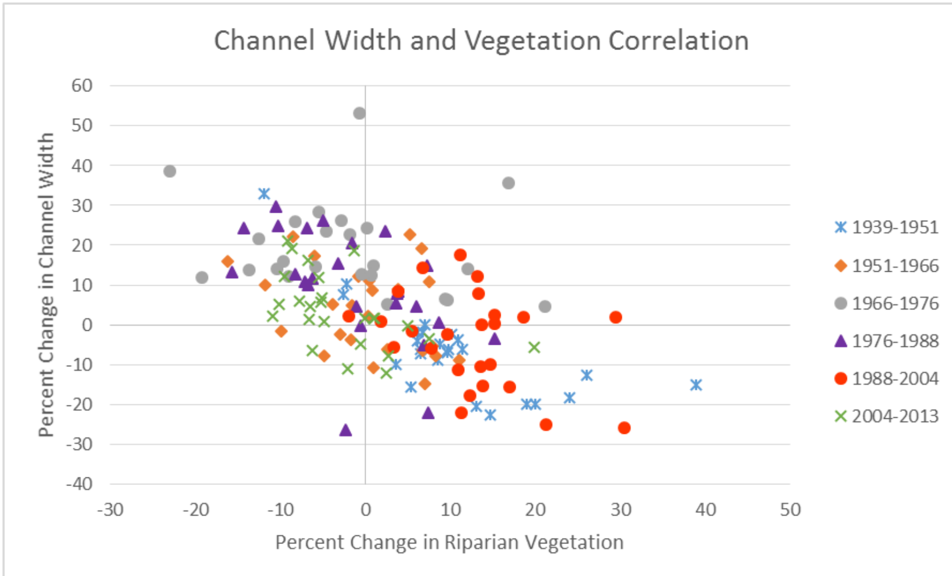

Figure 60. Scattergram of percent change in channel width vs. percent change in vegetation for all time periods, with Study Reach 25 data point 1966-1976 omitted.

Spearman's correlation was also calculated using total percent woody vegetation in the riparian buffer and mean channel width (i.e., not changes in the variables) for each photo year and for all reaches. This was completed to determine whether it is the simple amount of woody vegetation present or if it is the change in that vegetation that is a more important factor associated with channel width. Results show that the only statistically significant coefficient in this case is for the 1939 and 2013 data (Table 15). Over the data set as a whole, total percent vegetation and mean channel width for the upper Hocking River have a weak positive correlation with $r_s = 0.25$ ($p<0.05$, and $n=150$) (Figure 61).

Table 15. Spearman's correlation results between total percent vegetation and mean channel width.

	1939	1951	1966	1976	1988	2004	2013
r_s	0.39	0.29	0.33	0.00	0.26	0.20	0.39
t value	2.011	1.479	1.671	0.006	1.278	0.989	2.008
p value	<.05	>.05	>.05	>.05	>.05	>.05	<.05

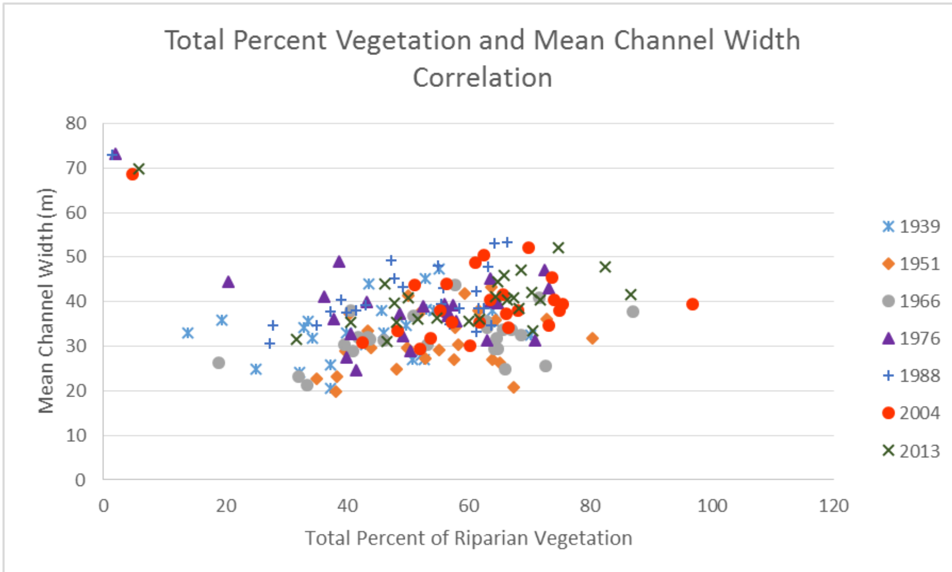

Figure 61. Scattergram of mean channel width versus total percent extent of vegetation at all study reaches for all photo years.

Change in percent vegetation cover and rate of change in channel position have no correlation for the overall upper Hocking River, with r_s = 0.04, p = <0.05, and n=150. For the individual pairs of photo years, there was either a very weak to no correlation; furthermore, none of the comparisons of the photo pairs was statistically significant. The weak positive correlation value gets progressively smaller for more recent photosets (Table 16). Once again, the data point for Study Reach 25 for the 1966-1976 photo pair appears to be an outlier (Figure 62). Re-calculation without that point, however, had little effect on the results. Again, the only value that changed when comparing successive years is in the 1966-1976 column, which changes from the original value of -0.16 (Table 16) to -0.05 (Table 17). For the entire lumped set of data points, omitting the Study Reach 25 1966-1976 data point improves the positive correlation by 0.02 (Figure 63).

Table 16. Spearman's correlation results between change in percent extent of vegetation and rate of change in channel position (lateral migration), with the Study Reach 25 1966-1976 outlier included.

	1939-1951	1951-1966	1966-1976	1976-1988	1988-2004	2004-2013
rs	0.11	0.2	-0.16	0.15	-0.28	-0.15
t value	0.512	0.971	0.797	0.716	1.39	0.724
p value	>.05	>.05	>.05	>.05	>.05	>.05

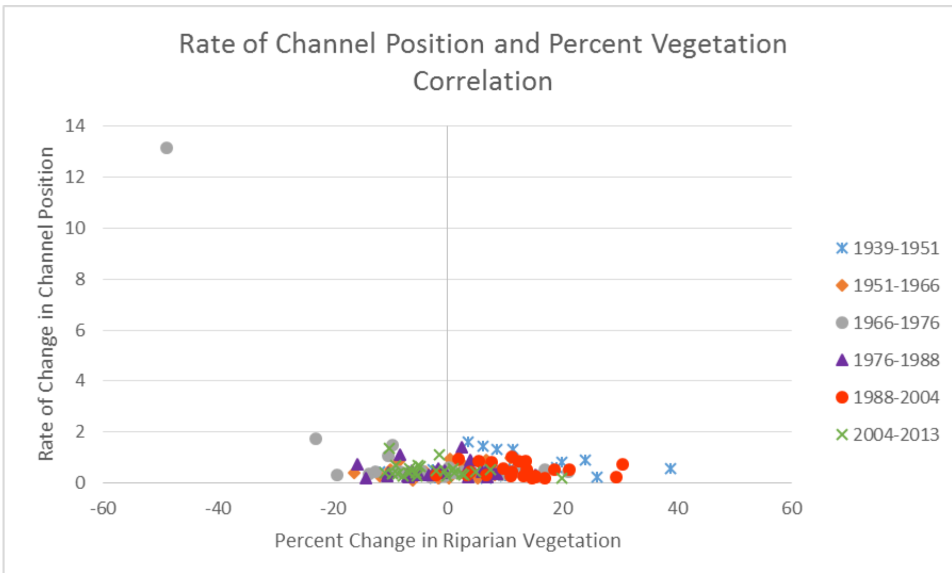

Figure 62. Scattergram of rate of change in channel position versus change in percent of woody vegetation in the riparian buffer.

Table 17. Spearman's correlation between change in percent of woody vegetation in the buffer and rate of channel position change, with the Study Reach 25 1966-1976 outlier omitted.

	1939-1951	1951-1966	1966-1976	1976-1988	1988-2004	2004-2013
rs	0.11	0.2	-0.05	0.15	-0.28	-0.15
t value	0.512	0.971	0.257	0.716	1.39	0.724
p value	>.05	>.05	>.05	>.05	>.05	>.05

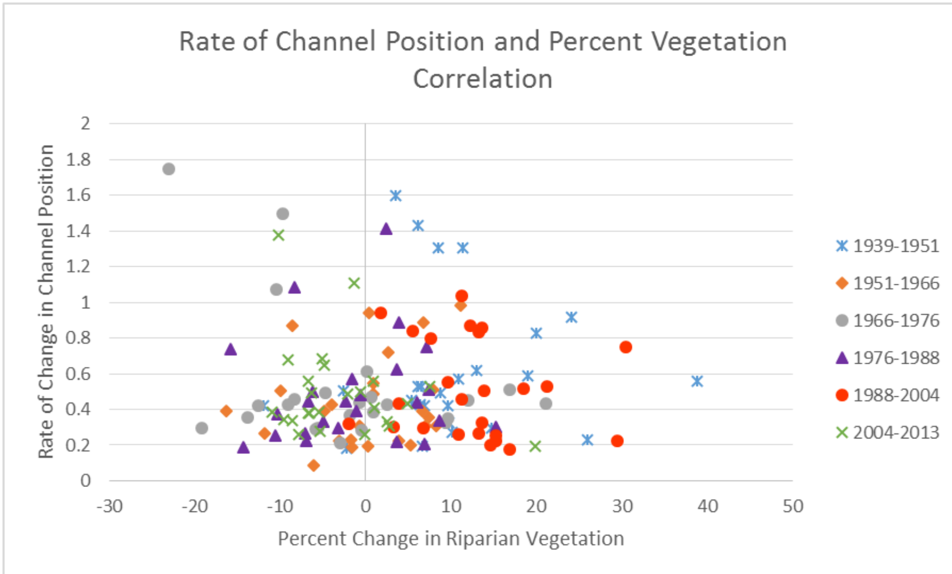

Figure 63. Scattergram of rate of channel position change versus change percent of woody vegetation in the riparian buffer, with the Study Reach 25 data point 1966-1976 omitted.

5.4.5 Discharge Impacts on Planform Change

Discharge data were analyzed throughout all study reaches and photosets. The direct impact that discharge appears to have had on channel planform occurred in several historic flood events. The results of these floods were interpreted as the primary factor that caused meander loop chute cut-offs in Study Reaches 10, 13, and 19.

Between 1979 and 1988 Study Reach 10 underwent a reduction of channel length of 545 m when meander loop Af1 was cut-off (Figure 64). The initial cut-off seen in 1966 appears to be the result of the major flood event on March 10, 1964, which reached a gage height of 6.5 m. Lastly, two moderate floods occurred within four days of each other, May 24 and May 28, 1968, with gage heights of 5.6 m and 5.4 m, respectively. Furthermore, flood events occurred with a flood stage of 4.7 m on February 24, 1975, while the next flood event of 4.3 m occurred on March 15, 1978. Flood events in Study Reach 13 appear to have caused the termination of meander loops Ar and Ar1 between 1966 and 1976, which reduced channel length approximately

130 m (Figure 65). While cut-offs in Study Reach 13 occurred between 1966 and 1976, that reach experienced the same flood events as Study Reach 10 with the exception of the flood stage event of March 15, 1978. Farther downstream, between 1951 and 1966 Study Reach 19 underwent cut-offs in both meander loops Am5 and Am6, which resulted in a 64 m reduction in channel length (Figure 66). The termination of meander loops in Study Reach 19 was in response to one flood stage event and one major flood event, which occurred on January 22, 1959, and March 10, 1965, resulting in gage heights of 4.8 m and 6.5 m, respectively. All of these meander cut-offs coincided with historic flood events recorded at the Enterprise gaging station.

Historic flood crests recorded at the Enterprise gaging station between 1940 and 1988 consisted of one major and five moderate flood events. The major flood event occurred on March 10, 1964, at a crest of 6.5 m. Of the six moderate floods, the two largest occurred on April 20, 1940, and March 6, 1945, with crest heights of 6.1 m. The next two moderate floods occurred on May 24 and 28, 1968, with crest heights of 5.6 m and 5.4 m, respectively. The smallest moderate flood event occurred on April 13, 1948, with crest height of 5.2 m.

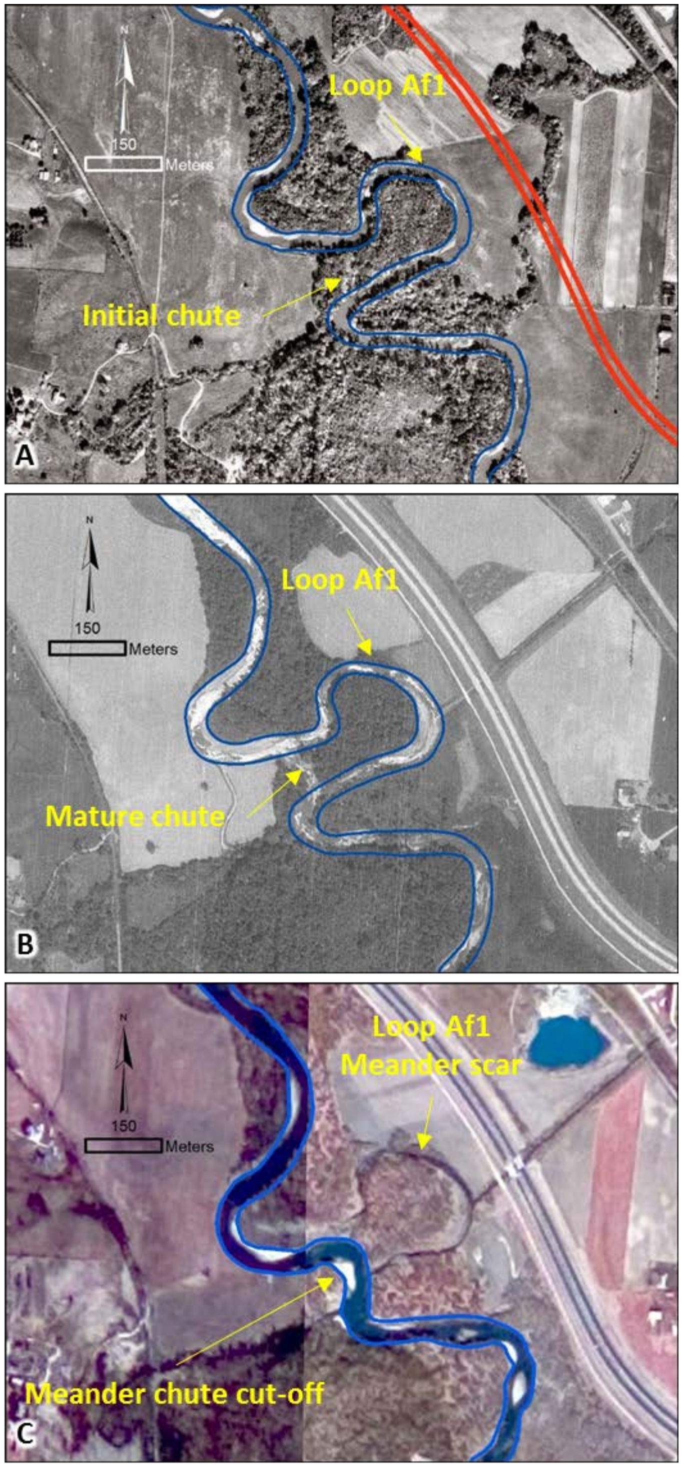

Figure 64. Complete sequence of meander loop chute cut-off of meander Af1 from 1966 (A), 1976 (B), and 1988 (C) in Study Reach 10. River flow is northwest to southwest.

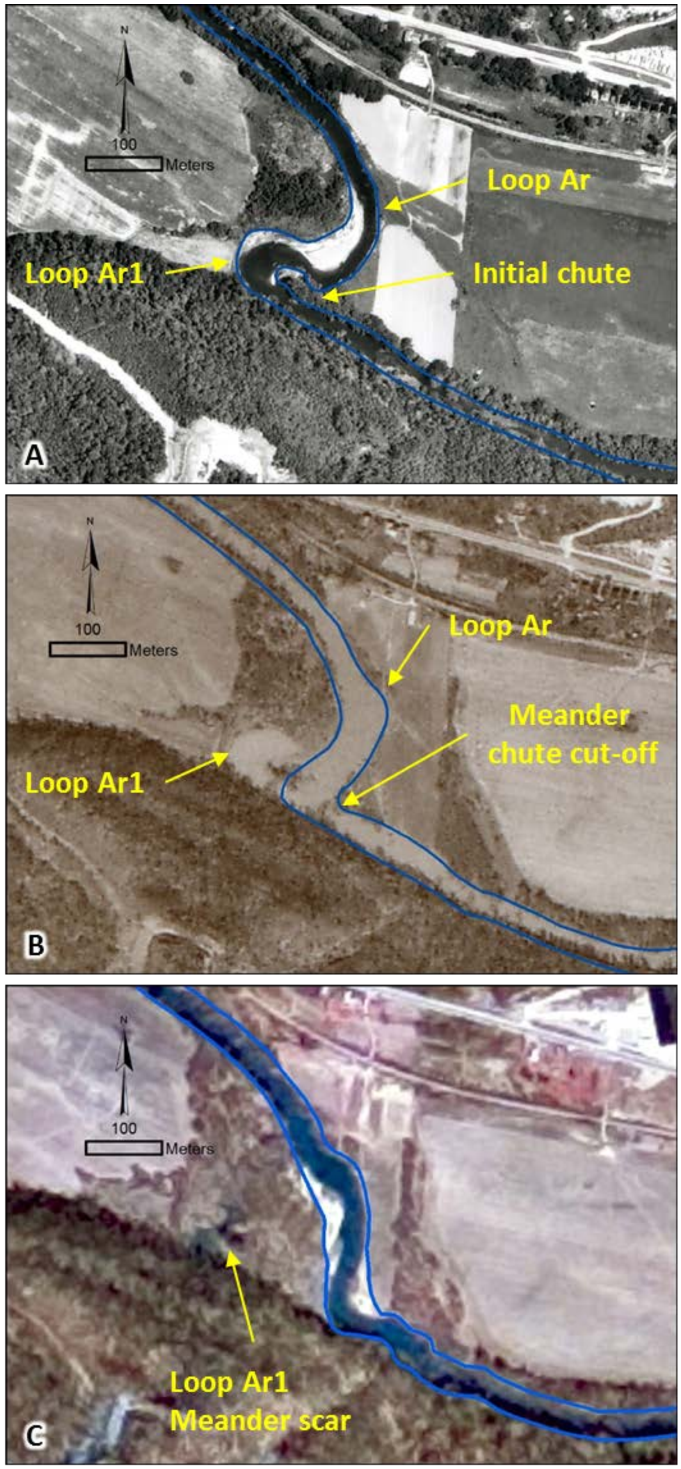

Figure 65. Complete sequence of the meander chute cut-off of meander loop Ar and Ar1 from 1966 (A), 1976 (B), and 1988 (C) in Study Reach 13. River flow is northwest to southwest.

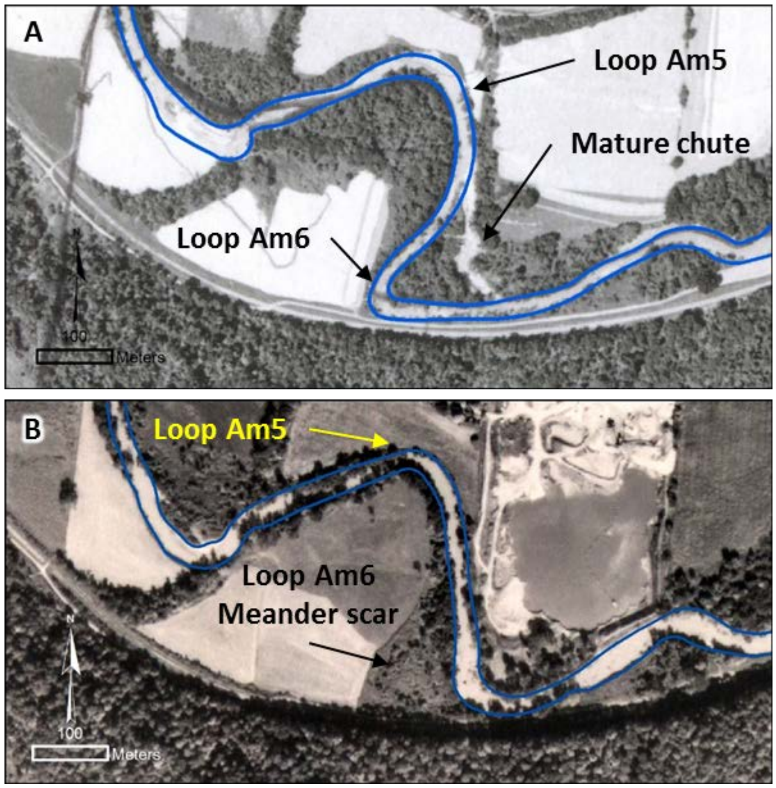

Figure 66. Complete sequence of meander loop chute cut-off of meander loop Am6 from 1951 (A) and 1966 (B) in Study Reach 19. River flow is west to east.

5.5 Summary of Results

In summary, planimetric analyses have determined that of all the human and environmental variables studied, the advent of transportation infrastructure, specifically establishment of US Route 33, as well as artificial channelization to mitigate property damage within the floodplain, were the leading contributors to planimetric change of the upper Hocking River over the 75-year span. In addition, historic floods causing meander cut-offs was the second most important variable associated with planimetric change. Lastly, extent of the vegetation buffer has a strong negative correlation with channel width, but no correlation with lateral migration.

CHAPTER 6: DISCUSSION

The results of this study indicate that human variables brought about abrupt change in the Hocking River planform to an extent not matched by the studied environmental variables. It was determined that historic flooding did modify the planform by meander chute cut-offs, but its effect on the planform was not as extensive as the effects from human-induced channelization, whether for transportation or flood mitigation purposes. Nevertheless, given the number of variables and large amount of data collected, there exists room for discussion and interpretation of influences on the planimetric variation found along the upper Hocking River over the 75 year span.

6.1 Flood Events

While the flood data and planform change indicated in the air photos suggest that specific meander loops were terminated by flood-induced chute cut-offs, it must be noted that this is a possible explanation. It is inferred that the observed meander chute cut-offs were flood-induced. Methods exist to predict how flooding will cut-off meanders and where. One suggestion for future study, not only in the upper Hocking River but applicable in other watersheds, is the use of LiDAR-derived digital elevation models to determine the topography of the floodplain, specifically meander loops and the presence of any chutes. These digital elevations models could then be used in conjunction with flood models using various gage height scenarios to determine at what flood level a particular chute would be inundated by stream flow.

6.2 Riparian Buffer

Over the course of the study period the spatial and temporal properties of the riparian vegetation buffer changed in all 25 reaches. These changes in vegetation are attributed to human actions, either through private or commercial means. Deforestation along the upper Hocking

River over the 75 years was associated with clearing for agriculture, surface gravel mining, transportation, and logging. While the results show a large increase in the woody vegetation along the river between 1939 and 1951, there was a continual decrease in it between 1966 and 1988 before it increased again. In order of importance, the mid-period decrease in riparian vegetation resulted from logging, transportation, gravel mining, and agriculture. The large increase that occurred between 1988 and 2004 was from the reestablishment of woody vegetation in the areas that were previously logged. Overall, riparian woody vegetation increased 37% over the 75 year study span. However, this is roughly half of the 79% increase in vegetation that Wryst (1995) found over 60 years between Athens and Guysville.

Interestingly, the planform of the upper Hocking River, as determined in this thesis, changed significantly more than what Gregorio (2008) found for the lower Hocking River. However, this difference is likely due to the less topographically constrained upper Hocking River compared to the lower Hocking River below Athens. The location and distribution of the riparian buffer along a river channel is also an important factor in influencing changes in planform. It was determined in this study that distribution of woody vegetation along the channel is important, as indicated by the strong negative correlation between percent change in vegetation and percent change in channel width. However, there was no correlation between percent change in vegetation and rate of channel position change. Due to the lack in this correlation it would be interesting to look at the specific location of riparian vegetation at cut-banks as a means to understand more about the relationship between the cut-banks and the amount of vegetation present. Specific location of woody vegetation along the channel is likely important because the highest velocity of stream flow is in the bend of maximum curvature of meander loops. This relationship could be determined in future studies and would be applicable to other humid-region watersheds.

6.3 Asymmetry

Both positive and negative asymmetry values were determined for the upper Hocking River, meaning that meander loops were migrating upstream and downstream. Some meander loops, however, maintained positive or negative values over the entire time span, while others changed designation. Although these variations signify that a meander shifted its migration trajectory, it is important to remember that the aerial imagery from which the data were collected are snapshots in time and it is not known how asymmetry varied between the approximately decadally spaced photo years.

Several meanders had negative asymmetry for the seven photoset years, which indicates upstream migration, yet the overall trend shows downstream migration, which is contradictory. One of the best examples is Study Reach 22 at meander loops Ao and Ao2 (Figure 67; Tables 18 and 19). In these two cases asymmetry for each photo year designates upstream migration, but combining all photo years from 1939 to 2013 shows that the actual trajectory of meander loops Ao and Ao2 was downstream (Figure 79). Other meander loops that show this issue include B-E, Aa, Ae-Ae3, Af, Aj2, Am1, Am5, Am6, An2, Aq1, and Ar1 (Appendix B). Changes in asymmetry result from channel position change at specific locations. Asymmetry, therefore, appears to be of value as a description of meander loops at a given point in time, and upstream or downstream asymmetry is not necessarily indicative of upstream or downstream meander translation over time.

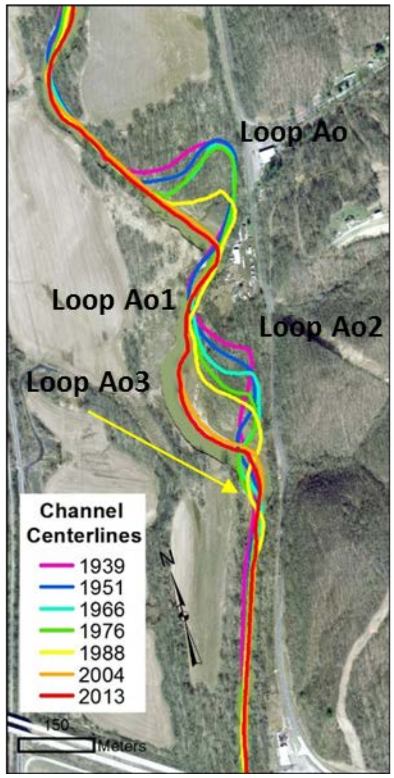

Figure 67. Asymmetry of meander loops Ao-Ao3 in Study Reach 22. River flow is north to south.

Table 18. Meander loop Ao asymmetry.

Ao	λu	λd	Δ	λh	Asymmetry
1939	97.5	231.6	-134.1	192.7	-0.6959
1951	79.2	250	-170.8	191.6	-0.8914
1966	55	237	-182	175.1	-1.0394
1976	79.2	189	-109.8	145.5	-0.7546
1988	30.5	109.7	-79.2	88.3	-0.8969
2004	146.3	67	79.3	177.1	0.4478
2013	55	30.5	24.5	77.2	0.3174

Table 19. Meander loop Ao2 asymmetry.

Ao2	λu	λd	Δ	λh	Asymmetry
1939	42.7	97.5	-54.8	109	-0.5028
1951	61	97.5	-36.5	133.6	-0.2732
1966	49	146.3	-97.3	143.3	-0.6790
1976	36.6	91.4	-54.8	103	-0.5320
1988	61	97.5	-36.5	137	-0.2664
2004	42.6	189	-146.4	203	-0.7212
2013	42.7	207.2	-164.5	215.2	-0.7644

6.4 Sinuosity

Over the 75 years considered in this study of the upper Hocking River, human impacts by means of artificial channelization altered channel sinuosity faster and to a greater degree than natural variability. Study Reaches 1, 3, 9, 12, 14, 18, 19, and 20 had modifications to the channel planform either through artificial channelization or natural meander chute cut-off or were located in the reach directly downstream from a reach that did. However, sinuosity did not increase or decrease for these reaches over the 75 years.

Study Reach 1 was channelized between 1951 and 1966, while Study Reach 19 was channelized between 1939 and 1951, and had natural meander chute cut-off between 1951 and 1966. In both cases these modifications were not enough to change the ratio between channel length and valley length. Study Reaches 3, 9, 12, 14, 18, and 20, while located directly below modified Study Reaches 2, 8, 10, 13, 17, and 19, did not change sinuosity as expected. This suggests that some intrinsic thresholds were not crossed to induce change in the system (Schumm and Lichty, 1965). Remaining reaches that were not modified and were not located directly below a modified section, yet also did not change in sinuosity, are 4, 7, 15, 16, and 24. These reaches maintained their sinuosity due to channel constraints because of their continuous riparian buffer or because of being limited by roads or railroads. These constraints are known to mitigate lateral migration, which, in turn, reduces the development of sinuosity. It appears that sinuosity is relatively stable until the planform is significantly modified.

6.5 Width

Over the 75-year study span width was determined to have an increasing trend downstream among the 25 reaches, which is typical for humid region, perennial streams. As a whole, the upper Hocking River widened from 33 m in 1939 to 41 m in 2013. As shown in section 5.3.3, the largest changes in channel width (Study Reaches 1, 2, 8, 10, 11, 13, 17, 19, and 25) are attributed to artificial channelization for the construction of US Route 33 and flood mitigation, and meander chute cut-offs during historic flood events. The remaining fluctuations in width appear to be the result of the combination of vegetation change and channel position change.

The tendency for width to increase downstream over the 75 years could be caused by an increase in stream power resulting from the artificial channelizations and flood-induced meander cut-offs, which tend to increase a river's ability to do work. It is also possible that some of the observed changes in width can be attributed to digitization error, especially resulting from the spatial resolution of the acquired air photographs. Nevertheless, the results of the channel width analyses demonstrate that humans changed the fluvial system to a far greater extent than the environmental variables did.

6.6 Channel Position Change

Over the course of the study span channel position displayed continuous change in all 25 reaches. Again, human modification through channelization and construction of US Route 33 altered this channel planform variable at a faster rate than natural variability alone. Environmental variables did, however, have an effect on channel position. In fact, it inferred that historic flooding was the primary cause for meander chute cut-off in Study Reaches 10, 13, and 19. Of these three reaches, Study Reach 10 was a unique case in terms of the interplay of human and environmental variables.

The termination of meander loop Af1 in Study Reach 10 was likely a result of the combination of human modification and flood events, specifically those directly upstream in this site and in Study Reach 8. Because of the channelizations of Study Reach 8 and 10 between 1966 and 1976, discharge and sediment load probably increased and impacted downstream channel geometry through aggradation of the channel bed (Brookes, 1985). This aggradation would likely have decreased the discharge capacity of the channel (Nakamura et al., 1997) increasing the frequency of flooding and potential of chute establishment, which in the case of meander loop Af1 did occur (Figure 68).

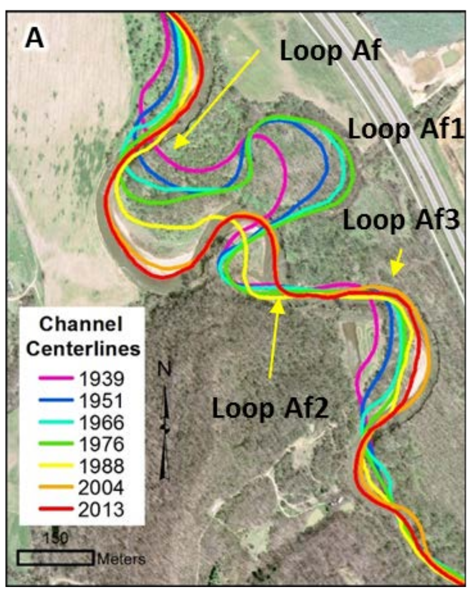

Figure 68. Meander loop Af1 in Study Reach 10. River flow is northwest to southeast.

Another interesting aspect of channel planform change is seen in Reaches 4, 6, and 21-23, all of which had large channel position changes despite not undergoing any modification or being adjacent to upstream modified reaches. These locations show that while human impact was the dominant force in terms of channel planform modification, natural variability also produced large shifts in channel position.

The three large spikes in channel position change that occurred in Study Reach 4 (Figure 53) may have been due to the lack of a riparian vegetation buffer along the cut-banks in the agricultural fields that are adjacent along the left bank as indicated in the air photos. Channel position change in Study Reach 6 appears to have been the result of downstream translation of meander loop Aq1 (Figure 55). The most change at Reach 6 seems to be related to the confluence between the Hocking River and Helber Run. This confluence appears to have created a lateral bar on the left bank, which over the period between 1951 and 2004 shifted the channel to the right.

The other three reaches, 21, 22, and 23, represent large unique channel position changes. Study Reach 21 exhibited substantial position change between 1988 and 2004 (Figure 69). It is likely that the cause of the rapid channel position change during this period was the 11 flood stage and one moderate flood stage events, as recorded at the Enterprise gaging station. As determined by Wolman and Miller (1960), higher frequency, lower magnitude flood events are more effective at modifying channel morphology than less frequent, higher magnitude flood events. Between 1939 and 1976 the channel shifted to the northeast and initialized the formation of meander loop An (Figure 69). This initiation, in turn, increased the migration of the cut-bank in meander loop An and shifted the location of the inflection point to deflect the water velocity into the cut-bank of meander loop An1. In conjunction with discharge, the lack of a riparian buffer in both meander loops An and An1, specifically on the cut-bank side, likely encouraged the lateral movement.

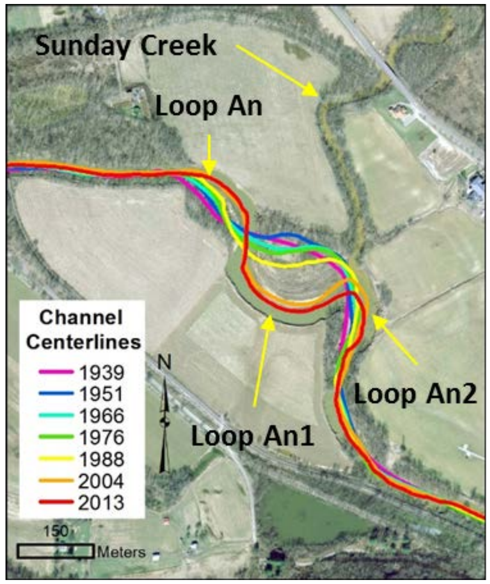

Figure 69. Meander loop An in Study Reach 21. River flow is northwest to southeast.

Migration in Study Reach 22, on the other hand, was the result of heavy deforestation, particularly on the right bank and floodplain of meander loop Ao1. Aerial image interpretation of all seven photosets suggests that this large reduction in riparian buffer vegetation accelerated cut-bank erosion on meander loop Ao1 (Figure 70). It also appears that the road along the left bank in meander loop Ao might have influenced the rapid channel position change. This constraint eventually prevented the Hocking River from further lateral movement and thus led to the eventual cut-off of meander loop Ao between 1988 and 2004. While meander loop Ao1 shifted throughout the seven photo years, the largest shift occurred between 1988 and 2004. It is suggested that the suspended sediment from Ao helped to establish the point bar in meander loop Ao1 between 1988 and 2004 and perhaps increase erosional power at the cut-bank.

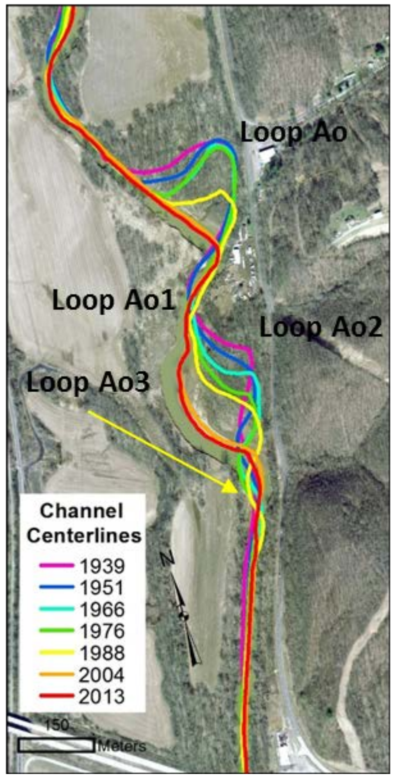

Figure 70. Meander loop Ao-Ao3 in Study Reach 22. River flow is north to south.

Meander loops A-E in Study Reach 23 displayed almost a textbook example of a meander wave train and the downstream translation of meander loops (Figure 71). All loops exhibited lateral and longitudinal movement within the floodplain over the 75-year span. While this area remained heavily forested over the 75 years, sections of the cut-banks in meander loop A and C allowed lateral movement. In addition, the railroad prevented lateral movement in meander loops B and D after 1976 and 1988, respectively. As the consequence of this constraint, the meander loops translated downstream. If a meander wave train is constrained on both sides, it may translate downstream in order to dissipate energy and absorb system changes.

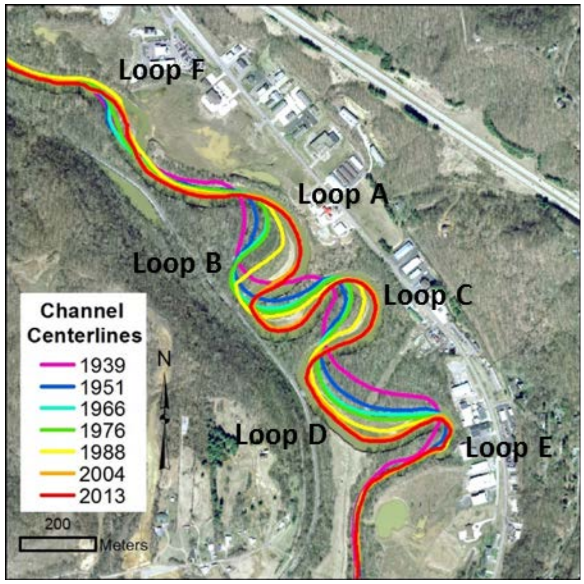

Figure 71. Meander loop A-F in Study Reach 23. River flow is northwest to southeast.

Lastly, Study Reach 17 is unique in having the most recently created meander loops, Ac-Ac2, along the upper Hocking River (Figure 72). While there was a change in channel position between 1939 through 1976, there was much greater change in channel position between 1976 and 1988. The probable cause of this surge was the reduction of woody vegetation in the riparian buffer at the cut-banks of meander loops Ac and Ac1 between 1951 and 1988, as well as two flood and three moderate flood stage events. A second surge in channel position change between 1988 and 2004/2013 could be attributed to the 11 flood and one moderate flood stage events.

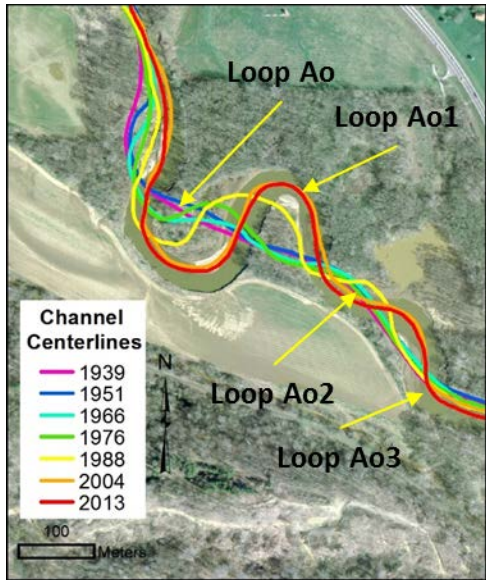

Figure 72. Meander loop Ac-Ac3 in Study Reach 17. River flow is northwest to southeast.

Another interesting matter are the study reaches that display a comparatively small amount (+-20 m) of channel position change over the six photosets. These are Study Reaches 3, 5, 7, 12, 14, 16, 18, 20, and 24, mentioned in section 5.3.4, that did not undergo channelization or meander chute cut-off. Analysis of the aerial photos suggests that consistent riparian buffer vegetation and the location of roads, railroads, and bedrock were influential in limiting channel position change to within +/-20 m over the 75 year span.

Results of this thesis provide an update to and expansion of the assessment of planimetric changes by Engelman (1996) for the part of the upper Hocking River between Nelsonville and The Plains. Engelman (1996) hypothesized that the significant planform changes that occurred between Nelsonville and The Plains between 1938 and 1995 were the direct result of sediment pulsing from surface mining in Monday Creek. It is important to note that Engelman's research only looked at photo years 1938, 1958, and 1995. However, the research presented in this thesis determined that changes in planform, at least in Study Reach 19 for meander loops Am3 and Am4, was due to artificial channelization to mitigate property damage between 1939 and 1951, whereas meander loops Am5 and Am6 experienced flood-induced meander cut-offs between 1951 and 1966. Although sediment pulsing from surface mining in Monday Creek could be influential in the planform change observed in Study Reach 19, results of this thesis point to the importance of artificial channelization and flood-induced cut-offs in enacting the changes.

6.7 Vegetation Correlations

Woody vegetation in the riparian buffer along the Hocking River has had a strong negative correlation with channel width, as indicated by the aggregated 25 reaches. As the percent of vegetation in the riparian buffer increased the percent of change in channel width decreased. Riparian vegetation that exists along the stream channel reduces the amount of channel erosion that takes place. This finding agrees with those of other authors, such as Eschner et al. (1983) and Brookes et al. (2000), who attribute the reduction in bank erosion to the various root systems and root depths that armor the soil and reduce flow velocity. Furthermore, the comparison of percent change of width versus percent change of vegetation (Figure 60) and mean width versus the total vegetation (not change in these variables) (Figure 61) indicated that it is the amount of change that is more important, not simply the amount.

While the negative correlation between percent change in vegetation and percent change in channel width results were expected, the lack of correlation found between percent change in vegetation and rate of change in channel position was not expected. The latter appears contrary to the mitigating influence of vegetation buffer on bank erosion (Smith, 1976; Beeson and Doyle, 1995; Micheli et al., 2004). Vegetation should reduce the rate of channel migration through bank armoring and increased friction.

A possible explanation as to why the upper Hocking data yielded no correlation instead of a negative correlation between the vegetation and channel migration variables is the way in which the channel position change was calculated. Most previous workers calculated channel migration specifically at the cut-banks of meander loops (e.g., Hickin and Nanson, 1975). However, for this thesis, the position change along the entire channel was used to give a fuller view of planform changes. Measuring just the cut-banks may have yielded results similar to others (e.g., Hickin and Nanson, 1974).

Another plausible explanation for lack of negative correlation between rate of change in channel position and percent change in vegetation is colonization of vegetation on newly established point bars. As a channel migrates, a point bar widens and provides terrain for vegetation colonization. However, this may not always be the case given the spatial and temporal variability of the rates of channel migration, vegetation establishment, and discharge regime. Variations in discharge can impede vegetation growth by uprooting seedlings or, if depositing a significant amount of sediment, it can cover young seedlings and prevent further growth.

The research conducted for this thesis corroborates work by other authors in concluding that vegetation inhibits changes in stream width and channel migration. For this reason, it is accepted that the change in vegetation and change in width are more appropriate in the understanding of the impact vegetation has on channel planform than was indicated by the correlation between change in vegetation and rate of channel position change.

6.8 Land Use History

Given the temporal and spatial extent of this study, it was not in the scope of this research to complete an in-depth analysis of the changes in land cover over the 75-year span. There is no doubt that changes in land cover impact planform change, however it would be of interest to see to what extent these changes would align with periods of planimetric change. Future studies of the upper Hocking River could complete supervised and unsupervised classification of land use/land cover from multiple years of satellite or aerial imagery. The history of changes in land use/land cover could then be compared to that of changes in planform in order to more fully investigate the role more extensive watershed properties on the stream system.

CHAPTER 7: CONCLUSIONS

This study documents how the planform of the Hocking River between Sugar Grove and Athens, OH, varied between 1939 and 2013 through seven historic air photo sets, and it assesses whether any significant changes are associated with major human and environmental activities in the watershed. Of the studied human and environmental variables, human-induced changes through the advent of transportation infrastructure, specifically US Route 33, and channelization to mitigate property damage within the floodplain, were the leading causes of planimetric change of the upper Hocking River over the 75-year span. While small mining and small urban areas have been present on the floodplain, the mining operations were distant or separated from the channel by trees, whereas urban areas along the channel changed little over the study period, thus their effect on the river's planform geometry is considered to be minimal. Historic floods triggering meander cut-offs is second in importance to artificial channelization in effecting planimetric change. Lastly, increasing woody riparian vegetation in corridors adjacent to the channel is shown to be associated with smaller changes in channel width but unrelated to channel position change.

Overall, while the upper Hocking River displayed some natural planimetric variability over the 75-year study span, human-induced modifications caused greater magnitudes of change in the planform variables. Significant change occurred during the study period in all planimetric variables throughout the upper Hocking River; however, it was also determined that these changes are not continuous throughout the system but can display periods of stability and fluctuations that vary on a reach by reach basis.

While this research focuses on the broad spectrum of channel planform change, given the large size of the study area, there is still much to learn about the relationship between planform change and human and environmental variables. It would be advantageous for additional research on the upper Hocking River to be conducted on lateral migration rates of meander loops in conjunction with the extent of riparian buffer vegetation as well as on the effects of land cover changes. These additional studies would contribute to a more thorough understanding of the planform changes that the upper Hocking River has experienced over the course of the past 75 years.

Overall, this research contributes to an improved understanding of the nature of stream planform change and of planform sensitivity to the array of environmental and land cover variables found in the upper Hocking River, a mid-latitude humid-region perennial stream. The methods and results of this research can be applied to other, similar watersheds.

In a world becoming increasingly smaller, leading to heightened modification of nature through human ingenuity, the changes in planform geometry are far greater than those due to environmental factors alone. The more that is known about this interplay, the better prepared people can be to mitigate impacts on watersheds while still providing industrial services. Effective communication between scientists and managers/stakeholders is essential for applying this knowledge in a way that provides for both the river system and human needs. With increasing modification of floodplains it is critical to understand the importance of maintaining or improving the riparian buffer along river channels in an effort to improve channel stability and reduce property damage. The importance of riparian vegetation is applicable in a variety of river systems. It is also important for local and state governments to understand that channelization of a reach will have immediate downstream impacts on planform change, notably increasing in sediment and discharge, which can have adverse consequences throughout the floodplain.

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APPENDIX A: ASYMMETRY

Meander loops Aq-Aq2 in Study Reach 6.

Aq	λu	λd	Δ	λh	Asymmetry
1939	140.2	48.7	91.5	168.2	0.5440
1951	207.2	55	152.2	206.2	0.7381
1966	189	61	128	204	0.6275
1976	213.3	48.7	164.6	215.5	0.7638
1988	182	55	127	212.2	0.5985
2004	256	48.7	207.3	275.4	0.7527
2013	213.3	61	152.3	246.6	0.6176

Aq1	λu	λd	Δ	λh	Asymmetry
1939	67	109.7	-42.7	153	-0.2791
1951	79.2	67	12.2	125.4	0.0973
1966	55	109.7	-54.7	139.2	-0.3930
1976	61	73.1	-12.1	118.1	-0.1025
1988	79.2	73.1	6.1	138.4	0.0441
2004	42.6	73.1	-30.5	106.7	-0.2858
2013	67	61	6	123.7	0.0485

Aq2	λu	λd	Δ	λh	Asymmetry
1939	85.3	30.5	54.8	95.6	0.5732
1951	134.1	36.5	97.6	121	0.8066
1966	67	91.4	-24.4	121.1	-0.2015
1976	67	79.2	-12.2	112.7	-0.1083
1988	61	55	6	92	0.0652
2004	61	55	6	105.1	0.0571
2013	73.1	61	12.1	122.4	0.0989

Meander Af-Af3 in Study Reach 10.

Af	λu	λd	Δ	λh	Asymmetry
1939	231.6	97.5	134.1	220	0.6095
1951	183	195	-12	204	-0.0588
1966	93.2	323	-229.8	215.5	-1.0664
1976	128	305	-177	212	-0.8349
1988	103.6	207.2	-103.6	180.1	-0.5752
2004	384	103.6	280.4	248.2	1.1297
2013	378	103.6	274.4	247.7	1.1078

Af1	λu	λd	Δ	λh	Asymmetry
1939	61	219.4	-158.4	144.7	-1.0947
1951	91.4	317	-225.6	144.7	-1.5591
1966	195	274.3	-79.3	143	-0.5545
1976	207.2	225.5	-18.3	170.2	-0.1075
1988	73.1	103.6	-30.5	128.5	-0.2374
2004	103.6	103.6	0	134.4	0.0000
2013	109.7	115.8	-6.1	139.1	-0.0439

Af2	λu	λd	Δ	λh	Asymmetry
1939	122	158.5	-36.5	146.2	-0.2497
1951	152.4	189	-36.6	145.4	-0.2517
1966	158.5	213.3	-54.8	152.5	-0.3593
1976	237.7	219.4	18.3	167.4	0.1093
1988	61	146.3	-85.3	174	-0.4902
2004	85.3	122	-36.7	155.4	-0.2362
2013	61	122	-61	148.5	-0.4108

Af3	λu	λd	Δ	λh	Asymmetry
1939	146.3	164.6	-18.3	211	-0.0867
1951	140.2	201.1	-60.9	232.3	-0.2622
1966	158.5	219.4	-60.9	255	-0.2388
1976	152.4	231.6	-79.2	265.1	-0.2988
1988	201.2	201.2	0	276.2	0.0000
2004	213.4	189	24.4	260.4	0.0937
2013	128	274.3	-146.3	266.6	-0.5488

Meander loops Ag and Ag1 in Study Reach 10.

Ag	λu	λd	Δ	λh	Asymmetry
1939	146.3	213.3	-67	188.2	-0.3560
1951	103.6	213.3	-109.7	154.3	-0.7110
1966	213.3	243.8	-30.5	284.1	-0.1074

Ag1	λu	λd	Δ	λh	Asymmetry
1939	61	219.4	-158.4	173.5	-0.9130
1951	207.2	274.3	-67.1	171.4	-0.3915
1966	97.5	152.4	-54.9	189.3	-0.2900

Meander loop Ai in Study Reach 10.

Ai	λu	λd	Δ	λh	Asymmetry
1939	103.6	97.5	6.1	160.2	0.0381
1951	128	61	67	144	0.4653
1966	35.6	177	-141.4	154	-0.9182
1976	109.7	116	-6.3	165.6	-0.0380
1988	109.7	109.7	0	164.7	0.0000
2004	55	207.2	-152.2	191.26	-0.7958
2013	79.2	177	-97.8	191	-0.5120

Meander loops Ae-Ae3 in Study Reach 11.

Ae	λu	λd	Δ	λh	Asymmetry
1939	115.82	54.86	60.96	141.38	0.4312
1951	103.63	103.63	0	136.26	0.0000
1966	56.86	152.4	-95.54	119.43	-0.8000
1976	85.34	122	-36.66	113.01	-0.3244
1988	237.74	109.73	128.01	155.53	0.8231
2004	195.07	195.07	0	139	0.0000
2013	170.68	182.8	-12.12	134.87	-0.0899

Ae1	λu	λd	Δ	λh	Asymmetry
1939	97.53	146.3	-48.77	201.62	-0.2419
1951	73.15	176.78	-103.63	157.32	-0.6587
1966	67.06	243.84	-176.78	184.01	-0.9607
1976	103.63	225.55	-121.92	183.7	-0.6637
1988	103.63	195.07	-91.44	125.8	-0.7269
2004	122	256.03	-134.03	142.14	-0.9429
2013	122	268.22	-146.22	149.15	-0.9804

Ae2	λu	λd	Δ	λh	Asymmetry
1939	85.34	182.88	-97.54	175.51	-0.5558
1951	73.15	280.42	-207.27	219.35	-0.9449
1966	237.74	73.15	164.59	216.5	0.7602
1976	250	97.54	152.46	230.3	0.6620

Ae3	λu	λd	Δ	λh	Asymmetry
1939	195.07	140.21	54.86	217.42	0.2523
1951	67.05	237.74	-170.69	221	-0.7724
1966	109.73	103.63	6.1	114.01	0.0535
1976	61	182.88	-121.88	125	-0.9750

Meander loop Ad in Study Reach 13.

Ad	λu	λd	Δ	λh	Asymmetry
1939	225.55	213.36	12.19	204.11	0.0597
1951	323.08	122	201.08	221.78	0.9067
Compound Upstream half					
1966	146.3	152.4	-6.1	216	-0.0282
1976	122	195	-73	219	-0.3333
1988	134.1	170.7	-36.6	202	-0.1812
2004	134.1	256	-121.9	233.4	-0.5223
2013	122	292.6	-170.6	238.2	-0.7162
Compound Downstream Half					
1966	152.4	128	24.4	223	0.1094
1976	146.3	97.5	48.8	200	0.2440
1988	177	122	55	228	0.2412
2004	189	128	61	213.6	0.2856
2013	170.7	109.7	61	206.3	0.2957

Meander loops Ar and Ar1 in Study Reach 13.

Ar	λu	λd	Δ	λh	Asymmetry
1939	85.3	24.4	60.9	91	0.6692
1951	170.7	42.6	128.1	164.2	0.7801
1966	335.3	61	274.3	326.2	0.8409
1976	35.5	85.3	-49.8	109.3	-0.4556
1988	73.1	42.6	30.5	111	0.2748

Ar1	λu	λd	Δ	λh	Asymmetry
1939	225.5	109.7	115.8	278.7	0.4155
1951	42.6	128	-85.4	130.4	-0.6549
1966	91.4	122	-30.6	76.2	-0.4016
1976	36.5	61	-24.5	71	-0.3451
1988	91.4	42.6	48.8	121	0.4033

Meander loops Aj-Aj2 in Study Reach 15.

Aj	λu	λd	Δ	λh	Asymmetry
1939	116	164.6	-48.6	207	-0.2348
1951	158.5	177	-18.5	244.2	-0.0758
1966	195	152.4	42.6	261.2	0.1631
1976	152.4	170.7	-18.3	247.2	-0.0740
1988	195	109.7	85.3	230	0.3709
2004	262.1	91.4	170.7	265.7	0.6425
2013	183	189	-6	271.3	-0.0221

Aj1	λu	λd	Δ	λh	Asymmetry
1939	91.4	67	24.4	136.5	0.1788
1951	97.5	48.7	48.8	110.7	0.4408
1966	91.4	49	42.4	109.6	0.3869
1976	97.5	61	36.5	124.4	0.2934
1988	103.6	79.2	24.4	151.4	0.1612
2004	55	116	-61	132.3	-0.4611
2013	71.1	79.2	-8.1	122.5	-0.0661

Aj2	λu	λd	Δ	λh	Asymmetry
1939	48.7	146.3	-97.6	181.6	-0.5374
1951	48.7	109.7	-61	145.3	-0.4198
1966	67	61	6	112.1	0.0535
1976	42.6	85.3	-42.7	122.1	-0.3497
1988	42.7	164.6	-121.9	191	-0.6382
2004	36.6	109.7	-73.1	132	-0.5538
2013	42.6	134.1	-91.5	162	-0.5648

Meander loop Ab in Study Reach 17.

Ab	λu	λd	Δ	λh	Asymmetry
1939	195.07	79.25	115.82	211.89	0.5466
1951	164.59	115.82	48.77	229.87	0.2122
1966	122	24.38	97.62	123.36	0.7913
1976	152.4	42.67	109.73	164.6	0.6666
1988	152.4	85.34	67.06	180	0.3726
2004	176.78	54.86	121.92	179.81	0.6780
2013	274.32	73.15	201.17	242.92	0.8281

Meander loops Ac-Ac6 in Study Reach 17.

Ac	λu	λd	Δ	λh	Asymmetry
1976	134.11	36.57	97.54	121.55	0.8025
1988	158.49	36.57	121.92	115.65	1.0542
2004	195.07	91.44	103.63	129.82	0.7983
2013	188.97	79.24	109.73	129.35	0.8483

Ac1	λu	λd	Δ	λh	Asymmetry
1976	36.57	67.05	-30.48	91.2	-0.3342
1988	79.24	115.82	-36.58	142.72	-0.2563
2004	54.86	122	-67.14	108.23	-0.6203
2013	85.34	103.63	-18.29	104.21	-0.1755

Ac2	λu	λd	Δ	λh	Asymmetry
1976	48.76	42.67	6.09	87.73	0.0694
1988	24.38	42.67	-18.29	59.12	-0.3094
2004	61	61	0	112.44	0.0000
2013	48.76	60.96	-12.2	101.36	-0.1204

Ac3	λu	λd	Δ	λh	Asymmetry
1976	48.76	97.54	-48.78	140.37	-0.3475
1988	42.67	67.6	-24.93	96.82	-0.2575
2004	54.86	54.86	0	97.43	0.0000
2013	48.76	79.24	-30.48	112.62	-0.2706

Ac4	λu	λd	Δ	λh	Asymmetry
1939	49	158.5	-109.5	182.6	-0.5997
1951	128	91.4	36.6	181	0.2022
1966	109.7	73.1	36.6	145	0.2524
1976	225.5	42.6	182.9	203.3	0.8997
1988	231.6	79.2	152.4	240.3	0.6342
2004	280.4	48.7	231.7	270.7	0.8559
2013	280.4	79.2	201.2	285	0.7060

Ac5	λu	λd	Δ	λh	Asymmetry
1939	158.4	140.2	18.2	207	0.0879
1951	201.2	140.2	61	247	0.2470

Ac6	λu	λd	Δ	λh	Asymmetry
1939	85.3	426.7	-341.4	266.5	-1.2811
1951	103.6	439	-335.4	269	-1.2468

Meander loop Ak1 in Study Reach 19.

Ak1	λu	λd	Δ	λh	Asymmetry
1939	103.6	213.4	-109.8	261	-0.4207
1951	91.4	122	-30.6	165	-0.1855
1966	109.7	55	54.7	111.3	0.4915
1976	110	49	61	109.5	0.5571
1988	128	36.6	91.4	116	0.7879
2004	91.4	85.3	6.1	117.4	0.0520
2013	79.2	110	-30.8	120	-0.2567

Meander loop Al in Study Reach 19.

Al	λu	λd	Δ	λh	Asymmetry
1939	91.4	207.6	-116.2	137.6	-0.8445
1951	73.1	140.2	-67.1	126	-0.5325
1966	134.1	128	6.1	125.5	0.0486
1976	128	154.4	-26.4	128	-0.2063
1988	146.3	122	24.3	135	0.1800
2004	164.6	122	42.6	123.1	0.3461
2013	201.2	128	73.2	127.5	0.5741

Meander loops Am-Am6 in Study Reach 19.

Am	λu	λd	Δ	λh	Asymmetry
1939	73.1	55	18.1	118.4	0.1529
1951	146.3	42.7	103.6	184	0.5630
1966	91.4	42.7	48.7	123.3	0.3950
1976	91.4	55	36.4	139	0.2619
1988	49	36.6	12.4	78.7	0.1576
2004	30.4	49	-18.6	74.7	-0.2490
2013	55	30.5	24.5	80	0.3063

Am1	λu	λd	Δ	λh	Asymmetry
1939	110	103.6	6.4	186	0.0344
1951	42.7	128	-85.3	156.1	-0.5464
1966	85.3	122	-36.7	187.6	-0.1956
1976	79.2	122	-42.8	180.2	-0.2375
1988	103.6	79.2	24.4	168.5	0.1448
2004	85.3	116	-30.7	185	-0.1659
2013	85.3	140.2	-54.9	206.2	-0.2662

Am2	λu	λd	Δ	λh	Asymmetry
1939	73.1	55	18.1	92.2	0.1963
1951	195	134.1	60.9	304.6	0.1999
1966	85.3	213.4	-128.1	256	-0.5004
1976	213.3	85.3	128	252.6	0.5067
1988	213.3	146.3	67	304.6	0.2200
2004	128	170.7	-42.7	261.6	-0.1632
2013	97.5	201.1	-103.6	270	-0.3837

1939	λu	λd	Δ	λh	Asymmetry
Am3	42.6	49	-6.4	83.5	-0.0766
Am4	73.1	67	6.1	130	0.0469

Am5	λu	λd	Δ	λh	Asymmetry
1939	79.2	225.5	-146.3	213.6	-0.6849
1951	116	250	-134	222	-0.6036

Am6	λu	λd	Δ	λh	Asymmetry
1939	152.4	323	-170.6	217.4	-0.7847
1951	103.6	274.3	-170.7	225	-0.7587

Meander loops An-An2 in Study Reach 21.

An	λu	λd	Δ	λh	Asymmetry
1939	67	177	-110	223.3	-0.4926
1951	42.7	79.2	-36.5	113.1	-0.3227
1966	73.1	103.6	-30.5	164	-0.1860
1976	85.3	85.3	0	153.7	0.0000
1988	85.3	85.3	0	154.3	0.0000
2004	225.5	49	176.5	229.6	0.7687
2013	225.5	67	158.5	240	0.6604

An1	λu	λd	Δ	λh	Asymmetry
1939	79.2	140.2	-61	212.3	-0.2873
1951	122	36.6	85.4	150	0.5693
1966	73.1	109.7	-36.6	171.5	-0.2134
1976	140.2	55	85.2	177.3	0.4805
1988	140.2	85.3	54.9	196	0.2801
2004	128	140	-12	199.3	-0.0602
2013	158.5	97.5	61	196.4	0.3106

An2	λu	λd	Δ	λh	Asymmetry
1939	109.7	158.5	-48.8	228.3	-0.2138
1951	146.3	183	-36.7	265.4	-0.1383
1966	79.2	201.1	-121.9	225.5	-0.5406
1976	195	55	140	197.4	0.7092
1988	67	231.6	-164.6	222.1	-0.7411
2004	30.5	103.6	-73.1	88.3	-0.8279
2013	55	116	-61	101.3	-0.6022

Meander loop Aa in Study Reach 22.

Aa	λu	λd	Δ	λh	Asymmetry
1939	79.25	201.17	-121.92	216.26	-0.5638
1951	109.73	146.3	-36.57	193.18	-0.1893
1966	79.25	152.4	-73.15	174.48	-0.4192
1976	79.25	97.54	-18.29	140.93	-0.1298
1988	103.63	122	-18.37	152.41	-0.1205
2004	121.92	61	60.92	122.89	0.4957
2013	170.69	97.54	73.15	173.02	0.4228

Meander loops Ao-Ao3 in Study Reach 22.

Ao	λu	λd	Δ	λh	Asymmetry
1939	97.5	231.6	-134.1	192.7	-0.6959
1951	79.2	250	-170.8	191.6	-0.8914
1966	55	237	-182	175.1	-1.0394
1976	79.2	189	-109.8	145.5	-0.7546
1988	30.5	109.7	-79.2	88.3	-0.8969
2004	146.3	67	79.3	177.1	0.4478
2013	55	30.5	24.5	77.2	0.3174

Ao1	λu	λd	Δ	λh	Asymmetry
1939	73.1	152.4	-79.3	186	-0.4263
1951	103.6	128	-24.4	196.2	-0.1244
1966	231.6	49	182.6	238.3	0.7663
1976	158.5	189	-30.5	300.1	-0.1016
1988	177	177	0	308.1	0.0000
2004	48.7	109.7	-61	151.4	-0.4029
2013	103.6	91.4	12.2	186	0.0656

Ao2	λu	λd	Δ	λh	Asymmetry
1939	42.7	97.5	-54.8	109	-0.5028
1951	61	97.5	-36.5	133.6	-0.2732
1966	49	146.3	-97.3	143.3	-0.6790
1976	36.6	91.4	-54.8	103	-0.5320
1988	61	97.5	-36.5	137	-0.2664
2004	42.6	189	-146.4	203	-0.7212
2013	42.7	207.2	-164.5	215.2	-0.7644

Ao3	λu	λd	Δ	λh	Asymmetry
1939	67	48	19	112.6	0.1687
1951	48.7	55	-6.3	95	-0.0663
1966	55	42.6	12.4	87	0.1425
1976	42.7	71.1	-28.4	106	-0.2679
1988	73.1	36.6	36.5	102	0.3578
2004	48.7	85.3	-36.6	117	-0.3128
2013	30.5	97.5	-67	113.4	-0.5908

Meander loops A-F in Study Reach 23.

A	λu	λd	Δ	λh	Asymmetry
1939	201.16	207.26	-6.1	331	-0.0184
1951	231.65	189	42.65	307.86	0.1385
1966	176.78	152.4	24.38	215.11	0.1133
1976	188.97	134.11	54.86	230.05	0.2385
1988	377.95	85.34	292.61	326	0.8976
2004	329.18	54.86	274.32	286.27	0.9583
2013	292.6	97.53	195.07	276.48	0.7055

B	λu	λd	Δ	λh	Asymmetry
1939	109.73	140.2	-30.47	199	-0.1531
1951	48.76	237.74	-188.98	202	-0.9355
1966	115.82	231.65	-115.83	202	-0.5734
1976	122	262.13	-140.13	195	-0.7186
1988	85.34	298.7	-213.36	179.15	-1.1910
2004	122	213.36	-91.36	113.73	-0.8033
2013	255.55	115.82	139.73	111.6	1.2521

C	λu	λd	Δ	λh	Asymmetry
1939	85.34	18.28	67.06	92	0.7289
1951	73.15	134.11	-60.96	110	-0.5542
1966	95.12	142.62	-47.5	111.38	-0.4265
1976	103.63	122	-18.37	108.69	-0.1690
1988	85.34	182.88	-97.54	121.43	-0.8033
2004	189	219.45	-30.45	117.82	-0.2584
2013	170.68	176.78	-6.1	130.03	-0.0469

D	λu	λd	Δ	λh	Asymmetry
1939	121.92	274.32	-152.4	317	-0.4808
1951	103.63	329.18	-225.55	321.5	-0.7016
1966	122	311	-189	305.28	-0.6191
1976	128.01	329.18	-201.17	316.26	-0.6361
1988	109.72	377.95	-268.23	308.64	-0.8691
2004	329.18	158.46	170.72	301.42	0.5664
2013	384.05	103.63	280.42	284.68	0.9850

E	λu	λd	Δ	λh	Asymmetry
1939	121.92	195.07	-73.15	187	-0.3912
1951	97.53	146.3	-48.77	147.27	-0.3312
1966	91.44	158.5	-67.06	119.09	-0.5631
1976	115.82	122	-6.18	110	-0.0562
1988	115.82	85.34	30.48	88.1	0.3460
2004	73.15	134.11	-60.96	79.6	-0.7658
2013	109.73	176.78	-67.05	72.3	-0.9274

F	λu	λd	Δ	λh	Asymmetry
1939	73.1	152.4	-79.3	207.6	-0.3820
1951	170.7	42.7	128	185	0.6919
1966	164.6	24.4	140.2	168.1	0.8340
1976	128	79.2	48.8	189.6	0.2574
1988	152.4	48.7	103.7	181.3	0.5720
2004	183	55	128	215.5	0.5940
2013	140.2	73.1	67.1	197	0.3406

Meander loops Ap-Ap6 in Study Reach 25.

Ap	λu	λd	Δ	λh	Asymmetry
1939	402.3	475.5	-73.2	777.2	-0.0942
1951	463.3	487.7	-24.4	828.4	-0.0295
1966	439	500	-61	818.7	-0.0745

Ap1	λu	λd	Δ	λh	Asymmetry
1939	177	713.2	-536.2	759	-0.7065
1951	146.1	707.1	-561	740.3	-0.7578
1966	122	756	-634	770.1	-0.8233

Ap2	λu	λd	Δ	λh	Asymmetry
1939	402.3	561	-158.7	798	-0.1989
1951	433	561	-128	801.5	-0.1597
1966	384	579.1	-195.1	786	-0.2482

Ap3	λu	λd	Δ	λh	Asymmetry
1939	451.1	883.4	-432.3	805.6	-0.5366
1951	1036	237.7	798.3	820.1	0.9734
1966	1018	305	713	814	0.8759

Ap4	λu	λd	Δ	λh	Asymmetry
1939	146.3	183	-36.7	308.3	-0.1190
1951	170.7	158.5	12.2	306.2	0.0398
1966	189	122	67	288.2	0.2325

Ap5	λu	λd	Δ	λh	Asymmetry
1939	122	97.5	24.5	206.3	0.1188
1951	134.1	128	6.1	247.6	0.0246
1966	158.5	109.7	48.8	255.5	0.1910

Ap6	λu	λd	Δ	λh	Asymmetry
1939	73.1	128	-54.9	194.6	-0.2821
1951	85.3	91.4	-6.1	176	-0.0347
1966	79.2	109.7	-30.5	183.2	-0.1665

APPENDIX B: SINUOSITY

Valley length (VL) and channel length (CL) are represented in meters.

Study Reach 1 Sinuosity			
Year	VL	CL	Sinuosity
1939	1098	1320	1.2
1951	1097	1321	1.2
1966	1097	1305	1.2
1976	1098	1289	1.2
1988	1098	1296	1.2
2004	1098	1293	1.2
2013	1098	1291	1.2

Study Reach 2 Sinuosity			
Year	VL	CL	Sinuosity
1939	2279	3209	1.4
1951	2281	3182	1.4
1966	2281	3132	1.4
1976	2281	3117	1.4
1988	2278	3082	1.4
2004	2281	3071	1.3
2013	2280	3070	1.3

Study Reach 3 Sinuosity			
Year	VL	CL	Sinuosity
1939	925	996	1.1
1951	921	983	1.1
1966	920	985	1.1
1976	922	991	1.1
1988	926	991	1.1
2004	921	991	1.1
2013	925	995	1.1

Study Reach 4 Sinuosity			
Year	VL	CL	Sinuosity
1939	885	1031	1.2
1951	889	1045	1.2
1966	890	1061	1.2
1976	886	1064	1.2
1988	889	1071	1.2
2004	885	1096	1.2
2013	885	1083	1.2

Study Reach 5 Sinuosity			
Year	VL	CL	Sinuosity
1939	1236	1555	1.3
1951	1231	1550	1.3
1966	1228	1541	1.3
1976	1232	1540	1.2
1988	1229	1552	1.3
2004	1231	1543	1.3
2013	1233	1546	1.3

Study Reach 6 Sinuosity			
Year	VL	CL	Sinuosity
1939	950	1251	1.3
1951	950	1258	1.3
1966	954	1251	1.3
1976	952	1235	1.3
1988	951	1218	1.3
2004	956	1193	1.2
2013	953	1174	1.2

Study Reach 7 Sinuosity			
Year	VL	CL	Sinuosity
1939	7288	9042	1.2
1951	7283	9039	1.2
1966	7285	9054	1.2
1976	7282	9031	1.2
1988	7287	9043	1.2
2004	7283	9030	1.2
2013	7283	9039	1.2

Study Reach 8 Sinuosity			
Year	VL	CL	Sinuosity
1939	1401	1652	1.2
1951	1408	1642	1.2
1966	1404	1663	1.2
1976	1408	1571	1.1
1988	1403	1597	1.1
2004	1405	1576	1.1
2013	1407	1581	1.1

Study Reach 9 Sinuosity			
Year	VL	CL	Sinuosity
1939	741	748	1.0
1951	741	745	1.0
1966	741	747	1.0
1976	741	745	1.0
1988	741	747	1.0
2004	742	747	1.0
2013	740	746	1.0

Study Reach 10 Sinuosity			
Year	VL	CL	Sinuosity
1939	6914	8687	1.3
1951	6911	9230	1.3
1966	6911	9165	1.3
1976	6911	8819	1.3
1988	6911	8275	1.2
2004	6914	8505	1.2
2013	6911	8475	1.2

Study Reach 11 Sinuosity			
Year	VL	CL	Sinuosity
1939	1738	2213	1.3
1951	1736	2351	1.4
1966	1736	2477	1.4
1976	1735	2518	1.5
1988	1736	2333	1.3
2004	1739	2503	1.4
2013	1735	2497	1.4

Study Reach 12 Sinuosity			
Year	VL	CL	Sinuosity
1939	976	1006	1.0
1951	978	1008	1.0
1966	970	997	1.0
1976	969	995	1.0
1988	969	994	1.0
2004	961	982	1.0
2013	973	995	1.0

Study Reach 13 Sinuosity			
Year	VL	CL	Sinuosity
1939	2806	3971	1.4
1951	2806	4126	1.5
1966	2812	4397	1.6
1976	2808	4267	1.5
1988	2807	4263	1.5
2004	2810	4414	1.6
2013	2807	4408	1.6

Study Reach 14 Sinuosity			
Year	VL	CL	Sinuosity
1939	1530	1611	1.1
1951	1529	1615	1.1
1966	1533	1625	1.1
1976	1530	1608	1.1
1988	1530	1606	1.1
2004	1530	1610	1.1
2013	1531	1608	1.1

Study Reach 15 Sinuosity			
Year	VL	CL	Sinuosity
1939	2783	3582	1.3
1951	2783	3607	1.3
1966	2785	3647	1.3
1976	2784	3635	1.3
1988	2783	3692	1.3
2004	2785	3685	1.3
2013	2784	3698	1.3

Study Reach 16 Sinuosity			
Year	VL	CL	Sinuosity
1939	2909	3522	1.2
1951	2910	3535	1.2
1966	2911	3541	1.2
1976	2911	3536	1.2
1988	2909	3531	1.2
2004	2912	3535	1.2
2013	2910	3533	1.2

Study Reach 17 Sinuosity			
Year	VL	CL	Sinuosity
1939	5012	6053	1.2
1951	5014	6187	1.2
1966	5014	5672	1.1
1976	5026	5720	1.1
1988	5013	5816	1.2
2004	5015	6027	1.2
2013	5014	6070	1.2

Study Reach 18 Sinuosity			
Year	VL	CL	Sinuosity
1939	1761	2065	1.2
1951	1757	2074	1.2
1966	1758	2083	1.2
1976	1744	2054	1.2
1988	1754	2086	1.2
2004	1749	2089	1.2
2013	1754	2090	1.2

Study Reach 19 Sinuosity			
Year	VL	CL	Sinuosity
1939	3124	5105	1.6
1951	3133	5029	1.6
1966	3129	4964	1.6
1976	3144	4968	1.6
1988	3135	5033	1.6
2004	3139	5030	1.6
2013	3131	5061	1.6

Study Reach 20 Sinuosity			
Year	VL	CL	Sinuosity
1939	1124	1206	1.1
1951	1124	1210	1.1
1966	1124	1213	1.1
1976	1124	1218	1.1
1988	1125	1217	1.1
2004	1128	1208	1.1
2013	1126	1213	1.1

Study Reach 21 Sinuosity			
Year	VL	CL	Sinuosity
1939	1366	1547	1.1
1951	1366	1573	1.2
1966	1366	1584	1.2
1976	1368	1604	1.2
1988	1369	1620	1.2
2004	1373	1698	1.2
2013	1370	1694	1.2

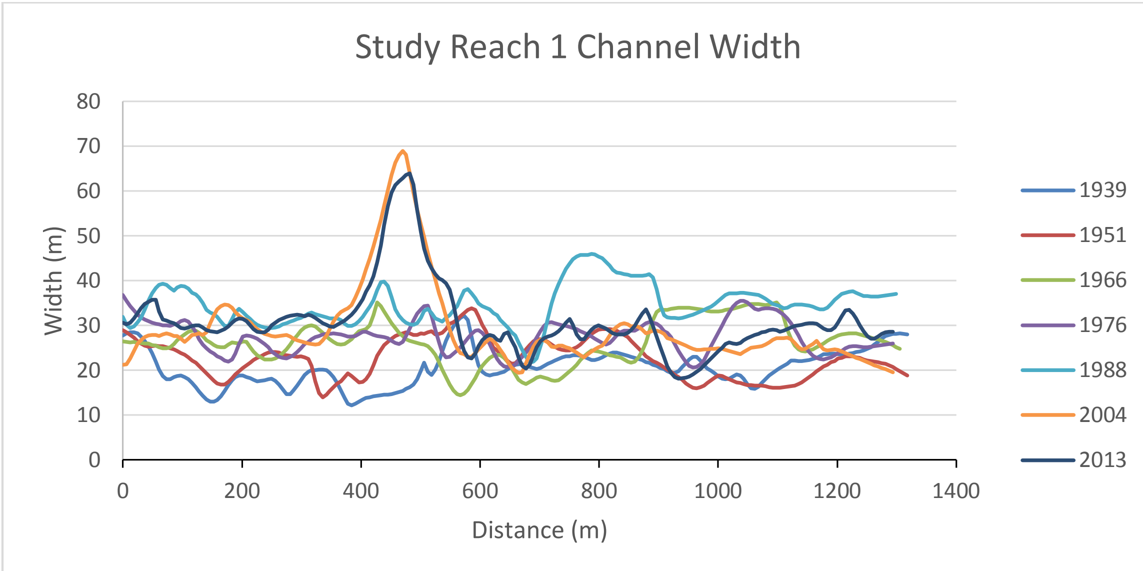
Study Reach 22 Sinuosity			
Year	VL	CL	Sinuosity
1939	2445	3146	1.3
1951	2444	3184	1.3
1966	2446	3236	1.3
1976	2445	3201	1.3
1988	2449	3105	1.3
2004	2451	3011	1.2
2013	2449	3013	1.2

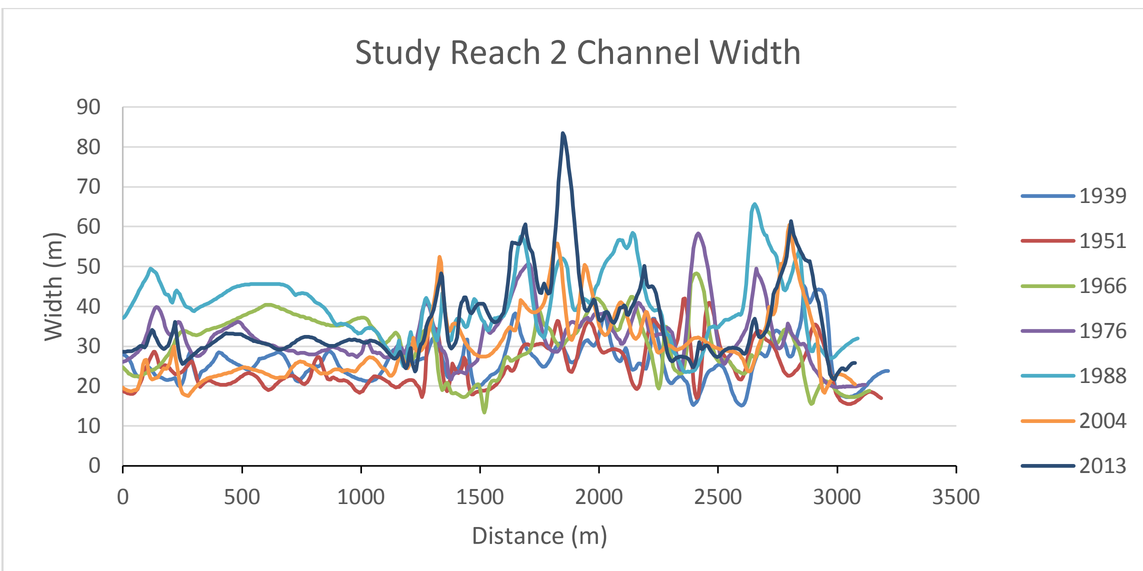
Study Reach 23 Sinuosity			
Year	VL	CL	Sinuosity
1939	2196	2955	1.3
1951	2200	3163	1.4
1966	2200	3312	1.5
1976	2204	3336	1.5
1988	2199	3484	1.6
2004	2202	3634	1.7
2013	2199	3657	1.7

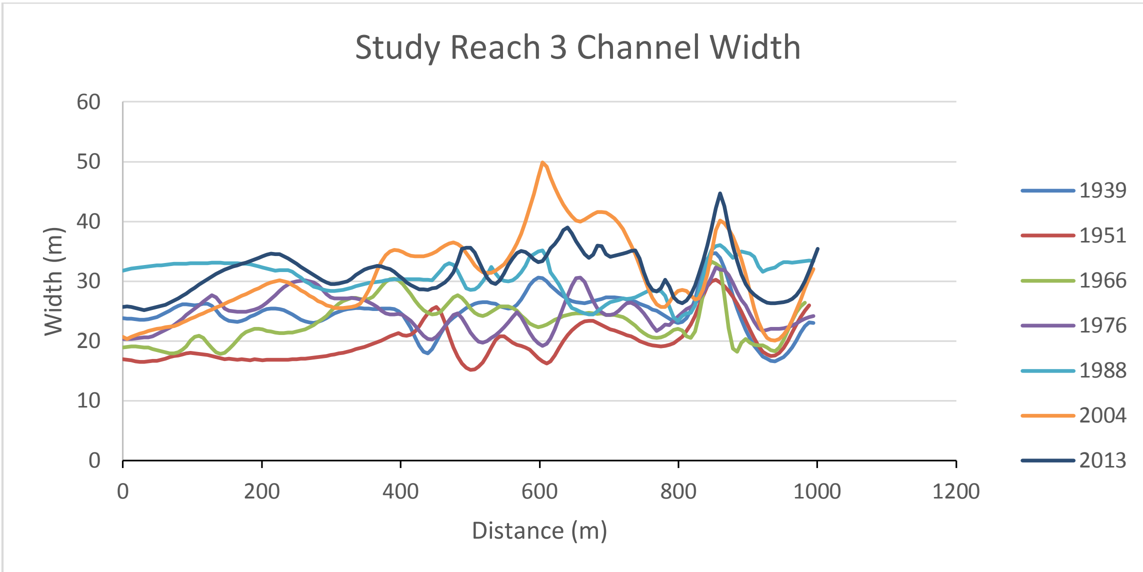
Study Reach 24 Sinuosity			
Year	VL	CL	Sinuosity
1939	2888	3181	1.1
1951	2877	3183	1.1
1966	2886	3190	1.1
1976	2883	3193	1.1
1988	2879	3184	1.1
2004	2887	3197	1.1
2013	2887	3198	1.1

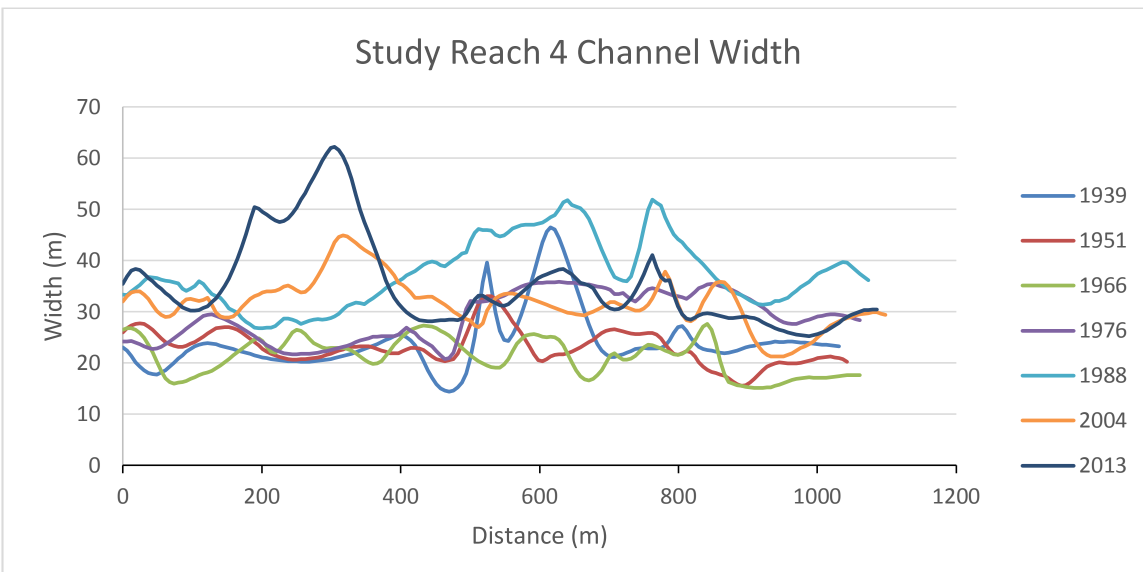
Study Reach 25 Sinuosity			
Year	VL	CL	Sinuosity
1939	3657	5726	1.6
1951	3647	5697	1.6
1966	3647	5734	1.6
1976	3658	5133	1.4
1988	3662	5136	1.4
2004	3666	5135	1.4
2013	3668	5141	1.4

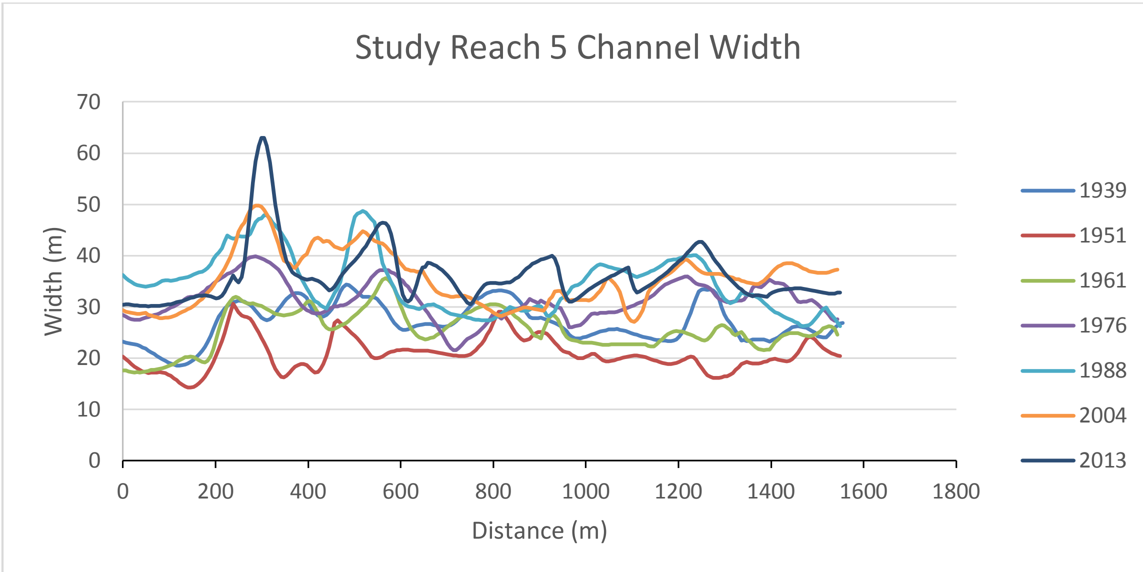
APPENDIX C: CHANNEL WIDTH VS. DISTANCE DOWNSTREAM

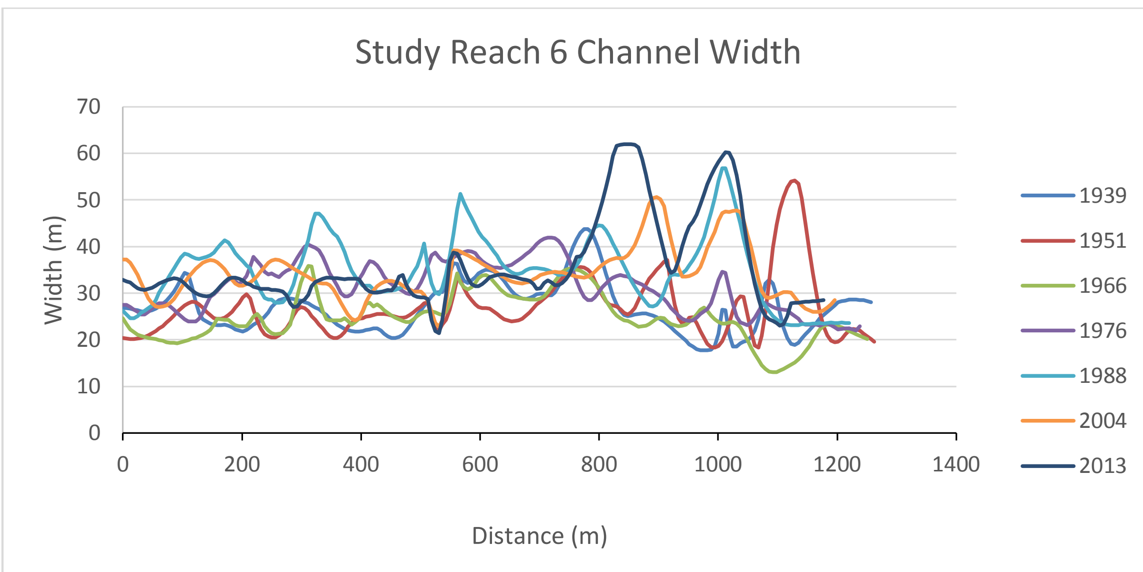


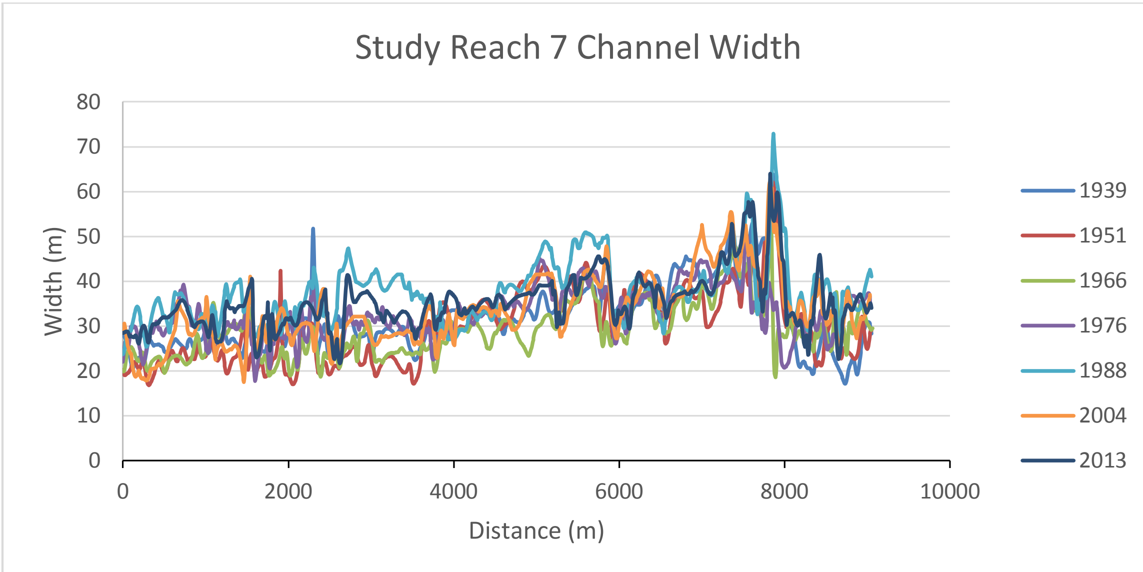


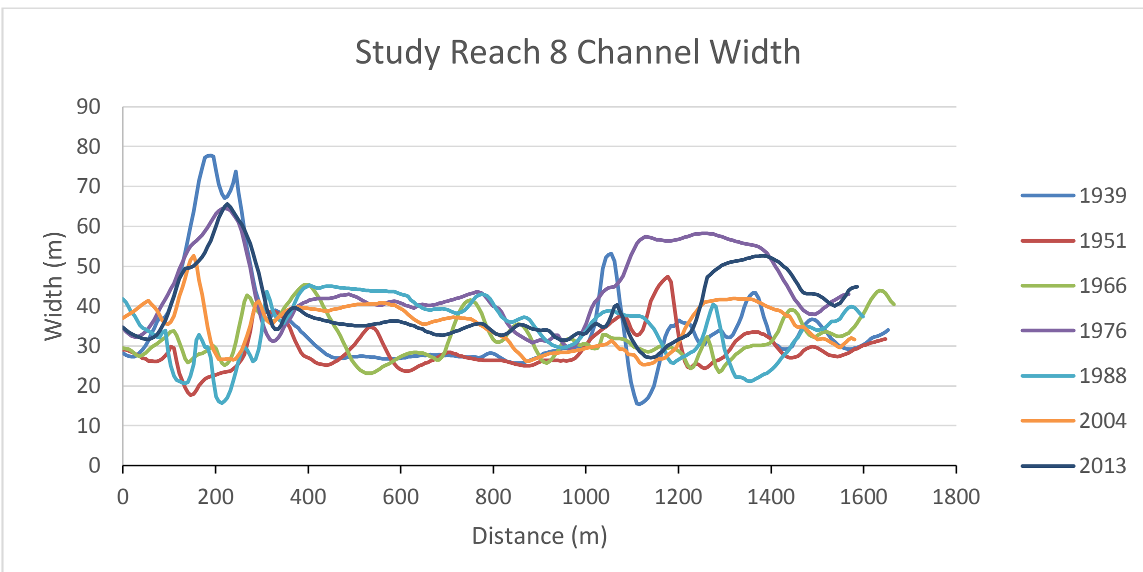

Study Reach 3 Channel Width
Width (m)
60
50
40
30
20
10
0
0
200
400
600
800
1000
1200
Distance (m)
1939
1951
1966
1976
1988
2004
2013

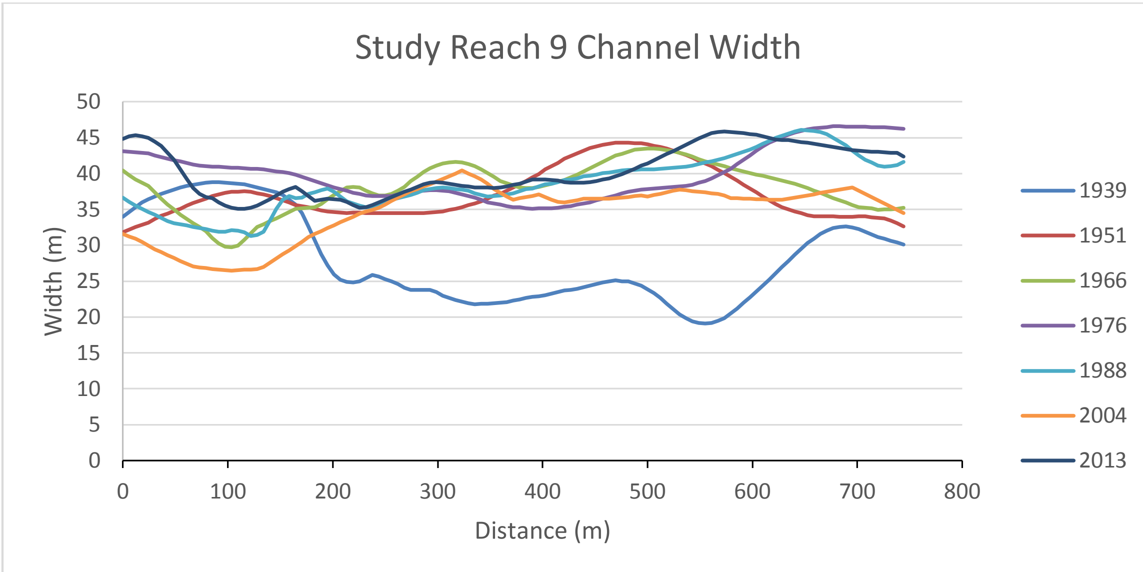

Study Reach 4 Channel Width
Width (m)
70
60
50
40
30
20
10
0
0
200
400
600
800
1000
1200
Distance (m)
1939
1951
1966
1976
1988
2004
2013

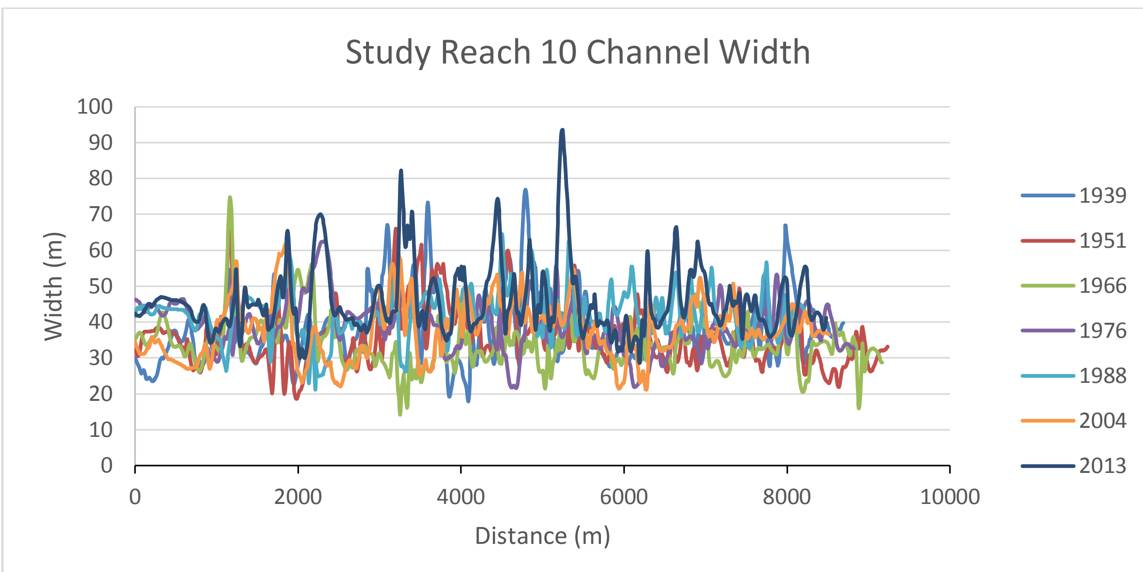

Study Reach 5 Channel Width
Width (m)
Distance (m)
0
10
20
30
40
50
60
70
0
200
400
600
800
1000
1200
1400
1600
1800
1939
1951
1961
1976
1988
2004
2013

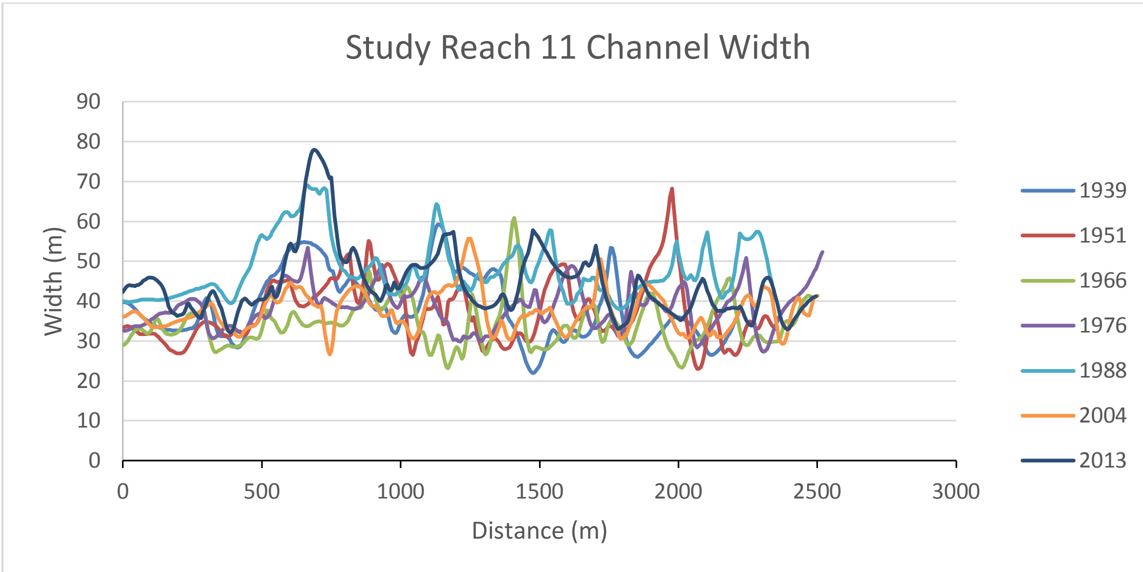

Study Reach 6 Channel Width
Width (m)
Distance (m)
0
10
20
30
40
50
60
70
0
200
400
600
800
1000
1200
1400
1939
1951
1966
1976
1988
2004
2013

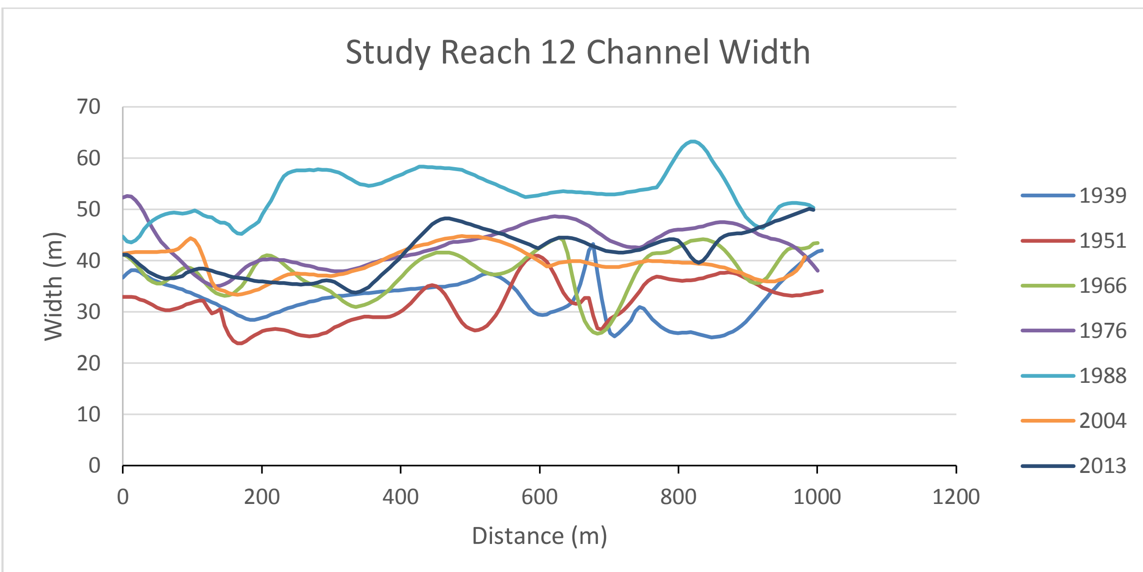

Study Reach 7 Channel Width
Width (m)
Distance (m)
0
10
20
30
40
50
60
70
80
0
2000
4000
6000
8000
10000
1939
1951
1966
1976
1988
2004
2013

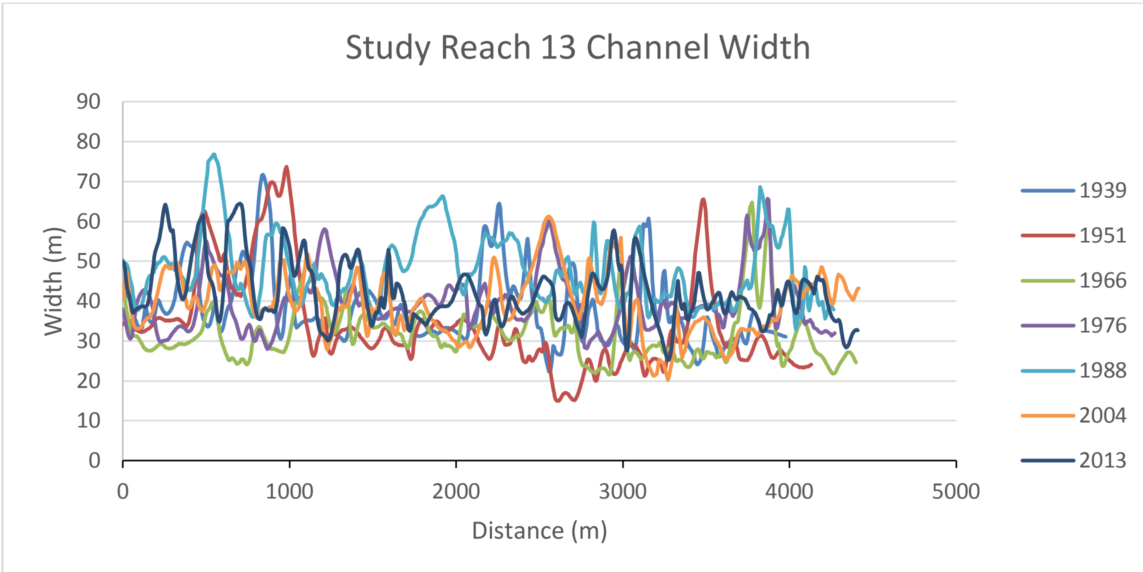

Study Reach 8 Channel Width
Width (m)
Distance (m)
0
10
20
30
40
50
60
70
80
90
0
200
400
600
800
1000
1200
1400
1600
1800
1939
1951
1966
1976
1988
2004
2013

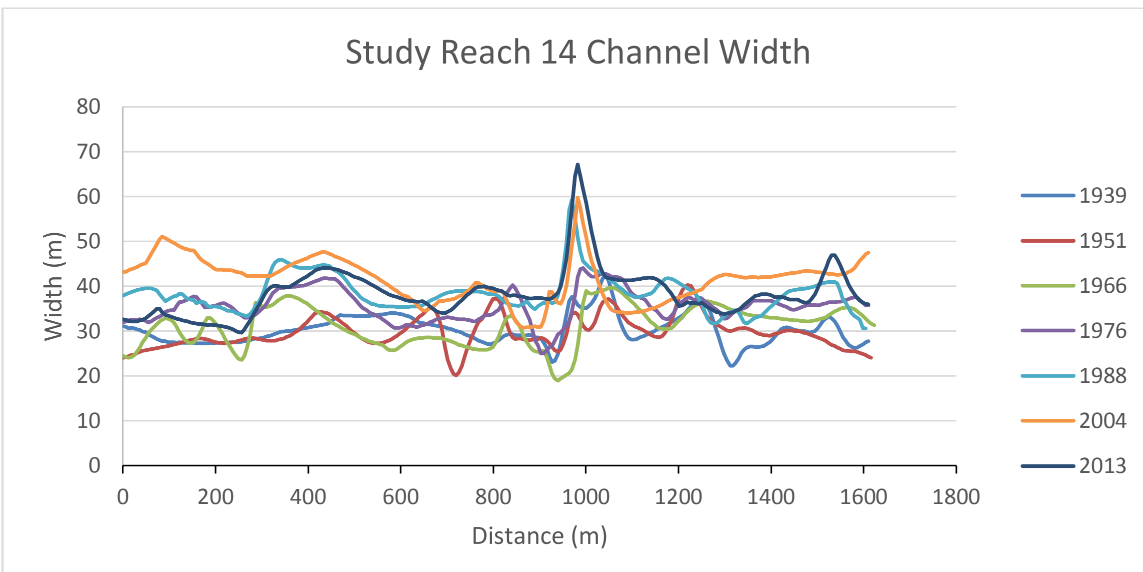

Study Reach 9 Channel Width
Width (m)
50
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
800
Distance (m)
1939
1951
1966
1976
1988
2004
2013

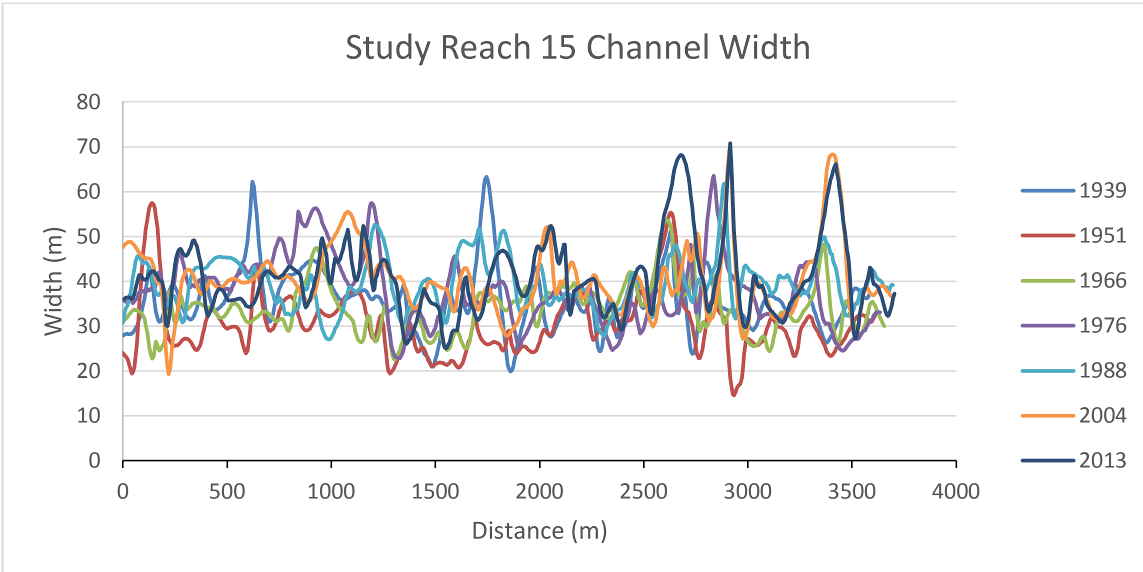

Study Reach 10 Channel Width
Width (m)
100
90
80
70
60
50
40
30
20
10
0
0
2000
4000
6000
8000
10000
Distance (m)
1939
1951
1966
1976
1988
2004
2013

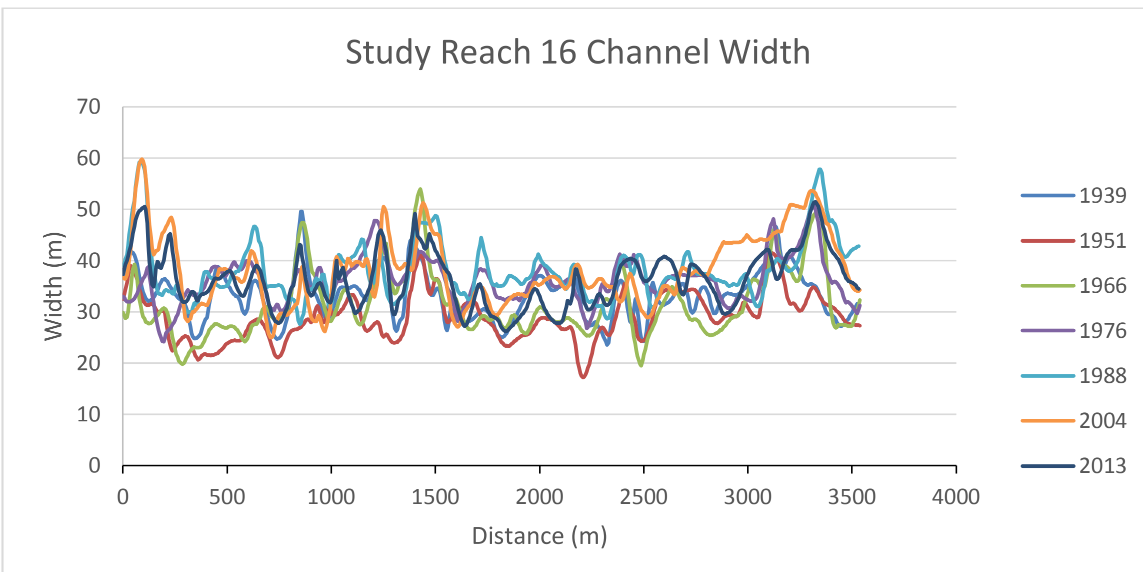

Study Reach 11 Channel Width
90
80
70
60
50
40
30
20
10
0
Width (m)
0
500
1000
1500
2000
2500
3000
Distance (m)
1939
1951
1966
1976
1988
2004
2013

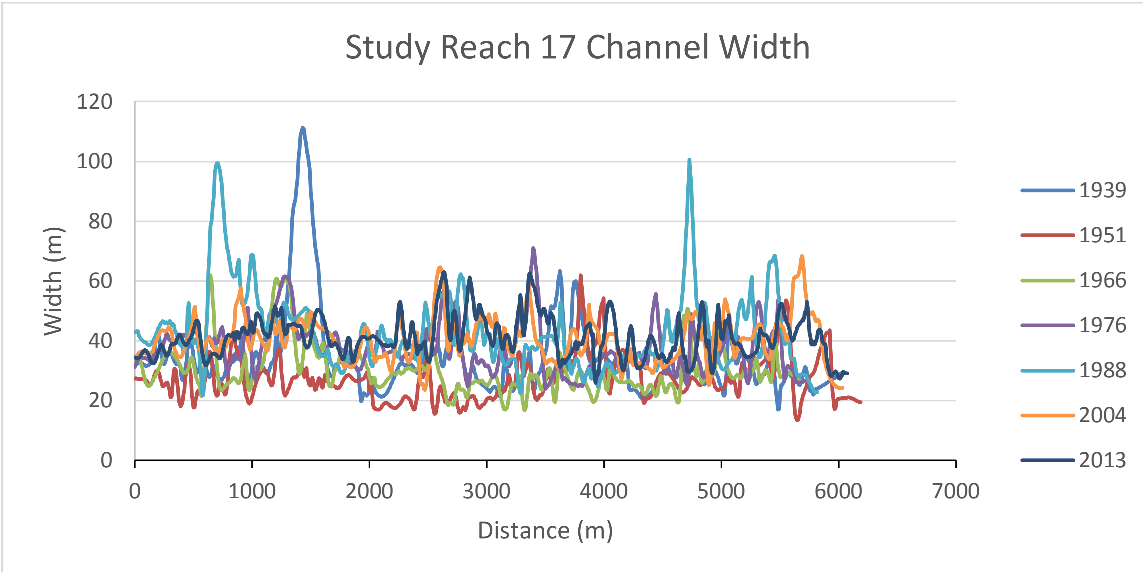

Study Reach 12 Channel Width
70
60
50
40
30
20
10
0
Width (m)
0
200
400
600
800
1000
1200
Distance (m)
1939
1951
1966
1976
1988
2004
2013

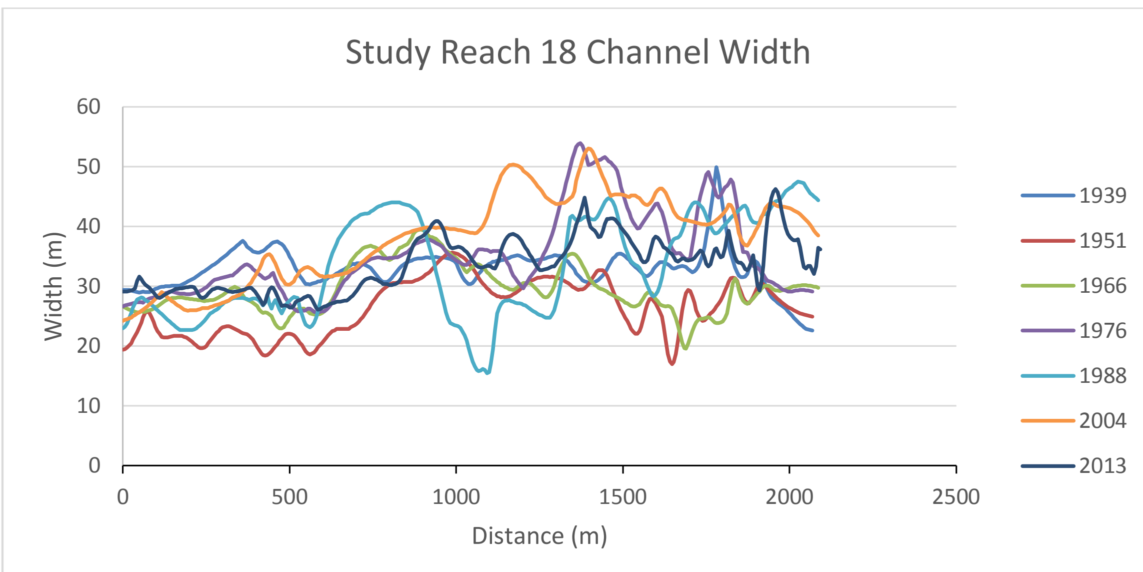

Study Reach 13 Channel Width
Width (m)
Distance (m)
0
10
20
30
40
50
60
70
80
90
0
1000
2000
3000
4000
5000
1939
1951
1966
1976
1988
2004
2013

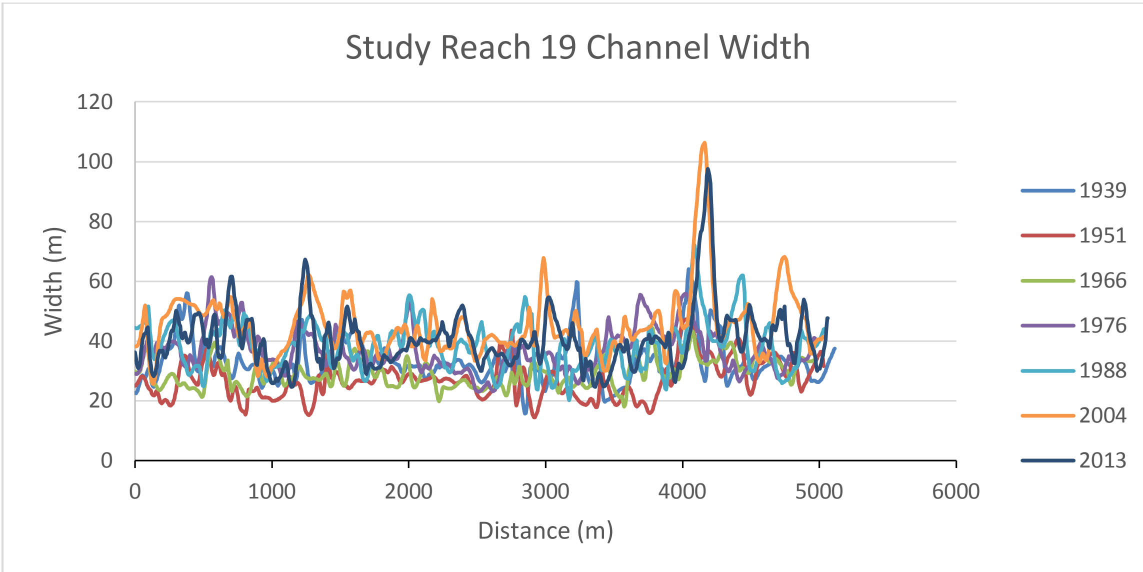

Study Reach 14 Channel Width
Width (m)
Distance (m)
0
10
20
30
40
50
60
70
80
0
200
400
600
800
1000
1200
1400
1600
1800
1939
1951
1966
1976
1988
2004
2013

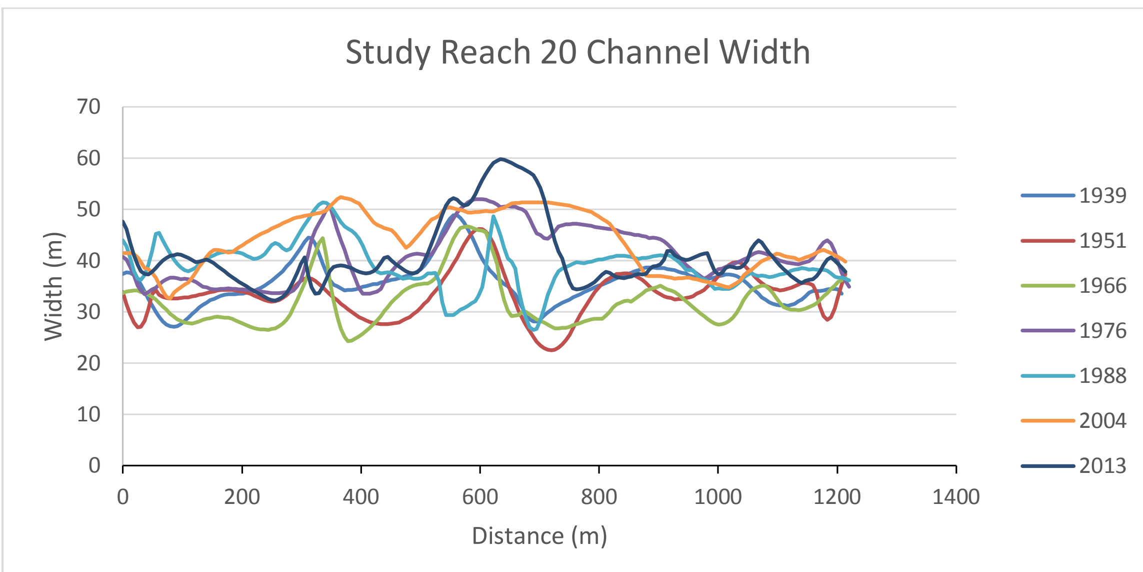

Study Reach 15 Channel Width
Width (m)
Distance (m)
0
10
20
30
40
50
60
70
80
0
500
1000
1500
2000
2500
3000
3500
4000
1939
1951
1966
1976
1988
2004
2013

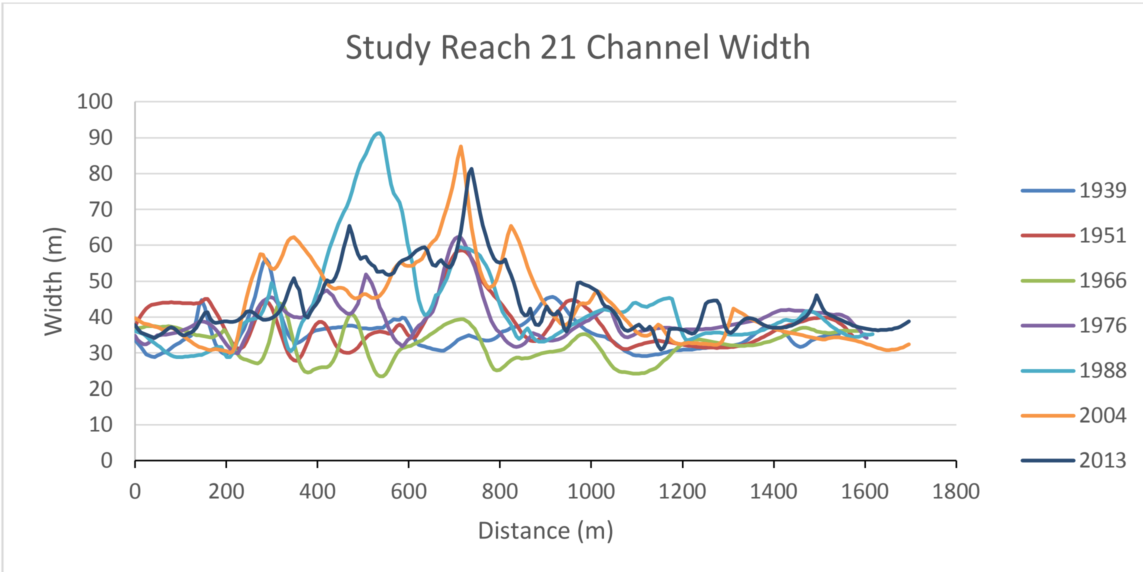

Study Reach 16 Channel Width
Width (m)
Distance (m)
0
10
20
30
40
50
60
70
0
500
1000
1500
2000
2500
3000
3500
4000
1939
1951
1966
1976
1988
2004
2013


Study Reach 17 Channel Width
Width (m)
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
Distance (m)
1939
1951
1966
1976
1988
2004
2013

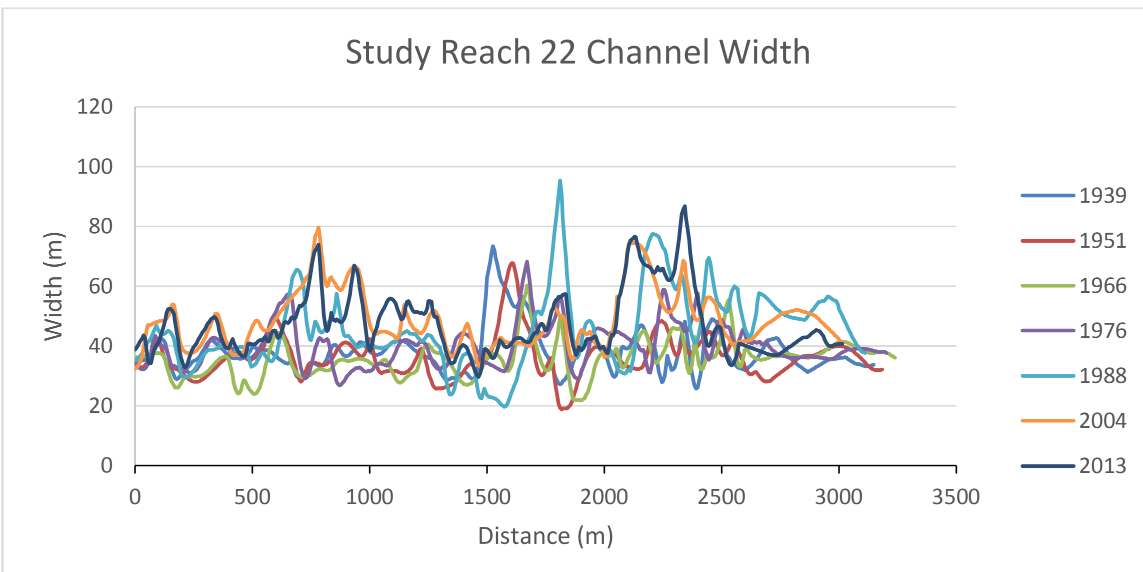

Study Reach 18 Channel Width
Width (m)
60
50
40
30
20
10
0
0
500
1000
1500
2000
2500
Distance (m)
1939
1951
1966
1976
1988
2004
2013


Study Reach 19 Channel Width
Width (m)
0
20
40
60
80
100
120
0
1000
2000
3000
4000
5000
6000
Distance (m)
1939
1951
1966
1976
1988
2004
2013

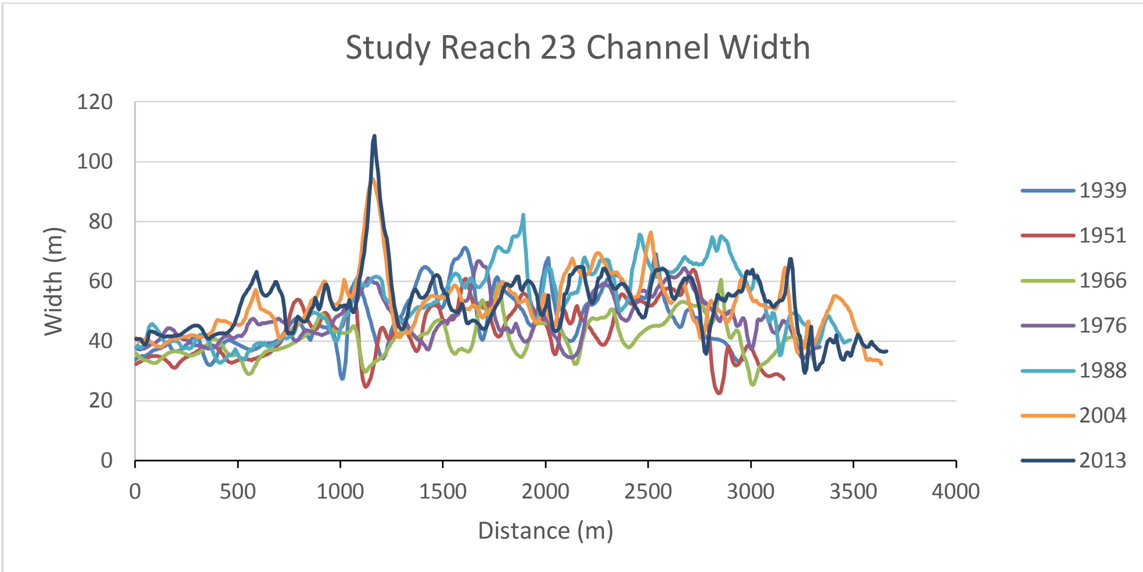

Study Reach 20 Channel Width
Width (m)
0
10
20
30
40
50
60
70
0
200
400
600
800
1000
1200
1400
Distance (m)
1939
1951
1966
1976
1988
2004
2013

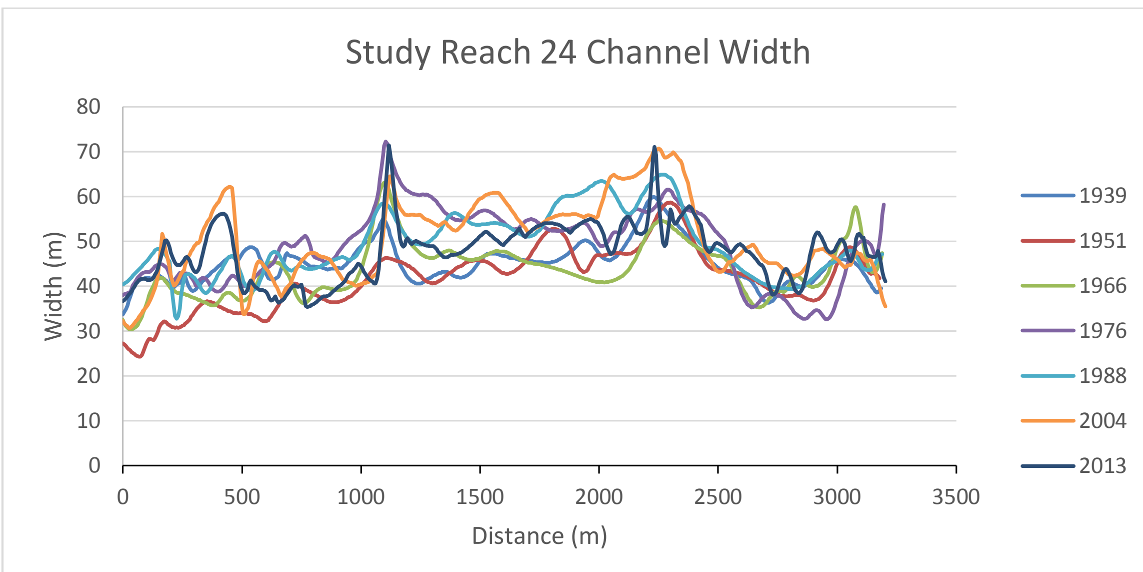


Study Reach 21 Channel Width
Width (m)
Distance (m)
100
90
80
70
60
50
40
30
20
10
0
0
200
400
600
800
1000
1200
1400
1600
1800
1939
1951
1966
1976
1988
2004
2013

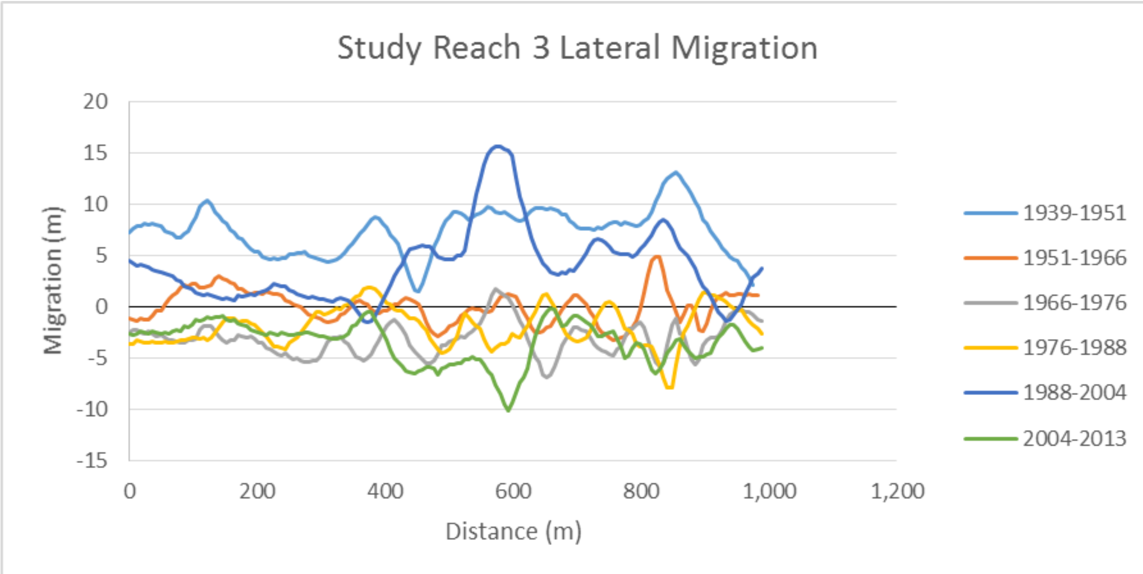


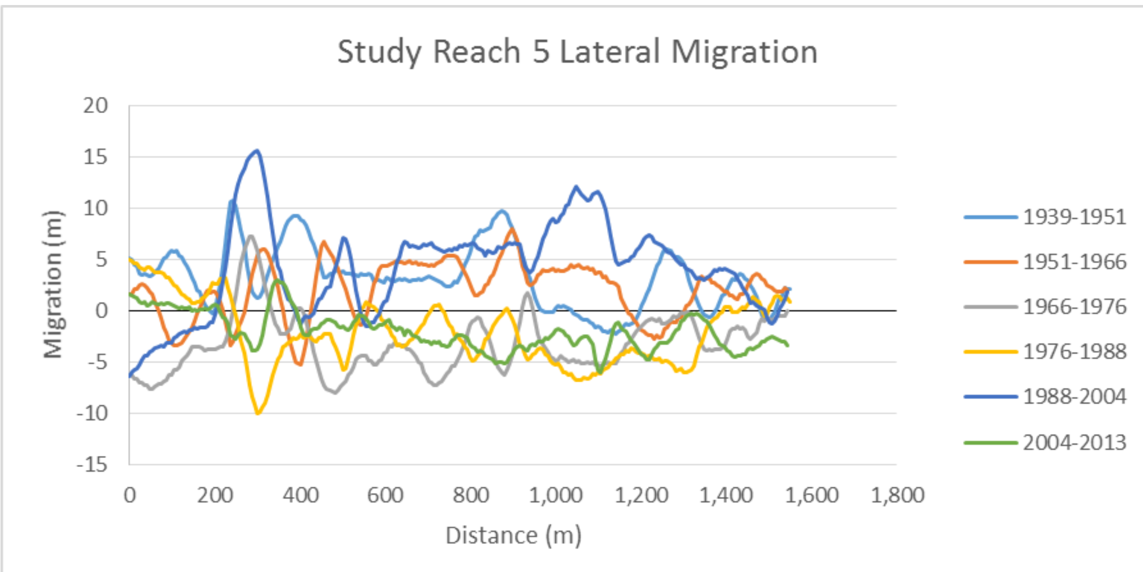
Study Reach 22 Channel Width
Width (m)
Distance (m)
120
100
80
60
40
20
0
0
500
1000
1500
2000
2500
3000
3500
1939
1951
1966
1976
1988
2004
2013

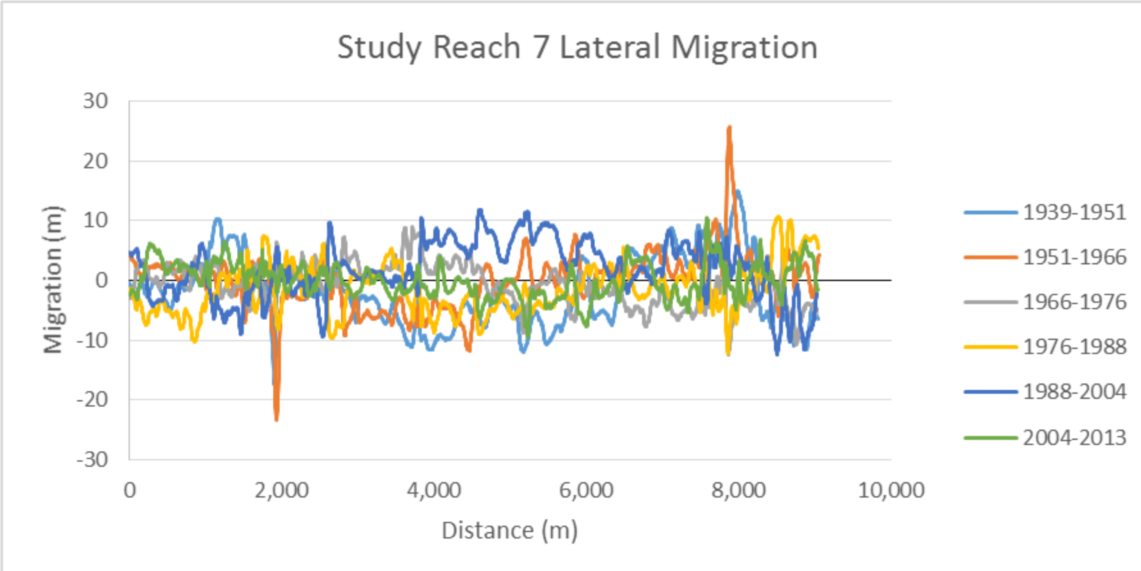

Study Reach 23 Channel Width
Width (m)
120
100
80
60
40
20
0
0
500
1000
1500
2000
2500
3000
3500
4000
Distance (m)
1939
1951
1966
1976
1988
2004
2013

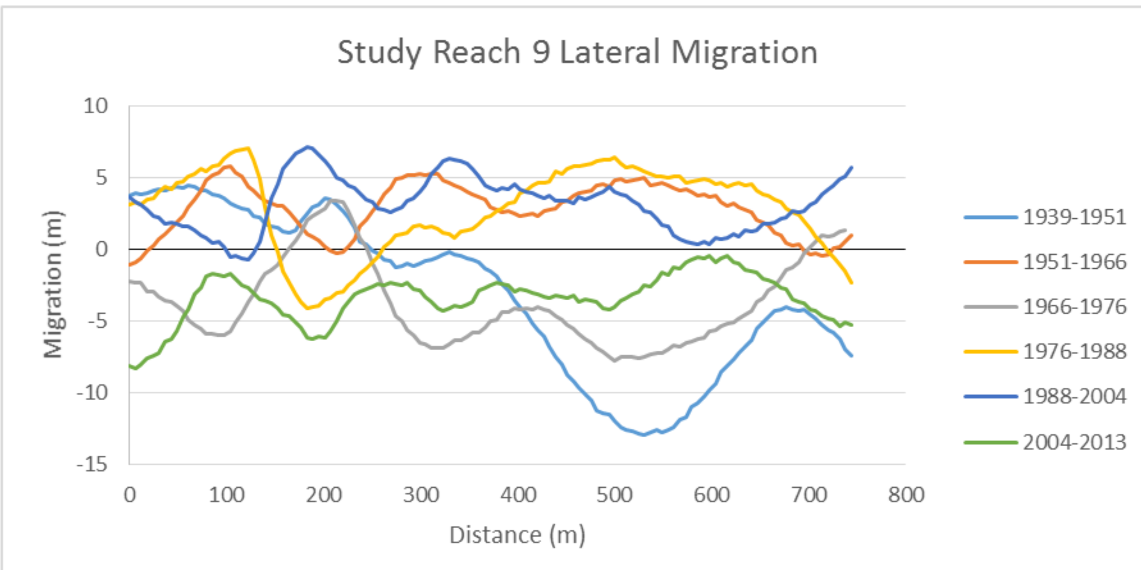

Study Reach 24 Channel Width
Width (m)
80
70
60
50
40
30
20
10
0
0
500
1000
1500
2000
2500
3000
3500
Distance (m)
1939
1951
1966
1976
1988
2004
2013

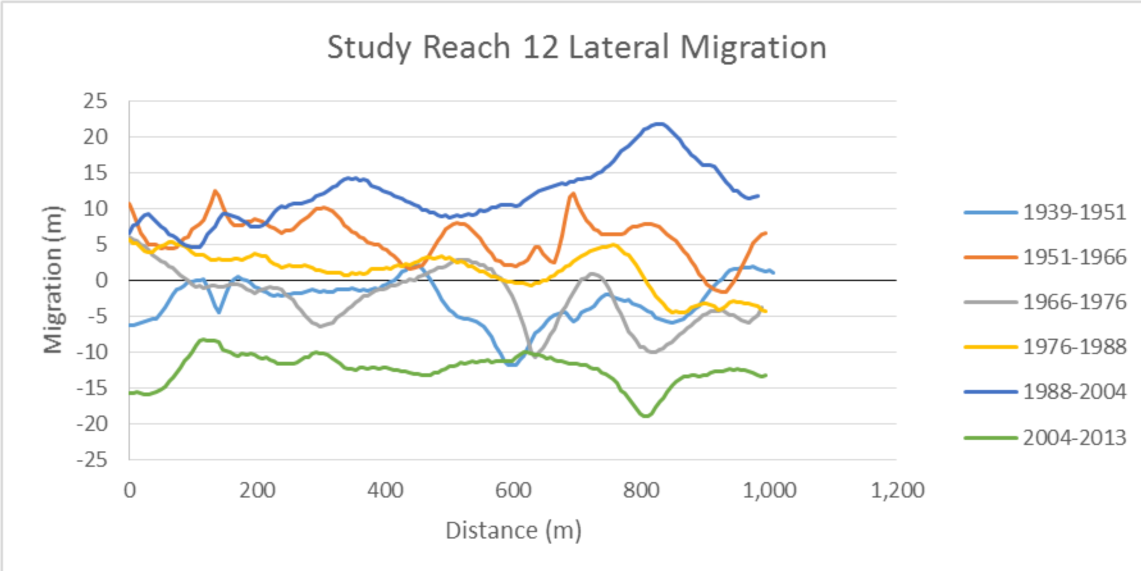
APPENDIX D: CHANNEL POSITION CHANGE

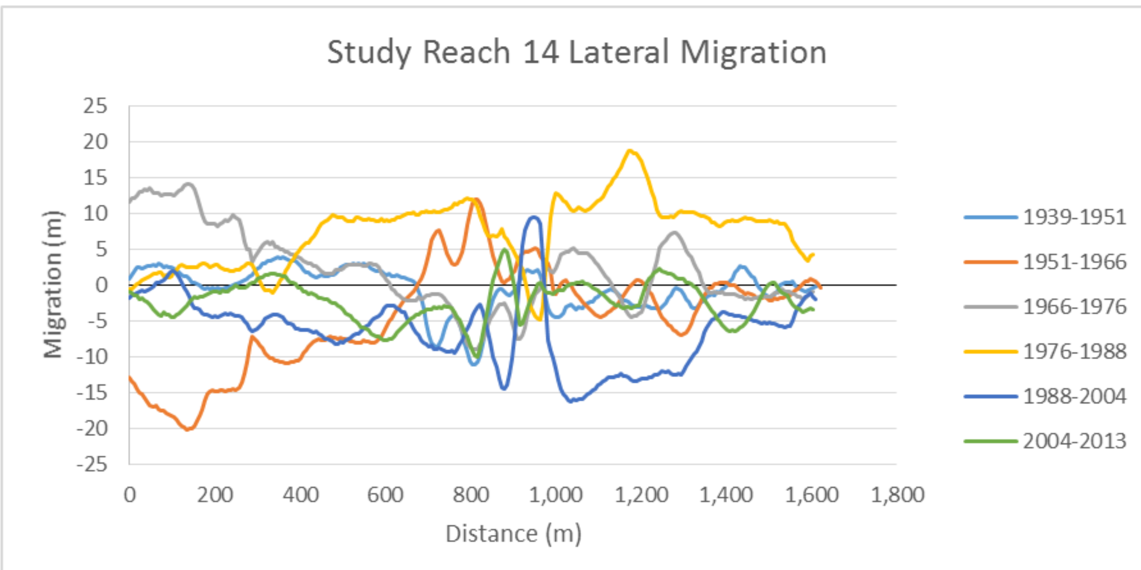


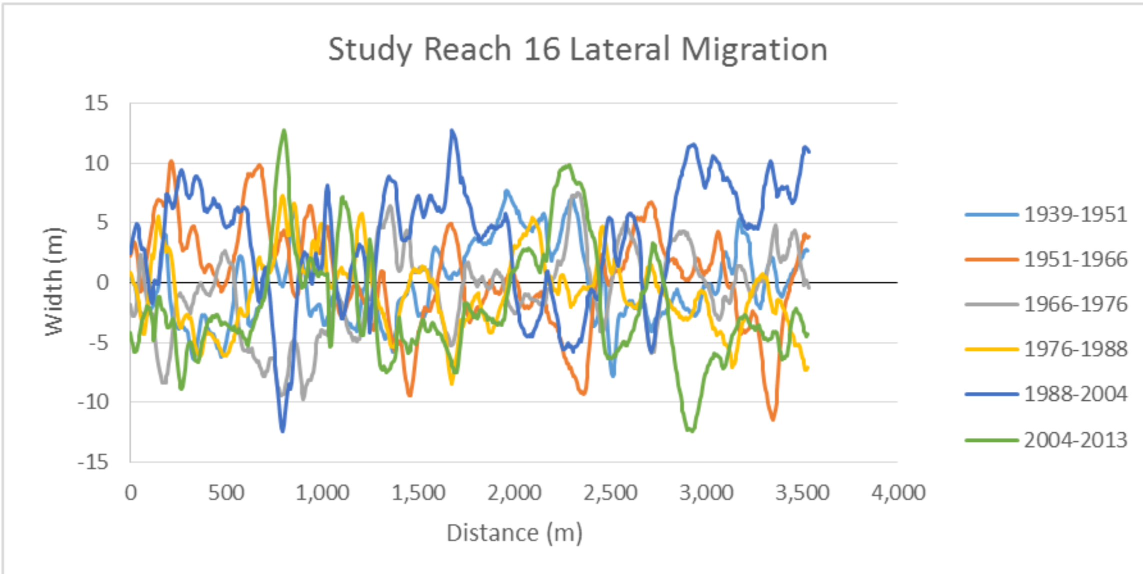


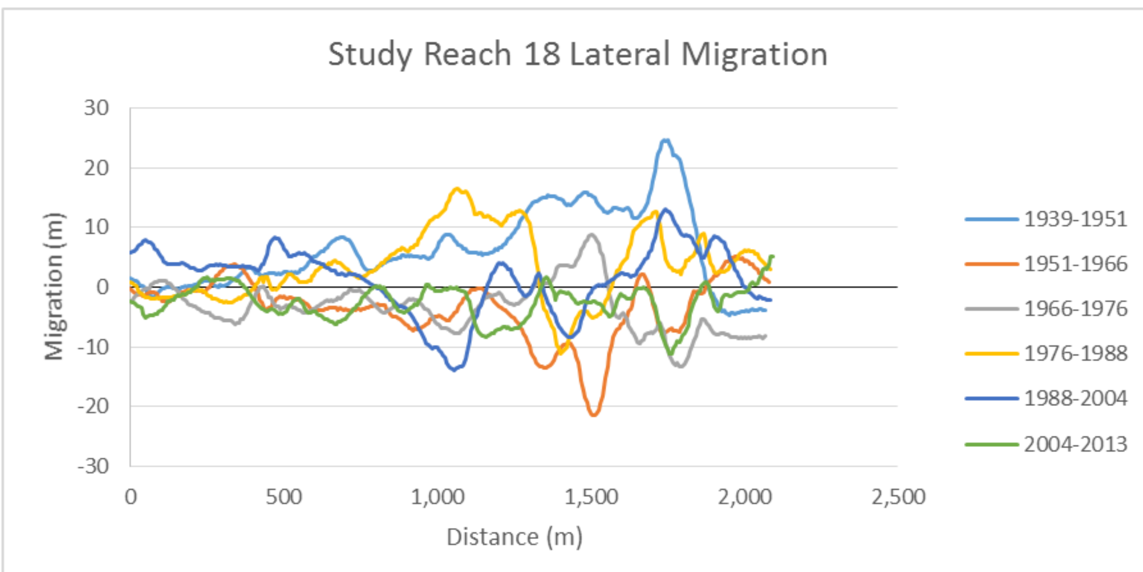

Study Reach 7 Lateral Migration
Migration (m)
30
20
10
0
-10
-20
-30
0
2,000
4,000
6,000
8,000
10,000
Distance (m)
1939-1951
1951-1966
1966-1976
1976-1988
1988-2004
2004-2013

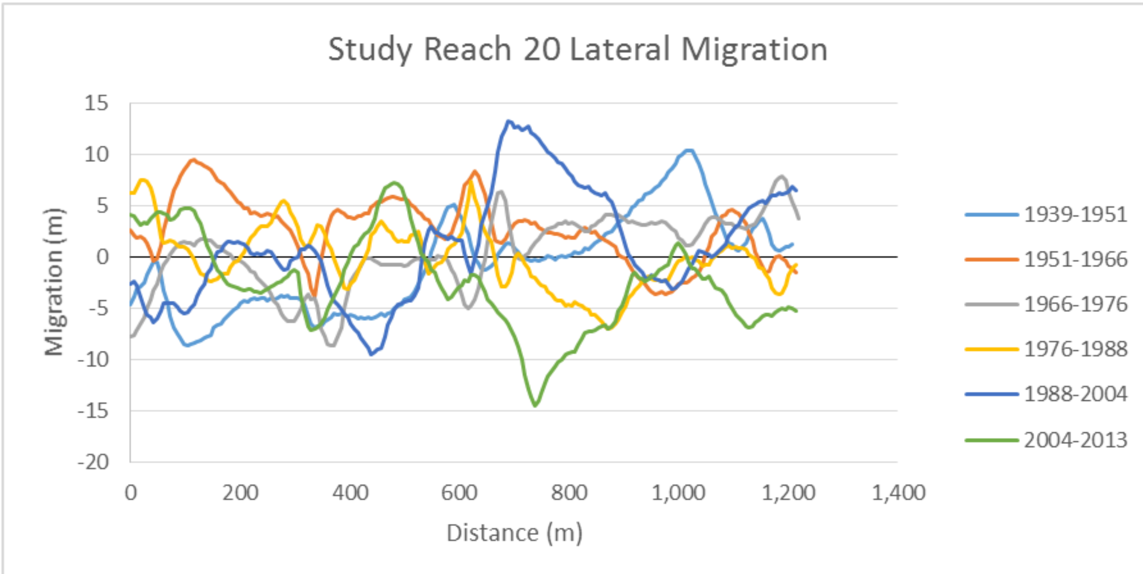

Study Reach 9 Lateral Migration
Migration (m)
10
5
0
-5
-10
-15
0
100
200
300
400
500
600
700
800
Distance (m)
1939-1951
1951-1966
1966-1976
1976-1988
1988-2004
2004-2013

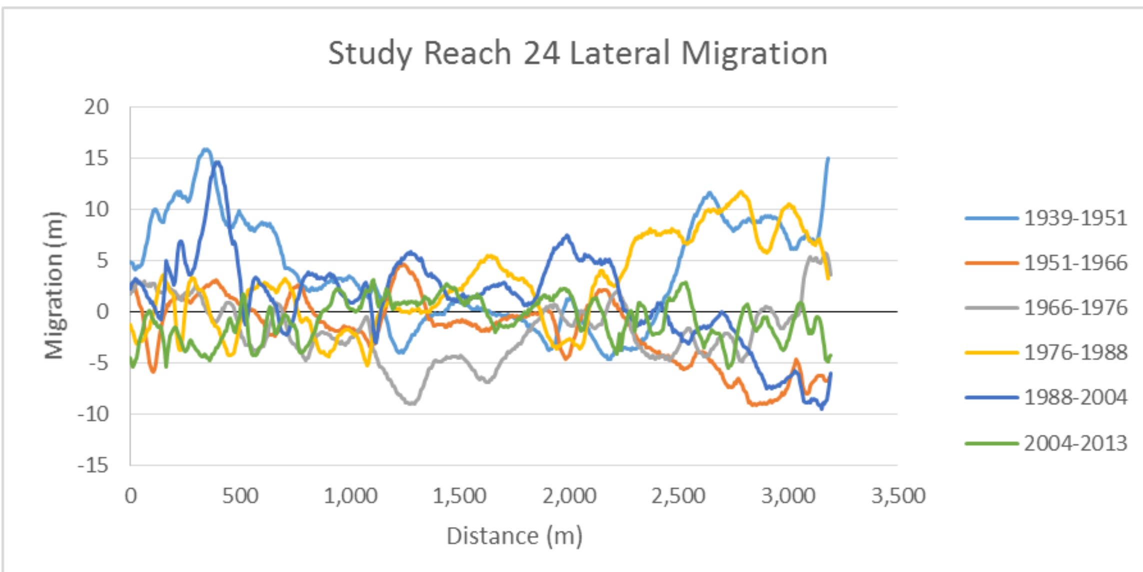

Study Reach 12 Lateral Migration
Migration (m)
25
20
15
10
5
0
-5
-10
-15
-20
-25
0
200
400
600
800
1,000
1,200
Distance (m)
1939-1951
1951-1966
1966-1976
1976-1988
1988-2004
2004-2013


Study Reach 14 Lateral Migration
Migration (m)
25
20
15
10
5
0
-5
-10
-15
-20
-25
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
Distance (m)
1939-1951
1951-1966
1966-1976
1976-1988
1988-2004
2004-2013


Study Reach 16 Lateral Migration
Width (m)
15
10
5
0
-5
-10
-15
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
Distance (m)
1939-1951
1951-1966
1966-1976
1976-1988
1988-2004
2004-2013


Study Reach 18 Lateral Migration
Migration (m)
30
20
10
0
-10
-20
-30
0
500
1,000
1,500
2,000
2,500
Distance (m)
1939-1951
1951-1966
1966-1976
1976-1988
1988-2004
2004-2013


Study Reach 20 Lateral Migration
Migration (m)
15
10
5
0
-5
-10
-15
-20
0
200
400
600
800
1,000
1,200
1,400
Distance (m)
1939-1951
1951-1966
1966-1976
1976-1988
1988-2004
2004-2013


Study Reach 24 Lateral Migration
Migration (m)
20
15
10
5
0
-5
-10
-15
0
500
1,000
1,500
2,000
2,500
3,000
3,500
Distance (m)
1939-1951
1951-1966
1966-1976
1976-1988
1988-2004
2004-2013