CHAPTER ONE

INTRODUCTION

1.1 Background to the study

Fluvial processes and river form evolve simultaneously and operate through mutual adjustments toward self-stabilization (Rosgen, 1994). The form and operational character of a river is a product of the adjustments of the river's boundaries to the processes taking place within the catchment. Alluvial river channels exhibit different patterns or forms along their courses. These patterns can be straight or sinuous, single or multi-channelled; however, channel pattern is not static and may change over time or over the length of a stream (Schumm, 1979).

The pattern exhibited by a stream channel is influenced by the nature of the stream and its sediment load; the composition of the bed and bank material of the channel and geologic controls (Leopold and Wolman, 1957; Schumm, 1979; Hooke 2004). Besides, over time, channel form and pattern can be stable, or change naturally as a result of variations or changes of channel parameters (Leys and Werrity, 1999; Winterbottom, 2000; Hooke, 2004). Human activities, such as urbanization, deforestation, intensive agriculture, sand and gravel mining, damming and channelization can also bring about changes in channel form and pattern through interference with the flood plain and channel dynamics (Hooke 1994; Gregory, 2006).

The study of the temporal and spatial changes in a river channel's plan form has been one of the most researched topics in the field of fluvial geomorphology for more than a century (Gilbert, 1880; Davis, 1899; Mackin, 1948; Hickin, 1974; Schumm, 1979; Gurnell and Downward, 1994; Winterbottom, 2000; Hooke, 2004; Hughes *et al*., 2005). As W.M. Davis (1889: 482) observes, "no one regards a river as a ready-made feature on the earth's surface, ---- rivers have come to be by slow processes of natural development, in which every peculiarity of a river's course and valley form has its appropriate cause." Uncovering the natural influences of change and those induced by human interference in the fluvial system through time, has been a fundamental part of fluvial geomorphic research ever since this very important observation. With advances in geospatial technology over the past two decades, measuring changes in a channel plan form, as well as other physical features of streams, has fortunately been much easier to accomplish, especially with the introduction of aerial photographs, satellite imagery and geographic information systems (GIS).

1.2 The research problem

The course of River Osun generally appears as a single-thread meandering stream channel. However, there is some evidence in the downstream section of the river channel showing alternating single and multithread (anabranching) sections. Images of the stream channel showed that anabranching within the lower stream segment has persisted from 1963 (date of first image) to the present. This reach has multiple channels with low width-to-depth ratios, separated by stable islands carved in the flood plain sediments. The presence of such a reach in the downstream section of River Osun provides an excellent opportunity to study the threshold of change of channel plan form from a single to a multiple-thread stream within a tropical river system.

Furthermore, there is no agreement as to the causes of anabranching in a stream, Makaske (1998: 122) argues that understanding the causes of anabranching "is one of the major challenges in current fluvial research". Nanson and Huang (1999: 478) assert that anabranching rivers "remain the last major category of alluvial systems to be described and explained". Three classes of explanation have been put forward for their origin. First, anabranching is a consequence of frequent avulsions and slow abandonment of earlier channels. In other words, the fluvial system exists in a perpetual transition state consisting of multiple co-existing channels (Makaske, 2001). Anabranching is thus not a "graded" state, but a by-product of the competition between channel creation and abandonment. Secondly, anabranching rivers are thought to be an equilibrium form where channels are adjusted in geometry and hydraulic friction to just transmit the imposed water and sediment discharges (Nanson and Knighton, 1996; Nanson and Huang, 1999). Thus, like changes in slope and channel form, anabranching is viewed to be another mechanism whereby a fluvial system can maintain grade. The third explanation was put forward by Galay *et al.* (1984), based on a study of the Columbia River. He postulated that ponding behind alluvial fans led to the formation of large lakes in the upper Columbia Valley. The lakes were gradually filled by river-dominated "bird's-foot" deltas, of which the present anabranched river system is a final stage. However, a paleo-environmental reconstruction from cores by Makaske (1998), has shown that this is not a viable hypothesis.

In short, although anabranching has been accepted as a distinct channel pattern, a widely accepted and convincing theoretical explanation for their occurrence has remained elusive. Therefore, this study adds to the body of knowledge on the conditions that give rise to anabranching within the fluvial system.

1.3 Significance of the study

The planimetric movement of rivers is difficult to explain or predict because of the numerous variables involved and the complexity of their interactions. Channel plan form is one of the most rapidly changing features of a river channel and is, therefore, highly sensitive (Hooke 1997). Analysis of plan form changes provides opportunity to quantify sensitivity and estimate the time scale of adjustments to various disturbances to the fluvial system. In addition to increasing basic understanding of plan form processes in tropical areas and for developing fluvial geomorphological theory, such knowledge has potentially important benefits to society. Because property and structures are often threatened by channel movement, there is a need for improved predictive capability with respect to the deformation of stream channels (Simon and Downs 1995; Li and Eddleman 2002).

The findings of fluvial geomorphological research were until recently, rarely employed in river management and river engineering; as a consequence, river management has witnessed dramatic failures of structures such as river bank revetments and bridges (Leeks *et al.*, 1988; Wohl *et al.*, 2005). Consequently, there has been a radical shift in the nature of river management (Leeks *et al.*, 1988) towards working with, rather than against, natural processes and accepting the dynamic nature of river channels (because the long-term viability of many engineering structures cannot be assured given the highly mobile nature of rivers). Therefore, knowledge of plan form is important in critical decisions on construction of engineering structures. For example, channel migration may influence the site selection, design, and maintenance of structures such as highways, railways, bridges, pipelines, transmission lines, flood control works, buildings, dams, navigation channels, and river intakes and outlets built on the flood plain. Knowledge of rates and patterns of plan form change may also be important in understanding habitat diversity in flood plain environments, of archaeological studies, and even oil and gas exploration (Swanson 1993; Sun *et al* 1996). Migrating river systems may be the least recognized of the destructive effects caused by flooding (Perkins 1996). The results of this study should be useful to planners, engineers, and other professionals in delineating channel hazard zones.

Anabranching river systems are now regarded as a separate class in river classifications owing to their distinctive morphological/hydrological characteristics and fluvial processes. Detailed data from different environmental and geographical settings are still needed for a better understanding of anabranching rivers. A better understanding of the conditions under which a channel plan form may change is another critical concern. Osun River, a stream with alternating anabranching and meandering channel reaches, provides a unique environment that exhibits threshold conditions where a meandering channel transforms into an anabranching channel and then back to a meandering channel. Because the processes involved in the production and maintenance of anabranching channels are difficult to document in the field (Schumann, 1989; Knighton and Nanson, 1993), much work still needs to be done before such transformations could be well understood.

Lastly, stream channel forms have been well studied in temperate environments (Leopold and Wolman 1957; Wolman and Miller 1960; Hooke 1980), but the same level of research has not been achieved for streams in tropical areas. Although there are notable tropical river studies like those of Salo *et al*. (1986) on the Peruvian Amazon and Ucayili Rivers and Speight (1965) on the Angabunga River in central Papua, there remains a dearth of studies examining the nature of tropical rivers in general. This paucity of studies has made Gupta (1995) to call for more research into the channel form of tropical rivers. Gupta and Dutt (1989) also suggest that humid tropical rivers may not fit well with the existing geomorphic models owing to strong seasonality of discharge. Theories developed for humid temperate rivers may, therefore, also not apply (because the tropical climate frequently produces precipitation rates that are more than double their temperate counterparts). Unlike temperate streams, tropical rivers are additionally not exposed to the physical extremes created by freeze-thaw cycles. The incommensurate amount of research on tropical rivers, therefore, limits opportunities for meaningful contrasts with their temperate counterparts, which hinders theory development. Because tropical areas represent a large proportion of the surface of the earth (Mark, 2002), enhanced understanding of the operation of tropical rivers is critical to fluvial geomorphologic theory in general.

1.4 Aim and objectives

The aim of the study is to examine the channel plan form dynamics of Lower River Osun in order to characterize the spatial and temporal changes along the channel.

The research objectives are to:

(i) quantify downstream changes in the channel plan with the aid of two river pattern indices (average number of channel across valley and sinuosity) and four shape variables (width, depth, width/depth ratio and area).

(ii) examine the spatial differences in plan form factors (discharge, bank clay content, bank strength, bed material size (D50), valley width and valley gradient), in order to evaluate the possible significance of each factor in the formation of observed plan form.

(iii) examine temporal changes in the plan form of River Osun with reference to channel sinuosity, width, area and lateral migration with the aid of sequential remotely sensed images (1963-2012).

1.5 The study hypotheses

The study tested the following hypotheses:

1. There is no significant increase in channel efficiency with change from meandering to anabranching plan form.
2. Transition from meandering to anabranching plan form is not a function of change in discharge, bank strength, valley width, bed sediment grain size and valley slope.).
3. There is no significant difference in plan form change over time between meandering and anabranching channel reaches.

1.6 The study area

1.6.1 Location and extent

The study area is located along the alluvial section of Lower River Osun in southwestern Nigeria within the Osun river basin. The village of Telewi located on the Osun River to the south-east of Ijebu-Ife marks the upper boundary of the study stretch, while Iro village to the south of Fawosedi, about four kilometres from the Lekki lagoon marks the lower boundary. The stream length within the area is about 42km and flows on alluvial bed and is underlain by sedimentary rocks.

River Osun drainage basin is located approximately between latitude 6^{0} 33'N and 8^{0} 20'N and longitudes 3^{0} 23'E and 5^{0} 16'E (Figures 1.1 and 1.2). The Osun drainage system rises in the Oke-Mesi ridge about 5km north of Effon Alaiye on the border between Oyo and Ekiti States and flows through the Itawure gap before winding its way first westward through Osogbo and Ede and then southward to enter the Lekki Lagoon. River Osun is one of the series of West African rivers which discharge directly into coastal lagoons and creeks bordering the Atlantic Ocean.

River Osun has a total drainage area of approximately 9,135km^2, of which the greater part of the basin is located in Osun (about 4,092km^2) and Oyo (about 2,987km^2) States; while about 1,222km^2 is located in Ogun, about 99km^2 in Ekiti, about 654km^2 in Kwara and about 81km^2 in Lagos States. The study area is located within Ogun and Lagos States; the stream length studied is about 42km, and the basin area is about 674km^2.

The Osun river basin can be divided into the Upper and Lower basin areas. The Upper basin makes up the main body of the Osun basin. This area is underlain by rocks of the Crystalline Basement complex. It is characterised by rolling hills, with elevations ranging from about 70 m to 450 m in the north and north-eastern parts of the basin. Peaks of about 700-750 m exist in the mountain range east of Ilesa. The Upper Osun area is drained by the Osun, Erinle and Oba Rivers. No distinct geomorphological feature marks the boundary between the Upper and Lower Osun basin, so the area from Eridu, through Telewi to Ijebu Ife, which marks the beginning of the sedimentary formations, is used to mark the boundary between the Upper basin to the north and the Lower basin to the south.

The Lower Osun basin is a narrow stretch underlain entirely by sedimentary formations. It starts at the boundary of the Basement Complex and extends to the mouth of the Osun River at the Lekki Lagoon. It is characterised mainly by flat low lying areas adjacent to the river, which makes up the extensive flood plain of the Osun River. Further away from the river are areas of flat to slightly undulating plateau of the low elevation terrace. Elevation within the Lower basin is between 3 to 20 metres above sea level. In the Lower Osun basin the stream flows on alluvial bed, the thickness of which increases from north to south and is about 100 metres at the mouth of the river (Osun River Basin Feasibility Study, 1982). The stretch of the river between Telewi, which is located at the beginning of the alluvial section to Iro village about 42km downstream make up the study area.

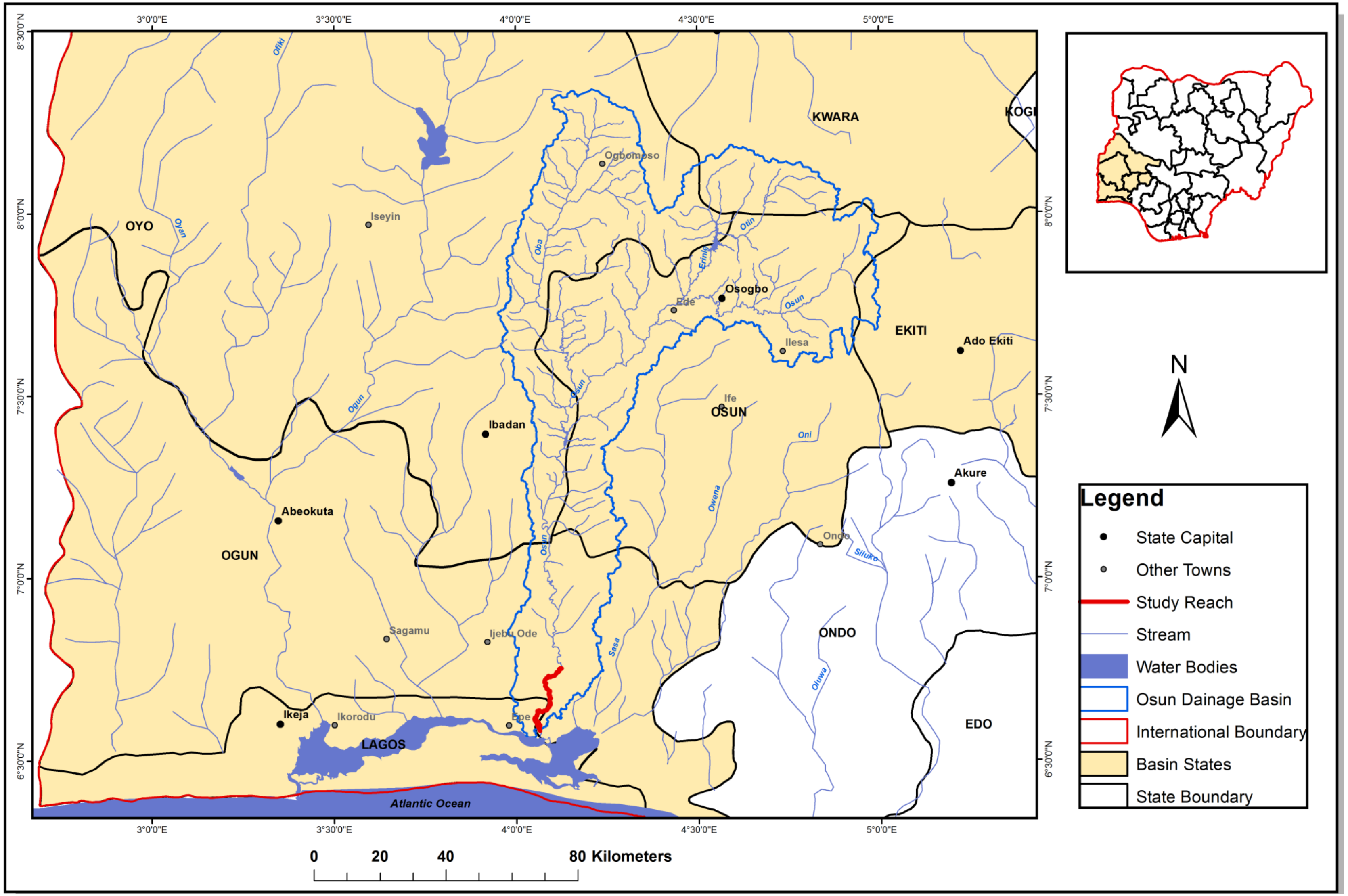


Figure 1.1: Osun drainage basin showing the study area

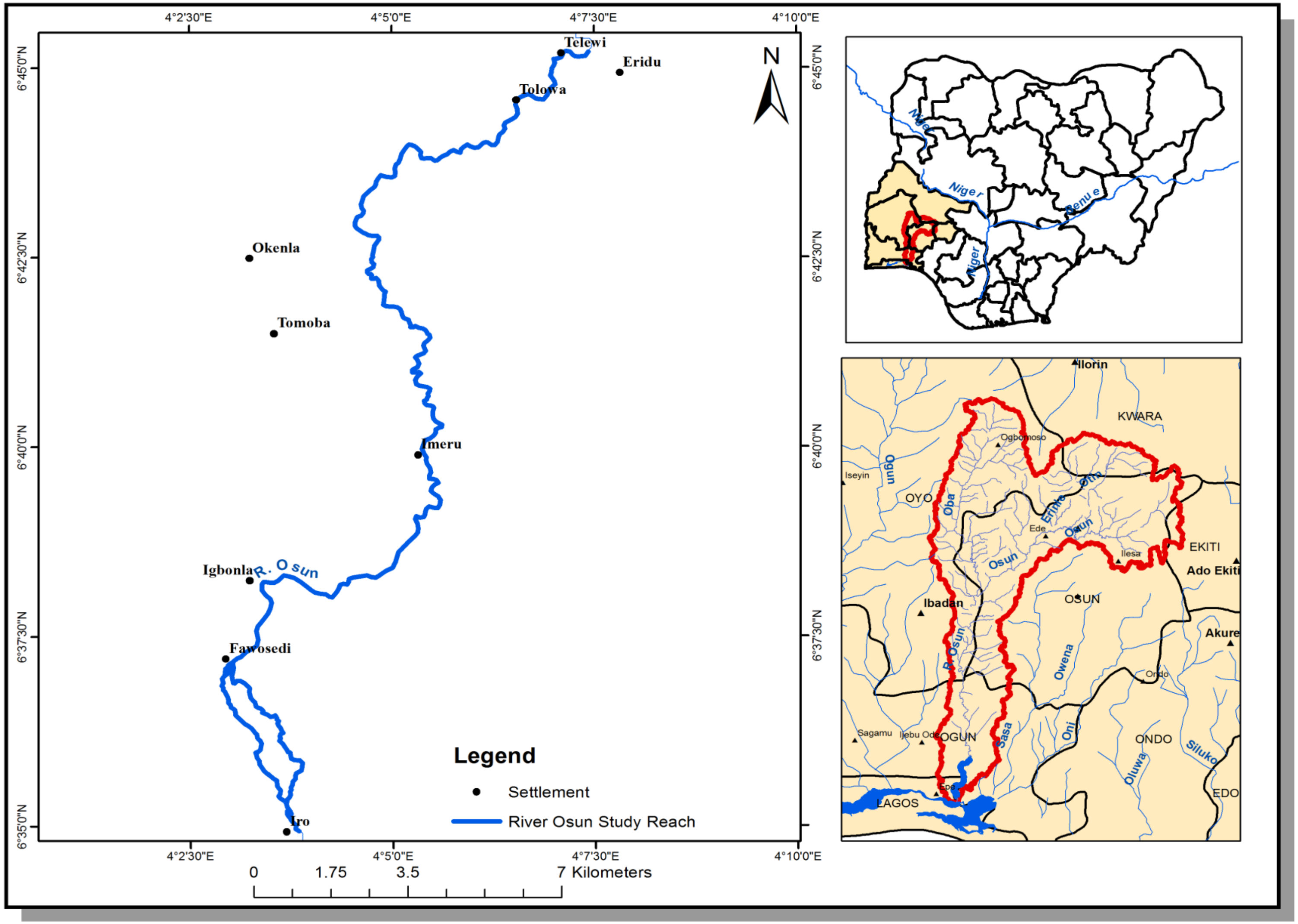


Figure 1.2: Osun River showing settlements along the study reach

1.6.2 Relief and drainage

The topography of the Osun River drainage basin reflects the contrast between the hummocky terrain underlain by the crystalline rocks to the north, and the thickly forested undulating hills and swampy lowlands of the sediments to the south. The topography of the basin overlying the crystalline basement is characterised by a gradually rising elevation from about 30 m in the south to about 600 m in the north east. The relief is moderate with low, forested hill and occasional hog back quartzite ridges which can be traced for several kilometres. The larger older granite masses and, in some places, the gneisses and migmatites, create a rugged topography with inselbergs rising abruptly above the surrounding country.

This initial structural surface have strong controls in the development of river systems. The elevation, shape and gradient of the landform determine, to some extent, the character of the drainage system. The region is well drained (apart from the river valleys which are given to periodic water logging during the latter part of the rainy season). The main rivers (Osun and its main tributaries, Oba, Erinle and Otin) flow all year round but there is a marked seasonal variation in their volume (Adeboye, 2005). The smaller tributaries (for example, Omi, Idogun and Okoseru) are dry each year for periods varying from a few weeks to several months (Oyedotun, 2011).

Within the study area, the topography is characterised by two main features, the Ewekoro Depression and the alluvial flood plains. The Ewekoro Depression is a low-lying marsh belt, which runs east-southeast across the lower basin about 3 to 15 metres above sea level. The alluvial plain is flanked by the northern and southern uplands lying north and south of the Ewekoro Depression, respectively.

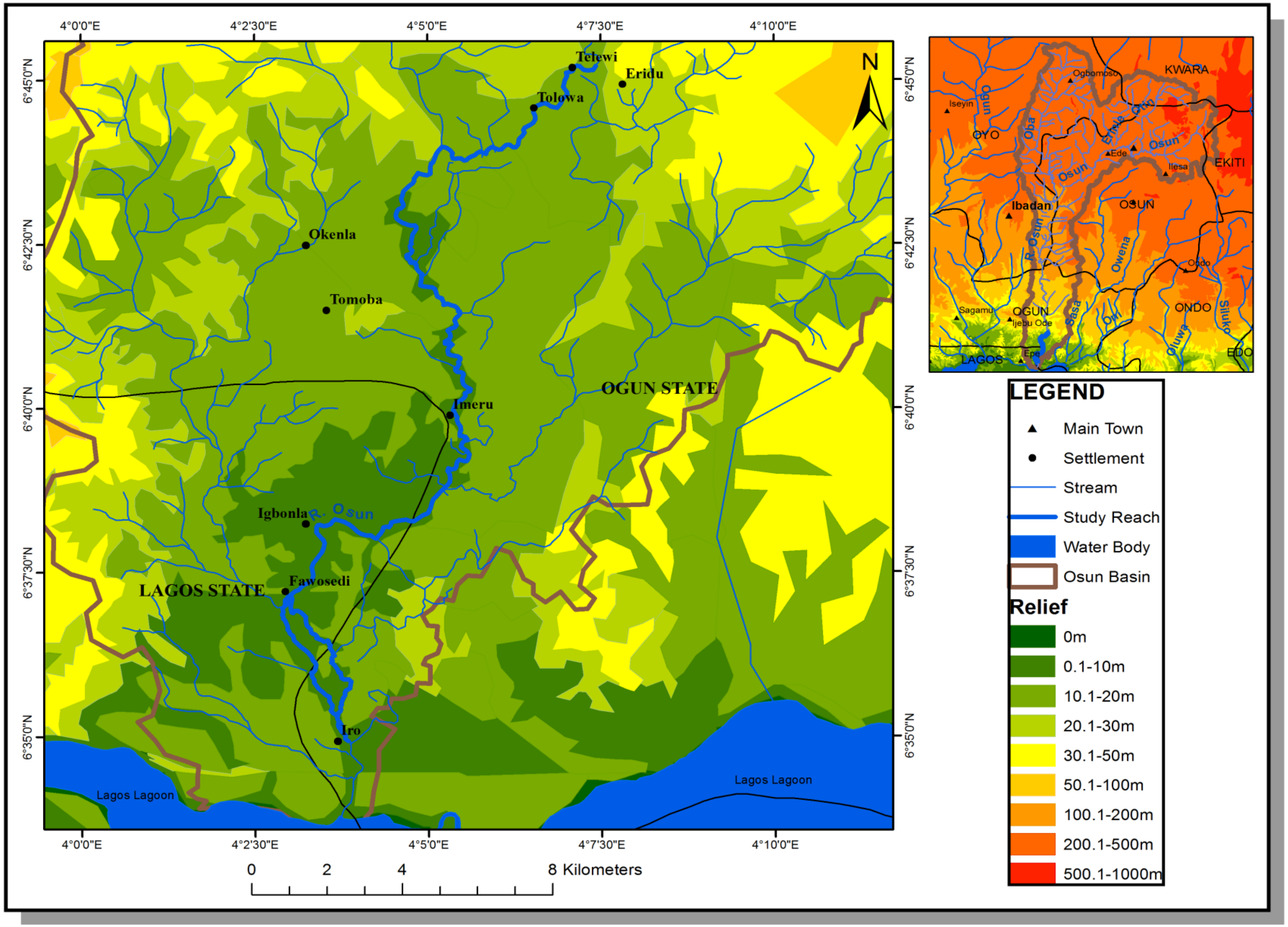


Figure 1.3: Relief and drainage of the study area

There are two distinct topographical units within the study area. The first is the lowlands. These are flat low-lying areas adjacent to the river, which are flooded with each rainy season and remain inundated till December. The second is the uplands, which are flat to slightly undulating plateau of low elevation terrace further from the river. These areas, although not flooded by the river, have a high water table owing to the heavy texture of the soil and poor natural drainage system for evacuating the excess rainfall (Osun River Basin Feasibility Study, 1982).

A major tributary flows into the Osun channel within this study area from the north-west direction. There is an abundance of small tributaries draining the area, these streams flow in a north to south-east direction into the Osun River and most flow all year round. Three of the largest tributaries that flow into it within the study area are of the fourth order. Generally, the study area is well dissected with drainage channels, except the region to the extreme north-east that shows an absence of drainage channels. Most of the central and northern parts of the study area are well drained. However, the area towards the southern part of the study area gets waterlogged during the rainy season as a result of relatively flat nature of slopes. Between a few metres from Fawosedi to areas close to the Lekki Lagoon is an area of swamp forest, which is waterlogged for most parts of the year (see Figure 1.3)

The calculated drainage density within the study area is found to be 0.67km/km^2. The measurement of drainage density provides a useful numerical measure of landscape dissection and run-off potential. It has been observed from drainage density measurements made over a wide range of geologic and climatic types that a low drainage density is more likely to occur in regions of highly permeable subsoil material under dense vegetative cover and where relief is low (Pidwirny, 2006). On these highly permeable landscapes, with small potential for run-off, drainage densities are sometimes less than 1 kilometre per square kilometre (Pidwirny, 2006). The drainage density of the Calabar River basin, a major tributary of the Cross River in southern Nigeria was low at 0.34km per sq. km (Eze and Effiong, 2010), while that of River Lamurde (the main river draining Jalingo town and environment) was 0.389km per sq. km. (Oruonye1 *et al.*, 2016). Low drainage densities are often associated with widely spaced streams owing to the presence of less resistant materials (lithologies or rock types) or those with high infiltration capacities.

1.6.3 Geology

The Osun drainage basin mainly lies on the Precambrian Basement Complex of southwestern Nigeria. The Basement Complex within the drainage basin consists of four groups of rocks: Gneiss-migmatite-quartzite complex; Schist belts; Pan-African granites (Older granites) and associated rocks; minor felsic and mafic intrusive (Adekoya *et al.*, 2003). The principal rock component of the Basement Complex includes the Gneiss Complex, which are the oldest known rocks in the crystalline Basement. They appear to be a bedded series, predominantly of sedimentary origin, but migmatised to a variable extent. The older granites comprise dominantly granitic rocks which have been emplaced by intrusion and replacement in the Gneiss Complex. During the period of crustal tension, dykes of olivine-dolerite were emplaced along joints trending east-north-east (ENE). Their age is not known but it is probable that they are considerably younger than the older Granites.

The southern part of the Osun drainage basin falls within the Dahomey Basin, an extensive sedimentary basin stretching from eastern Ghana, Togo and the Republic of Benin to the western part of Nigeria (Adegoke, 1969). This basin is one of the sedimentary basins of Nigeria. It is the eastern part of the Dahomey basin that is exposed in the study area. The sediments of the eastern Dahomey Basin are early Cretaceous to Holocene (Agagu, 1985) in age and are dominantly clastic with occurrence of shale and limestone. The lithostratigraphy of the basin has been grouped into the following:

- The Abeokuta Group
- The Ewekoro Formation
- The Oshosun Formation
- The Ilaro Formation
- The Coastal Plain Sands and Alluvium

The Abeokuta Group: This is the oldest unit in the eastern Dahomey Basin (Jones and Hockey, 1964). It lies unconformably on the basement complex rocks. It used to be referred to as the Abeokuta formation but was upgraded to a Group status, comprising three lithosgraphic units, with the age ranging from Neocomian to Paleocene (Omatsola and Adegoke, 1981). This outcrops over an area of about 230 km^2 within the drainage basin. This group consists of conglomerate, sandstones, clays, shale and thin limestone. The sediments of the group are deposited in partly marine, partly brackish water and partly fresh water and have been described as the lateral equivalent of the Nsukka formation (Kogbe, 1974).

The Ewekoro Formation: Immediately to the south of the Abeokuta group is found the Ewekoro Formation and it covers an area of about only 57 km^2 within the study area. This formation unconformably overlies the Araromi formation of the Abeokuta group. The Ewekoro formation is a lensoid shaped unit, which pinches out east and south. The formation consists of limestone and marl that are rich in fossils particularly moluscs (Agagu, 1985). The limestone is sandy towards the base and varies in thickness between 13 m and 35 m.

The Ilaro Formation: The formation covers an area of approximately 185 km^2 within the study area and is exposed close to Igbonla area within the study area. The formation consists of coarse to fine-grained sands, clays and shale. Textural analysis of the sand from the formation indicated beach, shoreline and near shore environments of deposition. The formation is poor in fossils but some benthic foraminifera have been described. The age of the formation is put at Eocene (Agagu, 1985).

The Coastal Plain Sands and Alluvium: The Coastal Plain Sands together with the Recent Alluvium constitute the youngest sedimentary unit of the Eastern Dahomey Basin. The coastal plain sands overlie the Ilaro formation. Within the study area, this formation is exposed close to the Lekki Lagoon and covers an area of approximately 202 km^2. The coastal plain sands are made up of soft, very poorly sorted clayey sands, pebbly sands, sandy clays and rare thin lignite. The age of the unit has been placed at Oligocene to Pleistocene (Agagu, 1985). The Alluvium represents the modern sediments deposited along the main river valley (Osun River) as it empties its content into the lagoon. A combination of the coastal plain sands and recent alluvium underlies the Lagos and lower Ogun area of the study drainage basin (see Figure 1.4).

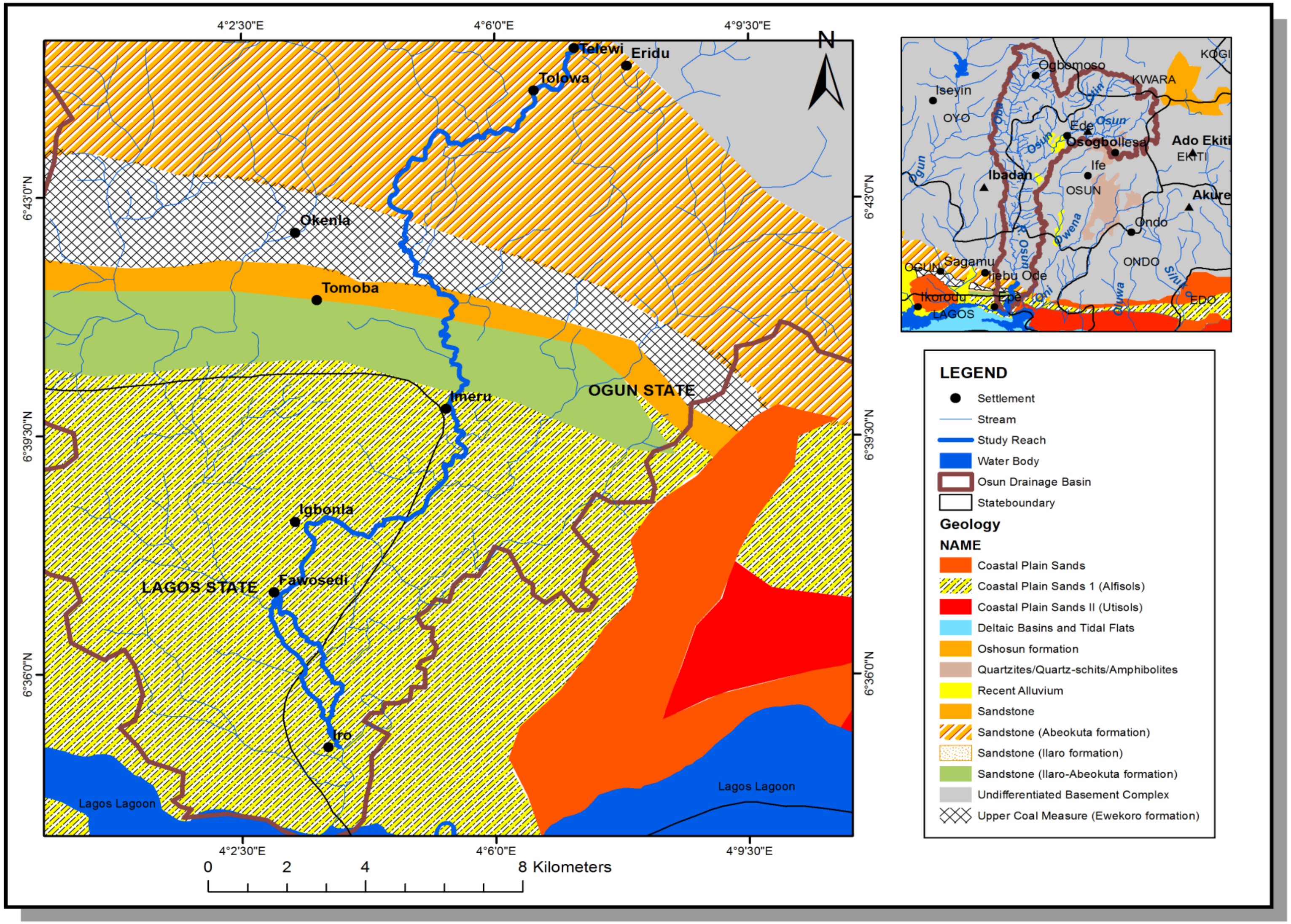


Figure 1.4: Geology of the study area

1.6.4 Climate

The climate of the study area, like that of many parts of Nigeria, is influenced by the north-south movement of a zone of surface discontinuity (ITD) between maritime air masses and dry continental air masses. The regular movement of these air masses creates distinct climate seasons in the area.

1.6.4.1 Rainfall

Rainfall is influenced by altitude and the orientation of the coastline relative to the direction of the rain-bearing winds. The east-west orientation of the coastline appears to increase the effective distance of the south-westerlies from the hinterland.

The main feature of the rainfall pattern within the study area is its seasonal distribution. As can be seen from the twenty-five years' average rainfall in some stations within the drainage basin (See Table 1.1 and Figure 1.5), the rainy season begins earlier in the south of the drainage basin where it occurs in March and continues until the end of October or early November, giving at least seven months of rainfall. In late July and early August, dry days are frequent and sufficiently regular and constitute the August break or “little dry season.” North of Ogbomoso, the rain begins in April or early May and ends in mid-October, giving seven months of rainfall. The rainfall data revealed that there is the absence of the August break. The mean monthly figures for the wet months are about 182 mm while the mean annual rainfall amount varies from 1,400 mm to 1,625 mm in the south of the basin and is a little over 1,300 mm in the north. The mean dry season rainfall varies from 127 mm to 178 mm in the north and from 178 mm to 254 mm in the south.

1.6.4.2 Temperature

The mean annual temperature in the basin under study is about 27^0C, with little monthly variations around this average value. Data from stations in the basin showed that February and March are the hottest months of the year both in the north and the south of the river basin. These months have the highest means of daily maximum and minimum temperature. During these months, temperatures are high over the entire area. The daily maximum temperature for February is 31.4^0C in the south and as high as 34.6^0C in the north.

Table 1.1: Twenty-five years' average monthly precipitation (mm/day) within the Osun Drainage Basin

	Fawosedi	Asejire	Ogbomoso
Jan	20.15	14.26	8.37
Feb	34.69	26.25	17.77
Mar	98.27	78.12	58.59
Apr	140.4	122.7	104.7
May	190.65	174.22	157.79
Jun	250.9	214.5	188.1
Jul	242.89	222.27	221.65
Aug	171.74	195.92	220.1
Sep	214.2	219	223.8
Oct	183.52	155.31	127.72
Nov	56.1	38.4	20.4
Dec	22.32	14.88	7.44

Source: NASA Surface Meteorology and Solar Energy (2012)

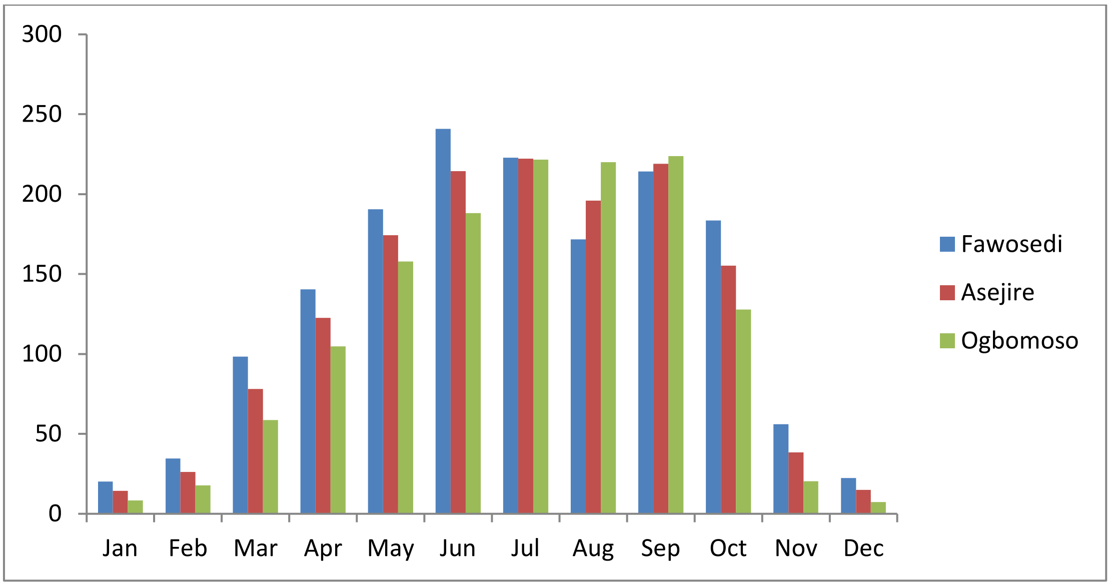


Figure 1.5: Twenty-five years' average rainfall for some stations within the study drainage basin

The lowest mean minimum temperature in the north is recorded in December and January that is during the harmattan. In the southern parts, the lowest mean minimum temperature is recorded in July and August during the rainy season. Table 1.2 as well as Figures 1.6 and 1.7 show variations in minimum and maximum temperature within the study area.

1.6.4.3 Relative humidity

Humidity within the drainage basin is generally high but decreases northwards. The lowest mean monthly humidity at Ogbomoso, north of the drainage basin, is 42% in January and 68% in Fawosedi, to the south (Figure1.8). The relative humidity (RH) is high throughout the year in the southern parts of the drainage basin with nine months of the year having relative humidity of over 80%. December, January and February are the months with the lowest relative humidity in the drainage basin. The mean annual humidity varies from 75% in the south to 55% in the north**.**

1.6.4.4 Wind

Records of winds showed that, in the rainy season, westerly and south-westerly winds are the most frequent; while, in the dry season, there is a prevalence of the northerly and north-easterly winds. Wind velocities are in the range of 1 to 10 knots most of the time. Spatial variations are small, but calms are more frequent in the southern than in the northern parts of the basin.

Table 1.2: Twenty-five years' monthly minimum temperatures

Minimum Temperature	**Fawosedi**	**Asejire**	**Ogbomoso**
January	22.9	20.9	20.4
February	23.7	21.8	21.4
March	24.5	22.9	22.7
April	24.7	23.1	22.9
May	24.7	23	22.7
June	24	22.4	22.1
July	22.9	21.4	21.3
August	22.3	20.9	20.9
September	22.8	21.4	21.4
October	23.3	21.7	21.4
November	23.3	21.1	20.9
December	22.6	20.3	20.1

Source: NASA Surface Meteorology and Solar Energy (2012)

Table 1.3: Twenty-five years' maximum temperatures within the drainage basin

Maximum Temperature	Fawosedi	Asejire	Ogbomoso
January	34.8	39.2	42.7
February	34.9	38.7	42.3
March	32.8	34.5	37.3
April	32.1	32.5	33.5
May	31.6	31.8	32.2
June	29.7	29.9	30.3
July	28.2	28.4	28.9
August	28.3	28.8	29.4
September	28.9	29.6	30.6
October	29.7	30.6	31.9
November	30.8	32.1	35.7
December	32.5	35.7	40

Source: NASA Surface Meteorology and Solar Energy, 2012

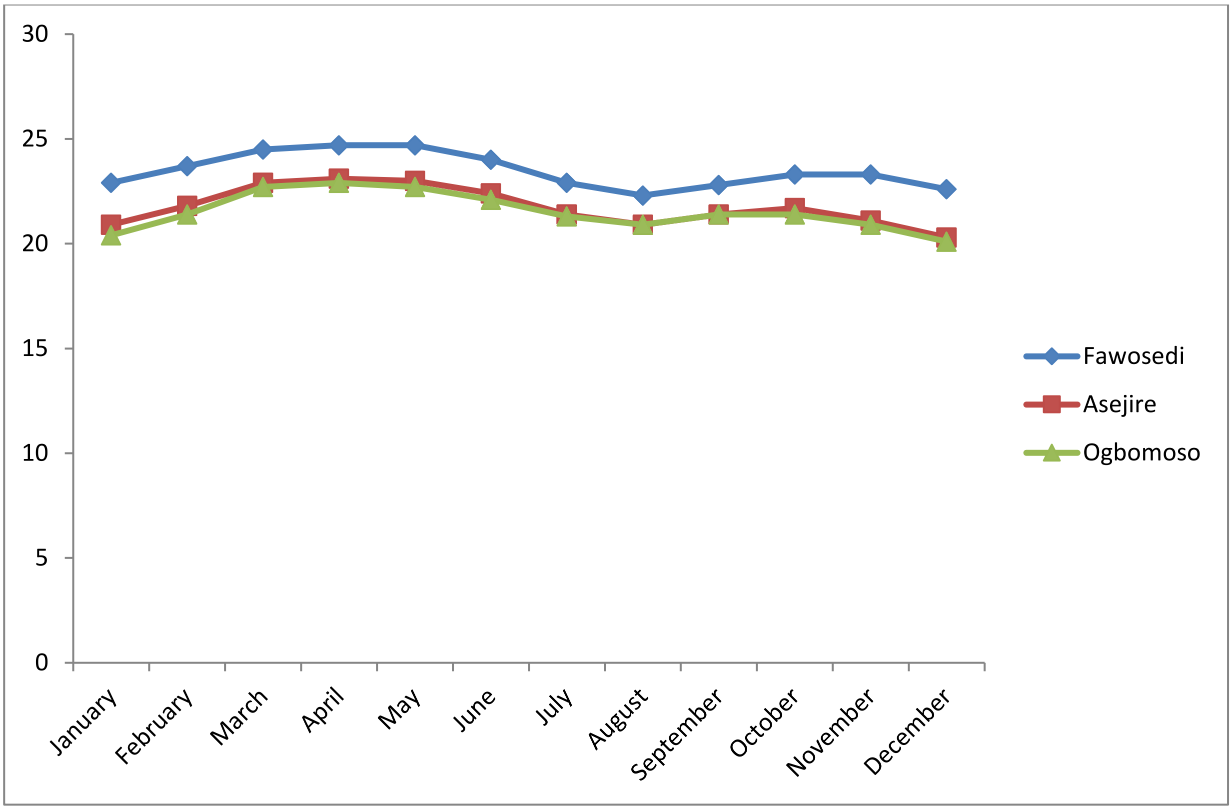


Fig 1.6: Minimum temperature in selected stations within the study drainage basin

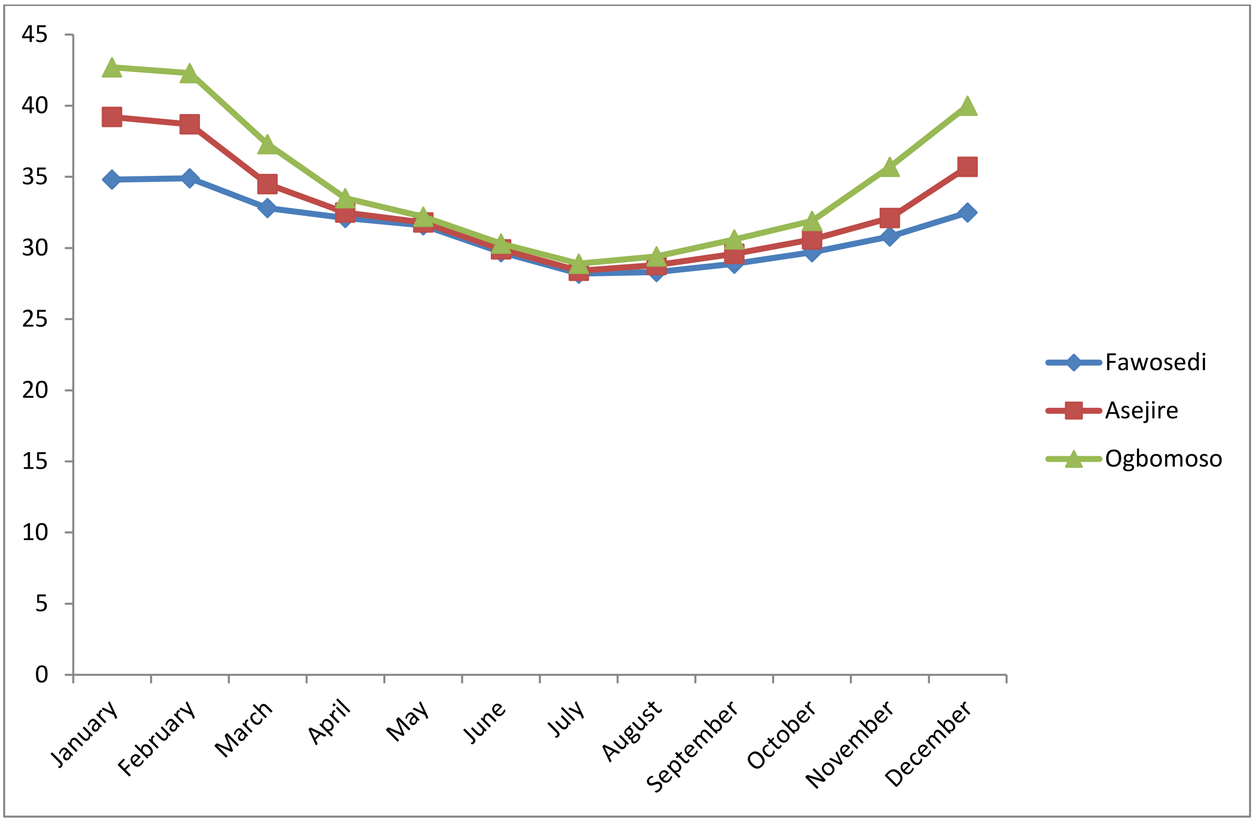


Fig 1.7: Maximum temperature in selected stations within the study drainage basin

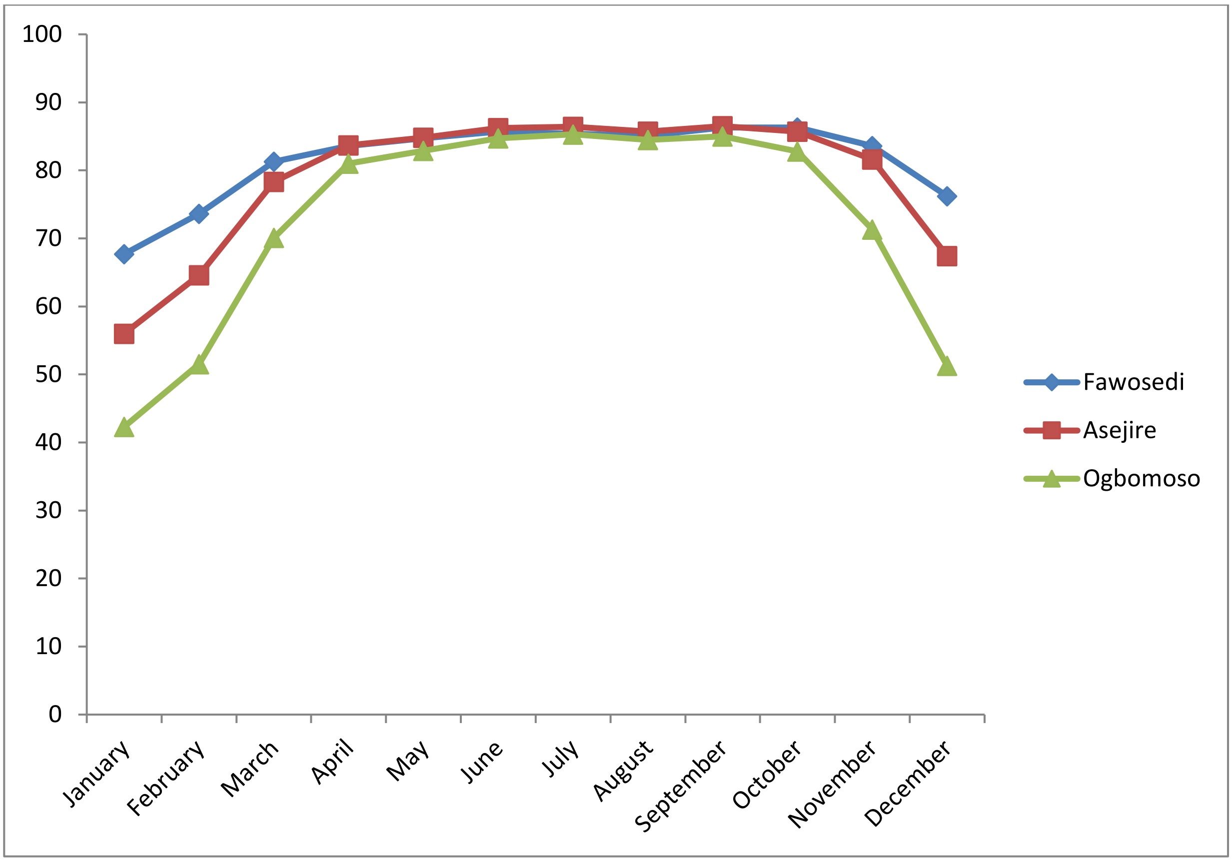


Fig 1.8: Ten years' mean monthly relative humidity for the study area
Source: NASA Surface meteorology and Solar Energy (2012)

Table 1.5: Ten years' average wind speed

	Fawosedi	Asejire	Ogbomoso
Jan	2.67	2.46	2.35
Feb	2.86	2.54	2.33
Mar	2.73	2.65	2.61
Apr	2.44	2.47	2.48
May	2.09	2.09	2.24
Jun	2.25	2.12	2.14
Jul	2.5	2.22	2.14
Aug	2.6	2.27	2.13
Sep	2.35	2.13	2
Oct	2.04	1.9	1.86
Nov	2.11	2.16	2.2
Dec	2.41	2.2	2.16

Source: NASA Surface Meteorology and Solar Energy (2012)

1.6.5 Soil

The soils within the drainage basin can be broadly grouped into three: these are the ferruginous tropical soils, the ferralitic soils and the hydromorphic soils. The basement complex in the upper parts of the Osun drainage basin gives rise to a wide variety of soils, generally coarse in texture and with low fertility. The ferralitic soils are derived from sandstone parent material; the texture is generally sandy especially in the top horizons. The lower parts of the basin have developed over sedimentary and alluvial parent materials.

The upper part of the drainage basin is made up of ferruginous soils. The soils are brownish grey to brownish red, depending on their topographical location and drainage condition. They are deep, well-drained to shallow, well-drained, loamy to sandy soils that may be gravelly in nature. The clay fractions of the soils are mainly Kaolinite with small quantities of Illite. The nutrient-holding capacities of these soils are poor to moderate probably because of the low nutrient-holding capacity of the predominant clay.

Soils within the study area include the ferralitic soils derived from sandstone. These are found in the north-western part as well as the in the north-eastern periphery of the study area. They are well drained soils formed from tertiary sandstones. The parent materials have been well weathered and therefore are deep (Smyth and Montgomery, 1962). There are different soils derived from sandstones within the study area. The first is the Owode series. This soil series is found in the western and central parts of the study area. The soil is brown to dark brown in colour and is not mottled within 150 cm of the soil surface. The texture is medium to fine. The soil is moderately acidic in the upper horizon (pH 5.8 to 6.1). The cation exchange capacity of this soil type varies from about 3.5me/100g to 5.6me/100g of soil. The available water-holding capacity in the top one metre varies from 4.8 to 6.2% by weight. This soil types can be found in the Ijebu Ife and Itele areas along the study drainage basin, where they appear as very deep well-drained soils. Two soil phases are associated with this soil series. They are the Owode red phase and the Owode sandy phase.

The second is the Agege series. The Agege soil series occupies most of the north-eastern and north-western parts of the study area. A typical profile consists of a greyish-brown, medium textured upper horizon overlaying a pale brown, medium to fine textured subsoil that is mottled at depths of between 80 and 120 cm (Ajunwon and Olomu, 1982). The soil type is moderately acidic in the upper horizon, with pH values of between 5.2 and 6.1 and cation exchange capacity of between 3.3 and 4.2me/100g of soil.

The third is the Iju Series. This series is imperfectly drained and occurs in local depressions in the western part of the study area. The chemical and physical characteristics are similar to those of the Agege series apart from the profile, which is generally paler.

Soils derived from fluvial deposits: These are found within the lower parts of the study area and are poorly drained or swampy and are formed from quaternary fluvial deposits. In most cases, the deposits and soils are very clayey. These soil types are also found in along valleys of small streams that drain into the Osun River. A small percentage of the alluvial soils is derived from sandy deposits and are relatively sandy. The soils derived from fluvial deposits are of different types. The first is the Badeggi Series. They are found along the banks of the Osun River. The soils cover most of the southern and south-eastern parts of the study area. The soils from this series are formed from clayey deposits and are hence clayey and fairly massive up to the surface. The surface horizon is humic, dark greyish-brown, while the subsoil horizons are generally brownish. In most cases, the degree of wet mottling appears from a depth of about 5 cm, as the clay content tends to increase with depth (Ajunwon and Olomu, 1982). The available water-holding capacity of the soil is moderate to high (7.3 to 14.2% by weight for one metre depth). The upper horizon of the soil is acidic (pH values between 4.0 and 5.2), while the cation-exchange capacity is relatively high (6.3 to 11.1me/100g of soil.

The second is the Oji Series. Soils of the Oji series are also found along the banks of the Osun River and its tributaries. The soils are hydromorphic and differ from the Baddegi series soils in being medium textured. The soils are also acidic in the upper horizon (pH values 4.4 to 4.9) with the cation-exchange capacity low to moderate (1.6 to 4.0me/100g of soil) (Ajunwon and Olomu, 1982). The soil appears admixed with those of the Baddegi series with no clearly defined boundary between the two.

The third is the Indaloke Series. Soils of this series are sandy, hydromophic soils found within limited extents within the study area. These are found within the vicinity of Igbonla village on the western bank of the River Osun. Owing to the deep sandy nature of these soils, their moisture- and nutrient-holding capacities are low.

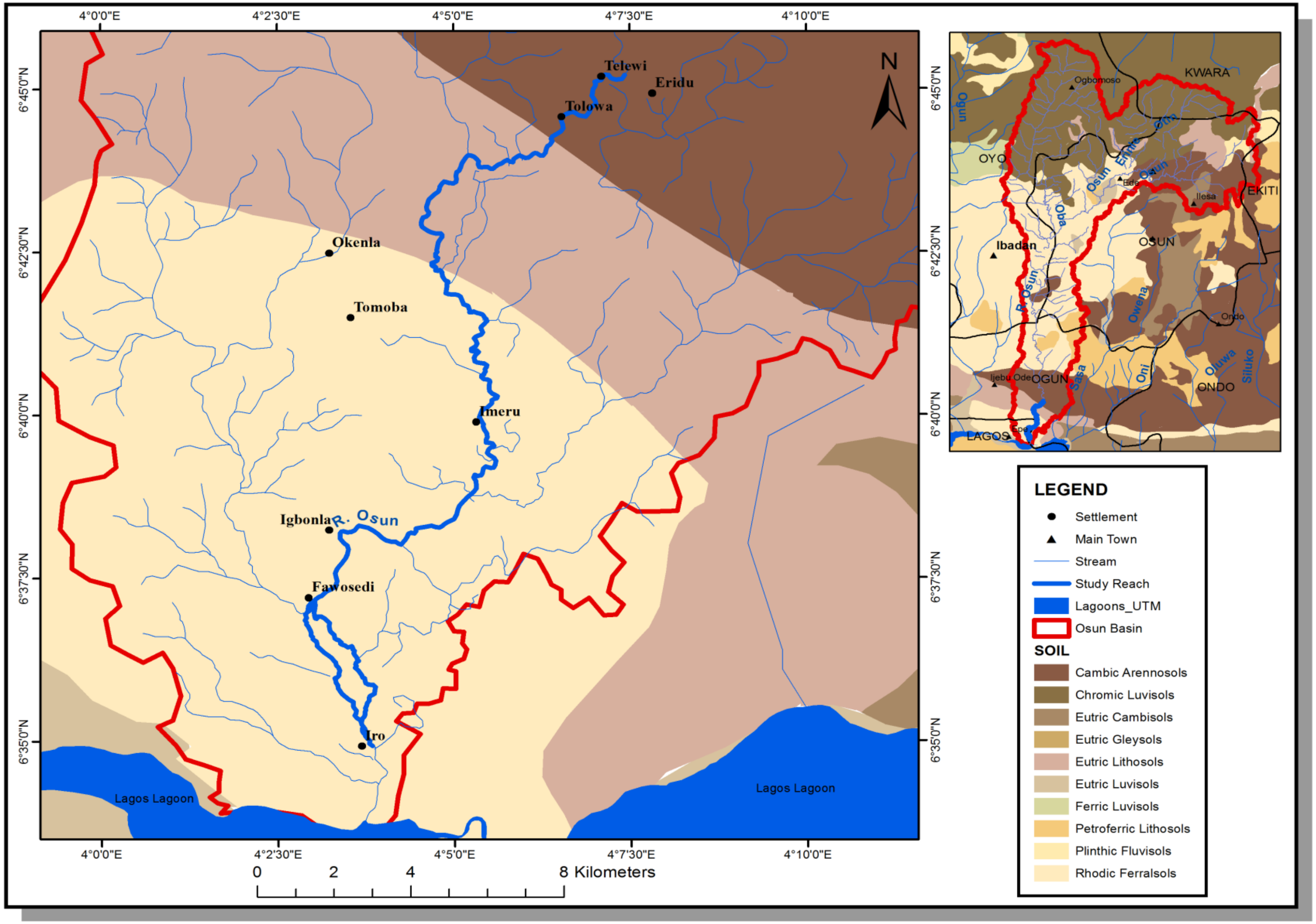


Figure 1.9: Soils of the study area, River Osun, Nigeria

The available water-holding capacity in the upper one metre of the soil is between 3.9 and 4.6% by weight. The soils are strongly acidic with a pH value of 4.0 or less. The cation-exchange capacity in the upper horizon is about 1.0me/100g of soil.

1.6.6 Vegetation and landuse

The Osun River basin spans three vegetal communities, namely: the swamp forest, the rain forest and the forest/savanna mosaic vegetation belts (Figure 1.10). The derived savanna mosaic is made up of forest and savanna species. This is a zone of transition between rain forest and dry savanna. Reported to be once covered by high forest, the forest/savanna mosaic is increasingly dominated by secondary regrowth's by invasive herbaceous species and by savanna grasses.

The Rain Forest Vegetation Zone: This vegetation zone comprises a complicated mosaic of communities. Mature lowland rain forest exhibits three stratum: the top, with isolated wide spreading crowns; the middle, made up of large numbers of species with small crowns; and the understory made up of woody climbers and short trees with spreading crowns. Most of the lowland rain forest is currently secondary, with areas dominated by extensive stands of oil-palm (*Elaeis guineensis*) although patches of the old climax high forest remain. The families Meliaceae and Leguminosae are dominant. Typical species within this forest type include *Khaya ivorensis*, *Cylicodiscus gabunensis*, *Pentaclethra macrophylla*, *Lovoa kleineana*, *Lophira procera*, *Sarcocepphalus diderrichii* and *Hylodendron gabunense*. Other common species found within this vegetation type in the study area are *Chlorophora exelsa; Cola gigantia* and *Antania Africana.* Some economic species found in the rain forest within the study area include *Triplochiton scleroxylon*, *Lovoa trichilioides*, *Cola gigantia*, *Khaya ivorensis*, *Pterygota macrocarpa* and *Cylicodiscus gabunensis.*

Freshwater Swamp Forest: This vegetal belt is found in the southern part of the study area. This vegetation type is dominant in lowland areas as well as along the flood plain of the Osun River. The freshwater swamp forest belt, where undisturbed, consists entirely of tall slender trees of between 30 and 50m, with stilt roots. But owing to human activities within the study area, most of the trees have been replaced by raphia palms. The common tree species found within this freshwater swamp forest are *Raphia gigantea*, *Alstonia congensis*, *Ficus spp*, *Spondianthus preussii*, *Symphonia gabonensis*, *Acalypha sp; Elaesis guinensis* and *Eupatorium odorotum.* Others are *Anthonota macrophylla*, *Raphia vinifera*, *Lophira* *procera, Carapa Procera, Berlinia auriculata Alstonia boonei, Xylopa rubescens* and *Pterocarpus mildbraedii*. There are some associated herbaceous types occurring in the eateries of the Osun River, especially in the anabranching section of the stream. They include floating grass (*Vossia cuspidate*), water lily (*Nymphaea lotus*) and large masses of the invasive species water hyacinth (FORMECU, 1999). The fresh water swamp forest differs in structure from the lowland rain forest in that it has a more open canopy and dense tangled undergrowth. Numerous commercial timber species are also found in the freshwater swamp forest. They include: *Symphonia gabonensis, Alstonia congensis, Mitragyna ciliate, Symphonia globulifera* and *Cleistopholis patens*.

Riparian Forest: This forest type within the study area consists of remnant forests (lowland rainforest and freshwater swamp forest) along the Osun River and its tributaries. This vegetation type serves as an important watershed protection forest. It is usually left in place as a result of the environmental constraints limiting the landuse for other purposes. There are narrow strips of riparian vegetation which are usually surrounded by agricultural fields; and so most of the merchantable timber has been extracted from them.

Marshland Vegetation: This vegetation belt is found on a narrow strip within the study area close to the Lekki Lagoon. This area consists of marshes. The associated vegetation types, include floating grass (*Vossia cuspidata*), water lily (*Nymphaea lotus*), Pistia stratiotes, *Pandanus, Cyperus papyrus*, *Lemna*, *Salvinia*, *Ipomoea* and *Jussiaea* as well as large masses of water hyacinth (FORMECU, 1999, Fieldwork, 2009). At the mouth of the Osun River, where it discharges into the Lekki Lagoon, a large mass of water hyacinth has almost blocked the entrance.

The common phenomenon among these vegetal belts is the destruction of the natural vegetation through clear felling for farming activities and also through selected logging of some economic species, without replacement. Forests and savannas have played a critical role in the survival of human population; they provide food and shelter for people and also regulate our environment. Loss of forests and woodlands, therefore, means loss of vital resources and disruption of the socio-economic activities they support.

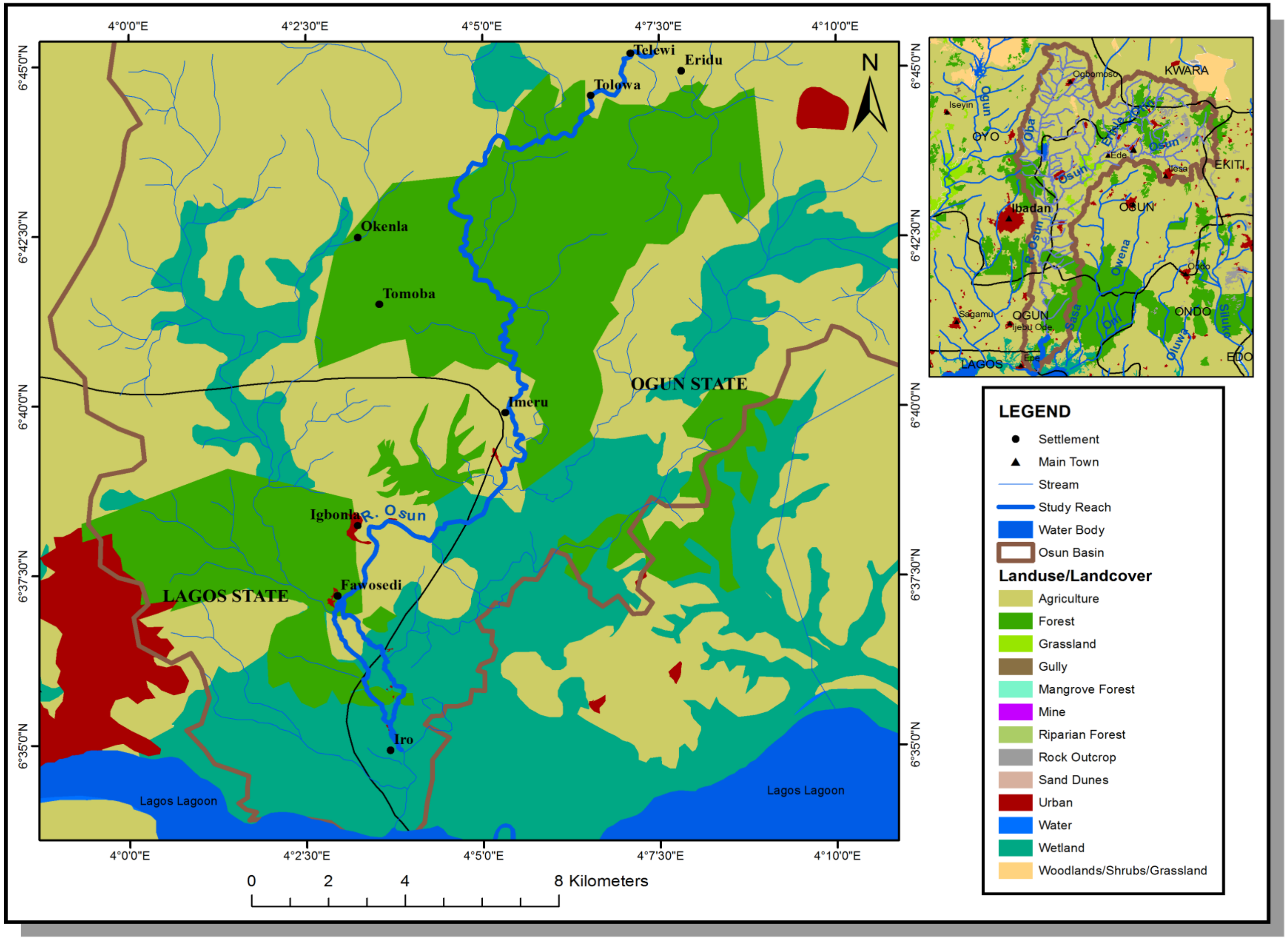


Figure 1.10: Vegetation and landuse of the study area, River Osun River, Nigeria

1.6.7 Hydrology

Surface Water: Natural water resources in the Osun River basin include streamflow and groundwater storage, the former playing the major role. Owing to streamflow variability both in time and space, streamflow records should ideally span long observation periods, but there is limited streamflow records for the study area and the Osun River basin as a whole.

Groundwater: The two major potential sources of groundwater in the Osun River basin are the coastal plain sands (including the upper parts of the Ilaro Formation) and the Abeokuta Formation. These formations have the following characteristics in common: The origin of the deposited material; the mode of deposition and alternation of sands, lenticular horizons and clayey units with relatively thin sand horizons. The Ewekoro Formation constitutes an impervious barrier between the Abeokuta Formation, on the one hand, and the coastal plain sands and Ilaro Formation on the other. Hence the two sources are hydrogeologically independent of each other (Osun River Basin Feasibility Study, 1982). The general direction of the groundwater flow appears to be from the north to the south towards the sea.

The Abeokuta Formation comprises two characteristic units. The first is the phreatic zone. Delineated by the formation outcrop, this zone comprises an area approximately 200 km^2. This zone is replenished by rainfall infiltrating through the unsaturated formation. Flow across the boundary between Abeokuta Formation and the Basement complex is marginal on account of the impervious nature of the latter. The second is the confined zone: dipping to the south of the formation outcrop, this zone has an area considerably in excess of the unconfined zone (Osun River Basin Feasibility Study, 1982). Based upon information from the well drilled in the Abeokuta Formation, it is assumed that the average total thickness of sandy units in the zone is 40 m.

The Coastal Plain Sands: The Coastal Plains Sands aquifer is a multi-aquifer system consisting of three aquifer horizons separated by silty or clayey layers (Longe *et al.,* 1987). They are essentially unconfined, being overlain by alluvium in the valleys along rivers. The aquifers have variable thickness with first and third horizons attaining thickness of about 200m and 250m respectively, and the second horizon is approximately 100m thick (Longe *et al.,* 1987). The aquifers are sometimes underlain by impermeable horizons of shale and lenses of clay.

Groundwater Yield: Studies by the Ogun-Osun River Basin Development Authority (1982) showed an estimated groundwater exploitation potential of 9 lit/sec/km in the coastal plain sands' front of the Ogun-Osun basin within the study area. This figure, which was derived from analysis of existing borehole logs in the coastal plain sand formations available in the literature (Jones and Hockey, 1964), amounted to about 12 MCM per annum for the front. Studies from the Abeokuta aquifer in the vicinity of Ijebu Ife produced net replenishment figures of the order of 30 to 35 MCM/year or a yield of 2 to 2.3 lit/sec/sq.km. These estimates are regarded as the upper limit of groundwater potential.

Water Quality: Streams within the study area flow through alluvium and the quality of surface water is characterised by turbidity with extreme values occurring during floods. It has relatively high iron content and is low in chlorides (Osun River Basin Feasibility Study, 1982). The water is coloured, acidic, with low alkalinity. Groundwater, on the other hand, is clear and colourless and up to potable standards.

1.6.8 Suitability of the study area for the research

The study area is found suitable for this research for some reasons. First, the drainage basin of the Osun River is almost entirely on Basement complex rocks, and only within these few kilometres downstream (about 44km) between Ijebu Igbo and the Lekki Lagoon does the stream flow on sedimentary rocks. In the study of channel change, changes are more easily detected within the sedimentary terrains than within Basement complex terrains.

Second, the Osun River exhibits a meandering (single thread) plan form over most of its length, but towards its entrance into the Lekki Lagoon, the channel changes into an anabranching (multi-thread) plan form before it reverts to the original pattern. This provides the opportunity to study the factors responsible for the transformation of a stream channel within the same geologic, climatic and hydrologic regimes, from a single-thread to a multiple-thread pattern.

CHAPTER TWO

THEORETICAL FRAMEWORK AND LITERATURE REVIEW

2.1 Theoretical background of channel change studies

2.1.1 The drainage basin as a system

The river basin has been recognised as the basic geomorphic unit for the study of landscape processes. Within this unit, it is possible for data to be collected, organised and analysed (Chorley, 1962). The use of this geomorphic unit as a basic research and planning unit was elaborated by numerous authors, including Horton (1932; 1945), Strahler (1952; 1956; 1957; 1964), Shreve (1966), Wigwe (1966), High and Richards (1970), and Faniran (1972; 1977).

The drainage basin offers a unique opportunity for the study of activities that shape the form of the earth surface and its use stems from the work of von Bertalanffy (1950). He explored the implications of viewing organisms as open systems, and, building on the ground-breaking work of Lotka (1924, 1954), which drew on chemical reaction theory, couched the dynamics of biological systems in terms of simultaneous differential equations. This work was the inspiration for the eventual injection of open systems concepts into geomorphology.

The Davisian concept that bases its theme on “stage of development,” among others, for a long time, constrained geomorphology to observe the drainage basin as a static closed system. This concept views streams as tending to develop a graded longitudinal profile provided a long-enough period of “still stand” could be guaranteed. Yet, there is a striking similarity between this historic Davisian approach to landform studies and the von Bertalanffy (1952) closed system thinking: von Bertalanffy (1952) asserts that a closed system is that which possesses clearly defined and closed boundaries across which there is no import or export of materials and energy. This implies that, once a closed system is set in motion, energy and materials tend to be degraded over time without replenishment or maintenance. This approach makes it virtually impossible to conceptualize problems in a dynamic sense.

Open systems contrast markedly with closed systems. For instance, Reiner and Spiegelmen (1945) aver that an open system needs a source of energy for its maintenance and preservation and is, in effect, maintained by this constant supply and removal of energy and material. Thus, there is a close similarity between the open system and the drainage basin, for instance, the input of energy from the sun and precipitation into the basin is balanced by the output in the form of river discharge and evapotranspiration. Accordingly, the drainage basin is now being viewed as an open system in which all components of the system work towards a steady state where impute and output of energy is balanced. Within this framework, energy is seen to move from one component to another with no loss but a change in the form. The energy source has to be consistent for the maintenance and preservation of the open system.

The drainage basin is an entity composed of diverse but interrelated parts that function as a complex whole. Within the drainage basin, all the component parts are linked, and this linkage of the component parts (coupling) allows for the flow of energy and matter from one component to another. There are two types of coupling within the system- positive and negative. In a positive coupling, a change (increase or decrease) in one component is a stimulus that leads to a change of the same direction in the linked component. When one component increases, a positively coupled component responds by increasing. Conversely, in a negative coupling, a change in one component stimulates a change of the opposite direction in the linked component. The status of the drainage system's components as either 'dependent' or 'independent' of other components is a matter of scale (Lane and Richards, 1997; Schumm and Lichty, 1965). For instance, on short-time scales, channel slope is independent of sediment transport, but on (much) larger time scales it is dependent on it, because channel slope slowly adjusts to the prevailing sediment transport regime by means of incision/aggradation and/or sinuosity adjustment (Schumm and Lichty, 1965). Changes within the drainage basin are also complex; change in one portion of the system may result in complex changes, both locally and throughout the remainder of the system. During complex response, the system responds through the activation of different processes at different locations and times as a result of one triggering event or intervention. Consequently, when a part of the drainage system is subjected to intervention, for example, through the construction of a dam across a channel, depending on the scale of the river and the length downstream, changes should be expected to occur throughout the system and over a prolonged period, especially downstream of the impoundment.

Open systems thinking led to a new typology of systems, as first proposed by Chorley and Kennedy (1971), and adopted by Strahler (1980). According to these authors, there are several levels of systems: morphological (form) systems, cascading (flow) systems, and process-response (process-form) systems. Morphological or form systems are conceived as sets of morphological variables which are thought to interrelate in a meaningful way in terms of system origin or system function. An example is a hillslope represented by variables pertaining to hillslope geometry, such as slope angle, slope curvature, and slope length; and to hillslope composition, such as sand content, moisture content, and vegetation cover, all of which are assumed to form an interrelated set.

Cascading systems or flow systems are conceived as “interconnected pathways of transport of energy or matter or both, together with such storages of energy and matter as may be required” (Strahler, 1980). An example is a hillslope represented as a store of materials: the weathering of bedrock and wind deposition both add materials to the store; slope processes transfer materials through the store; and erosion by wind and fluvial erosion at the slope base remove materials from the store. Other examples of cascading systems include the water cycle, the biogeochemical cycle, and the sedimentary cycle, all of which may be identified at scales ranging from minor cascades in small segments of a landscape, medium-scale cascades in drainage basins and seas, to mighty circulations involving the entire globe. Process-response systems or process-form systems are conceived as an energy flow system linked to a morphological system in such a way that system processes may alter the system form and, in turn, the changed system form as well alters the system processes. A hillslope may be viewed in this way with slope form variables and slope process variables interacting. Thus, Small and Clark (1982) view a hillslope as a natural system within which there are numerous complex linkages between controlling factors, processes, and form. For example, change in land use and effects on transpiration, runoff, and solute dynamics.

2.1.2 Dynamic equilibrium theory and the fluvial system.

The concept of dynamic equilibrium, and its ideal steady state, considers landscape features that result from the interaction of matter and energy passing through a system; it assumes a tendency toward a balance between process and form. The model is time-independent in the sense that, after dynamic equilibrium has been established, it cannot be ascertained how long that condition has prevailed. The concept of dynamic equilibrium is an open system model because it assumes that, during short periods of time, relative to a geomorphic time frame, equal amounts of material and energy enter and leave the system (Chorley, 1962). This means that there exists a balance of inputs to outputs, the amount of sediment and water passing through a given upstream cross section is the same as that passing through a given downstream cross section. This implies that nothing is gained or lost over a reach of finite length.

This theory argues that a system will continue to be in a state of equilibrium because the integrated feedback subsystems will operate in a self-regulatory manner and enrich the system by providing it with greater flexibility of response. In fluvial systems, apart from the effect of geology, the channel form reflects the discharge characteristics and the adjustments that are made when the variables of the components are changed either naturally or by external influence.

With this conceptualization, it is possible to predict how a river will adjust through its cross-sectional form, bed configuration, planimetric geometry and bed slope to accommodate the water and sediment entering the channel (Brookes, 1992). River systems behaviour therefore can be classified on the basis of their equilibrium state as determined by the balance in three kinds of parameters:

- Driving Variables
- Boundary Conditions and
- Adjusting Variables

Lane's equation:

$$\mathbf{Q_s \bullet D_{50} \propto Q_w \bullet S}$$

Where:

Q_s = Sediment Discharge,

D_{50} = Sediment Particle Size,

Q_w = Water Discharge and

S = Channel Slope

Lane's equation summarizes the concept of channel adjustment towards a state of equilibrium. This equation equates the product of a river's sediment load and sediment size with the product of the same river's slope and discharge. It is used to demonstrate how channels will adjust to certain variations in the supply or capacity of water and sediment. The adjustments made are in an effort to return to a state of "balance" or equilibrium. Provided the driving variable remains constant, the adjustment within the system may remain constant and, as long as the energy exchange continues, this state will be maintained indefinitely.

Montgomery (1989) introduces the concept of structural stability to distinguish between far-from-equilibrium systems and equilibrium systems. Given the nature of the fluvial systems which can be said to be ordered, it cannot be regarded as a far-from-equilibrium system, like most biological systems. For example a living organism is far from equilibrium singular system, whose non-equilibrium is obtained from the environment. When a living organism loses its ability, as a singular system, to hack into environmental no-equilibrium, it turns into a more equilibrated system (dies). The system is driven by an expected potential energy and this makes the fluvial system largely distant from a far-from-equilibrium condition. Thus, when a change occurs in the internal fluctuations or change in driving variable, the system will adjust mutually some or all of its parameters (adjusting variables) to accommodate the change in the driving variable. In most of the far-from-equilibrium situations, the system wanders, thereby bifurcating and creating new diverse forms.

Stability with respect to fluvial systems refers to determinate structural regularity of channel form which is sustained by the constancy of the constraints imposed on the systems. Chorley (1962) postulates that the channel will develop towards a steady state, and therefore undergo changes in the process. But in the light of the present conceptualization, the steady state should be replaced by a local equilibrium in which case the transport of mass (sediments) and energy (water) will be done in the most economic manner.

Schumm (1973; 1977) introduces the notions of metastable equilibrium and dynamic metastable equilibrium. He shows that thresholds within a fluvial system cause a shift in its mean state. The thresholds are not part of a change continuum, but show up as dramatic changes resulting from minor shifts in system dynamics, such as caused by a small disturbance and may be extrinsic or intrinsic. In metastable equilibrium, static states episodically shift when thresholds are crossed. In dynamic metastable equilibrium, thresholds trigger episodic changes in states of dynamic equilibrium. A steady state equilibrium involves fluctuations about an average, but a metastable equilibrium occurs when an external influence carries the system over some threshold into a new equilibrium regime.

2.1.2.1 Time scale issue

Rivers can only attain an approximate equilibrium at some suitable time scale between short-term fluctuations and long-term evolutionary tendencies, when the river channel adjusts to external controls (Lane and Richards, 1997; Cammeraat, 2002). Hence, the time scale issue is addressed and forms one of the major challenges in the fields of environmental studies. Commonly, time periods can be defined as:

1. Instantaneous time scale (<10^{-1} years);
2. Short time scale (10^{1} -10^{2} years);
3. Medium time scale (10^{3} -10^{4} years);
4. Long time scale (>10^{5} years).

Channel change in instantaneous time scale cannot make much sense neither in describing channel form change nor understanding channel evolution dynamics. Over the short time scale, the stream transports its load selectively and the temporal pattern of discharge may be thought of as a single entity. This time period is most significant for examining the relationship between the independent variables and certain elements of channel form (Leopold and Maddock, 1953; Sandra, 2000), for example impute spate flow. At the medium time scale, the stream adjusts its internal geometry in such a way that the sediment supplied can be transported with the discharge available, so that material does not accumulate indefinitely. These two time periods (short and medium time scales) are the most relevant as regards channel form adjustment, since mean water and sediment discharge are independent variables to which average channel geometry is related (Winterbottom, 2000; Sandra, 2000).

Over longer time periods, geological events, such as large climatic fluctuation and tectonic movement, become the major controls on channel change, since discharge and load conditions are no longer constant in the mean and adjustment (Knighton, 1984; Lane and Richards, 1997). Most of the fluvial geomorphology studies deal with the channel changes in the short and medium time scales.

2.1.3 Hydraulic geometry concept

Channel geometry refers to the three-dimensional form of the channel. The adjustment of channel geometry to external controls can be considered in terms of four degrees of freedom: (1) Cross-sectional form: the size and shape of a channel in cross-profile either at a point or as a reach average; (2) bed configuration: the distinct forms moulded in the bed of particularly sand- and gravel-bed streams; (3) planimetric geometry or channel pattern: the two-dimensional form of the channel when viewed from above, the commonest subdivision being into straight, meandering and braided; (4) channel bed slope: the gradient of a stream at the reach and longitudinal scales, where the latter also refers to the overall shape of the longitudinal profile (Knighton, 1984).

Hydraulic geometry connotes the relationships between the mean stream channel form and discharge both at-a-station and downstream along a stream network in a drainage basin. The channel form includes the mean cross-section geometry (width, depth, cross-section, meander length), and the hydraulic variables, which include the mean slope, mean friction, and mean velocity for a given influx of water and sediment to the channel and the specified channel boundary conditions. Leopold and Maddock (1953) express the hydraulic geometry relationships for a channel in the form of power functions of discharge as

$$B = aQ^b, d = cQ^f , V = kQ^m \qquad (1a)$$

where B is the channel width; d is the flow depth; V is the flow velocity; Q is the flow discharge; and *a, b, c, f, k,* and *m* are parameters. Added to equation (1a) is

$$\mathrm{n = NQ^p , S = sQ^y} \qquad (1b)$$

where n is Manning's roughness factor; S is slope; and N, p, s, and y are parameters. Exponents b, f, m, p and y represent, respectively, the rate of change of the hydraulic variables B, d, V, n and S as Q changes; and coefficients a, c, k, N and s are scale factors that define the values of B, d, V, n and S when Q = 1.

The hydraulic variables, width, depth and velocity, satisfy for rectangular channels the continuity equation:

$$\mathrm{Q = BdV} \qquad (2)$$

Therefore, the coefficients and exponents in equation (1a) satisfy:

$$\mathrm{ack = 1 , b + f + m = 1} \qquad (3)$$

The at-a-site hydraulic geometry entails mean values over a certain period, such as a week, a month, a season, or a year. The concept of downstream hydraulic geometry involves spatial variation in channel form and process at a constant frequency of flow. Downstream hydraulic geometry (DHG) characterizes systematic downstream changes in channel geometry as power-law relationships with discharge, and may be used to quantify the influence of fluvial controls on channel form (Leopold and Maddock, 1953). Downstream hydraulic geometry has been used successfully to describe river patterns worldwide in many physiographic environments.

2.1.3.1 Maximum flow efficiency (MFE)

With the introduction of a channel form factor, Huang and Nanson (2000) illustrate the self-adjusting mechanism of alluvial channels with the basic flow relations of continuity, resistance, and sediment transport. Natural channels adjust their form and attain maximum flow efficiency. Under such conditions, rivers exhibit regular hydraulic geometry relations at dominant or bankfull stage. The maximum flow efficiency (MFE) is defined as the maximum discharge and sediment transporting capacity of flow per unit available unit stream power. Thus, the theory of maximum flow efficiency combines the theory of maximum sediment transporting capacity and the theory of minimum stream power. These three theories can also be explained in terms of the physical principle of least action. Using the continuity equation, Lacey’s flow equation (Lacey, 1957-58), DuBoys’ sediment transport formula (Graf, 1971), and a non-dimensional channel shape factor defined by the width/depth ratio, Huang and Nason (2000) derived optimum channel geometry relations.

Maximum flow efficiency has recently been suggested as the underlying mechanism behind anabranching (Nanson and Knighton, 1996; Nanson and Huang 1999; Jansen and Nanson, 2004). The proponents of the MFE concept argue that multiple-channel anabranching reaches convey water and sediment downstream more efficiently than single-channel reaches. They argue that, in addition to adjusting slope, bed configuration and channel cross section, anabranching provides another degree of freedom for a river to maintain the conveyance of water and sediment downstream. Channel efficiency is related to the lower cross-sectional area in multiple-channel sections than single-channel sections. Total cross-sectional area is lower where total width decreases, which increases the average cross-sectional velocity for a given discharge and hence increases efficiency.

2.1.4 Synthesis

The above section has shown some of the approaches used in explaining the relationships between process and form in a river system, and the complexity of morphological adjustments taking place within river channels. In this study, results from an extensive field survey was used to compare downstream changes in cross-sectional geometry, and channel pattern within two adjacent channel reaches in the alluvial section of River Osun. The comprehensive dataset was used to test the hypotheses on the potential controls on stream channel morphology. The study was, therefore, hinged on the concept of downstream hydraulic geometry, with the traditional dynamic equilibrium theory.

2.2 Literature review

River channels adjust their channel slope, cross section, pattern and bed morphology over a range of time scales in relation to natural and anthropogenic changes. This section of the study deals with the review of the literature in the different areas of channel change. The first part deals with the literature on methods and data sources used in previous channel change studies. The second part deals with studies of different channel plan forms (pattern and cross-sectional form). The third part is concerned with controls of channel plan form, while the last part focuses on studies of plan form changes.

2.2.1 Methods and data sources used in previous channel change studies

Most instrumental and observational records of streams are limited in time and space. Historical records, such as maps, vertical stratigraphic sections, and contemporary observations, are valuable for reconstructing past channel conditions. Studies at various time- and space-scales have attempted to understand and explain river channel change, a long-term aspect of landform behaviour (Braga and Gerasoni, 1989; Bravard and Bethemount, 1989; Mcewen, 1989; Stuart and Keith, 1997; Ashmore *et al.*, 2000). In order to study channel change at the long time scale and medium time scale, sediment cores and archaeological sites are commonly used to analyse channel planform change, riverbed change and types of channel deposits (Brown, 1995; Starkel, 1995; Walling, 1995; Owens *et al.*, 1999; Brewer and Lewin, 1998; Brown *et al.*, 2001; Couper *et al.*, 2002; Rãdoane *et al.*, 2003). For instance, in the Middle Trent, scholars employed data from gravel pits, archaeological sites and documentary source and acquired abundant structural evidence of changes in channel pattern and channel type since the 11th century AD (Brown *et al.*, 2001).

Historical records, including documents, survey notes, maps and photographs, can also provide valuable information about channel changes in a shorter time scale (Patrick *et al.*, 1992; Gurnell, 1998; Warner, 2000; Winterbottom, 2000; Daba *et al.*, 2003). Based on historical maps and aerial photographs, Brewer and Lewin (1998) examined channel changes in two time scales (2.5 years and 150 years) in the River Seven, mid-Wales. Likewise, Gurnell (1997) used historical maps and air photographs, supplemented with GIS, to identify channel change within the same river over 115-year period and over 50 years, respectively. They drew a similar conclusion on spatial and temporal trends of the same river stretch in two different scales. Ghimire *et al.*, (2004) assessed landuse and stream planform changes in eastern Siwalik Hill of Nepal from the period between1964 and 2003 based on analysis of historical aerial photographs.

Owing to the varying quality and accuracy, small-scale maps have not been adequately employed in fluvial researches so far. Particularly, the shorter the time period one studies, the greater difficulty the study has in identifying channel changes which exceed the errors incurred in information extraction from the photographs and registration to a common map base (Gurnell, 1997). In contrast, despite their snapshot character, fragmentation of records and other limitations, large-scale maps consist of considerable details of river channel changes, which are unattainable in small-scale maps. One typical example of using historical maps in recent studies is Pišút's (2002) research in the Danube River, Bratislava. Channel adjustments of the Danube River were reconstructed on the basis of historical river maps for 1712-1886, the period preceding mid-course channelization. Thirteen local maps were converted to the same scale of topographic map (1: 50,000) in the 1950s to reconstruct channel planform changes of the pre-channelized river and to examine the impact of floods and human activities on the channel changes (Pišút, 2002).

Historic ground photographs have been shown to document changes along river channels that are too subtle to be observed on historic aerial photographs or that predate the earliest aerial photographs. To this end, historic ground photographs of the Batten Kill and its tributaries in Vermont, U.S.A, were collected and scanned at the Russell Collection in Arlington, Virginia, U. S. A., and the Manchester Historical Society, U. S. A. by Field (2007); it was concluded that historic ground photographs could document system wide responses to future watershed restoration efforts. With the development of geospatial processing tools for georeferencing digital maps and images—and their increasing ease of use—a greater degree of quantification and a higher level of precision can now be obtained by co-registering sets of historical maps and images made at different scales and projections.

GIS and remote sensing techniques are now of great importance in the study of geomorphological processes, for example in quantifying and predicting erosion, change of topography, and channel change in fluvial basin in short-time scale (Franklin and Wulder, 2002; Henry *et al.*, 2002; Poole *et al.*, 2002; Chappell *et al.*, 2003; Daba *et al.*, 2003; Lane *et al.*, 2003; Martinez- Casasnovas *et al.*, 2003; Rippin *et al.*, 2003). Also, many landscape models have been developed in the past decades for reconstructing historical channels (Yin and Wang, 1999; Hancock and Willgoose, 2001; Finlayson and Montgometry, 2003; Khan and Islam, 2003; Martínez-Casasnovas, 2003; Rippin *et al.*, 2003). Gurnell *et al.*, (1994) investigated channel planform change along an 18km section of the River Dee on the Welsh-English border by overlaying information from historical maps and air photographs. The information on river planform change spanned 115 years, during which the river was subject to increased flow regulation. The study successfully identified channel planform change because it utilized a GIS-based approach, as opposed to a manual approach.

Aerial photograph comparison techniques were used by Lagasse *et al.* (2003) to predict meander migration on the White River in Indiana, U.S.A. Aerial photographs from 1937 and 1966 were acquired for a reach of the river; the banklines were delineated and registered for comparison. The rate of change of bend centroid position and length of the radius of curvature were also extrapolated to construct a circle that would describe the location of the outer bankline of each bend at some selected date in the future. A comparison of the actual bankline locations with the predicted bankline positions revealed that aerial photograph comparison techniques can predict meander migration with relatively good accuracy.

Digital Elevation Model (DEM) has been used in previous studies to simulate channel evolution processes in the last decade. This is because they show good representation of landform surface variability and provide the opportunity to measure and monitor morphological change (Sandra, 2000; Warner, 2000; Brasington and Smart, 2003; Rinaldi, 2003). Using the elevation data from a ground-based three-dimensional tachometric survey in two reaches of the River Nent, UK in two periods, DEMs for each reach and for each survey period were built up to elucidate the relationship between process and the form of channel change operating at different spatial and temporal scales (Chappell, 2003). Lane *et al.*, (2003) developed a DEM coupling the use of remote sensing for channel change detection (erosion and deposition volumes) in a wide, braided, gravel-bed river. The rates of channel incision and sediment production were computed from the subtraction of multi-temporal DEMs.

Aerial photograph and orthphotos have also been employed to map gully erosion and determine erosion rates with DEMs (Martinez-Casasnovas, 2003). Usually geomorphologists use three methods to generate DEMs according to the required scale, quality and resolution: (1) radar interferometry for scales higher than the 1/1000e; (2) the Global Position System (GPS) if the relief is very marked or if many obstacle exist; (3) digital photogrammetry with various resolutions according to the scale of photographs (Henry *et al.*, 2002; Mount *et al.*, 2002; Brasington and Smart, 2003). Van Der Wal and Pye (2003) however note that digital photogrammetry and remote sensing images cannot provide under-water bathymetric information, but with the help of GIS, historical bathymetric charts can help make up for the shortage of historical bathymetric data for DEM under water bodies, although source errors and uncertainty in the charts cannot be eliminated. Henry *et al.,* (2002) recommend small-format and low-altitude aerial photos to generate a DEM in mountainous areas. Their study applied in-situ aerial photos to the 3-D modelling of the Super-Sauze earthflow and its environs. Another successful application of aerial photos is the 3D mapping of the Nyack flood plain of Middle Fork Flathead River, MT, USA.

Brasington *et al.* (2000) used an alternative approach to the study of three-dimensional morphological dynamics of a divided reach of the gravelly River Feshie, Scotland, in which topographic survey of both exposed and submerged areas of the reach was undertaken using the Global Positioning System (GPS) and DEM differential techniques. However, the resolution effects of DEM remain a factor of uncertainty in many hydrological and geomorphologic modelling approaches. Schoorl *et al.* (2000) found that DEM elucidated the processes of erosion and sedimentation, and that erosion predictions increased with coarser resolution. Heesom and Mahjoubi (2001) tested the effect of grid resolution and terrain characteristics on data from digital terrain model (DTM) and found that both increasing the grid resolution and varying the characteristics of the terrain would affect the accuracy of any derived data.

The success of these methods for study of channel change varies with the level of precision of the original maps or images and the availability of ground-control points or other reference points common to precise spatial data.

2.2.2 Studies on channel plan form

The form of a river can be regarded as the response by the channel to its inputs, which can be considered in terms of adjustments to the long profile, the cross-sectional profile and to the form of the channel in plan or channel pattern (White *et al.*, 2000). Studies of channel plan form involve studies of the pattern, cross section and the longitudinal profile of a stream.

2.2.2.1 Channel pattern

Channel pattern is the planimetric geometry, or the form of the channel when viewed from above (Leopold and Wolman, 1957). Thus, pattern represents a form of adjustment in the horizontal plane that influences resistance to flow.

Straight, meandering, and braided patterns were described by Leopold and Wolman (1957). But subsequently, anabranching streams were also identified as a different channel pattern (Mollard, 1973; Rust, 1978; Brice, 1984; Schumm, 1985; Nanson and Croke, 1992; Knighton and Nanson, 1993; Rosgen, 1994; Makaske, 2001). The term “anastomosing” was initially used synonymously with “braiding”: however recently (since the 1960s), with the input of more data on anabranching streams, the anastomosing pattern has been described as a distinct form of anabranching (Smith and Putnam, 1980; Smith and Smith, 1980; Miller, 1991; Knighton and Nanson, 1993; Smith *et al.*, 1997, 1998; Makaske 1998, 2001). The wandering pattern was added as a transitional form between braiding and meandering (Neill, 1973; Church 1983). The recent extension of the range of river types has been an important development in appraisals of fluvial geodiversity (Blue and Brierley, 2013; Li *et al.*, 2013).

Sinuosity, or the ratio of stream length measured thalweg to valley length, is commonly used to describe channel pattern (Brice 1984; Hooke 1977). Leopold and Wolman (1957) originally proposed a sinuosity of 1.5 as the boundary between straight and meandering, but others have suggested that this traditional classification is insufficient in describing the range of patterns that exist in nature. Schumm (1963) recommends five classifications depending on sinuosity value: straight (1.1), transitional (1.3), regular (1.7), irregular (1.8), and tortuous (2.3). Brice (1984) similarly asserts that, if sinuosity is less than 1.05, the channel is straight; if sinuosity is within the 1.05 to 1.50 range, the pattern as sinuous; and if it is greater than 1.5, the river is meandering. Brice (1984) adds additional classifications, such as sinuous canaliform, sinuous point bar, sinuous braided and nonsinuous braided. An even more elaborate classification scheme developed by Rosgen (1996) defines 41 types of channels.

Regardless of the system being used, however, it is clear that the categorization of channel pattern types are arbitrary.

Channel pattern has also been distinguished on the basis of sediment load parameters (Mollard, 1973; Rust, 1978; Brice, 1984; Schumm, 1985). Width-depth ratio was used as a measure of river channel shape by Schumm (1960; 1961 and 1962). Qian (1985) developed a widely accepted classification system differentiating among wandering, anabranching, meandering and straight channels on the basis of their planform, manner of channel shifting, stability and bank erodibility.

According to Makaske (2001:152), a channels pattern is considered a two-dimensional, planform configuration only, regardless of any other flood plain characteristics. In this respect, two properties are most relevant: channel sinuosity and channel multiplicity (Makaske, 1998, 2001). Based on sinuosity, straight and meandering plan forms are recognised while braided and anabranching (including anastomosing and wandering) are recognised based on multiplicity.

Straight pattern

A straight river is generally regarded as one of the typical river patterns in conventional classifications in terms of its channel plain landforms (Sui-ji and Jin-ren, 2002). Straight stream channels are not common in nature. Where they occur, they are short reaches usually controlled by a linear zone of weakness in the underlying rock, like a fault or joint system (Leopold and Wolman, 1957). Reaches which are straight for distances exceeding ten times the channel reach are rare. Streamflow in straight channel segments is not straight but rather sinuous, with the deepest part of the channel changing from near one bank to near the other. Velocity is highest in the zone overlying the deepest part of the stream, (Leopold and Wolman, 1957).

The drainage of Walnut Gulch in SE Arizona illustrates channel alignment forced by geological controls (Murphy *et al.*, 1972). Walnut Gulch and its tributaries drain alluvial fills of tertiary and quaternary age and are characterised by wide, shallow, sinuous single- and multi-thread courses. However, the channels are essentially straight where they are bounded by outcrops of caliche and traverse resistant conglomerates with marked and abrupt changes of direction signalling entrenched, fault-controlled drainage.

Sui-ji and Jin-ren (2002) carried out a review of studies on straight channel patterns. Based on the analysis of existing theories, observations, evolution processes of the channel patterns in the experimental results, they concluded that the straight pattern should not be included as one of the typical patterns that are self-formed and developed.

Meandering pattern

The pronounced and universal sinuosity of meandering rivers has been the subject of scientific curiosity among river scientists for many years. This has led to serious research with concomitant hypothesizing as to the scientific explanation for the phenomenon. While there are theories as to causality, there is no accepted doctrine for their formation.

The meandering pattern is thought to develop in streams because of small perturbations in flow bends (Leopold and Wolman, 1957; Stolum, 1996; Hooke, 2007). These disturbances, caused by such things as large rocks, pools, riffles, and large woody debris, direct the flow of a stream into the riverbank. The riverbank then deflects and pushes the flow into the opposite bank of the river, with erosion taking place along both channel sides and the stream depositing these sediments in areas of lower stream flow. Stolum (1996; pp 1710) states that "river meandering needs to be understood in terms of chaotic dynamics and self-organization." Two opposing processes are at play in the river channel: lateral migration from bank erosion that increases the sinuosity of the river and cut-offs that act to decrease sinuosity.

The development of numerous meanders from an initially straight stream sometimes transform the channel into a chaotic state, causing cut-offs to occur, and allowing the river to transit back into a steady state (Stolum, 1996). Accelerated local change in the river may lead to the occurrence of many cut-offs, which creates a period of slow change thereafter (Hickin, 1977; Stolum, 1996). These changes are simply part of the natural evolution of meanders, caused by variations of stream flow, adjustments in the stream channel, climatic variations, and the impacts of urbanization (Hooke, 1994).

Braided pattern

Braided rivers are characterised by frequent shifts in channel position. As a result, the braided channel form has often been regarded as disequilibrium aggradational response to high sediment loads (Parsons and Abrahams, 2003). However, even though individual channels may be transient, the fact that braiding appears to be favoured by particular environmental conditions (high and variable discharges, steep slopes, dominant bedload transport and erodible banks) suggests that it represents a valid equilibrium form (Parsons and Abrahams, 2003).

Braiding can also be understood as a response to maintaining transport competence in relation to the imposed grain size (Henderson, 1961; Carson, 1984) and/or transport capacity in relation to the imposed sediment load (Kirkby, 1977; Bettess and White, 1983; Chang, 1985). From these perspectives, the occurrence of braided rivers reflects the availability of large amounts of coarse sediment and its movement as bedload. Such approaches provide important links with the underlying causes of braiding, namely local aggradation (often linked to the stalling of bedload sheets, channel bars or loss of competence in flow expansions), bar growth (by vertical and lateral accretion) and subsequent dissection (Ashmore, 1991).

Anabranching (including anastomosing) pattern

Anabranching rivers (or anastomosing, see Makaske, 2001) may be defined as a system of multiple channels (branches) that are separated by relatively stable, often vegetated islands (Nanson and Knighton, 1996; Jansen and Nanson, 2004). Individual branches of an anabranching river may themselves be straight, sinuous or braided (Nanson and Knighton, 1996). The factors governing the occurrence and maintenance of anabranching regimes have become the focus of considerable recent investigation (Nanson and Knighton, 1996). The persistence of anabranching systems, both temporally and spatially, indicates that, in certain situations, they are likely to exhibit considerable advantages over their single-thread counterparts (Nanson and Knighton, 1996).

It was found that, in certain situations, anabranching systems appear to be closer to exhibiting the most efficient sections of flow for the conveyance of both water and sediment than are equivalent wide, single channels at the same slope (Nanson and Huang, 1999). However, not all anabranching systems are hydraulically efficient (Nanson and Huang, 1999). Once formed, some channels may, owing to inability to change with time, continue to operate despite increasing inefficiency (Nanson and Huang, 1999). The finding that they are sometimes not efficient is particularly interesting considering the fact that vegetation has been linked to the formation and maintenance of some anabranching systems owing to its influence on bank strength, and the fact that it may also cause the system to resist change over time. Therefore, a quantitative analysis of the role of vegetation on the formation and maintenance of anabranching reaches will enable the above finding to be thoroughly investigated.

Anabranching rivers are recognized as one of the four main river types, together with meandering, braided and straight rivers. Nanson and Knighton (1996) define an anabranching river as a “system of multiple channels characterized by vegetated or otherwise stable alluvial islands that divide flows at discharges up to nearly bankfull” (pp. 218). A number of different anabranching river patterns have been categorised by Nanson and Knighton (1996). These were classified on the basis of stream power, fluvial morphology, sedimentology and fluvial processes. They found that hydraulic, physiographic, geological and botanical conditions appear to play a role in influencing anabranching river types. The development of anabranching rivers is dependent on the combination of hydraulic and sedimentary conditions (Smith and Smith, 1980; Knighton and Nanson, 1993).

Nanson and Knighton (1996) claim that anabranching rivers can be found in a variety of environments and that climate itself does not appear to be a determining factor. There appears to be a number of factors that play an important role in the formation of anabranching rivers. These include: low flow strength, low bank erodibility, sediment supply that exceeds the rate of onward transport, and a high degree of flow variability (Smith and Smith, 1980; Knighton and Nanson, 1993; Nanson and Knighton, 1996; Makaske, 2001). Magela Creek, Autralia, was classified as a type 2, sand-dominated, island-forming anabranching river by Nanson and Knighton (1996).

Anabranch stability in the fine to medium sands of the area requires low specific stream powers, a high proportion of overbank flow and riparian vegetation that is believed to provide considerable protection to the banks, bars, islands and flood plains with tree roots penetrating well below the level of the river bed (Nanson *et al*., 1993). It is shown that even during major flood events in the area, erosive energy remains low because of the relatively low channel gradients. Under such conditions, both stream flow and bed-material sediment load are concentrated along sections of relatively narrow, deep channels rather than spread over less efficient, wider and shallower channels that are partially obstructed by trees growing within the channel (Nanson *et al.*, 1993). The dense riparian forest appears to be essential for lateral stability, without which the system would probably form braided channels (Nanson *et al.*, 1993).

The role of climate, base level and flood-plain sedimentation rates, as causes of anabranching remain unclear (Smith, 1973; Makaske, 2001). Knighton and Nanson (1993) and Makaske (2001) note that climate itself does not appear to be a significant factor, although Makaske (2001) observes that climate and geology are important external controls of the processes leading to the formation of such rivers. He adds that certain controls, especially vegetation, seem to differ with climate. There appears to be a distinction between erosional systems and accretional anabranching systems. Erosional systems excavate channels within the flood plain while accretional systems build islands within, or flood plains around existing channels (Nanson and Knighton, 1996).

The characteristics of the four channel patterns discussed in the section above suggest that all natural channels are interwoven. Studies (for instance, Leopold and Wolman, 1957; Rosgen, 1996) have shown that, although channels can be classified into individual patterns, there is no sharp distinction among these patterns; rather, river pattern is a continuum from one extreme to another. Lane (1957), Leopold and Wolman (1957), and Thorne (1997) describe the continuum of channel pattern, which, simply stated, describes a gradual merging of one river pattern into another in response to commonly recognized factors of stream power (discharge and slope), sediment regime (sediment load and bedload grain size), and less noted factors, including geology and vegetation.

Leopold and Wolman (1957) also note the transitional nature of channel pattern: a braided stream can change into a meandering one within a relatively short reach and individual channels of a braided stream may meander. The continuum of channel types, therefore, emphasizes the similarity in physical characteristics which determine the nature of individual channels.

2.2.2.2 Channel cross-sectional form

Width and mean depth give the gross dimensions of the channel, and width and mean depth (W/D) is commonly used as an index of channel shape even though it is also not the most appropriate. Channel cross sections with high width/depth ratios are wide compared to their mean depths, and vice versa (Rosgen, 1996). The width/depth ratio of the cross section controls the distribution of flow in the channel, especially in meander bends (Markham and Throne, 1992).

Any important adjustment of channel form is reflected in the bankfull capacity of the cross - section (Pickup and Spring, 1984; Garcia, 1995; Hickin, 1995; Niekerk *et al.,* 1999; Inbar, 2000; Emmett and Wolman, 2001; Dollar, 2002; Moody and Troutman 2002). Variables of cross section are of great importance for hydraulic geometry and channel geomorphology studies.

2.2.3 Controls on channel plan form

The ability of a river to modify its form depends on the balance between the erosional force exerted by the river flow and the strength or resistance to erosion of the material forming its bed and banks. This balance is influenced by independent variables that control the physical processes in the river. The principal controls are stream discharge and valley slope (representing force) and the sediment load, bed material size, bank material composition and strength (representing resistance; Richards 1982; Robert 2003). The size of the bedload, the capacity of the stream to transport it, and the relative stability of the channel banks are, therefore, key variables in determining channel plan form.

2.2.3.1 Controls on Channel Pattern

Various empirical equations have been developed to differentiate between straight, meandering or braiding patterns using such variables as bankfull discharge, channel slope and bank material composition. Leopold and Wolman (1957) were the first to distinguish channel patterns based on channel slope and bankfull discharge.

$$\mathbf{S_b = 0.013\ Q_b^{-0.44}}$$

Here S_b is channel slope and Q_b is bankfull discharge. In this seminal work, this equation differentiated fields corresponding to straight, braided or meandering reaches on a graph of discharge versus slope. Thus, a threshold slope exists below which the channel would experience braiding. This was also indicated in the work of Lane (1957). The experimental work reported by Schumm and Khan (1972) showed that, for a given discharge, as valley-floor slope is progressively increased, a straight river becomes sinuous and then eventually braided at high values of stream power and sediment transport (Schumm, 2007). Rivers that are situated close to the meandering-braided threshold should have a history which is characterized by transitions in morphology from braided to meandering and vice versa.

Numerous equations have differentiated among straight, meandering or braiding patterns using other parameters. Channel pattern has been shown to also reflect sedimentary controls. Schumm (1963) found that channel sinuosity of sand-bed rivers in the Great Plains of the USA increased with the percentage silt/clay in the bed and banks. Kellerhalls (1982) and Carson (1984) found that sand-bed rivers braided at lower slopes than gravel-bed rivers with similar discharges. In these studies, grain size was used as a surrogate for bank strength (as in studies of cross-sectional adjustment discussed earlier) with the implication that channel pattern is dependent on the erodibility of the channel banks as well as the erosivity of the flow. Ferguson (1987) distinguishes channel patterns based on channel slope, discharge and the silt-clay contents of the banks.

$$\mathbf{S = 0.0013\ Q^{-0.24}\ B^{1.00}}$$

Here S is the channel slope, Q is discharge and B is the silt-clay content of the banks. Slopes that are steeper than those predicted by this equation will induce braiding. Analogous equations exist using other parameters, such as slope, discharge and median bed material diameter (Ferguson 1987).

Parker and Anderson (1975) and Hayashi and Ozaki (1980) found a clear boundary between braided and meandering channels in a field defined by the dimensionless variables channel slope/ Froude number and width/depth ratio. Fredsoe (1978) and Fukuoda (1989) showed that braided, meandering and straight rivers could be distinguished by the product of the width/depth ratio and the Shields parameter. In a graph defined by the ratio of adaptation length of bed topography and flow versus the Shields parameter related to grain roughness (Struiksma and Klaassen, 1988) meandering and braided rivers also plot in different areas.

Occasional references to the effects of valley confinement on river pattern are scattered in the literature (Schumm and Meyer, 1979; Van den Berg, 1995; Chew and Ashmore, 2000; Burge, 2004), often in conjunction with rock controls on channel alignment. Burge (2005), in his study on controls of channel pattern of the Miramichi Rivers, concluded that valley width was the primary control on the location of the wandering plan form in the Miramichi Rivers in New Brunswick, Canada. Tributary junctions and bedrock lithology (measured by relative bedrock hardness and valley width) were used to analyse the processes responsible for the formation of the anabranched river systems of the Yellowstone River, Montana, USA by Jenkins (2007).

Analysis of aerial infrared photographs as well as geologic and topographic maps revealed a weak relationship between tributary junctions and anabranches (R^2=0.38). The results further showed that neither valley width nor bedrock resistance to erosion had a perceptible control on the number of anabranches. It was concluded that high tributary stream power relative to Yellowstone River stream power (ωt / ωY >1) resulted in increased anabranching downstream from tributary confluences. Physical models of gravel braided rivers were used by Egozi and Ashmore (2009) to investigate the adjustment of braiding intensity to step changes in channel-forming discharge and the mechanisms by which channel pattern adjustment and maintenance occurred. The study showed that braided channel pattern dynamics is closely tied to, and explained by, the local dynamics and symmetry/asymmetry of bifurcations and avulsions.

2.2.3.2 Controls on cross-sectional form

The shape of the cross section of a river channel at any location is a function of the flow, the quantity and the character of the sediment transported through the section, and the character or composition of riverbank and riverbed (Leopold *et al*., 1964; Knighton, 1984).

Discharge is often deemed the key variable controlling channel cross-sectional dimensions of a river (Leopold *et al.*, 1964; Miller, 1984). This is, perhaps, best illustrated by Ferguson's (1986) observation that channel width and depth increase systematically with increasing bankfull discharge, as it varies over nine orders of magnitude from small laboratory channels to the world's largest rivers. Empirical geomorphological investigations of the relationships between channel geometry and stream discharge have traditionally followed the downstream hydraulic geometry approach of Leopold and Maddock (1953), in which downstream changes in width (w; m), depth (y; m) and velocity (u; m s−1) are expressed as power functions of an assumed dominant discharge.

The erodibility of channel banks exerts important secondary controls on cross-sectional adjustment (Powell, 2009). In dry-land areas, weathering processes do not produce significant amounts of cohesive silts and clays; bank materials often lack the strength to resist processes of bank erosion. As a result, channels tend to respond to floods by widening, rather than deepening, their cross section. Rosgen (1996) asserts that channel width is a function of three main factors: discharge frequency and magnitude, transported sediment size and type, and bed and bank material composition.

The key variable to explaining channel depth morphology is sediment regime and present streamflow (Miller, 1984; Rosgen, 1996). Additional factors controlling mean depth include valley morphology, basin relief, and bed and bank materials. Geology is also said to play a role in channel morphology (Cooke and Doornkamp, 1974). Bedrock channels tend to be wider as a response to the resistant bed preventing the channel from deepening (Leopold, 1994).

Hydrological research has found that stream channels correct themselves by balancing discharge and the sediment load (Hooke, 2004). If there is a change in one of these factors from interference in the system, then adjustments will take place within the stream channel to accommodate them (Mackin, 1948; Hooke, 2004). As the shape of a river changes in one location, it can have a profound effect that reverberates downstream. An increase of discharge will increase the competence and capacity of the stream, which improves the transportation power. This allows more sediment particles to be transported, increasing the amount of erosion that can take place from the channel banks and streambed (Friedkin, 1945; Mackin, 1948; Hickin, 1974; Brookes, 1985).

There is considerable uncertainty as to how channels adjust their cross sections. Much is known about the geotechnical and hydraulic forces that control bank stability and retreat, and attempts have been made to couple models of specific bank erosion processes (fluvial entrainment and mass wasting of bank materials and the downstream transport of failed bank materials) to predict cross-section adjustment in alluvial channels (Simon *et al*., 2000).

2.2.4 Spatial and temporal changes in channel plan form

Experimental studies and numerous field studies have shown that channel plan form (both pattern and cross-sectional form) change in response to changes in controlling variables. These changes could be spatial or temporal. The following section reviews studies on spatial and temporal changes in channel plan form.

2.2.4.1 Spatial and temporal changes in channel pattern

The fluvial geomorphology of the Yukon River in Alaska, USA (which had an anomalous assemblage of alluvial channel patterns, including meandering, anabranched, wandering and braided reaches) was studied by Clement (1999) with the aid of GIS and radiocarbon dating. The anomaly of the multi-channelled morphology was explained by bank instability owing to gravel comprising the lower 30 - 50% of bank facies. An anabranch cycle model was developed from the literature and field observations in a study by Burge and Lapointe (2005) to illustrate how channel pattern within the wandering Renous River, New Brunswick, Canada changed from single to multiple channels and vice versa over a number of decades. Aerial photographs of 1945, 1965, 1983 and 1999 were used to determine river pattern statistics and for historical analysis of case studies. The results revealed that, within the Renous study area, the frequency of channel formation and abandonment were similar over the 54 years of analysis, indicating that the wandering pattern was being maintained.

Fotherby (2008) studied spatial changes in river pattern of the Platte River, with the main objective of identifying the factors that determined the occurrence of a fully braided main channel. Aerial photography, gauge flow data, ground-surveyed cross sections, bed material samples and the results of sediment transport modelling were used to examine factors controlling spatial change in the main river pattern of the central Platte River. The study identified valley confinement as the determining factor of the braided pattern of the river. A study by NEDECO (1959) showed the river Niger in Nigeria to change from a braided pattern in the middle Niger valley to a more meandering course between Lokoja and Aboh.

Schumm (2005) assessed the temporal changes in both river width and river pattern of the Platte River, Nebraska, U.S.A. to hydrologic change. He divided the river into two segments – a braided reach from Brady (upstream of Lexington) to Kearney and an anastomosed reach from Kearney to Grand Island – and presented a description of channel evolution over time for one site in each reach. The study showed that, as a result of decreasing discharge, the river in the braided reach evolved from fully braided to island braided to anastomosed to wandering.

The effects of historical and recent floods on the channel pattern of the Omo River in Ethiopia were analysed by Ayalew (2009). The results showed that cross-sectional changes resulting from floods in the nineteenth and twentieth centuries were limited to small degree channel widening and entrenchment, and flood-plain erosion and deposition. The study also showed that the effects of the 2006 flood were also modest in terms of adjustment of channel pattern.

Some studies have demonstrated the sinuosity of rivers to change over time. For example, the study by Laliberte (2001) revealed Catherine Creek in north-eastern Oregon to have experienced a sinuosity change of six percent from 1979 to 1998. In England, sinuosity changes of 18% were measured in the River Culm, 16% in the River Creedy, 20% in the River Otter, and 28% in the River Yarty from 1903 to 1953 (Hooke, 1977). The change in the River Culm was attributed to human interference with the channel. For the other rivers, the extent of human interference and how much the change was an adjustment of agricultural practices, filed drainage, and urban activity were difficult to assess (Hickin, 1977; Hooke, 1977).

2.2.4.2 Spatial and temporal changes in cross-sectional form

Any important adjustment of channel form and flood plain development is reflected in the bankfull capacity of the cross section and the relationship of flood plain sedimentation and construction to channel pattern (Pickup and Spring, 1984; Garcia, 1995; Hickin, 1995; Niekerk *et al*., 1999; Inbar, 2000; Emmett and Wolman, 2001; Dollar, 2002; Moody and Troutman 2002).

Variables of cross section are of great importance for hydraulic geometry and channel geomorphology studies. Cross sections downstream from a river diversion were used to show the limitations of the spatial interpolation method of identifying and interpreting channel adjustments in River Derwent in Yorkshire (Richards and Greenhalgh, 1983), Allen Diaz *et al.* (1998) used permanent channel cross-sectional transects perpendicular to flow to estimate changes in spring and resultant creek channel morphology. Analysis of cross sections in the lower Rhône River demonstrated the dominance of channel incision over a century in the river (Antonelli *et al*., 2004), which is consistent with the study of Arnuad-Fassetta (2003). Although hydraulic data (boundary shear stress and stream power) employed in the study have no direct relationship with the channel deformation, channel geomorphology bound with these hydraulic controls locally regulate the incision rates. Cross sections in the Raba River, Poland showed that 3m of river incision occurred in the last century. This is associated with the increase of stream power and decrease of bedload resulted from river control works and gravel extraction (Wyżga, 1991).

Cross sections were also employed to examine the relationship between channel change and flood occurrence. Stover and Montgomery (2001) analysed 45 years of cross-section data along the Skokomish River, and figured out that the increased flooding on the mainstream of this river without an increase in peak discharge resulted from the reduction of channel conveyance owing to aggradation in the riverbed. Block *et al.* (2009) documented cross-sectional form changes of the Little Colorado River, Arizona, U.S.A., by repeat mapping from aerial photography flown in 1936, 1953, 1979-1980, 1992, 1997 and 2007.

Dry-land rivers have been noted for considerable changes in channel width in response to variations in flow without significant changes in bed elevation. The 90-kilometre sand-bed reach of the Little Colorado River, between Winslow and Leupp, Arizona, adjusted to flow perturbations by narrowing of the channel through flood plain development and by substantial lateral channel migration. Although the magnitude of change in channel width is variable along the study reach, there is an overall decrease in average width (175 to18 metres) from 1936 to 2007. In a spatial context, Wolman and Gerson (1978) demonstrated that the rate of change of channel width with increasing drainage is more rapid in dry-land rivers than it is in humid-temperate rivers, at least in catchments up to about 100km^2.

2.2.5 Synthesis

In the light of the foregoing, river channel change cannot be attributed to a single cause or any single human activity. Rather, several factors acts on the river channel at the same time. These factors are often considered in isolation, and one of the greatest challenges to contemporary tropical geomorphology is the conceptual integration of these processes. A valid conceptual model for the maintenance of hydro-geomorphic integrity across the study area must, therefore, incorporate processes acting and interacting over a wide range of spatial and temporal scales. Bio-physical changes in small areas may be controlled through a combination of ecological dynamics (competition), edaphic constraints (microsite suitability) and reduced anthropogenic activities.

CHAPTER THREE

METHODS OF DATA COLLECTION AND ANALYSES

3.1 Study data and data sources

3.1.1 The data sources

The data for this study were obtained from two major sources:

1. Data on historic plan form change were derived from topographical maps, aerial photographs and satellite imagery.
2. Data on channel form variables were collected through field measurements

3.1.2 Study data

The choice of variables for this study was guided by the need to measure those processes and variables that best describe channel plan form and, therefore, plan form change. Discharge, bank materials (clay content), bank strength, valley slope, valley width and median bed material sediment size were selected as plan form control variables, as shown in Table 3.1.

In the description of historic plan form and plan form change, the variables selected were sinuosity, width and lateral migration. In the description of downstream plan form and plan form change, the variables selected were channel width, channel depth, width-depth ratio and channel area.

The choice of variables was guided by the works of Lane (1957), Leopold and Wolman (1957), Rust (1978), Brice (1984), Schumm (1981; 1985) and Knighton and Nanson (1993) as they best described plan form change. The methods of collection and analyses of the data are discussed in the subsequent sections.

Table 3.1: Variables

SN	Variable	Channel Aspect Described	Category	Data Source
1	Maximum/Mean Bankfull Depth (m)	Depth	Channel form	Field
2	Bankfull Width (m)	Width	Channel form	Field
3	Width-depth Ratio	Shape	Channel form	Derived
4	Cross-Sectional Area (m^2)	Size	Channel form	Derived
5	Channel Slope	Friction, Stream power	Channel form	Field
6	Valley Width (m)	Containment	Channel form	Field
7	Bank Shear (kPa)	Friction, Bank strength	Channel form	Field
8	Bank Clay (%)	Friction, Bank strength	Channel form	Field
9	Bed Material (D_{50})	Friction	Channel form	Field
10	Channel sinuosity	Pattern	Channel form	Derived
11	Velocity	Flow	Channel process	Field
12	Discharge	Flow	Channel process	Derived

3.1.3 The study reaches

The data for both historic and downstream plan form change were collected from two study reaches within the study area (the alluvial section of River Osun). The study area which was demarcated from the Nigeria topographical map, was subdivided into two reach blocks based on the observed channel pattern, including a single thread reach and a multi thread reach. These study reaches were then digitized and clipped with the aid of the ArcGIS software.

Study Reach I (meandering reach): Located between Telewi village (latitude 60 47′ 15″N and longitude 40 05′ 30E) and Fawosedi village (latitude 60 41′ 45″N and longitude 40 30′ 00″E), this comprised the single thread reach with length of 35.9km. This reach was divided into thirty-four sections, each about 500m apart from where data were collected.

Study Reach II (anabranching reach): Located immediately downstream of Study Reach I, from downstream Fawosedi village to Iro village (between latitude 60 41′ 45″N and longitude 40 30′ 00″E and latitude 60 35′ 10″N and longitude 40 03′ 45″E), this is about 5km. in length. The river within this reach is a multiple-thread system, consisting of numerous channels of various sizes interconnected in an irregular network. This reach is essentially a seasonal wetland area, often inundated between June and September due to heavy rainfall and low topography. Data were collected from 10 cross sections placed about 500m apart along the main anabranch.

3.2 Field data collection

Data collection was carried out along forty-four cross sections within the study area. According to Riley (1972) and Grippel (1985), more than one section needs to be averaged for each study reach to give a suitable result. Along each cross section, the following data were collected:

3.2.1 Channel mean depth (*d*)

Channel depth is the elevation difference between channel bank and channel bed. The mean depth is the average of depth values of equally placed points within the channel. Measurements were taken at equally spaced points in the cross section and averaged to find the mean depth. The mean depth was used because it is a better expression of the average of the conditions obtained in the channel than a single maximum point. Depth was determined through echo sounding using the Garmin GPSMAP 420s chart plotter/sounder, with sounding done at 5m intervals.

The Garmin GPSMAP 420s chart plotter/sounder dual frequency transducer plots depth contours and structure. The transducer was attached to the side of the boat and suspended into the water. The transducer sends out and receive sound signal at regular interval and calculates the depth of the stream by the time it takes the sound to travel to the bottom of the steam and back to the transducer (echo). This depth value for each sounding is then transmitted to the LCD visual interface which was mounted inside the boat. Also attached to it is the memory box that receives the depth value from the transducer. This information when transferred to the plotter is used to plot the cross section of the steam channel.

3.2.2 Channel width (*w*)

The width of the channel is defined as the distance between both sides of the stream channel. There are three types of width measurement: (a) the bed width, this is the distance separating the stream bed; (b) the water surface width, which is the width of the flowing water surface; and (c) bankfull width, which is the dominant discharge water surface width and is equal to the bank-to-bank length. The latter was the width used in this study. Field measurement was carried out as follows: A pole was fixed firmly at the left and right banks of the stream; a steel metric tape was then used to measure the distance between both banks.

3.2.3 Width/Depth ratio (*w/d*)

This is a measure of the channel shape and flow pattern (Leopold and Maddock, 1953; Huang and Nanson, 1992). The width-depth ratio is calculated by dividing the width at a section by the maximum depth of the same section. Where channels are cohesive, the ratio is stable; but where the channels are non-cohesive, the width-depth ratio could be very variable. Channels within the study area are observed to be cohesive as they mainly comprised silt and clay.

3.2.4 Cross-sectional area (*A*)

Cross-sectional area (*A*) is the product of stream width multiplied by average water depth. Channel cross-sectional area at each cross section was calculated from the width and mean depth data using the following formula:

$$A = w \text{ X } d$$

where A = Cross-sectional area
w = Width
d = Depth

3.2.5 Valley slope (S)

Valley slope is the difference in elevation between two points along the stream channel divided by the distance between them. Valley slope determines the overall rate of energy loss along a river and is, therefore, an additional potential control variable on channel processes. Water surface gradient was taken with the aid of the GPS between the cross sections. The slope was calculated as gradient change between two cross sections divided by the distance between them.

3.2.6 Bank shear strength (Bs)

This parameter, in addition to clay composition of banks, was also chosen as a variable of resistance because the finer-grained soils of the banks of streams increase cohesiveness that is expected to increase the strength of the bank. Previous studies provide guidance on how to measure *in situ* streambank soil shear strength (for example, Braja, 2000; Micheli and Kirchner, 2002). The shear vane tester measures the shear strength of a soil (Braja, 2000) and this was the method used in this study. At the cross section, four vane shear strengths were taken over a 1m^2 area, with the average taken. The blade of the vane was pushed into the soil; the vane was then rotated at a slow rate of 6° to 12° per minute. The torque was measured at regular time intervals and the test continued until a maximum torque was reached. The strengths were reported in kilo Pascal (kPa).

3.2.7 Bank clay

The clay content of banks was selected as a variable of resistance. Although bank resistance is not simply the function of one material property, it depends on the degree of cohesion, which can be expressed by its silt-clay content (Ferguson 1973). Most river banks contain significant amounts of clay, and possess some degree of cohesion and resistance to erosion through inter-particle, and electromagnetic bonding (Robert 2003). In this study, bank material samples were collected from the left and right banks at each cross section with the aid of a soil auger. Within each sampling point, soil samples were taken at five points at depths of 0-15cm and 20-30cm. The core samples were thoroughly mixed in a plastic bucket so as to have a true representative of the soil at that cross section. A separate, well mixed composite sample from the sample was removed and placed in the laboratory sample bag and taken for analysis.

3.2.8 Bed sediment

Samples were collected at each cross section using a bucket sampler (height 15cm, diameter 10cm). This was carried out at only one point within each cross section because of the difficulty in collection. The bucket was used to scoop sediments by dragging in the upstream direction. Particle size analysis was carried out on the collected sediments using the sieve method.

3.2.9 Velocity

The velocity of a river refers to the rate of water movement. Velocity was measured with the aid of the current meter. The two point methodology which uses velocity observations at 0.2 and 0.8 of the depth below the surface was employed. The average of these two observations is the mean velocity in the vertical. To determine velocity, a stopwatch was used in order to plot revolutions against time. Since the depth of the river varies across its width, the cross-section of the stream was divided into a number of vertical sections at 10 m interval for the measurement of velocity. Due to general pulsation of flow velocity in natural channels, velocity was measured for at least 40 seconds in an effort to better represent average velocity at a point. The correction factor for the propeller size used was applied.

3.2.10 Discharge

Discharge is the volume of water moving down a stream per unit of time, usually expressed in cubic metres per second. Discharge at each cross-section within the study area was derived using the velocity- cross sectional area formula.

$$Q = A \times V$$

where Q = Bankful discharge
A = Cross-sectional area
V = Velocity

3.3 Laboratory analyses

3.3.1 Analysis of channel bank and bed materials

Wolman (1954) first developed the “pebble-count” method for determination of the particle size distribution of channel materials. This method has since been modified to account for both bank and in-channel materials, for sand and smaller particle sizes, and for bedrock. There are different methods for particle size analysis. In this study, the sieve method was used for the analysis. Other studies, for example Brilly (2010) also used this method. The advantage of this method over the Wolman's method is that there can be differentiation between the silt and clay particles from the other particles, especially as the interest is on the percentage of silt and clay content of the bank material.

3.3.1.1 Sieve analysis

The weights of each sieve as well as the bottom pan to be used in the analysis were recorded. The soil samples were oven-dried at below 100^0C, allowed to cool and weighed. The sieves were then assembled in an ascending order of sieve numbers (#4 sieve at top and #200 sieve at bottom). The collection pan was placed below #200 sieve. The soil sample was carefully poured into the top sieve and the cap placed over it. This sieve stack was placed in the mechanical shaker and shaken for 10 minutes. The stack was removed from the shaker and the weight of each sieve with its retained soil was recorded. The weight of the bottom pan with its retained fine soil was also recorded to determine the weight of the silt and clay particles. The mass of soil retained on each sieve was then obtained by subtracting the weight of the empty sieve from the mass of the sieve + retained soil. This mass was recorded as the weight retained on the data sheet. The sum of these retained masses should approximately be equal to the initial mass of the soil sample. A loss of more than two percent is not acceptable. The percent retained on each sieve was calculated by dividing the weight retained on each sieve by the original sample mass. The percent passing (or percent finer) was calculated, starting with 100 percent and subtracting the percent retained on each sieve as a cumulative procedure.

Quantity passing = Total mass - Mass retained in sieve Number N – Mass retained in sieve Number N-1,

while the percent retained is calculated as: % retained = Mass retained/Total mass.

3.4 Image data pre-processing and collection

3.4.1 Topographic map data

Topographic map sheets (Ijebu-Ife Sheets 281 N.W and 281 S.W) were obtained from the cartographic section of the Department of Geography, University of Ibadan. The maps were at a scale of 1: 50,000 (although larger scaled maps would have been preferable, they were not available). The topographical map was used as the base map for the study.

3.4.2 Remotely sensed data

The use of remotely sensed imagery (satellite images and aerial photographs) in channel change analysis provides a fast means for obtaining data about large areas within a limited time and so has been used since the development of remote sensing. Remotely sensed data hold information about places so that repeat scenes can be used for change analysis. Aerial photographs for 1963 and Landsat images for 1984, 2005 and 2012 were used for the study. Remotely sensed images are very useful for environmental monitoring because they provide repeat observation of large areas over time. Their choice was based on their ready availability and because they are often used in land-use change detection analysis. The choice of the years was based on availability of image for that year as well as the percentage cloud cover on the image. Thus the years for which suitable images were found were 1984, 2005 and 2012.

3.4.3 Image data pre-processing techniques

3.4.3.1 Aerial photograph pre-processing

The topographical map of Ijebu-Ife S. W. of 1963 (Scale 1:50000) was scanned and imported into the digital image processing program ArcGIS as a TIFF file. This was geo-referenced using a network of visually selected ground control points taken from features, mainly road junctions, which semi-permanent manmade features. The study area was subsetted from the photo-mosaic. There was a resulting root-mean-square error (RMSE) of 0.37 pixels (10.5 m). All other processes carried out on the photographs were the same for the satellite images and these are discussed below.

3.4.3.2 Satellite image: development of false colour composite

The first step in the image pre-processing involved the development of a colour composite image for the study area. This was done using the “Layer Selection and Stacking” function contained in Erdas Imagine software. The result of this function produces a colour composite image from three bands of byte binary imagery (Crist and Cicone, 1984; Jensen, 1986; FGDC 1992). Bands 3, 4 and 5 of Landsat satellite imagery were used in developing the false colour composite. Band 3 corresponds to the visible red wavelengths; band 4 corresponds to the reflected near-infrared (near-IR) wavelength; and band 5 corresponds to the reflected middle IR wavelengths. These bands were selected because of the windows with which they collect electromagnetic energy. To remove atmospheric effects from the TM and ETM+ data, atmospheric correction was performed using atmospheric/topographic correction software package (ATCOR)-2 (ReSe, Switzerland). This model used the post-launch offsets and gains and a tropical atmospheric model to produce reflectance images.

3.4.3.3 Geometric correction

Remotely sensed data usually contain both systematic and unsystematic geometric errors. In order to get a cartographic uniformity of the different scenes used, a geometric correction technique was applied based on control points from a pre-registered image and those that were extracted from the existing digital drainage covering the study area. Geo-referencing was done to a common base layer using ground control points. This process was carried out with the geo-reference toolbar in ESRI ArcGIS version 10.2 ArcMap software. Hughes *et al.* (2006) note that the number, distribution, and type of ground control points (GCPs) affect the accuracy of the overall map. Leys and Werrity (1999) state that “ground control points should be widely distributed across the image to provide a stable warp.” Hughes *et al.* (2006), however, argue that GCPs should actually be concentrated near the feature of interest, rather than across the entire image. A minimum number of 18 points were used to rectify each image. All the images were rectified to the Nigeria datum using a first-order (linear), nearest neighbour resampling method. The nearest neighbour resampling technique was used so that the original data values would be maintained. This resulted in a root-mean-square error (RMSE) of 0.70 pixels (20m). The root-mean-square error is used in ArcMap to assign a value of the geospatial accuracy. Each point deviates from its correct position as an image is warped onto the base layer. The difference in location between a GCP on the transformed layer and base layer is represented by the RMSE. Hughes *et al.* (2006) explains that the RMSE is useful in “reconstructing channel change with remotely sensed images” and that it “may be an acceptable proxy for average error, though it is a poor indicator of geo-rectification accuracy across entire image.” Co-registration of the images to a common scale and projection was applied, set in metric units.

3.4.3.4 Radiometric correction

Radiometric correction was done to improve the interpretability of data by introducing estimated brightness values for bad scan lines or by removing the attenuation effect of the atmosphere. The images used for the study were radiometrically corrected, in order to normalize the reflectance values of each pixel to those pixel values of the reference image.

3.4.3.5 Data conversion

ArcGIS software was used for data conversion and analysis. The study area between latitude 6^{o} 34 and 6^{o} $48^{\prime}$ N, and longitude 4^{o} and 4^{o} $10^{\prime}$ E was cut out from the various images (topographical map, air photo and satellite images) and the data were converted from analogue to digital format using a procedure called digitizing. Digitizing converts the spatial features on the analogue map into a digital format. Point, line and area features that make up a map are converted into x and y coordinates. In digitizing the maps, each layer/theme/coverage was kept separate on the map so as to facilitate easy analysis of the various data. The root mean square (RMS) error was kept as low as possible. The transformation scale indicates how much the map being digitized will be scaled to match the real-world coordinates. In order to maintain highly accurate geographic data, the RMS error was kept under 0.009 inches (or its equivalent measurement in the coordinate system being used).

3.4.3.6 Image classification

The different land use/land cover within the study reach was classified with the use of a supervised classification scheme. This was used to classify the land-use into major /minor land-use types. In a supervised classification, the analyst identifies in the imagery homogeneous representative samples of the different surface cover types (information classes) of interest. These samples are referred to as training areas (Lillesand and Kieffer, 2000). The selection of appropriate training areas is based on the analyst's familiarity with the geographical area and his/her knowledge of the actual surface cover types present in the image.

3.4.4 Image data collection

After the image pre-processing, historic plan form change data were collected using different techniques, as discussed below.

3.4.4.1 Historic channel width (*w*)

Measurement of channel width on the images was accomplished using stationary transects along the different study reaches of the Osun River. Gurnell and Downward (1994) claim that at fixed points, “spatial and temporal changes can be observed without the introduction of bias in the study.” The majority of published papers on fluvial research (for example Lecce 1996; Lecce and Pavlowsky, 2004; Makaske *et al.,* 2009) used cross-valley transects of the flood plain. However, this research employed a different approach to creating transects. Instead of using cross-valley transects, the historical migration zone (HMZ) was used for the placement of transects along the river. This was because use of cross valley transects is better when changes along the flood plain is being considered. Since the focus of this study was on changes along the river channel, the HMZ which captures the areas migrated by the river channel was more appropriate (Rapp and Abbe, 2003).

HMZ is described by Rapp and Abbe (2003) as the “area the channel has occupied over the course of the historical record and is delineated by the outermost extent of the channel locations plotted over that time.” Transects were located 500 metres apart along each study area, channel width was then measured along each transect. Channel width change was investigated along 44 individual historical migration zone transects. Transects were created perpendicularly to the channel banks to identify channel shift and direction between the image dates. Where transects ran diagonally across a channel, the channel midpoint was found and the channel width was measured perpendicularly to the channel banks through that midpoint. All channel width measurements were made with the measure analysis tool provided in the ArcMap software. Gurnell (1997) asserts that, when measuring channel width, overhanging vegetation will obstruct certain stretches of the channel bank. Indistinguishable areas of the channel were measured in a systematic way to provide consistency, by assuming the location of the channel bank based on the arrangement of vegetation.

3.4.4.2 Valley width (*w*)

For this study, valley width was defined by the break in slope between fluvial dominated and hill slope dominated landforms. Valley width is potentially an important parameter in determining channel pattern because it defines the maximum available space in which channel belts can form. Valley width was calculated from the topographical map and The Shuttle Radar Topography Mission (SRTM) 30m digital elevation model of the study area

3.4.4.3 Channel Surface Area

The area between two cross sections was digitized within the study areas and the "Area and Volume Statistics" tool in 3D analysis extension was used to calculate the surface area of stream sections.

3.4.4.4 Channel sinuosity (*S*)

Channel sinuosity is the ratio of stream length to the valley length. It can also be described as the ratio of valley slope to channel slope. The sinuosity of a stream is one of the ways the stream maintains a constant slope; the more sinuous a stream is, the gentler the slope will be. Meander geometry characteristics are directly related to sinuosity, consistent with the principle of minimum expenditure of energy. Sinuosity is best measured from an aerial photograph (Rosgen, 1986) or satellite image. Sinuosity ratio (ratio of stream length to valley length) was measured and determined from the digitized channel centreline for each image year and the river valley centreline of each of the five study years. To reduce measurement error by the author, the centrelines of the channel and the valley were measured at 1km intervals and added to attain a total length value. It was found that mistakes increased with increasing length owing to computer mouse fatigue. Sinuosity measurement was done on the different images for each study reach. Sinuosity (s) ratio was calculated using the formula:

$$S = \text{Stream Length} / \text{Valley Length}$$

3.4.4.5 Lateral migration

Rates of lateral migration were derived from the study reaches for the river system. Different types of natural and disturbed reaches will change in different ways and their plan form changes were quantified using aerial change ratios. Patterns of lateral migration, erosion and deposition were mapped by superimposing the 1963, 1984, 2005 and 2012 stream channel boundaries on one another using ArcGIS software. This made it possible to assess the degree and type of change or instability in various reaches. With the aid of the Geoprocessing wizard function of the ArcGIS software, channel boundaries from two time periods were overlaid and the themes were intersected and the channel area labelled according to whether and how they have changed from the earlier year into the following categories: E (erosion), D (deposition), B (between), or U (unchanged) (Mossa and McLean, 1997).

The area of intersect was labelled U (unchanged) because this represented the area of stream that remained in the same position in the latter time period as the initial time period. The remaining area of the latter channel was labelled E (erosion) because this represented the area of new channel created. The remaining area of the former channel was labelled D (deposition) as it represented the area of initial channel deposited or abandoned. Area of channel in between the initial and the later channel was labelled B (between) and this represented the area of channel migrated between the initial and the later year. Because rivers migrate naturally, some erosion and deposition are expected in an interval of a decade or longer, but high values of B (area between channels), other than occasional cut-offs in sinuous reaches, are usually indicative of instability. Some other studies, for example MacDonald *et al.* (1993) and Micheli and Kirchner (2002), used the eroded-area polygon method, which captures net migration of a bend over an elapsed time period. The method of Mossa (1999) was thought to be more appropriate for this study because lateral migration along the entire stream channel was studied.

The aerial change variables were then normalized by the initial channel area or I (also D+U). This allowed a comparison of the different size channels along the stream. Thus, the proportional area change ratios (U-I, D-I, E-I, B-I) was used to compare the type and amount of areal plan form change within the different study reaches for different time periods (Mossa, 1999).

U-I: U divided by I, shows the proportion of initial channel that is unchanged or in its initial position

D-I: D divided by I, shows the proportion of initial channel that has been deposited or abandoned

E-I: E divided by I, shows the proportion of initial channel area that has been eroded

B-I: B divided by I, is a measure of displacement through cut-offs, rapid migration, or local avulsions into pits and secondary channels.

3.5 Statistical analyses methods

The statistical techniques employed in this study include Analysis of Variance (ANOVA), paired samples t-test, correlation and regression analysis. These were all carried out with the aid of Microsoft excel and the Statistical Package for Social Sciences (SPSS). The channel parameters measured were entered and variables calculated in Microsoft Excel spreadsheet and SPSS. Temporal and spatial averages of all variables were calculated and graphically represented. Descriptive analyses through the use of graphs were applied.

In the comparison of plan form variables along the different study reaches, ANOVA was used to determine variances in the plan form variables along the different study reaches. A 95% confidence interval for the mean was used as the threshold for significance: $p \leq 0.05$.

In a similar way, channel parameters values measured along the same transects for different years were compared using one-tailed t-tests. This was to determine if the parameters for one image year are significantly different from those for the next image year. The t-test assesses whether the means of two groups are statistically different from each other. This analysis is appropriate for comparing the means of two groups. In the analysis of temporal changes in channel plan form, a 99% confidence interval for the mean was used as the threshold for significance: $p \leq 0.01$. A 95% confidence level was not used because change is expected to occur from image year to image photo year in most cases. A value lower than 0.01 is truly significant and the null hypothesis can be rejected.

Correlation analysis was employed to establish the relationships occurring among the channel form variables. Correlation is a bivariate analysis that measures the strengths of association between two variables and their statistical significance. The Pearson product-moment correlation coefficient, which measures the nature and strength between quantitative variables, was used.

Multiple regression analysis was used to determine the contribution of the various plan form control variables to the observed plan form. The channel width-depth ratio and pattern were the dependent variable Y, and discharge, bank strength, bed sediment size and valley width were the independent variables X_1, X_2, X_3, X_4 and X_5, respectively. The multiple regression model explains and predicts variation of a single dependent variable from a number of predictor terms (independent variables). These independent variables may or may not be correlated among themselves; and it is generally better that they are not.

CHAPTER FOUR

SPATIAL CHANGES IN CHANNEL PLAN FORM

4.1 Analysis of channel plan form characteristics

4.1.1 Introduction

Alluvial streams are dynamic landforms subject to rapid change in plan form (as described by the cross-sectional form, longitudinal slope, and pattern) of the channel. Alluvial channels respond to change in regional physiography, hydrology and sediment load by adjusting their plan form. The cross-sectional form (shape) of a natural channel is irregular, but can be represented by several variables, including the channel width at bankfull discharge, average and maximum depth, width-depth ratio, channel side or bank slope, cross-sectional area, and wetted perimeter. Alluvial channel shape can vary from narrow and deep to wide and shallow on a continuous scale (Nanson and Knighton, 1996). Alluvial channel pattern are described as straight, meandering, braided or anabranching; a single channel can show multiple patterns within different reaches.

The aim of this chapter is to analyse the channel plan form of the study area (pattern and cross-sectional form), examine the spatial and temporal differences in the characteristics of the plan form variables, and examine the relationship between plan form and plan form control variables. In the following section the morphological variables are evaluated for the downstream channel pattern and cross-sectional form.

4.1.2 Downstream channel pattern

The downstream channel pattern within the study area was classified on the basis of channel multiplicity (average number of channels across valley) and channel sinuosity (see Table 4.1 and Appendix 1). In geomorphology, classification can be used to identify common processes and morphologies, separate disparate ones and thereby assist in understanding the causal relationships between form and process (Nanson and Knighton, 1996). The results are presented below.

Table 4.1:

Descriptive statistics for channel pattern indices

	STUDY REACH 1 (*n*=34)						STUDY REACH 2 (*n*=10)					
Parameters	Mean	S.E	Std. D.	Skewness	Kurtosis	Var.	Mean	S.E	Std. D.	Skewness	Kurtosis	Var.
No. of Channels Across Valley	1.03	0.029	0.17	5.83	34.00	0.029	4.50	0.342	1.08	0.00	-1.03	1.167
Sinuosity	1.54	0.025	0.15	0.69	-0.34	0.022	1.12	0.019	0.06	0.43	-1.19	0.004

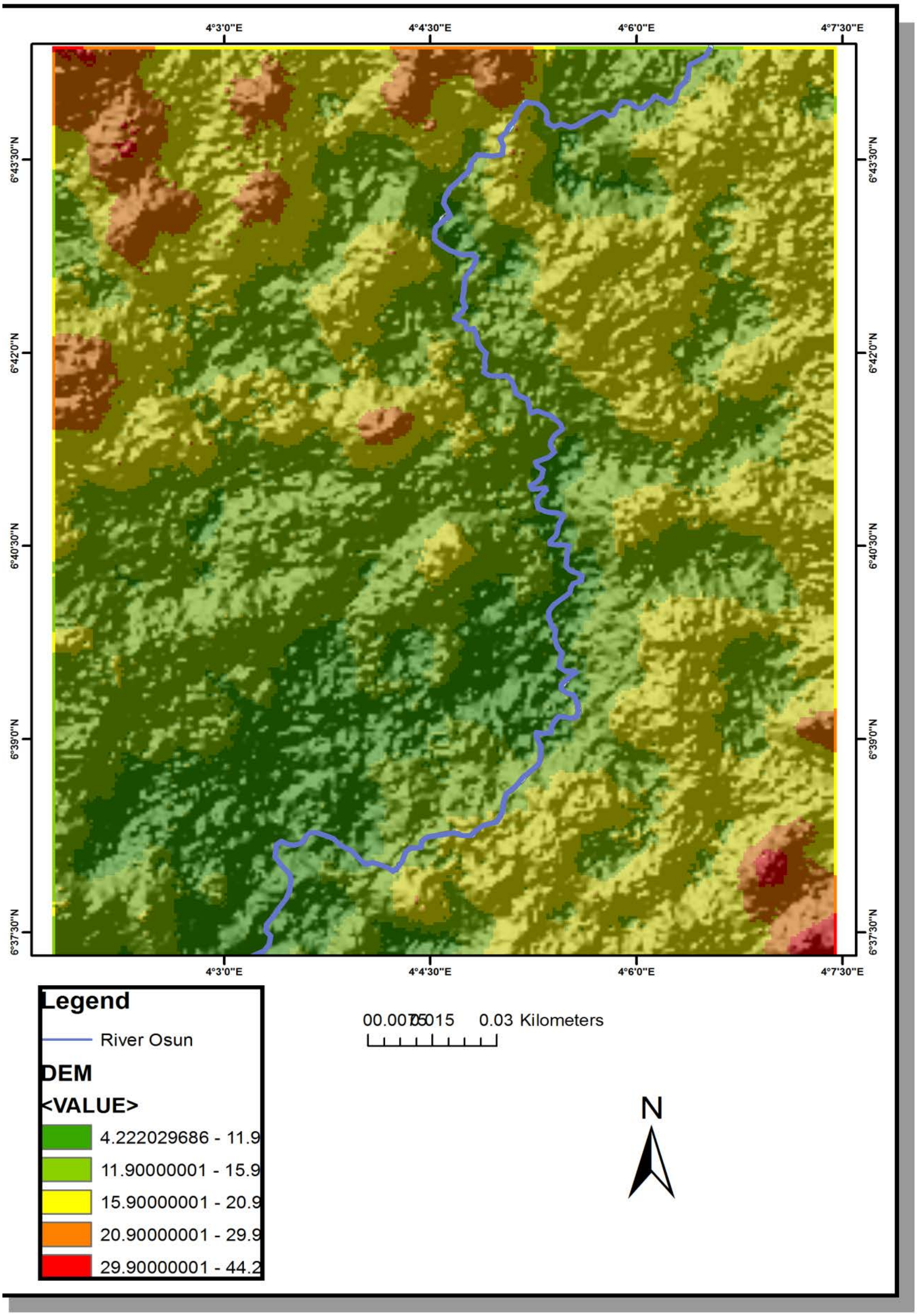


Figure 4.1: The meandering reach

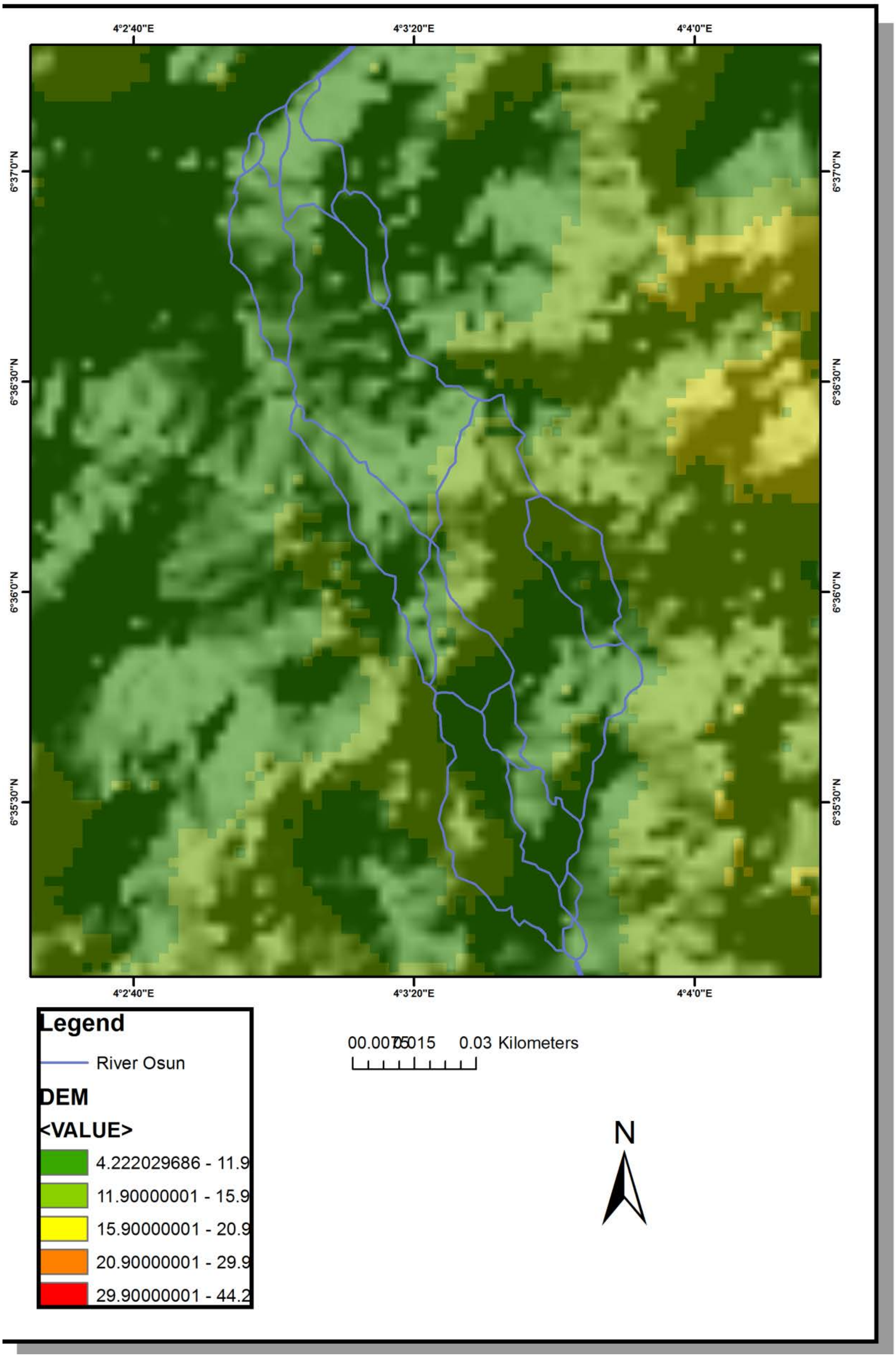


Figure 4.2: The anabranching reach

4.1.2.1 Average number of channels across valley

The results of the analyses of plan form indices (Table 4.1 and Appendix 1) reveal that the average number of channels across valley is 1.03±0.17, with a range of between 1 and 2 for the meandering reach. The result also showed that the mean number of channels across valley was 4.5±1.08 for the anabranching reach, with a range of between 3 and 6. This result showed that the stream channel within the meandering reach was single thread, while the stream channel within the anabranching reach was multi-thread (see Figures 4.1 and 4.2).

Meandering and straight rivers are classified as rivers with both a single channel belt and a single thalweg, since the flow in their channels is not split by in-channel bars. Rivers with multiple channels are either classified as braided or anabranching (including anastomosing). Braided rivers are regarded as rivers with a single channel belt, but multiple thalwegs; while anabranching (including anastomosing and wandering rivers) are classified as rivers with multiple coexistent channel belts, each having a single thalweg as in the study reach II. The plan form of the study area was, therefore, divided into two based on channel multiplicity: a single-thread reach (reach I) and a multiple-thread, anabranching reach (reach II).

4.1.2.2 Channel sinuosity

The result of analysis of channel sinuosity for the study area revealed the calculated sinuosity index of study reach 1 as 1.54, with a standard error of 0.025, while the sinuosity index of study reach II is 1.12 with a standard error of 0.02. Channel sinuosity is a common descriptor of the channel plan form. It indicates how a river has adjusted its slope to that of its valley. Leopold and Wolman (1957) and Leopold *et. al.,* (1964) proposed a sinuosity of 1.5 as the boundary between straight and meandering channels. From the results of the measurements, which were 1.54 for study reach I and 1.11 for study reach II, study reach I can be classified as meandering, while study reach II can be classified as straight.

Schumm (1963) recommends five classifications depending on sinuosity value: straight (1.1), transitional (1.3), regular (1.7), irregular (1.8), and tortuous (2.3). Based on Schumm's (1963) classification, study reach I had a regular plan form, while study reach II has a straight plan form. Brice (1984) gives additional classifications for meandering rivers, such as sinuous canaliform, sinuous point bar, and sinuous braided. The canaliform tend to have the narrowest widths and the highest sinuosity's (Brice, 1984).

Sinuosity values have been determined for many rivers in temperate climate regions. For example, the Powder River, the Solomon River, and the Republican and Sappa Rivers showed sinuosity values of 1.2, 2.4, 1.3 and 1.9, respectively (Schumm, 1963). The Beaver River in Alberta, Canada, and the Mississippi River, from Cairo to Memphis, also exhibited sinuosity values of 1.25 and 1.55, respectively (Chitale, 1970); whereas the Murrumbidgee River in New South Wales, Australia, had a sinuosity of 2.0 (Schumm, 1977). Also, a study of 47 rivers in the Great Plains, U.S.A. showed a mean sinuosity of 1.57, with a range of values from 1.2 to 2.6 (Schumm, 1963). Sinuosity values have been determined for some rivers within the humid tropics, including the study by Fashae (2011) of River Ogun in southwest Nigeria, which showed average meander sinuosity of 1.6; and the Angabunga, in Central Congo, Africa, which also showed sinuosity of 1.60 (Chitale 1970).

As observed in previous studies, individual anabranching channels are highly varied; they can be straight, stable-sinuous, meandering or braided (Schumm, 1985; Thorne *et al.*, 1993; van den Berg, 1995; Nanson and Knighton, 1996; Makaske, 2001; Amos *et al.*, 2008). The sinuosity index of 1.12 for this study showed that anabranches within the Osun channel were relatively straight. Latrubesse (2008) notes that channel belts of anabranching rivers, such as Amazon, Japura and Madeira, are relatively straight and have a sinuosity for main channels of < 1.3. In the same vein, other authors (Smith and Smith, 1980; Rust, 1981; Nanson *et al.*, 1986) are also of the opinion that there appears to be a bias towards straight channels in anabranching/anastomosing rivers. Anabranching Rivers composed of multiple braided channel belts, although rare, has been given by Smith and Smith (1980), and also by Taylor (1999).

Table 4.2: Descriptive statistics for channel cross-sectional form

	Study Reach I (*n*=34)								Study Reach II (*n*=10)							
Parameters:	Mean	Min	Max	S.E	Std. D.	Skew.	Kurt.	Var.	Mean	Min	Max	S.E	Std. D.	Skew.	Kurt.	Var.
Width	59.92	46.44	83.32	1.34	7.82	1.45	2.37	61.10	20.49	14.35	28.61	1.57	4.96	0.70	-0.88	24.59
Depth	3.61	2.72	4.33	0.08	0.46	-0.28	-0.89	0.21	3.70	3.04	4.66	0.16	0.50	0.47	-0.12	0.25
W/D Ratio	16.74	11.83	30.63	0.71	4.14	1.81	3.29	17.14	5.60	3.08	7.52	0.42	1.34	-0.47	0.04	1.79
Area	212.04	126.78	256.26	4.78	27.87	-1.03	1.66	776.97	75.90	48.25	117.87	6.88	21.76	0.87	-0.09	473.45

Table 4.3: Analysis of Variance of cross-sectional form

Parameters		Sum of Squares	Difference	Mean Square	F.	Significance
Width	Between Groups	12017.906	1	12017.906	225.569	0.000
	Within Groups	2237.683	42	53.278		
	Total	14255.589	43			
Depth	Between Groups	0 .055	1	0.055	0.255	0.616
	Within Groups	9.141	42	0.218		
	Total	9.196	43			
WD Ratio	Between Groups	958.172	1	958.172	69.201	0.000
	Within Groups	581.543	42	13.846		
	Total	1539.715	43			
Area	Between Groups	43220.889	1	143220.889	201.173	0.000
	Within Groups	9900.973	42	711.928		
	Total	173121.861	43			

4.1.3 Downstream cross-sectional form

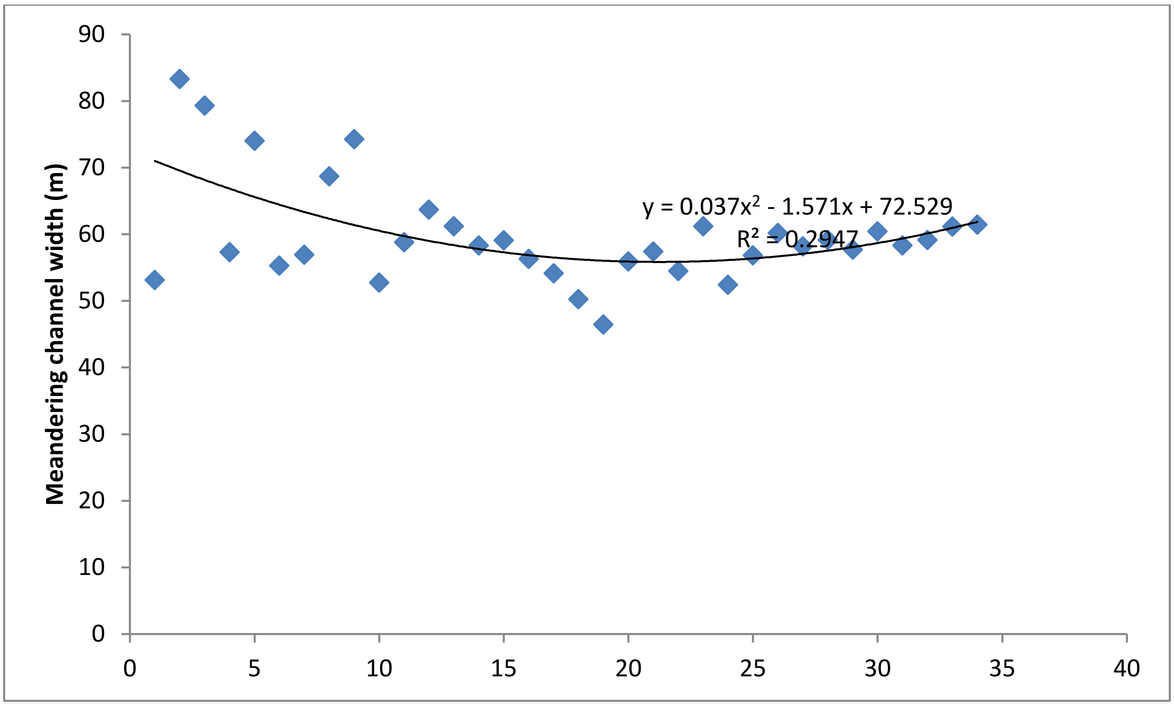
Downstream plan form changes also take the form of changes in the form of channel cross sections or channel hydraulic geometry. The changes in the downstream cross-sectional form of the study area were characterised along the two study reaches. Parameters that describe channel cross-sectional form include channel width, depth, area and the width-depth ratio. These were analysed for the forty-four cross sections, thirty-four within the meandering reach and ten within the anabranching reach. The results are shown in Tables 4.2 and 4.3.

4.1.3.1 Channel width

The channel width within the meandering and anabranching reaches of the study area (Plate 4.1) is given in Table 4.2. The average channel width for the meandering reach was 59.92m, while the minimum and maximum channel width figures were 46.44m at cross section 19 and 83.32m at cross section 2, respectively. The average channel width within the main anabranch was 20.48m, while minimum and maximum width figures within this reach were 14.35m and 28.61m, respectively. Results from the analysis of variance between channel cross-sectional width within the meandering and anabranching reaches showed that the between-sum of squares (12017) were much larger than the within-sum of squares (2237). This showed that channel width varied significantly between the channel reaches.

The results revealed that within the meandering this reach, there was no clear pattern of width increase in the downstream direction; there was generally an initial increase in width towards the downstream direction, followed by a decrease and a subsequent increase. The regression tread line reveals a downstream decrease in channel cross-sectional width within this study reach. The cross-sectional width within the anabranching reach was less than cross-sectional width within the meandering reach. Although channel width was highly varied within the anabranching reach, there was a pattern of decrease in cross-sectional width with downstream distance within the main anabranch, as shown in Figure 4.3. The significance value of p=0.000 revealed that channel width within the meandering reach was larger than those within the anabranching reach at the 99% confidence level.

Plate 4.1: Osun River showing: (a) Single channel reach and (b) an anabranch channel



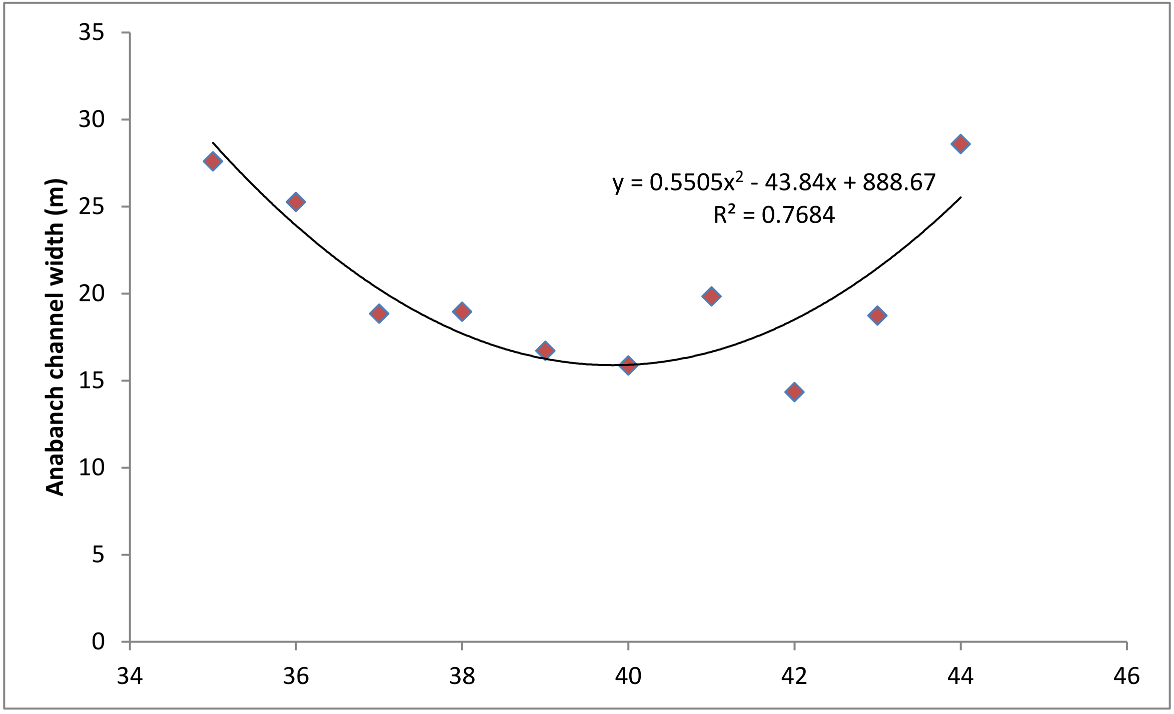


Figure 4.3: Channel cross-sectional width

Stream width is a function of the occurrence of streamflow and magnitude; size and type of transported sediment; and the bed and bank materials of the channel. Leopold and Wolman (1957) describe channel width as the single most important factor in channel change. Although Rosgen (1984) avers that the bankfull width of alluvial channels remains relatively constant, channel width is primarily adjusted to changes in discharge and can be modified by direct channel disturbances, such as flow regulation, sand and gravel mining, changes in riparian vegetation that may alter the boundary resistance and susceptibility to stream bank erosion.

The results showed that, within the study area, cross-sectional width decreased in the downstream direction. This did not conform to the expected pattern of increase in cross-sectional width in the downstream direction, especially with the inflow of water and sediments from tributary channels. In most streams within the humid tropics, width increases in the downstream direction. However, some conditions, including a reduction in discharge or change in the boundary materials into more cohesive materials, may make channel widening more difficult and lead to a reduction instead of an increase in channel width downstream.

This result which revealed a significant reduction of channel width within the anabranching reach is consistent with the findings of other studies. For instance, Wende and Nanson (1998), Tooth and Nanson (1999, 2000) and Jansen and Nanson (2004). Reduction in channel width in river systems results in significant decrease in width/depth ratio, causing flow efficiency to increase. In the study of some anabranching rivers in Australia, it was found that the combined width of the anabranching reaches was usually less than that of the adjacent single thread reaches that are presumed and, in some cases, known to be carrying the same long-term flow discharge and sediment load (Wende and Nanson, 1998; Tooth and Nanson, 1999; 2000; 2004; Tooth, 2000; Jansen and Nanson, 2004). Thus, reduction of channel width of the anabranching reach of River Osun could be a mechanism for increase in the flow efficiency of the stream.

4.1.3.2 Channel depth

Channel depth was also measured within the meandering and anabranching reaches. The results (Appendix I) showed that channel depth varied within the alluvial section of River Osun. Minimum depth within the meandering reach was 2.72m at cross section 19, maximum depth was 4.33m at cross section 26; while mean depth was 3.61m. The anabranching section showed varied depth, with values within this section ranging between 3.04m and 4.66m. The mean depth within this reach was 3.70m. The results of Analysis of Variance between depth within the meandering and anabranching reaches revealed that between-group difference was 0.055, while within-group difference was 9.14.

In the study of channel depth within the meandering reach, although no clear pattern of depth increase in the downstream direction was observed from the data, the regression line (see Figure 4.4), however, revealed an increase in depth in the downstream direction. This increase in depth in the downstream direction is observable in most streams within the humid tropics. The mean depth of 3.70m within the anabranching reach showed the reach to be relatively deep. The first as well as the last cross sections had the largest depth values. There was also a pattern of depth increase in the downstream direction within this section, as shown in Figure 4.4. The ANOVA result also revealed within group sum of squares to be much higher than between group sum of squares, thus revealing a greater variation in depth within each reach than between the two study reaches. Anabranching channels tend to be deep because oftentimes lateral erosion is reduced as a result of cohesive banks, making them more liable to vertical erosion.

The results revealed that within the study section of River Osun, stream channel was slightly deeper along the anabranching reach, with a mean cross-sectional depth of 3.70m as compared to the meandering reach, where the average depth was 3.61m. The P value of 0.616 indicated that there was no statistically significant difference between cross-sectional depth within the meandering and the anabranching reaches.

4.1.3.3 Channel width/depth ratio

The width/depth ratios of the two reaches within the study area were calculated to determine if the width/depth ratios and, therefore, cross-sectional shape were alike for the meandering and anabranching reaches. The results of the analysis revealed that the width/depth ratios were moderate to high for the meandering reach, with a mean of 12.84. The minimum value was 9.74 in cross section three; while the maximum value was 16.8 in cross section five. The width/depth ratio was low for the anabranching reach, where the mean was 7.34. The minimum width/depth ratio was 4.14 in cross section seven and maximum width/depth ratio was 9.32 in cross section two, as shown in Appendix 1 and Figure 4.5.

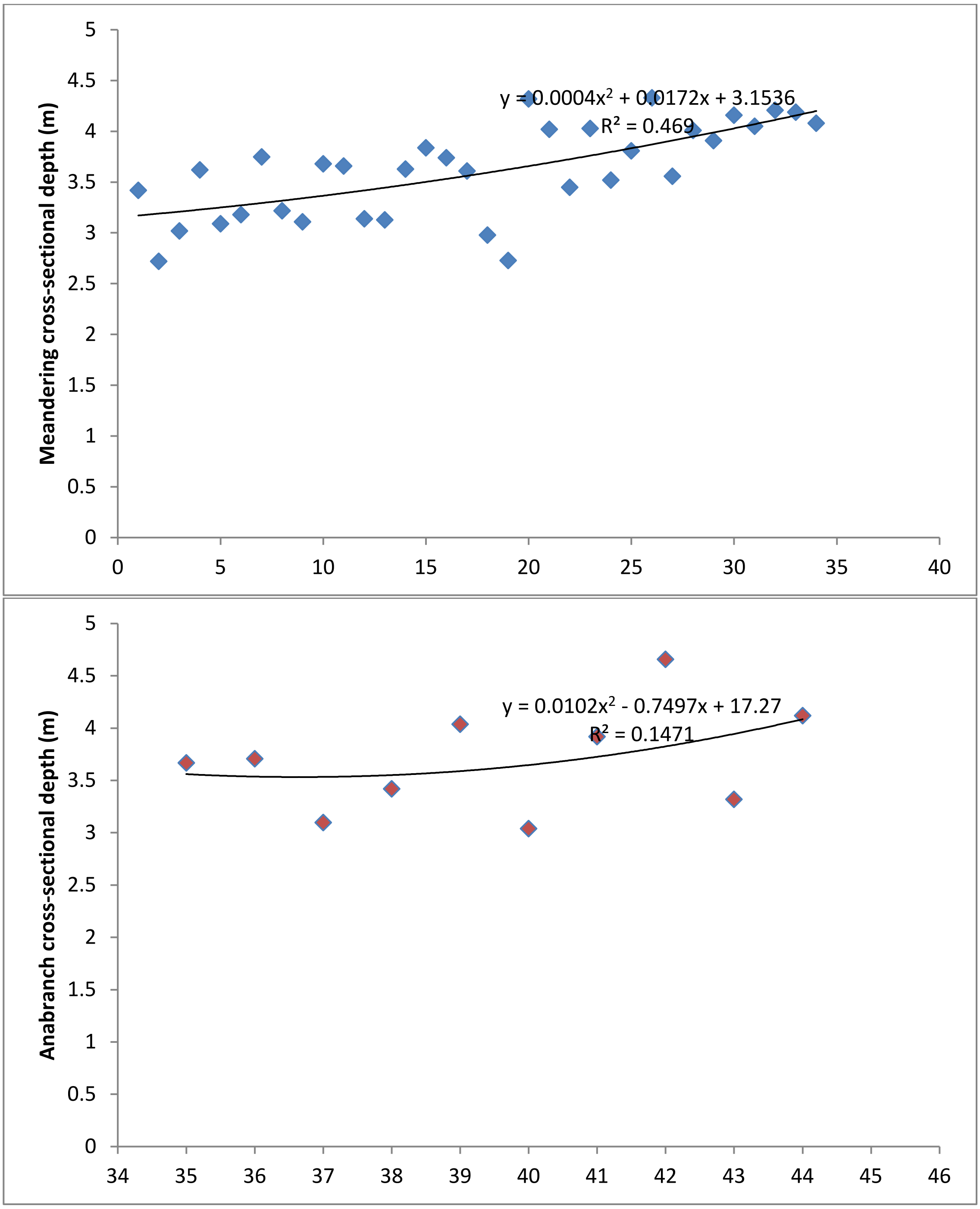


Figure 4.4: Channel Depth

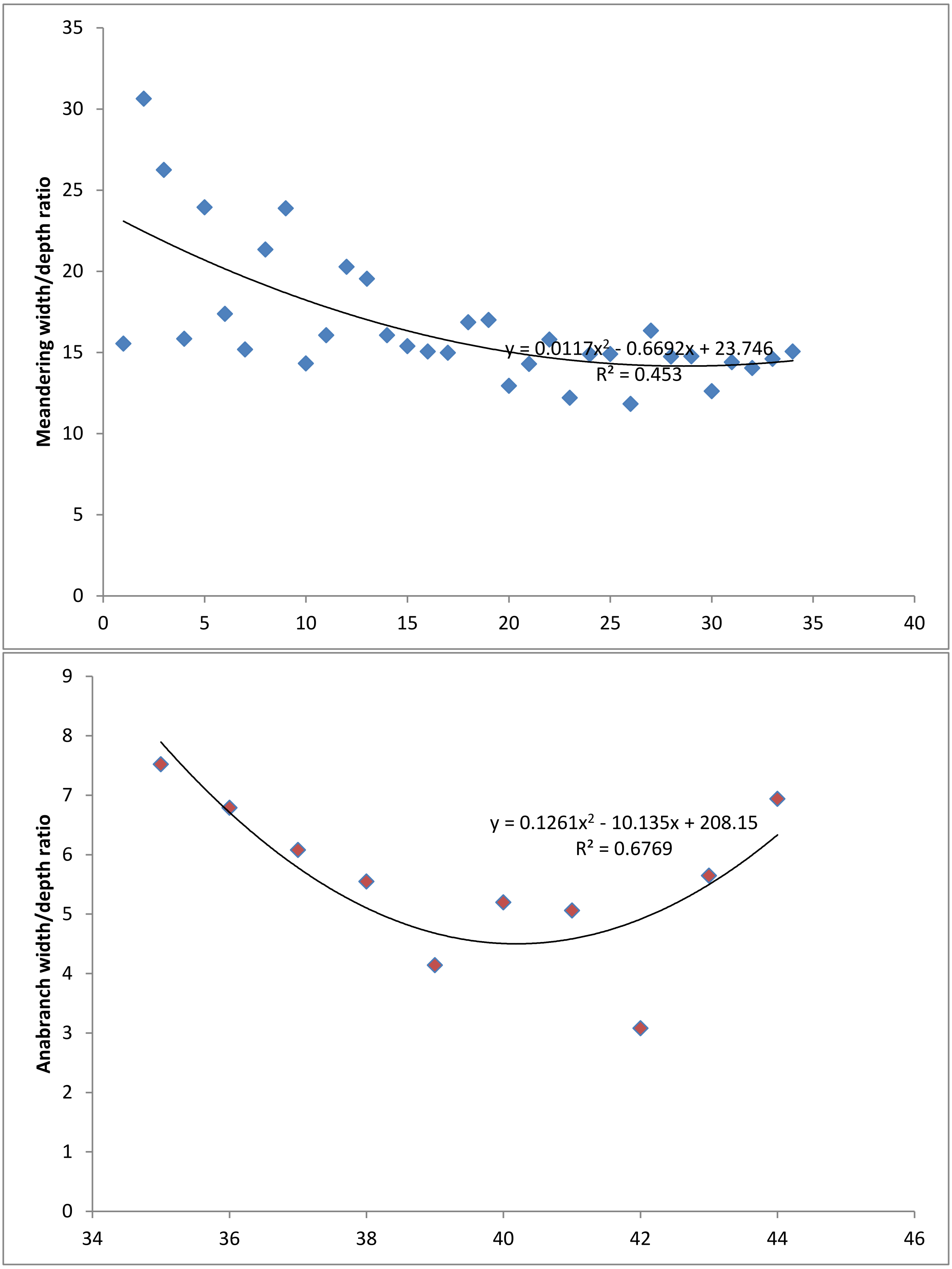


Figure 4.5: Channel width/depth ratio

The analysis of variance revealed that width/depth ratios was totally different between the meandering and anabranching reaches (P = 0.000) at the 99% confidence level. Thus, within the study area, width-depth ratios were considerably lower within the anabranching reach than within the meandering reach. The results further revealed that the channel shape changed from a wide and relatively deep reach (average w/d 12.84) to narrow and deep sections (average w/d 9.26) in the downstream direction.

The width/depth ratio is one of the most widely used measures of river channel shape. This was popularised by Schumm (1960; 1961; 1962) in a series of papers describing the relationship between channel shape and perimeter sediment for stable and unstable channels. Channels with high width-depth ratios tend to be shallow and wide, while channels with low width/depth ratios tend to be narrow and deep. In this study, channel plan form of the study reaches was also distinguished based on their width/depth ratios.

The result of this study agrees with other studies of anabranching rivers. For example it has been well documented on a range of Australian anabranching rivers that channels are generally wide and shallow in the single-thread reaches and narrow and deep in adjacent multi-thread reaches. Jansen and Nanson's (2004) detailed study of Magela Creek in northern Australia showed that the stream exhibited a width/depth ratio of 152 in a single-thread sandy reach, whereas, in an anabranching reach immediately upstream, this ratio for individual channels was only 5 to 12, with a total width only 33% that of the single-thread reach. Also the analysis of the width/depth ratio of the Baghmati River in India showed that the channel shape changed from a wide and shallow section (average w/d 117) at the upstream station (Dhengbridge) to a narrow and deep anabranching section (average w/d 15) at the downstream station (Hayaghat).

The results of the width/depth ratios further substantiated river pattern divisions, since anabranching channels commonly have the lowest width/depth ratios and braided rivers commonly have the largest width/depth ratios, larger than meandering and anabranching systems. The width/depth ratio of a channel, apart from describing the shape of a channel cross section, determines the efficiency of a channel in transporting the imposed water and sediment discharge. Studies have shown that the optimal width/depth ratio where sediment discharge (Qs) achieves a maximum is 35, below which there is a progressive decline in transport capacity. Therefore, the Osun channel, both within the meandering and anabranching reaches, does not display maximum efficiency for sediment transport.

4.1.3.4 Cross-sectional area

Within the study area, cross-sectional area were calculated and analysed for the two study reaches. The results showed mean cross-sectional area within the meandering reach 212.04m^2, while it was 75.90m^2 for the main anabranch within the anabranching reach. This revealed that cross-sectional area were much larger within the meandering reach than within the anabranching reach. The minimum cross-sectional area was 126.78m^2 along cross section nineteen and the maximum area was 256.26m^2 along cross section thirty-three, with a standard error of 4.78. The maximum within the anabranching reach was 117.87m^2 at the last cross section while the minimum area was 48.25m^2 along cross section six.

Cross-sectional area alludes to the size of a stream channel as well as the channel efficiency of streams. Previous research suggested that channel efficiency is also related to reduced cross-sectional area. Nanson and Huang (1999) and Jansen and Nanson (2004) aver that channel efficiency is related to lower channel cross-sectional area within multiple-channel sections as compared to single-channel sections.

The total cross-sectional area is lower where the total width decreases, which increases the average cross-sectional velocity for a given discharge, and hence increases efficiency. Thus, it is expected that, within the study area, reduced cross-sectional area within the anabranching reach leads to greater channel efficiency in moving the water and sediments imposed on it. The analysis of variance revealed that cross-sectional area was totally different between the meandering reach and the main anabranch ($P = 0.000$) at the 99% confidence level. Thus, within the study area, cross-sectional area were considerably lower within the anabranches than the meandering reach.

4.1.3.5 Cross-sectional form and channel efficiency

Stream channels have been postulated to transform from single to multiple channels to increase the efficiency of the channel in conveyance of discharge and sediment (Maximum Flow Efficiency [MFE] hypothesis).

Table 4.4: Analysis of Variance of Plan form variables between the meandering and anabranching reaches

a:Descriptives

		N	Mean	Minimum	Maximum	Std. Deviation	Std. Error
Width	Meandering	34	59.92	46.44	83.32	7.81	1.34
	Anabranching	10	64.69	48.19	82.60	9.92	3.14
	Total	44	61.01	46.44	83.32	8.46	1.28
Area	Meandering	34	212.04	126.78	256.26	27.87	4.78
	Anabranching	10	228.82	171.07	272.32	34.67	10.96
	Total	44	215.86	126.78	272.32	29.97	4.52

b: ANOVA

		Sum of Squares	df	Mean Square	F	Significance
Cross-sectional Width	Between Groups	175.91	1	175.91	2.54	0.118
	Within Groups	2902.94	42	69.12		
	Total	3078.85	43			
Cross-sectional Area	Between Groups	2176.36	1	2176.36	2.51	0.121
	Within Groups	36460.35	42	868.10		
	Total	38636.72	43			

The MFE hypothesis, as proposed by Nanson and Huang (1999), attempts to provide a unifying theory of the origin of anabranching in rivers. It states that anabranching result in channels that are more efficient in conveying water and sediment than single channels (Nanson and Huang, 1999; Jansen and Nanson, 2004). The analysis of downstream channel plan form of River Osun revealed a change from a wide and relatively deep, single channelled meandering reach to a narrow and deep, multi-channelled anabranching reach. The flow efficiency hypothesis for anabranch formation was tested within the study river.

The MFE hypothesis for the formation of anabranches could explain the change from a single to multiple channels within the alluvial section of River Osun if anabranches are more efficient in conveying water and sediments than the single channel. Nanson and Huang (1999) and Jansen and Nanson (2004) assert that channel efficiency is related to lower channel cross-sectional area in multiple-channel sections than single-channel sections. The total cross-sectional area is lower where the total (cumulative) width decreases, which increases the average cross-sectional velocity for a given discharge, and hence increases efficiency. This hypothesis was tested by comparing the total cross-sectional area as well as cumulative width within the anabranching reach with cross-sectional area and width within the meandering reach. This was achieved with the aid of ANOVA. The result is shown in Table 4.4.

The ANOVA result revealed that the mean cross-sectional area within the meandering reach was 212.04m^2 while the mean cumulative cross-sectional area for the anabranching reach was 228.82m^2, revealing that the cross-sectional area was larger within the anabranching reach (total mean) than within the meandering reach. The ANOVA result of $p = 0.12$ indicated that, although total cross-sectional area was larger within the anabranching reach, the difference was not statistically significant at the 95% confidence level. There was, however, greater within-group variability (within-group sum of squares = 36460.35) than between-group variability (between-group sum of squares = 2176.36), meaning that there was greater variability of cross-sectional areas within each group than between them.

The result also revealed that the mean cross-sectional width within the meandering reach was 59.92m, while the mean cumulative cross-sectional width for the anabranching reach was 64.69m. This indicated that cross-sectional width was larger within the anabranching reach (cumulative mean) than within the meandering reach. The ANOVA result of $p = 0.11$

revealed also that, although the total cross-sectional width was larger within the anabranching reach, the difference was not statistically significant at the 95% confidence level.

Using the channel efficiency concept, for the sum of all channels across a valley to be more efficient than single channels, the efficiency gain by individual channels would have to be greater than the efficiency loss due to the addition of channel banks created by the additional channels. The anabranching channels within the alluvial section of River Osun did not appear to be more efficient than single channels because the multiple-channel sections within River Osun displayed greater cumulative width and mean total channel cross-sectional area than the mean within the meandering reach, indicating lower velocities within multiple channels than single channels. Therefore, the hypothesis that anabranching within the alluvial section of River Osun increases the efficiency of the channel was rejected.

The study indicated that Nanson and Huang’s (1999) hypothesis of channel efficiency for anabranch formation did not apply to the formation of anabranches in River Osun. This is not to say that the Nanson-Huang conjecture was invalidated. In cases where the cumulative cross-sectional width of multiple channels is reduced relative to a single channel, channel efficiency rates will be increased. In the Osun River, however, the observed cross-sectional area and cumulative cross-sectional width did not lead to increase in channel efficiency with increase in number of channels. Tabata and Hickins (2003) did not find evidence of MFE as the cause of anabranching on the anastomosed reach of the Columbian River in British Colombia. This was also the case within the wandering Miramichi rivers of New Brunswick, Canada, where Burge (2005) found that anabranched sections displayed greater total channel width than single-channel sections.

Other studies have found evidence for Maximum Flow Efficiency, for example that of Jansen and Nanson (2004), in Majela Creek in northern Australia. The conclusion is that the maximum flow efficiency concept for the development of anabranches does not hold in all streams, as it has not been able to explain the formation of anabranches in River Osun.

4.2 Relationship between plan form and plan form control variables

Alluvial channel plan form has been largely explained on the basis of endogenous adjustments in flow resistance and sediment transport dynamics. There is now, however, a widespread recognition of the fact that alluvial channel plan form are also the product of exogenous factors imposed on a reach by the physical environment (Huang and Nanson, 2007).

Empirical studies (Leopold and Wolman 1957; Schumm, 1963; Schumm and Khan 1972; Schumm, 1981; 1985; Knighton and Nanson, 1993; Rosgen, 1994; 1996; Nanson and Knighton, 1996; Brierly and Fryirs, 2000; Huang and Nanson, 2007) have shown that a change in river plan form is associated with the following:

- changes in slope (gradient) due to tectonic activity, changes in base level
- changes in available energy due to climatic change or contribution of tributary streams (discharge)
- changes in resistance of banks to erosion
- changes in sediment supplied to stream due to land use change, glacials - interglacials

Leopold and Wolman (1957) and Lane (1957) describe the gradual merging of one river pattern into another (continuum of channel pattern) in response to stream power (discharge and slope) and sediment regime (sediment load and bedload grain size). Thorn (1997) adds boundary conditions of valley topography, valley slope, bed and bank materials and riparian vegetation to the driving variables of water and sediment as controls of channel form.

The aim of this section is to analyse the factors controlling channel plan form (pattern and cross-sectional form) within the study area.

4.2.1 Analysis of plan form control variables for study stream

The plan form (pattern and cross-sectional form) control variables considered in this study included discharge (Q), resistance of bank materials (percentage bank clay content [Bc] and bank shear [Bs]), mean size of bed sediments, valley slope (S) and valley width (Vw). The variables were also measured along the forty-four cross sections, thirty-four within the meandering reach and ten within the anabranching reach. These variables were subjected to both descriptive statistics and regression analysis. The results are given in Tables 4.5 and 4.6 and Figure 4.6.

Table 4.5: Descriptive statistics for plan form control variables

a: Study Area

STUDY AREA *(n=44)*								
Parameters	Mean	Min	Max	S.E	Std. D.	Skewness	Kurtosis	Var.
Discharge (m^3 /s)	229.02	20.36	384.32	16.47	109.26	-0.85	-0.52	11938.11
Bank Clay (%)	15.05	4.40	41.27	1.34	8.93	1.59	1.91	79.70
Bank Shear (kPa)	14.63	5.86	37.24	1.19	7.94	1.35	0.77	63.01
Bed Sediment (mm)	1.35	0.30	2.20	0.08	0.56	-0.47	-0.92	0.32
Valley Slope (m)	0.003	0.00013	0.0068	0.0029	0.0019	-0.28	-0.97	0.000
Valley Width (m)	344.83	103.96	968.08	34.84	231.10	1.48	1.29	53409.34

b: Study Reaches

	MEANDERING REACH 1 (*n*=34)						ANABRANCHING REACH 2 (*n*=10)					
Parameters	Mean	S.E	Std. D.	Skewness	Kurtosis	Var.	Mean	S.E	Std. D.	Skewness	Kurtosis	Var.
Discharge (m^3 /s)	282.80	8.21	27.91	0.20	0.21	2295.46	482.24	14.80	46.82	1.19	-0.85	557.40
Bank Clay (%)	10.88	0.51	2.99	0.11	0.30	8.95	29.22	2.43	7.69	0. 39	-1.11	59.27
Bank Shear (kPa)	10.72	0.42	2.44	-0.53	-0.34	2.44	27.93	1.58	5.00	-0.15	1.00	25.02
Bed Sediment (mm)	1.6	0.06	0.35	-0.17	-0.82	0.12	0.50	0.05	0.16	0.44	-0.03	0.02
Valley Slope (m)	0.004	0.00	0.001	0.055	0.15	0.00	0.0002	0.000	0.00003	-1.00	0.009	0.00
Valley Width m)	235.33	12.79	74.62	-0.41	-1.03	5568.37	717.14	59.53	188.26	-0.24	-1.15	35445.48

Table 4.6: Regression of plan form control variables

			Model Summary					Parameter Estimates	
Varable		Equation	R Square	F	df1	df2	Sig.	Constant	b1
Discharge	Meandering	Linear	0.276	12.214	1	32	0.001	238.550	2.529
	Main Anabranch	Linear	0.011	0.090	1	8	0.772	41.685	0.821
	Anabranching	Linear	0.894	67.403	1	8	0.000	401.828	14.622
Percentage Bank Clay	Meandering	Linear	0.250	10.694	1	32	0.003	8.253	0.150
	Anabranching	Linear	0.142	1.320	1	8	0.284	34.486	-0.957
Bank Shear	Meandering	Linear	0.449	26.101	1	32	0.000	7.849	0.164
	Anabranching	Linear	0.007	.055	1	8	0.820	27.179	0.137
Bed Sediment (D_{50})	Meandering	Linear	0.542	37.830	1	32	0.000	2.049	-0.026
	Anabranching	Linear	0.291	3.291	1	8	0.107	0.653	-0.028
Valley Slope	Meandering	Linear	0.470	28.351	1	32	0.000	0.005	-8.720E-5
	Anabranching	Linear	0.025	.205	1	8	0.663	0.000	-1.576E-6
Valley Width	Meandering	Linear	0.696	73.203	1	32	0.000	125.940	6.251
	Anabranching	Linear	0.013	0.103	1	8	0.757	755.667	-7.005

4.2.1.1 Discharge

The results from the descriptive statistics revealed that the minimum discharge for the study area was 40.72m^3/s along cross section 40 (within the anabranching reach), while the maximum discharge was 384.32m^3/s along cross section 34 (within the meandering reach). The results further indicated that the mean discharge for the study area was 328.13m^3/s, with a standard error of 16.47. The mean discharge within the meandering reach was 282.80m^3/s, with a standard deviation of 27.91 and a standard error of 8.21. Within the anabranching reach, discharge was calculated along the main anabranch as well as the entire reach.

The results revealed that along the main anabranch, mean discharge was 92.40m^3/s, with a standard deviation of 47.22 and a standard error of 14.93, while the mean total discharge within the anabranching reach was 482.25m^3/s, with a standard deviation of 26.82.

The results of the regression analysis revealed a significant increase in discharge in the downstream direction (p=0.001) within the meandering reach. Within the main anabranch, although there was a rising trend in discharge in the downstream direction, it was not statistically significant (p=0.772). However there was a statistically significant increase in total (cumulative) discharge in the downstream direction within the anabranching reach (p=0.000).

The result, therefore, revealed that discharge was higher within the anabranching reach than within the meandering reach. This is to be expected since the anabranching reach is downstream of the meandering reach. With the exception of streams in desert environments and in some peculiar bedrocks, discharge increases in the downstream direction. There is an increase in discharge in the downstream direction in most streams especially, with the introduction of discharge from tributary streams. Within the study area, several tributaries flow into the Osun River. However, it was noticed that a large tributary enters into the stream immediately downstream of Igbonla village, introducing a large amount of water and sediments.

4.2.1.2 Bank strength

Bank strength is defined in terms of the percentage silt/clay content of bank materials as well as the bank shear strength, which has to do with the binding properties of vegetation root on the soil. For this study, bank strength was defined in terms of percentage clay content of bank materials and bank shear strength. Bank sediments within the study area ranged in size, from clay particles to stones and small boulders (Plate 4.2).

The result of the statistical analysis showed that the minimum percentage clay content of bank material for the study area was 4.40% and maximum was 41.27%. The mean percentage clay content of channel bank was 15.05%, with a standard error of 1.34. Within the study area, percentage bank clay was higher within the anabranching reach, with mean of 22.9% compared to the meandering reach, with mean of 10.88%. However, the range was larger within the anabranching reach where minimum percentage clay content was 19.15% in cross section five and maximum percentage clay content was 40.27% in cross section two. The range was less in meandering reach. Here the minimum percentage clay content was 4.40% in cross section eight and the maximum was 18.28% in cross section thirty-four.

It was also observed that the mean bank shear strength for the study area was 14.63kPa with a standard error of 1.20, while the minimum and maximum values were 5.86kPa and 37.24kPa, respectively. There were observed differences in values of bank shear strength between the anabranching and meandering reaches. The mean bank shear was 29.22kPa within the anabranching reach and only 10.72kPa within the meandering section. Regression analysis revealed a significant increase of percentage bank clay content ($b=0.15$, $p=0.003$) downstream and bank shear strength ($b=0.16$, $P=0.000$) within the meandering reach. Within the anabranching reach, there was a reduction in percentage bank clay content ($b=-0.96$, $p=0.284$) and an increase in bank shear strength ($b=0.137$, $p=0.82$) downstream, although these were not statistically significant.

The combination of higher percentage clay content of bank materials and higher bank shear strength due to the influence of vegetation within the anabranching reach, compared to the meandering reach, provides greater resistance to deformation, leading to lower rates of erosion. The results further revealed that, within the anabranching reach, there may be higher erosion within the downstream section leading to wider channels downstream owing to less bank clay content downstream.

Plate 2: Bank material types within the study area

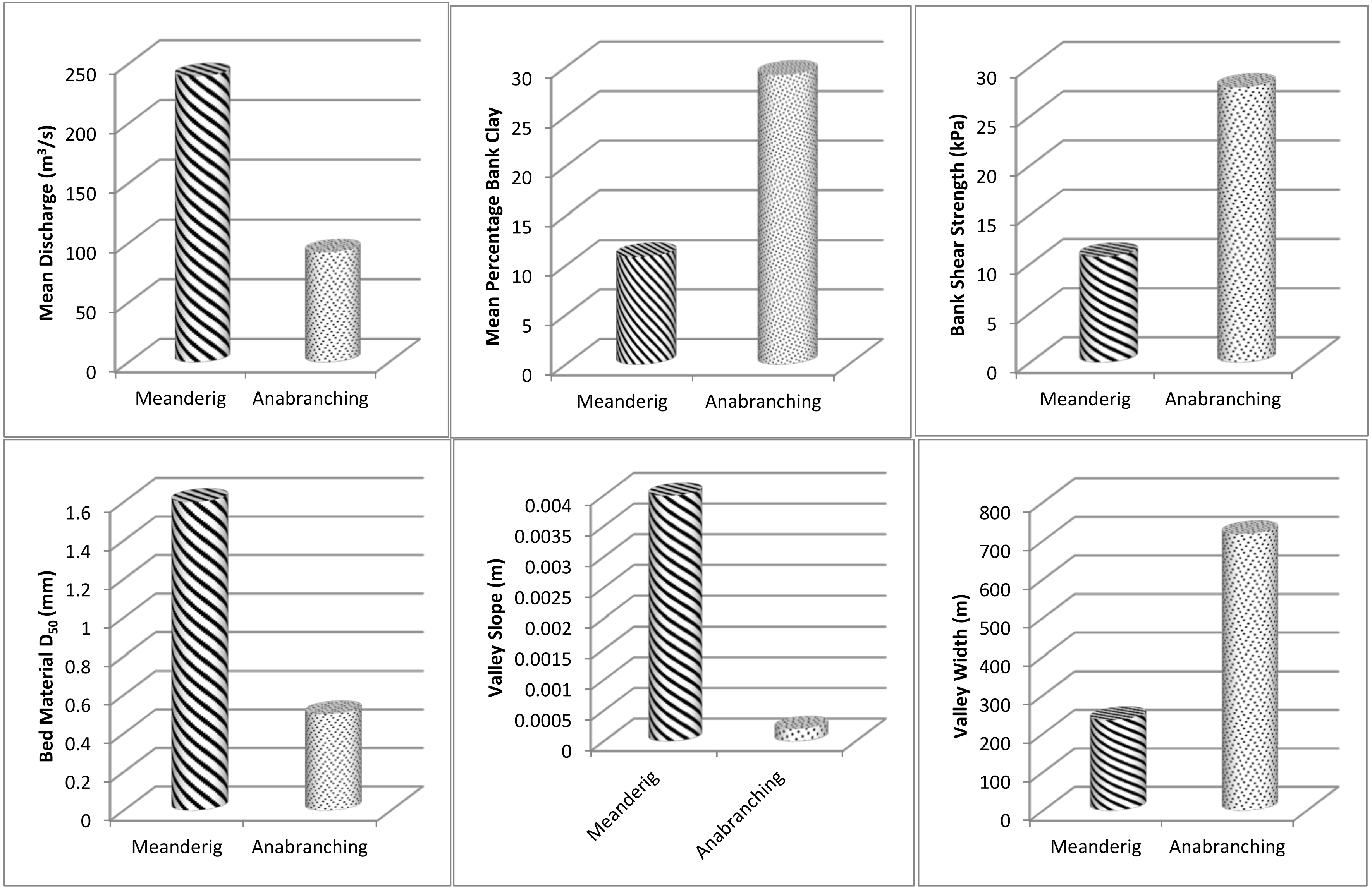


Figure 4.6: Mean of plan form control variables within the study area

4.2.1.3 Median size of bed sediments (D_{50})

The minimum median size (D_{50}) of channel bed sediments for studied cross sections within the study area was 0.30mm while the maximum value was 2.20mm. The average D_{50} for the study area was 1.35mm with a standard error of 0.085. Within the study area, bed sediment grain size changed along the length of the river. Coarser sediments (mean 1.6mm) were found in the meandering reach, while finer sediments (mean 0.50mm) were found in the anabranching reach, which was further downstream. The range in median grain size of bed materials was larger within the meandering reach (1.30), where the minimum median bed sediment grain size was 0.90mm in cross section thirty and maximum median bed sediment grain size was 2.20mm in cross section eight. The range was less in the anabranching reach (0.50). The minimum median bed sediment grain size was 0.30mm in cross sections three and eight; while the maximum median bed sediment grain size was 0.80mm in cross section one.

The regression analysis also revealed a statistically significant reduction in the average size of bed sediments (b=-0.026, p=0.000) downstream within the meandering reach. Within the anabranching reach, there was also insignificant decrease in the average size of bed sediments (b=-0.028, p=0.10) downstream. It was, therefore, concluded that, within the study area, there was a progressive decrease in mean bed grain sediment size.

Most river systems exhibit a progressive decrease in the mean diameter of grain size from the headwaters downstream. Generally, downstream fining in particle size occurs owing to both abrasion and sorting (Ferguson *et al.,* 2006) and is also a result of the reduction in transport capability of the stream with the reduction in slope.

4.2.1.4 Valley gradient

The minimum and maximum values for valley gradient within the study area were 0.00013m and 103.96m, while the mean values for slope were 0.00309m with standard error of 0.0003m. As with the other plan form control factors, channel slope values were different between the anabranching and meandering reaches, the mean slope was much lower within the anabranching reach at 0.0002m than the meandering reach at 0.004m. The range in valley slope was larger within the meandering reach (0.0054). Here the minimum value of valley slope was 0.0014m in cross section thirty-two and the maximum value for valley slope was 0.0068m in cross section five. The range was less in the anabranching reach (0.00009). The minimum value of valley slope 0.00013m in cross section seven, while the maximum value for valley slope was 0.00022m in cross sections one and ten.

The regression analysis also revealed a statistically significant reduction in valley slope (b= 8.72, p=0.000) downstream within the meandering reach. Within the anabranching reach, there was also a downstream decrease in valley slope (b=-1.578, p=0.663), which was not statistically significant. It was, therefore, observed that within the study area, there was also a progressive downstream decrease in valley slope.

4.2.1.5 Valley width

The minimum and maximum values for valley width were 103.96m and 968.08m, respectively; while the mean value for valley width was 344.83m, with standard error of 34.84. The valley width was much larger within the anabranching reach than the meandering reach. The mean valley width within the anabranching reach was 717.14m; while the mean valley width within the meandering reach was 235.33m.

The regression analysis revealed a statistically significant increase in valley width downstream (b=6.25, p=0.000) within the meandering reach. Within the anabranching reach, there was also a downstream decrease in valley width (b=-7.005, p=0.757), which was not statistically significant. The results revealed that stream valley was relatively confined within the meandering reach compared to the anabranching reach which had wider valleys.

The result of the analysis of plan form factors revealed that discharge was much larger within the anabranching reach, while slope was larger within the meandering reach (0.004), compared to the anabranching reach (0.0002m). A basic tenet of the channel pattern continuum concept of Leopold and Wolman (1957) is that rivers with greater stream power (as defined by discharge and slope) tend to braid while rivers with lower stream power tend to meander, and that anabranch rivers are formed where there is low stream power. The reduction in channel slope may have led to the inability of channel to carry the increased discharge, leading to the formation of anabranches within the study area. The analysis also revealed that sediments within the meandering reach were coarse (1.6mm). Smaller sediments (0.50) in the anabranching reach reflected a downstream finning of materials.

Table 4.7: **Correlation between channel pattern and plan form control variables**

	Channel pattern	Discharge	Bank Clay	Bank Shear	Bed Material	Slope	Valley Width
Channel Patten	1						
Discharge	0.863**	1					
Bank Clay	0.787**	0.772**	1				
Bank Shear	0.873**	0.835**	0.804**	1			
Bed Material	-0.783**	-0.854**	-0.796**	-0.840**	1		
Slope	-0.778**	-0.818**	-0.767**	-0.805**	0.810**	1	
Valley Width	0.813**	0.807**	0.780**	0.947**	-0.840**	-0.821**	1

**. Correlation is significant at $\alpha._{0.01}$.

Table 4.8: Analysis of variance of plan form control variables

		Sum of Squares	df	Mean Square	F	Significance
Discharge	Between Groups	432571.693	1	432571.693	224.943	0.000
	Within Groups	80767.113	42	1923.027		
	Total	513338.806	43			
Bank Silt Content	Between Groups	2598.345	1	2598.345	131.651	0.000
	Within Groups	828.938	42	19.737		
	Total	3427.282	43			
Bank Strength	Between Groups	2287.444	1	2287.444	227.726	0.000
	Within Groups	421.879	42	10.045		
	Total	2709.322	43			
Bed Material (D50)	Between Groups	9.350	1	9.350	93.500	0.000
	Within Groups	4.200	42	0.100		
	Total	13.550	43			
Slope	Between Groups	0.000	1	0.000	86.615	0.000
	Within Groups	0.000	42	0.000		
	Total	0.000	43			
Valley Width	Between Groups	1793836.447	1	1793836.447	149.853	0.000
	Within Groups	502765.541	42	11970.608		
	Total	2296601.988	43			

4.2.2 Relationship between the control variables and channel pattern

Field and laboratory data indicate that channel pattern is controlled by discharge and slope (Leopold and Wolman 1957; Schumm and Khan 1972). Channel pattern also reflects sedimentary controls. Schumm (1963) found that channel sinuosity of sand-bed rivers in the Great Plains of the USA increased with the percentage slit/clay in the bed and banks, Kellerhalls (1982) and Carson (1984) argue that sand-bed rivers braid at lower slopes than gravel-bed rivers with similar discharges. In the explanation of the different channel patterns observed within the study area, correlation and the analyses of variance were used to explore the relationship between plan form control variables and channel pattern within the study area (see Tables 4.7 and 4.8).

4.2.2.1 Discharge channel pattern relationship

Discharge has been observed to be one of the most important factors of change in channel pattern. The relationship between discharge and channel pattern was investigated within the study reach. The results revealed that average discharge within the meandering reach was 282.80m^3/s; average discharge for the main anabranch was 92.40^3/s; and average total discharge for the anabranching reach was 482.25m^3/s. Therefore, mean discharge was higher within the anabranching reach than the meandering reach. Correlation analysis was run between discharge and channel pattern (see Table 4.7) to show the nature of relationship between them. The correlation revealed that within the study area, channel pattern was directly related to discharge (r=0.86), thus discharge was higher in sections with more branches.

Analysis of variance of discharge for the study area showed that between-group sum of squares (432571.69) was larger than within-group sum of squares (80767.11), indicating a statistically significant difference between discharge within the meandering reach and the anabranching reach (p = 0.000). Thus, within the study area, average discharge was higher within the anabranching reach than within the meandering reach. Increased discharge has been shown to lead to changes in channel pattern. For example, a study by Hu *et al.* (2013) of a small river system in the Uinta basin in Utah, USA showed that discharge influenced channel sinuosity and morphology to produce initial meandering patterns changing downstream to braided patterns. Stevens *et al.* (1975) assert that differences in peak flood discharge between two rivers in the same geological settings are responsible for differences in river forms (straight and sinuous planforms).

4.2.2.2 Bank strength channel pattern relationship

As shown in section 4.2.1.2, percentage bank clay content was higher within the anabranching reach, with mean of 29.22%, compared to the meandering reach with mean of 10.88%. Correlation analysis revealed that channel pattern was directly related to bank strength. Correlation between channel pattern and percentage bank clay as well as bank shear were r=0.79 and r=0.87, revealing that areas with higher the bank strength had more anabranches.

Analysis of variance of percentage bank clay in the study reaches revealed a significant difference between percentage clay content within the meandering reach and the anabranching reach (p=0.000). The between-group sum of squares (2598.34) was much larger than the within-group sum of squares (828.94), revealing a greater variance in percentage bank clay content between the meandering and anabranching reaches. The greater percentage bank clay content within the anabranching reach (mean 29.22%), compared to the meandering reach (mean 10.88%), could explain the observed change in channel shape downstream from a wide and relatively deep channel within the meandering reach to a narrow and deep channel within the anabranching reach.

Analysis of variance in bank shear within the study reaches revealed a significant difference between bank shear strength within the meandering reach and the anabranching reach (p=0.000). The between-group sum of squares (2287.44) was much larger than the within-group sum of squares (421.88), revealing a greater variance in bank shear strength between the meandering and anabranching reaches.

Bank strength is another important factor of channel plan form and its effects on the formation of river channel patterns have been quantified with several integrated models (for example, Wang and Zhang, 1989; Millar, 2000; Eaton and Church, 2004). Vegetation was described as one of the factors of lateral channel stability in the channel Narew valley (an anabranching river system) where it contributes to the growth of the layer of peat, relatively resistant to erosion. The study found that vegetation in the banks formed a protective zone in the nature of grill-like margins; the vegetation also invaded the channels constricting them. Stanistreet *et al*, (1993) and McCarthy *et al.* (1996) also documented a similar role played by rushes in the anastomosing system of the Okavango delta. The greater bank shear strength within the anabranching reach, compared to the meandering reach, could be another important factor in explaining pattern change within the study area.

The importance of bank strength as defined by the cohesiveness of materials and the added strength provided by vegetation in the formation of channel pattern has been shown by various studies (for instance, Murray and Paola, 1994). According to Parker (1976), in dryland environments where sediments are not generally rich in cohesive silts and clays, unless riparian vegetation is sufficient to stabilise the channel banks and/or discourage the formation of new channels, channel widening promotes the development of a braided channel pattern through the instability of sediment transport in wide channels. Murray and Paola (1994) consider the braided channel form as the inevitable consequence of unconstrained flow over a non-cohesive bed,

This study considered bank stability as a sensitive factor in the formation of anabranches in the alluvial section of Osun River. Within the study area, bank strength, as defined by percentage clay content of the bank sediments, and the binding force exerted by vegetation, as defined by bank shear strength, could be an explanation for the difference in observed channel pattern.

4.2.2.3 Bed material - channel pattern relationship

The impact of bed material grain size on channel pattern was also explored in this study. The analysis revealed that the average median bed sediment grain size (D_{50}) was 1.6mm within the meandering reach, while it was 0.50mm within the anabranching reach. Correlation analysis revealed that within the study area, channel pattern was inversely related to bed sediment grain size (-0.78), thus areas with more channel branches had smaller bed sediments.

Analysis of variance of average median bed sediment grain size (D_{50}) in the study reaches showed a significant difference between average median bed sediment grain size (D_{50}) within the meandering reach and the anabranching reach (f=93.50, p=0.000). The between-group sum of squares (9.35) was much larger than the within-group sum of squares (4.20), implying a greater variance in average median bed sediment grain size (D_{50}) between the meandering and anabranching reaches.

This revealed finer sediment transport within the anabranch reach, than within the meandering reach. Coarse bed material transport is responsible for creating and altering channel morphology, in contrast to fine sediment, such as silt and clay that are transported through the system more rapidly. Thus stream channels or channel reaches that transport coarser materials are exposed to greater erosional activities. Within the study area, transport of coarser materials within the meandering reach than within the anabranching reach leads to more channel bed and bank erosion potential of discharge.

4.2.2.4 Valley gradient - channel pattern relationship

Channel gradient is such a factor that has been widely recognized to cause a change in the stream channel pattern (for instance, Schumm, 1977; Bettess and White, 1983; Schumm and Winkley, 1994; Montgomery and Buffington, 1998; Eaton and Church, 2004; Huang *et al.*, 2004a; Tooth and Nanson, 2004).

Within the study area, valley slope was relatively high within the meandering reach (mean slope = 0.004m), while valley slope was less within the anabranching reach (mean slope = 0.00022m). Correlation analysis revealed that channel pattern was inversely related to valley slope (-0.78), revealing that areas with lower valley slope were more anabranched. Low relief is believed to encourage anabranch formation as a mechanism by which the river can adjust to increase its flow efficiency (Nanson and Huang, 1999). Much of the current debate on anabranch development is concerned with theories of least action principle (Nanson and Huang, 2007), where valley slope is seen as a critical parameter in a channel's ability to maintain equilibrium form (Jansen and Nanson, 2004).

Analysis of variance in valley slope between the study reaches revealed a significant difference in valley slope between the meandering and anabranching reaches (f=86.62; p=0.000). Thus, reduction in slope could be a main factor in the observed change in channel pattern within the alluvial section of River Osun, from a meandering pattern to an anabranching pattern.

Studies have shown that the impact of change in slope on the formation of channel pattern vary. Although some studies have illustrated that the transition of a meandering channel to an anastomosing (anabranching) channel occurs where a slight decrease in valley gradient exists (Watson *et al.*, 1983; Miller, 1991), others have documented only alterations of cross-sectional geometry in meandering channels faced with a local decrease in valley gradient (Ferguson and Ashworth, 1990; McEwen, 1994). A study by Burrows and Harrold (1983) revealed that the change in channel pattern from braided to anastomosing correlated with a change of river slope in the Fairbanks area. The study showed that water surface slope of the Tanana at the USGS measuring site, "Tanana River at North Pole," averaged 0.0012 and decreased to 0.0005 downstream of Goose Island and 0.0003 downstream of the confluence with the Chena River.

4.2.2.5 Valley width - channel pattern relationship

Within the study area, variation in valley width between the anabranching and meandering reaches was analysed to determine the impact of valley width on pattern formation. Correlation analysis revealed that, channel pattern was directly related to bed sediment grain size (0.81), thus channel sections with wider valleys were more anabranched.

The result of the analysis of variance in valley width in the reaches revealed a significant difference in the valley width of the anabranching and meandering reach (p=0.000). The between-group difference (1793836) was much larger than the within-group difference (502765), revealing a great variance in valley width between the anabranching and meandering reaches. The larger mean width of valley within the anabranching, compared to the meandering reach, could be a factor in anabranch formation.

Valley width is a factor of channel confinement, which is correlated to bedrock resistance to erosion, with streams flowing on less resistant bedrock having wider valleys than streams flowing on more resistant bedrocks (Jenkins, 2007). Jenkins (2007) compared the number of anabranched channels at cross sections to valley width but the results revealed a negligible correlation between them. The study showed that although single channel reaches correlated with more narrow valley sections, there was no significant difference between valley widths at single channel cross sections and valley widths at cross sections with multiple channels (p=0.7620). However, other studies have revealed a positive relationship between valley width and channel pattern.

The results of the analysis of relationship between control factors and channel pattern revealed a statistically significant difference in all plan form factors between the meandering and the anabranching reaches. Overall, the anabranching reach had a higher discharge, higher bank strength, smaller bed material sediment size, lower slope and higher valley width than the meandering reach. This indicated that they were important variables in the change in channel pattern from meandering to anabranching.

4.2.3 Relationship between the control variables and the channel cross-sectional form

4.2.3.1 Discharge - cross-sectional form relationship

The dominant control on the cross-sectional dimensions of a river is discharge. This is, perhaps, best illustrated by Ferguson's (1986) observation that channel width and depth increase systematically with increasing bankfull discharge as it varies over nine orders of magnitude from small laboratory channels to the world's largest rivers.

In order to determine the relationship existing between discharge and cross-sectional form control variables within the study area, a graphical plot of each of the cross-sectional form variables against discharge was done. This enabled the determination of the relationship between the response variables (width, depth and area) and the governing variable (discharge), with a view to analysing and explaining the nature of adjustments of the cross sections along the stream. The graphs presented below (Figure 4.7) show the relationship between cross-sectional variables and discharge within the study area. From the graphs it is seen that almost all the cross-sectional form variables were positively correlated with discharge.

It is seen from Figure 4.7 that, within the study area, cross-sectional width, depth and area were positively related to downstream discharge, revealing that increase in discharge led to increase in all the plan form parameters. But it can be observed from the trend that width and area showed a steeper trend line when compared with that of depth.

Correlation analysis was run between discharge and cross-sectional form variables (see Table 4.9) to show the nature of relationship between them. The results of the correlation revealed a statistically significant positive correlation between discharge and width (P= 0.000), area (P= 0.000) and W/D ratio (P=0.000). Correlation analysis also revealed a positive relationship between discharge and cross-sectional depth. This was, however, not statistically significant (P= 0.191).

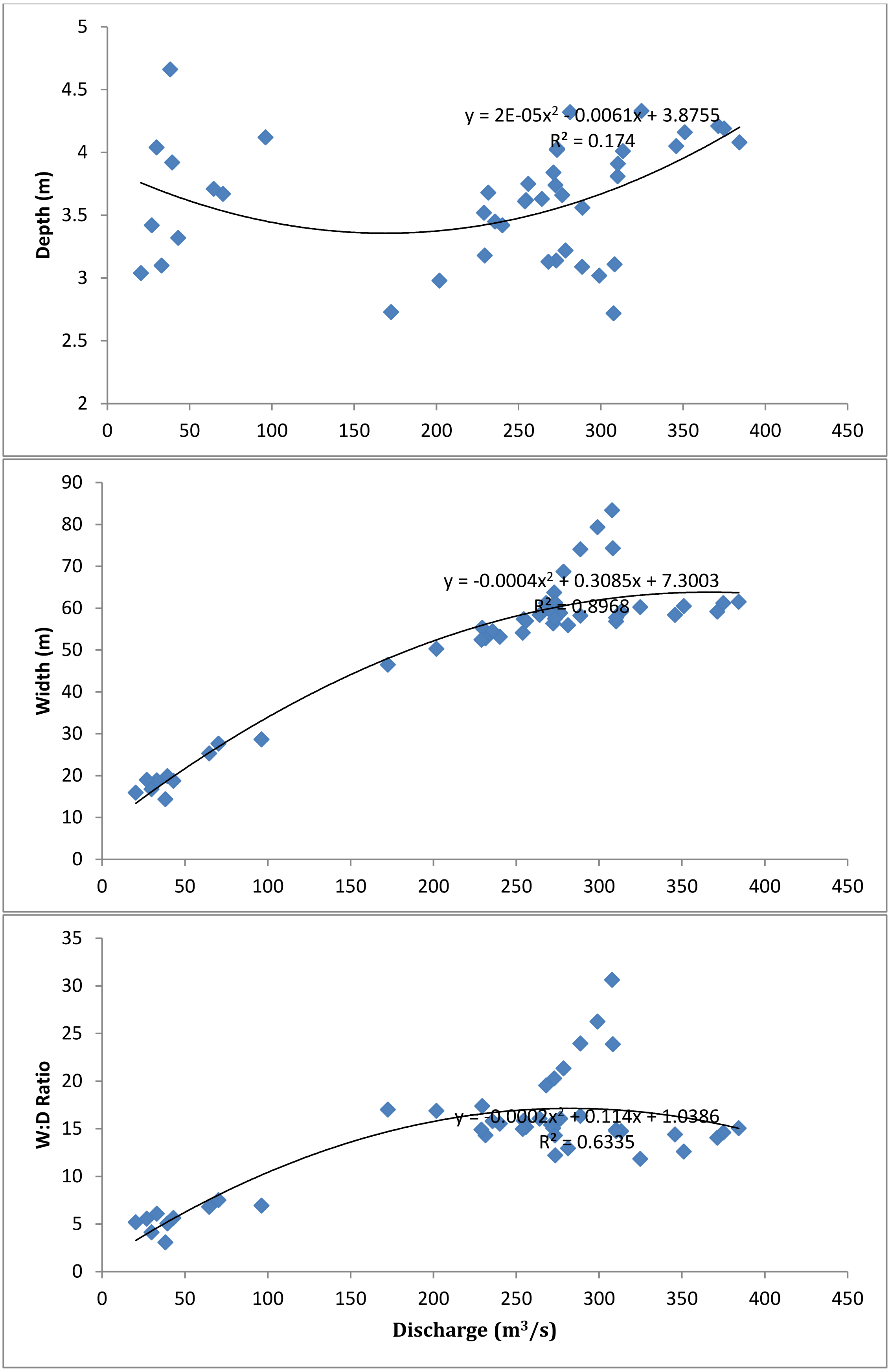


Figure 4.7: Discharge cross-sectional form relationship within the study area

Table 4.9: Correlation between discharge and cross-sectional form variables

a: Study Area

		Width	Depth	Area	W/D Ratio	Discharge
Discharge	Pearson	0.918**	0.135	0. 978**	0.	1
Correlation		0.000	0.191	0.000	720**	
	Sig. (1-tailed)	44	44	44	0.000	44
	N				44	

b: Meandering Reach

		Width	Depth	Area	W/D Ratio	Discharge
Discharge	Pearson Correlation	0.444**	0.571**	0.866**	-0.045	1
	Sig. (1-tailed)	0.004	0.000	0.000	0.400	
	N	34	34	34	34	34

c: Anabranching Reach

		Width	Depth	Area	W/D Ratio	Discharge
Discharge	Pearson Correlation	0.908**	0.348	0..959**	0.661*	1
	Sig. (1-tailed)	0.000	0.162	0.000	0.019	
	N	10	10	10	10	10

*. Correlation is significant at the 0.05 level (1-tailed).

**. Correlation is significant at the 0.01 level (1-tailed

Table 4.10: Hydraulic geometry relationship within the study reaches

	Meandering Reach			Anabranching Reach		
Parameters	R^2	R^2 Adjusted	Exponent	R^2	R^2 Adjusted	Exponent
Width	0.28	0.27	0.38	0.18	0.08	0.12
Depth	0.31	0.29	0.42	0.74	0.70	0.42
Velocity	0.31	0.03	0.23	0.84	0.82	0.46

Table 4.11: Hydraulic geometry statistics

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
Meandering				
1	0.536[a]	0.287	0.265	0.04552
2	0.560[a]	0.314	0.292	0.04748
3	0.555[a]	0.308	0.286	0.02917
Anabranch				
1	0.427[a]	0.182	0.080	0.05607
2	0.857[a]	0.734	0.701	0.05565
3	0.919[a]	0.845	0.826	0.04308

a. Predictors: (Constant), Log of Discharge

Model	Unstandardized Coefficients		Standardized Coefficients		
	B	Std Error	Beta	t	Significance
Meandering					
1	0.379	0.105	0.536	3.591	0.001
2	-0.420	0.110	0.560	3.823	0.001
3	0.233	0.068	0.555	3.772	0.001
Anabranch					
1	0.121	0.090	0.427	1.335	0.218
2	0.421	0.090	0.857	4.696	0.002
3	0.459	0.069	0.919	6.611	0.000

Dependent Variables: Log of width – 1; Log of depth – 2; Log of velocity - 3

The result of the correlation between discharge and cross-sectional form variables for the individual study reaches revealed a significant positive correlation between discharge and width (P=0.004), depth (P=0.000) and area (P=0.000) and a negative correlation between width/depth ratio (P=0.400), which was not statistically significant, and discharge within the meandering reach. There was a statistically significant positive correlation between discharge and width (P=0.000), area (P=0.000), width/depth ratio (P=0.019) and discharge within the anabranching reach. Conversely, the relationship between discharge and channel cross-sectional depth within this reach, although positive, was not statistically significant at the 95% confidence level (P=0.162).

Empirical geomorphological investigations of the relationships between channel geometry and stream discharge have traditionally followed the downstream hydraulic geometry approach of Leopold and Maddock (1953). Hydraulic geometry involves the interactions between discharges in a stream channel and the channel itself, and is concerned with how changes in discharge are accommodated at a given cross-section. Hydraulic geometry is, therefore, a canonical example of mutual adjustments in fluvial systems. In the approach of Leopold and Maddock (1953), downstream changes in width (w; m), depth (y; m) and velocity (u; m/s) are expressed as power functions of an assumed dominant discharge. They are of the view that increasing discharge at a given cross section, the width, mean depth and velocity increases as a power function.

The downstream hydraulic geometry relationship for the study reaches was investigated using the bankfull discharge, the log of bankfull channel width, mean depth and flow velocity were plotted against bankfull discharge for the study area (see Tables 4.10 and 4.11). Linear regression of the data resulted in the following exponents:

$b = 0.38$; $f = 0.42$ and $m = 0.23$ ..… meandering
$b = 0.12$; $f = 0.42$ and $m = 0.46$ …. anabranching

The exponents of the equation should sum up to 1 by virtue of continuity, but the proportionality coefficients varied because hydraulic geometry was not controlled solely by discharge; it was controlled also by the grain size and transport rate of the sediment, and bank erodibility (that is related to cohesion of bank material and vegetation). The exponents summed up to 1.03 within the meandering reach and 1.0 within the anabranching reach.

The power equation for the hydraulic geometry relationship within the meandering and anabranching reaches is given as:

$$w_{bf} = xQ_{bf}^{0.4} \quad \text{……………………………………………………..} \quad 4.1$$

$$d_{bf} = yQ_{bf}^{0.4} \quad \text{……………………………………………………..} \quad 4.2$$

$$v_{bf} = zQ_{bf}^{0.2} \quad \text{……………………………………………………..} \quad 4.3$$

and

$$w_{bf} = xQ_{bf}^{0.1} \quad \text{……………………………………………………..} \quad 4.4$$

$$d_{bf} = yQ_{bf}^{0.4} \quad \text{……………………………………………………..} \quad 4.5$$

$$v_{bf} = zQ_{bf}^{0.5} \quad \text{……………………………………………………..} \quad 4.6$$

where:

w = Cross-sectional width,

d = Mean depth, and

v = Mean velocity

The exponents of the regression equation for the meandering and anabranching reaches revealed that within the meandering reach, depth increased faster (0.42) than width (0.38) and velocity (0.23) in the downstream direction. Conversely, within the anabranching reach, velocity and depth had the highest rate of increase downstream (0.46 and 0.42), while width increased at a lower rate in the downstream direction (0.12). Thus, variation in the proportionality coefficients between both reaches could be explained by the differences in the erodibility of bank materials, as the anabranching reach had more cohesive materials and so adjustment within this area to imposed discharge was more in the form of increase in depth and flow velocity. Within the meandering reach, relatively lower cohesion of bank materials meant that lateral erosion was more rampant than increase in depth.

The exponents b = 0.5, f = 0.4 and m = 0.1 defined for streams in the American Midwest using the mean annual flood indicated that width increased faster than depth (generating downstream changes in channel shape, as indexed by the width/depth ratio) and that velocity increased downstream (contradicting traditional Davisian assumptions). A study of the downstream adjustment of ephemeral channels in New Mexico, USA showed that, although the increase in width was about the same as that observed in humid-temperate perennial rivers, the increase in velocity was more rapid and the increase in depth was less rapid (Leopold and Miller, 1956). The study by Latrubesse (2008) of the Amazon at Jatuarana revealed that velocity increased to a rate of 0.65, while depth increased with an exponent of 0.3. The study further showed that at the Itapeua gauging station, the velocity exponent m was as high as 0.71, while exponent f was only 0.2. The study suggested that the situation was likely influenced by the reach-scale specific geomorphic characteristics of the areas, where the channel is narrow and controlled by stable levees. However a study of one hundred and fifty eight stations in the United States of America by Leopold *et al.,* (1964) revealed that depth increased more rapidly downstream than either width or velocity.

Nanson and Huang (1999) and Jansen and Nanson (2004) assert that channel efficiency is related to lower channel cross-sectional area in multiple-channel sections than single-channel sections. One way to increase the transport capacity of a stream, according to them is by increasing the velocity of the stream either by changing the channel shape (w/d ratio) or by increasing the number of channels. Based on river data of anabranch rivers in Australia, Nanson and Huang (1999) claim that, in anabranch rivers, decrease in aggregate width and increase in flow depth produces an increase in velocity.

This was also viewed within the anabranching reach of River Osun, where there was an increase in downstream velocity as a result of a decrease in channel width-depth ratio and cross-sectional area. Thus, the change in channel shape (w/d ratio) and the increase in the number of channels of the alluvial section of River Osun in the anabranching reach could be a way of increasing the transport capacity of the stream.

4.2.3.2. Bank strength (erodibility) - cross-sectional form relationship

The erodibility of channel banks exerts important secondary controls on cross-sectional adjustment. Significant amounts of cohesive silts and clays in bank materials increases strength to resist processes of bank erosion. As a result, channels tend to respond to increased discharge by deepening, rather than widening their cross-sections.

Hupp and Osterkamp (1997) showed that vegetation provides additional stability to stream channel in addition to the make-up of channel materials. For this study, both the clay content of bank materials and the influence of vegetation as determined by bank shear force were measured and analysed to determine the influence of bank strength on channel cross-sectional form (see Table 4.12 as well as Figures 4.8 and 4.9). The result is discussed below.

Table 4.12: Correlation between bank strength and cross-sectional form

a. Study Area

		Width	Depth	Area	W/D Ratio
% Bank Clay	Pearson Correlation	-0.816**	0.156	-0.749**	-0.753**
	Sig. (1-tailed)	0.000	0.156	0.000	0.000
	N	44	44	44	44
Bank shear	Pearson Correlation	-0.928**	0.201	-0.863**	-0.869**
	Sig. (1-tailed)	0.000	0.096	0.000	0.000
	N	44	44	44	44

b. Meandering Reach

		Width	Depth	Area	W/D Ratio
% Bank Clay	Pearson Correlation	-0.401**	0.503**	0.147	-0.512**
	Sig. (1-tailed)	0.009	0.001	0.204	0.001
	N	34	34	34	34
Bank shear	Pearson Correlation	-0.528**	0.718**	0.116	-0.764**
	Sig. (1-tailed)	0.001	0.000	0.256	0.000
	N	34	34	34	34

c. Anabranching Reach

		Width	Depth	Area	W/D Ratio
% Bank Clay	Pearson Correlation	0.565*	-0.200	0.421	0.625*
	Sig. (1-tailed)	0.044	0.290	0.113	0.027
	N	10	10	10	10
Bank shear	Pearson Correlation	-0.857**	0.262	-0.864**	-0.671*
	Sig. (1-tailed)	0.001	0.232	0.001	0.001
	N	10	10	10	10

*. Correlation is significant at the 0.05 level (1-tailed).

**. Correlation is significant at the 0.01 level (1-tailed).

Percentage bank clay content

The results of the analysis of bank materials showed that the mean percentage clay content of the bank sediments was relatively high for all the study sections. High percentage of clay within the bank sediments made the banks more cohesive and, therefore, more resistant to lateral erosion. Correlation between percentage bank clay and plan form (cross-sectional form) variables for the study area revealed a significant negative correlation between percentage clay content of bank sediments and cross-sectional width (p = 0.000), area (p = 0.000) and width depth ratio (p = 0.000). There was a positive correlation between percentage bank silt and cross-sectional depth, which was not statistically significant (p = 0.156).

Within the meandering reach, there was a significant negative correlation between percentage content of bank clay and channel width (P=0.009) and width-depth ratio (p=0.001). There was a positive correlation between percentage content of bank clay and channel depth (P=0.001), while the correlation between percentage of bank clay and channel cross-sectional area, although positive, was not statistically significant (p=0.204). The negative correlation between percentage bank clay content and width depth ratio revealed that cross sections with higher bank clay content were narrower and deeper than cross sections with less percentage bank clay content.

The relationship between percentage clay content of bank material for the anabranching reach was different from that within the meandering reach. Within this reach, there was a significant positive relationship between percentage bank clay content and cross-sectional width (p=0.044) and width depth ratio (p=0.027). There was also a positive correlation between channel area and percentage bank clay content (p=0.133), which was not statistically significant. The results, however, revealed a negative correlation between percentage bank clay content and cross-sectional depth (p=0.290), which was also not statistically significant.

Schumm (1960) asserts that the shape of cross sections expressed as the width-depth ratio depends on sediment type (amount of silt-clay in bed and bank material). Channels containing little silt and clay are wide and shallow, whereas high silt-clay content is related to narrow and deep channels. Osterkamp and Hedman (1982) found similar results as Schumm (1960). Merritt and Wohl (2003) examined the downstream adjustment of Yuma Wash in SW Arizona to an event with a discharge estimated at 20% of the maximum probable flood.

They found that increases in width were substantial (b = 0.78), whereas the increases in depth and velocity were modest (f = 0.15 and m = 0.14). They attributed the rapid increase in channel width to the low cohesion of the bank material which comprised less than 3% silt and clay.

The absence of significant bank retreat in channels in the northern Negev Desert, which are able to maintain relatively deep and narrow cross sections despite the high transport stages generated by flash floods, has been attributed to the cohesive properties of the loess-rich soils (Powell *et al*., 2003).

Most of the relation between bank clay content and cross-sectional form within the anabranching reach did not follow the norm. For example, the correlation between channel cross-sectional width and percentage bank clay content revealed that areas with higher bank clay content were wider than areas with lower percentage bank clay content. This, however, may be due to the fact that, within this reach, percentage bank clay content was high for all the cross sections. This also points to the fact that other variables, such as the removal of vegetation could be having a higher impact on cross-sectional form than just the bank silt content.

Bank shear strength

Within the meandering reach, there was a significant negative correlation between bank shear strength and width (p=0.001), width/depth ratio (p=0.000) and a significant positive relationship with cross-sectional depth (p=0.000). There was no significant correlation between bank strength and cross-sectional area (p=0.256). Correlation of bank shear strength, therefore, followed the same trend as that of percentage bank clay content.

Within the anabranching reach, there was a significant negative relationship between bank shear strength and width (p=0.001), width/depth ratio (p=0.001) and cross-sectional area (p=0.001), a positive correlation with cross-sectional depth (p=0.262), which was not significant. The result showed that bank shear strength (the presence of vegetation) was more important than bank clay content alone in the definition of cross-sectional form within the anabranching reach. Areas with greater bank shear strength had lower width/depth ratios, revealing that areas with reduced vegetation were wider and shallower than areas with vegetation.

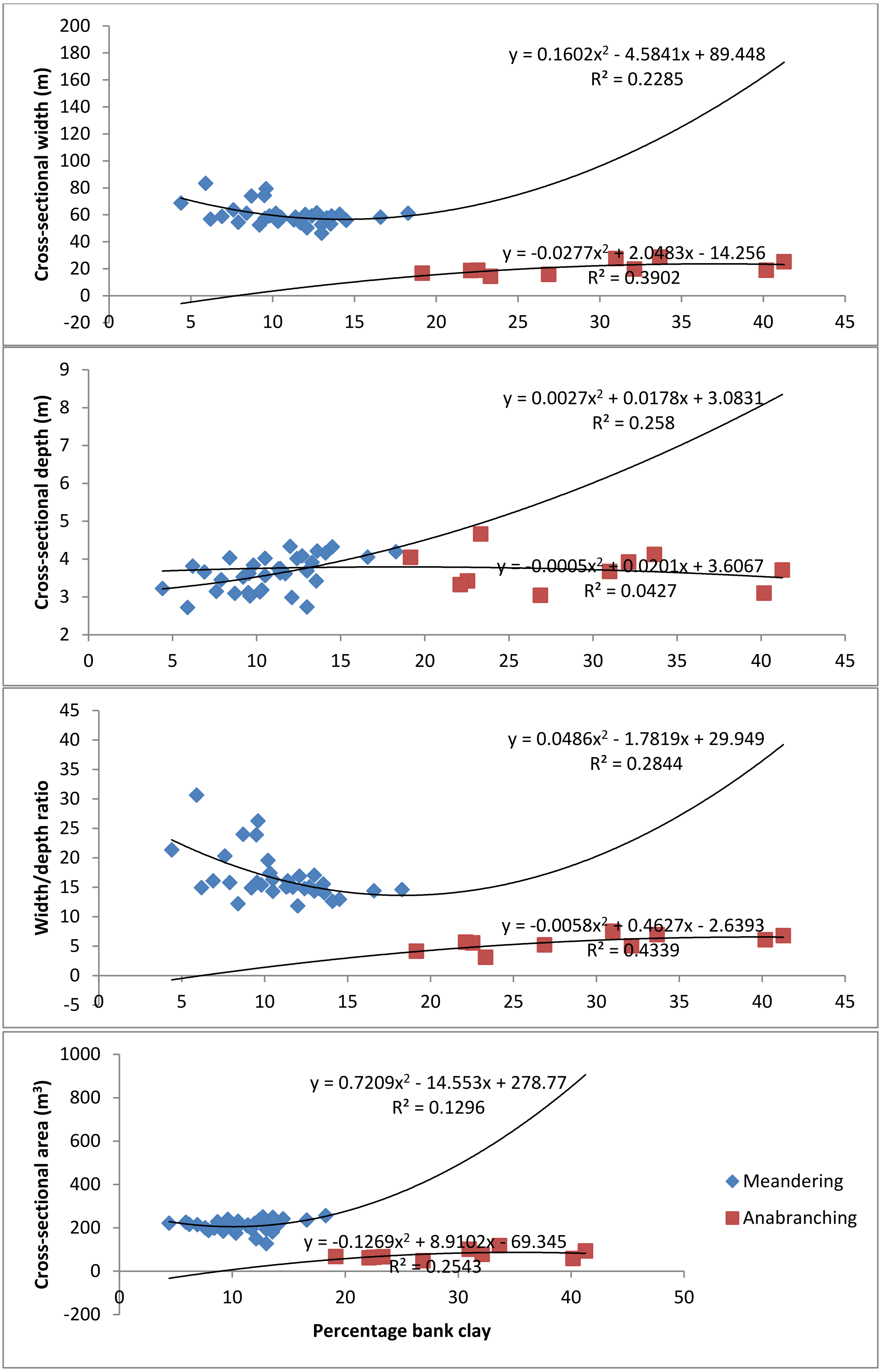


Figure 4.8: Relationship between percentage bank clay and channel form

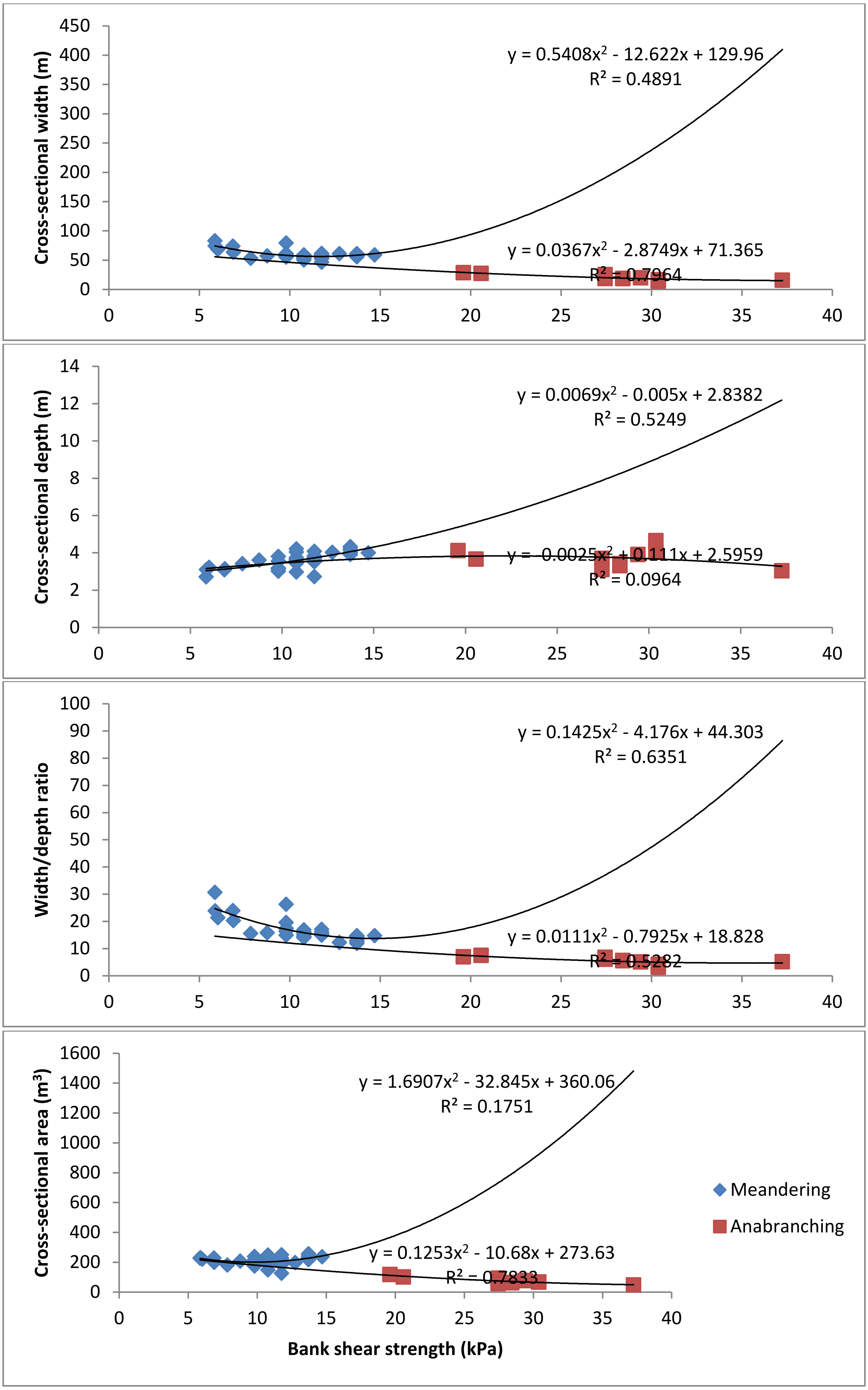


Figure 4.9: Relationship between bank shear strength and channel shape

Bank stability is not only controlled by the silt/clay content but also by the presence and type of vegetation. Stabilising effects of vegetation include root-binding of bank material which increases the tensile strength and elasticity of soils and helps to distribute shear stresses rather like the bars in reinforced concrete or the fibres in a carbon fibre material (Tal *et al.*, 2003).

According to Hickin, (1984), vegetation binds sediment and increases its strength, well-vegetated banks are associated with lower ratios of width to depth than poorly vegetated banks. Numerous studies have shown that bank strength is a very important factor influencing the adjustment of channel geometry and pattern (Wang and Zhang, 1989; Millar and Quick, 1993; Huang and Nanson, 1998; Millar, 2000; Brooks and Brierley, 2002; Eaton and Millar, 2004).

Within anabranching channels, the stabilizing importance of vegetation has been difficult to access. For example, McCarthy *et al.* (1991) showed its importance on the Okavango mega fan, the North Saskatchewan River (Smith, 1976) and the sandy systems of northern and central Australia (Nanson and Knighton, 1996). The stability of islands in anabranching channels of the Amazon basin are attributed by Baker (1978) to rapid plant colonization.

However, anabranching systems with cohesive muddy banks, lined with well-spaced trees that lacked understory or a dense network of roots are found in Channel Country of western Queensland (Nanson and Knighton, 1996). According to Nanson and Knighton (1996), gravel-dominated, laterally active anabranching rivers are probably least aided by bank-stabilizing vegetation because the vegetation root mat does not extend down to and protect the lower parts of the river banks.

4.2.3.3 Bed sediment grain size - cross-sectional form relationship

Changes in the size of sediment supplied to the channel has been shown to be an important factor affecting the cross-sectional forms of channels. The relationship between median bed sediment grain size (d_{50}) and cross-sectional form was analysed.

Table 4.13: Correlation between bed sediment grain size (D_{50}) and cross-sectional form

a. Study Area

		Width	Depth	Area	W/D Ratio
% Bed Material	Pearson Correlation	0.802^{**}	-0.316*	0.704^{**}	0.789^{**}
	Sig. (1-tailed)	0.000	0.018	0.000	0.000
	N	44	44	44	44

b. Meandering Reach

		Width	Depth	Area	W/D Ratio
% Bed Material	Pearson Correlation	0.163	-0.504*	-0.266	0.415^{*}
	Sig. (1-tailed)	0.179	0.001	0.064	0.007
	N	34	34	34	34

c. Anabranching Reach

		Width	Depth	Area	W/D Ratio
% Bed Material	Pearson Correlation	0.370	-0.248	0.220	0.445
	Sig. (1-tailed)	0.146	0.244	0.271	0.099
	N	10	10	10	10

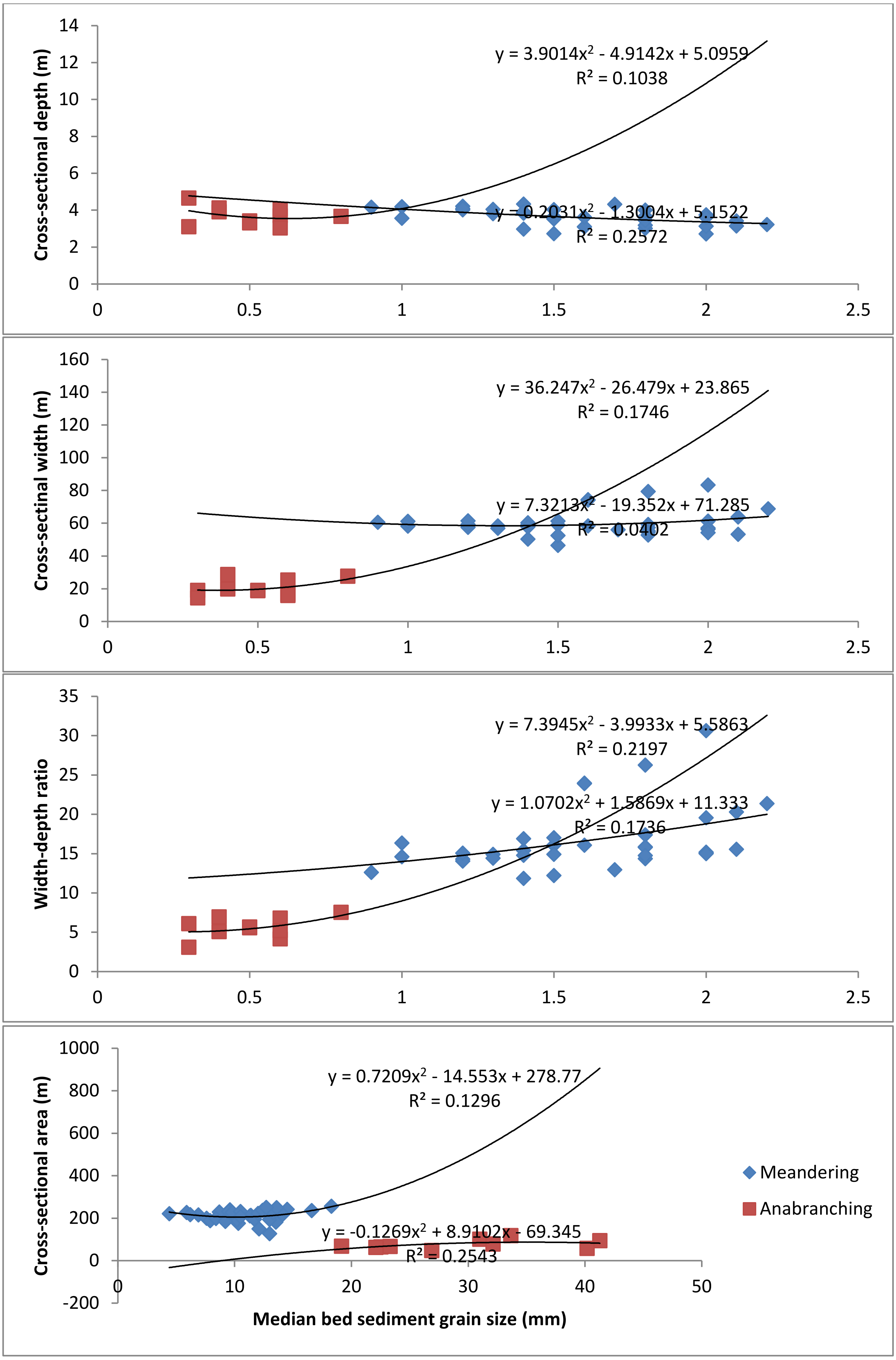


Fig 4.10: Relationship between bed sediment grain size (D_{50}) and cross-sectional form

The results (Table 4.13 and Figure 4.10) revealed a positive correlation between bed sediment grain size and channel width (p=0.179) and a significant negative correlation with cross-sectional depth (p=0.001) within the meandering reach. The median bed sediment grain size and width/depth ratio within this reach was also positive (p=0.007) and significant at the 95% confidence level. The result revealed that within the meandering study reach, cross sections with smaller bed sediment were deeper and narrower than cross sections with larger bed materials.

Within the anabranching reach, bed material grain size also showed a positive correlation with cross-sectional width (p=0.146), a negative correlation with cross-sectional depth (p=0.244) and a positive correlation with width/depth ratio (p=0.099), none of which were statistically significant.

The results revealed a similar trend in the relationship between median bed sediment grain size and channel cross-sectional form within both the meandering and anabranching reaches. Within the meandering and anabranching reaches, cross sections with larger bed sediment grain size were wider than areas with smaller bed sediment grain size. Areas with coarse materials are expected to change actively owing to the erosive action of these sediments. The relationship was also the same for cross-sectional width-depth ratios. It is inferred that there is more active erosion of the channel sides than the channel bed by coarse material transport within the study area. Decreasing width-depth ratio in the downstream direction within the study area may, therefore, be a result of decreased sediment load and/or a fining of grain size.

4.2.3.4 Valley gradient - cross-sectional form relationship

The relationship between valley gradient and cross-sectional shape was also examined within the study area (Table 4.14 and Figure 4.11). The result revealed a significant positive correlation between valley gradient and cross-sectional width (p = 0.000), width/depth ratio (p = 0.000) and cross-sectional area (p = 0.000) and negative correlation between valley gradient and cross-sectional depth (p = 0.051) within the study area.

Table 4.14: Correlation between valley slope and cross-sectional form

a. Study Area

		Width	Depth	Area	W/D Ratio
Slope	Pearson Correlation	0.816**	-0.249	0.727**	0.788**
	Sig. (1-tailed)	0.000	0.051	0.000	0.000
	N	44	44	44	44

b. Meandering Reach

		Width	Depth	Area	W/D Ratio
Slope	Pearson Correlation	0.288*	-0.377*	-0.090	0.404*
	Sig. (1-tailed)	0.049	0.014	0.307	0.009
	N	34	34	34	34

c. Anabranching Reach

		Width	Depth	Area	W/D Ratio
Slope	Pearson Correlation	0.464	0.116	0.438	0.417
	Sig. (1-tailed)	0.088	0.375	0.103	0.115
	N	10	10	10	10

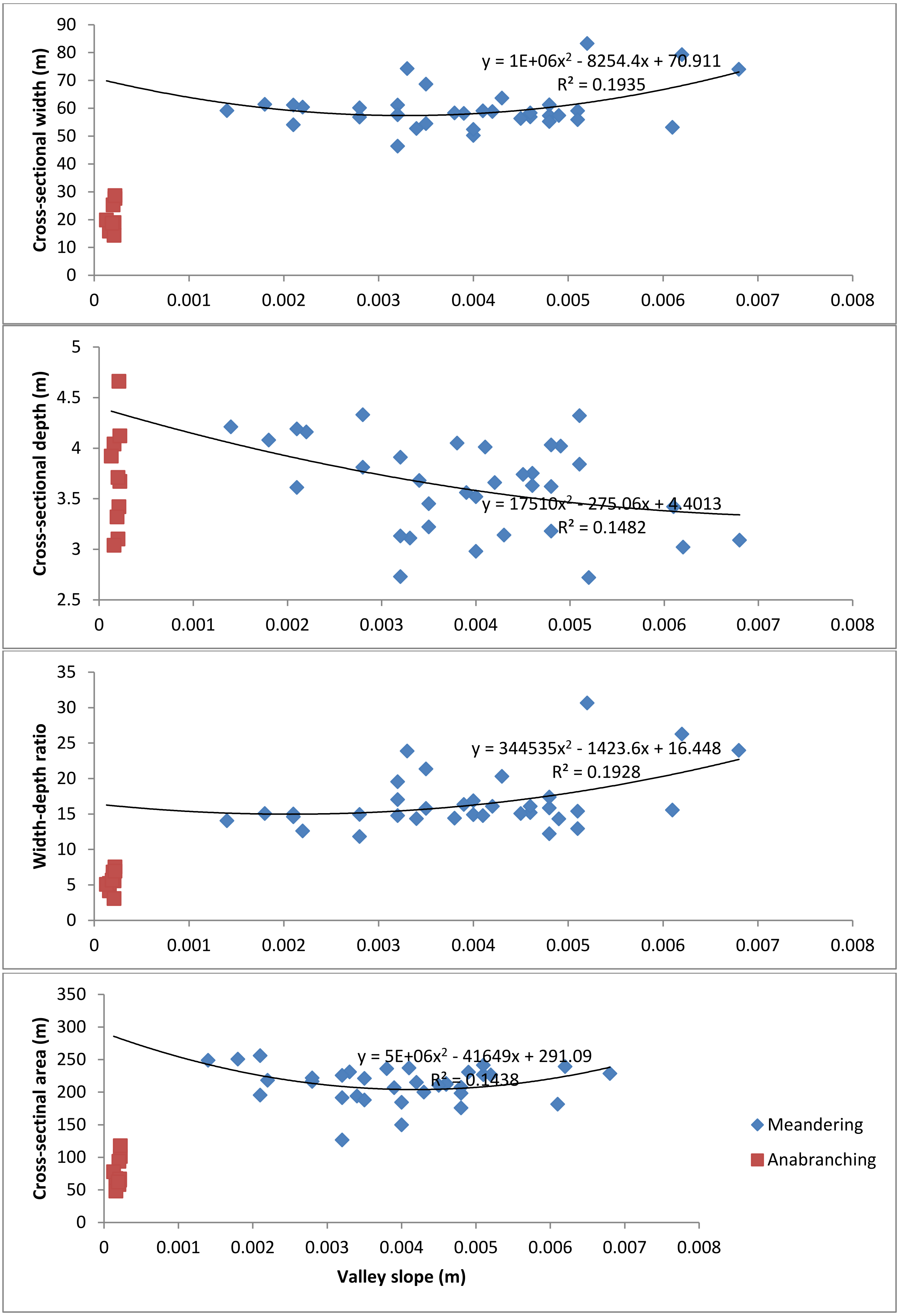


Figure 4.11: Relationship between valley gradient and cross-sectional form

The nature of correlation between valley gradient and cross-sectional shape was different between the meandering and anabranching reaches. Within the meandering reach, there was a significant positive correlation between valley gradient and cross-sectional width (p = 0.049) and width/depth ratio (p = 0.009). The analysis revealed a significant negative correlation with cross-sectional depth (p = 0.014) and cross-sectional area (p = 0.307). Within the anabranching reach there was a positive correlation between valley gradient and all the cross-sectional shape variables as follows: cross-sectional width p = 0.464, depth p = 0.116, p = 0.438 for area and p = 0.417 for the correlation with width/depth ratio.

This result revealed that, within the meandering reach, cross sections with steeper gradients had larger width and width to depth ratios but lesser depth and cross-sectional area. Within the anabranching reach cross sections with steeper gradients had larger width, depth, width/depth ratio as well as cross-sectional area. Steeper gradient is related to higher stream power which may lead to greater erosive capacities for a given discharge. Therefore cross sections with steeper gradients will be more susceptible to erosion and, therefore, widening and deepening than cross sections with lesser gradient.

Channel morphology has been shown to be related to several factors within the drainage basin. For this study, factors including discharge, bank strength, bed material and valley gradient were analysed to determine which were related to the channel morphology. The study revealed the importance of all these factors in the plan form observed within the alluvial section of River Osun, as they were significantly different within the meandering and anabranching reaches. Therefore, within the alluvial section of River Osun, change from a meandering to an anabranching plan form could be related to all these factors.

The range of channel morphologies found in Pacific Northwest landscapes can be related qualitatively to watershed conditions of streamflow, sediment supply, valley gradient, and channel confinement. According to Buffington *et al.* (2001), greater valley slope and channel confinement create channels with steeper bed slopes, larger particle sizes, and lower width-to-depth ratios, giving rise to systematic changes in channel morphology, for example, changes in alluvial channel type from dune-ripple through cascade morphologies.

4.2.4 Controls of channel plan form within the study area

Interactions among a set of continuous variables produce variations in channel pattern, suggesting a continuum of patterns. Channel pattern continuum has been used to account for changes in channel plan form within rivers. Geomorphologists have developed significant insight into controls upon channel cross-sectional form types and patterns (for example, Leopold and Wolman, 1957; Schumm, 1968; 1985; Berg, 1995; Eaton *et al.,* 2010). Initially, differentiation of braided, meandering and straight rivers was framed in relation to discriminant analysis of channel slope and bankfull discharge (Leopold and Wolman, 1957). Subsequent analyses highlighted the importance of bed material size and bank strength as determinants of channel geometry and pattern (Henderson, 1961; Carson, 1984; Eaton *et al.*, 2004; 2007; 2010). Some studies concluded that low gradients and fine grain sizes are necessary conditions for anastomosis (Makaske, 2001).

In this study, the importance of these variables in explaining channel plan form change within the alluvial section of River Osun from meandering to anabranching was explored. In order to establish the factors controlling plan form change the study hypothesis, which states that change in channel plan form within the study area is due to increased discharge (Q), reduced slope (S) and increased bank strength (Bs) was tested with the aid of regression analysis (multiple regression). The predictors of channel plan form used in the analysis included discharge (Q), mean bed material grain size (d_{50}) (Bm), percentage bank clay content (Bc), bank shear strength (Bs), valley gradient (S) and valley width (Vw).

The regression model was run and the coefficient of determination was computed (R^2; the square of the correlation coefficient). A value of 1.0 indicates that the model predicts 100% of the variability of the dependent values by variability of the independent variables, and there is nothing left unexplained.

Table 4.15: Regression of plan form control variables

Regression Model:

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.958[a]	0.918	0.907	0.129

a Predictors: (Constant), Discharge, Bank Clay, Bank Shear, Valley Slope, Valley Width

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	7.09	5	1.42	85.05	0.000[a]
	Residual	0.63	38	0.02		
	Total	7.73	43			

a. Predictors: (Constant), Discharge, Bank Clay, Bank Shear, Valley Slope, Valley Width

Table 4.16: Regression analysis between pattern and plan form control variables

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	1.180	0.501		2.354	0.024
	Discharge	0.001	0.000	0.213	2.198	0.034
	Bank Clay	0.014	0.004	0.300	3.545	0.001
	Bank shear Strength	0.032	0.007	0.595	4.769	0.000
	Slope	-25.79	22.34	-0.118	-1.154	0.256
	Valley Width	-0.349	0.196	-0.213	-1.783	0.083

a. Dependent Variable: Channel Pattern

Excluded variables[d]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics
						Tolerance
2	Bed Material	0.011[a]	0.091	0.928	0.015	0.159

b. Predictors in the Model: (Constant), Discharge, Bank Clay, Bank Strength, Valley slope, Valley Width.

Table 4.17: Regression analysis between cross-sectional form and plan form control variables

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.901[a]	0.812	0.782	2.796

a Predictors: (Constant), Discharge, Bank Clay, Bank Shear, Bed sediments, Valley Slope, Valley Width

		Unstandardized Coefficients		Standardized Coefficients		
Model		B	Std. Error	Beta	t	Sig.
1	(Constant)	8.01	5.557		2.354	0.024
	Discharge	0.21	0.010	0.344	2.159	0.037
	Bank Clay	0.043	0.089	-0.064	-0.480	0.634
	Bank Strength	0.683	0.185	-0.905	-3.685	0.001
	Bed Sediments	3.039	1.754	0,285	1.733	0.091
	Slope	966.01	448.429	0.314	2.154	0.038
	Valley Width	0.008	0.006	0.308	1.283	0.204

a. Dependent Variable: Width/depth Ratio

In the prediction of channel pattern, when all variables were entered, the model gave an adjusted R^2 value of 0.905. When five of the variables, excluding bed sediment grain size, was used in the model, an adjusted $R^2 = 0.907$ was obtained, as shown in Table 4.14. Bed sediment grain size was, therefore, excluded from the model, since prediction was improved by its exclusion.

The result of the regression analysis showed an R^2 value of 0.918, revealing that the model was able to predict about 92% of the variability of the dependent variable (pattern) by variability of the independent variables. The analysis of variance table showed a P value of 0.000, implying that the model was significant at the 99% confidence level.

The regression equation of the relationship found between plan form control variables (x) and channel pattern (y), as shown in Tables 4.15 and 4.16 is given as:

$$\mathbf{y = 1.18 + 0.21Q + 0.3\,Bc + 0.60Bs - 0.12S - 0.21Vw + e} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \mathbf{4.7}$$

Multiple regression analysis tested the hypothesis of no predictive value for each of the independent variables. In the prediction of channel pattern, the significance level for each of the control factor was determined.

For the model, the bankfull discharge showed a value of $p=0.034$, indicating that the hypothesis of predictive value was accepted, since at the 95% confidence level, bankfull discharge explained the change in plan form within the study section. The bank clay percentage and bank shear strength showed values of $p=0.001$ and $p=0.000$ indicated that the hypothesis of prediction was strongly accepted. The valley width showed a value of $p=0.083$ and was significant at the 92% level, which was outside the level of 95% for this study. Thus the hypothesis of predictive value was rejected. The valley slope showed a value of $p=0.256$ and, therefore, had no predictive value and so the hypothesis was rejected.

The result obtained revealed that, although all the analysed factors of plan form change were significantly different in both reaches at the 95% confidence level, as shown in section 5.3. The regression analysis, however, indicated that only discharge and bank strength factors were significant in the explanation of the different patterns observed within the study area.

The result of this study, when compared to other studies, revealed that factors of channel pattern change differ for different streams and within different environments. For example, Fotherby (2008) found that stream power (flow and slope) and sediment grain size explained the river pattern of the main channel in two of the eleven divisions of the central Platte River. The study, however, found that valley confinement was the most dominant factor controlling the occurrence of fully braided river in nine of the eleven divisions of the stream, thereby adding valley confinement to the conceptual model of the continuum of channel pattern. Tal and Paola (2007) argue that transitions between channel patterns depend on the mean grain size of the sediment load, the channel-forming discharge, and valley slope.

In the prediction of channel cross-sectional form as best described by the width/depth ratio, the regression equation of the relationship found between the plan form control variables (x) and w/d ratio (y) is shown in Table 4.17 and is given as:

$$\mathbf{y = 8.01 + 0.34Q - 0.06Bc - 0.91Bs + 0.29Bm + 0.31S + 0.31Vw + e \quad \ldots\ldots\ldots\ldots\ldots\ldots 4.8}$$

Multiple regression analysis also tested the hypothesis of no predictive value for each of the independent variables as related to cross-sectional form. In the prediction of channel cross-sectional form, the significance level for each of the control factor was also determined.

For the model, the bankfull discharge showed a value of $p=0.037$, bank shear strength showed a value of $p=0.001$ and valley slope showed a value of $p=0.038$ indicating that the hypothesis of predictive value was accepted, since at the 95% confidence level, these variables explained the change in cross-sectional form within the study section. The percentage of clay in bank materials showed a value of $p=0.634$, bed sediment size showed a value of $p=0.091$, while valley width showed a value of $p=0.204$. These values were not significant at the 95% confidence level and so the hypotheses of predictive value were rejected.

Identifying channel continuum factors advances our understanding of river response to changed conditions and can improve our predictive capabilities for the outcomes of management options. The influence of discharge, bank material strength, bed material size, valley gradient and valley width on channel plan form was tested on the alluvial section of Osun River. Neither median bed material sediment size nor valley gradient or valley width significantly influenced the change in channel plan form. Bankfull discharge and bank strength as well as valley slope were the main influence on plan form within the study area. The results of this investigation identified three expected controls and limited the other potential controls on channel plan form.

CHAPTER FIVE

TEMPORAL CHANGES IN CHANNEL PLAN FORM

5.0 Introduction

Temporal changes in plan form parameters within the study area were analysed with the aid of a Geographic Information System (GIS). Images for five years' period - 1963, 1984, 2005 and 2012 - were digitized and the rate and direction of change in plan form variables were calculated. The results are discussed below.

5.1. Temporal changes in channel sinuosity

The analysis of temporal changes in channel sinuosity for the two study reaches revealed variations. There were observed changes in the sinuosity of the meandering reach, where sinuosity showed an overall significant increase of 6.14% for the 49 years' study period at p=0.005 or 99% confidence level, as shown in Table 5.1 as well as Figure 5.1.

The meandering reach showed an increase in channel sinuosity of 5.14% between 1963 and 1984. Sinuosity increased again between 1984 and 2005 by 1.17%; while sinuosity was relatively stable between 2005 and 2012, as shown in Table 5.1 Sinuosity of a river increases or decreases to adjust channel gradient, which may then increase or decrease flow velocity. This is used as a mechanism to dissipate excess energy. Also, sinuosity increases frictional resistance to flow as a function of the sediment load characteristics (Richards, 1982).

Sinuosity trend was calculated for the main anabranch within the anabranching reach and the result shows that sinuosity was 1.10 in 1963 and 1.11 in 2012. This revealed a mere 0.90 % change in sinuosity within the 49 years' study period. The sinuosity for the secondary anabranches ranged between 1.02 and 1.21.

Sinuosity of both tropical and temperate rivers have been demonstrated to change over time. For example, Catherine Creek in north-eastern Oregon experienced a sinuosity change of 6% from 1979 to 1998 (Laliberte, 2001). In England, sinuosity changes of 18% were measured in the River Culm, 16% in the River Creedy, 20% in the River Otter, and 28% in the River Yarty from 1903 to 1953 (Hooke, 1977). The sinuosity of the Rio Grande de Añasco (humid tropical) showed an overall increase of 13% for the 33 years' study period (Alvarez, 2005).

Table 5.1: Temporal changes in channel sinuosity

Year	Valley length (m)	Channel length (m)	Sinuosity ratio	Percentage change	Significance
Meandering Reach					
1984	15.30	23.26	1.52	5.14	P=0.338
2005	15.30	23.41	1.53	1.17	
2012	15.30	23.56	1.54	0.52	
1963-2012				6.14	P=0.005**
Anabranching Reach					
1963	4.50	4.95	1.10		P=0.051
2005	4.50	5.00	1.11	0.01	
2012	4.50	5.00	1.11		
1963-2012				0.01	P=0.051

****Test significant at 99% confidence level** **Source: Authors Analysis**

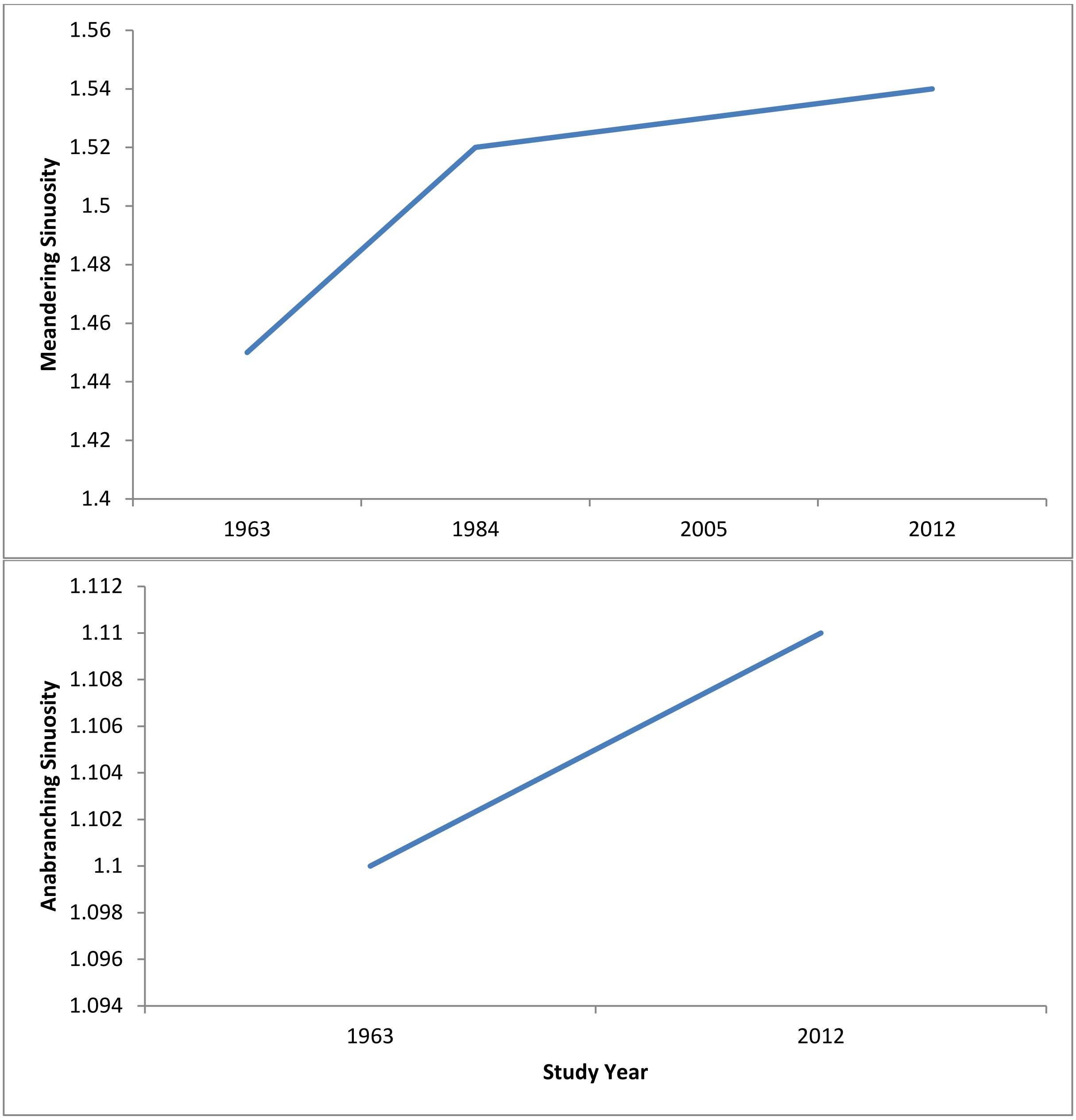


Figure 5.1: Sinuosity within meandering and anabranching reaches

Changes in channel sinuosity has been attributed to several factors, Schumm (1962) relates changes in stream sinuosity of alluvial rivers in the Great Plains, USA, to response to changes in the proportions of bed load and suspended load. Sinuosity changes were found by Timar (2003) to correlate with discharge and sediment load changes at the inflow of tributaries, as well as with active deformation areas, like differential subsidence and wrench fault zones in the Tisza river in Hungary. Hooke (1977) observed changes in the sinuosity of River Culm, which could only be attributed to human interference with the channel.

Within the Osun basin, there has been no drastic change in climatic variables, such as precipitation, but human interference, which includes damming of the stream channel and land clearance for agricultural development are the most likely cause of change in the channel sinuosity. Damming of a river channel has been known to lead to active down-cutting of channel downstream of the dam, and this could be the processes that led to the sharp increase in channel sinuosity by 1984 after the construction of the Asejire Dam.

5.2 Temporal changes in channel width

From the 34 width measurements taken for the meandering reach (see Appendix 3), the mean stream channel width for 1963 was 62.05m, while that of 2012 was 49.83m. Overall, there was a mean decrease in channel width of 12.22m at a rate of 0.26m/yr. between the study years. This result showed that there was a decrease of 19.69% of the original stream channel width within the 49 years' time interval. Table 5.2 shows that this decrease in stream channel width was statistically significant at P = 0.000. The result of the analysis of channel width within the anabranching reach showed that the mean channel width was about 22.65m in 1963 and reduced to about 21.40m in 2012. This implied a reduction of about 5.29% of the 1963 width of the main anabranch channel.

5.2: Paired sample one-tailed t-test results of mean channel width for study reaches

Samples	Sample size	Value (metres)	Significance
Meandering Reach			
Mean Channel width 1963	34	62	P=0.000**
Mean Channel width 1984	34	65	
Mean Channel width 1984	34	65	P=0.000**
Mean Channel width 2005	34	51	
Mean Channel width 2005	34	51	P=0.118
Mean Channel width 2012	34	50	
Mean Channel width 1963	34	62	P=0.000**
Mean Channel width 2012	34	52	
Anabranching Reach			
Mean Channel width 1963	10	22.7	P=0.166
Mean Channel width 2012	10	21.4	

****Test significant at 99% confidence level** **Source: Authors Analysis**

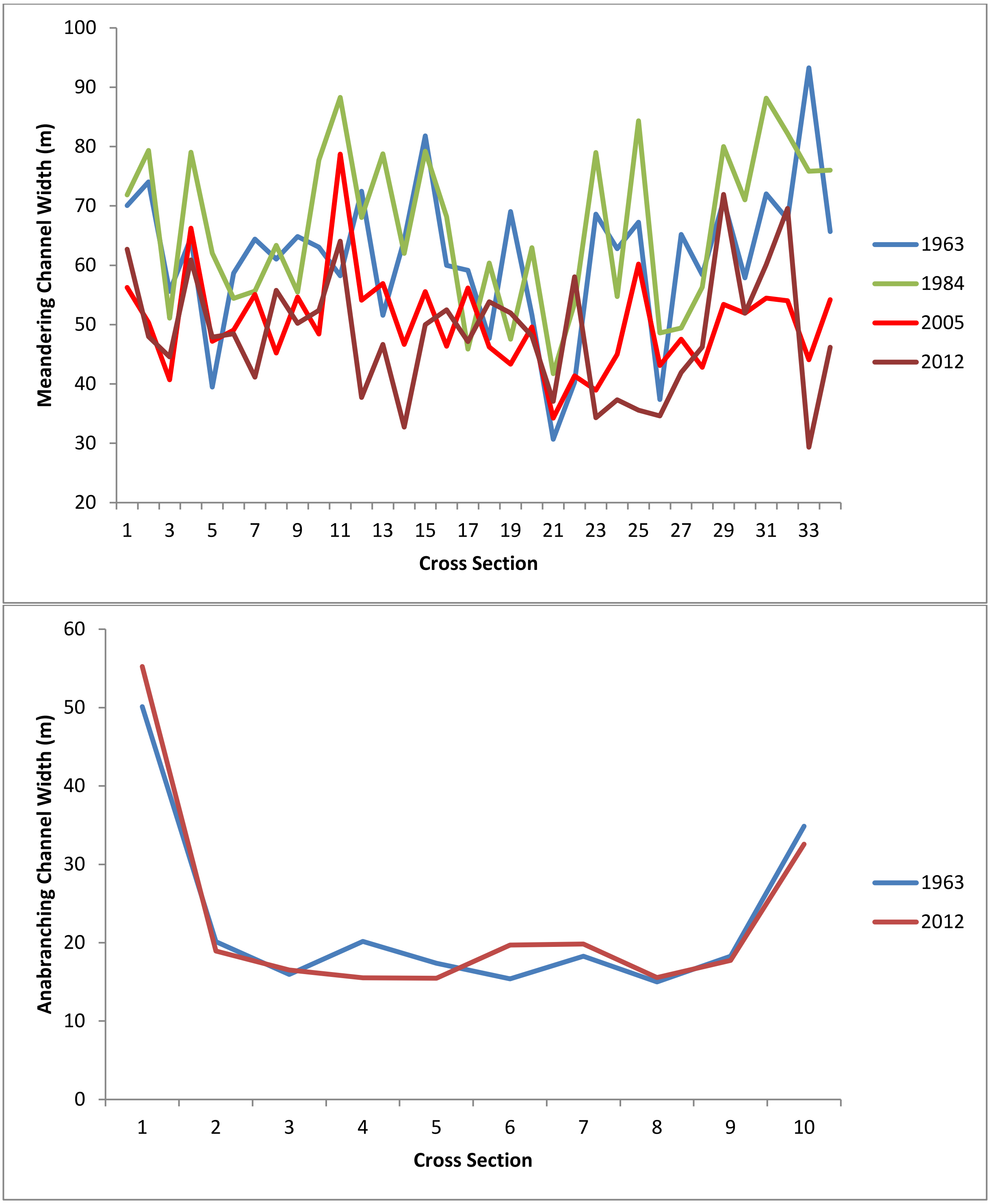


Figure 5.2: Temporal changes in channel width within the meandering and anabranching study reaches

Comparisons were made on the images of the study area to determine if change was a regular occurrence in the Osun River channel in the different time periods. The statistical results and graphs (Table 5.2 and Figure 5.2) indicated that changes in the channel width over the forty-nine years' study period were variable. The results from the measurement of channel width showed that channel width is one major variable that changed in the meandering reach within the study years, with first a general increase in width, which was followed by a reduction.

Eschner *et al*. (1981), Peake *et al*. (1985), Currier *et al.* (1985), Sidle *et al*. (1989) and Williams (1978) all showed a substantial narrowing in the historically un-vegetated central Platte River channel (Nebraska, U.S.A) in the twentieth century. Narrowing of channel width was also observed within the middle reach of Rio Grande, New Mexico, U.S.A (the Bosque Hydrology Group, 2009). Channel width narrowed by about 5% along the Green River in Utah, U.S.A between about 1930 and 1940, while channel width was stable in the 1940s and 1950s, further narrowing by an additional 14% occurred after 1959 (Allred and Schmidt, 1999).

Reduction in stream channel width can occur as a result of deposition of materials within the stream channel which could result from reduced flood flow (Kondolf and Wilcock, 1996) or other activities within the drainage basin. Change in the flow regime of a stream is an important factor in channel narrowing, for example within the Green River, Utah, channel narrowing occurred when the magnitude of two-year flood, mean annual discharge, and effective discharge decreased, respectively, by about 30%, 28%, and 37% (Allred and Schmidt, 1999).

Vegetation has the impact of reducing channel width. For example, the colonization of exposed bars especially as a result of low flows leads to reduction in channel width. Plant stems promote sediment deposition by decreasing flow velocity. Plant roots promote sediment stability by increasing bank resistance to failure (Thorne, 1990) and the shear stress necessary to mobilize sediment (Smith, 1976). Both effects promote channel narrowing (Wolman and Gerson, 1978; Andrews, 1984). Channel width reduction within the Central Platte River (USA) was attributed to flow reduction ensuing from reservoir construction and water storage in the North Platte and South Platte systems (Murphy *et al.*, 2004). The reduction in width of Middle Rio Grande was related to reservoir installation, arroyo dams, bank stabilization, and non-native vegetation, which all contributed to starvation of sediment within the reach.

In the study of channel width change within the anabranching reach, width of the main anabranch channel was used. This method has been used in most studies of width change in anabranching streams, for example Burge (2005). The result as shown above revealed a reduction in channel width within this reach.

This reduction in channel width of the anabranch was consistent with the general reduction in channel width that was experienced within this alluvial section of the Osun River during the study period. The results revealed that channel width for the two study years were rather similar. Within the anabranches of the central Platte River in Australia channel, there was also an observed decrease in main anabranch width between 1858 and 2006. Average change in width was about 59% and was attributed to the encroachment of vegetation along the margins of the channels and subsequent lateral accretion (Horn *et al.*, 2012).

A decrease in the width of the main anabranch does not necessarily indicate a reduction in the width of all the anabranches within a channel reach. This is because preferential flow orientation down one of the channels may lead to a reduction in flow in the others or the complete abandoning of an entire or part of an anabranch. Within the Osun channel, it was observed that blockage of the channel by tree branches and water weeds during periods of low flow leads to a slow abandonment of anabranches.

5.3 Temporal changes in channel surface area

Changes in channel surface area were also calculated for the different study periods within the anabranching and meandering reaches. The results showed that, during the forty-nine years' study period channel surface area within the meandering reach reduced by about 311m^2. Channel surface area was 2,313m^2 in 1963 and reduced to 2,002m^2 in 2012. This indicated a 36.19% reduction in the stream surface area over the study period within the meandering reach, as shown in Table 5.3.

Table 5.3: Temporal changes in channel surface area

Reach	Area(km^2)	Area Change (m^2)	Change/yr.(m^2)	Significance
Meandering				
1963	2.440			
1984	2.618	178	14.83	0.001
1984	2.618			
2005	1.964	-654	-31.14	0.000
2005	1.964			
2012	2.002	38	5.43	0.000
1963	2.313			
2012	2.002	-31	-0.63	0.001
Anabranching				
1963	0.160			
2005	0.226	66	1.57	0.000
2005	0.226			
2012	0.252	26	3.71	0.380
1963	0.160			
2012	0.252	92	1.88	0.000

Stream channel surface area was about 2.313km^2 in 1963. This increased by an area of about 305m to 2.618km^2 in 1984. This increase in the stream channel surface area was at the rate of 11.87m^2/yr., while the cross-sectional areas increased at the rate of about 0.0048m^2/yr. During the period between 1963 and 2005, surface area decreased from about 2.618km^2 to about 1.964km^2 in 2005. This decrease was at the rate of about 31.14m^2/yr., while stream cross-sectional area reduced at an average rate of about 0.0118m^2/yr. There was, however, an observed increase in channel area during the last study period, between 2005 and 2012, where the channel area increased from its initial value of 1.964km^2 in 2005 by about 38m^2 to a final channel surface area of 2.002km^2 by 2012. This increase in channel area was at the rate of 7.6m^2/yr. while the cross-sectional area increased at a rate of about 0.0038m^2/yr.

Within the anabranching reach, the channel surface area of the main anabranch was 0.16km^2 in 1963 and decreased to about 0.101km^2 in 2005 but later increased by to 0.108km^2 in 2012. Within the entire anabranching reach, the surface area of the channels increased from 0.226km^2 to 0.250km^2 in 2005 and then to 0.252km^2 in 2012. The increase in the surface area of the anabranching reach could be related to the increase in the number of anabranching channels between 1963 and 2012. This increase in channel surface area within this reach was significant at the 95% alpha level.

5.4 Temporal changes in channel course

Image analysis of the study area showed that within the meandering reach, the channel migrated by an area of 30356.48m^2 within the 49 years' study period. This translated to a lateral migration rate of 0.84m/yr. The results further revealed that the lateral migration of the river channel was variable for the study reach among the four study images (Figures 5.4 - 5.7). The lateral migration rate was highest for the study reach between 2005 and 2012, with average rate of 1.7m/yr.; and was lowest between 1984 and 2005 at about 0.52m/yr. This analysis showed that rates of channel migration were varied for the different study years (see Appendix 3 and Table 5.4) within the meandering reach.

Channel migration was also calculated for the anabranching reach along the main anabranch. The analysis of the images showed very low rates of channel migration (0.02m/yr.) along the main anabranch within the study period, as shown in Figures 5.8 - 5.10. Channel migration was highest for the study reach between 2005 and 2012 at the rate of 0.13m/yr. but was virtually non-existent in the period between 1963 and 2005 (0.002m/yr.).

Table 5.4: Rates of lateral migration within the study reaches

	Period	Right (m^2/yr.)	Left (m^2/yr.)	Total (m^2/yr.)	Rate (m/yr.)
Meandering					
	1963-1984	23884.04	23404.57	47288.62	1.32
	1984-2005	12357.13	6358.95	18716.05	0.52
	2005-2012	41666.47	19339.39	61005.86	1.70
	1963-2012	15534.12	14822.36	30356.48	0.84
Anabranching					
	1963-2005	9.33	2.43	11.76	0.002
	2005-2012	501.71	123.86	625.57	0.13
	1963-2012	69.84	18.42	88.26	0.02
Difference	1963-2012				P=0.000

Source: Author’s Analysis

The rate of lateral migration was significantly lower within the anabranching channel reach compared to the meandering reach (p=0.000). Schumann (1989) observes that high bank-stability and low flow-strength hinder lateral migration in anabranching stream systems. The lateral channel stability within this reach is consistent with the scarcity of point bars or eroding banks. The results of the analysis are presented in Table 5.4 as well as Appendix 3.

Meandering rivers shift their position primarily by extension, translation, rotation or enlargement of meanders (Hooke, 1977). Within the study area, temporal changes in channel course through lateral migration were studied using the method of Mossa and Coley (2004). The result revealed the rate of migration within the study stream is higher than rates found in most temperate rivers. For instance, Brooks *et al.* (2004) studied migration rates in Thurra and Cann rivers in SE Australia and found rates of 0.000253, 0.000077, 0.000295 and 0.045m/yr. However in the UK, some medium-sized meandering rivers have been reported to have migrated across more than 50% of the flood plain in less than 200 years (Nanson and Hickin, 1983). Hooke (1980) also documented migration rates for temperate rivers to range from less than 0.1 m per year to more than 7.26 m per year (Nanson and Hickin, 1983). In other words, high variability and distribution of channel migration rates have been documented for temperate rivers.

Alvarez (2005) calculated mean meander migration rate for the Rio Grande de Añasco, (a humid tropical stream) to be 2.64m per year between 1966 and 1999. In contrast, some meandering channels appear to be static, with little or no changes in plan form over a few hundred years or more. This showed that, although the meandering reach of the alluvial section of River Osun has not been static, migration rates were, however, low for the study period.

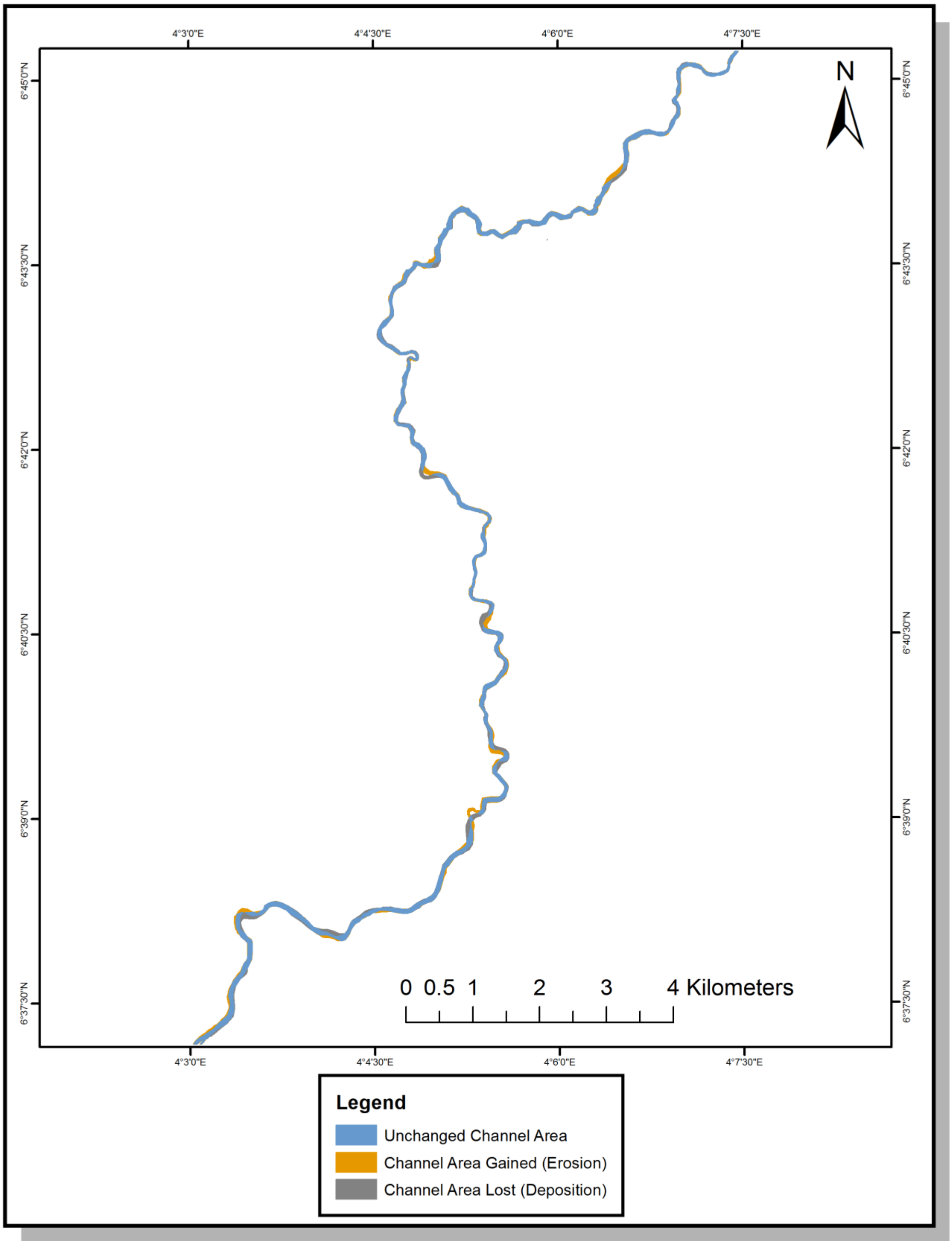


Figure 5.3: Osun River channel between 1963 and 1984 showing areas of channel migration within the meandering reach

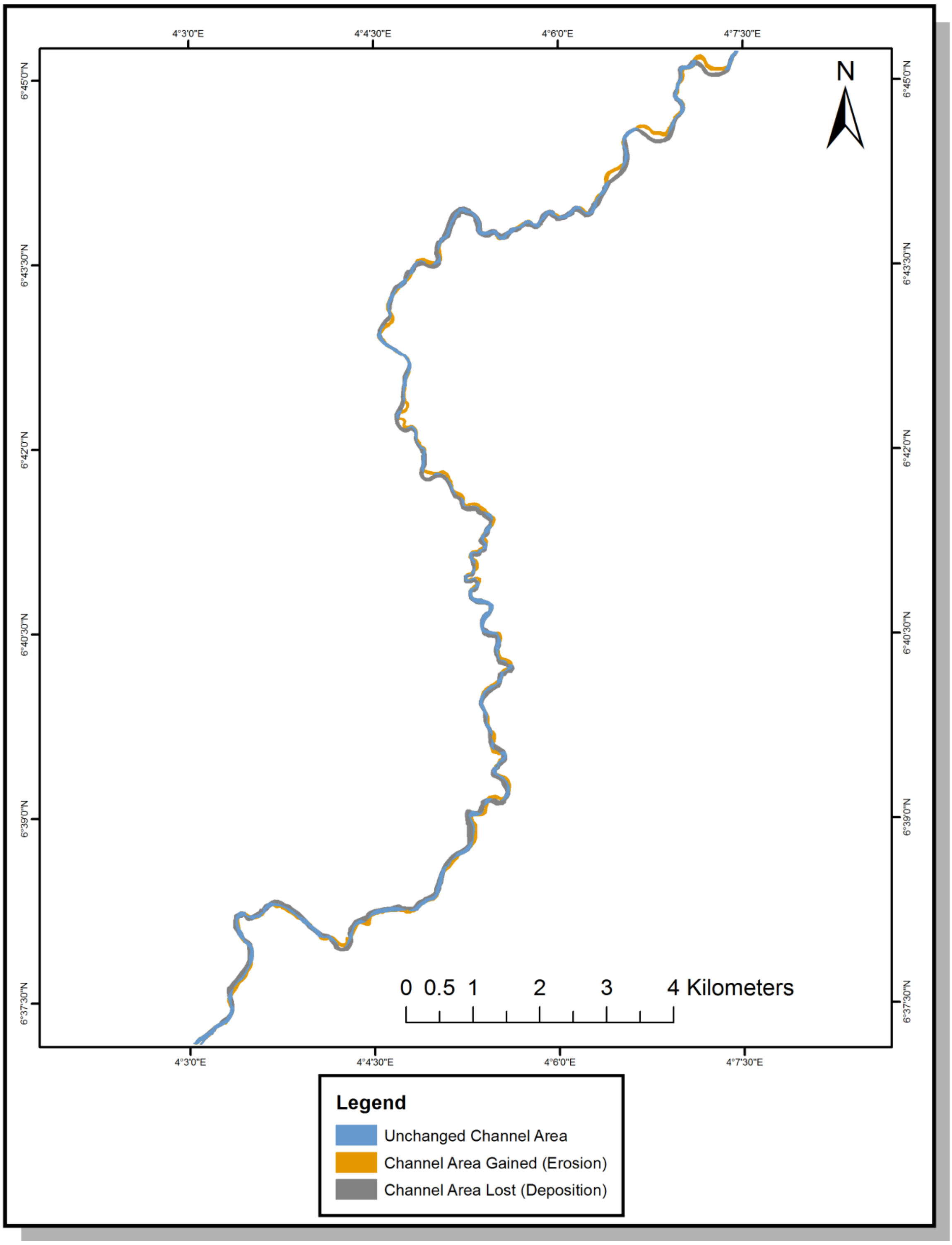


Figure 5.4: Osun River channel between 1984 and 2005 showing areas of channel migration within the meandering reach

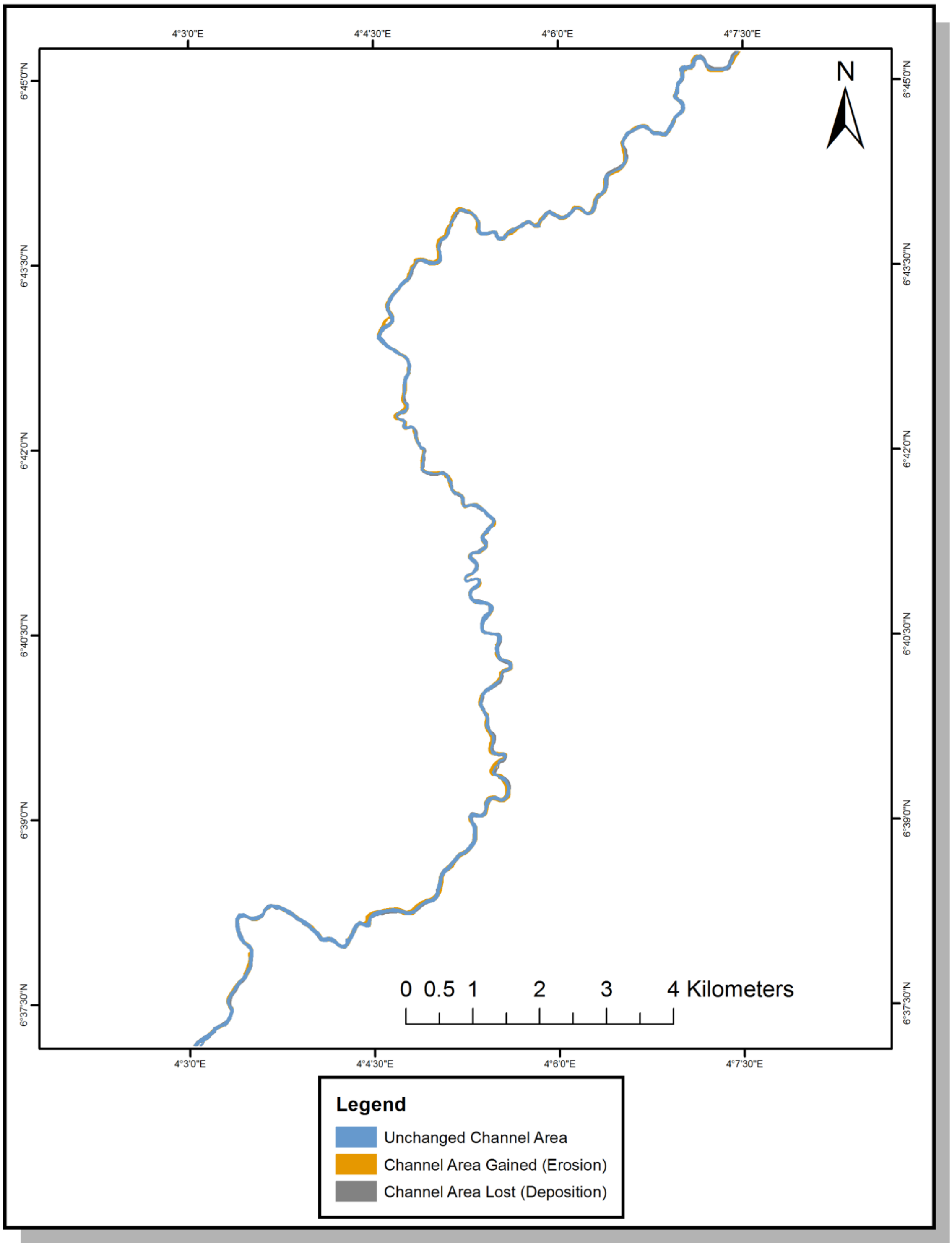


Figure 5.5: Osun River channel between 2005 and 2012 showing areas of channel migration within the meandering reach

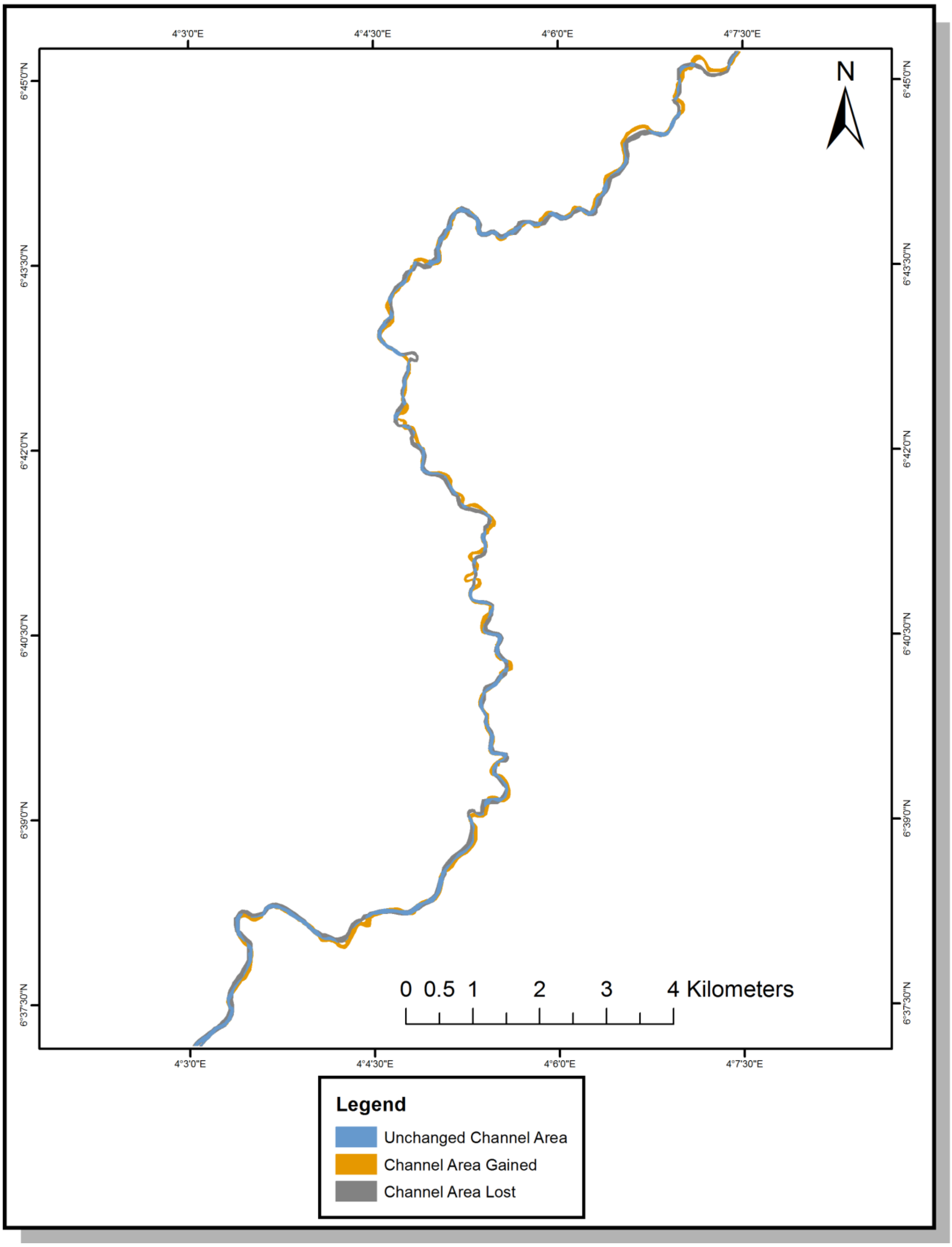


Figure 5.6: Osun River channel between 1963 and 2012 showing areas of channel migration within the meandering reach

High variability in channel migration results from differences in bank erosion rates, which occur for several reasons. Some of these are the variability of the magnitude-frequency of discharge events, increase in urbanization, and changes in agricultural practices and drainage (Hooke, 1980). Within the study area, it was observed that there was large-scale reduction in vegetation cover within the channel bank and flood plain, as a result of conversion of forest areas into farmlands (1984 image), which might have led to an increase in bank erosion (see Plates 5.1 and 5.2), leading to increased migration. This was consistent with the results of the analysis of lateral migration rates, as results showed an increase in channel migration within this study period (from 0.69m/yr. to 1.32m/yr.). Another important factor of stream bank erosion within the meandering reach of the study area is sand mining. This activity destabilizes the channel banks, thereby increasing its susceptibility to erosion.

It was also observed that the stream channel was dammed some kilometres upstream from the study area in 1972 (the Asejire Dam) and subsequently the Erinle (1990) and Ejigbo (2010) dams were constructed on the Osun river. Dams have been observed to stabilize stream channels, thereby reducing lateral migration (Shields *et al.*, 2000). This is the best explanation for the observed reduction in lateral migration observed within the Osun River channel within the other study periods.

Lords *et al*. (2009) note that lateral migration is not necessarily an indicator of channel instability, as most naturally meandering streams have channel that migrate laterally, but that they merely reflect how the stream operates in a condition of equilibrium. However, the rates of lateral migration may increase or decrease significantly in response to a stressor, such as increased storm flow discharges as a result of altered hydrology or weakening of channel banks due to removal of riparian vegetation (Lords *et al.*, 2009). Within the meandering reach of River Osun, migration is seen to have reduced significantly and almost stabilized between 1984 and 2005 in most of the stream course, with the exception of areas that are affected by human activities. This reduction in lateral migration along this reach most probably could be explained as resulting from a change in hydrology occasioned by the dam constructed along the stream channel.

Plate 5.1: Cut bank of the meandering reach close to Telewi village

Plate 5.2: Vegetation destruction occasioned by bank erosion

The lateral stability of the individual anabranch/anastomosing channels has been pointed out in many studies (Smith, 1976; 1983; 1986; Smith and Smith, 1980; Rust, 1981; Nanson *et al.*, 1986). Stable anabranch channels have been observed to be related to gentle gradients as well as high amounts of silt, clay, and vegetation in the banks (Smith and Putnam, 1980). These conditions were obvious within the anabranch reach of River Osun. Although channels were stable within this reach, there was an increase in the number of anabranches over time. This could be related to the process of anabranch formation through channel avulsion.

Channel avulsion (the relatively sudden and major shift in the position of a channel to a new part of the flood plain or the sudden reoccupation of an old channel on the flood plain) has been described as the dominant form of lateral channel displacement in anabranching/anastomosing stream systems (Smith, 1976; Harwood and Brown, 1993). The overview of avulsion causes by Jones and Schumm (1999) describes triggers as short-term events that abruptly modify channel capacities by changing bed geometry, discharge, or other factors. Trigger events are most commonly floods, but could also be processes as varied as abrupt tectonic movements, ice jams, log dams; vegetative blockages, debris dam, beaver dams, hippopotami trails, or other bank failures and downstream migration of bars that temporarily block the throat of a branch (Stanistreet *et al.*, 1993; Jones and Schumm, 1999; Mohrig, 2000; Slingerland and Smith, 2004). This study area of the Osun system experience large-scale floods on a yearly basis. For about two months of the year, between July and September, some parts of the flood plain are covered by flood waters and could lead to avulsions.

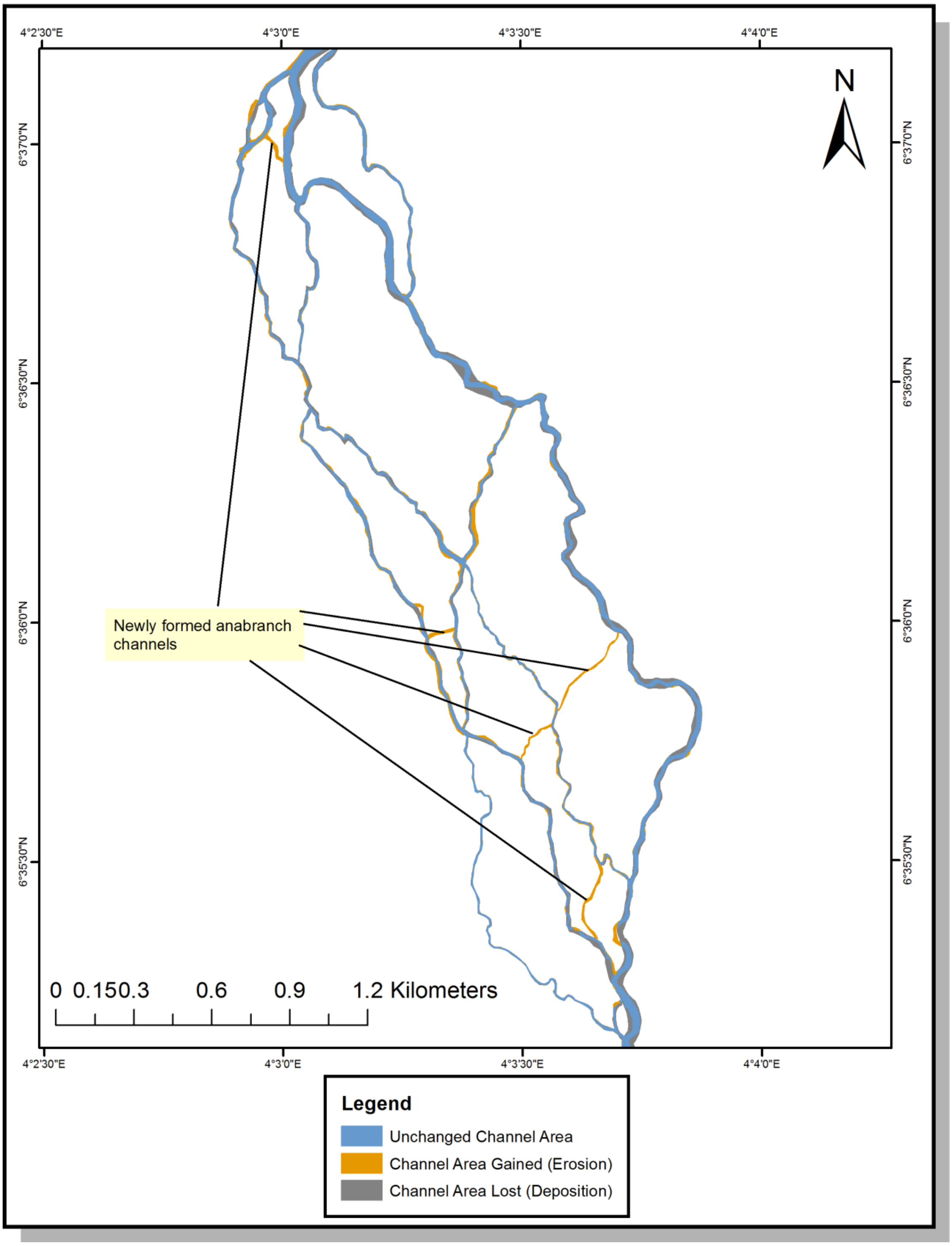


Figure 5.7: Osun River channel between 1963 and 2005 showing areas of channel migration within the main anabranch

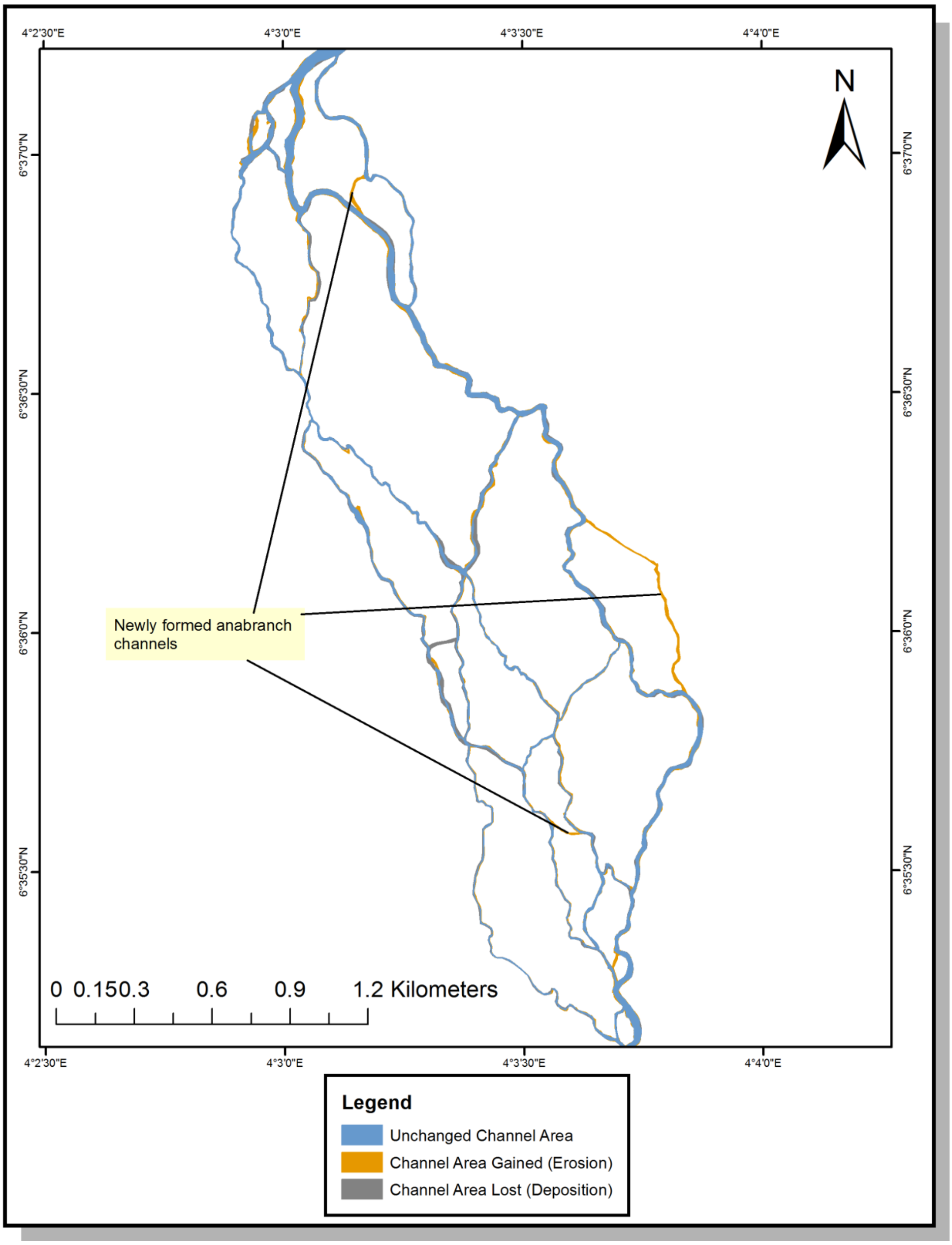


Figure 5.8: Osun River channel between 2005 and 2012 showing a stable channel area within the main anabranch

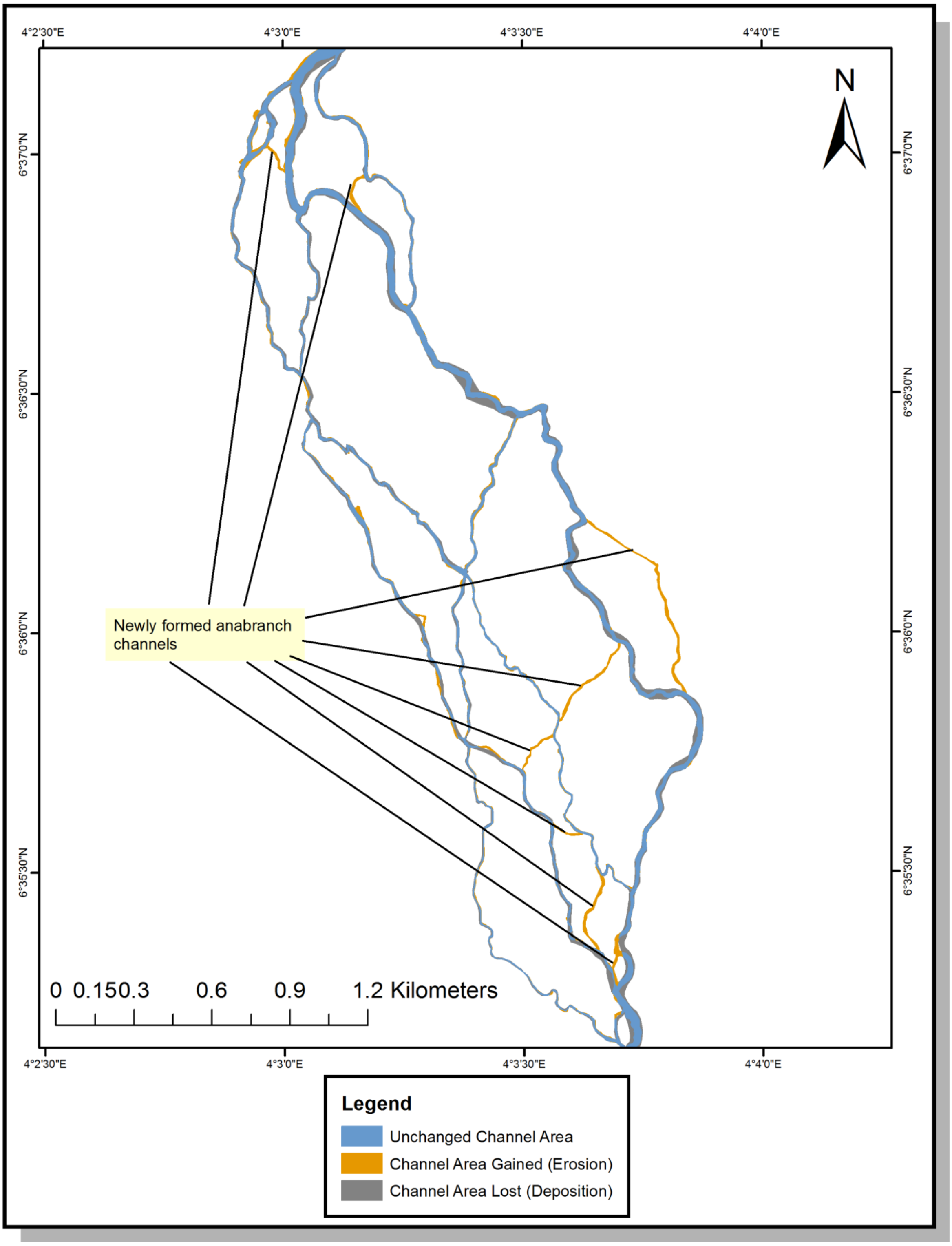


Figure 5.10: Osun River channel between 1963 and 2012 showing areas of channel migration within the main anabranch

Channel avulsion through breaching or crevassing of levees has been widely observed to initiate anabranch development in accreting systems. This is often triggered by the clearing of vegetation from stream banks. Bernal *et al.* (2011) gave three examples of avulsions resulting from crevasse-splays evolving in anastomosed channels along the Rio Pastaza, a tropical humid river sourced in the Ecuadorian Andean Cordillera and flowing into the Amazonian foreland.

Within the anabranching reach of the study area small holder farms for pepper and other vegetables are seen on the flood plains, this activity which mainly takes place during the dry season involves the clearing of riparian vegetation (mainly mangrove and raphia palm). Vegetation clearance leads to the loosening of stream bank materials, which may trigger crevassing with floods during the rainy season. Crevassing could most probably be the initiator of new anabranch channels within River Osun.

5.5 Synthesis

The study of temporal changes in channel plan form revealed an increase in channel sinuosity of 6.14% (p=0.005) and 0.01% (p=0.051) during the 49 years' study period for the meandering and anabranching reaches, respectively. Analysis of temporal changes in channel width also revealed that within the meandering reach, channel width reduced by 19.69% significant at 95% alpha level (p=0.000), while within the anabranching reach, channel width of the main anabranch reduced by 5.29%. This was not statistically significant at the 95% alpha level (P=0.166). Surface area within the meandering reach reduced by 36.19% (p=0.001). Within the anabranch reach, channel surface area increased by 10.32% (p=0.000), mainly as a result of increase in numbers of anabranches. Rate of lateral migration was 0.84m/yr. within the meandering reach, and 0.02m/yr. within the anabranching reach, showing relative stability of the channel. The result revealed that lower rate of channel migration within the anabranching reach compared to the meandering reach was significant at the 95% alpha level (p=0.000). Changes in stream course within the anabranching reach were mainly due to the formation of new anabranches through channel avulsion. The study therefore revealed that temporal changes in plan form within the study area was more evident within the meandering reach compared with the anabranching reach.

CHAPTER SIX

SUMMARY AND CONCLUSION

The overall aim of this research was to gain an increased understanding of both spatial and temporal plan form changes within the alluvial section of River Osun as well as the controls of plan form changes. This was accomplished by pursuing five specific objectives. The results of the analysis are summarized in this chapter. The chapter also contains conclusion.

6.1 Summary of findings

6.1.1 Downstream changes in channel plan form

The first objective was to characterise the downstream channel pattern of the alluvial section of River Osun. Downstream changes in channel pattern was characterised with the aid of two river pattern indices, namely, average number of channels across valley and channel sinuosity (Bridge, 1993; Burges, 2005) using remotely sensed imagery. The second objective was to quantify downstream changes in cross-sectional form of the alluvial section of river Osun. This was carried out using width, depth, width/depth ratio and area data from 34 cross sections within study reach 1 and 10 cross sections from study reach II as obtained from field work. The hypothesis was that plan form change from single to multiple channels is to enable increase in channel efficiency within the downstream section of the river.

The result of characterisation of channel pattern within the alluvial section of River Osun revealed two distinct channel patterns. The first was a meandering pattern with an average of 1.03 channels across valley and channel sinuosity of 1.51. The second, an anabranching pattern had an average of 4.5 channels across valley and channel sinuosity of the main anabranch of 1.12. This made this reach to be relatively straight.

The cross-sectional form of the study reaches was studied along 34 cross sections within the meandering reach and 10 cross sections within the anabranching reach. The results revealed that the mean channel width of the meandering reach (59.92m) was significantly larger ($p=0.000$) than the mean channel width of the main anabranch (20.48m). The mean depth of the meandering reach (3.61m) was similar ($p=0.616$) to that of the main anabranch (3.70m), while the width/depth ratio of the meandering reach (12.84) was significantly larger ($p=0.000$) than that of the main anabranch (7.34), revealing the channel cross-sectional form of the meandering reach to be wide and relatively deep and the anabranching reach as narrow and deep. The mean cross-sectional area of the meandering reach (212.04m^2) was significantly larger (p=0.000) than the mean cross-sectional area of the main anabranch (75.90m^2). The results also showed that width and depth decreased in the downstream direction within the meandering reach, while depth increased downstream within the anabranching reach.

The results further revealed that the total mean area for all the anabranches were larger than the mean area of the meandering reach, although the difference (p=0.120) was not significantly different at the 95% confidence level. This means velocity was not higher within the anabranching reach. Thus the hypothesis of maximum flow efficiency as a cause for anabranching was rejected.

6.1.2 Relationship between plan form and plan form control variables

Differences and similarities in the factors controlling plan form were analysed to determine the factors responsible for the observed change of stream pattern and cross-sectional form within the study area. The control factors considered were discharge (Q), bank strength (bank shear strength and percentage clay content of the bank material), median bed sediment grain size as well as valley slope and width. The hypothesis was that observed change in channel plan form from a meandering to an anabranching plan form is due to increased discharge, bank strength and valley width and reduced bed material sediment size and valley slope.

The mean discharge for the meandering reach (282.80m^3/s) was significantly larger (p=0.000) than mean discharge within the main anabranch (146.20m^3/s). However, the total mean discharge for the anabranching reach, which was 482.25m^3/s, was significantly larger (p=0.000) than that of the meandering reach. The results revealed a significant increase in discharge in downstream direction within the meandering reach (p=0.001), a non-significant increase in downstream discharge within the main anabranch (p=0.772) but a significant downstream increase in total discharge of the anabranching reach (p=0.000). The mean percentage bank clay content as well as mean bank shear strength were significantly higher within the anabranching reach than the meandering reach (p=0.000). The average median bed sediment grain size (D_{50}) was larger (p=0.000) within the meandering reach. The valley slope was less (p=0.000) within the anabranching reach, while the valley width was larger within the anabranching reach (p=0.000). The results revealed statistically significant differences in all the plan form factors between the meandering and anabranching reaches.

Correlation analysis was carried out between the plan form factors cross-sectional form variables. The result showed that correlation between discharge and channel width was significant and positive (p=0.000), revealing that an increase in discharge led to increased channel width. The relationship with cross-sectional depth was positive, although not statistically significant (p=0.191) at the 95% confidence level. Within the meandering reach, discharge displayed a significant positive correlation with cross-sectional width (p=0.004), depth (p=0.000) and area (p=0.000) and a negative correlation with the w/d ratio (p=0.400) all at the 95% confidence level. Downstream hydraulic geometry relationship for the study reaches resulted in the following exponents: b= 0.38; f= 0.42 and m= 0.23 for the meandering reach and b= 0.12; f= 0.42 and m= 0.46 for the anabranching reach.

The percentage clay content of bank materials showed a negative correlation with cross-sectional width (p=0.000), w/d ratio (p=0.000) and area (p=0.000) and a positive correlation with depth (p=0.156). Bank shear strength negatively correlated with cross-sectional width (p=0.001) and w/d ratio (p=0.000), while it had a positive correlation with cross-sectional depth (p=0.000) and area (p=0.256). Valley gradient displayed a positive correlation with cross-sectional width (p=0.000), w/d ratio (p = 0.000) and cross-sectional area (p = 0.000) and a negative correlation with cross-sectional depth (p = 0.051).

Regression analysis was used to explore the contribution of all the plan form control variables in the change in downstream plan form within the study area. In the regression of plan form control variables and channel pattern, the regression model displayed an adjusted R2 of 0.917, revealing that the model could account for 92% of variance in channel pattern within the study area. The analysis also displayed a value of p=0.034 bankfull discharge (Q), p=0.001 and p=0.000, for percentage bank clay content (Bc) and bank shear strength (Bs), a value of p=0.083 for valley width (Vw) and p= 0.26 for valley slope (S). The equation predicting the relationship between plan form control variables and channel pattern was $y = 1.18 + 0.21Q + 0.3Bc + 0.60D50 - 0.12S - 0.21Vw + e$. The regression of plan form control variables and cross-sectional form (as best described by the w/d ratio) displayed a value of p=0.037 for bankfull discharge (Q); p=0.634 for percentage bank clay content (Bc); p=0.001 for bank shear strength (Bs); p=0.09 for median bed sediment grain size (D50); p=0.038 for valley slope (S) and p=0.204 for valley width (Vw). The equation predicting the relationship between plan form control variables and cross-sectional form was $y = 8.01 + 0.34Q - 0.06Bc -0.91Bs + 0.29D50 + 0.31S + 0.31Vw + e$. It was, therefore, concluded that, although there were statistically significant differences in all the plan form factors between the meandering and anabranching reaches, only discharge, bank strength and valley slope factors were significant in the transition from a meandering to an anabranching plan form.

6.1.3 Temporal changes in channel plan form

The third objective was to examine temporal changes in the plan form of River Osun through measurement of channel sinuosity, width, area and lateral migration over the forty-nine years' study period, 1963 and 2012. This was carried out through the analysis of sequential remotely sensed imagery (aerial photographs and satellite images) of the study area for 1963, 1984, 2005 and 2012. The study of the temporal trends in channel plan form revealed that sinuosity of the meandering reach increased by 6.14% within forty-nine years, while there was little change in sinuosity within the anabranching reach, which increased 0.01% in forty-nine years. There was a decrease of channel width of 19.69% of original channel within the meandering reach at a rate of 0.26m/yr. The paired samples t-test result of p=0.000 revealed that the observed decreased stream channel width was statistically significant at the 95% confidence level. Within the anabranching reach, channel width of the main anabranch reduced by 5.29%. This reduction was, however, not statistically significant at the 95% alpha level (P=0.166). Surface area within the meandering reach reduced by 36.19% (p=0.001). It also reduced by 48.1% (p=0.000) within the main anabranch. Within the entire anabranch reach, channel surface area increased by 10.32% (p=0.000), mainly as a result of increase in numbers of anabranches.

The study further revealed that anabranches within the alluvial section of the Osun River is not transient and has been relatively stable with reduction in size of islands resulting from creation of new anabranches. Lateral migration within the meandering reach was at the average rate of 0.84m/yr., increasing from 0.69m/yr. between 1963 and 1984 to 1.70m/yr. between 2005 and 2012 (p=0.001). Lateral migration was significantly lower within the anabranching reach (0.02m/yr.) compared to meandering reach (p=0.000). This revealed a relative stability of the channel within the anabranching reach. There was, however, evidence of channel avulsion within this reach. It was concluded that temporal changes in channel plan form was more evident within the meandering reach compared to the anabanching reach. It was concluded that temporal changes in plan form within the study area was more evident within the meandering reach compared with the anabranching reach.

5.2 Conclusion

The research is an attempt to gain an increased understanding of channel plan form dynamics in the Osun River in southwest Nigeria. The answers to the research questions summarized above are a contribution toward theoretical understanding of humid tropical rivers. The statements and results provide an explanation for plan form behaviour, as well as describe spatial and temporal variations. In addition to increasing basic understanding of channel plan form processes in tropical areas and for developing fluvial geomorphological theory, the knowledge gained has potentially important benefits to society. The results of this study could be useful for planners, engineers, and other professionals in estimating meander movement as well as transition of channel pattern in order to reduce potential geomorphological hazards.

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APPENDIX 1: PLAN FORM VARIABLES

Cross Section	Downstream Distance (km)	Number of Channels across Valley	Width (m)	Log of Width	Depth (m)	Log of Depth	Width/Depth Ratio	Area (m^2)
Meandering Reach								
CS.1	5.3	1	53.14	1.73	3.42	0.53	15.54	181.74
CS.2	5.86	1	83.32	1.92	2.72	0.43	30.63	226.63
CS.3	7.28	1	79.29	1.9	3.02	0.48	26.25	239.46
CS.4	7.74	1	57.33	1.76	3.62	0.56	15.84	207.53
CS.5	11.24	1	74.01	1.87	3.09	0.49	23.95	228.69
CS.6	11.66	1	55.28	1.74	3.18	0.5	17.38	175.79
CS.7	12.14	1	56.92	1.76	3.75	0.57	15.18	213.45
CS.8	12.59	2	68.7	1.84	3.22	0.51	21.34	221.21
CS.9	13.05	1	74.28	1.87	3.11	0.49	23.88	231.01
CS.10	13.47	1	52.74	1.72	3.68	0.57	14.33	194.08
CS.11	16.37	1	58.82	1.77	3.66	0.56	16.07	215.28
CS.12	16.87	1	63.69	1.8	3.14	0.5	20.28	199.99
CS.13	17.39	1	61.18	1.79	3.13	0.5	19.55	191.49
CS.14	17.87	1	58.34	1.77	3.63	0.56	16.07	211.77
CS.15	19.28	1	59.11	1.77	3.84	0.58	15.39	226.98
CS.16	19.81	1	56.31	1.75	3.74	0.57	15.06	210.6
CS.17	20.31	1	54.12	1.73	3.61	0.56	14.99	195.37
CS.18	20.84	1	50.26	1.7	2.98	0.47	16.87	149.77
CS.19	22.35	1	46.44	1.67	2.73	0.44	17.01	126.78
CS.20	22.87	1	55.92	1.75	4.32	0.64	12.94	241.57
CS.21	23.42	1	57.43	1.76	4.02	0.6	14.29	230.87
CS.22	23.91	1	54.48	1.74	3.45	0.54	15.79	187.96
CS.23	24.45	1	61.22	1.79	4.03	0.61	12.21	198.36
CS.24	25.98	1	52.43	1.72	3.52	0.55	14.89	184.55

CS.25	26.47	1	56.81	1.75	3.81	0.58	14.91	216.45
CS.26	27.06	1	60.21	1.78	4.33	0.64	11.83	221.74
CS.27	27.99	1	58.16	1.76	3.56	0.55	16.34	207.05
CS.28	28.51	1	59.13	1.77	4.01	0.6	14.75	237.11
CS.29	29.07	1	57.71	1.76	3.91	0.59	14.76	225.65
CS.30	29.57	1	60.45	1.78	4.16	0.62	12.61	218.19
CS.31	30.02	1	58.34	1.77	4.05	0.61	14.4	236.28
CS.32	31.69	1	59.16	1.77	4.21	0.62	14.05	249.06
CS.33	32.21	1	61.16	1.79	4.19	0.62	14.6	256.26
CS.34	31.72	1	61.45	1.79	4.08	0.61	15.06	250.72
Anabranching Reach								
CS.35	34.35	4	27.61	1.44	3.67	0.56	7.52	101.33
CS.36	34.81	5	25.28	1.4	3.71	0.57	6.79	93.79
CS.37	35.32	3	18.85	1.28	3.1	0.49	6.08	58.44
CS.38	35.77	5	18.97	1.28	3.42	0.53	5.55	64.88
CS.39	36.48	4	16.72	1.22	4.04	0.61	4.14	67.55
CS.40	36.98	4	15.87	1.2	3.04	0.48	5.2	48.25
CS.41	37.56	5	19.85	1.3	3.92	0.59	5.06	77.81
CS.42	38.05	6	14.35	1.16	4.66	0.67	3.08	66.87
CS.43	38.56	6	18.74	1.27	3.32	0.52	5.65	62.22
CS.44	38.91	3	28.61	1.46	4.12	0.61	6.94	117.87

APPENDIX 2: PLAN FORM CONTROL VARIABLES

Cross Section	Downstream Distance (km)	Velocity (m/s)	Log of Velocity	Discharge (m/s)	Log of Discharge	Bank Clay (%)	Bank Shear (kPa)	Bed Sediments (D_{50}) (mm)	Valley Slope (m)	Valley Width
Meandering Reach										
CS.1	5.3	1.32	0.12	240.09	2.38	13.54	7.84	2.1	0.0061	119.97
CS.2	5.86	1.36	0.13	307.83	2.49	5.9	5.86	2	0.0052	119.42
CS.3	7.28	1.25	0.1	299.11	2.48	9.6	9.8	1.8	0.0062	103.96
CS.4	7.74	1.23	0.09	254.48	2.41	9.54	8.76	1.8	0.0048	117.45
CS.5	11.24	1.26	0.1	288.64	2.46	8.7	6.86	1.6	0.0068	130.32
CS.6	11.66	1.31	0.12	229.45	2.36	10.32	9.8	1.8	0.0048	154.9
CS.7	12.14	1.2	0.08	255.92	2.41	11.4	11.76	2	0.0046	128.21
CS.8	12.59	1.26	0.1	278.5	2.44	4.4	6.02	2.2	0.0035	123.4
CS.9	13.05	1.34	0.13	308.31	2.49	9.5	5.88	1.6	0.0033	169.11
CS.10	13.47	1.19	0.08	231.52	2.36	13	10.78	1.8	0.0034	188.5
CS.11	16.37	1.28	0.11	276.49	2.44	6.9	11.76	1.5	0.0042	284.9
CS.12	16.87	1.37	0.14	272.94	2.44	7.6	6.88	2.1	0.0043	256.05
CS.13	17.39	1.4	0.15	268.06	2.43	10.2	9.8	2	0.0032	216
CS.14	17.87	1.25	0.1	264.14	2.42	11.4	10.78	1.6	0.0046	221.35
CS.15	19.28	1.2	0.08	271.14	2.43	9.8	11.76	1.4	0.0051	265.85
CS.16	19.81	1.29	0.11	272.36	2.44	11.3	10.78	2	0.0045	296.32
CS.17	20.31	1.3	0.11	253.93	2.4	11.7	11.76	2	0.0021	270.46
CS.18	20.84	1.35	0.13	201.86	2.31	12.1	10.78	1.4	0.004	294.96
CS.19	22.35	1.36	0.13	172.48	2.24	13	11.76	1.5	0.0032	302.12
CS.20	22.87	1.17	0.07	281.34	2.45	14.5	13.72	1.7	0.0051	296.49
CS.21	23.42	1.18	0.07	273.3	2.44	10.5	13.72	1.2	0.0049	306.93
CS.22	23.91	1.25	0.1	235.67	2.37	7.9	10.78	1.8	0.0035	209.79
CS.23	24.45	1.38	0.14	273.52	2.44	8.4	12.74	1.5	0.0048	284.15
CS.24	25.98	1.24	0.09	229.04	2.36	9.2	11.76	1.5	0.004	218.34

CS.25	26.47	1.43	0.16	310.22	2.49	6.2	9.8	1.3	0.0028	240.62
CS.26	27.06	1.47	0.17	324.8	2.51	12	13.72	1.4	0.0028	243.39
CS.27	27.99	1.4	0.14	288.75	2.46	10.5	9.8	1	0.0039	281.31
CS.28	28.51	1.32	0.12	313.4	2.5	12.4	14.7	1.8	0.0041	258.95
CS.29	29.07	1.38	0.14	310.36	2.49	13.3	13.72	1.4	0.0032	309.86
CS.30	29.57	1.61	0.21	351.13	2.55	14.1	13.72	0.9	0.0022	296.54
CS.31	30.02	1.46	0.17	345.85	2.54	16.6	10.78	1.3	0.0038	264.12
CS.32	31.69	1.49	0.17	371.41	2.57	13.6	10.78	1.2	0.0014	321.06
CS.33	32.21	1.46	0.17	374.93	2.57	18.28	13.72	1	0.0021	342.91
CS.34	31.72	1.53	0.19	384.32	2.58	12.7	11.76	1.2	0.0018	363.45
Anabranching Reach										
CS.35	34.35	0.69	-0.16	397.76	1.85	30.99	20.58	0.8	0.00022	415.8
CS.36	34.81	0.69	-0.16	447.03	1.81	41.27	27.44	0.6	0.0002	699.63
CS.37	35.32	0.57	-0.25	459.82	1.52	40.18	27.44	0.3	0.0002	773.03
CS.38	35.77	0.42	-0.38	431.55	1.43	22.54	28.42	0.5	0.00021	943.44
CS.39	36.48	0.44	-0.35	492.13	1.48	19.15	30.38	0.6	0.00016	847.38
CS.40	36.98	0.42	-0.37	493.75	1.31	26.88	37.24	0.6	0.00016	968.08
CS.41	37.56	0.51	-0.29	504.11	1.6	32.12	29.4	0.4	0.00013	829.91
CS.42	38.05	0.57	-0.24	523.44	1.58	23.32	30.38	0.3	0.00021	647.96
CS.43	38.56	0.69	-0.16	535.88	1.63	22.11	28.42	0.5	0.00019	543.27
CS.44	38.91	0.82	-0.09	537.01	1.98	33.66	19.6	0.4	0.00022	502.91

APPENDIX 3: TEMPORAL CHANGE VARIABLES

S/N	Downstream Distance	Width				Change
		1963	1984	2005	2012	1963-2012
CS.1	5.3	70.04	71.84	56.24	62.69	-7.35
CS.2	5.86	74.03	79.34	50.35	47.99	-26.04
CS.3	7.28	55.58	51.08	40.72	44.54	-11.04
CS.4	7.74	64.64	79.03	66.27	60.89	-3.75
CS.5	11.24	39.46	62.03	47.19	47.87	8.41
CS.6	11.66	58.65	54.43	49.09	48.47	-10.18
CS.7	12.14	64.41	55.64	55.08	41.14	-23.27
CS.8	12.59	61.05	63.35	45.23	55.78	-5.27
CS.9	13.05	64.84	55.49	54.63	50.21	-14.63
CS.10	13.47	63.06	77.71	48.43	52.42	-10.64
CS.11	16.37	58.25	88.29	78.73	64.05	5.8
CS.12	16.87	72.47	68.05	54.11	37.74	-34.73
CS.13	17.39	51.57	78.77	56.91	46.66	-4.91
CS.14	17.87	64.27	62	46.67	32.75	-31.52
CS.15	19.28	81.8	79.22	55.55	50.01	-31.79
CS.16	19.81	59.99	68.18	46.36	52.48	-7.51
CS.17	20.31	59.14	45.89	56.16	47.16	-11.98
CS.18	20.84	47.67	60.37	46.21	53.83	6.16
CS.19	22.35	69.07	47.55	43.35	51.95	-17.12
CS.20	22.87	51.66	62.96	49.58	48.07	-3.59
CS.21	23.42	30.68	41.73	34.24	37.06	6.38
CS.22	23.91	40.26	53.6	41.37	58.04	17.78
CS.23	24.45	68.6	79	38.97	34.29	-34.31
CS.24	25.98	62.79	54.71	44.99	37.34	-25.45
CS.25	26.47	67.27	84.33	60.19	35.59	-31.68
CS.26	27.06	37.39	48.61	43.13	34.63	-2.76
CS.27	27.99	65.18	49.43	47.56	41.93	-23.25
CS.28	28.51	58.4	56.29	42.79	46.23	-12.17
CS.29	29.07	70.89	79.99	53.39	71.94	1.05
CS.30	29.57	57.86	71.04	51.93	51.93	-5.93
CS.31	30.02	72.03	88.17	54.48	60.13	-11.9
CS.32	31.69	67.72	82.22	54.04	69.57	1.85
CS.33	32.21	93.27	75.83	44.07	29.34	-13.93
CS.34	31.72	65.7	76.03	54.18	46.18	-19.52

Lateral Migration (m^2)										
S/N	Downstream distance	1963-1984			1984-2005			2005-2012		
		Left	Right	Total	Left	Right	Total	Left	Right	Total
Meandering Reach										
CS.1	5.3	4819.15	9432	14251.15	35886.68	0	35886.68	32168.11	0	32168.11
CS.2	5.86	11436.23	7674.56	19110.79	9364.5	3924.19	13288.69	9364.5	7924.19	17288.69
CS.3	7.28	4427.89	20852.01	25279.9	2407.23	5111.56	7518.79	1307.23	5111.56	6418.79
CS.4	7.74	15726.26	23789.31	39515.57	0	21573.54	21573.54	1321.75	21573.54	22895.29
CS.5	11.24	10272.27	0	10272.27	17363.16	0	17363.16	17673.19	132.78	17805.97
CS.6	11.66	14068.81	7973.44	22042.25	4410.56	0	4410.56	5610.52	1762.9	7373.42
CS.7	12.14	12962.99	14053.04	27016.03	3680.11	0	3680.11	348.22	3620.15	3968.37
CS.8	12.59	3622.34	11228.5	14850.84	0	1011.93	1011.93	178.93	1321.97	1500.9
CS.9	13.05	1308.56	19145.55	20454.11	0	0	0	2571.02	149.7	2720.72
CS.10	13.47	4237.22	3250.64	7487.85	10948.08	8068.96	19017.04	8948.88	18008.16	26957.04
CS.11	16.37	8282.87	3394.21	11677.08	2396.67	11888.22	14284.89	2976.35	11888.22	14864.57
CS.12	16.87	2683.05	0	2683.05	0	4423.92	4423.92	465	4423.92	4888.92
CS.13	17.39	0	0	0	0	7592.41	7592.41	974	7592.41	8566.41
CS.14	17.87	9366.36	3250.31	12616.67	0	16246.85	16246.85	1902	16246.85	18148.85
CS.15	19.28	4804.35	8206.36	13010.71	0	16782.02	16782.02	1392	16782.02	18174.02
CS.16	19.81	11829.83	13060.79	24890.62	0	25158.84	25158.84	857.02	25158.84	26015.86
CS.17	20.31	20212.7	10476.63	30689.33	5368.48	7556.61	12925.08	5368.48	7556.61	12925.08
CS.18	20.84	26058.55	14979.61	41038.16	3452.64	8338.88	11791.52	3452.64	8338.88	11791.52
CS.19	22.35	13047.75	0	13047.75	0	4106.86	4106.86	0	4106.86	4106.86
CS.20	22.87	11273.09	0	11273.09	2492.78	11450.99	13943.77	2492.78	11450.99	13943.77
CS.21	23.42	3307.72	16079.43	19387.15	5189.2	3075.22	8264.42	5189.2	10075.22	15264.42
CS.22	23.91	5739.22	1561.18	7300.4	7467.11	7126.02	14593.12	7467.11	9126.02	16593.12
CS.23	24.45	7104.44	17966.96	25071.4	9220.48	23768.44	32988.93	9220.48	23768.44	32988.93
CS.24	25.98	21425.33	10718.73	32144.06	0	19319	19319	0	19319	19319
CS.25	26.47	7757.63	0	7757.63	0	1295.23	1295.23	0	1295.23	1295.23

CS.26	27.06	0	0	0	0	0	0	0	0	0
CS.27	27.99	9910.2	2105.87	12016.08	0	7817.52	7817.52	0	7817.52	7817.52
CS.28	28.51	0	31261.34	31261.34	1044.4	14294.55	15338.95	1044.4	14294.55	15338.95
CS.29	29.07	0	28989.99	28989.99	10793.28	4286.49	15079.77	10793.28	4889.29	15682.57
CS.30	29.57	6750.76	0	6750.76	0	9228.34	9228.34	0	13228.31	13228.31
CS.31	30.02	12416.37	1701.77	14118.14	0	1138.75	1138.75	0	1138.75	1138.75
CS.32	31.69	5632.8	5456.25	11089.05	0	2536.14	2536.14	236.14	1184.18	1420.32
CS.33	32.21	7042.27	0	7042.27	1919.26	12378.16	14297.42	1919.26	12378.16	14297.42
CS.34	31.72	3327.83	0	3327.83	133.33	0	133.33	133.33	0	133.33
Total		280854.8	286608.5	567463.3	133537.9	259499.6	393037.6	135375.8	291665.2	427041
Anabranching Reach										
		1963-2005			**2005-2012**			**1963-2012**		
		Left	Right	Total	Left	Right	Total	Left	Right	Total
CS.35	34.35	26	0	26	1054	207	1261	1340	207	1547
CS.36	34.81	0	0	0	0	0	0	0	0	0
CS.37	35.32	0	0	0	0	201	201	0	201	201
CS.38	35.77	0	102	102	0	234	234	0	378	378
CS.39	36.48	0	0	0	0	0	0	0	0	0
CS.40	36.98	0	0	0	12	0	12	0	0	0
CS.41	37.56	0	0	0	0	0	0	0	0	0
CS.42	38.05	0	0	0	0	117	117	0	117	117
CS.43	38.56	213	0	213	512	0	512	615	0	615
CS.44	38.91	153	0	153	1173	0	1173	1467	0	1467
Total		392	102	494	3512	867	4379	3422	903	4325

Lateral Migration Rates (m^2/yr.)										
S/N	**Downstream distance**	**1963-1984**			**1984-2005**			**2005-2012**		
		Left	**Right**	**Total**	**Left**	**Right**	**Total**	**Left**	**Right**	**Total**
Meandering Reach										
CS.1	5.3	401.6	786	1187.6	1708.89	0	1708.89	4595.44	0	4595.44
CS.2	5.86	953.02	639.55	1592.57	445.93	186.87	632.79	1337.79	1132.03	2469.81
CS.3	7.28	368.99	1737.67	2106.66	114.63	243.41	358.04	186.75	730.22	916.97
CS.4	7.74	1310.52	1982.44	3292.96	0	1027.31	1027.31	188.82	3081.93	3270.76
CS.5	11.24	856.02	0	856.02	826.82	0	826.82	2524.74	18.97	2543.71
CS.6	11.66	1172.4	664.45	1836.85	210.03	0	210.03	801.5	251.84	1053.35
CS.7	12.14	1080.25	1171.09	2251.34	175.24	0	175.24	49.75	517.16	566.91
CS.8	12.59	301.86	935.71	1237.57	0	48.19	48.19	25.56	188.85	214.41
CS.9	13.05	109.05	1595.46	1704.51	0	0	0	367.29	21.39	388.67
CS.10	13.47	353.1	270.89	623.99	521.34	384.24	905.57	1278.41	2572.59	3851.01
CS.11	16.37	690.24	282.85	973.09	114.13	566.11	680.23	425.19	1698.32	2123.51
CS.12	16.87	223.59	0	223.59	0	210.66	210.66	66.43	631.99	698.42
CS.13	17.39	0	0	0	0	361.54	361.54	139.14	1084.63	1223.77
CS.14	17.87	780.53	270.86	1051.39	0	773.66	773.66	271.71	2320.98	2592.69
CS.15	19.28	400.36	683.86	1084.23	0	799.14	799.14	198.86	2397.43	2596.29
CS.16	19.81	985.82	1088.4	2074.22	0	1198.04	1198.04	122.43	3594.12	3716.55
CS.17	20.31	1684.39	873.05	2557.44	255.64	359.84	615.48	766.93	1079.52	1846.44
CS.18	20.84	2171.55	1248.3	3419.85	164.41	397.09	561.5	493.23	1191.27	1684.5
CS.19	22.35	1087.31	0	1087.31	0	195.56	195.56	0	586.69	586.69
CS.20	22.87	939.42	0	939.42	118.7	545.29	663.99	356.11	1635.86	1991.97
CS.21	23.42	275.64	1339.95	1615.6	247.1	146.44	393.54	741.31	1439.32	2180.63
CS.22	23.91	478.27	130.1	608.37	355.58	339.33	694.91	1066.73	1303.72	2370.45
CS.23	24.45	592.04	1497.25	2089.28	439.07	1131.83	1570.9	1317.21	3395.49	4712.7
CS.24	25.98	1785.44	893.23	2678.67	0	919.95	919.95	0	2759.86	2759.86
CS.25	26.47	646.47	0	646.47	0	61.68	61.68	0	185.03	185.03

CS.26	27.06	0	0	0	0	0	0	0	0	0
CS.27	27.99	825.85	175.49	1001.34	0	372.26	372.26	0	1116.79	1116.79
CS.28	28.51	0	2605.11	2605.11	49.73	680.69	730.43	149.2	2042.08	2191.28
CS.29	29.07	0	2415.83	2415.83	513.97	204.12	718.08	1541.9	698.47	2240.37
CS.30	29.57	562.56	0	562.56	0	439.44	439.44	0	1889.76	1889.76
CS.31	30.02	1034.7	141.81	1176.51	0	54.23	54.23	0	162.68	162.68
CS.32	31.69	469.4	454.69	924.09	0	120.77	120.77	33.73	169.17	202.9
CS.33	32.21	586.86	0	586.86	91.39	589.44	680.83	274.18	1768.31	2042.49
CS.34	31.72	277.32	0	277.32	6.35	0	6.35	19.05	0	19.05
Anabranching Reach										
		1963-2005			2005-2012			1963-2012		
CS.35	34.35	0.62	0	0.62	150.57	29.57	180.14	27.36	4.23	31.57
CS.36	34.81	0	0	0	0	0	0	0	0	0
CS.37	35.32	0	0	0	0	28.71	28.71	0	4.10	4.10
CS.38	35.77	0	2.43	2.43	0	33.43	33.43	0	7.71	7.71
CS.39	36.48	0	0	0	0	0	0	0	0	0
CS.40	36.98	0	0	0	1.71	0	1.71	0	0	0
CS.41	37.56	0	0	0	0	0	0	0	0	0
CS.42	38.05	0	0	0	0	16.71	16.71	0	2.38	2.38
CS.43	38.56	5.07	0	5.07	73.14	0	73.14	12.55	0	12.55
CS.44	38.91	3.64	0	3.64	167.57	0	167.57	29.94	0	29.93