RIVER PLANFORM CHANGE DOWNSTREAM OF THE SINCLAIR DAM, OCONEE RIVER, GEORGIA

By

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The Sinclair Dam on the Oconee River in Central Georgia was built in 1953 to generate electricity and has acted as a sediment trap most likely creating post-dam stream flows that were largely reduced of much of the pre-dam sediment loads. The dam is not used to practice flood control. The section of the Oconee River that is the focus of the research for this dissertation is located in both the Piedmont province with its more resistant igneous and metamorphic rocks and narrow, steep sided valleys and the more level Coastal Plain comprising wider, gentler valleys with highly developed floodplains. The length of the Oconee River that comprises the study area is 75 km. Spatial data were obtained from eight decades of aerial photographs that covered periods before and after the closure of the dam. Methods of data extraction and geospatial analysis involved the use of GIS and spatial adjustments of images using ERDAS Imagine.

It is hypothesized that the closure of the dam has caused the river downstream of the dam to be more stable through a reduction in the movement or changes in the planform of the river across its floodplain. The measurement of the river planform changes have determined that closure of the dam has led to a reduction of the lateral movement of the river over the floodplain, creating more stable conditions.

There is also a comparative analysis of the planform change of the Oconee of the two geologic provinces. Analysis shows that differences do exist in the rates of planform behavior of the river in the two geologic provinces. Furthermore, geological influence upon the Oconee River in the Piedmont province is limited with the riverine characteristics strikingly similar to the alluvial channel found in the Coastal Plain province. The evidence strongly supports the idea that river planform change follows a cycle of adjustment ranging between low to high lateral movements across the landscape.

There is also a discussion of meander migration of river and how this may be explained by the meander geometry of the curves along the river's course. The ratio of the radius value of the meander bend and the width of the curve are important variables in determining the degree of lateral and down-valley movement of the meanders themselves. The literature shows that maximum lateral movement of meanders occurred at r_c/w ratios between 2 & 3. Findings of this study show that while 63% of all meanders show the maximum lateral migration rate occurring when the r_c/w ratios fall between 2.64 and 2.92, maximum lateral movements of the channel between photographic years commonly occur outside of this optimal r_c/w ratio of 2 & 3 proving that meander geometry does not fully explain the rates of channel migration. Furthermore, this approach does not explain the variability of ratios that exist from year to year throughout the data. The theory of organized criticality was tested with the available data and this found limited use in explaining why three of the ten existing cutoffs occurred after the critical threshold sinuosity was exceeded.

Very little work has been done on the effects of dam closure on lateral migration rates. This study is quite useful because it is based upon information that covers over four decades of data on stream channel migration after the closure of a dam, and just over two decades of data before the closure of the dam. Although only some theories pertaining to fluvial geomorphology were tested, there is, owing to the richness of the data, the possibility to test other theories that explain river channel behavior across landscapes.

Dams upon rivers are common features within the US and they will continue their influence upon the way rivers move across the landscape. Rivers undermine man-made structures such as bridges, road embankments, retaining walls, etc. They remove large sections of land as they create new land as they chart new courses in the course of their existence. Rivers therefore challenge engineers, land managers, property owners and scientists alike since they are generally not static with a tendency to remain in one position within the floodplain, but fluid with a propensity to change positions over time. This project is quite useful since it demonstrates that theories cannot always provide the best explanations for river channel movement across the landscapes. This study demonstrates that rivers the uniqueness of each river makes it difficult to provide a suitably comprehensive model that explains how rivers behave over time.

CHAPTER 1
INTRODUCTION: RIVER PLANFORM CHANGE DOWNSTREAM OF THE OCONEE RIVER, GEORGIA

Societies have derived tremendous benefit from the presence of dams on rivers. Dams provide electricity, act as reservoirs for irrigation purposes, provide flood control and safer navigation along rivers, and the lakes they create are sometimes used for recreation (Brandt, 2000; Graf, 2005; Gordon and Meentemeyer, 2006). Because these benefits provide opportunities for economic and industrial development, dams are generally seen as favorable features and may be still constructed in the near future. Studies that examine the effects of dam upon stream morphology and stream geomorphology are therefore relevant primarily because of these effects will continue almost in perpetuity because of the permanent presence of dams across streams and rivers.

Dams sometimes modify and alter the amount of water flowing through the river channel. They also change the amount of sediment within the river's channel by acting as sediment traps, causing the river's load to be stored in the lake created by the dam (Knighton, 1998; Shields et al., 2000; Choi et al., 2005; Graf, 2005). Subsequently, the geomorphology of the river beyond or downstream of the dam is affected by the presence of the dam (Shields et al., 2000).

The volume of streamflow affects the ability of the stream to transport material and erode its bed and banks. In addition, in-stream sediment determines the nature and characteristic morphology of the channel itself. Changing any or both of these variables alters the characteristics of the stream channel (Graf, 1980; Petts, 1984; Knighton, 1998; Shields et al., 2000 Choi et al., 2005; Petts and Gurnell, 2005; Gregory, 2006). When changes in one or both of these two variables take place, the river adjusts to accommodate these changes (Charlton, 2008).

This adjustment is manifested in the way a river channel changes position within its floodplain. A river normally does this by meandering or moving in a sinuous manner (Richards, 2004). The meanders or bends of the river change position in three ways. They move laterally, down-valley and sometimes up-valley (Knighton, 1998; Lagasse et al., 2004). The degree to which a river may change its position depends upon several factors. The rate of change and degree of change varies from river to river and along different sections of the same river as well.

The study of river planform change is important since the movement of river channels negatively impact man-made structures such as the foundation of bridges and other infrastructural works and roads (Kondolf et al., 2002). River migration can also destroy valuable agricultural holdings and property (Larsen and Greco, 2002). Stream ecosystems that are dependent upon rivers are affected as a river changes course (Burge, 2005; Grams and Schmidt, 2005; Gordon and Meentemeyer, 2005).

The Oconee River is located in the state of Georgia, USA. The Oconee River flows from two headwater tributaries – the North Oconee River and Middle Oconee River. These headwater tributaries join at a point just south of the City of Athens forming the Oconee River. The Oconee flows for about 228 kilometers until it reaches a dam called the Sinclair, which was completed in 1953 (Georgia Power, 1997). From then it flows for a further 230 kilometers until it reaches the confluence of the Ocmulgee River. The total area of the Oconee River basin is 13,805 square kilometers. Lake Sinclair, created by the Sinclair Dam, has a surface area of approximately 5204 hectares, though this figure changes as the level of the lake varies by as much as 0.6 meters within short time periods (a few hours) due to demands for water by the power generating units (Georgia Power, 1997). In addition, natural conditions such as droughts and heavy rain tend to affect the lake water surface levels.

This dissertation research primarily examines the impact of the Sinclair Dam upon the part of the Oconee River below or downstream of the dam. This study section begins at the dam and ends approximately 75 kilometers downstream. This study area was selected because it provided the availability of spatial data that covered a significant section of the Oconee before and after the Sinclair Dam was completed. Aerial photographs of the study area captured the river in planform from 1937 to 2005. The scale of these images were detailed enough to allow accurate measurements of changes in the Oconee River over time.

The Sinclair dam was completed in 1953 thus it was feasible to perform comparative analysis on the geomorphic change of the river before and after completion of the dam. The section of the Oconee within the study area is located primarily in a rural setting that has not been overly developed, thus reducing other direct man-made impacts such as land use change. As a result, it became easier to determine the impact of the dam upon the planform movement of the river itself. These impacts were measured using software designed to perform geo-spatial analysis.

The research is presented in three sections. In the first section or Chapter 2, the hypothesis is that since the amount of sediment delivered by the river has been significantly reduced by the dam, the propensity of the stream to migrate across its floodplain will be lessened (Williams and Wolman, 1984). All but the minutest particles of sediment are trapped behind the dam. While figures for the trap efficiency of the Sinclair Dam are not provided here, the trap efficiency of some dams across the US show varying degrees of trapping efficiency of sediments. For example, the Glen Canyon Dam on the Colorado River showed a trap efficiency of 87%. The Garrison Dam on the Missouri River at Bismark North Dakota had a trap efficiency of 79.8%. Gavins Point Dam in Yankton South Dakota had a trap efficiency of 98.8% while the Denison

Dam on the Red River in Oklahoma had a trap efficiency of 99.2% (Williams and Wolman, 1984). Fluvial geomorphic theories purport that the response of streams to the closure of dams can be quite complex, with streams exhibiting adjustments ranging from a reduced lateral migration rate, adjustments in channel width through widening and narrowing to almost very little change (Shields et al., 2000).

The hypothesis in Chapter 3 is that geology plays a significant role in determining the rate of planform change in the Oconee River. The study area passes through two contrasting geologic provinces, that is, the Piedmont and Coastal Geologic provinces with more resistant igneous and metamorphic rocks and less resistant sedimentary rocks respectively. The rationale is that the section of the river within the Piedmont Geologic province would exhibit less lateral movement than the section in the Coastal Geologic province because the rates of erosion would be greater in the section of the river in the Coastal Geologic province. In this paper, there was a comparative analysis of migration rates between the sections of the river in both Geologic provinces.

River planform change does not occur at the same rate throughout the length of a river. Factors that affect these rates include differences in the composition of the material comprising the channel substrate and channel banks and the presence of and different types of riparian vegetation along the course of the river. Since movement of the river channel occurs primarily along the meanders or bends of rivers, it was hypothesized that the nature of the river meanders determines the degree of lateral migration along the Oconee River (Knighton 1998; Hooke, 2007).

Hickin and Nanson (1984) theorized that the relationship between the radius of the bend of a river and the width of that bend determines the degree of lateral movement of the river. In

Chapter 4, measurements of the meanders are done to determine these ratios in order to test this theory. There is also a description of the movement of the meanders as they migrated along the valley. The development and growth of river meanders occur until a threshold point is reached beyond which the growth can no longer take place. The theory of organized criticality states that as a river reaches a state of chaos or extreme meandering or sinuosity, cutoffs are created and the river assumes a less torturous course as it approaches a state of order (Stolum, 1991).

The primary source for the spatial data used in this dissertation was aerial photography. The photographs were taken roughly once each decade starting from 1937 to 2005. Using aerial photographs to measure and assess planform change has been used extensively by a number of researchers including Gurnell (1997), Rumsby et al. (2001), Gaeuman et al. (2004), Tiegs and Pohl (2005), Richard et al. (2005) and Hooke (2006). The images were prepared for data analysis by being geo-rectified using ERDAS Imagine Software. The spatial measurements and spatial interpolations were performed using ArcGIS software.

Measurements of changes in the planform of the river were done in order to determine the degree of lateral migration of the Oconee River over time. The variables that were assessed to determine these changes were the sinuous nature of the river and the degree of lateral shift of the river channel from one time period to another. The shifting of the river channel over time was measured by determining the relative positions of the channels to each other over time.

CHAPTER 2
DAM CLOSURE AND CHANNEL MIGRATION RESPONSE, OCONEE RIVER, GEORGIA USA

Introduction

The harnessing of water for the benefit of human existence has been done for millennia and the building of dams across rivers is no exception (Brandt, 2000; Graf, 2001; Assani and Petit, 2004; Wellmeyer et al., 2005; Graf, 2006). Dams have significantly improved the lives of humans because they have been built for hydroelectricity, recreation, water supply, improvements in navigation and flood control (Brandt, 2000; Graf, 2005; Gordon and Meentemeyer, 2006). Graf (2005) stated that by the end of the 20th Century, over 80,000 dams existed in the United States alone with some rivers having multiple dams. In fact, most of the interruptions that have occurred along the rivers in the United States are the result of dam construction (Gregory, 2006). Globally, at least 400,000 km2 of land has been inundated due to large dams (Gregory, 2006).

The importance of dams and their continued impacts upon human existence can be clearly understood in terms of population trends in both growth and the distribution of those populations over space. According to Petts and Gurnell (2005), worldwide population growth is expected to reach 8.5 billion by 2025 with 5 billion concentrated in urban areas. Such growth places additional demands for water resources and one strategy to avoid this potential crisis is to construct more reservoirs along rivers. A large amount of water resources provided by dams are directed towards urban areas, thus the 3 billion people living outside urban areas may suffer water stress or scarcity. In response to these projected water needs, 400 mega-projects have been constructed or planned in the first decade of the 21st century (Petts and Gurnell, 2005).

In the US, however, the re-evaluation of the benefits of dams have shown that in some instances, the ecological costs may far outweigh the benefits and there has been a call by some agencies for the removal of some dams (Magilligan and Nislow, 2005). Owing to increasing environmental, economic and regulatory concerns, there is a national debate about the implementation of dams in the US (Doyle et al., 2003).

Dams modify the flow regime of streams by regulating stream flow discharge and decrease sediment delivery downstream by trapping sediment (Knighton, 1998; Shields et al., 2000; Choi et al., 2005; Graf, 2005). The sediment trap efficiency of some dams is as high as 99.2 % (Williams and Wolman, 1984). The degree to which stream flow is altered is dependent upon the purpose of the dam. Some dams reduce flow entirely while others regulate flows to the extent that the natural pre-dam high flows and pre-dam low flows are altered to become lower and higher respectively (Williams and Wolman, 1984). The response of streams to the closure of dams may be quite complex with streams exhibiting adjustments ranging from a reduced lateral migration rate, adjustments in channel width through widening and narrowing to very little change (Shields et al., 2000).

Stream flows and sediment are key factors in determining the geomorphology of alluvial streams below dams and fluvial geomorphic theories explain how these two variables interact to produce typical stream behavior downstream of dams (Graf, 1980; Petts, 1984; Shields et al., 2000; Choi et al., 2005; Petts and Gurnell, 2005; Gregory, 2006). Some of these theories explain how modification or changes in these variables determine the extent to which a river migrates across its floodplain. River planform change or lateral movement of the channel across the floodplain occurs when river banks are eroded and when in-stream channel deposits occur (Hickin and Nanson, 1984; Williams and Wolman, 1984; Carson, 1986; Leopold et al., 1992; Wellmeyer et al., 2005). Changes in bank stability are important in determining the propensity of a stream to meander (Simon et al., 2002) and low flows are responsible for less active floodplain areas (Graf, 2006).

Flow regime controls the movement of a river channel across a floodplain and this is manifested in the rate of channel avulsion and/or migration of the channel through meander (bend) change (Petts, 1979; Williams and Wolman, 1984; Hooke, 1995; Shields et al., 2000; Winterbottom, 2000; Wellmeyer et al., 2005; O'Connor et al., 2003; Simon et al., 2002; Harmar and Clifford, 2006). Indeed, the propensity of a river to sinuously meander across its floodplain is a naturally occurring phenomenon in most rivers that are unconstrained by intrinsic and extrinsic factors because rivers by nature do not flow in a straight direction (Leopold et al., 1992; Richards, 2004).

As the outer wall or bank of a bend of a meander (the concave side) or the cut bank, moves laterally through erosion, there is a corresponding deposit of sediment in the opposite inner bank (the convex side) or point bar, of the same bend (Jones and Harper, 1998; Wellmeyer et al., 2005). These formations cause the bend to migrate laterally and if this lateral movement is unconstrained, a series of convoluted sinuous loops and patterns tend to be formed across the floodplain (Ikeda, 1989; Mount, 1995; Charlton, 2008). Some meander loops become so exaggerated in form that there is a progressive narrowing of the land between two opposite banks forming a narrow neck.

This meander neck becomes narrowed to the point where the two limbs of the meander meet and there is a complete breach by the river. The section of the stream channel that is abandoned is known as a cut-off or oxbow lake. The new river course becomes shorter in length than the original (Gay et al., 1998; Charlton, 2008). Sometimes a stream may abandon an existing channel and flow in an entirely new channel on the adjacent floodplain through the avulsion process or chute flows causing a radical change in the direction of the stream channel (Jones and Harper, 1998; Field, 2001; Törnqvist and Bridge, 2002; Makaske et al., 2002; Slingerland and Smith, 2004).

While there is yet no totally acceptable explanation about why channels meander (Rhoads and Welford, 1991; Knighton, 1998), it is clear that sediment deposits in the form of alternate lateral and point bars are responsible for the continued development of meanders in floodplains (Jones and Harper, 1998, Knighton, 1998). This is so because for an initially straight channel to develop meanders, the channel must at regularly spaced intervals, retreat from the banks at alternate sides. The removal of sediment from the banks and the subsequent deposition of these sediments (forming lateral bars) is often associated with stream flow that is oscillating, indicating some disturbance in a stream that was once stable (Rhoads and Welford, 1991).

Purpose and Study Area

The Sinclair Dam on the Oconee River in Georgia, USA was closed in 1953 and Lake Sinclair was created. The lake has an average area of 6,204 hectares with 671 kilometers of shoreline, although this varies with changes in the volume of water in the lake. The dam was built for electric power generation and the lake serves a recreation function. The length of the section of the river downstream of the dam that is part of the study area is about 75 kilometers. This paper tests the hypotheses that the regulated stream flow and altered sediment loading by the dam has reduced channel migration rate, resulting in increased stability. This hypothesis is tested by examining the degree of variability of planform change of the river downstream of the dam. Variability is measured spatially – that is, with distance downstream of the dam and temporally – that is, in terms of when changes occur over time. The effects of the dam closure upon rates of planform migration are shown through a comparative analysis of rates of migration before and after dam closure. There is also a comparison of stable reaches versus active meandering or less stable reaches of the river. Active river reaches are evidenced by deformed channel boundaries through bank erosion and point bar formation. Primary data used to measure the degree of planform change were aerial photographs dating 1937, 1942, 1955, 1966, 1973, 1988, 1999 and 2005. Since the Oconee Dam was completed in 1953, the photographic data covered time periods before and after the closure of the dam.

The measure of the degree of planform change, also referred to as planimetric instability by Knighton (1998) is a measure of channel stability (Graf, 1980; Simon et al., 2002; Hooke, 2003; Richard et al., 2005a). Channel stability is determined by superimposing a stream of a later time upon a stream of an earlier time. If the two streams do not match closely with each other, then instability has occurred. Since low flows are associated with dams, the primary effect of dams upon channel migration of reaches downstream of dams is a reduction of the propensity of the channel to migrate (Shields et al., 2000; Larsen and Greco, 2002). Bradley and Smith (1984) and Johnson (1992) claim that studies of two rivers, located in the north and eastern US show that migration rates were reduced to approximately 75% following dam closure. The analysis of channel planform change therefore, is indicative of the sensitivity of a river system as it adjusts to various disturbances within the fluvial system (Hooke, 1995).

The Oconee River is located in the state of Georgia, USA and the Sinclair dam is located in Baldwin County, Georgia. The Oconee River flows from two headwater tributaries – the North Oconee River and Middle Oconee River in the physiographic province called the Piedmont. The Piedmont is characterized by bedrock consisting of granite, gneiss, schist and quartzite. The natural vegetation type in this province is mainly pine-oak-hickory. These headwater tributaries join at a point just south of the City of Athens forming the Oconee River. The Oconee flows for about 228 km until it reaches the Sinclair Dam.

From then it flows for a further 230 kilometers until it reaches the confluence of the Ocmulgee River. Eight km downstream of the Sinclair Dam, the river crosses the Fall Line and enters the physiographic province called the Coastal Plain. This province is underlain predominantly by cretaceous and younger sediments of sand, clay, sandstone, dolomite and limestone. The total area of the Oconee River basin is 13,805 km^2. The area of the drainage basin south of the Sinclair dam (called the Lower Oconee) is 6276 km^2. The vegetation type in this lower basin is primarily southeastern evergreen and bottomland swamp forest of cypress-tupelo (EPD, 1998). The study reaches of the Oconee River are located in Baldwin County, and flows along the border of Washington and Wilkinson Counties.

Materials and Methods

Spatial data from aerial photographs of the Oconee River valley were used. The dates of the images covered the pre- and post-dam periods. The years covered were 1937, 1942, 1955, 1966, 1973, 1988, 1999 and 2005. The use of aerial photographs to delineate planform change and rates of lateral migration of streams have been used extensively by several authors (Thorne and Lewin, 1979; Nanson and Hickin, 1983; Gurnell, 1997; Gilvear et al., 2000; Graf, 2000; Rumsby and McVey, 2001; Gaeuman et al., 2004; Tiegs and Pohl, 2005; Richard et al., 2005b; Burge, 2005; Hooke, 2005).

All the air photographs, with the exception of the 1999 and 2005 images, were paper images that were scanned using a flat bed scanner. Before any measurements of spatial features could be done in the GIS, the images had to be processed by being converted into a usable format. This involved the geometric correction of the images so that all the planimetric positions of the features on the images could be viewed in a standard map projection (Jensen, 2005). The images were then co-registered using available 2005 Digital Ortho Quarter Quads (DOQQs). Thus the photographs were brought to a common scale which helped to minimize digitizing errors (Gurnell, 1997; Hughes et al., 2006). All the scanned aerial photographs were at the scale of 1:20,000 except the 1988 photographs which were at a scale of 1:40,000. Since the 2005 DOQQs were at a 2 meter spatial resolution, the geometrically corrected images were at the same resolution. The study area, that is, the reaches of the images and its surrounding environs was then extracted for each image. Then a complete mosaic of all images for each year was created using the ERDAS Imagine software.

The stream channel left and right banks were digitized using the ArcGIS software. The channel boundaries were defined as the line that separated the water from the land. Lateral and point bars larger than half the channel width and as long as the full channel width at that point were digitized. This was done since it was impractical to digitize all the bars. The centerline of the channel was then demarcated using the midpoint tool in the ArcGIS software.

Lateral Migration Rates (LMR).

This method was used by Micheli et al. (2004) and Larsen et al. (2006) to compare changes in centerlines. Stream centerlines for different periods were superimposed and the average rate of migration of the stream was calculated by measuring the following: 1) the area of the polygon created between the two centerlines; 2) the average lengths of the centerlines that formed the polygon or half the length of the perimeter of the polygon, and 3) the elapsed time in the number of years that between the two images. Using this information, the channel migration rate was calculated by dividing the area of the polygon (created by the two centerlines) by the average length of the two centerlines. This rate was then multiplied by the numbers of years that elapsed between the years in which the images were taken.

This overlaying analysis was done for the section of the river being studied and was divided into sections called reach blocks. Seventy six 1 km reach blocks were created to analyze spatial changes. This size of the reach block was able to capture enough spatial variability, given the size of the river. Since there were eight decades of photographic data, it was possible to calculate the lateral migration rates for eight time periods.

Proportional Area Change Ratios.

This is achieved by overlaying river channels for two different time periods as shown in Figure 2-2. The light grey mottled line represents the river in time one or T1 (in this case, the 1937 channel) while the solid grey line represents the river in the second time period or T2 (in this case, the 2005 channel).

The overlaying of the two channels produces four different types of polygons as shown in Figure 2-3. E means the portion of the floodplain that has been eroded to accommodate the new location of the river. D means the portion of the floodplain that has been abandoned, also called deposited (which once was occupied by the river in the previous time). B means the portion of the floodplain that is between channels (and this reflects the amount of displacement that has taken place). U means the portion of the channel that has remained unchanged denoting that no channel migration has taken place. Data were normalized in order to compare planform change for different reach blocks of the river for different time periods. The data were normalized by channel area or I (also calculated by adding D to U). So the following proportional area change ratios were obtained:

E/I will show what proportion of the initial channel area has been eroded

U/I will show what proportion of the initial channel area has remained unchanged;

D/I will show what proportion of the initial channel area has been abandoned;

B/I will show what proportion of the initial channel area has been displaced through channel migration or avulsions.

The time interval between years was calculated by subtracting the earlier year of the photograph from the latter year of the photograph. Thus it is possible to calculate the rate of change per time period.

Degree of Sinuosity.

The degree of sinuosity characterizes the deviation of a river from a straight pattern. This index (SI) ratio is defined as or channel length divided by the valley length (Mount, 1995; Knighton, 1998). Sinuosity indices are categorized as straight (SI approximates 1.1), sinuous (SI = 1.1 to 1.5) and meandering (SI is greater than 1.5) (Charlton, 2008). The channel centerline was used as the channel center length. The SI was calculated for each of the 1 kilometer reach blocks for each of the decades of stream data.

Results and Discussion

Lateral Migration Rates.

Overall, the migration rates for the 75 km section of the Oconee River downstream of the dam showed varying degrees of adjustment. Figure 2-4 shows the planform view of the centerlines for the channels for the Oconee River for each time period. The centerlines are placed in chronological order from left to right, with the earliest air photographs (1937) to the latest (2005) and show the reach from approximately 31 kilometers to approximately 63 kilometers downstream of the dam. This portion shows some of the most obvious changes in the planform of the river over time. The solid symbols (arrows and circles) highlight features that previously existed along the river and the dashed symbols (arrows and circles) denote the same features that have now been changed over time. The solid arrow on the 1937 channel at the top shows an obvious loop in the general meander pattern of the river. The corresponding dotted arrow (to the right of the solid one) in the 2005 centerline shows that the loop no longer exists. The other solid arrow, approximately 5 kilometers downstream from the previous one shows a loop in 1937 that progressively became smaller until it disappeared as shown by the dotted arrow on the 2005 channel. The solid circles show a group of meander bends that existed along the course of the river in the 1937 centerline. The dotted circles on the 2005 centerline show that many of these loops no longer exist. The river has now assumed a less sinuous course.

The horizontal dotted lines mark various kilometers downstream of the dam such as 35 km, 41 km, 45 km and so on. This is included to illustrate any possible downward migration of the some of the features highlighted by the special markings. The solid arrow at km 35 shows a loop that has shifted downwards by the 1999 channel. Likewise, the loop shown by the solid arrow at km 41 has shifted or migrated downwards by 2005. The solid circle at km 51 shows a series of meander loops where the most southerly loop has shifted downstream by 1988.

Downstream changes due to the creation of dams result from the changes of discharge beyond the dam and the reduction of the sediment load (Richards, 1982). Howard and Knutson (1984), state that lateral, channel migration rates are dependent upon the resistance of the bank materials, the characteristics of stream flow and the amount of sediment being transported. If force overcomes bank resistance, then lateral mobility of the bank will occur. In describing a model of lateral long-term migration rates of channels, Nanson and Hickin (1983) identified stream power, the resistance of the material comprising the concave channel banks, the height of those concave banks, the rate of sediment supplied to the river and the characteristics of the bends of the meanders. These authors conclude that a river's propensity to migrate laterally is episodic and not a continuous process over time and the shifts of the channel across the landscape are the result of seasonal fluctuations in stream flow.

Fundamentally, changes in channel shifting across the landscape occur through the operation of three mechanisms, namely, bank erosion, in-stream deposition and the shifting of the channel to a new location through avulsions or chute flows (Hooke, 1995). Chute flows create cutoffs when a channel takes a shortcut across a bar. The abrupt change of the channel from one location to another may occur through bank erosion in a section of a channel that is curved (Bridge, 2003; Robert, 2003; Mack and Leeder, 1998).

Figure 2-5 shows digitized channels of a section of the study area from the 1937 and 2005 images. These reaches clearly show that in 2005, the channel has assumed a shorter course with less loops. The dotted arrows in Figure 2-5 show the loops in the 2005 channel that have migrated laterally more than the earlier (1937) loops, while the solid arrows show sections of the 2005 channel that are less sinuous than the 1937 channel thus making the course shorter.

Figure 2-6 shows the 1942 digitized channel and the DOQQ showing the 2005 channel. The solid white arrows show reaches where channel changes occurred through the formation of cutoffs. The dotted white arrows show where channel change has occurred through lateral channel movement. Therefore, channel change the Oconee River is a combination of lateral migration as well as through the occurrence of cutoffs over time.

Possible reasons that explain how the Sinclair Dam has affected the rate of erosion of the Oconee are found in Kondolf's research on the effects of reservoirs upon river channels (1997). The propensity of dammed streams to show an increased rate of erosion downstream of dams is explained in a phenomenon he calls 'hungry water'. Because dams act as sediment traps the downstream water released by the dam is relatively sediment free. Since very little sediment is being transported, the excess energy of the water is expended in erosion of the bed and banks of the channel. There is downcutting of the channel bed (Williams and Wolman, 1984) which results in the coarsening of the bed material and results in an armored layer. This armored layer is not easily eroded and so downcutting ceases to occur. With the arresting of the downward erosion of the bed, the banks of the river become targets of the river's energy and increased bank erosion ensues (Shields et al., 2000).

An Overview of Lateral Migration Rates.

A more comprehensive perspective of migration rates of all the reaches before and after the closure of the Sinclair Dam may be viewed by a comparative analysis of the migration rates of the streams for all the years in which data was extracted from the aerial photographs. Figure 2-7 shows lateral migration rates (in meters) from the dam to 75 kilometers downstream of the dam for all the years in which the aerial photographs were taken. So the rates from 1937 to 1942, 1942 to 1955, etc are documented here, giving a total of 7 time-steps.

A better perspective of the possible influence of the dam upon lateral migration rates is seen in Figure 2-8 which has grouped the rates into two categories, before and after the closure of the dam. The 1937-1942 time step (representing before dam closure) remains as is, and the average lateral migration rates from 1966 to 2005 (representing the post dam period) is presented. Since the dam was completed in 1953, the 1942-1955 time-step is excluded from this graph because that time period is not accurately representative of a pre- or post-dam period. This averaged lateral migration rate does suppress some of the more extreme movements of the channel across the landscape such as the 1999-2005 shift of the channel at about 36 kilometers downstream of the dam as shown in Figure 2-7.

Figure 2-8, however, shows that the rates of lateral migration for the post-dam period are generally lower than for the pre-dam period. The larger differences in rates between the two time periods are found at reaches (or kilometers downstream of the dam) 6 (8.91 m/yr), 7 (7.26 m/yr), 17 (8.88 m/yr), 18 (7.02 m/yr), 19 (6.19 m/yr), 39 (11.02 m/yr), 40 (10.18 m/yr) and 72 (6.79 m/yr).

Comparing the location of the earliest channel centerlines with the latest does account for the degree of variability or channel shifting that may have occurred during the intervening periods. This is achieved through an examination of the rates of lateral migration at different time steps rather than averaging of the rates of planform change as they occurred after the closure of the dam. The description of these changes is shown in Figure 2-9 (A to F).

Figure 2-9 (A to F) shows the lateral migration rates (in meters per year) for each of the time steps shown in Figure 2-7 except the 1942-1955 time step. For each of the subsections of this Figure, that is, A to F, the five highest lateral migration rates have been marked with symbols to highlight where they occurred and what sort of channel movement occurred at each of those points. The symbols represent four types of channel changes that have occurred from one time step to another. These changes are 1) downstream migration of the channel from one time period to another; 2) upstream migration of the channel from one time period to another; 3) the lateral shifting of the channel from one time period to another and 4) the occurrence of a cutoff.

In Figure 2-9 A, the shifting of the channel from 1937 to 1942 in a downstream direction accounted for the two highest rates of lateral migration. These were measured at the 39 and 40 kilometer points downstream of the dam and were calculated as 11.49 m/yr and 13.23m/yr respectively. The occurrence of a cutoff at the 31 kilometer mark accounted for the third highest rate of lateral migration. The straight line distance between the channel centerlines for the 1937 and 1942 channels at the point where the cutoff occurred is 306 meters. Lateral shifting of the channel at 6 (9.96 m/yr) and 17 (9.79 m/yr) kilometers downstream of the dam accounted for the other two reaches in the river with the fourth and fifth highest lateral migration rates.

In Figure 2-9 B, three of the five highest reaches of the river are due to the downstream movement of the channel from 1955 to 1966. These occurred at 51, 55 and 56 kilometers downstream of the dam with annual migration rates in meters of 5.20, 5.20 and 6.79 respectively. Lateral shifting of the channel at 28 and 28 kilometers downstream of the dam account for the other two highest lateral migration rates occurring in that time step.

Figure 2-9 C shows that four of the five highest lateral migration rates between 1966 and 1973 occurred due to lateral shifting of the channel. These took place at 31, 46, 28 and 30 kilometers downstream of the dam with recorded rates of 10.15, 9.26, 8.56 and 8.24 m/yr respectively. The movement of the channel in the upstream direction accounted an annual lateral migration rate of 8.72 meters.

Four of the five places along the river with the highest measured lateral migration rates between 1973 and 1988 occurred due to lateral shifting of the river (Figure 2-9 D). These occurred at 11 kilometers (3.82 m/yr); 13 kilometers (5.54 m/yr); 25 kilometers (5.04 m/yr) and 53 kilometers (4.46 m/yr). A cutoff that occurred at kilometer 49 accounted for a lateral migration rate of 3.93 m/yr.

Figure 2-9 E shows that four of the five highest lateral migration rates between 1988 and 1999 occurred due to lateral shifting of the channel. These took place at 11, 13, 25 and 53 kilometers downstream of the dam with recorded rates of 6.52, 7.53, 8.10 and 4.89 m/yr respectively. A cutoff that occurred at kilometer 39 accounted for a lateral migration rate of 5.53 m/yr.

Figure 2-9 F (the 1999 to the 2005 time step) shows that the highest of the five lateral migration rates took place due to the occurrence of a cutoff at 35 kilometers downstream of the dam. This cutoff shortened the length of the channel by approximately 1,470 meters. This accounts for the relatively large annual migration rate of 25.38 meters at that reach of the river. Lateral channel shifting at 60 kilometers accounted for a lateral migration rate of 5.73 m/yr. Downstream migration of the channel from 1999 to 2005 accounts for the other three of the five highest reaches of the river where the lateral migration rates were the highest. These took place at kilometers 49, 50 and 56 with annual migration rates in meters of 4.96, 6.23 and 4.78 respectively.

Table 2-1 shows the average lateral migration rates, standard deviation and maximum lateral migration rates for each of the six time steps shown in Figure 2-9. For the 1999-2005 time step, the cutoff that occurred between these two years is 19.15 m/yr higher than the second highest lateral migration rate and therefore is not truly representative of average lateral migration rates for that time step. The numbers in parenthesis do not include the data for this cutoff that occurred.

The 1937-1942 time step has the highest average lateral migration rate of 4.20 m/yr as well as the highest standard deviation of 2.78. This represents a range of movement of the river channel within these years that is higher than other years. This time step is also in the pre-dam era. The time steps with the average lateral migration rates in order of second highest to lowest are as follows: 1966-1973; 1999-2005; 1955-1966; 1988-1999 and 1973-1988. This order suggests that the river generally becomes less active that is, having a reduced propensity to migrate across the landscape after a period of relatively high activity. This is discussed further by the examination of the data in Table 2-1.

The standard deviation (SD) measures how the data is dispersed from the mean. The 1937-1942 time step has the highest standard deviation of 2.78. This shows that the river was, in relation to the other time steps, quite active covering a wider range in its movements across the floodplain. In the 1955-1966 time step, the small standard deviation of 1.49 shows that the lateral migration rates in this time step does not vary as much from the mean as the 1937-1942 time step.

The data for 1966-1973 time step shows that the movement of the river across the floodplain was greater than the 1955-1966 time step. Data in Table 2-1 show that this time step has the second highest measured lateral migration rate and standard deviation. This also is the highest active period of lateral migration in the post-dam era. The lowest period of inactivity in terms of lateral migration follows this active period as shown by the average lateral migration for the 1973-1988 time step which is 1.53 m/yr. The SD for the same period is also the smallest at 1.26.

This relatively low period of inactivity still occurs in the 1988-1999 time step which has a similar average lateral migration rate of 1.56. The difference between these two relatively inactive periods is in the SD with the 1988-1999 time step having the higher SD. The greater range of movement of the channel across the floodplain from 1988 to 1999, accounts for this larger SD.

Even if the 25.38 maximum value is discounted and using only the values in parenthesis (Table 2-1) for the 1999-2005 time step, the average lateral migration rate and the standard deviation for this time step is higher than the previous two time steps. Figure 2-9 F shows that unlike the two previous time steps, the position of the river channel within the floodplain in 1999 and 2005 is different for all the reaches of the river. From 1999 to 2005, there were no reaches where no lateral movement of the channel occurred. Between 1973 and 1988, however, there are 9 reaches where no lateral movement occurred while between 1988 and 1999, there are 12 reaches where no movement occurred. The 1999-2005 period was therefore much more active in terms of channel movement within the floodplain.

Table 2-9 shows the results of a Wilcoxon signed-rank test that was used to test the significant difference of lateral migration rates when comparing lateral migration rates for time steps. Lateral migration rates for the 1937-1942 time step was compared with the 1942-1955 time step showed a highly significant difference. The fact that the Sinclair Dam was completed in 1953 along with its influence on planform change rates may account for this difference. The next comparison shows no significant difference in the lateral migration rates although the 1942 year is included in this analysis. The effects of the dam were probably significant even before completion in 1953.

The next two comparisons, that is, 1955/56 and 1966/73 along with 1966/73 and 1973/88 show a marked significant difference in the lateral migration rates. All of these years are post-dam years and the variability in the data maybe the fact that accounts for these significant differences. During these years, 6 cutoffs were created with channels straightening and meander bends becoming exaggerated in form as they radically change shape and configuration. The last comparison with significant lateral migration rates are the 1988/99 and 1999/05 years. Although only two cutoffs were created in this time period, there were 14 flood events which would be expected to cause the river channel to change position within the floodplain.

Determining the causes for the differences between lateral migration rates for the pre- and post-dam era is complex because rates of bank erosion and the corresponding in-stream deposition vary both spatially, that is downstream from the dam and temporally, that is, from decade to decade. In summary, during the 1937 to 1942 period, the highest rates of lateral planform change (with the exception of the single case in 1999-2005) were recorded along with the highest average lateral migration rate. The abandonment of a large loop at 37 km downstream of the dam accounts for the relatively large high maximum migration rate of 25.38 m for the 1999-2005 time-step. Even so, the mean lateral migration rate of the pre-dam era is still higher than that of the 1999-2005.

Using these results only, it would appear as if the river channel (with the exception of the one case in 1999-2005), in the pre-dam era migrated across the floodplain more in terms of range from the lowest (0 meters) to the highest. During that time, the highest average rate of lateral planform change was 4.2 m, while the lowest average rate of lateral planform change (1.53 m) was recorded for 1973-1988.

Table 2-1 also shows that the average rate of movement of the channel did not decrease with time since the 1966-1973 time-step showed the second highest planform migration rate. Therefore, rate of channel migration across the landscape does not necessarily diminish with time by the occurrence of the perturbation, in this case, the closure of the dam. Furthermore, the largest lateral shifts in the channel did not always take place at the same reach as shown in the parentheses next to the maximum rates for each time step.

Since the measure of the movement of a river channel across the landscape is an indication of river planform stability, then the pre-dam era shows the least stability. When a river changes course through abandonment of loops (creating cutoffs), it results in a shorter course (Gay et al., 1998; Brewer and Lewin, 1998). If the river channel becomes progressively shorter over time, it would therefore suggest greater stability or less fluctuation across the floodplain. Table 2-2 is a summary of the length of each centerline of the river for each year in which the aerial photographs were taken.

This table shows that the 1942 channel is just over 2 km shorter than the 1937 channel. A total of 3 cutoffs were created because of channel shifting. Between 1942 and 1955, the channel lengthened by 2.9 km. During this time step, no oxbow lakes or cutoffs were created. Rather, the meander bends became more pronounced through bank erosion along with in-stream deposition. This is clearly an active channel even though the Sinclair Dam officially closed in 1953. The discernable differences in the position of the meanders in relation to each other began from about 32 km downstream of the dam.

The 1966 channel is almost 2 km shorter than the 1955 channel. Two cutoffs were created between 1955 and 1966 and this is most likely the result of the sustained erosion. The same trend continues from 1966 to 1973 where two more cutoffs were created, shortening the river channel by a further 1 km.

From 1973 to 1988, the river increased slightly in length (0.84 km) despite the creation of 2 more cutoffs. The growth of the existing loops or meanders can account for the increased length of the river channel. Therefore, bank erosion and in-stream deposition still occurred during this time. A possible reason for this may be the increased velocity that was created as the stream channel gradient became shorter and steeper after the cutoff (Brewer and Lewin, 1998). This caused greater downcutting eventually leading to a coarser, more resistant channel bed. The banks then absorbed much of the river's energy and so bank erosion accelerated (Shields et al., 2000) with subsequent bank deposition.

One cutoff was created between 1988 and 1999. This helps to account for the fact that the 1999 stream is shorter than the 1988 stream (by 1.52 km). The position of the 1988 and 1999 channels within the floodplain are not overly dissimilar. Despite the creation of a very large cutoff in reach 35, between 1999 and 2005, the 2005 channel is still 1.5 km longer than the 1999 channel.

Figure 2-10 shows the range of lateral migration rates for all the time steps except the 1942-1955 time-step. The range was calculated by subtracting the smallest lateral migration rate (for all time steps) from the largest lateral migration rate (for all time steps) for each reach of the river. This figure shows how stable/unstable the river was spatially over time, that is, which reaches downstream of the dam exhibited the greatest propensity to move laterally across the floodplain.

This figure shows that largest lateral migration took place at approximately reach 36 (36 km downstream) and that was due to the creation of a large cutoff that took place between 1999 and 2005. The range of lateral migration rates was not steady over space. Rather, they occurred in waves where the river's lateral movement across the landscape crested or peaked at various distances downstream of the dam. Therefore, the greatest lateral migration took place in intervals downstream of the dam. Because the peaks were interspersed with troughs of relatively low migration rates, there were reaches where very little lateral movement took place.

Bank erosion rates and the concomitant point bar deposition have therefore not been constant along the reaches of the stream. Non-homogeneities of bank material and vegetation are possible explanations for this as the stream banks offer different degrees of resistance to erosion (Howard and Knutson, 1984; Brewer and Lewin, 1998; Shields et al., 2000; Tooth et al., 2002). Second, in an examination of the nature of meander morphology across floodplains, Hooke (2007; 2003) has examined several theories that attempt to explain the complexities common to meanders and the inherent nature of rivers to migrate across their floodplains. Part of those complex patterns include clustering of meanders, and the development of unstable reaches with compound loops mixed with stable reaches.

The theory of self organized criticality describes meanders in rivers increasing in sinuosity to the point where cutoffs are formed followed by a reduction in sinuosity. This occurs when the system reaches a critical state and this causes a sudden change or readjustment to occur. In time the levels of sinuosity will increase again to critical levels where in an unconstrained state, more cutoffs will occur after a certain level is reached. A straight course would represent the river in a state of order while a highly sinuous course would represent a river in a state of chaos (Hooke, 2003; Fonstad and Marcus, 2003; Hooke, 2007). This idea of chaos versus order, however, is tested in a comparative analysis of lateral migration rates and highly sinuous reaches later in this chapter and it is shown that straight reaches may not necessarily reflect order and sinuous reaches may not reflect chaos.

Between the 1930s and 1940s, three cutoffs occurred. From the 1940s to the 1950s, one cutoff was created. From the 1950s to 2005, 7 cutoffs were created. For avulsions to take place, there sometimes needs to be several high-water episodes (Gay et al., 1998) or a series of flood events (Mack and Leeder, 1998; Hooke, 2004). It may be too simplistic to claim that the flood events or the high water events by themselves are the sole cause of the cutoffs that took place along the Oconee River. The role that the dam plays as a sediment trap has to be considered as well as sediment free water downstream of the dam can have deleterious effects on stream channel morphology. Therefore, even without a major flood event, the river’s propensity to erode its banks would increase.

Stream channel adjustments are responses to the discharge and the sediment loads. An analysis of the stream flow data must be considered here. The streamflow data was collected at a gauging station located approximately 2.8 km downstream of the dam and this is shown in Figure 2-11. The dotted line shows the year in which the dam was closed. The effect of dams upon streamflow is usually a moderation of the higher flows and an elevation of the low flows (Shields et al., 2000; Wellmeyer et al., 2005). The horizontal line in Figure 2-11 shows the discharge above which flooding would occur. This flood stage is 8.2296 meters with a discharge of 1214.268 m^3/sec and it is determined by the NOAA's Advanced Hydrologic Prediction Service. The pre-dam stream flow data is from 1910 to 1950 and this shows that the flood stage was exceeded 45 times with stream discharge ranging from 1239.54 to 2329.09 m^3/sec. The post-dam stream flow data is from 1954 to 2006 and the flood stage was exceeded 28 times with stream discharge ranging from 1216.9 to 2306.45 m^3/sec.

Flood discharges are more important in determining the propensity of a river to effect channel planform change (Knighton, 1988). Since cutoffs are features that denote channel change, Table 2-8 shows the occurrences of cutoffs along the course of the Oconee River by time-steps and the number of flood events that occurred during each of those time steps. The duration of the flood events are important as a series of recurring flood events would normally have a greater propensity to effect change than the occurrence of a single event. In the 1937-1942 time step, two flood events occurred in sequence, while there was another sequence of three flood events occurring in sequence.

From 1942 to 1955, no cutoffs occurred and there was 1 flood event. Two cutoffs were created between 1955 and 1966 and there were 4 flood events, none of which occurred in sequential order. From 1966 to 1973, two cutoffs were formed and there were 3 flood events, two of which occurred in sequence. From 1973 to 1988, 2 cutoffs occurred with 7 flood events. Two of these flood events were in sequence. From 1988 to 1999, 1 cutoff took place and there were 12 flood events. There were two sequenced flood events over the course of these years. A single cutoff occurred between 1999 and 2006 and there were two non-sequenced flood events. The Advanced Hydrologic Prediction Service describes a major flood event for the Oconee River as that which the discharge exceeds 2000 m^3/sec. Five such events occurred between 1937 and 2005, with two occurring (in sequence) between 1937 and 1942, one between 1955 and 1966, one between 1966 and 1973 and the fifth occurring between 1988 and 1999. Based upon the occurrence of cutoffs, one cannot conclude that the cutoffs on the Oconee River occurred simply due to the flood events (as shown in Table 2-8) alone.

Flow duration curves (Fig 2-X) shows the degree of variability in the data related to the streamflow (Gregory and Walling, 1973; Knighton, 1998). The various magnitudes of flow are displayed by flow duration curves and it shows the frequency at which these flows are equaled or exceeded. In Figure 2-27, a discharge of 300 m^3/sec is equaled or exceeded 4 % of the time for the post-dam flow while a discharge of the same magnitude is exceeded 5.5 % of the time for the pre-dam flow. A careful examination of the Figure reveals that a flood event (that is, discharge in excess of 1214.268 m^3/sec) in the pre-dam era would occur about 2 % of the time, while a flood event in the post-dam era would occur at or less than 1 % of the time. Post-dam streamflows therefore, would have less of a propensity to erode and effect planform change than the pre-dam streamflows.

Figures 2-12 to 2-17 along with Tables 2-5 and 2-6 provide more statistics on the nature of the streamflow data from 1910 to 2006 with the data separated into two categories, that is, before and after the closure of the Sinclair Dam. The annual average streamflow, average maximum streamflow, average minimum streamflow, all show higher readings in cubic m/s for the pre-dam era than the post-dam era. The effect of the dam upon stream flow was a moderation of both the high flows and the low flows with the largest percentage change taking place on the annual minimum flow at 51%. The standard deviations for these datasets are also smaller in the post-dam era, proving that the range of streamflow data was also smaller in this era.

The occurrence of low flows are important since low or reduced streamflows reduces a stream's transport capacity and induces deposition of material creating in-stream deposits in the form of sandbanks. Since the post-dam annual minimum flow of the Oconee is 51 % lower than the pre-dam flow, it is expected that not only would greater deposition would occur after the closure of the dam, but there would be a greater possibility for the occurrence of the establishment of riparian vegetation and subsequent stabilization of the banks and stream channel.

The monthly average and the monthly maximum streamflows show similar trends like the annual streamflow data. The dataset for the monthly minimum flow (Figure 2-17) had a wider range in the post-dam era than the pre-dam era. This is confirmed by the higher standard deviation (Table 2-6). A total of 6 rivers were chosen in order to compare how a dam may affect the streamflow regime of a river after the closure of a dam. This is shown in Table 2-7 and these examples were chosen owing to the proximity of the dam to the stream gauge which is not very dissimilar to the location of the stream gauge from the dam for the Oconee River and the Sinclair Dam. The data shows that average daily and annual peak discharge for all the cases were suppressed after closure of the dams on each of the rivers (Williams and Wolman, 1984). Percent changes ranged from 10 to 85% with the Oconee River among the lower of the set of rivers.

Proportional Area Change Ratios.

The planform change indices along the Oconee River for the pre-dam era and the post-dam era are shown by Figures 2-18 and 2-19 respectively. Large values of U/I indicate that little change has taken place since the river has not migrated extensively across the floodplain while low values would indicate greater channel instability. In the pre-dam period (as seen in Figure 2-18), for the first 22 km downstream of the dam, most of the highest index values are U/I. Correspondingly, the B/I values which indicate land between the channels for the different time periods are low. A channel that has not changed position over time is fairly stable and values for the U/I variable are useful in indicating channel stability (Mossa, 2006). In Figure 2-18 the U/I values which are, with one exception, the highest recorded values for the first 24 kilometers begin to experience lower values at about 25 km downstream of the dam. There are a series of loops and bends at this point in the river's course. Lateral migration or shifting of a channel occurs mainly through erosion of the concave bank of a bend or meander and with a net deposit of sediment on the convex side of the same bend. It is therefore expected that channel instability would manifest itself in these sections of the river.

In Figure 2-18 also, the E/I values which indicate the location of a new channel on the floodplain show relatively high values at reaches 30, 40, 53 and 61. It is at these reaches where the river has some pronounced meanders. However, not all reaches of the river that have a series of loops and pronounced meanders show high values for E/I. Reaches 49 to 52 have 6 meanders with the potential for intense bank erosion, yet the B/I values are fairly low for these reaches. At these reaches, the channels have remained fairly stable over time.

Figure 2-19 shows that the index values generally do not vary greatly relative to each other as in the pre-dam period. The E/I values are 'suppressed' and unlike the pre-dam period, there are only four points along the river where these values are the highest. In the pre-dam era, there were 8 points along the river where this occurred. The highest E/1 value in the post-dam era occurred at reach 25 (0.98) while for the same reach in the pre-dam era, the E/1 values were

0.41. At this reach, there was little difference between the location of the 1966 and the 1972 channels. Between 1972 and 1988 there was a shift in the channel to a new location. From 1988 to 1999, the channel shifted back to the approximate location of the 1972 channel. This proves that lateral migration channel rates within the floodplain can be better understood in the time-step sequential changes rather than just in the pre- and post-dam perspectives.

This data shows that channel migration does not occur along all bends or meanders of the Oconee River. Some bends have the propensity to erode more than other bends. The likely reason for this is the differences in bank resistance to erosion (Hooke, 2004). The data also shows that channel migration within the floodplain occurs at different rates at the same reaches. The differences in rapidity may be due to the variations of the composition of the channel substrates and material. The newer deposited material on the floodplain would have zones or areas that are more easily erodible than the older substrates (Hooke, 2004). This may explain why the channel at reach 25 showed no great discernible lateral movement from 1966 to 1972; then moved to a new location by 1988 and quite quickly moved back to the 1972 position by 1999. That section of the floodplain had newer, recently deposited material and was more easily reworked.

Separating the proportional change ratios from each other and categorizing them into pre- and post-dam periods allows for further comparison of reach ratio to analyze the effects of the closure of the dam. In Figure 2-20, the U/I values are generally higher in the post-dam era than in the pre-dam era. Several of the reaches where the post-dam values are higher than the pre-dam values are found further from the dam. Starting at reach 39, there are 8 reaches where the U/I values are higher in the post dam than in the pre-dam.

These reaches are 41, 49, 55, 58, 62, 73 and 74. It would appear therefore, that stability of the channels generally increases with distance downstream of the dam. U/I values are not only elevated at the higher reaches but show less variability in the post-dam period as well. Figure 2-21 shows wider oscillations of the E/I values in the pre-dam era than in the post-dam era throughout most of the length of the stream. Post-dam channel lateral movement is far less because of less erosive activity in the formation of newer channels.

Figure 2-22 supports the findings of Figure 2-21 because the amount of land between the channels in the two pre- and post-dam periods is far greater in the pre-dam period. For the first 22 kilometers downstream of the dam the amount of movement of the channel in both eras in relation to each other was small. There was post dam instability and much of this occurred further away from the dam rather than closer to the dam. The degree of instability was lower in the post-dam period than in the pre-dam period given the greater fluctuations of the graphs.

D/I ratios show land that was once occupied but is now abandoned as new channels were opened up through erosion and/or avulsion. Figure 2-23 shows this and clearly the lower values of D/I as shown in the post-dam era indicate that less channel switching has occurred since there is a smaller value for abandoned land.

Sinuosity.

Figure 2-24 shows the sinuosity index for two time periods, that is, pre-dam and post-dam. Sinuosity for both time periods does differ with the degree of sinuosity for the pre-dam period showing a wider range than the post-dam period. The minimum sinuosity index for both periods is 1 which means that reaches of the river were approximately straight. The maximum sinuosity indexes for the pre- and post-dam were 5.01 and 4.07 respectively. However, since this figure does not account for the variability within the different years, it is necessary to examine the data in greater detail for other differences.

Figure 2-25 shows the number of reaches for the stream that are classified as being straight, sinuous and meandering, with straight approximating a SI of 1.1; sinuous with SI from 1.1 to 1.5 and meandering reaches having SI greater than 1.5 (Charlton, 2008). This is done for each decade in which the aerial photographs were taken as well as for an average of the pre- verses the post-dam periods. In the pre-dam period, the number of reaches of the stream that were categorized as meandering was 36 while the post-dam period recorded 29. The post-dam period recorded a higher number of reaches that were straight (25) than the pre-dam period (21). A straighter channel does not necessarily mean that there is greater stability. In fact, the post-dam era had more cutoffs that were created than the pre-dam era which is evidence that over time, the river was actively shifting positions within the floodplain.

In the post-dam era, the 1950 decade recorded the lowest number of reaches that were classified as straight (a total of 24). This number eventually increased through time with the 1990 and 2000 decades each having 27 straight reaches.

As a measure of stream straightness verses un-straightness, the stream was divided into two categories instead of three; that is meandering and sinuous were combined to form one category. This non-straight category had the highest recorded number in the 1930s with 53 followed by 52 for the 1940s. The number rose to 53 in the 1950s. In the 1960s, 1970s and 1980s, the number of un-straight reaches dipped to 51 and during the last two decades, it further dropped 50 counts each. The rise in the 1950s may be the result sediment free water released by the dam with greater erosive power (Kondolf, 1997). This in turn exploits the weaknesses in the bank material promoting greater bank erosion with an eventual less straight channel.

Overall, the stream in the pre-dam period was less straight than in the post-dam period. This statistic does not necessarily prove that the pre-dam stream was less stable than the post-dam stream because sinuosity is not always an accurate measure of stream stability. Table 2-3 shows the sinuosity indexes for the Oconee River from km 21 to 30 for the years 1937 to 1973. This table shows that none of these reaches may be classified as being straight. 19 of the 50 reaches are classified as being meandering. Figure 2-26 shows the channel centerlines of the Oconee River (1937-1973) from reaches 21 to 30. Table 2-4 shows the lateral migration rates for the same reaches and the same time period, that is, from 1937 to 1973. The largest LMR occurs at reach 29 from 1966 to 1973. The SI for the 1966 and 1973 channels at this reach are 1.54 and 1.53 respectively. While these SI are categorized as reaches that are meandering, they are not the reaches in the table that have the highest SI.

Table 2-3 shows that the SI for reach 22 for the 1937 and 1942 channels are 1.04 and 1.03 respectively which fall into the category as relatively low sinuous reaches (SI for sinuous reaches range from 1.1 to 1.5). The LMR for this reach for 1937 to 1942 is 3.67 meters per year, which is much higher than several other LMR for other reaches for other time steps which have higher SI.

Table 2-10 shows the results of the Wilcoxon rank-sum test statistic which compares the sinuosity indices for paired years, that is, 1937 and 1942, 1942 and 1955, etc to test for significant differences in the sinuosity indices for each pair. The results record that the sinuosity indices between the 1937 and 1942 years as being not being different. Both years are in the pre-dam era and both do not show the effects of the presence of the dam. Comparisons of the next two pairs show that the differences are highly significant with reported scores below 0.05. A possible explanation for the significant difference between the 1942 and 1955 sinuosity is that one is post dam and the other is pre-dam. The 1955 and 1966 comparisons do show a significant difference in sinuosity indices even though both are post-dam. Perhaps this fact that there were four flood events between 1955 and 1966 which account for the significant difference in sinuosity between the two.

The two other pairs recorded differences that were not statistically significantly different. The 1988 and 1999 years recorded differences that were significantly different. Between 1988 and 1999, 12 flood events occurred and perhaps this may account for the marked difference in sinuosity between the two years. Finally, the 1999 and 2005 years also recorded a difference that was significant with, however, only 2 recorded flood events. A huge cutoff that occurred between these two years is perhaps the primary reason for the significant difference in sinuosity between the two years.

Conclusion

Measurements show that the Oconee River has constantly shifted positions within the floodplain throughout the eight decades covered by the air photographs. This movement has occurred primarily through lateral shifting with the concomitant growth or resizing of the meander loops or bends, and the shortening and straightening of the channel which sometimes led to the creation of cutoffs. The channel throughout the decades has occupied different positions on the floodplain. Comparisons between the changes in floodplain location between the pre- and post-dam era show that the major differences between the two are that on average, the post-dam era has on average, a reduced lateral migration rate as well as a lower range of movement from across the floodplain.

Sinuosity for the post-dam period is also smaller than the pre-dam era but this is not necessarily the result of a more stable river. Rather the river has straightened out more (as indicated by the increased number of reaches that are classified as straighter) because of the creation of more cutoffs which are accompanied by a straightening of the channel within the immediate vicinity of the location of the cutoff.

Separating the stream merely into pre- and post-dam periods, however, provides an overly simplistic perspective of river planform change over time. The dynamics and complexities of the movement of the river are better understood by an examination of the time-step sequence of movements each decade rather than just in two snapshots in time. For example, reaches of the river shifted across the floodplain then re-shifted and occupied the once abandoned channel after a few years.

The degree of planform change was not consistent throughout all reaches of the stream and over time and as there were marked differences temporally and spatially. Distance from the dam did not appear to significantly dampen or suppress the propensity of the stream to migrate across the landscape.

Each of the three variables studied, that is, lateral migration rates, sinuosity and proportional area change ratios are useful in that they provide essential data in order to draw reasonable conclusions about river stability/instability over time and space. They provided data that complimented each other but should not be used separately to always draw suitable conclusions about river planform change. For instance, high and low sinuosity indexes by themselves should not be used as indicators of channel planform instability and stability. It was clearly shown that some reaches that had high sinuosity indexes had low lateral migration rates while some reaches that had high lateral migration rates had low sinuosity.

Furthermore, it is not clear which flood events were responsible for the creation of the cutoffs that were created along the stream due to a lack of evidence of when the actual avulsions took place. There are reaches in the river that have cutoffs followed by reaches of marked stability and then more instability and the creation of more cutoffs. Perhaps it is not just high flow events that trigger cutoffs but rather the increased velocity caused by shortened reaches and increased gradients following cutoffs.

Vegetation change has not been a significant factor since vegetation within the floodplain has not changed over time. The landscape has remained fairly rural in the decades in which the aerial photographs were taken. The closure of the Sinclair Dam has resulted in a reduction of much of the sediment load of the Oconee River. There is little evidence that streamflow volumes have been radically modified by the dam since there are several high flows in the post-dam era as well as in the pre-dam era.

It is therefore reasonable to conclude that the closure of the Sinclair Dam upon the Oconee River has had an effect upon the rates of planform migration both temporally and spatially. Measurements do show that though the Oconee River's movements across the floodplain after the closure of the Sinclair Dam are not as wide ranging as before the dam was constructed, the river is by no means stable after dam closure.

Table 2-1. The average lateral migration rates (LMR), standard deviation (SD) and maximum lateral migration rates corresponding to each of the six time steps shown in Figure 2-9

Time Step	Average LMR Meters/year	SD	Maximum LMR
1937-1942	4.20	2.78	13.23
1955-1966	2.23	1.49	6.79
1966-1973	3.21	2.47	10.15
1973-1988	1.53	1.26	5.54
1988-1999	1.56	1.72	8.10
1999-2005	2.70 (2.37)	2.95 (1.36)	25.38 (6.23)

The values in parenthesis for the 1999-2005 time step exclude the 25.38 maximum LMR

Table 2-2. Lengths of channel centerlines in km from 1937 to 2005

Year	1937	1942	1955	1966	1973	1988	1999	2005
Length (km)	77.013	74.993	77.883	75.965	74.913	75.753	74.238	75.544

Table 2-3. Sinuosity indexes for Oconee River from

Reach	1937	1942	1955	1966	1973
21	1.04	1.03	1.03	1.03	1.04
22	1.39	1.37	1.47	1.52	1.47
23	1.61	1.67	1.81	1.76	1.76
24	1.31	1.34	1.46	1.44	1.40
25	1.72	1.78	1.90	1.97	1.94
26	1.75	1.80	1.95	2.01	1.98
27	1.08	1.05	1.06	1.06	1.08
28	1.48	1.47	1.50	1.54	1.53
29	1.35	1.30	1.38	1.46	1.41
30	1.26	1.21	1.33	1.26	1.25

Table 2-4. Lateral migration rates for Oconee River from reaches 21 to 30: 1937-1973

Reach	1937-1942	1942-1955	1955-1966	1966-1973
21	1.50	2.78	2.72	4.22
22	3.67	3.92	3.01	1.94
23	1.66	0.36	0.88	0.32
24	0.96	1.60	1.20	1.28
25	2.28	2.12	1.92	1.23
26	5.49	2.02	2.79	2.41
27	6.39	1.74	4.10	3.61
28	5.10	1.04	4.18	3.35
29	7.48	0.39	6.22	8.56
30	4.58	1.28	4.60	7.74

Table 2-5. Streamflow regimes indicators for Oconee River, before and after dam closure. Figures are in cubic meters/sec

	Before dam (1910 – 1950)		After dam (1954 – 2006)	
	Mean	SD	Mean	SD
Annual average flow	99.05	37.25	85.81	31.08
Annual maximum flow	1095.61	573.88	937.89	533.46
Annual minimum flow	17.38	7.15	8.47	2.88
Monthly average flow	99.04	83.23	86.24	73.07
Monthly maximum flow	327.09	375.65	281.21	342.94
Monthly minimum flow	41.53	22.98	21.06	25.56

Table 2-6. Percentage change of flow indicators between pre- and post-dam: Oconee River.

Percentage change		
	Mean	SD
Annual average flow	13.36	16.56
Annual maximum flow	14.40	7.04
Annual minimum flow	51.27	59.72
Monthly average flow	12.92	12.21
Monthly maximum flow	14.03	8.71
Monthly minimum flow	49.29	11.23+

+ Denotes percentage increase. All other numbers show a percentage decrease.

Table 2-7. Summary of streamflow data comparing data for Oconee River with some rivers showing differences in discharge (m^3/s) before and after closure of dams and percentage change between before and after dam stream flows. (Taken from Williams and Wolman (1984).

River	Water Years		Average daily discharge (m^3/s)			Average annual peak discharge (m^3/s)		
	Pre-dam	Post-dam	Pre-dam	Post-dam	% change	Pre-dam	Post-dam	% change
Oconee, Milledgeville GA (6.86 km)	1910-1950	1954-2006	99.06	85.84	13.35	1095.61	973.89	11.11
Missouri, Gavins Point, SD (8 km)	1948-1954	1955-1978	930	740	20.43	5200	1200	76.92
Smoky Hill, Kanopolis, KS (1.3 km)	1941-1947	1948-1977	8.7	9.9	13.79+	320	135	57.81
Wolf Creek, Fort Supply, OK (2.6 km)	1938-1941	1942-1978	2.5	1.7	32	240	35	85.42
Canadian, Eufaula, OK (13 km)	1939-1962	1963-1978	175	120	31.43	3600	740	79.44
Chattahooche, Buford, GA (4 km)	1942-1955	1956-1971	60	54	10	660	270	59.09
Canadian, Ute, NM (3.2)	1943-1962	1963-1972	3.5	1.2	65.71	550	66	88

+ denotes increase in percentage change. Numbers in parenthesis next to the name of the river are the distance of the stream gauge downstream of the dam.

Table 2-8. Cutoff occurrence along the Oconee River along with the number of flood events.

Time steps	Number of cutoffs	Number of flood events
1937-1942	3	6
1942-1955	0	1
1955-1966	2	4
1966-1973	2	3
1973-1988	2	7
1988-1999	1	12
1999-2005	1	6

Table 2-9. Wilcoxon rank-sum test statistic: Lateral migration rates, Oconee River.

Time steps	1937-1942/ 1942-1955	1942-1955/ 1955-1966	1955-1966/ 1966-1973	1966-1973/ 1973-1988	1973-1988/ 1988-1999	1988-1999/ 1999-2005
Z	-3.522	-2.463	-3.535	-5.434	-.516	-4.144
Asymp. Sig. (2-tailed)	.000	.014	.000	.000	.606	.000

Table 2-10. Wilcoxon rank-sum test statistic: Sinuosity Indices, Oconee River.

Dates	1937-1942	1942-1955	1955-1966	1966-1973	1973-1988	1988-1999	1999-2005
Z	-1.093	-6.001	-4.605	-.981	-.473	-6.264	-3.355
Asymp. Sig. (2-tailed	.274	.000	.000	.327	.636	.000	.001

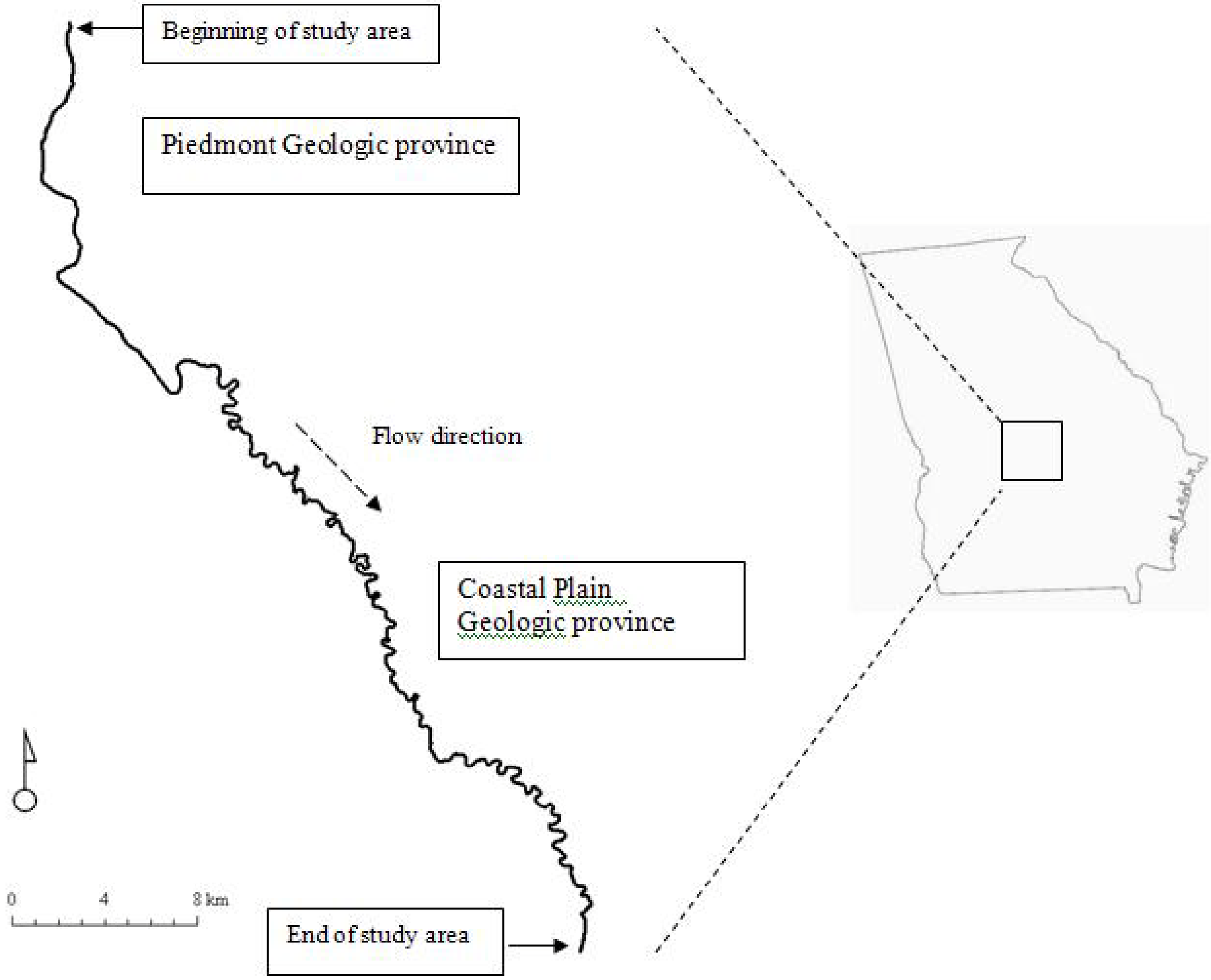

Figure 2-1. Location of the study area: Oconee River, GA

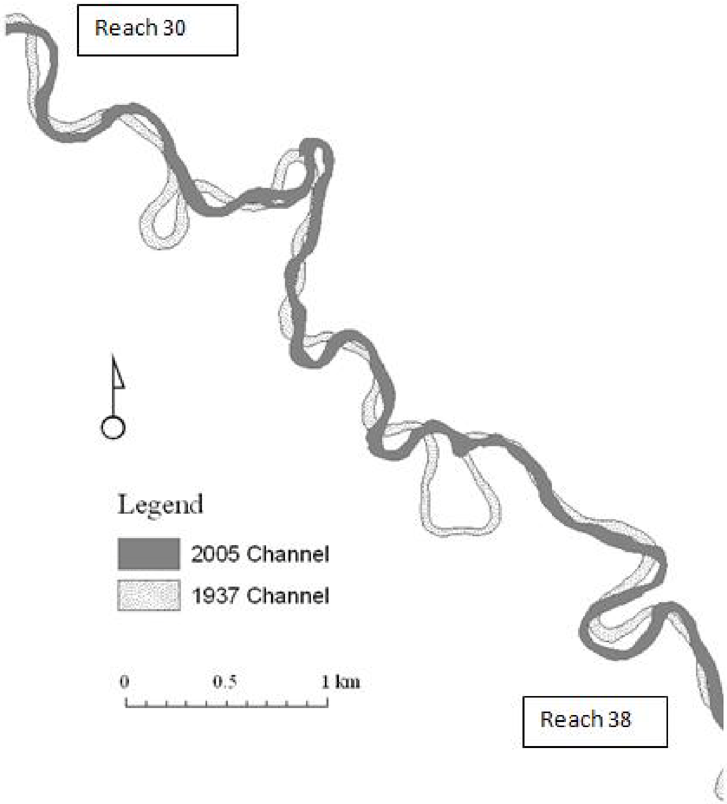

Figure 2-2. 1937(T_1) and 2005 (T_2) channels overlaid before change polygon creation. River reaches shown are from 30 km to 38 km.

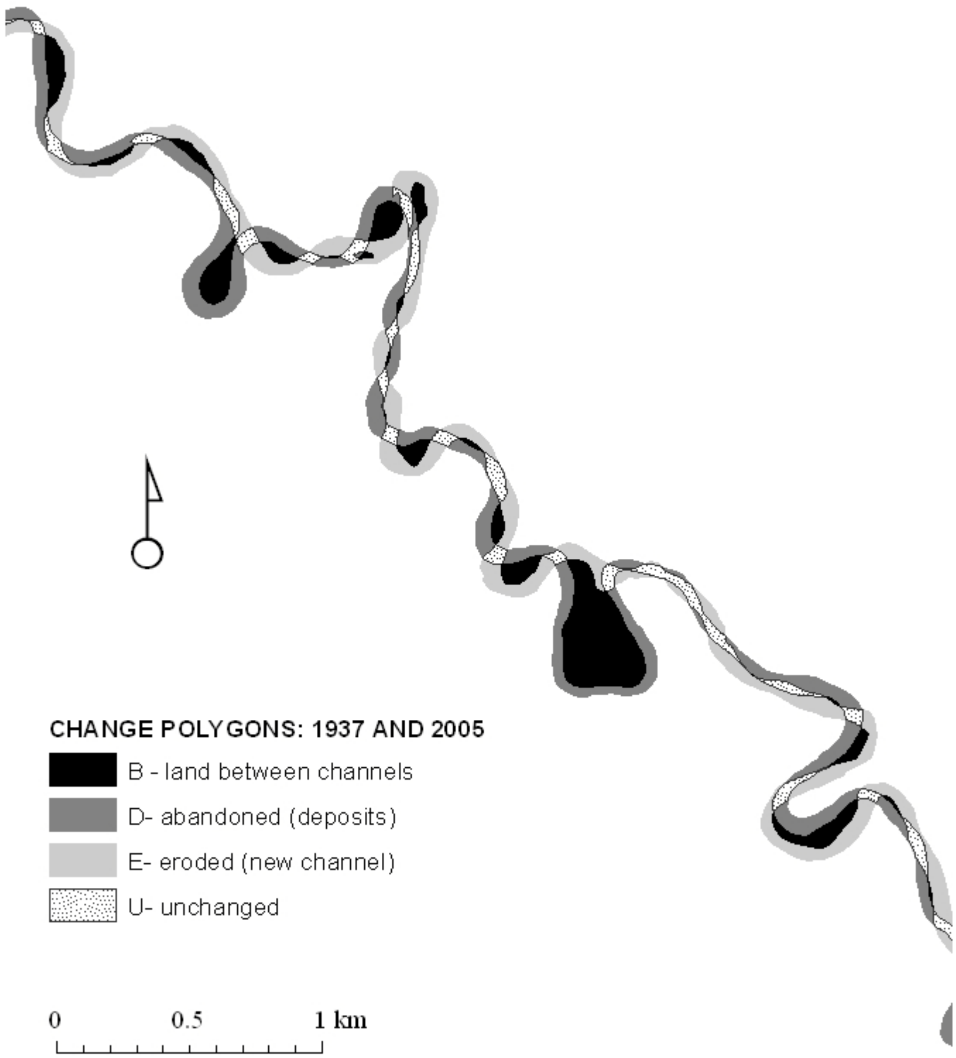

Figure 2-3. Change Polygons created from 1937 (T_1) and 2005 (T_2) channels. River km 30 – 38.

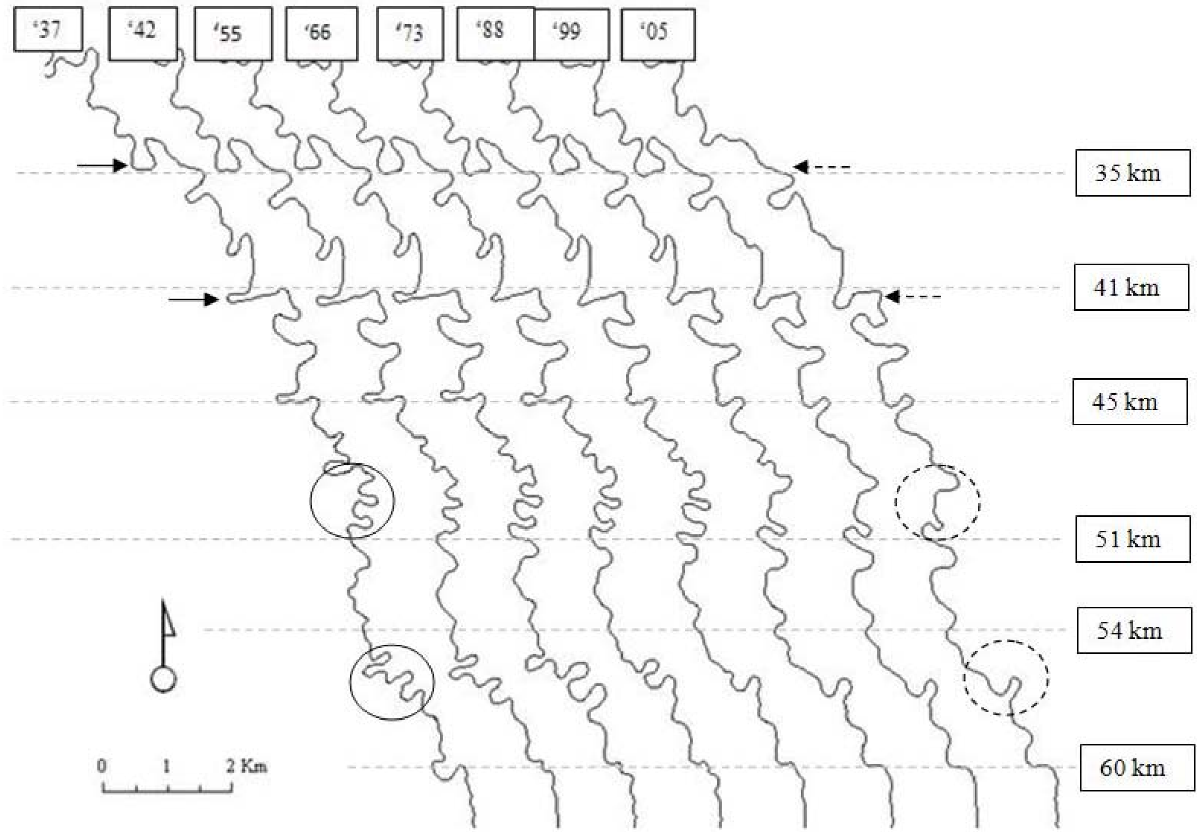

Figure 2-4. Planform view of centerlines: Oconee River, 1937-2005 for part of the study area (from 31 km to 63 km). Horizontal lines show selected distances downstream of the dam.

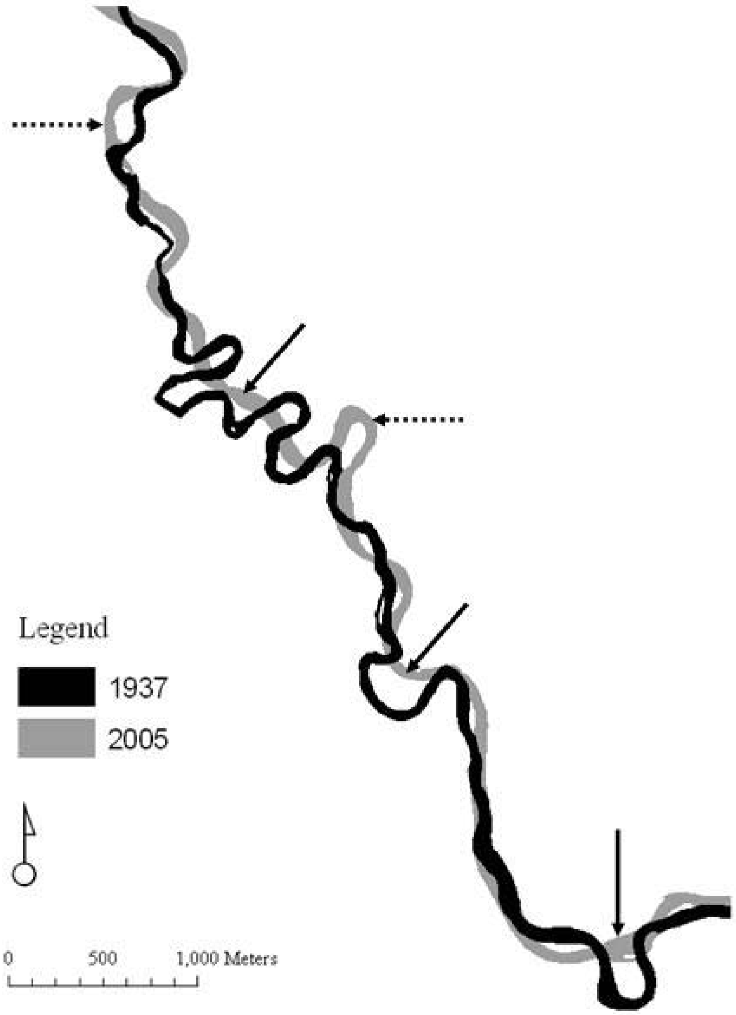

Figure 2-5. Digitized channels of section of the study area from 1937 and 2005 showing channel movement. Dotted arrows show channel movement through lateral migration. Solid arrows show cutoffs (less sinuosity than previous channel). River km 51 – 61.

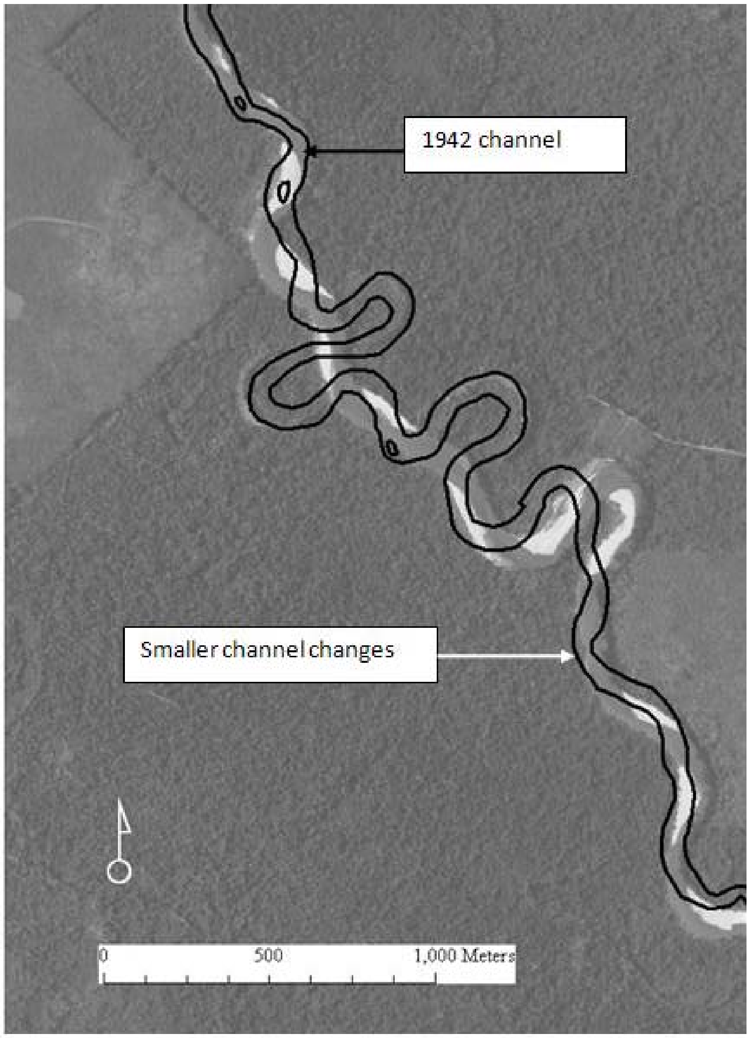

Figure 2-6. Reaches of the Oconee where radical and smaller changes occurred (white arrows denote radical changes): 1942 (digitized) and 2005 (photograph) channels. River km 52 – 57.

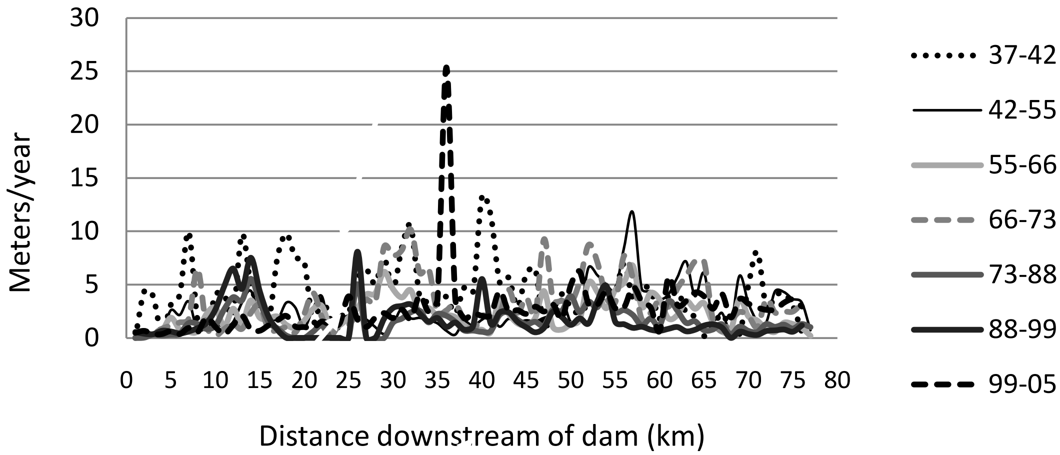

Figure 2-7. Lateral migration rates: 1937-2005

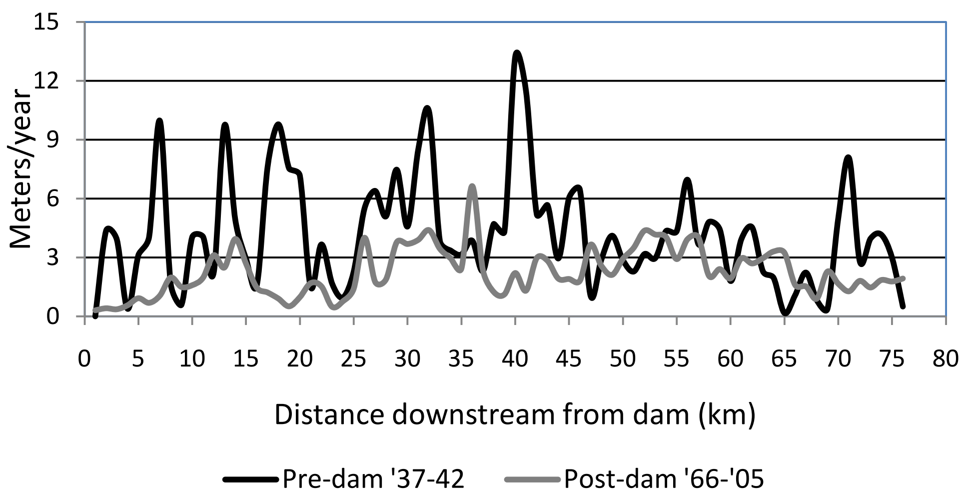

Figure 2-8. Lateral migration rates: Pre-dam (1937-1942) and Post-dam (1966-2005)

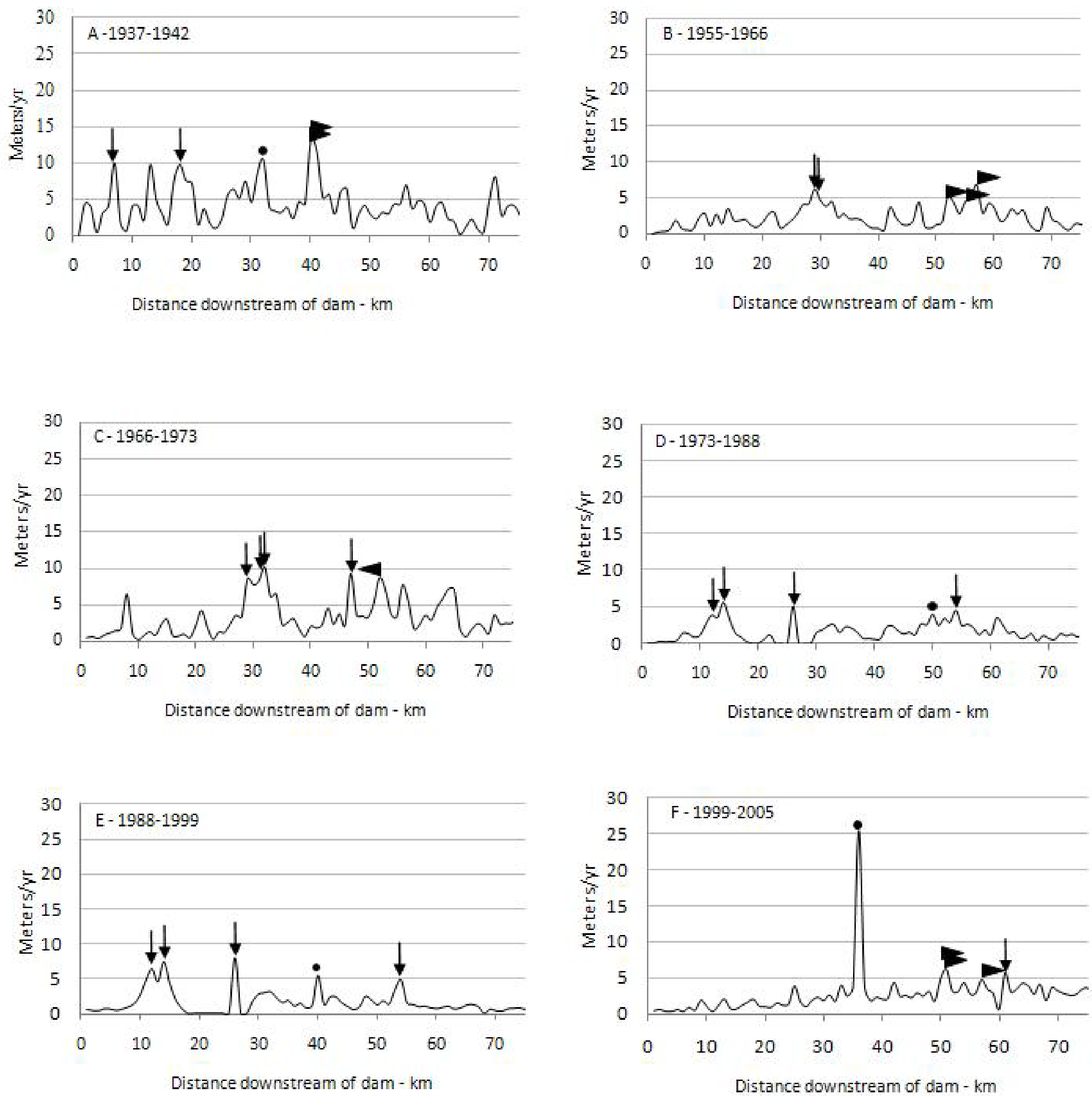

Figure 2-9 A to F. Lateral migration rates - LMR (meters per year): Pre-dam (1937-1942) and Post-dam (1955 to 2005) showing reaches where top 5 LMR occurred

Downstream migration of channel: ► Cutoff occurrence: ●

Upstream migration of channel: ◄ Lateral shifting of channel: ↓

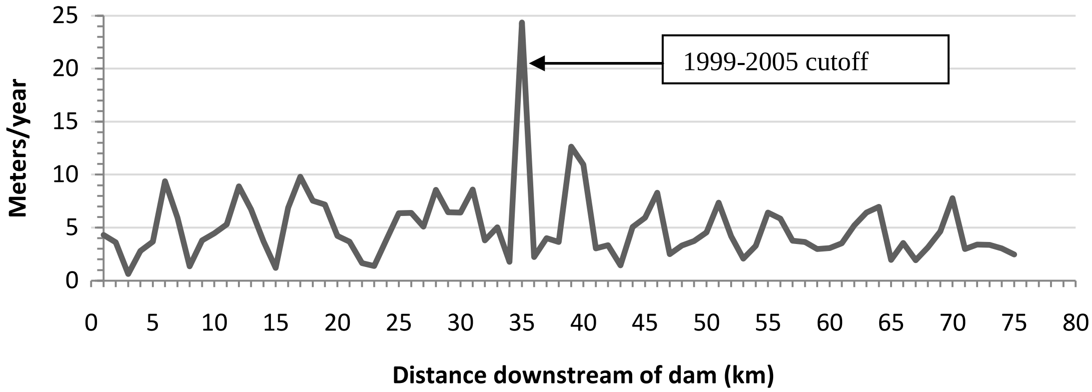

Figure 2-10. Range of lateral migration rates per reach

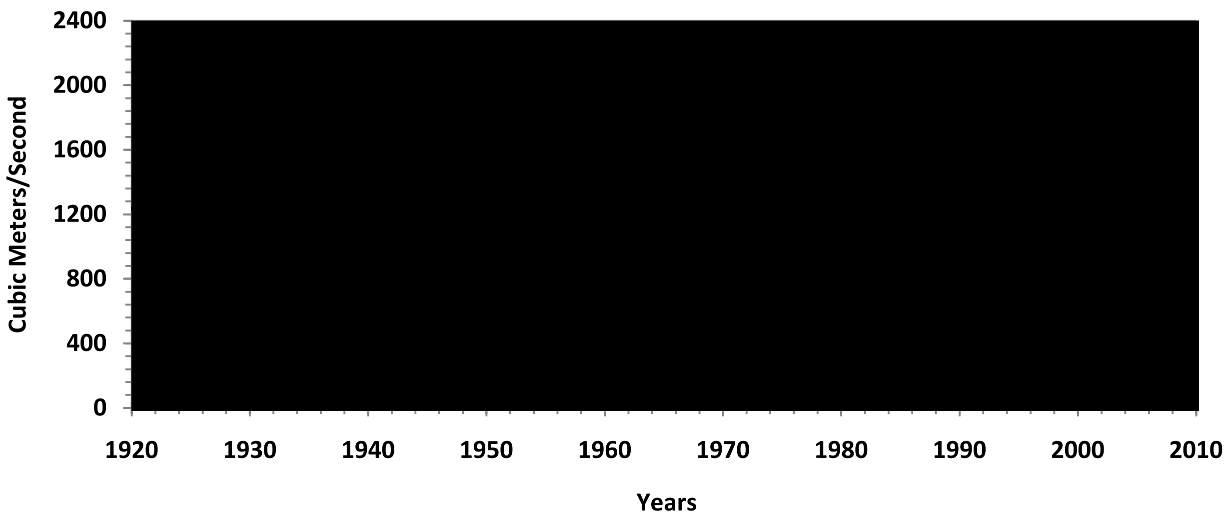

Figure 2-11. Streamflow data: Oconee River – 1920 to 2007. Vertical dotted line denotes date when Sinclair Dam closed. Horizontal dotted line denotes flood stage (8.2296 m). Stream gauge: 02223000 (Oconee River at Milledgeville, GA (USGS)

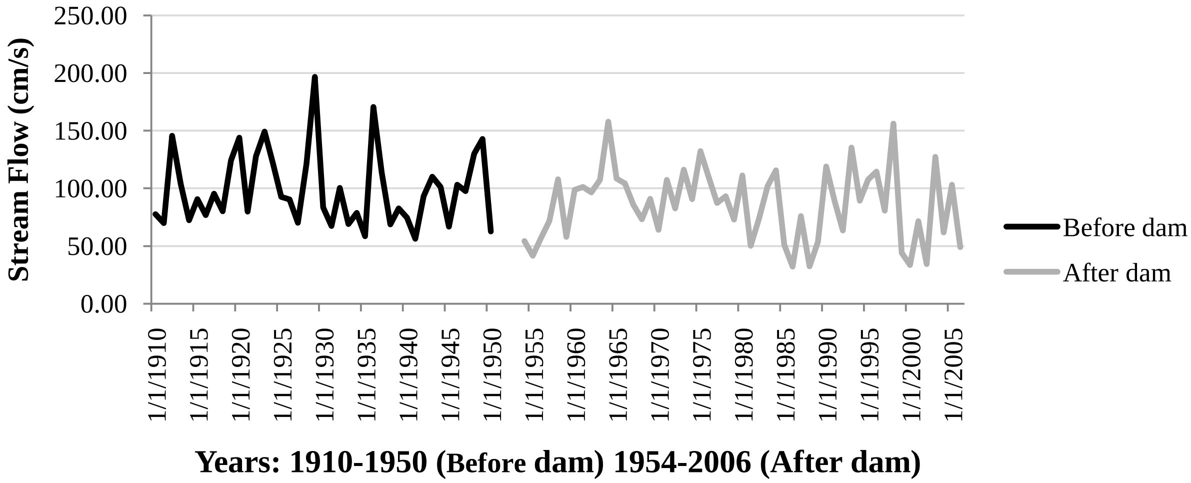

Figure 2-12. Annual Average Flow: Before dam (1910-1950) and After dam (1954-2006)

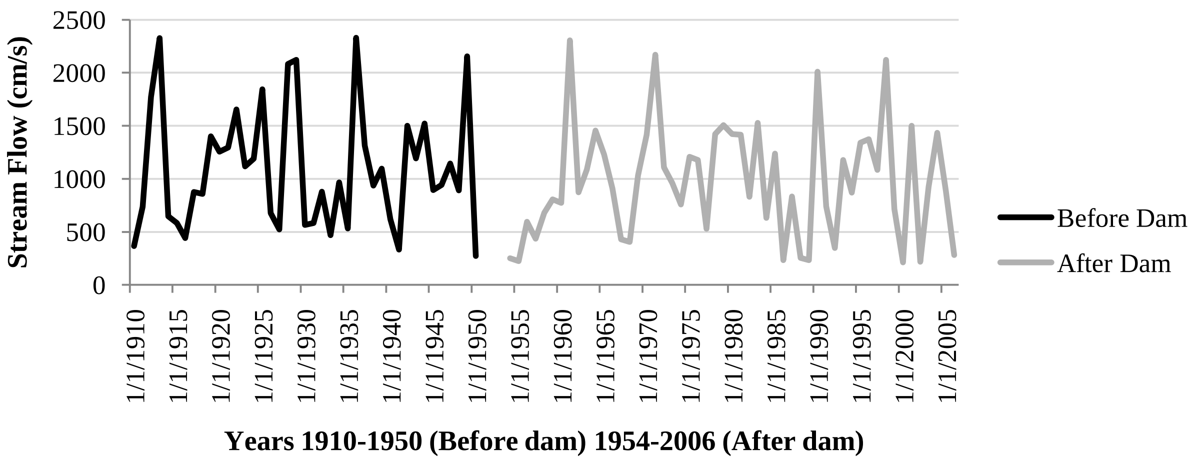

Figure 2-13. Annual Maximum Flow: Before dam (1910-1950) and After dam (1954-2006)

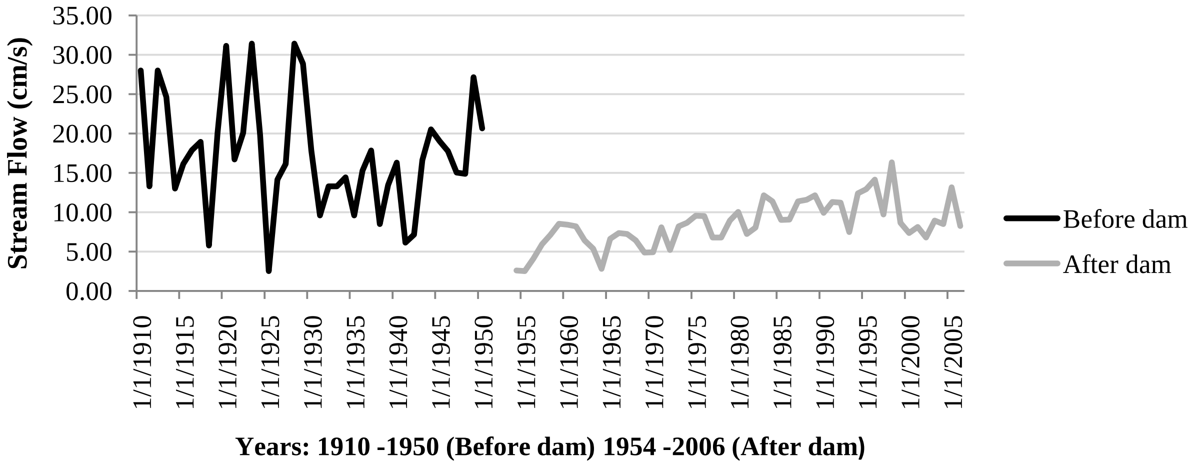

Figure 2-14. Annual Minimum Flow: Before dam (1910-1950) and After dam (1954-2006)

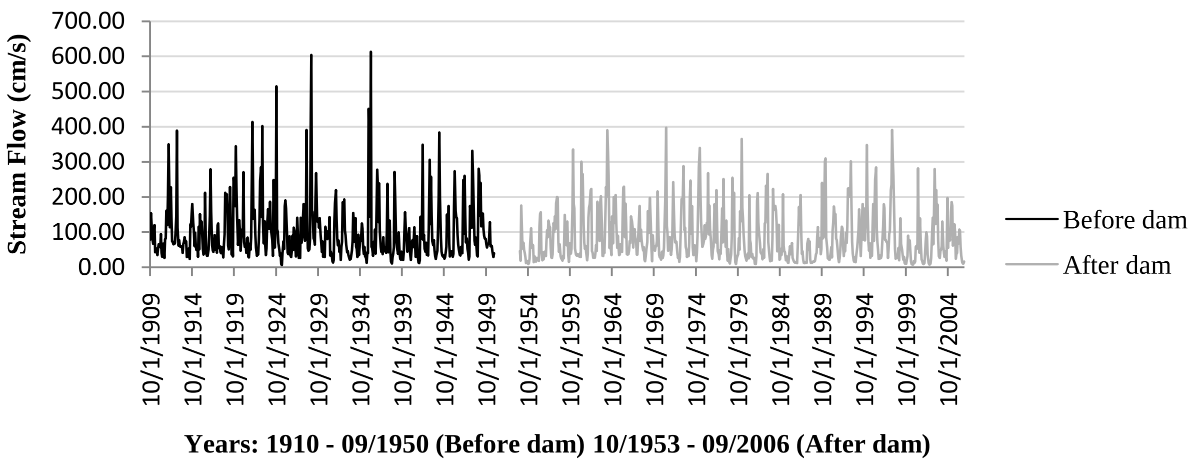

Figure 2-15. Monthly Average Flow: Before dam (1910-09/1950) and After dam (10/1953-09/2006)

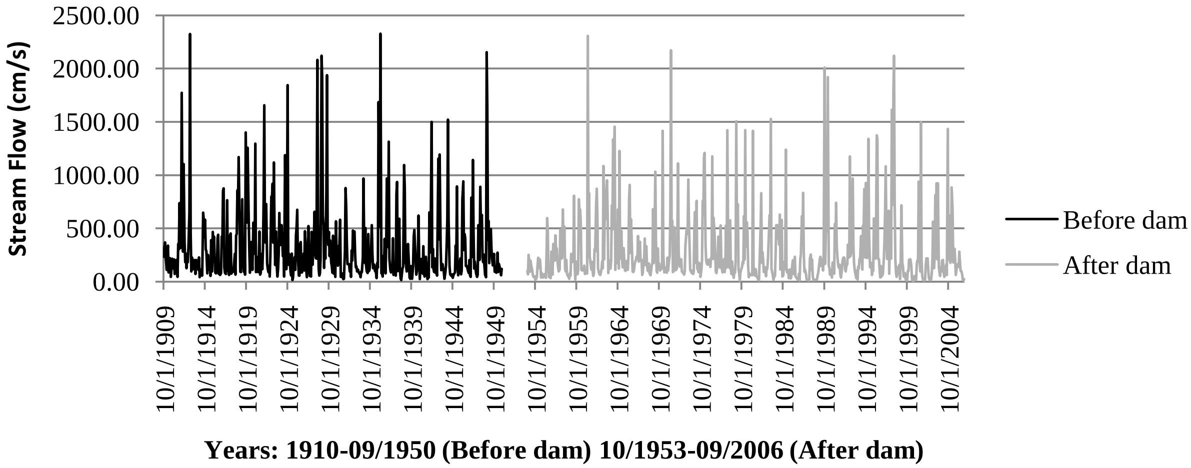

Figure 2-16. Monthly Maximum Flow: Before dam (1910-09/1950) and After dam (10/1953-09/2006)

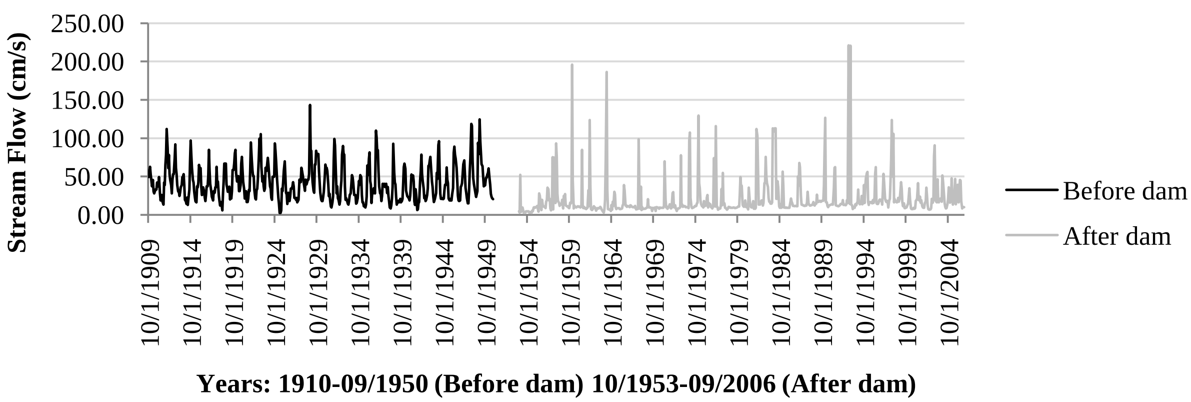

Figure 2-17. Monthly Minimum Flow: Before dam (1910-09/1950) and After dam (10/1953-09/2006)

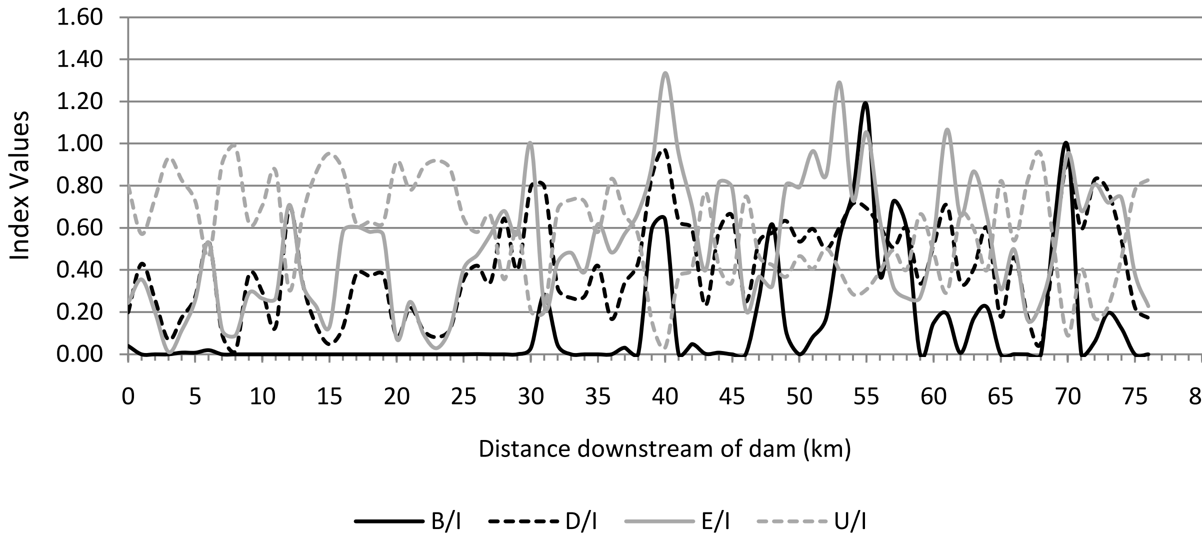

Figure 2-18. Proportional area change ratios: Pre-dam

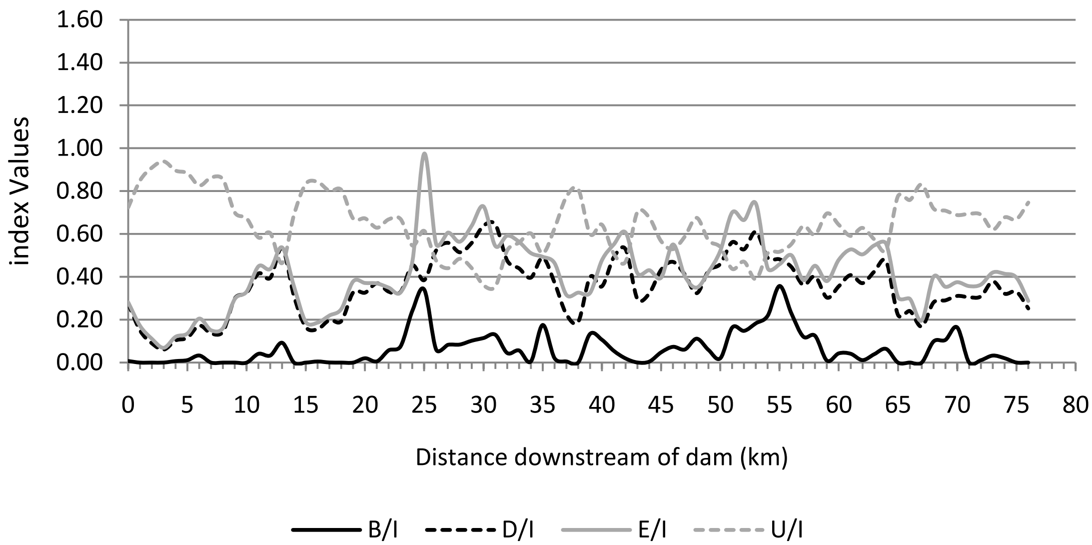

Figure 2-19. Proportional area change ratios: Post-dam

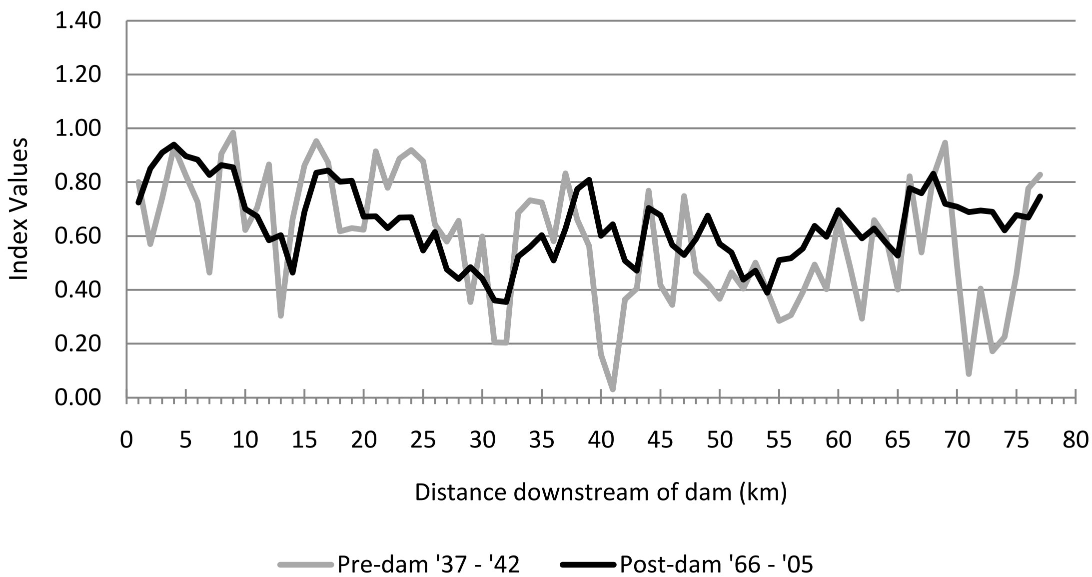

Figure 2-20. Proportional area change ratios: U/I

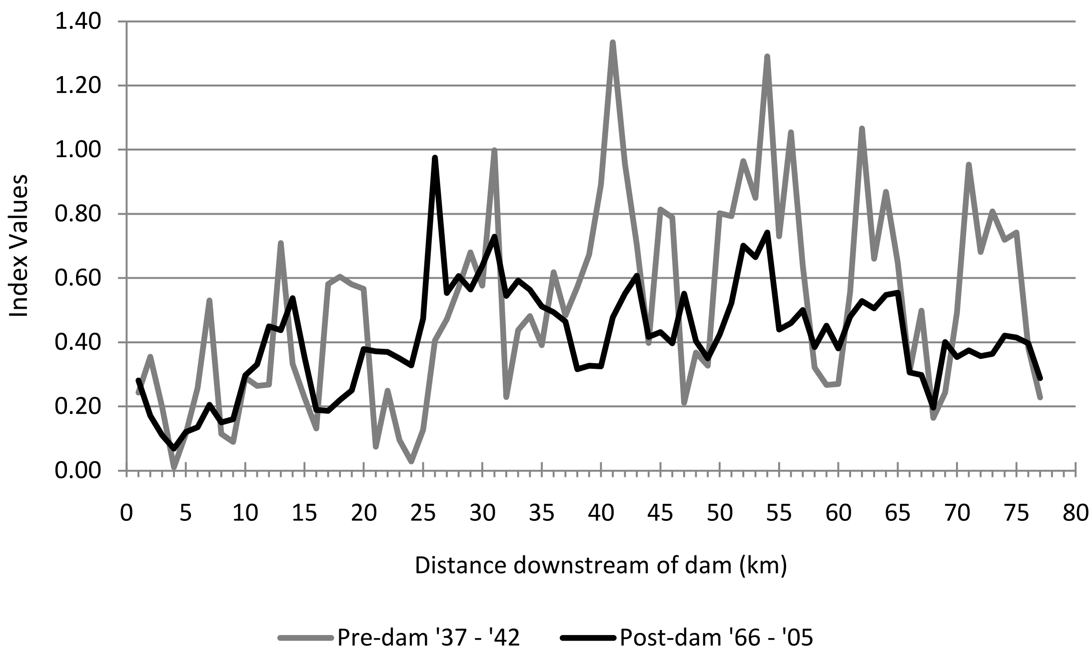

Figure 2-21. Proportional area change ratios: E/I

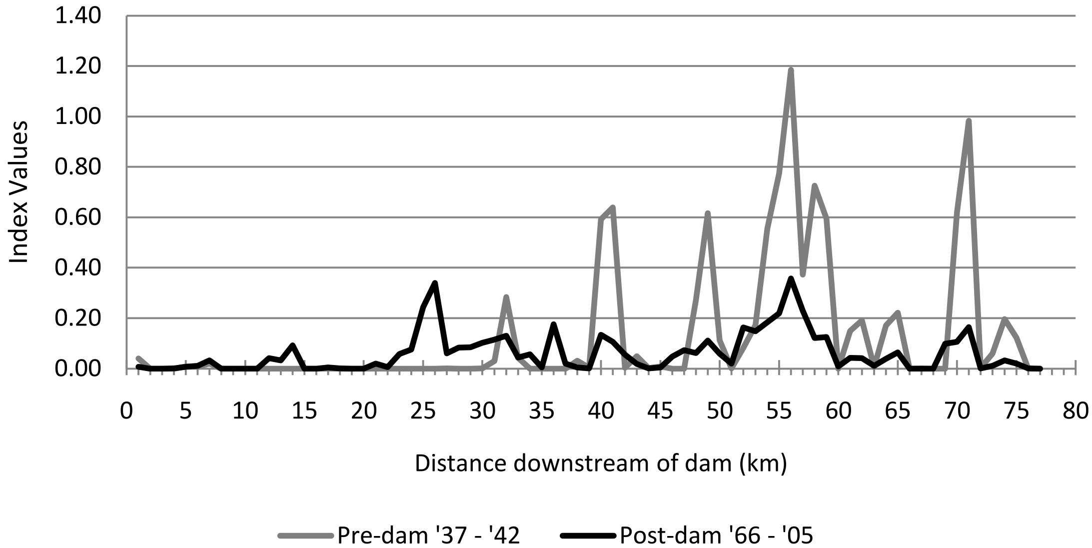

Figure 2-22. Proportional area change ratios: B/I

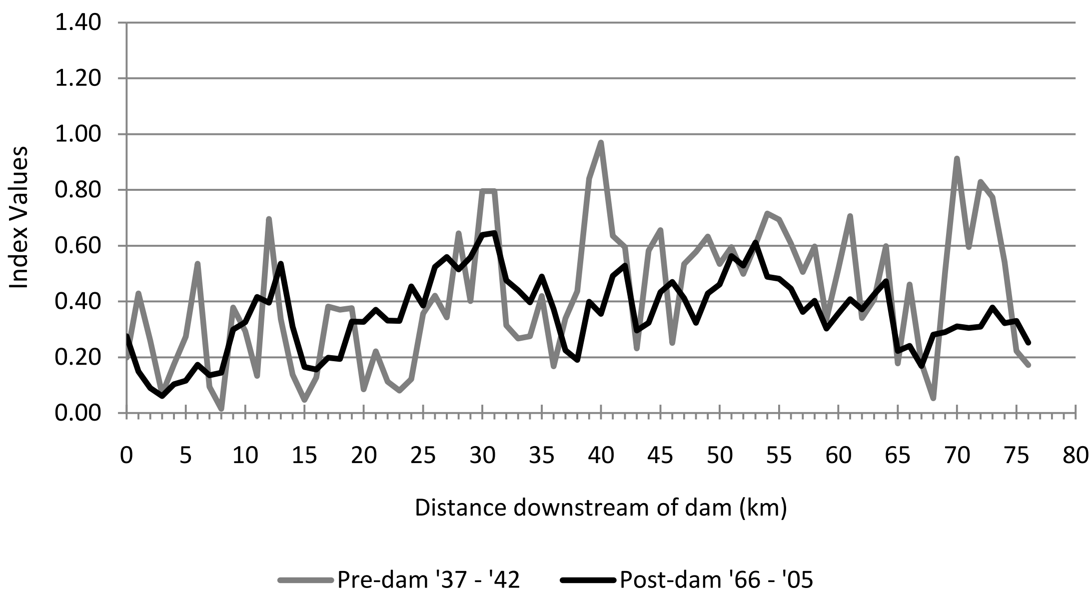

Figure 2-23. Proportional area change ratios: D/I

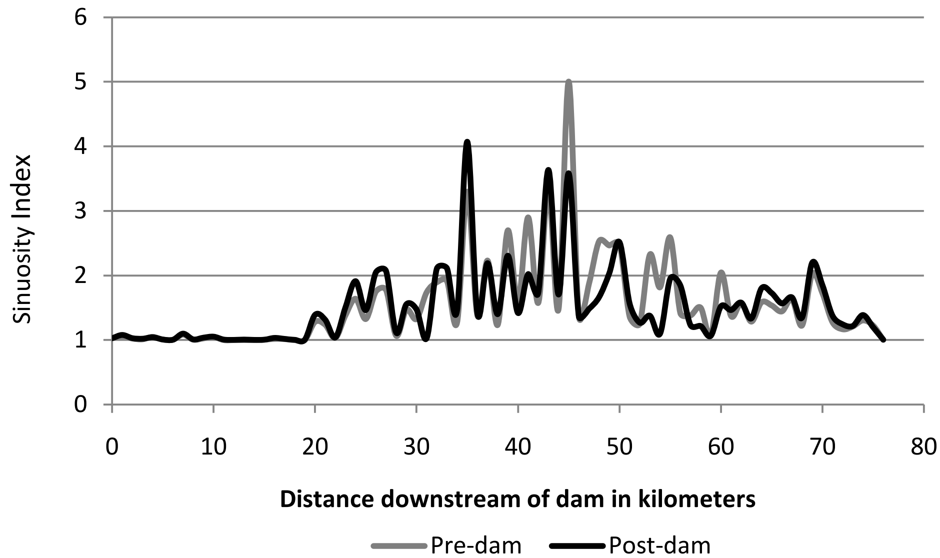

Figure 2-24. Sinuosity indexes (SI), pre-dam and post-dam

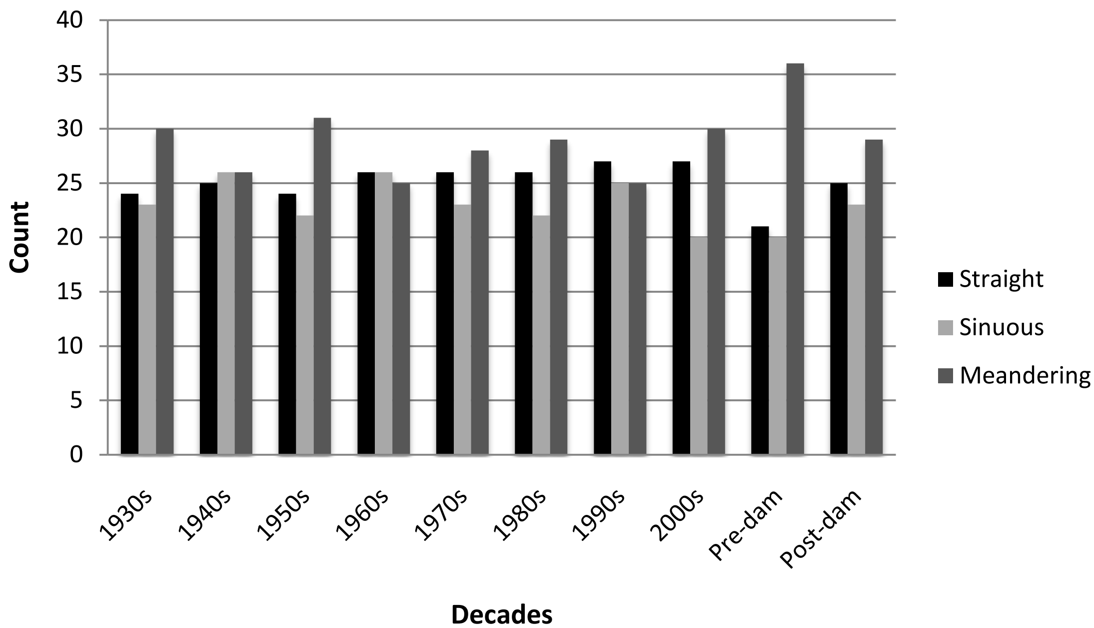

Figure 2-25. Classification of stream reaches in study area using SI: straight (1-1.1), sinuous (1.1 – 1.5) and meandering (greater than 1.5).

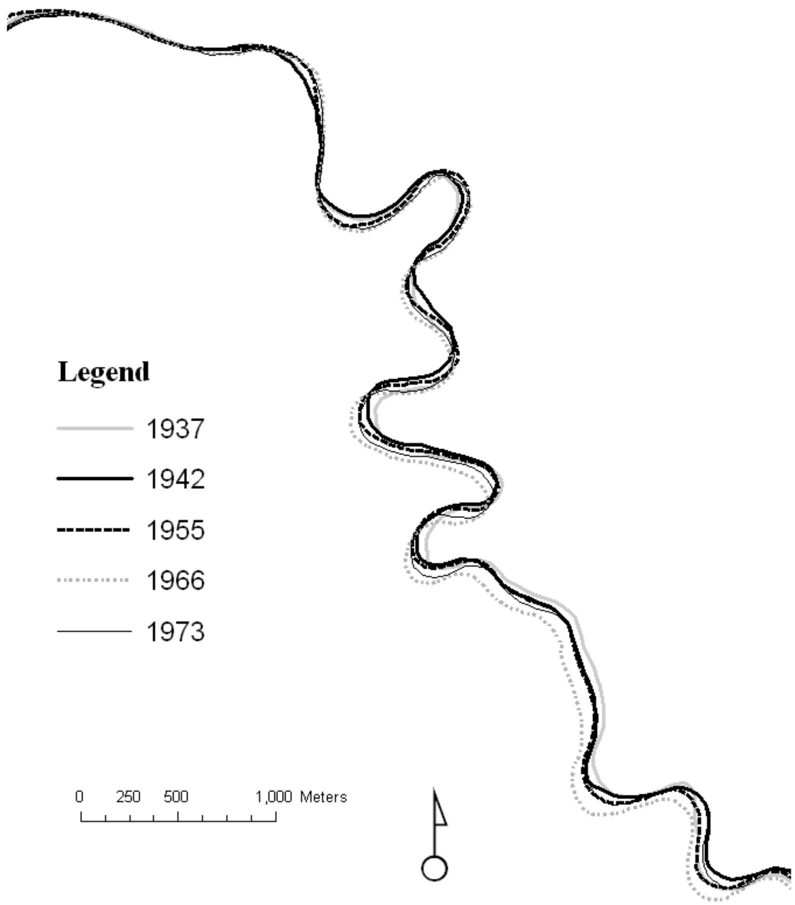

Figure 2-26. Oconee River channel centerlines – 1937 to 1973, from km 21 to 30, illustrating reaches that may be classified as sinuous and meandering

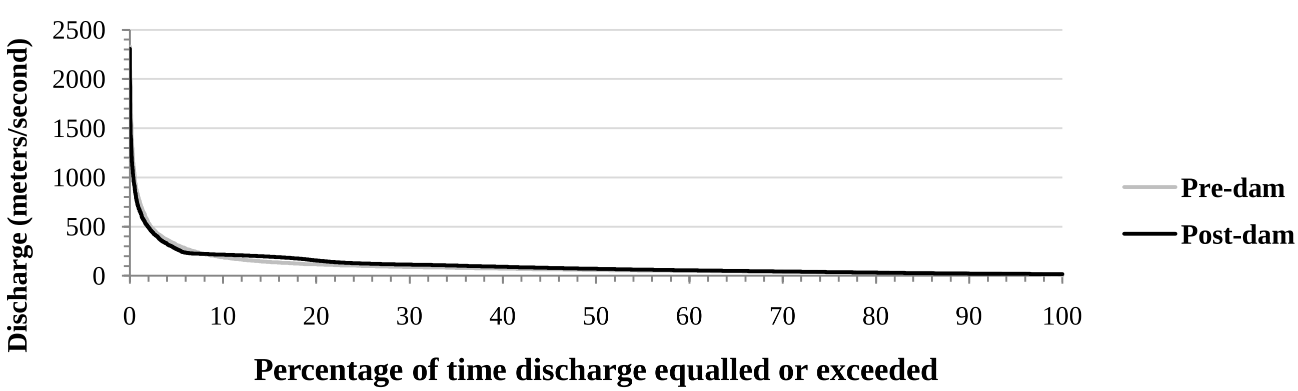

Figure 2-27. Streamflow duration curve: Oconee River, pre-dam (1910-1950) and post-dam (1954-2006).

CHAPTER 3
LATERAL MIGRATION OF THE OCONEE RIVER: PIEDMONT VERSUS THE COASTAL PLAIN

Introduction

A river's planform and the pattern it creates as it moves or migrates across the landscape are best observed from the air (Gurnell, 1997; Lewin, 1977). Although quite rare, some naturally occurring channels are described as being straight (Leopold et al., 1992; Charlton, 2008). Most channels, however, wander across the landscape and assume a variety of forms and configurations (Leopold et al., 1992; André, 2003). The degree to which this lateral movement occurs is a result of the complex relationships between sediment supply, stream flow and channel geometry (Montgomery and Buffington, 1998).

The planform movement of a river channel across the landscape or the snakelike pattern is also called meandering. The erodibility of the banks and the motion of water through a river channel are important in the degree of sinuosity of a meandering river (Knighton, 1998; Richards, 2004). A meander or bend in the river grows as the outer or concave bank is eroded with corresponding deposition occurring on the inner or convex bank (Hickin and Nanson, 1984; Williams and Wolman, 1984; Carson, 1986; Leopold et al., 1992; Wellmeyer et al., 2005).

As a river migrates through and across the landscape, it deposits materials and as it migrates it erodes and deposits sediments from previously deposited material or alluvium (Hickin, 1974; Jacobson and Gran, 1999; Simon and Thomas, 2002). This activity takes place in the floodplain which is a relatively flat feature that is adjacent to the river channel.

Floodplains become storage units of eroded material from catchment basins (Richards, 2004). The river in essence erodes its own floodplain. The nature of the eroded material or alluvium largely determines the nature of the course of a river as it flows through it. Therefore a floodplain that is composed of material that is easily erodible tends to have wider and shallower channels that migrate laterally, while floodplains with more resistant erosive materials, tend to be migrate less, with narrower, steeper banks (Mount, 2005).

Richards (2004) describes rivers that create these floodplain deposits as self forming alluvial river channels. These processes that take place within these floodplains are determined by a number of factors such as the river's flow, the amount, type of and nature of the sediment that make up the bed and banks of a river channel

These channel adjustments are constrained and modified by local factors such as the nature of the river valley, and the resistance of the bank materials to erosion and the vegetation present on the banks. Therefore, the nature of non-cohesive materials such as sand and cohesive material such as clay is important in determining the degree of bank erosion. In addition, non-homogeneities of bank material for a single river also determine the nature of channel form (Richards, 2004). In the case of the Luangwa River in Zambia, meander development was controlled by the amount of spatial variation in the materials that made up the river banks (Gilvear et al., 2000).

The rate of channel erosion is not just confined to the banks but also the nature of the bed material. Alluvial channels are those that are formed from sediment that was previously deposited by ancestral/former rivers in the valley floors while bedrock channels are those that are cut from the bedrock lying beneath the channel (Charlton, 2008). In most bedrock channels, when rock is removed it is not replaced.

Alluvial channels unlike bedrock channels, maintain their morphology even while aggrading, degrading and migrating while bedrock channels do not self repair nor conserve morphology (Tinkler and Wohl, 1998). A single river may have some reaches comprising of bedrock and some of alluvial material and some with a combination of both bedrock and alluvial material. River channels therefore, may be viewed as a continuum with bedrock and alluvial channels being the end points (Ashley et al., 1988)

One particular control on channel processes is the degree of or the way in which it is confined because of the nature of the valley in which it occupies (Charlton, 2008). Valley confinement of a river channel is defined by its measurement of the width of the historic banks of the river over a particular time span (Fotherby, 2009). Another definition for valley confinement is based upon the degree to which natural or unnatural impediments encroach upon meanders in such as way as to distort their natural tendency to develop freely due to spatial constraints (Lewin and Brindle, 1977).   In a confined valley, the topographic features such as the valley walls limit the path of a river as it influences the way the channel responds.   For this reason, channel migration and avulsions seldom occur in these confined settings (Montgomery and Buffington, 1998).

Fundamentally, an alluvial river having banks and a bed that are composed of malleable material such as sand would adjust more easily than one where the channel substrate is primarily bedrock (Charlton, 2008).   Although some bedrock channels may mimic or have some characteristics common to alluvial channels, their basic channel forms and morphologies are dependent upon or restricted to the lithologies and structures of the underlying rocks (Richards, 2004).

Some riverine ecosystems are better understood in the context of river channel changes across the landscape and how these rivers respond to changes in flow and sediment deliveries (Graf, 2006). The health and existence of stream invertebrates are linked to the repositioning of streams when they migrate or change positions within their floodplains (Burge, 2005; Grams and Schmidt, 2005; Gordon and Meentemeyer, 2005; Choi et al., 2005). This includes the structures of riparian ecosystems as well (Larsen and Greco, 2002). The habitats of larger species such as salmon are affected by changes in riverine environments as well (Ligon et al., 1995; Marston et al., 2005). Larsen et al. (2002) and Beechie et al. (2006) link some processes that govern biodiversity in floodplain ecosystems with the behavior of channel change in rivers. In the context of land management and planning, rivers that migrate across floodplains present some difficulties and challenges as efforts are made to protect agricultural holdings and other urban infrastructural developments (Larsen and Greco, 2002; Gupta and Liew, 2007), property loss and implications for flooding (Richard et al., 2005), engineering schemes (Thein, 1994) and the foundations of bridges (Kondolf et al., 2002).

Channel migration across the landscape is in some ways indicative of a channel's stability (Graf, 1981; Knighton, 1998; Simon et al., 2002; Hooke, 2003; Richard et al., 2005) and the degree of channel planform change is indicative of the sensitivity of a river system as it adjusts to various disturbances within the fluvial system (Hooke, 1995). These are issues that are important in understanding conceptual models for channel change (Grams and Schmidt, 2002), along with implications for interpreting how rivers respond to changes in the environment (Tooth et al., 2004).

However, it is the recognition and inclusion of the role of different geologies that control the movement of river across its landscape that places the study of river planform change in a broader context. The study of river planform change that includes geological barriers such as rocks that are difficult to erode, and not only alluvial environments, provide key information for testing theoretical models for long term changes in the fluvial landscape (Tooth et al., 2004). In fact, geology can play a dominant role in the nature of river channel activity as if affects alluvial channel change (Tooth et al., 2002).

Aim and Background

Stream flows and sediment are key factors that determine the geomorphology of alluvial streams as discussed by various researchers (Graf, 1980; Petts, 1984; Shields et al., 2000; Choi et al., 2005; Petts and Gurnell, 2005; Gregory, 2006).

Since the form of alluvial channels is maintained by the adjustment of the hydraulic and sedimentary controls, a river is said to be in equilibrium if the forces that control the flow of water is balanced by the resistance to erosion by the sediments (Ferguson, 1977; Richards, 2004). A river in equilibrium would reflect a balance between these two forces and the constant adjustment that a river makes to its cross section is in response to the need to maintain a state of equilibrium (Mount, 1995). As a river flows through its channel, the bed and banks of the channel experience shear stress. Shear stress is defined as the force per unit area that is exerted by the river (André, 2003; Leopold, 2004).

Equilibrium is achieved if the shear stress experienced by the banks and bed of the river is counterbalanced by the ability of the bank to resist the shear stress or force (Leopold, 2004). A section of a stream channel therefore, is a reflection of the interaction between two variables, force and resistance. Channels that migrate or shift laterally maintain the constant form of their cross sections through eroding one bank and depositing sediment on the opposite bank (Leopold, 1994). Since the Oconee River is located in different geologic provinces having material that should erode at very different rates, lateral migration rates and the degrees of equilibrium ought to be influenced by the rates of erosion that should take place within each geologic province.

The aim of this paper is to 1) determine the importance of geology and its influence upon the rates of planform migration of the Oconee River and 2) to compare how the influence of the Piedmont province differs from that of the Coastal Plain province upon the planform change of the Oconee River. In 1953, the Sinclair Dam on the Oconee River was closed with Lake Sinclair being created. The lake has 671 kilometers of shoreline and an area of 6204 hectares although this varies with the changes in the water level. The dam was built to generate electric power. The dam is not used for the practice of flood control and all but the most minute sediment particles are trapped behind the dam.

Since dams act as effective sediment traps, with some examples as much as a 99.2% trap efficiency (Williams and Wolman, 1984) and in varying degrees modify the flow discharge of rivers (Knighton, 1998; Shields et al., 2000; Choi et al., 2005; Graf, 2005), it is expected that channel behavior below dams would be altered to reflect these changes. These changes range from a reduced lateral migration rate to the adjustment in the width of the channel through widening or narrowing (Shields et al., 2000) to an increase in sinuosity (Richard, et al., 2005).

The physiographic settings of the Oconee River provide the opportunity to test the hypothesis that the Sinclair Dam is not the only factor that influences the degree and rate of planform change of the Oconee River that occurred downstream of the dam. The paper hypothesizes that in addition to the effects of the Sinclair Dam, geology plays an important role in determining the degree and rate of planform change of the Oconee River. Changes that take place in channel shifting occur gradually with consistent movement over time (Hooke, 1977). The examination of these channel changes will be done for both geologic provinces in order to make comparisons about the possible influences that each geologic province may have upon differences in channel planform rates of change. An explanation of river planform patterns must take into account the geologic history and geomorphology of the river channel since it is not just the interaction of hydrology and hydraulics that are important in determining planform change (Schumm, 1985).

Geologic Setting and Study Area

The study area is located in the Oconee River which is located in the Southeastern United States in the State of Georgia. The Oconee River flows from two headwater tributaries – the North Oconee River and Middle Oconee River. The natural vegetation type in this area is primarily pine-oak-hickory. These headwater tributaries join at a point just south of the City of Athens forming the Oconee River. The Oconee flows for about 548 kilometers until it reaches the confluence of the Ocmulgee River. The Oconee's drainage basin is 13,805 square kilometers. The Sinclair Dam was constructed on the Oconee in 1953 and is located approximately 230 km above the point where it joins the Ocmulgee River.

The study area is the section of the Oconee River that starts at the Sinclair Dam and ends at a point 75 km of the dam (Figure 3-1). This study area passes through two geologic regions, the Piedmont and the Coastal Plain provinces. The Sinclair Dam is located in the Piedmont Geologic province. The first 18 km of the Oconee River downstream of the Sinclair Dam are found within this province.

Topographically, the Piedmont province has rolling hills and comprises of Precambrian and older Paleozoic crystalline metamorphic and igneous rocks. It is composed of granites, gneisses, quartzites, schists containing biotite, phyllitic rocks and metavolcanic rocks. The Piedmont province is characterized by inactive fault zones and the surface stream patterns are dictated by these faults along with the joint patterns within the rocks (Lawton, 1977).

In the Piedmont province, the Oconee River valley is narrower with fairly steep sides. The valley becomes progressively wider as the river gets closer to the southern boundary of the Piedmont province. The valley widths (defined as the distance between the base contour lines) range from approximately 400 to 700 meters. The average gradient of the slope of the river valley from the Sinclair dam to the boundary that defines the Piedmont province is 0.000287.

Figure 3-2 shows the river valley that is found within this province. The closer contours depict steeper valley sides while wider contours depict valley slopes with gentler gradients.

These two regions are separated by the Fall Line. While the floodplains of rivers above the Fall Line are narrow or non-existent, those below the Fall Line are more developed and broad for sections of the rivers below the Fall Line (Lawton, 1977). Figure 3-3 shows a contour map of a section of the Oconee River that is located in both geologic provinces depicts relatively steep sided slopes in the Piedmont as against the wider, gentler valleys of the Coastal Plain province.

The Coastal Plain province is made up of Upper Cretaceous and Tertiary deposits that comprise primarily of sand, sandy clays and marls (Lawton, 1977). The rocks in the Coastal Plain province are less resistant to erosion and these account for the broader, non-confining valley giving rise to a distinct floodplain. Figure 3-3 shows the terrain that is typical of the Coastal Plain province. Here the river valley is wider giving rise to a well formed floodplain. The sinuosity of the Oconee is greater here with more pronounced meanders having complex forms. The average gradient of the slope of the river valley in the Coastal Plain province is 0.000284. Figure 3-4 shows the longitudinal profile of the Oconee River found within the study area.

Materials and Methods

Primary data were obtained from aerial photographs of the study area. The photographic images were from the following dates: 1937, 1942, 1955, 1966, 1972/3, 1988, 1999 and 2005. For the 1970s, photographs for Baldwin County were from 1973 while photographs for Washington County were from 1972. All calculations were adjusted to reflect this. From here on, the date 1973 will be used. The rate and degree of planform change was measured from these photographs and this approach to obtain spatial data has been used extensively by several researchers (Thorne and Lewin, 1979; Nanson and Hickin, 1983; Gurnell, 1997; Graf, 2000;

Gilvear, 2000; Rumsby et al., 2001; Gaeuman et al., 2004; Tiegs and Pohl, 2005; Richard et al., 2005b; Burge, 2005; Hooke, 2006).

With the exception of the 1999 and 2005 images (which were pre-processed and already geo-rectified), all were paper photographic images that were first scanned at 508 dots per inch using a flat bed scanner. The images were then processed and converted to a usable format. This was done by geometrically correcting the images in order to view all the planimetric features on the images on a common projection (Jensen, 2005). The images were co-registered using available 2005 Digital Ortho Quarter Quads (DOQQs). This process converted the images to a common scale and helped reduce errors (Gurnell, 1997; Hughes et al., 2006). A mosaic of the images for each year was created. These processes were performed using the ERDAS Imagine software.

For each year of photographic data, the left and right bank channels of the stream along with the lateral and point bars were digitized. The centerline of the channel was also demarcated using the midpoint tool in the ArcGIS software. There were eight decades of information derived from the aerial photographs.

Area Reworked and Rate of Migration:

Larsen et al. (2002), Larsen et al. (2004) and Micheli et al. (2004) used this method to determine two values, the area of land reworked and the lateral migration rate. The first value refers to the amount of land that was eroded or deposited through migration of the river over a period of time. This area is derived by overlaying the center line of the river in one time period with the centerline of the same river for another time period. The polygon that is created by the intersection of these two centerlines is then divided by the difference in years between the two centerlines. This value gives the area (calculated in hectares) of land that is reworked per year.

This rate is then calculated for each reach block of the study area. Each reach block is 1 kilometer in length.

The rate of migration for each year and for each reach of the study area is calculated by dividing the area reworked by the average length of the two centerlines that represent the river at different time periods and then dividing this result by the number of years between the time periods. This average rate of channel migration per year is also calculated for each reach block. The formula for this is as follows: [(Ar/L)/# years], where Ar is the area reworked for a given reach block; L is the average channel length of the two centerlines for the same reach block. A summation of all the results for all the reach blocks allows for comparisons between the total lengths of the stream for different years.

The stream centerlines were digitized and the results were derived for each reach block for the entire length of the stream. This allowed for comparative analysis for the reach blocks that were found in the portion of the Oconee River that was in the Piedmont province and the other portion that was found in the Coastal Plain province, as well as for varying distances downstream of the dam and at different years.

Measurement of the Degree of Sinuosity:

Sinuosity is used as an indicator of how much the river has meandered or curved within the floodplain. It then became possible to compare stream sinuosity temporally and spatially. The channel centerline was used as the channel center length in the calculation of the sinuosity index (SI). The SI was calculated for each of the 1 kilometer reach blocks and like the analysis of the lateral migration rates, the SI were divided into similar categories.

Proportional Area Change Ratio – Area between Channels:

This method compares the location of the river channel between different time periods. The digitized channel from one year is overlaid upon the digitized channel of another year and the sections of the two channels that overlap show which portions of the floodplain have been occupied by both channels. This allows for comparisons for both before and after the closure of the dam as well as for reaches found within the two geologic provinces (Mossa, 2006).

Results and Discussions

Sinuosity: Piedmont versus Coastal Plain

Figure 3-5 shows sinuosity indexes (SI) for the study area from 1937 to 2005. The SI are separated into the Piedmont and Coastal Plain geologic provinces. The data are also presented in two categories – before and after the Sinclair Dam was closed. The indexes for both pre- and post-dam eras are averages for the SI for all the times provided by the aerial photos. For the first 18 km, the SI is close to 1 for both the pre- and post-dam eras with little difference between the two periods along the reaches of the river. A SI of 1 or close to 1 indicates that a river in relation to its valley is straight. The first 18 km of the river are found within the Piedmont Geologic province. These small differences between the SI for both the pre- and post-dam eras proves that the river over time varied very little in its position in relation to the general orientation of the river valley.

The reaches of the study area that are beyond the fault line (that is, from the 18 km mark onward) show that very few reaches had SI at 1 or close to 1. Clearly, the most sinuous reaches of the river are located in the Coastal Geologic province. This departure of the SI from 1 in the Coastal Plain province is the similarity between sinuosity for the pre- and post-dam era. Figure 3-5 also shows that there are a few places where the SI are the same for both pre- and post-dam eras. Channel straightening that accompanies cutoff formation accounts for some of the major differences in the SI for the pre- and post-dam eras. For instance, at kilometer 44 and 45, a cutoff was created between 1966 and 1973 with the result that all the channels from 1973 to 2005 were far less sinuous than the 1937, 1942 and 1966 channels. This is illustrated by Figure

3-6. Figure 3-7 shows the same section of the river with the 2005 image with the cutoff that was created between 1966 and 1973 clearly marked by an arrow. That section of the 2005 channel represents a newer, straighter course of the river with a marked decrease in sinuosity having become straighter from the pre-cutoff channels.

Sinuosity, however, is not necessarily an accurate indicator of a river's stability. This is so because a section of a river may be quite sinuous over the course of several decades with the river in that section remaining in the same position over time.   Figure 3-8 shows the channel centerlines for the pre-dam era in bold black lines and the post-dam channel centerlines in bold grey, along a section of the river from reach 23 to 28. Although the SI along these reaches for the channels are not exactly the same, the positions of the channels relative to each other are not strikingly dissimilar.

Figure 3-9 shows a sequence of photographs at reach 35 showing the development of a cutoff.   All the main channels of all other times follow the outline or form of the cutoff while the 2005 main channel follows the newly avulsed channel with the right bank of this channel forming the neck of the cutoff. The separation of the main channel from the cutoff channel, though not totally complete, indicates that total abandonment of the older channel will eventually occur. The widest distance from the neck of the cutoff to the other side of the outer bend of the cutoff is provided by the 1999 channel while the shortest distance is provided by the 1937 channel. These distances are approximately 575 and 509 meters respectively.

This large shift in the channel's location accounts for the large change in sinuosity at reach 35. Furthermore, the loop that makes the cutoffs becomes progressively more pronounced over time, with the 1937 channel having the smallest loop with the widest neck while the neck of the cutoff becomes narrower over time. A meander loop becomes so developed in form that there was a progressive narrowing of the land between two opposite banks forming a narrow neck (Ferguson, 1977; Gay et al., 1998). This progressive narrowing caused by continued erosion and deposition is clear from aerial photographic evidence which shows the chronological shift of the opposite banks towards each other over time (Figure 3-9). Table 3.1 shows the progressive shortening of the distance of between the inner banks at the neck of the cutoff from 1937 to 1999.

Figure 3-10 shows the average SI for the sections of the study area that are found in the Piedmont and Coastal Plain provinces. For the Piedmont province, there is very little variation in the SI – none of which is higher than 1.02. Using the classification of types of streams based upon the range of SI, it would appear as if the section of river in the Piedmont province is straight. This, however, does not mean that the section of river within the Piedmont province has no turns or curves. Since SI are calculated by dividing channel length by valley length, it would be expected that the SI would be low if the channel and valley followed a similar course as shown in Figure 3-2. In this case, the Oconee River channel is confined to a relatively narrow river valley which is not straight but has turns and meanders across the landscape. A low SI of a section of a river would accurately indicate that the section in question is reasonably straight if that channel is in a locale that is free from restrictions or from the ability to move laterally.

Sinuosity indexes are therefore more applicable for describing channel river patterns in alluvial settings such as the case of the Oconee River in the Coastal Plain province. The use of the SI is therefore limited to some categories of stream channels and not adequate in providing an accurate description of the planform of rivers in some settings. The SI may therefore not be applicable for stream channel categories such as bedrock and semi-controlled as identified by Schumm (1985).

Overall, the average SI for the Coastal Plain province varied from decade to decade (Figure 3-10). The SI decreased from 1937 to 1942. The reason for this drop in the SI is that the river was actively eroding which resulted in three cutoffs causing the 1942 channel to become straighter and subsequently shorter. From 1942 to 1955, no cutoffs were created although some sections of the river that had a series of well formed, complex meander loops with the potential to create additional cutoffs.

The reason for this variation in sinuosity is because excessive sinuosity normally precedes the occurrence of cutoffs because the channel gradient is lowered and the stream's ability to transport material is considerably diminished (Schumm, 1985; Schumm et al., 1996; Knighton, 1998) and the avulsion is a response of channel's reduced efficiency (Schumm et al., 1996). Whenever cutoffs occur, the stream becomes straighter with its reduced sinuosity. The channel gradient then increases along with the stream's ability to transport material (Knighton, 1998). The corollary is that if a stream is too straight its banks will be eroded (Schumm, 1985).

Sinuosity and Equilibrium

A shortened stream through cutoff creation has the net effect of creating more instability downstream through the inducement of greater erosion and transportation or mobility of sediment through the channel. Channel bars then develop along with meandering reaches that continue to develop and mature over time (Knighton, 1998). Meandering is seen as a mechanism employed by a stream as an adjustment to maintain quasi-equilibrium conditions. The movement of water through a curved conduit is perceived as an effort to minimize energy expenditure (Gregory and Walling, 1973; Leopold, 1994; Richards, 2004). When a stream meanders, it is seen as an effort to regulate the gradient of that stream and re-establish stream equilibrium. Increased sinuosity is a response of a river to maintain a constant gradient; hence the steepening of a channel induces greater sinuosity (Gomez and Marron, 1991).

In fact, a straight channel may be more ineffective in transporting material than a meandering one (Knighton, 1998). The number of cutoffs subsequently increased from 1955 as two cutoffs were created during each of the successive time steps (Table 3.2), that is, from 1955 to 1966; 1966 to 1973; and 1973 to 1988. From 1999 to 2005, one cutoff was created. This is clear evidence that the river at this point is actively eroding its banks.

Although the average SI indexes of the river channel in the Piedmont province were low (1.01 to 1.02), the presence of lateral bars and point bars attest to a reasonable degree of in-stream activity causing erosion with subsequent deposition of sediment. The source of this sediment that comprises the sand bars is from the erosive activity of the river since the dam acts as a sediment trap effectively preventing any significant amount of sediment from entering the river. Since there is no adjoining tributary, there is no other source of sediment.

The lateral migration or movement of a river channel across the landscape is the result of the erosion of existing channel material along with the creation of new deposits (Petts and Foster, 1985), and this is occurring even within the narrower confines of the river valley within the Piedmont province. Figure 3-11 shows the 2005 air photograph of a section of the Oconee within the Piedmont with well developed in-stream deposits. The white arrows indicate the locations of these deposits. This river valley is described as being a semi-controlled river which is controlled by local geology which influences landform development (Tooth et al., 2004). The type of floodplain within this Piedmont province is described by Petts and Foster (1985) as confined and dominated by lateral floodplain accretion.

The valley floor within the Piedmont Geologic province is defined by the distance between the lowest contours that flank the channel (in this case, the 80 m contour). Measurements of the widths of the valley floor along the boundary line of reach blocks from reach 1 to reach 15 range from 277 m to 1771 m and a mean valley width of 512 m. The widest channel width for the river within this section for all the years is 150 m.

Three major categories of stream channels have been identified based upon the materials that make up the river valley through which a river flows. These are bedrock, semi-controlled and alluvial (Schumm, 1985). Bedrock channels may be defined as channels that have very little continuous alluvial cover (Whipple, 2004) or one whose channel is composed of mostly exposed rock with only a thin veneer of alluvial cover that is removed by high flows. A third definition states that a bedrock channel cannot become lower or shift or widen without substantially eroding its bedrock (Turowski et al., 2008).

The semi-controlled river may be defined as those whose movements across the landscape are controlled by local factors such as bedrock or alluvium that is resistant to erosion. Such rivers show little lateral movement whenever they encounter resistant bedrock and more movement whenever more easily resistant alluvial material is encountered (Schumm, 1985). Such rivers are also described by Ashley et al. (1988) as being intermediate rivers that have both bedrock and accumulations of alluvium.

Figure 3-2 shows the Oconee River located within a topographic region characterized by narrow valleys with a floodplain that is far less extensive in width than the floodplain shown in Figure 3-3. In Figure 3-3 which shows a different landscape, the floodplain is wider and more developed giving rise to less restrictive lateral movement of the river. The average gradients for the river valley in the Piedmont and Coastal Plain provinces are similar having a small difference of 0.000003. This lack of discernible difference in slope between the two geologic provinces shows that overall steepness of slope is therefore not a major factor when considering the reasons for the differences in sinuosity.

Yet the sediment source that makes up the stream deposits in the Piedmont province as shown (Figure 3-11) is from in-stream channel erosion. This in turn influences the shifting of the channel. The influence of the geology characteristic of the Piedmont province appears to be largely restricted to the configuration of the stream valley characteristics rather than the direct effects of more resistant erosive materials on channel migration patterns.

Average Area Reworked: Piedmont vs. Coastal Plain

The average area reworked is a measure of how much land is affected by the movement of the river over time. The area reworked indicates how much land has been deposited or eroded as the river migrates over time (TNC, 2002). Figure 3-12 shows the average amount of hectares that was eroded for each km per year. Rates are calculated using data from aerial photos from 1942 to 2005. The 1937 to 1942 time-step was excluded since the channel was deliberately re-routed between 1937 and 1942 and therefore this lateral movement is not representative of average area reworked.

Figure 3-12 shows that the average area reworked in the Piedmont Geologic province is more subdued than that of the Coastal Plain Geologic province. The lateral and downstream shifting of the meander loops account for this difference. In Figure 3-12, the average area reworked for Piedmont Geologic and the Coastal Plain Geologic provinces are 0.16 and 0.26 Ha per Year per km respectively. The range of area reworked for the Piedmont and the Coastal Plain Geologic provinces are 0.01 to 0.43 and 0.05 to 0.68 Ha per Year respectively. Clearly the river channel in Coastal Plain Geologic province represents a more active section.

Figure 3-13 shows data on the average area reworked per year per kilometer for the sections of the Oconee River located in the Piedmont and the Coastal Plain provinces for each of the time-steps (except the 1937-1942 time-step). The average hectares per year for each of the first 18 reaches of the Oconee River were used to calculate the data for the Piedmont province, while reaches 19 to the end of the study area were used to calculate the data for the Coastal Plain province.

The Mann-Whitney U Test was conducted to compare the average area reworked for the Piedmont and Coastal Plain Geologic provinces (for each of the time steps described in Figure 3-13), in order to test the values for significant differences between the two provinces. The results of this test are shown in Table 3-3. In Table 3-3, the Z values and the Asymp. Sig (2 tailed) numbers give the significance level. Values below 0.05 for the last line in this table are significant. Maximum hectares per year per kilometer for 1942 to 1955 for the section of the river in the Piedmont were 0.1974 while the values for the same section of the river for the Coastal Plain province were 0.3267. This represented a 65% increase and this difference is not significant at the 95% confidence level.

Maximum hectares per year per kilometer for 1955 to 1966 for the section of the river in the Piedmont were 0.1463 while the values for the same section for the section of the river in the Coastal Plain province were 0.2775. This represented a 90% increase and this difference is significant at the 95% confidence level.

Maximum hectares per year per kilometer for 1966 to 1973 for the section of the river in the Piedmont were 0.1391 while the values for the same section for the section of the river in the Coastal Plain province were 0.3516. This represented a 152% increase and this difference is significant at the 95% confidence level.

Maximum hectares per year per kilometer for 1973 to 1988 for the section of the river in the Piedmont were 0.1551 while the values for the same section for the section of the river in the Coastal Plain province were 0.1513. This represented a 2% decrease and this difference is not significant at the 95% confidence level.

Maximum hectares per year per kilometer for 1988 to 1999 for the section of the river in the Piedmont were 0.2203 while the values for the same section for the section of the river in the Coastal Plain province were 0.1203. This represented a 45% decrease and this difference is not significant at the 95% confidence level.

Maximum hectares per year per kilometer for 1999 to 2005 for the section of the river in the Piedmont were 0.10 while the values for the same section for the section of the river in the Coastal Plain province were 0.31. This represented a 218% increase and this difference is significant at the 95% confidence level.

There was much movement of the channel within the floodplain from 1942 to 1973. This increased the degree of sinuosity with the creation of and growth of several meanders. The growth of meanders signifies an increase in amount of land that reworked over time. The increased sinuous nature of the river channel significantly reduced the channel gradient and the propensity of the channel to erode its banks and bed. This is the possible reason for the reduction of the average area reworked between 1973 and 1999 which saw a small decrease in the average area reworked from the Piedmont to the Coastal Plain province from 1973 to 1988 but a significantly larger drop in difference from 1988 to 1999.

Figure 3-14 shows the land between the channels that was created by the movement of the channel across the floodplain. The black horizontal line on the graph shows the approximate border between the Piedmont and Coastal Plain provinces. The proportional area change ratio is the average of the data for the time steps. Figure 3-14 allows for comparison of the degree of lateral movement of the channel between the two geologic provinces.

In the Piedmont Geologic province, the range of B/I index values is 0.00 to 0.11 with an average of 0.01. The range of B/I index values for the Coastal Plain Geologic province is 0.00 to 0.41 with an average of 0.08. Clearly, the greater lateral movement of the channel occurred within the Coastal Plain Geologic province. The differences in the indexes results from the creation of different sized meander loops over time as well as the creation of cutoffs. For example, between 1999 and 2005, at about 35 to 36 kilometers downstream of the dam, a fairly large cutoff was created and this represented a shift of over 450 meters of the channel centerline from 1999 to 2005.

Figures 3-14 to 3-17 show the index values for the study area, namely B/1, D/I, E/I and U/I. Table 3-3 provides some brief descriptive statistics of the data provided by these figures that allows for comparative analysis. The B/I values for the Coastal Plain Geologic province represent a 100% increase in the land area from the Piedmont Geologic province. Likewise, there was an increase by 60% from the Coastal Plain Geologic province over the Piedmont Geologic province of the amount of land that has been abandoned (D/I). An increase in the E/I proportional area values also demonstrates that there was an increase in the degree of movement of the river channel. The Coastal Plain Geologic province had a 79.17% increase in this area. The amount of land that remained unchanged was higher in the Piedmont Geologic province than the Coastal Plain Geologic province with a 20% decrease from the Piedmont to the Coastal Plain Geologic province. These figures show that there was greater lateral movement of the channel within the Coastal Plain Geologic province.

Conclusion

This study shows that the movement of a river across the landscape suggests strongly that the rate of planform migration occurs in cycles with a series of highs and lows, causing a river to oscillate from wider lateral movements to narrower movements and back to wider movements. Owing to the shortness of the time span in this study, however, it is difficult to ascertain the periods or time-spans of cyclic activity. Furthermore, the study of migration rates over short time scales (20-30 years) demonstrate greater scatter than other migration rates measured over longer time scales like 100-200 years (Shields, 2000). Perhaps a longer-term study of planform change of the Oconee River may provide better clues as to the cyclical nature of the movement of the channel across the landscape.

Local factors such as varying degrees of resistance of bank materials, grain size and bed material, the slope of the channel gradient, stream discharge, all play a role in controlling the degree of planform change. This complicates trying to model how a river would migrate across a landscape. This is so especially since the degree of variability of lateral migration rates changes because the river is reworking previously deposited alluvium and this may affect the rate of lateral migration. Loosely deposited material that has not had a lot of time to consolidate would offer less resistance to lateral erosion. Therefore, even if the mineral composition of the bank material were the same, the compacted or non-cohesive nature of the material would affect the sheer stress on the bank as well as the response to the bank to mass wasting and rotational failure (Simon and Darby, 1999).

Models that are used to predict or approximate lateral river migration across the landscape oversimplify many of the key components that determine the rate of planform migration. Howard and Knutson (1984) proposed a digital model to simulate meandering patterns in streams. The assumptions included the same degree of bank erodibility, the in-stream sediment is uniform downstream, the migration is uniformed throughout the stream length and the width of the stream channel is of a constant width. These oversimplifications obviously do not reflect the true nature and complexities of river planform change. In efforts to manage the riverine landscape, scientists and engineers need to therefore understand the movement of rivers not only spatially but temporally as well. It is also necessary to acknowledge that similar processes vary over time and space within the river landscape.

While it is clear that alluvial channels demonstrate greater movement across the floodplain, streams that are located in zones that are not strictly alluvial do also manifest lateral movement, however, on a more subdued scale. The two geologic provinces clearly influence the river's planform but in different ways. In the Piedmont Geologic province, there seems to be less direct influence of the rock type. Though rocks within this zone are more resistant to erosion, the evidence shows that the channel is still actively eroding and depositing within this zone. There is strong evidence that the material that makes up the bank and bed of the river channel are just as or almost as easily susceptible to erosion as the material in the Coastal Plain province. The influence of the geology here is seen in the topography which influences the nature and shape of the river valley itself. Within in Piedmont province, the propensity of the stream to migrate laterally is restricted by the narrow river valley. Given the degree of average area reworked in the Piedmont, it is likely that the lateral migration rate of the river would have been greater.

Creation of a cutoff results from the gradual erosion of opposing banks with the inevitable narrowing of the land between banks. The literature states that cutoffs occur during high stage events (Gay et al., 1998; Hooke, 2004). This does not provide an accurate assessment of channel change in the context of the formation of a cutoff. Rather, it is the combination of the working of or the coming together of a few other factors such as the inefficiency of an over sinuous channel that may be the catalyst for a river to avulse and change course, and not just a major flood event.

Overall, the lateral movement of the river channel in the Coastal Plain Geologic province was greater than the Piedmont Geologic province. Stream channels were less sinuous in the Piedmont Geologic province than the Coastal Plain Geologic province. Comparisons of some proportional area change ratios show mean differences as high as 79 and 100 percent with the Coastal Plain Geologic province having these higher values. The amount of area reworked by migrating and shifting channels within the Coastal Plain Geologic province is also higher than the Piedmont Geologic province with values ranging from 0.01 to 0.43 for the Piedmont compared with values ranging from 0.05 to 0.68 Ha per Year for the Coastal Geologic province.

Table 3-1. Distance between inner banks at meander neck at reach 35 from 1937 to 1999: Oconee River as seen in Figure 3-9

Year	Distance in meters
1937	122
1942	115
1955	106
1966	89
1973	78
1988	50
1999	23

Table 3-2. Number of cutoffs, Oconee River: 1937 to 2005. All cutoffs occurred in the Coastal Plain Geologic province.

Time steps	Number of cutoffs
1937-1942	3
1942-1955	0
1955-1966	2
1966-1973	2
1973-1988	2
1988-1999	1
1999-2005	1

Table 3-3. Test for significant differences for average area reworked for the Piedmont and Coastal Plain Geologic provinces for time steps (for years 1942 through 2005) using Mann-Whitney U Test.

Time steps	42-55	55-66	66-73	73-88	88-99	99-05
Mann-Whitney U	428.000	310.000	191.000	495.000	499.000	109.000
Wilcoxon W	618.000	500.000	381.000	685.000	2152.000	299.000
Z	-1.453	-2.848	-4.205	-.662	-.511	-5.188
Asymp. Sig. (2-tailed)	.146	.004	.000	.508	.610	.000

Test Statistic – Grouping Variable: Piedmont and Coastal Plain Geologic provinces

Table 3-4. Summary of proportional area change ratios for D/I, E/I and U/I segments.

	Piedmont Geologic Province		Coastal Plain Geologic Province		
	Mean Index Value	Range of Index Values	Mean Index Value	Range of Index Values	% change of mean index values
B/I (land between)	0.04	0.00-0.19	0.08	0.00-0.53	100
D/I (land abandoned)	0.25	0.07-0.62	0.40	0.18-0.63	60
E/I (land eroded)	0.24	0.08-0.62	0.43	0.19-0.94	79.17
U/I (land unchanged	0.75	0.38-0.93	0.60	0.37-0.82	20

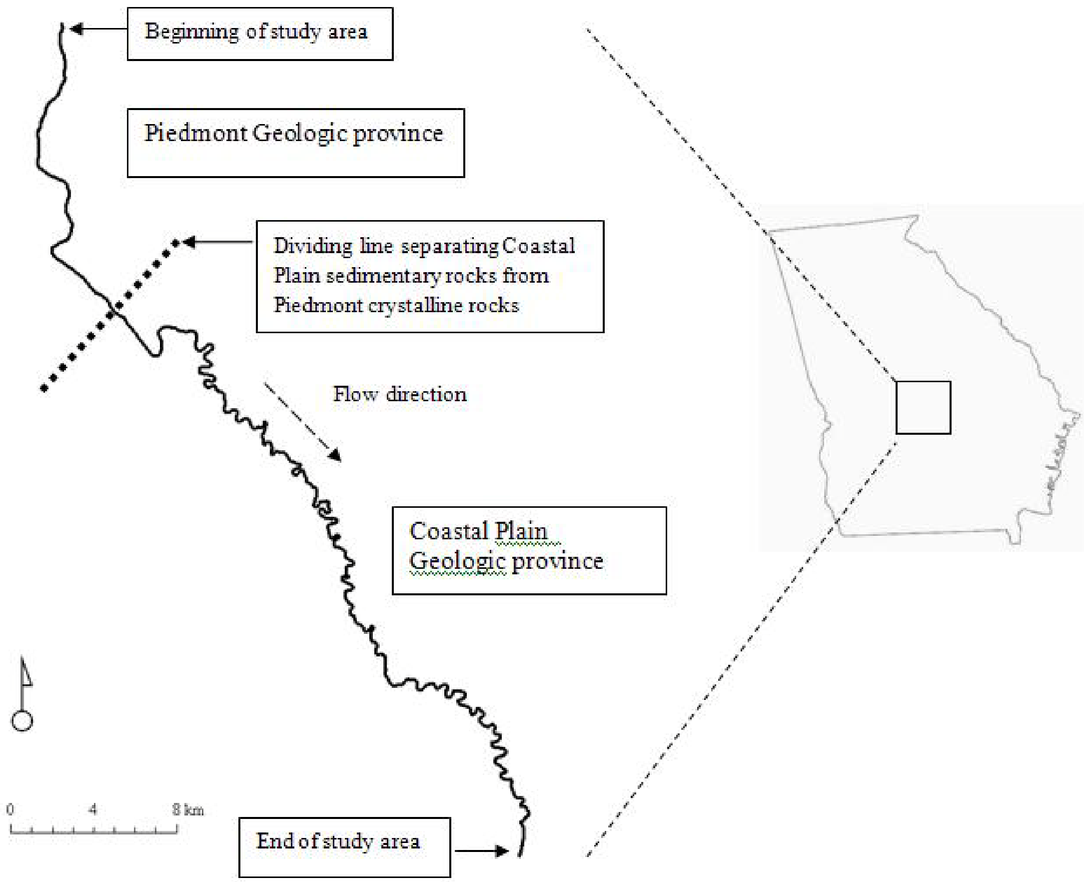

Figure 3-1. Location of the study area: Oconee River, GA with the dotted line separating the study area into the northerly Piedmont Geologic province and the southerly Coastal Plain Geologic province (Lawton, 1977).

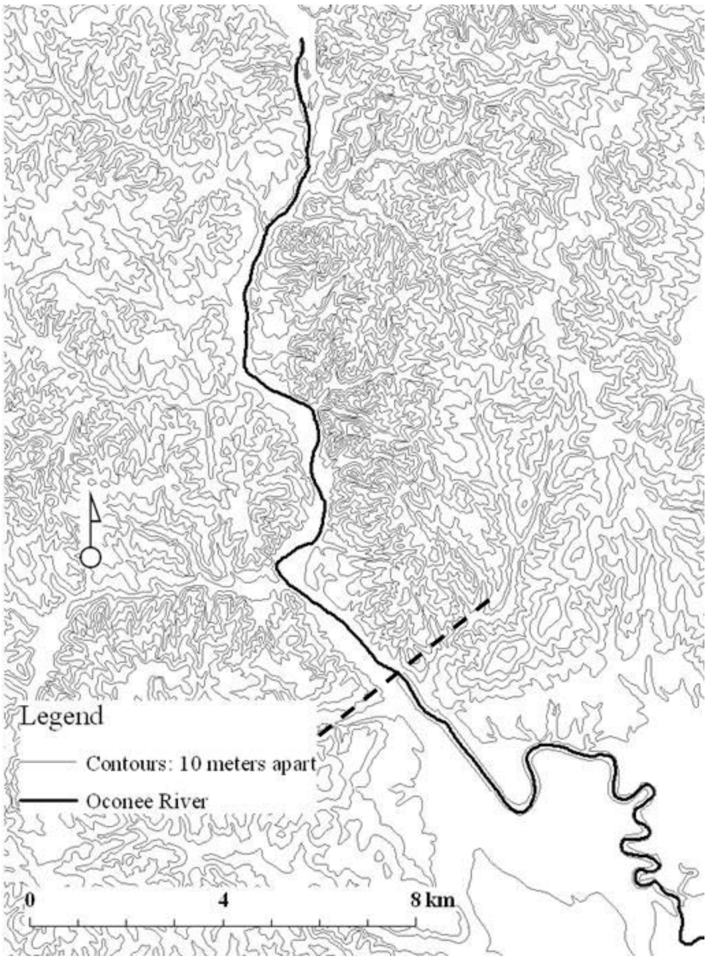

Figure 3-2. Section of Oconee River in the Piedmont Geologic province. The dashed line separates the Piedmont from the Coastal Plain Geologic province. Rocks south of the line are stream alluvium and undifferentiated surface deposits. Rocks immediately north of the line comprise of quartz, mica schist (Lawton, 1977).

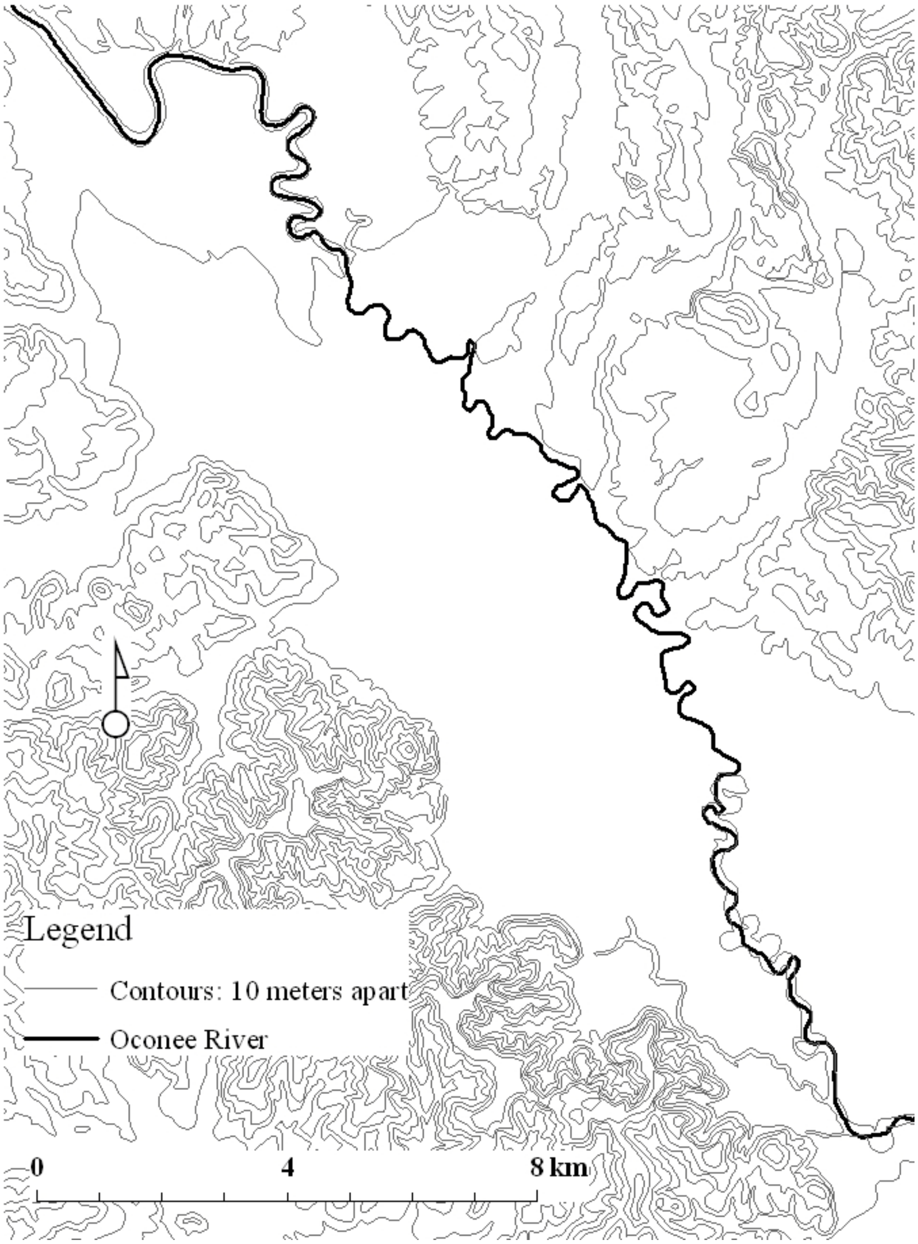

Figure 3-3. Section of the Oconee River in the Coastal Plain Geologic province

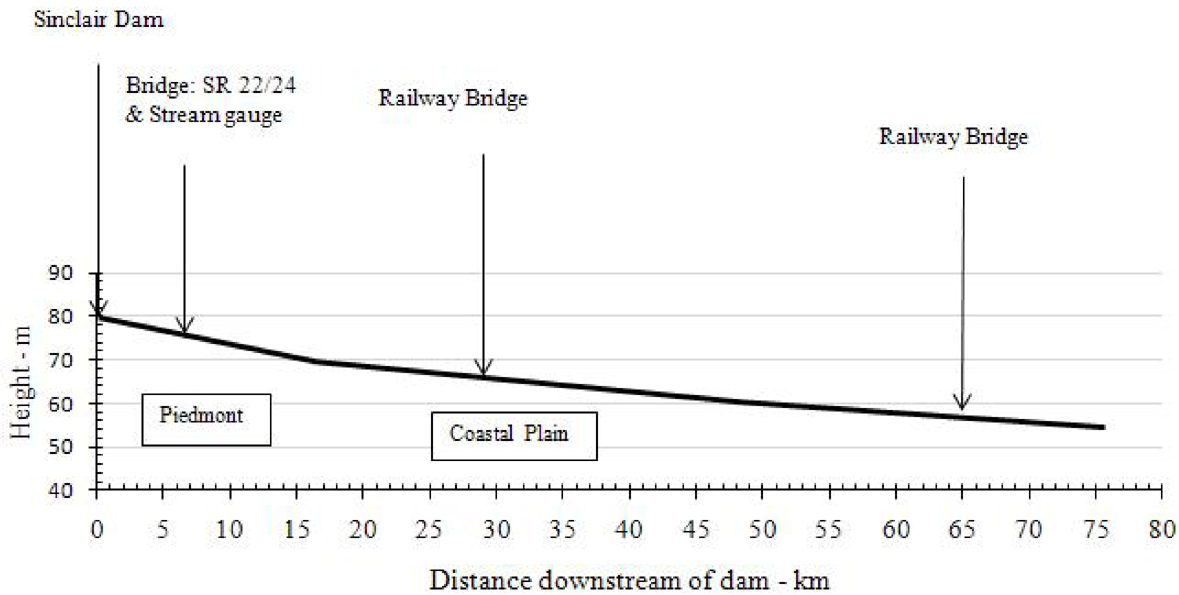

Figure 3-4. Longitudinal profile of Oconee River from Sinclair Dam to end of study area (km 0 – km 75.5)

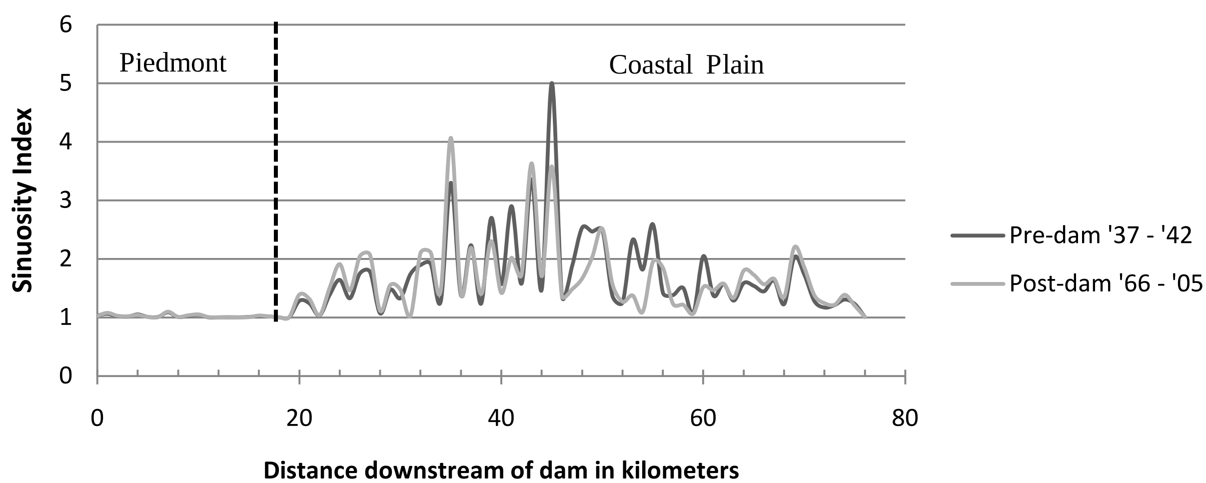

Figure 3-5. Sinuosity indexes: Pre-dam (1937-1942) and Post-dam (1966-2005)

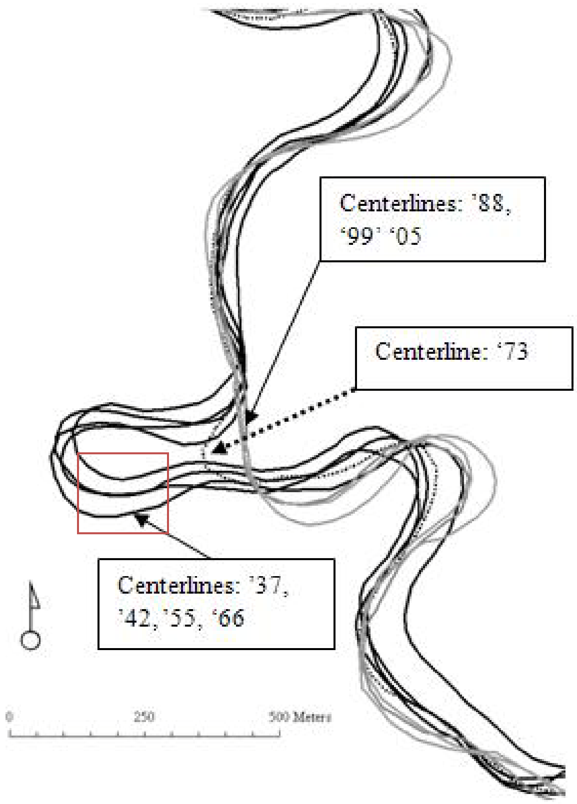

Figure 3-6. Centerlines of Oconee River channels showing shifting across the floodplain: Black lines - '37 to ''66. Grey lines – '88 to '05. Dotted line: '73. River km 44 – 46.

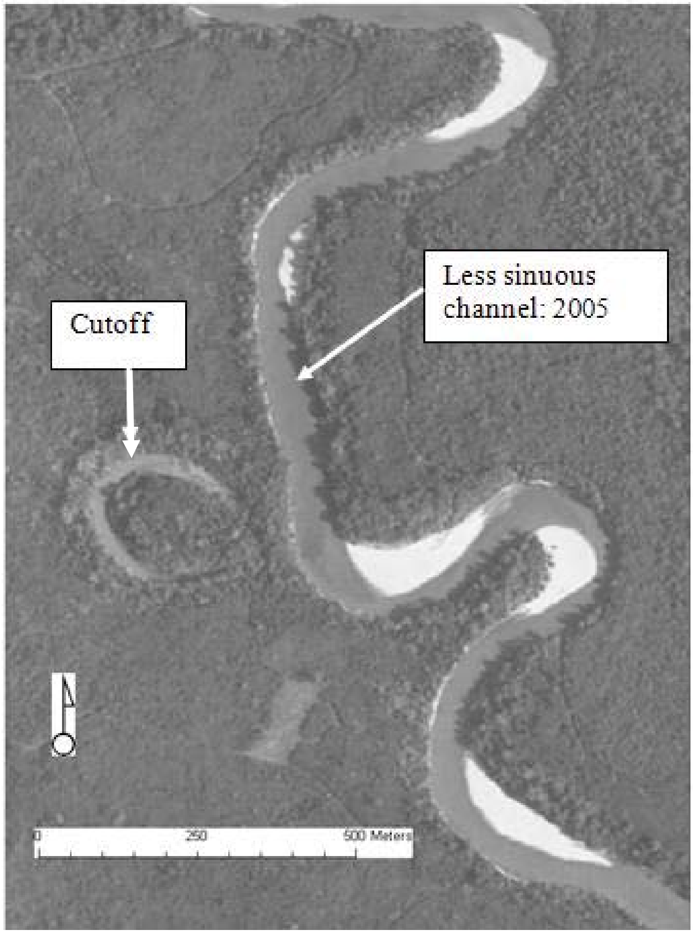

Figure 3-7. Section of Oconee River (as shown in Figure 3-6) showing aerial photograph with cutoff – 2005. River km 44 – 46.

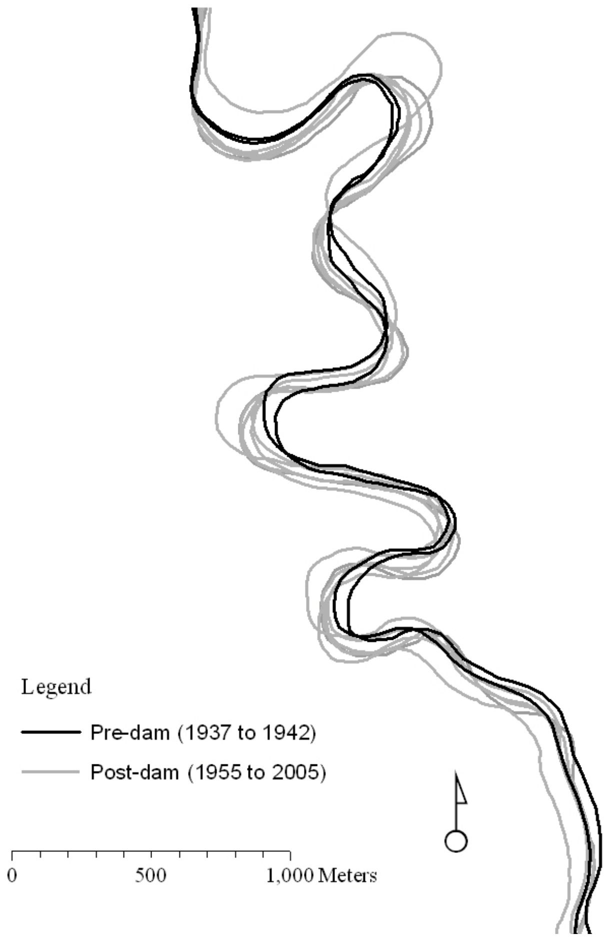

Figure 3-8. Centerlines of section (km 23 to km 28) of the Oconee River channel: Pre-dam and Post-dam.

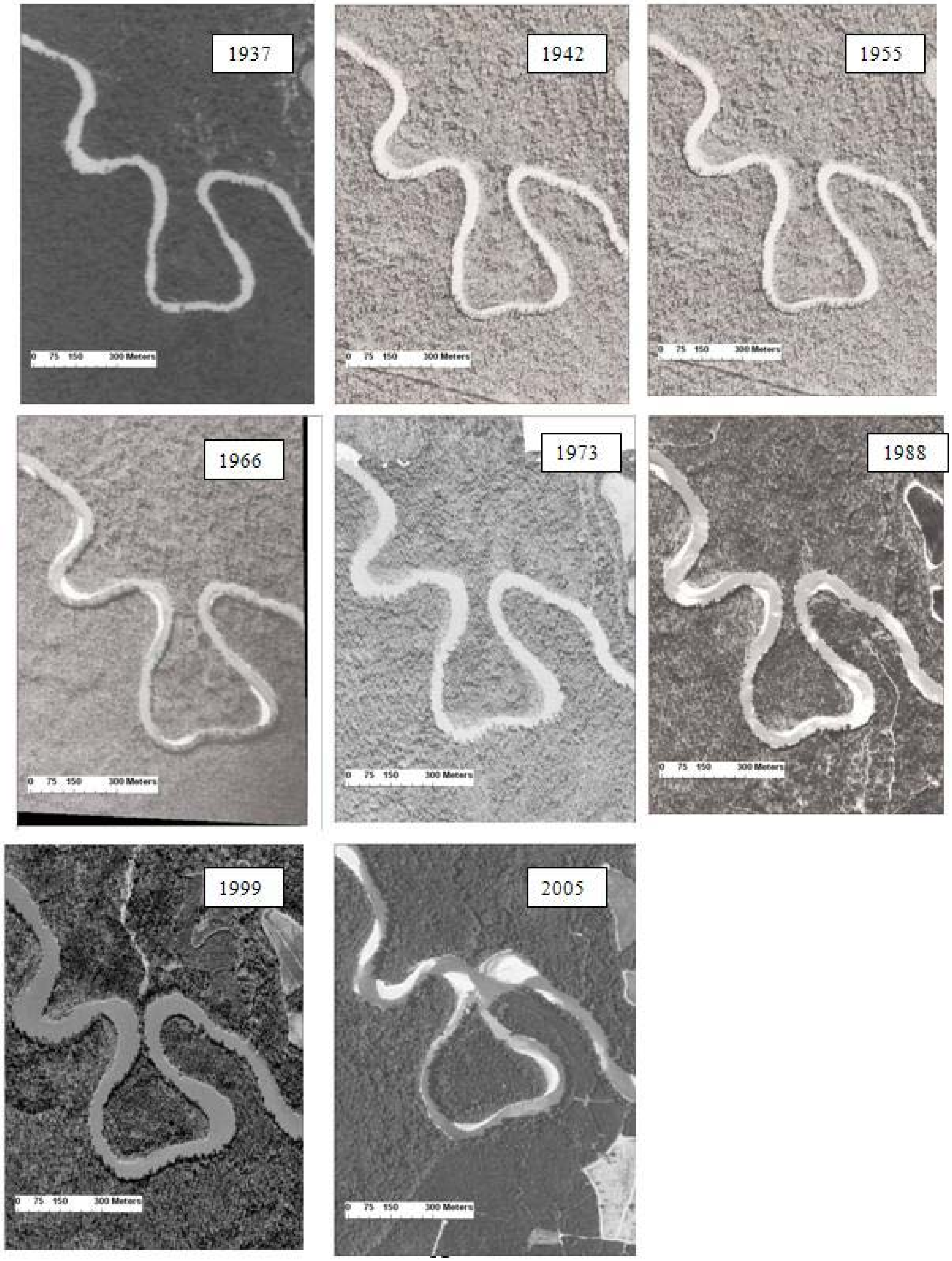

Figure 3-9. Sequential movement of the channel at about 35 km from 1937 to 2005 showing the gradual inward movement of the opposite meander bends eventually creating a cutoff. River km 34 – 36.

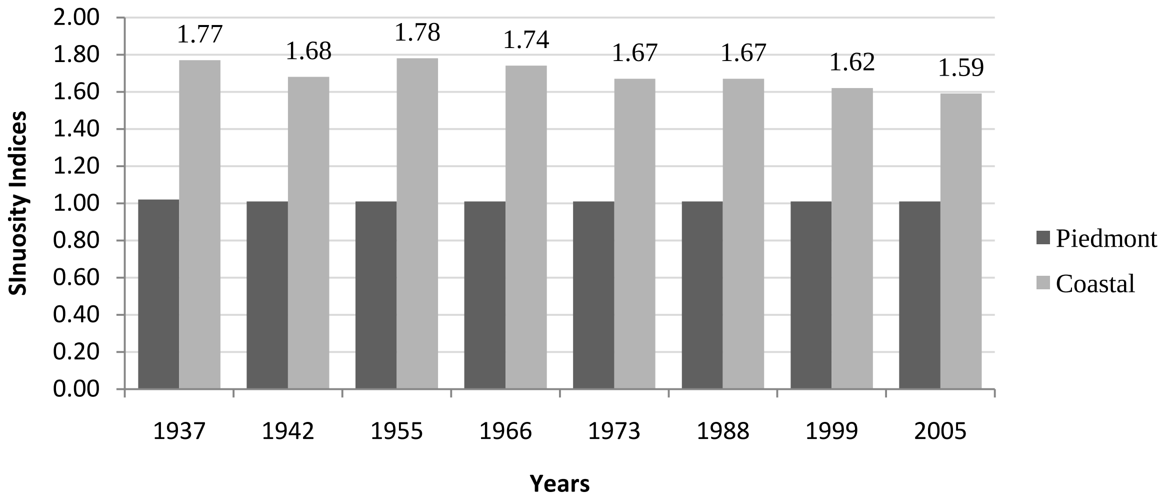

Figure 3-10. Sinuosity: Piedmont versus Coastal Plain

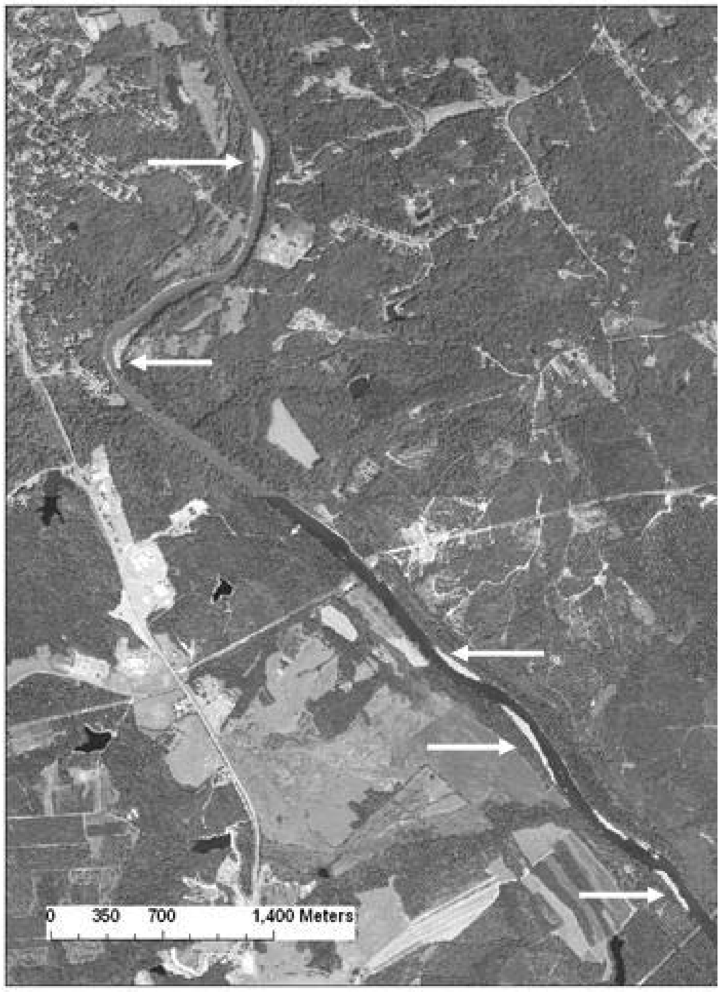

Figure 3-11. Oconee River, 2005: White arrows show in-stream deposits in the Piedmont Geologic province. River km 10 – 18.

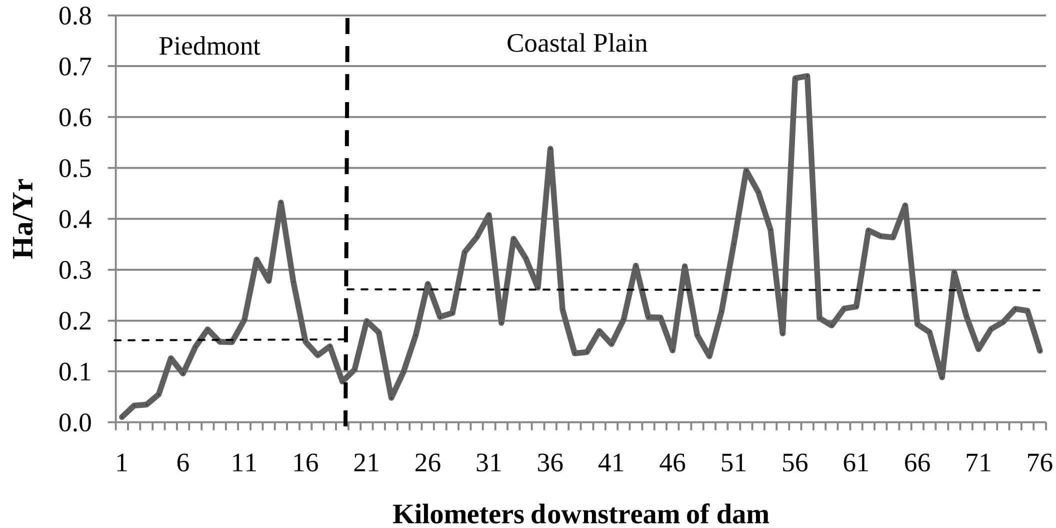

Figure 3-12. Average area reworked (in Ha/yr): Piedmont versus Coastal Plain: 1942-2005. Horizontal dashed lines are average values (for both Geologic provinces).

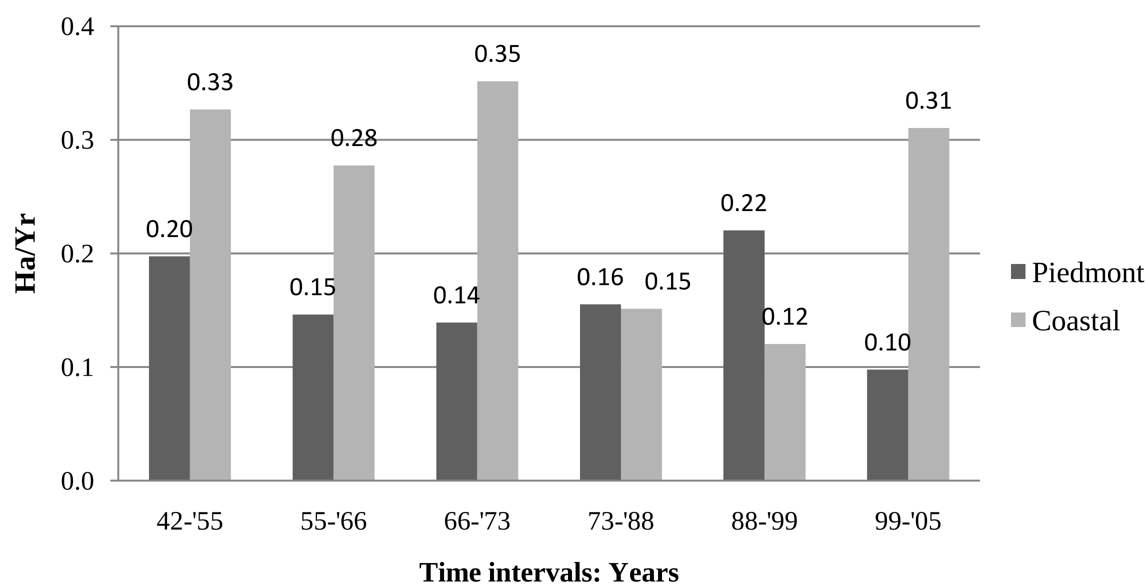

Figure 3-13. Average area reworked (in Ha/yr): Piedmont versus Coastal Plain: 1942-2005

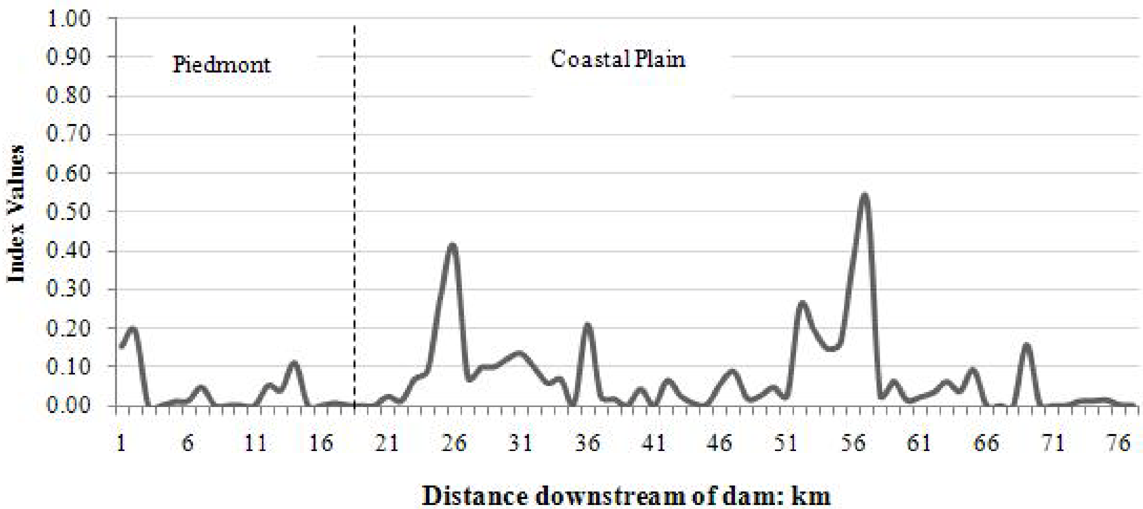

Figure 3-14. Proportional area change ratio: B/I (1942 to 2005).

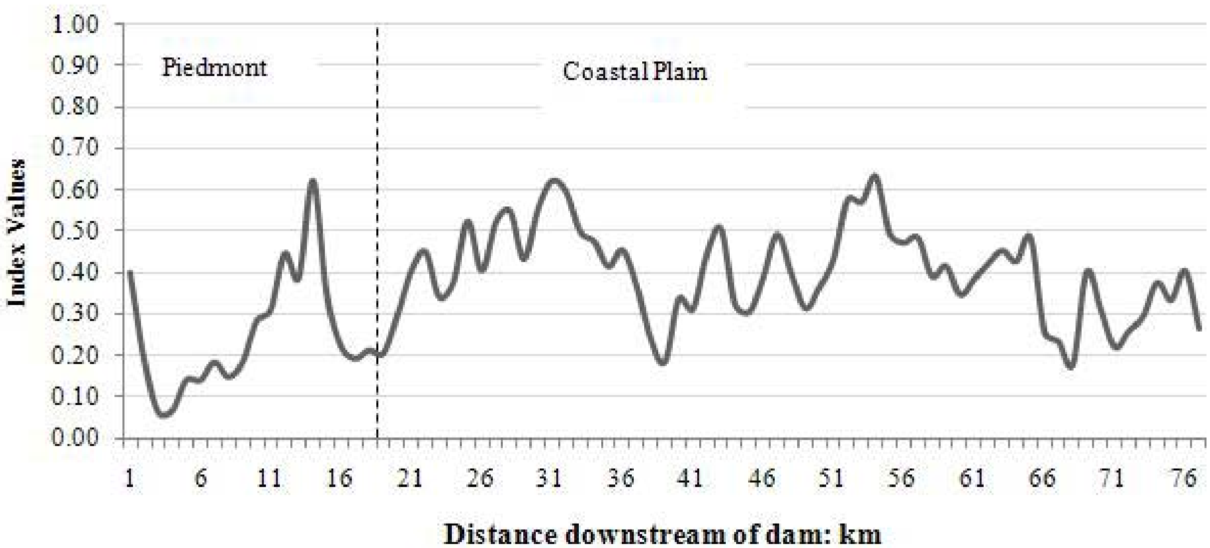

Figure 3-15. Proportional area change ratio: D/I (1942-2005)

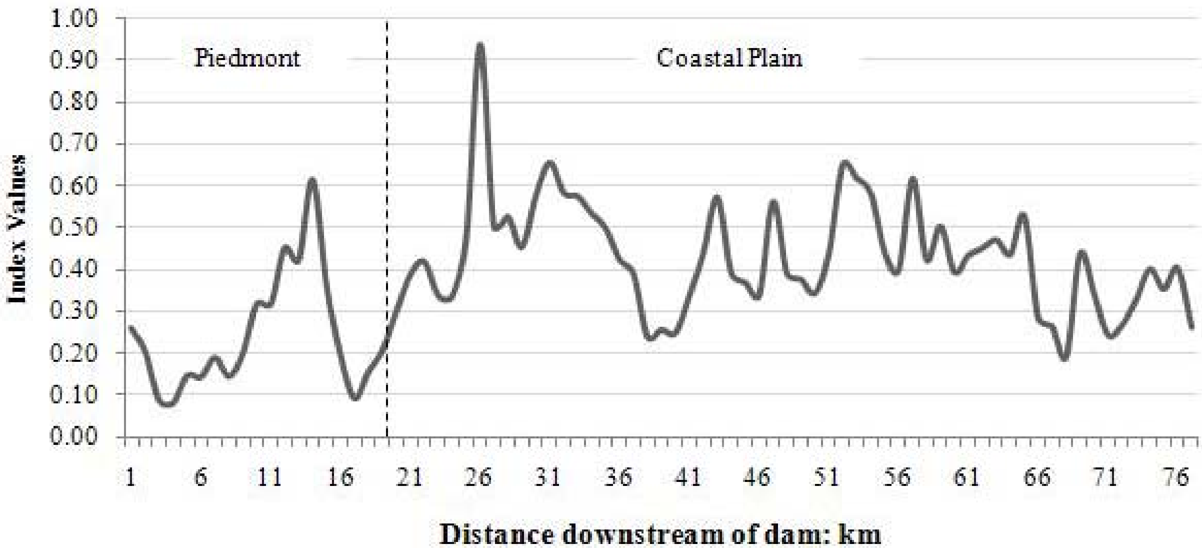

Figure 3-16. Proportional area change ratio: E/I (1942-2005)

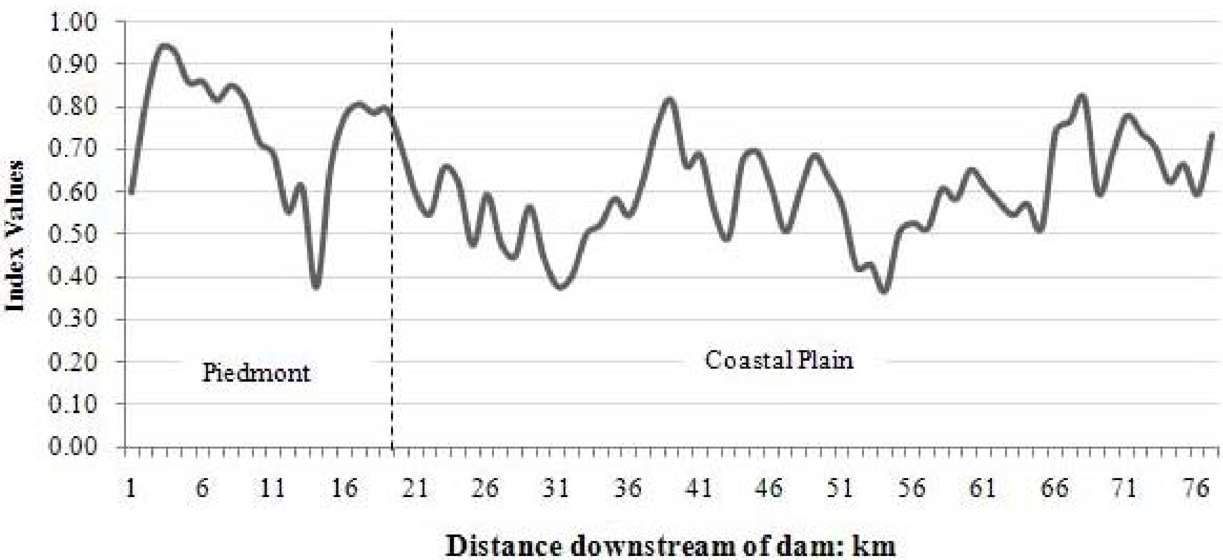

Figure 3-17. Proportional area change ratio: U/I (1942-2005)

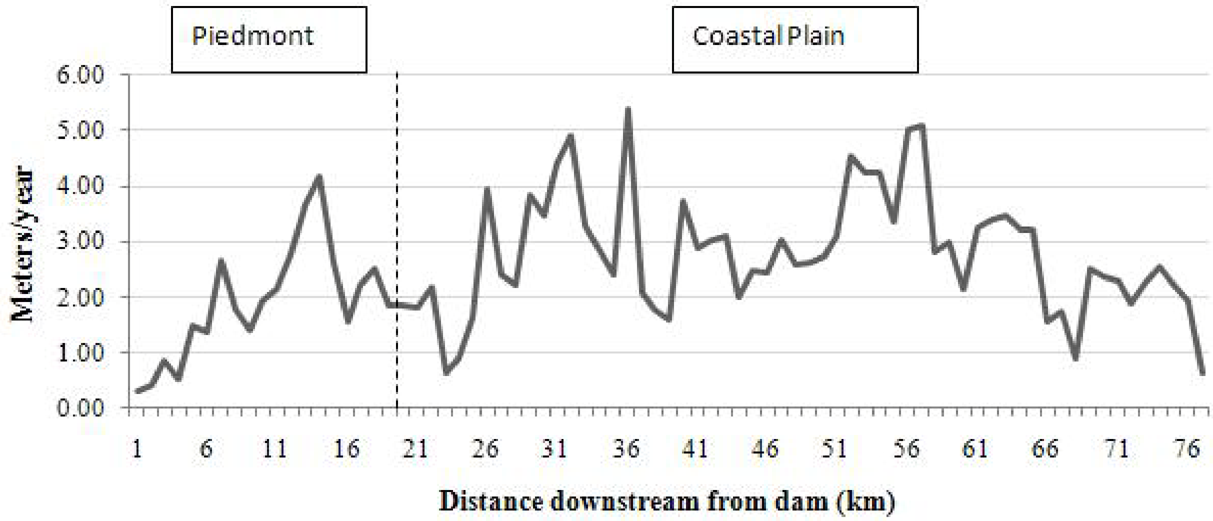

Figure 3-18. Mean lateral migration rate, Oconee River (1937-2005)

CHAPTER 4
MEANDER GEOMETRY AND CHANNEL MIGRATION ON THE OCONEE:1937 TO 2005

Introduction and Study Area

Meandering patterns in alluvial rivers are common features with the meanders themselves shifting continuously across the floodplain (Langbein and Leopold, 1966; Hooke, 1995). The patterns created by these shifting channels, their causes and their effects have been studied extensively (Thorne and Lewin, 1979; Carson, 1986; Rhoads and Welford, 1991; Gilvear et al., 2000). Models have been developed that explain the planimetric evolution of meanders across the landscape. These models range from the Kinoshita type train of meanders, sub-resonant and super-resonant meander growth and development (Seminara et al., 2001; Zolezzi and Seminara, 2001), the analysis of critical values of ratios involving channel curvature to channel width (Hickin, 1974; Hickin and Nanson, 1984; André, 2003), the theory of Minimum Variance (Langbein and Leopold, 1966) and the concept of geomorphic thresholds and drainage system response (Schumm, 1981).

Theory of minimum variance purports that the characteristics of meanders across the landscape are the result of the interaction of the processes that govern erosion and deposition. The meander represents a stable form that represents a stream adjusting to variations in erosion, deposition, bed forms which in turn affect hydraulic resistance and the ability of the channel to transport debris. The theory states that the meanders are the result of the minimum differences or variation that occurs between these variables (Langbein and Leopold, 1966).

Meanders of rivers display a characteristic feature called skewing (Parker et al., 1983), also called delayed inflection (Carson and LaPointe, 1983) causing a train or series of bends to become asymmetrical in form with the convex side of the curve facing a downvalley orientation.

This meander pattern is also referred to as a Kinoshita type train of meanders (Parker et al., 1983).

Sub-resonant and super-resonant meander growth and development is related to the study of how meander growth and development is related to the nature of bed instability and how it affects the migration of meander groups downstream (Seminara, 2006).

Concept of geomorphic thresholds and drainage system response: in a series of experiments on river meandering, it was shown that straight channels remained fairly straight in gentle slopes but began to meander as the slope was steepened. This change in the direction of the channel occurred when the velocity of the stream flow increased along with the sheer forces acting upon the bed and bank of the experimental channel. These increases reached a critical point or threshold that caused the bed material of the stream to shift causing a change in the flow direction and an initiation of meanders. (Schumm, 1981)

As rivers move across their landscapes, they rarely do so in a straight line. Most rivers travel in a meandering pattern (Schumm, 1985; Rhoads and Welford, 1991). More importantly, the movement of the channel occurs at the bends or meanders of the rivers. Erosion occurs at the concave or outer bend of the curve while deposition occurs at the convex or inner bend forming a point bar (Brotherton, 1979; Howard and Knutson, 1984). Even though the channel moves laterally, it continues to maintain its morphology (Hooke, 2007).

There must be available excess stream energy for bank erosion and channel migration to occur. A meandering river is evidence of that excessive stream energy.   As the river creates the curves through bank erosion and transport of the sediment within the channel, the channel gradient is reduced because of the expenditure of this excess energy. The meandering stream may be viewed as a mechanism whereby a stream adjusts to its excessive power. The characteristics of river bends, therefore, should enable researchers to model how rivers move across their landscapes. The nature of channel flow within curves is important as this influences and controls meander migration (Gilvear et al., 2000; Wellmeyer et al., 2005). An integral part of planform dynamics, therefore, is the curvature of meandering rivers (Güneralp and Rhoads, 2008).

These characteristics involve the study of the meander geometry of the curves or meanders. Meander geometry analyzes the characteristics or the geometric properties of the individual bends or meanders such as the meander wavelength (l) and the radius of curvature (r_C) (Knighton, 1998; André, 2003). As a river meanders across the landscape, these geometric properties are used to describe this movement. Differences in wavelength and the varying size of the curves determine the direction of the river. In addition, there is a significant relationship between the radius of curvature of a meander and the width of that channel (w) (Hickin and Nanson, 1984). In fact, meander bends may be characterized by their individual shape, amplitude and wavelength and radius of their bends (Lagasse et al., 2004).

It is quite common to find meander loops that are asymmetrical with most of the meander bends facing a down-valley orientation (Thompson, 1986; André, 2003). Bank erosion rates on the outer or concave banks of the meander loops or bends tend to take place just downstream of the apex of the bend giving rise to a down-valley migration of the meander. This encourages not just lateral but downstream migration of the meander loops (Thompson, 1986; Darby and Delvono 2002).

Meanders cannot continue to grow and develop indefinitely for the slope of the channel would become too gentle and the river would be unable to transport any of its load (Charlton, 2008). Some meanders attain or develop to a stage where lateral erosion is so pronounced with a high degree of lateral extension such that the sinuosity reaches a threshold point and a cutoff develops (Knighton, 1998). In alluvial rivers, meander cutoffs are primarily formed by two ways, that is, by a neck and a chute cutoff (Gay et al., 1998; Charlton, 2008). A neck cutoff is formed by the progressive narrowing of the neck of land between two limbs of the meander until a breach is made after the two limbs meet. A chute cutoff is formed when a stream cuts a new channel on the inside of an existing meander (Erskine et al.1992). Cutoff formation short circuits the meander loop and in effect shortens the channel and results in an increase in the slope of the channel (Knighton, 1998; Hooke, 2004).

Understanding how and why rivers move across their landscapes and the consequences of such movements is important for engineers and planners in their efforts to protect vulnerable infrastructural features such as roads, embankments, the foundation of bridges and agricultural holdings that are adjacent to alluvial rivers (Larsen and Greco, 2002; Gupta and Liew, 2007). Lateral migration also has implications for the health and existence of fauna (Burge, 2005; Grams and Schmidt, 2005; Choi et al., 2005; Gordon and Meentemeyer, 2006), salmonid habitats (Ligon et al., 1995; Marston et al., 2005) as well as riparian ecosystem ecologies (Larsen and Greco, 2002) and biodiversity on ecosystems within the floodplain (Larsen et al., 2002; Beechie et al., 2006).

A large section of the Oconee in Central Georgia, USA, is a single-thread alluvial river that meanders extensively across its floodplain. Aerial photographs of the Oconee River from 1937 to 2005 reveal a continually shifting channel across the landscape forming complex meander patterns such as lateral extensions, translations, double headings and neck cutoffs (Lagasse et al., 2004). The aim of this paper is to describe factors determining the downstream migration of meanders of the Oconee River.

The study area is located in the Oconee River which is located in the southeastern United States in the State of Georgia. The Oconee River flows from two headwater tributaries – the North Oconee River and Middle Oconee River. The natural vegetation type in this area is primarily pine-oak-hickory. These headwater tributaries join at a point just south of the City of Athens forming the Oconee River. The Oconee flows for about 548 kilometers until it reaches the confluence of the Ocmulgee River. The study area is the section of the Oconee River that starts at the Sinclair Dam and ends at a point 75 kilometers downstream of the dam (Figure 4-1). The Sinclair Dam is located about 228 kilometers downstream of the beginning of the Oconee River.

Flow Patterns and Bend Development

Meander Migration and Meander Geometry

A meander grows as bank erosion occurs on the outer banks of bends along with a corresponding deposition of material on the inner banks of bends (Hickin, 1974; Hooke, 1995). A combination of high velocity, sheer stress along with lower frictional losses with the stream flow directed towards one bank results in bank erosion and bank retreat on alternate sides of the channel (Richards, 2004). This lateral extension of the loop or bend increases the length of the channel as well as the amplitude of the bend of the meander (Charlton, 2008).

A curve of a river channel is defined by its radius or radius of curvature (r_C) whose measurements may be obtained by the radius of the circle that is drawn around the bend of the meander (Nanson and Hickin, 1983; Nanson and Hickin, 1986; Lagasse, et al., 2003). The r_C defines the tightness of the bends with larger r_C values for bends that are less tight (André, 2003). The tightness of the bends is expressed as a ratio between r_C and the width (w) of the channel at the bend or loop. This ratio (r_C/w) allows for comparisons between different sized channels with small r_C/w ratios denoting tight bends (Williams, 1986).

Another important feature of meander geometry is the meander wavelength (l). This is the straight line distance between successive meander bends (Williams, 1986). It has been established that l is about 10 to 14 times the width of the channel, while the average r_C is 2 to 3 times the channel width (Hickin and Nanson, 1975; Hickin and Nanson, 1984; Lagasse, et al., 2004). Bends are important in meandering channels since the bend curvature helps to reduce the excessive energy of the stream owing to its curvature. A curve with increasing amplitude continues to reduce the excess energy until the morphologic change of the bend is inhibited (Richards, 2004).

Channel migration rates reach their peak or maximum when the r_C/w is between 2 and 3 and taper off as the r_C/w ratios move beyond the 2-3 range (Hickin, 1974). This means that at the 2-3 range, the erosion of the beds and banks are at their maximum (Lagasse et al., 2004). Therefore, as the bend tightens with r_C/w ratios less than 2, the migration rate declines and reaches zero as r_C/w is equivalent to 1.0. Likewise, migration rates are reduced as the r_C/w values are in excess of 3 (Hickin and Nanson, 1984). A bend, therefore, with a maximum curvature r_C/w approximating 2.5 is the ratio that dissipates energy most efficiently (Richards, 2004). Bend geometry therefore controls the degree of or rate of channel migration (Knighton, 1998).

The rates of meander migration vary as no two streams are the same (Knighton, 1998). The size of the channel may indicate the rate of annual migration since generally, the size of the channel is scaled to the rate of migration. Rates of lateral migration have been recorded as being 10 to 20 % of the width of the channel (Lagasse et al., 2004). Absolute rates for large rivers show the lateral movement of some meanders as being as high as 750 m/yr (Lagasse et al., 2001).

The shape of the meander loops are normally asymmetrical (André, 2003; Richards, 2004) and not perfectly symmetrical such as sine generated curves (Lagasse et al., 2004). The asymmetry of the bends occur because the section of the bend that experiences the greatest erosion or deepest scouring effect is located just downstream of the bend apex (Knighton, 1998; Lagasse et al., 2004). The bends then become skewed in a down-valley direction (Lagasse et al., 2004). The point in the bend that is located just downstream of the apex bend is also called the delayed inflection point. This occurs because of a delayed thalweg (the deepest section of the channel) cross-over to the opposite bank which is in turn caused by the inertia of water flowing downstream of bends (André, 2003). This delayed inertia is caused by the current that is moving downstream (Lagasse et al., 2001).

There are several modes of meander loop development (Brice, 1974; Petts and Foster, 1985; Lagasse et al., 2004) into which the meander forms may be placed. These include extension (lateral extension), translation, rotation, enlargement, lateral movement and complex change (double heading) (Figure 4-2).

Figure 4-2 (mode a) is usually found in reaches of a river where the loops are of a low amplitude. Mode b shows meanders that are typical of streams that are confined to narrow flood plains or restricted valleys. Mode c shows meanders that are well developed with banks that are easily erodible. Mode d represents meanders of rivers that are very sinuous and the double head or loop (secondary meander) is the result of the meander becoming too long in relation to the width of the stream. Mode e is also found in streams that are highly sinuous with point bars that are narrow. Neck cutoffs tend to occur in stretches of the river where these modes exist. Modes f and g are found in streams that less sinuous with wider point bars and banks that are easily eroded (Lagasse et al., 2004).

Materials and Methods

Spatial data was obtained from aerial photographs. The photographic images were from the following dates: 1937, 1942, 1955, 1966, 1972/3, 1988, 1999 and 2005. The rate and degree of planform change was measured from these photographs and this approach to obtain spatial data has been used extensively (Thorne and Lewin, 1979; Gurnell, 1997; Gilvear, 2000; Graf, 2000; Rumsby et al., 2001; Gaeuman et al., 2004; Tiegs and Pohl, 2005; Richard et al., 2005; Burge, 2005).

All photographic paper images were first scanned using a flat bed scanner. The images were then processed and converted to a usable format. This was not done for the 1999 and 2005 images as they were already pre-processed. This was done by geometrically correcting the images in order to view all the planimetric features on the images on a common projection (Jensen, 2005). The images were co-registered using available 2005 Digital Ortho Quarter Quads (DOQQs). Images were converted to a common scale to reduce errors (Gurnell, 1997; Hughes et al., 2006). For each year of photographic data, the left and right bank channels of the stream along with the lateral and point bars were digitized. The centerline of the channel was also demarcated using the midpoint tool in the ArcGIS software.

Rates of Migration

Larsen et al. (2002); Micheli et al. (2004) and Larsen et al. (2006) used this method to determine two values, the area of land reworked and the lateral migration rate. The first value refers to the amount of land that was eroded or deposited through migration of the river over a period of time. This area is derived by overlaying the center line of the river in one time period with the centerline of the same river for another time period. The polygon that is created by the intersection of these two centerlines is then divided by the difference in years between the two centerlines. This value gives the area (calculated in hectares) of land that is reworked per year.

The rate of migration for each year and for each reach of the study area is calculated by dividing the area reworked by the average length of the two centerlines that represent the river at different time periods and then dividing this result by the number of years between the time periods. This average rate of channel migration per year is also calculated for each reach block. The formula for this is as follows: [(Ar/L)/# years], where Ar is the area reworked for a given reach block; L is the average channel length of the two centerlines for the same reach block. A summation of all the results for all the reach blocks allows for comparisons between the total lengths of the stream for different years.

The stream centerlines were digitized and the results were derived for each reach block for the entire length of the stream. This allowed for comparative analysis for the reach blocks that were found for varying distances downstream of the dam and at different years.

Measurement of the Degree of Sinuosity

Sinuosity is used as an indicator of how much the river has meandered or curved within the floodplain. It then became possible to compare stream sinuosity temporally and spatially. The channel centerline was used as the channel center length in the calculation of the sinuosity index (SI). The SI was calculated for each of the 1 kilometer reach blocks.

Results and Discussion

Modes of Meander Loop Development

The planform views of the Oconee River shows complex meander loops and patterns typical of an actively meandering river and these patterns conform to some of the patterns outlined in Figure 4-2. Extension type loops featuring the 1942 and 1955 channels are shown in Figure 4-3. Extension loops should decrease in radius as they migrates downstream (Lagasse et al., 2004). Figure 4-4A shows that channel locations in subsequent years (1942 to 1973) reveal a more complex development of the extension loops.

The lower of the two extension loops as shown in Figure 4-4A, from 1942 to 1955, extend outward by approximately 132 meters (measured from the apex of the outer bend of the former to the apex of the outer bend of the latter). The similarly measured distance between the 1955 and 1966 channels is smaller, being just 24 meters. From 1966 to 1973, the radius of the loop is smaller than the radius of the same loop from the previous time step proving that there was no growth of the extension meander between 1966 and 1973. The largest lateral movement or extension of this loop thus took place from 1942 to 1955. Downstream channel migration also is in evidence and this is shown by the dotted arrow. Measurements do show, however, that radii of the channel loops did not all decrease in size.

Figure 4-4B shows the channels of the river from 1973, 1988, 1999 and 2005 for the same reaches shown in Figure 4-4A. The channel changed position between 1973 and 1988 creating a cutoff. The apexes of the former extension meanders have been removed with the new channel location. The 1973 channel was included to show the last position of the channel before the shifting of the channel. Figure 4-5 shows the 2006 channel of the same area shown in Figure 4-4 along with the cutoff that was created between 1973 and 1988 and the location of the former positions for the two extension loops shown in Figure 4-4A. The cutoff shown has noticeably shrunk in size when compared with Figure 4-4B.

Sections of the river do have translation meander loops that migrate in a downstream direction. According to Lagasse et al., (2004) these meander loops are the result of being confined by the presence of artificial levees, narrow valleys with a narrow floodplain. Figure 4-6 does show the 60 meter contour appears to an extent to influence the lateral movement of the meanders. Movement of the channel from 1937 to 1942 show the development of a rotation meander loop as shown by Figure 4-7.

The continued movement of the meanders across the landscape results in the creation of neck cutoffs. A number of these types of cutoffs do occur throughout the length of the stream over different times as shown in Table 4-1. These cutoffs occur as a result of streams having large loops (sometimes with compound loops) with high sinuosities (Lagasse et al., 2004). All the cutoffs shown in Table 4-1, are neck cutoffs. Neck cutoffs are more common since they occur on deposits within the floodplain that have low elevation and across point bars in channels (Knighton, 1998).

The development of a neck cutoff by closure is shown in with the movement of the 1937 and 1942 channels (Figure 4-8). The 1966 image in Figure 4-9 shows the actual cutoff that was created between 1937 and 1942. The white dotted arrow in Figure 4-9 also shows the potential site for another cutoff due to the presence of another neck cutoff by closure meander loop.

Chute cutoffs occur in rivers that have wide point bars and are less sinuous with banks that are easily erodible. In the low-amplitude meander loops, the river breaks across the point bar cutting off the loops (Lagasse et al., 2004). The cutoff that occurred between 1973 and 1988, however, appears to be created by a meander mode of development called the diagonal cutoff by chute. Accurately discerning if the correct mechanism that created the cutoff is difficult since the time span between photographs is 15 years and in that time.

Some clues do exist that suggest that the cutoff created was not due to a chute cutoff mechanism. For instance, in Figure 4-10, the meander mode of the 1973 channel is the typical neck cutoff by closure meander mode as shown in Figure 4-2(e). In Figure 4-10, the position of the 1988 channel suggests that the cutoff may have been created by diagonal chute flow mechanism as shown in Figure 4-2(f). A continued evolving and movement of the river channel suggests that two features, diagonal cutoff by chute and neck cutoff by chute (Figure 4-2 (f) and (g). Figure 4-11 shows the 1988 photograph of the same reach shown in Figure 4-10 along with the location of the cutoff that was created. The width of the cutoff is noticeably smaller than that of the 1973 channel shown in Figure 4-10. This is proof that the cutoff was created closer to 1973 than to 1988 since the water in a cutoff is progressively reduced in volume after it has been removed from its primary source, that is, the river. Furthermore, the meander neck at its narrowest for the 1973 channel is in a similar location of the 1988 channel. This is important since the breaching of one bank by the river to another bank in the cutoff formation would most likely occur at the narrowest point in the neck of the meander. The narrowest points of the meander neck represent the greatest degree of erosion. Therefore, the mechanism most likely responsible for the creation of this cutoff is not a diagonal cutoff by chute, but by the neck cutoff by enclosure. The fact that no chute cutoff is present in the study area suggests that the right conditions needed to create a chute cutoff development are absent.

Meander Bend Geometry and Meander Migration

The lateral migration rates are calculated for each 1 kilometer reach. The r_C/w values are calculated as the average r_C/w values for each of the 1 kilometer reach blocks. Only reaches in the coastal plain were used in this analysis since those in the Coastal Plain are confined by the nature of the river valley and do not reflect meanders that are typical of an alluvial river. Also, the 1937-1942 lateral migration rates were plotted against the r_C/w values for the 1937 channel. The rationale is that the changes in the r_C/w values would most likely be reflected after the stream meander bend geometry had been established. Likewise, the 1942-55 lateral migration rates were plotted against the 1942 channel and so on.

Figure 4-12 shows the mean migration rates from 1937 to 1999 plotted against the mean of the r_C/w values from 1937 to 1999. This figure shows a cluster of points (enclosed within a circle) whose lowest ranked point is 0.13 m/yr higher than the next highest point. The average range of lateral migration rates for this cluster of points is 2.71 to 2.93 m/yr while their r_C/w values fall between 2.64 and 2.92 with an average r_C/w ratio of 2.73. This cluster represents 63% of all the meanders for which ratios were calculated.

Figure 4-12 shows that three meanders (enclosed in a dotted polygon) are located below the r_C/w ratio range of the cluster and the range of the average lateral migration rate per year for those three points is 1.76 to 2.17 meters. Sixteen meanders (enclosed in a dotted polygon) are located above the cluster's average lateral migration range with a lateral migration range of 2.01 to 2.58 m/yr meters per year. The figure also shows that a meander with an average r_C/w ratio of 2.87 does fall within this 2.64 and 2.92 r_C/w ratio range but the average lateral migration rate for this point is 2.22 m/yr meters per year which is 0.49 meters per year lower than the lowest lateral migration rate for the bends within the cluster. It is denoted by a rectangle. The possible reason for this is that the point of the river where the r_C/w ratios were obtained does have fairly large meanders, but overtime, there is relatively little shifting of the channels at that reach.

These finding do not perfectly match Hickin and Nanson's (1984) ideal r_C/w ratio of 2.5, where the greatest lateral migration of meanders would take place, it does strongly support their findings that generally, the least lateral movements occur when r_C/w ratios of meanders fall below and above the 2-3 range. Figures 4-13 and 4-14 show the results of field studies undertaken by Hickin and Nanson (1984) that show the relationship between relative migration rates and bend curvature. Both these figures show that the clustering patterns are generally similar to those of Figure 4-12. A total of 23 field sites were used by these researchers in deriving the r_C/w ratios of 2 to 3. Care, however, should be taken when implying that all alluvial rivers that have actively migrating channels should show similar relationships since Figure 4-12 is based upon average migration rates which mask many of the subtle differences from one time-step to the other.

Figures 4-15 to 4-21 show the relationships between r_C/w values and lateral migration rates for each of the 7 time steps and for each figure, parallel vertical lines are drawn at the points in the X axis at the 2 and 3 r_C/w ratios. For all the figures, except Figures 4-16 and 4-18, the majority of the highest lateral migration rates are found within the lines of the r_C/w range of 2 to 3. Figures 4-15 to 4-21 do show that while clustering of the points does occur, the maximum range of r_C/w from time step to time step differs.

Figure 4-15: Four of the top five migration rates occur outside the 2-3 R_C/W ratio range with three of these occurring above the 2-3 R_C/W ratio. The highest occurred above the 2-3 R_C/W ratio range. Figure 4-16. None of the top five migration rates occurs inside the 2-3 R_C/W ratio range with four of the five occurring below the 2-3 R_C/W ratio of 2. Figure 4-17. Four of the top 5 migration rates occur within the 2-3 R_C/W ratio range, with the fifth occurring above the 2-3 R_C/W ratio. The highest three rates occurred within the 2-3 R_C/W ratio range. Figure 4-18. Two of the top five lateral migration rates occur within the 2-3 R_C/W ratio range while two occur below the 2-3 R_C/W ratio range. The highest rate occurred within the 2-3 R_C/W ratio range. Figure 4-19. Three of the top five lateral migration rates occur within the 2-3 R_C/W ratio range while the other two occur below the 2-3 R_C/W ratio range. The highest rate occurred below the 2-3 R_C/W ratio range. Figure 4-20. Two of the top five lateral migration rates occur within the 2-3 R_C/W ratio range with two occurring above the 2-3 R_C/W ratio range. The highest rate occurred above the 2-3 R_C/W ratio range. Figure 4-21. Four of the top five lateral migration rates occur outside and below the 2-3 R_C/W ratio range and this includes the highest of the five points.

The rate at which fluvial entrainment and bank retreat occur are dependent upon a number of variables such as stream bank characteristics that to an extent determine the rate of mass wasting, stream velocity (Lagasse et al., 2004) bank height (Hickin and Nanson, 1984). Each river possesses unique characteristics that determine how these and other factors intertwine to retard or encourage lateral migration and downstream channel movement.

There is also evidence that some reaches of the Oconee when they do migrate, do not always migrate downstream. Figure 4-22 shows a 1966 aerial photograph of a section river and the outline of the 1973 digitized channel superimposed upon it. Clearly, the river migrated upstream at this point.

One possible explanation for this is given by Carson (1986) in a study of Waireka Stream which showed asymmetric meander patterns that tended to migrate upstream rather than downstream. This is caused when the channel flow is prematurely deflected to the concave or outer bank of the stream in a meander. The deflection point is just above the apex of the bend. This action scours a deep pool against the outer bank and creates an in-stream bar at the downvalley end of the pool. As this bank continues to become larger, it causes the stream flow that traverses the meander bend to be diverted to the up-valley section of the bend.

Upstream migration develops more readily in tight bends and in channels with gravel beds (though rarely in sand bedded streams) and banks simply because in low competent flows, these banks would not be easily entrained. It is difficult to discern if there are bars in the concave bends of the meanders shown in Figure 4-22 due to the quality of the image. Furthermore, the channel substrate of the Oconee in this section is predominantly sandy clays and marls (Lawton, 1977) and the banks are made up of sandy material that is coarse (Trimble, 1969). The bends in this section of the Oconee are tight with bend A and bend B (as seen in Figure 4-22) having r_C/w

ratios of 2.98 and 2.18 respectively. The aerial photographs dated after the 1973 photographs do show that the channel at this point migrated downstream. The reason for this upstream migration at this point in the stream is not clear although it is possible that local anomalies in the grain composition and structure of the banks at this reach in the river may cause the river to respond like a gravel type river. Another possible explanation is that increased competence due to increased flows may have removed these bars in the outer banks, thus creating the necessary conditions for the meanders to resume their downstream migration trend.

Conclusions

The approach used to explain lateral planform movement across landscapes was to discuss the relationship between the radius of a channel curve and the width of that channel. The discussion on the importance of meander bend geometry by Hickin and Nanson (1984) was useful for this study since the principles outlined by them were generally applicable to the patterns of the Oconee River. Hickin and Nanson’s approach did not fully explain the reason for the variation and range of differences of the rate of lateral migration of the Oconee River.

The r_C/w ratio, though useful, has its limits, especially in the practical difficulties involved in determining the radius of curvature. It was easier to measure and record the radii of tighter meander bends along the Oconee but where the bends were wider and less tight, a lot more subjectivity was involved in determining the most likely radius of curvature. Indeed, the method of defining the radius of curvature of meander loops is also not without its critics. It has been argued that traditional methods of measuring meander geometry are flawed and limit the application of models that attempt to explain more complex forms of meander development. Furthermore, there is a high degree of subjectivity that is involved with the identification of the inflection points at meander curves (Güneralp and Rhoads, 2008).

Many of the meanders of the Oconee do migrate downstream and this is explained by the theories that describe this movement across the landscape. Some of the Oconee's meanders do migrate upstream and while an explanation was provided, the mechanisms for this upstream movement are still not clear. It is the consensus of some researchers that the mechanisms and processes that govern meander migration are not clearly understood (Güneralp and Rhoads, 2008).

The theory of self organized criticality is useful because it shows that the typical alluvial river is dynamic because it is in a state of fluctuation as its meanders oscillate between one state and another state. This self organized process in rivers is best understood at the reach level scale rather than at the larger, more complex scales. This is so because it may be difficult to make a viable connection between processes taking place several kilometers apart in the same river.

In addition, the Oconee River challenges some of the basic tenets of this theory since cutoff creation did not always or inevitably occur at some reaches where the sinuosity indexes exceeded the threshold point. The theory does not account for unique characteristics of the Oconee River such as in-homogeneities in the bed and banks of the river, variations in stream flow, differences in slope of the channel bed, variations in cross sections along meanders, and the differences of how bank vegetation may influence bank erosion rates.

Furthermore, the fundamental assumptions and claims of this theory may be tenuous and not quite substantive. To claim that a river with a straight course is representative of a river that is ordered fails to account for the fact that by nature, streams are rarely straight because straight courses are unnatural. This is so because straight channels induce a river to move laterally across its floodplain and meander in an effort to achieve stability. A meandering stream is a reflection of a river's effort to maintain a graded profile (Gomez and Marron, 1991).

The Oconee is a river that is fairly mobile that keeps changing positions on its floodplain. These adjustments in its location over the course of time show a river that does not tend towards a straighter course. During one year, some reaches become less sinuous while others achieve greater sinuosity. The same sinuous reach may become less sinuous in another year and so on. Nesting or limiting or interpreting these changes in an order – chaos continuum, limits how one views rivers like the Oconee. This is especially crucial from a management perspective since the ultimate aim of land managers, etc should never be to achieve less movement of a river. Rather, managers should seek to establish the range of spatial parameters which allow a river to operate in its natural settings and make decisions based upon these parameters.

One crucial and important lesson demonstrated by the Oconee River is that theories that explain river planform movement have limits because they are constantly challenged by the uniqueness of each river since no two rivers are the same. This does not mean that models developed to explain river behavior across landscapes are unimportant or redundant. Rather this shows that the models need to be robust and flexible and more importantly, based upon sound theories of fluvial development. To view streams only in the context of order or chaos (as Stolum has done) is to fail to understand the complex nature of streams and some of the fundamental principles that govern alluvial stream behavior across landscapes.

The models that explain river behavior are by nature limited simply because they are abstractions of reality and do not include some of the important variables that allow them to fully explain river behavior. This section of the Oconee that is studied shows that the model of organized criticality is not robust enough to explain the changes that took place along these reaches that were studied.

In the riverine landscape, therefore, the concept of order should never be looked upon as a stream that does not migrate or one that has a reduced sinuosity. Neither should the concept of chaos be viewed as a river that is constantly changing locations across its floodplains. There should be the expectancy that an alluvial river will migrate across its landscape in various degrees of intensity over time and space simply because of the non-static nature of both the intrinsic and extrinsic variables that govern the very nature of rivers.

River management therefore ought to focus not only upon the behavior of the river itself, but also upon the significance of the factors that govern or influence river planform behavior. Questions such as why do some reaches exhibit the propensity to move more than other reaches, and why do rivers still maintain their steady locations over the course of several years while the location of the same stream changes rapidly at other reaches need to be asked and answered.

Table 4-1. Cutoff occurrence, Oconee River: 1937-2005

Time steps	Number of cutoffs
1937-1942	3
1942-1955	0
1955-1966	2
1966-1973	2
1973-1988	2
1988-1999	1
1999-2005	1

Table 4-2. Mean lateral migration rates (for time steps): Oconee River, 1937-2005

Time steps	Mean lateral migration rate(m/year)
1937-1942	4.20
1942-1955	2.68
1955-1966	2.23
1966-1973	3.21
1973-1988	1.53
1988-1999	1.56
1999-2005	2.70

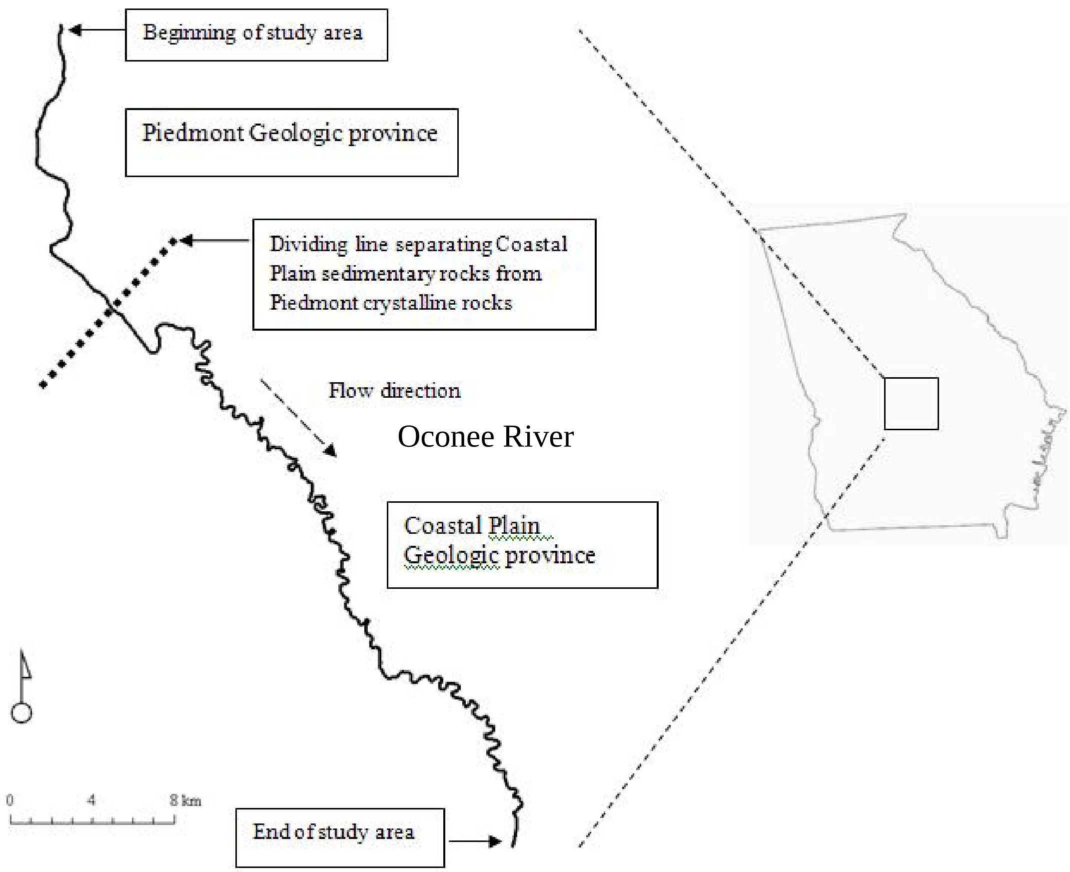

Figure 4-1. Location of the study area: Oconee River, GA

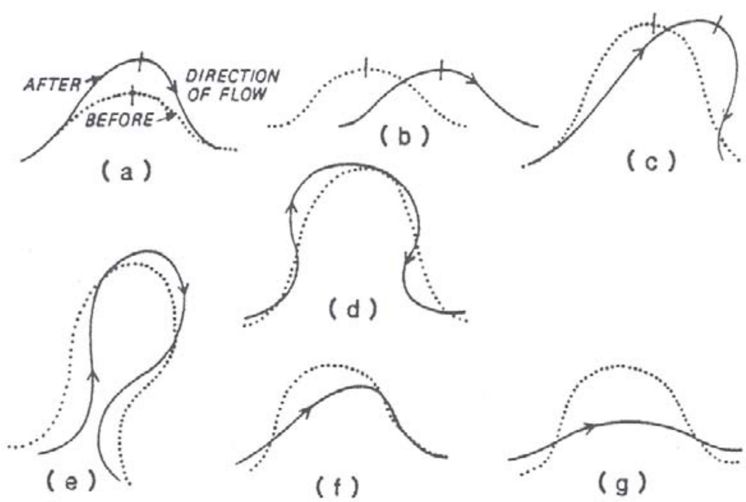

Figure 4-2. Modes of meander development: (a) extension, (b) translation, (c) rotation, (d) conversion to a compound loop, (e) neck cutoff by closure, (f) diagonal cutoff by chute, and (g) neck cutoff by chute. Taken from Lagasse et al., 2004. (Used with permission)

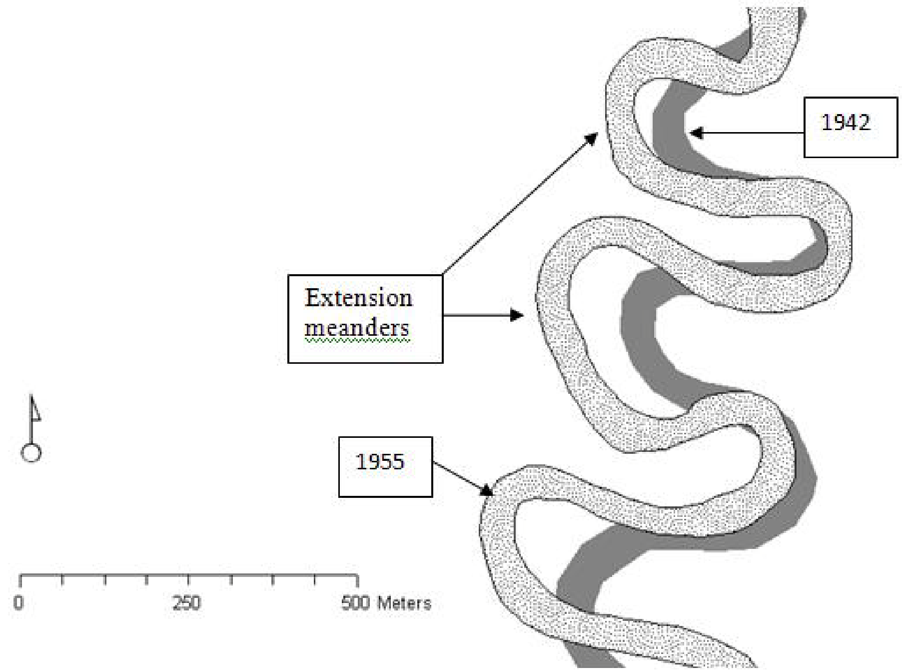

Figure 4-3. Extension meander, Oconee River: 1942 and 1955 channels. Streamflow is from north to south. River km 49 – 51.

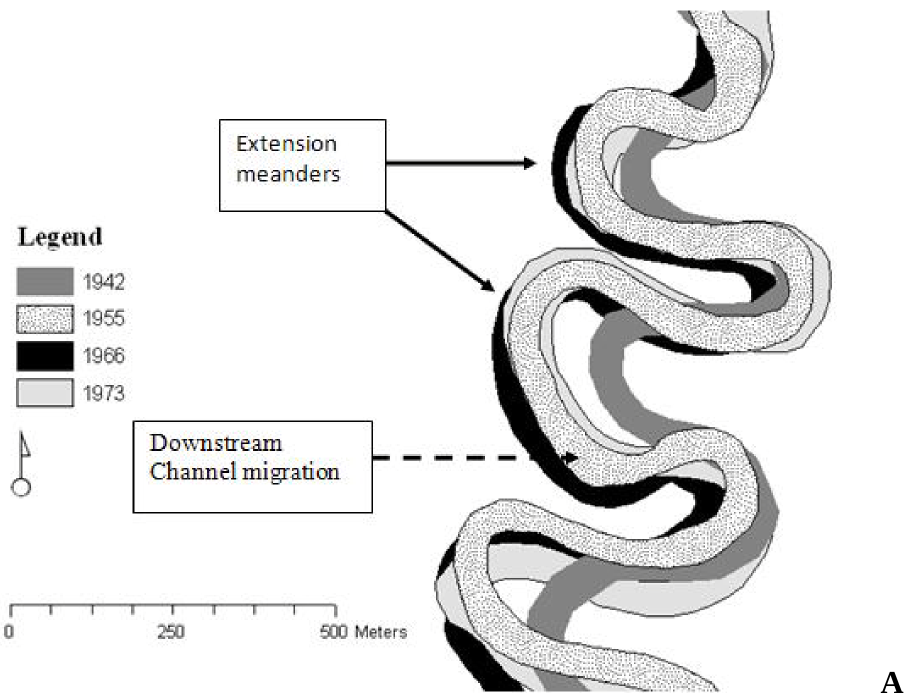

Figure 4-4. Meander migration A) Extension meanders and some downstream migration, Oconee River: 1942, 1955, 1966 and 1973 channels. Streamflow is from north to south. . River km 49 – 51. B. Shifting of the Oconee River from 1988 to 2005 showing neck meander by closure. The 1973 channel is the location of the river on the floodplain before the shifting occurred. River km 49 – 51.

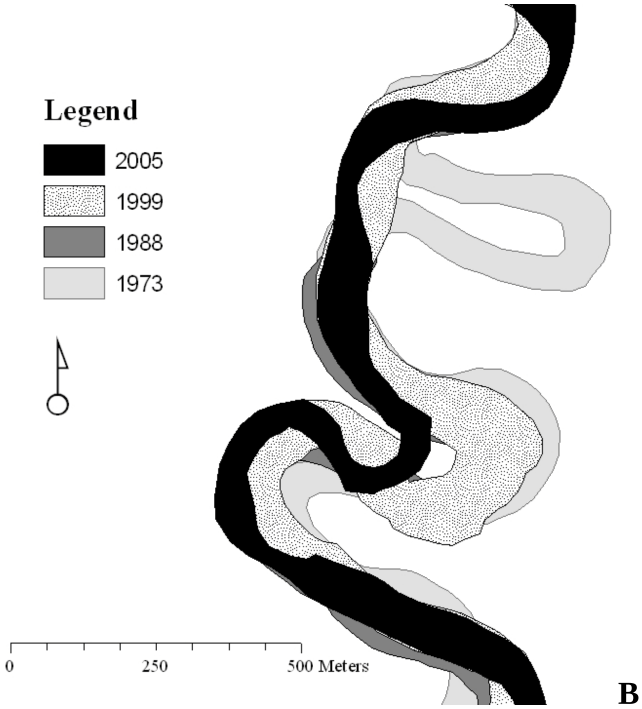

Figure 4-4. Continued

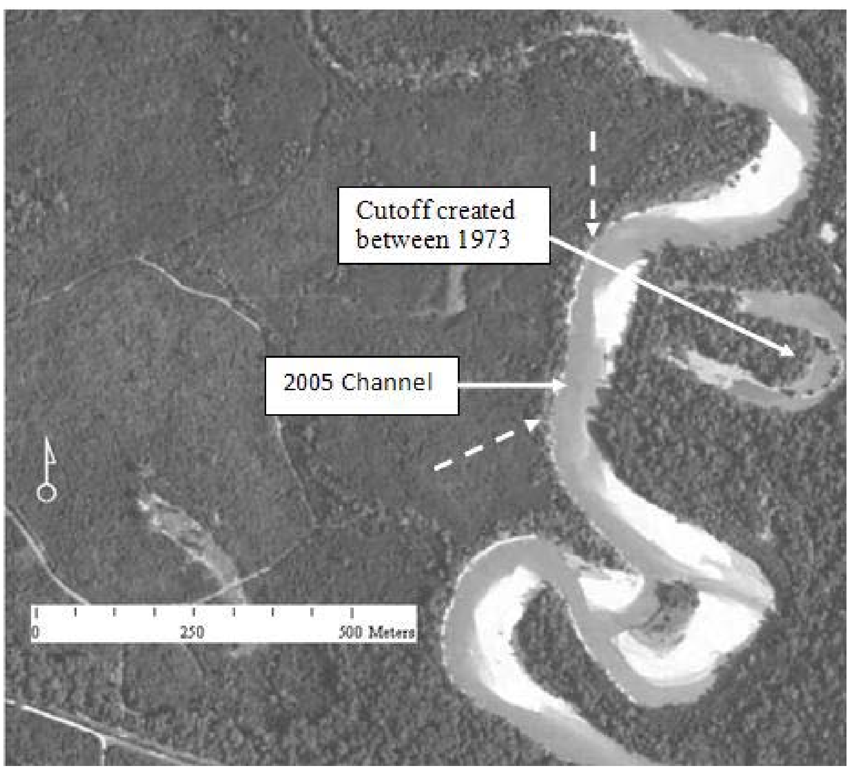

Figure 4-5. 2005 Oconee River with cutoff (created between 1973 and 1988). The apices of the extension meanders shown in Figure 4.4A, are shown by the dotted arrows. Reaches shown are similar to those shown in Figures 4-4A and B. River km 49 – 51.

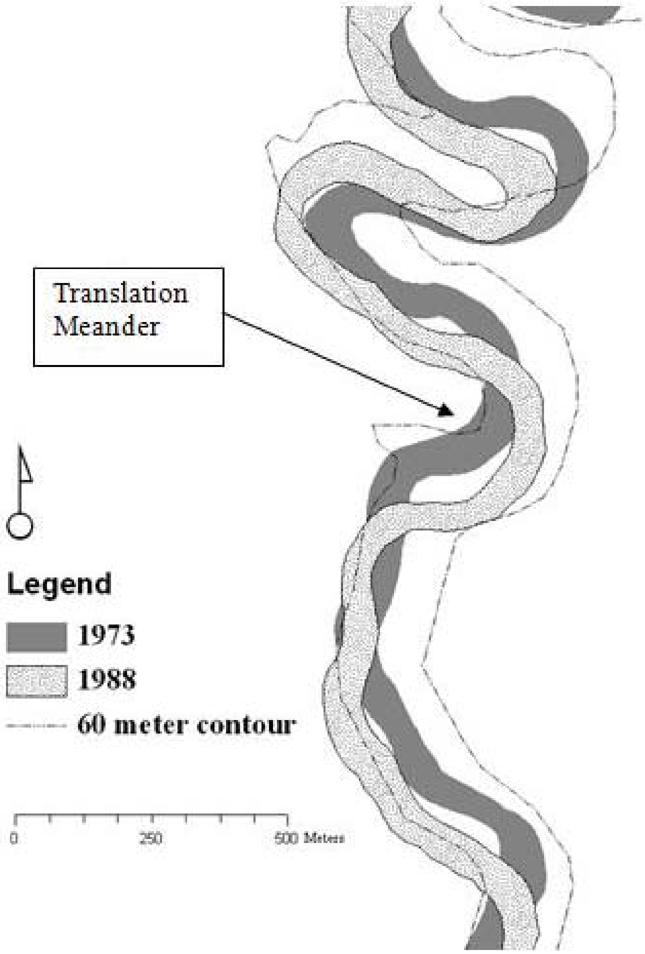

Figure 4-6. Translation meander, Oconee River: 1973 and 1988 channels. Streamflow is from north to south. River km 50 – 52.

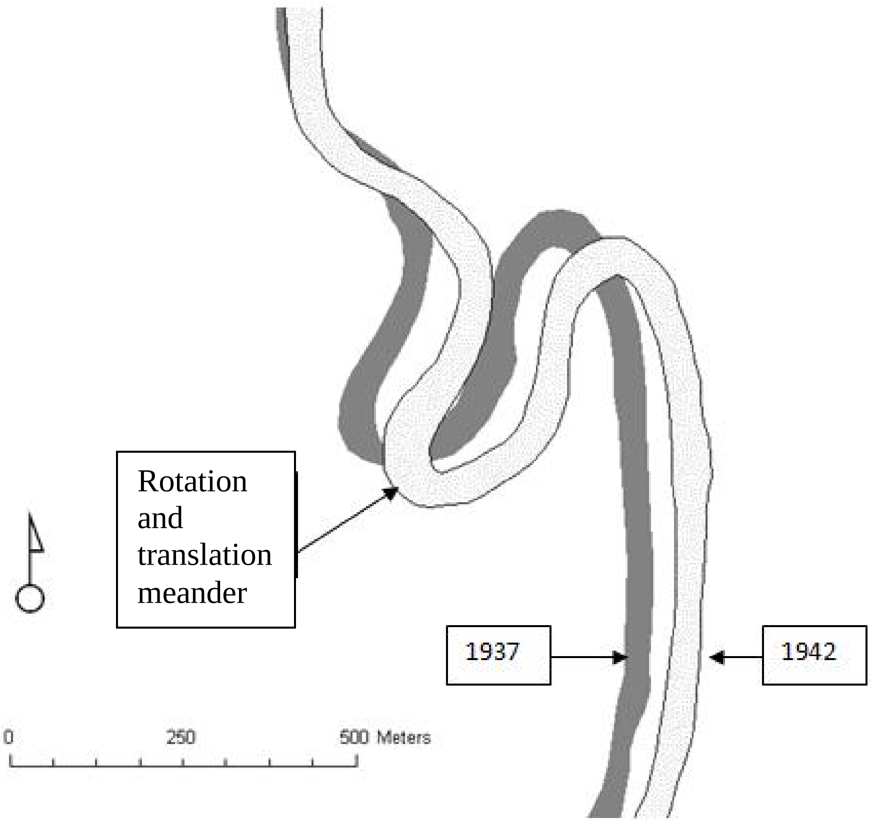

Figure 4-7. Rotation and translation meander, Oconee River: 1937 and 1942 channels. Streamflow is from north to south. River km 38 – 40.

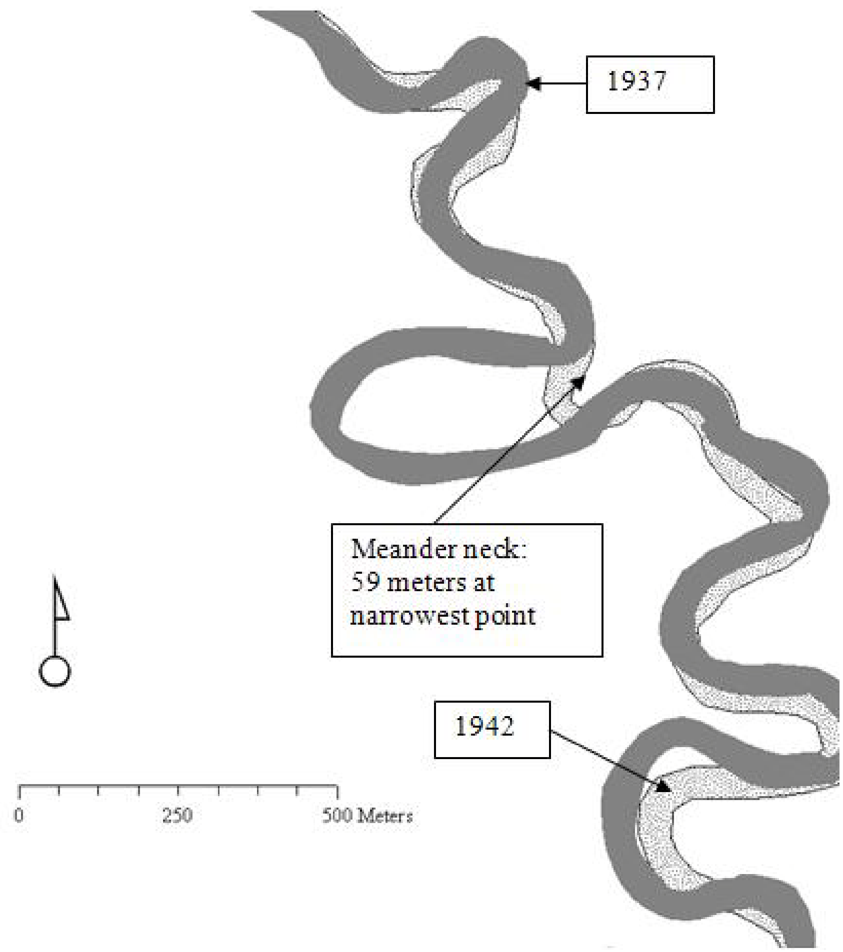

Figure 4-8. Neck cutoff by closure, Oconee River: 1937 and 1942 channels. River km 46 – 50.

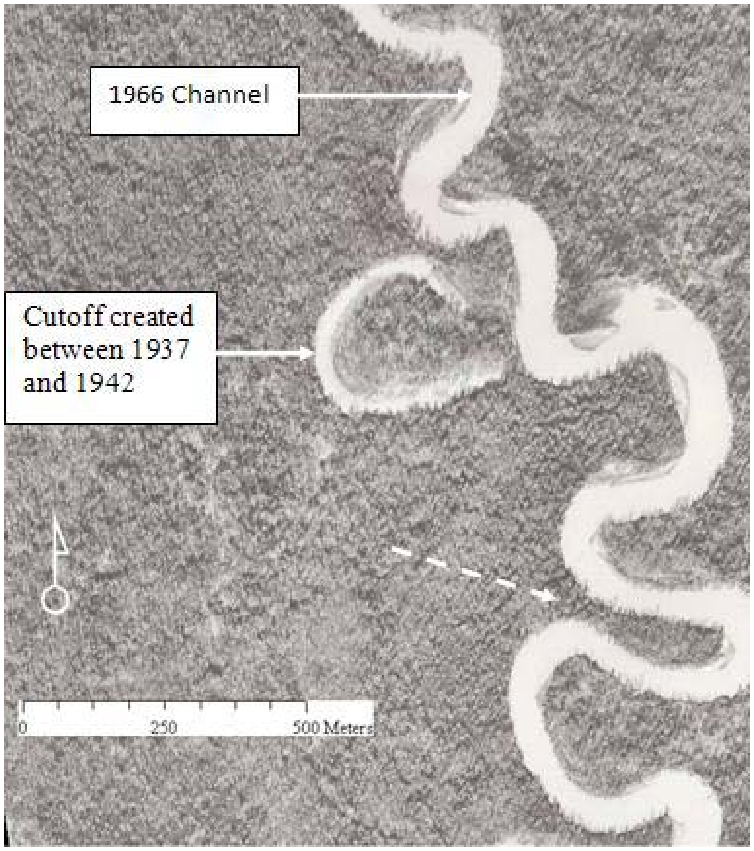

Figure 4-9. Oconee River showing cutoff that was created between 1937 and 1942: 1966 photograph. The dotted arrow shows the potential site for the creation of another neck cutoff. River km 46 – 50.

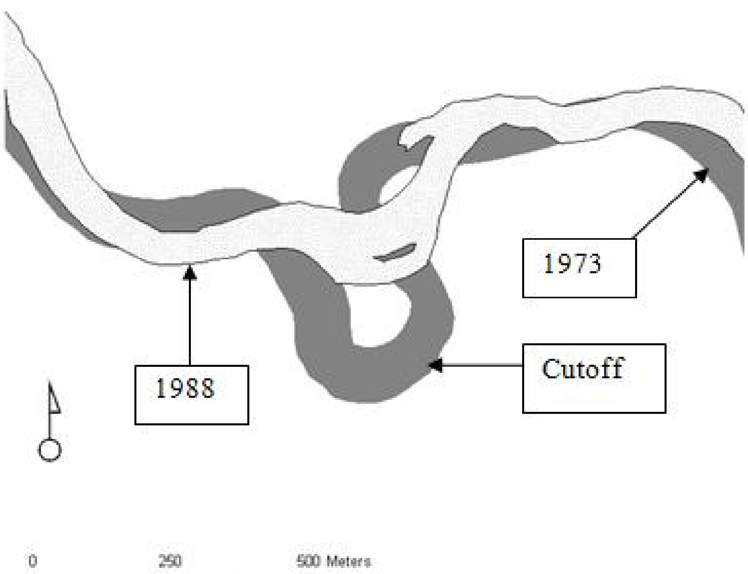

Figure 4-10. Possible diagonal cutoff by chute (with possible development of neck cutoff by chute), Oconee River: 1973 and 1988 channels. River km 59 – 61.

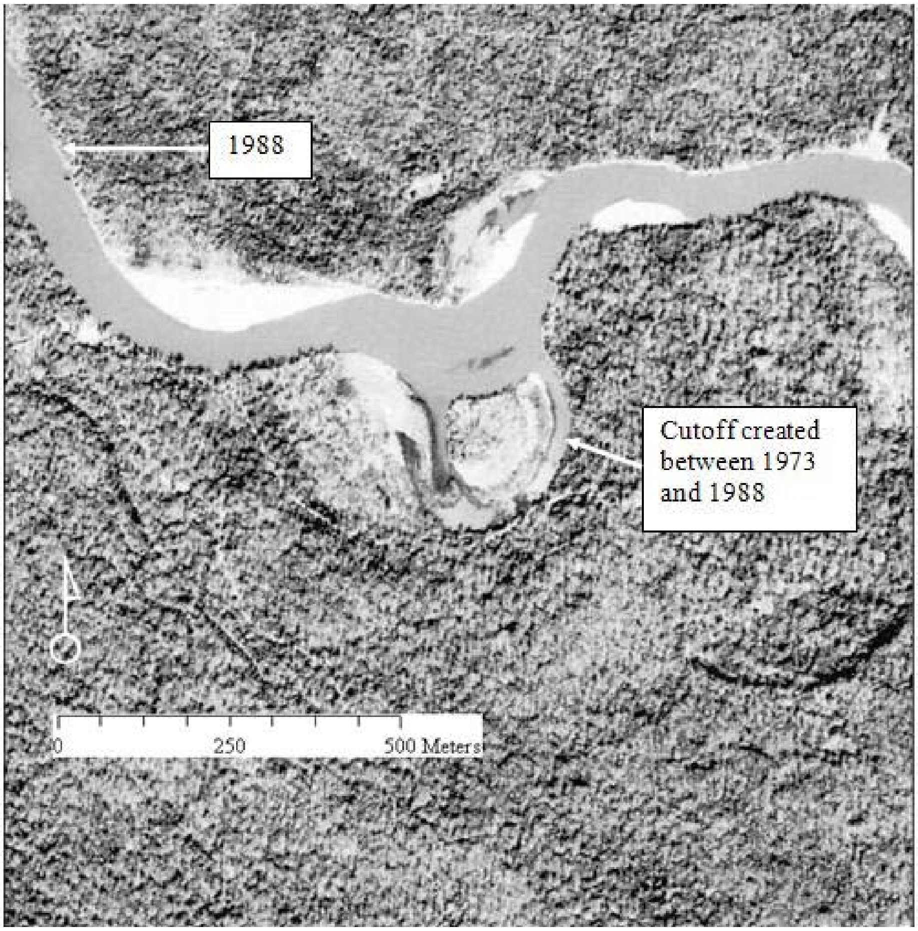

Figure 4-11. 1988 channel, Oconee River and outline of cutoff created after 1973. Streamflow is from left to right. Heading for 4-2g (neck cutoff by chute), but not yet complete. River km 59 – 61.

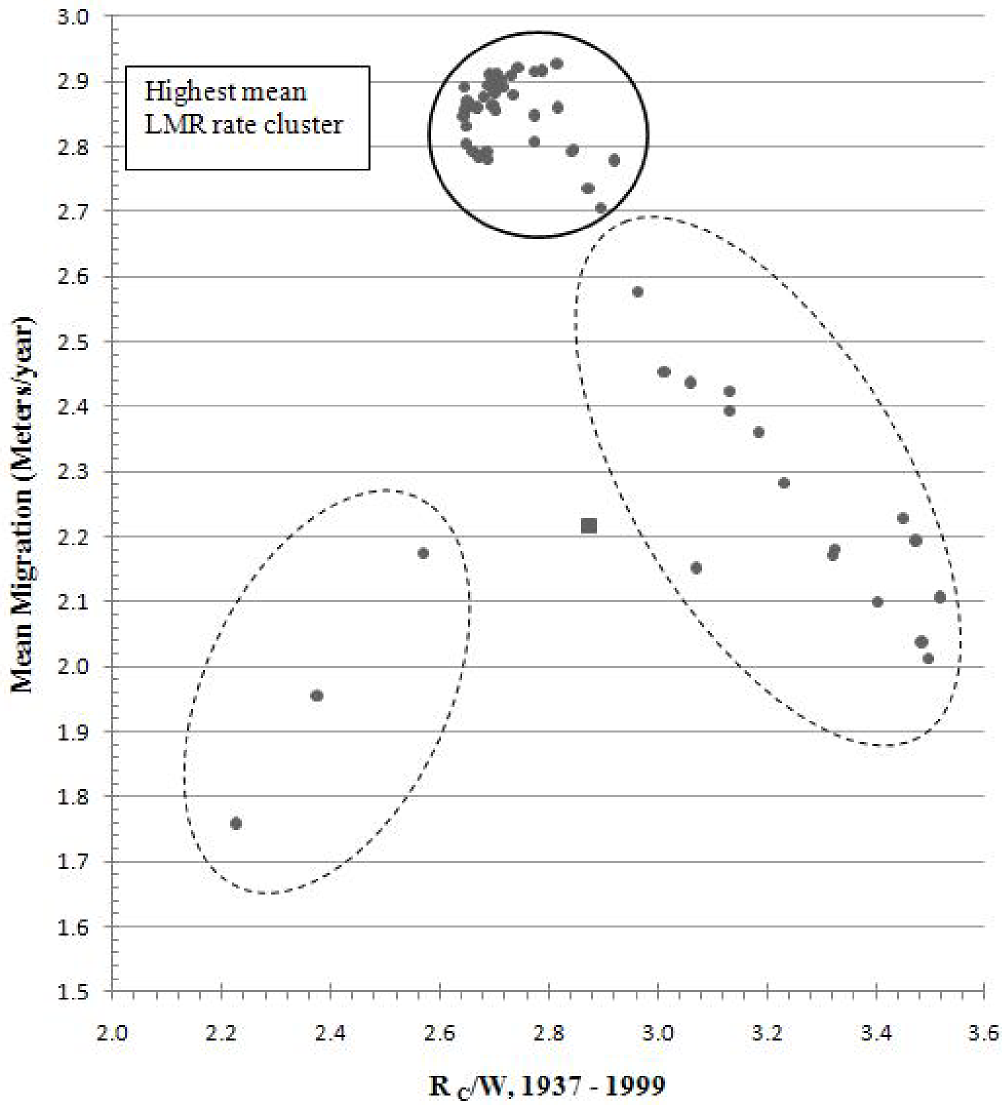

Figure 4-12. Lateral migration rates vs R_C/W ratios, Oconee River: 1937-1999, with solid polygon enclosing points with highest mean LMR and polygons with dotted borders showing points outside optimal R_C/W range for maximum lateral migration.

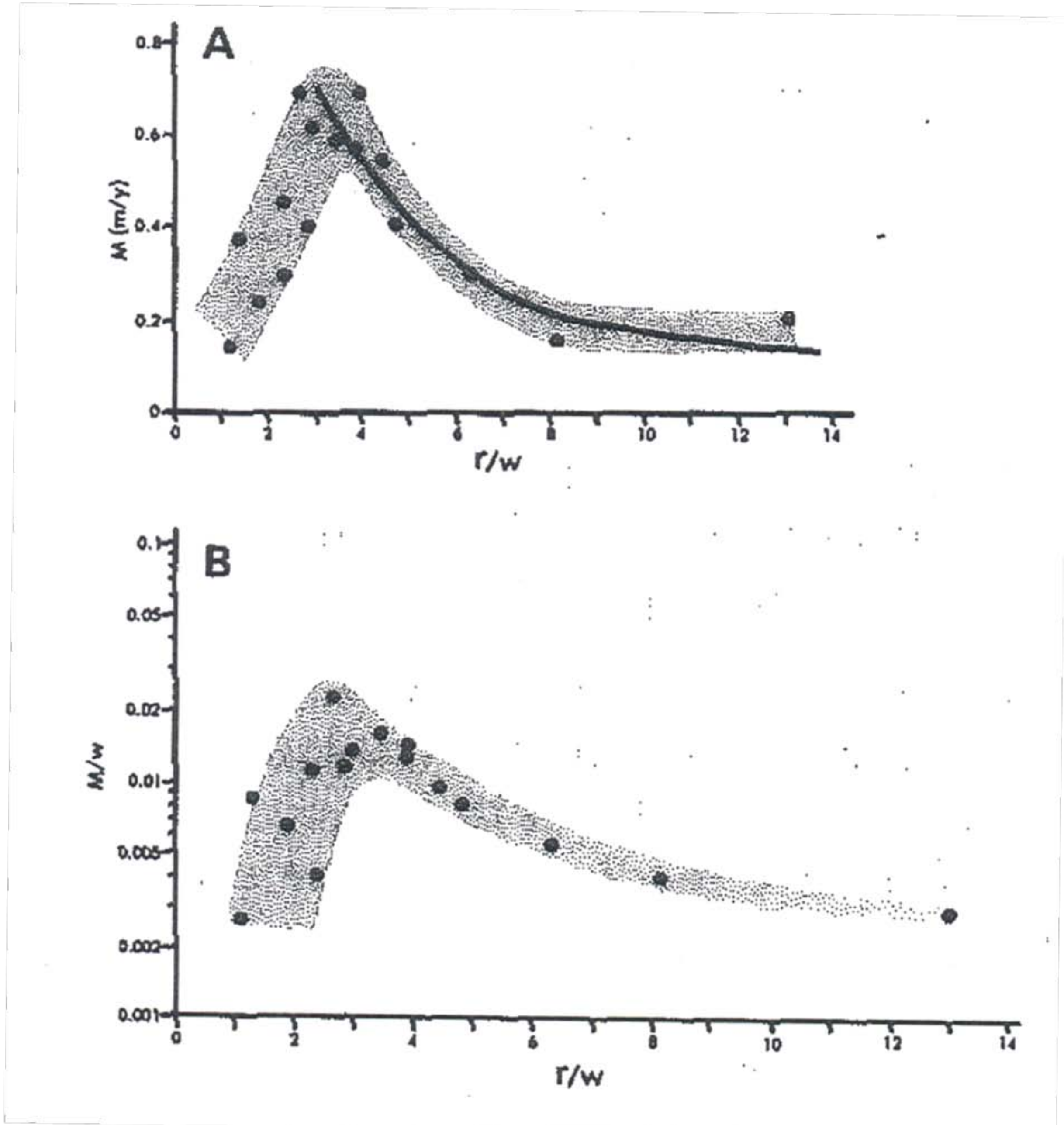

Figure 4-13. Locations of field sites in Western Canada. Taken from Hickin and Nanson, 1984. (Used with permission)

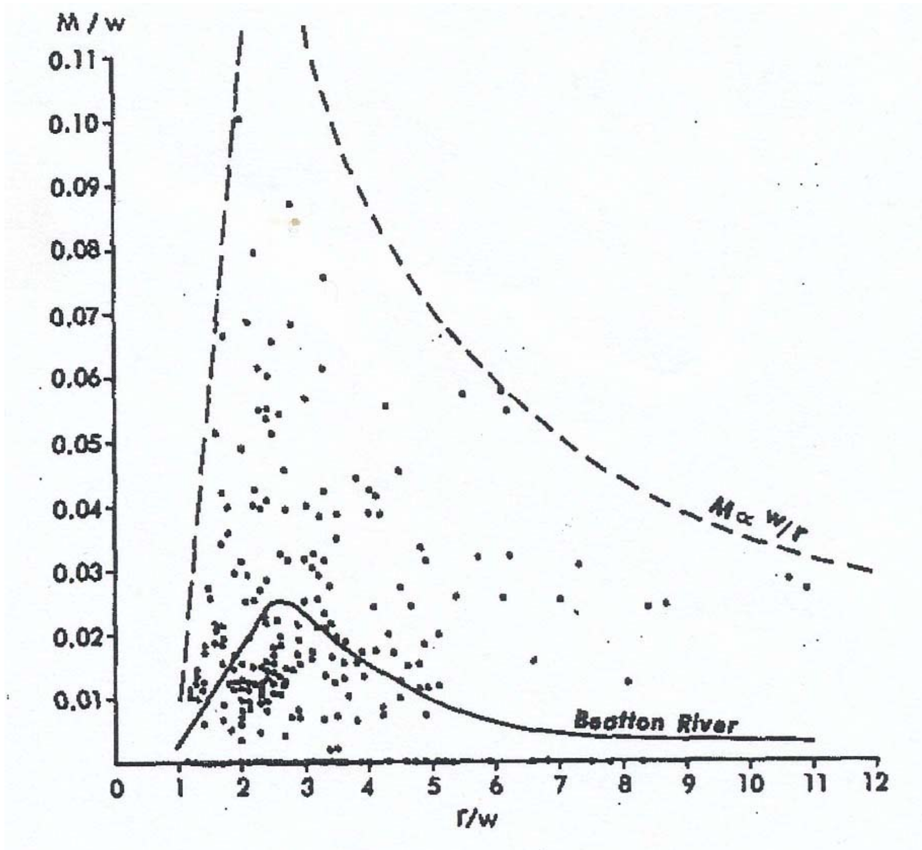

Figure 4-14. The relation between relative migration rates and bend curvature ratio for all field sites. (Taken from Hickin and Nanson, 1984. (Used with permission)

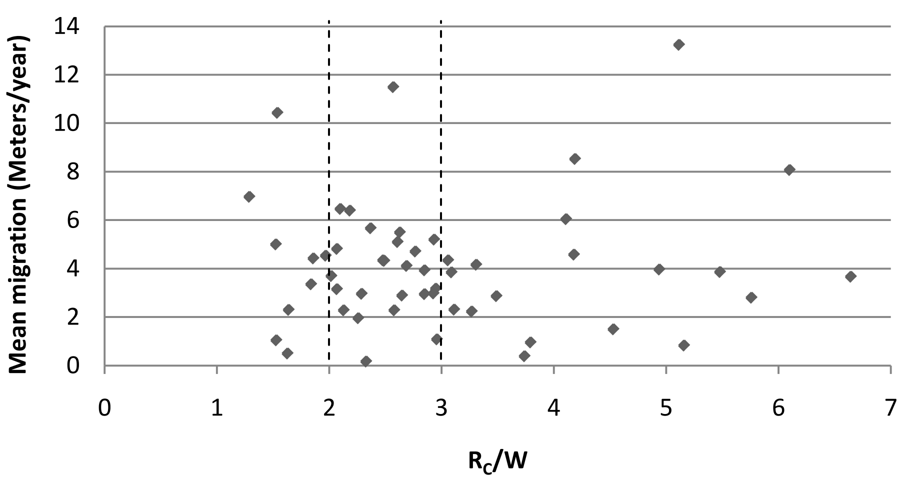

Figure 4-15. Lateral migration rates vs. R_C/W ratios: 1937-1942

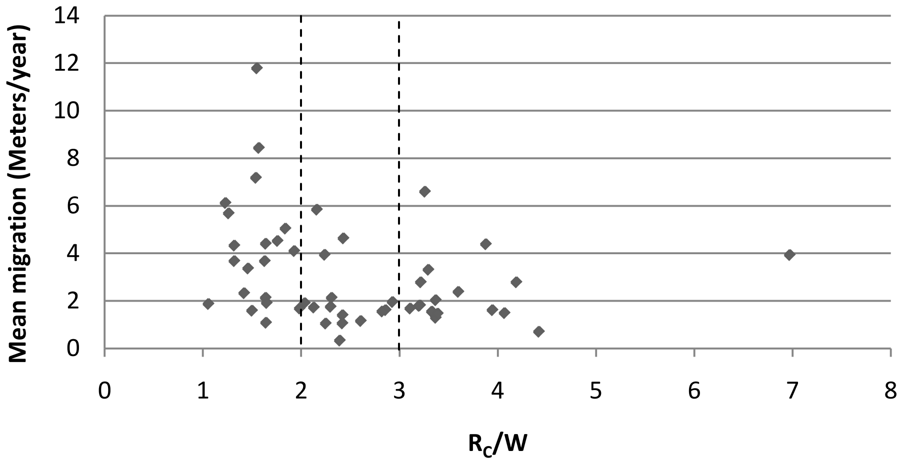

Figure 4-16. Lateral migration rates vs. R_C/W ratios: 1942-1955

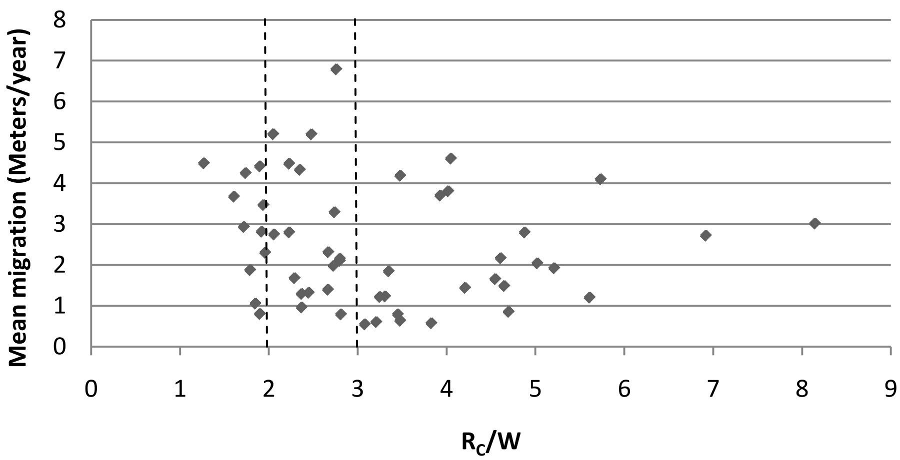

Figure 4-17. Lateral migration rates vs. R_C/W ratios: 1955-1966

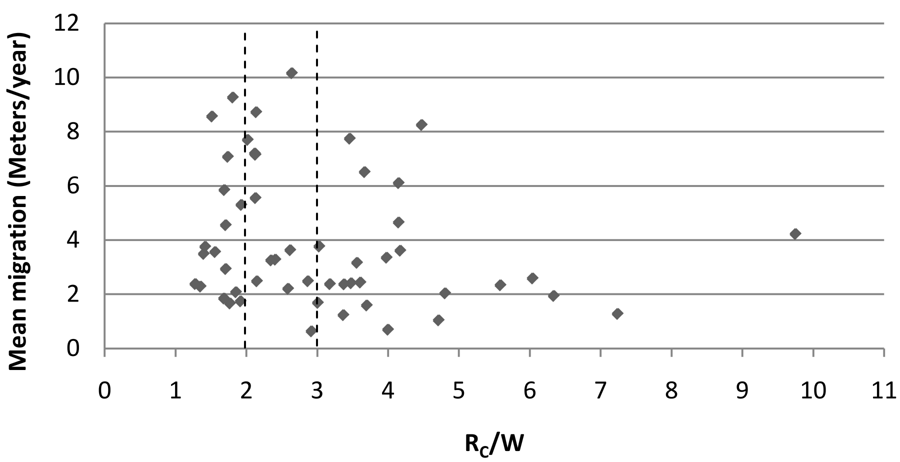

Figure 4-18. Lateral migration rates vs. R_C/W ratios: 1966-1973

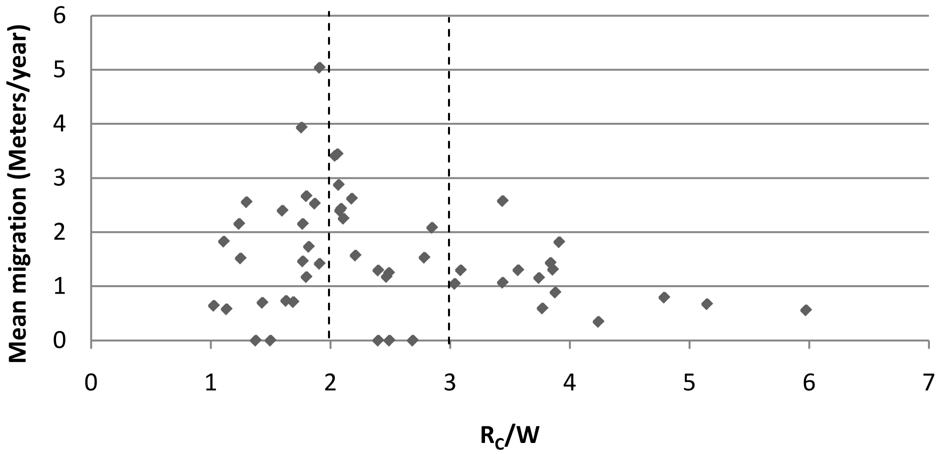

Figure 4-19. Lateral migration rates vs. R_C/W ratios: 1973-1988

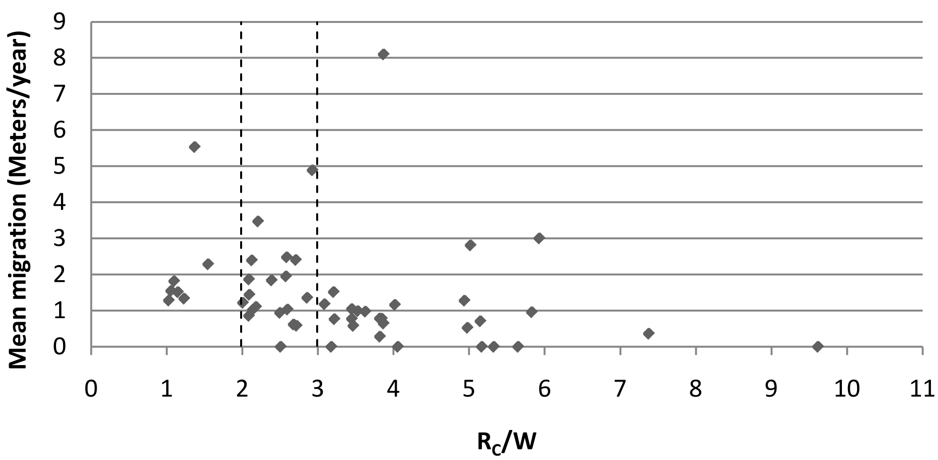

Figure 4-20. Lateral migration rates vs. R_C/W ratios: 1988-1999

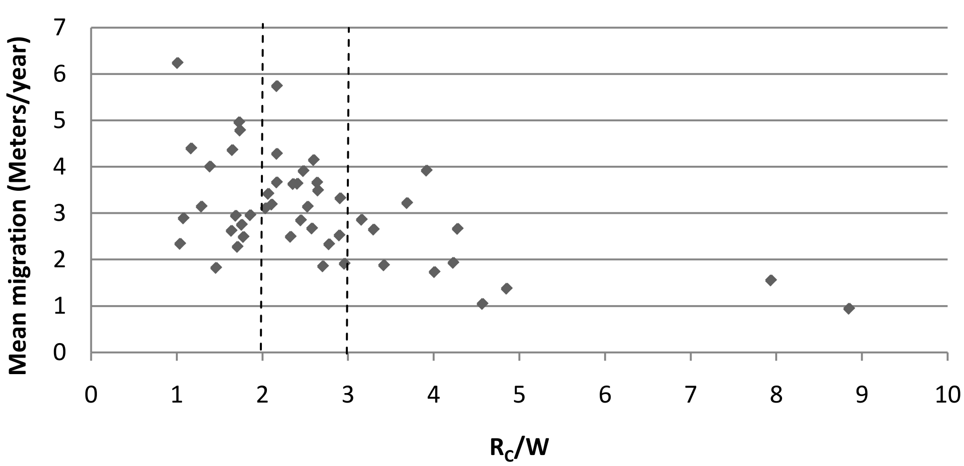

Figure 4-21. Lateral migration rates vs. R_C/W ratios: 1999-2005

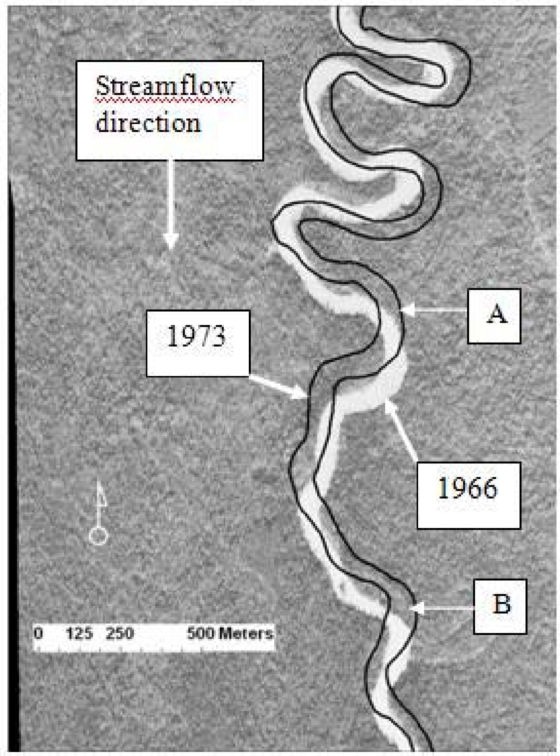

Figure 4-22. Upstream migration of meanders, Oconee River: 1966 to 1973. River km 49 – 52 .

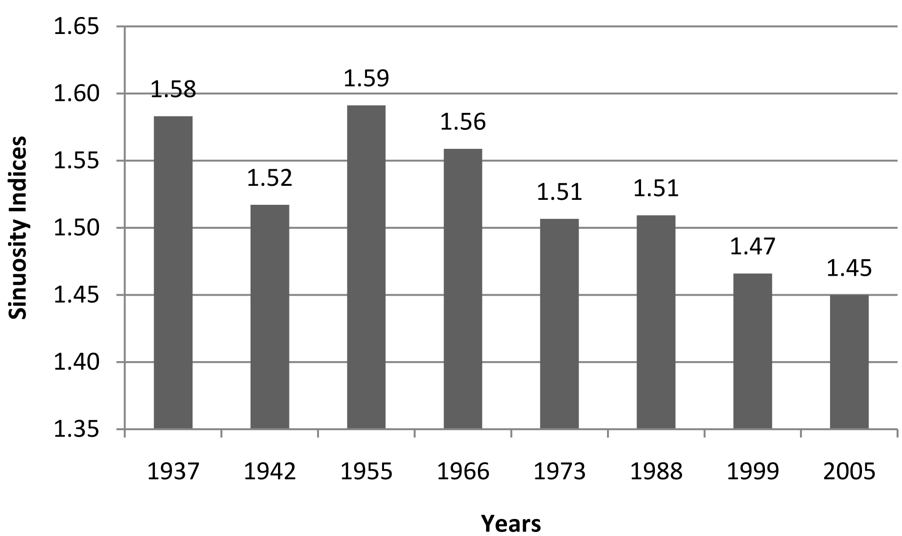

Figure 4-23. Sinuosity Indexes (SI) for Oconee River: 1937-2005. Mean SI for each year are indicated above the bars.

CHAPTER 5
CONCLUSION: RIVER PLANFORM CHANGE DOWNSTREAM OF THE OCONEE RIVER, GA

The measurements that were used to determine lateral migration rates are based upon the instant when the aerial photographs were taken. Aerial photographic data covered a wide enough time span to determine the effects of the Sinclair Dam upon the geomorphology of the Oconee River since it is possible to make comparisons between the pre- and post-dam time frames. Data provided in this study are therefore based upon the times when the aerial photographs were taken. The data is exceptionally useful since the scale and quality of the images allowed for detailed analysis for time frames in the past that would have been otherwise difficult to ascertain. The spatial analysis is reasonably accurate and clearly, the use of aerial photographs in this type of research has received widespread support (Thorne and Lewin, 1979; Nanson and Hickin, 1983; Gurnell, 1997; Gilvear, 2000; Graf, 2000; Rumsby et al., 2001; Gaeuman et al., 2004; 2005; Richard et al., 2005; Burge, 2005; Tiegs and Pohl, 2005; Hooke, 2006).

Contributions Made by This Dissertation

Even though it is common to find dams across several rivers across the planet, there are relatively few studies that have focused upon how dams affect the way rivers migrate across the floodplain. This dissertation uses eight decades of photographic evidence providing ample spatial data about the way the Oconee River behaved before and after the construction and completion of the Sinclair Dam. This research provided a useful framework in which to apply and test theories of fluvial geomorphology that pertain to the movement of river channels across the landscape. The work shows that the theories do not fully explain the nature of river planform change; neither do they explain why the rates differ among the sections where movements have occurred. For instance, the concept of chaos and order as it pertains to a river becoming more or less sinuous has its shortcomings because it has yet to prove that a straight stream is in a state of order while a more sinuous stream is in a state of chaos.

An understanding that a stream meanders because it strives to attain a state of equilibrium has considerable merit as it adds to the understanding in a general sense of why streams are more likely to migrate or not migrate across their landscapes. The theory of equilibrium may not provide a suitable explanation concerning the degree of sinuosity that a river must attain in order to achieve equilibrium, but it does point the researcher in a plausible direction.

Since models that explain river planform change have weaknesses and shortcomings, care should be taken when they are used as the only basis for making management decisions concerning river movement. Making an informed management decision first requires a fundamental understanding of river migration. Second, there is a need to understand how this knowledge applies to the specific river under consideration. Using models to explain the behavior of a specific river may be a fair approach in understanding or unraveling many of the causes of river behavior, but there is need to treat each river under consideration as a separate entity presenting unique challenges. It is best to recognize therefore, that models are in some cases severely limited in their use as a management tool since they may not provide solutions or explanations to those challenges presented by each river.

Land and river managers need to seek the spatial parameters within which each specific river operates. That is, there is the need to recognize the magnitude and amplitude of the oscillations of the meanders of the river and make contingency plans that reflect those parameters. An understanding of factors that cause river planform change across landscapes should be the management approach used in understanding river behavior and rather than harness the river, there should be an attempt to work in harmony with those factors.

Fundamentally, the ultimate goal of river and land management ought to be to allow a river to function in its natural environment as much as possible

This dissertation has shown that a valid approach towards an understanding of river planform change needs a spatial-historic perspective as has been given by the analysis of the aerial photographs. The challenge, nevertheless, is to discover what took place regarding the river's behavior between the times when the aerial photographs were taken. This is important because it would provide possible explanations and insight concerning different rates of movement and shifting of the Oconee River channel per year. The most ideal data set would have been images that show the position of the channel during or after every seasonal change in the weather in order to reflect changes in the weather pattern. Even so, if this data set were available, the specific reason why certain reaches of the Oconee exhibit different rates of movement at different times and scales and locations may still not be fully unraveled.

General Conclusions

The general conclusion is that planform rates after the closure of the Sinclair Dam have been reduced. This is not entirely accurate throughout the entire length of the river as the rates of planform change have been higher in the post-dam era both spatially and temporally. Local variations in resistance to stream bank erosion in both time and space, the nature of floodplain deposits that have been reworked and re-deposited over time and variations in stream flow most likely have contributed to this. The post-dam flow regime of the Oconee River has been generally altered with the average as well as peak flows showing recording lower averages than the pre-dam flows. Sinuosity indices overall, are lower in the post-dam era than in the pre-dam era although some of the reaches of the river in the post-dam era do have sinuosity indices that are higher than sinuosity indices in the pre-dam era.

The movements of a river's channel across its landscape can be described as cyclical with the lateral shifts taking place within a range from higher shifts to lower shifts and back to higher shifts. It is, however, difficult to identify the timing of the amplitude caused by these movements. These movements are the result of the river adjusting to extrinsic and intrinsic inputs that affect stream channel morphology and attest to the dynamic nature and idiosyncratic behavior of alluvial streams.

Geology seems to play less of a direct role in its influence upon planform change upon alluvial rivers. Rates of lateral movement of the Oconee River in the Piedmont province were similar to those of the same river in the Coastal Plain province. It was difficult to establish the role of the erosivity of rocks in the rate of planform migration. The river valley in the Piedmont is narrower and more restrictive and this retards lateral migration of the channel and this is where geology appears to have played a role in determining river planform change.

The planform movement of the Oconee river channel across the landscape generally do confirm to the literature that shows the maximum lateral movement of river meanders occurring at r_c/w ratios between 2 and 3. While 63% of the measured meanders show maximum lateral movement occurring between the r_c/w ratios of 2 and 3, several meanders show the maximum lateral movement occurring outside of this optimal range.

The theory of self-organized criticality did not fully support the fact that three of the ten cutoffs that did not occur took place after the critical value of 3.14 had been reached.

Limitations of the Primary Data

There are, however, some obvious limitations associated with using spatial data of this nature. Since the photographic evidence is a snapshot in time, the variable and minute changes associated with channel change that took place in the time spans between photographic images are not captured. Furthermore, stream discharge varies constantly and as the river channel boundary is defined by the separation between water and land, the delineation of this boundary is dependent upon the stage of the river at the time of image capture. Even when digitizing of the river channel is done with a high degree of accuracy, the location of the channel at the time the image of the stream was captured may not be truly representative of the width of the stream. This is important for studies that examine rivers where a shift in two or three meters may be large enough to significantly impact the results of spatial analysis.

Recommendations and Further Research

Extrapolating from past data how and to what extent a river will most likely move with reasonable accuracy may still be challenging even if all the elements of the data are available. This is because of the limitations of the theories that describe and explain planform change. These limitations result from a lack of data and this lack results from the shortcomings of the methods used to derive information upon which the theories rest. Clearly, there is greater need for more empirical investigations on a continual basis.

Since the floodplain is made up of previously reworked and deposited sediments, a study of the compaction rates and sediment characteristics of the material that comprises the floodplain deposits would most likely show why there are in-homogeneities in river bank and channel substrate materials. This is important since degree of resistance of floodplain material to erosion is a primary factor that influences the rate of a river's planform movement across the landscape. The challenge therefore is to establish an applicable and measurable erosion resistance index of the floodplain material.

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BIOGRAPHICAL SKETCH

Keith Ion Yearwood was born in a small village called Mocha-Arcadia on the east bank of the Demerara River in British Guiana. He migrated to the United Kingdom before his third birthday and lived there for about five years before returning to his native land. Upon completion of his baccalaureate degree, he migrated to Antigua and Barbuda and began teaching geography to high school students. Twelve and one half years later he moved to the Tortola, Virgin Islands (British) and taught Geography for four years at the British Virgin Islands High School.

Keith became severely disenchanted with teaching as a career and decided to change his vocation and leave teaching for good. In the 1999 fall semester, he enrolled in a graduate program at the University of Florida to pursue a degree in Urban and Regional Planning. About midway in that program, he discovered that he did not like the idea of becoming an urban planner but nevertheless completed the degree in December 2001.

He began his Ph.D. in geography in the 2002 spring semester and in his second semester he was asked to teach an undergraduate class called “Cities of the World”. He accepted the job as this was his only source of income and it also provided a valuable tuition waiver. During the first few weeks of teaching this class, he rediscovered his passion for teaching and has since dreamt of becoming a college professor. He has taught four other classes at the University of Florida and has thoroughly enjoyed the experience.