35-years decadal changes in planform morphology of the Niger and Benue Rivers confluence, West Africa

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November 23, 2022

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In this study, time-lapse data covering 35 years record (1987-2022) of publicly available Landsat imageries and shuttle radar topography mission DEM are used to investigate the changes in planform morphology at the confluence of River Niger and Benue in West Africa. The confluence is flanked by high elevation areas, with the Niger, bordered by ca. 400 m high plateaus and low-lying floodplains on its western bank. Intra-channel and bank-attached bars are abundant in the Benue compared to the Niger. The confluence is segmented, and its tip records a net downstream migration of about 880 m in the last 35 years. With the confluence angle significantly reduced from ca. 175° in 1987 to ca. 500 in 2006 and ca. 16° in 2022. The abrupt drop in confluence angle between 1987 and 2006 reflects a marked increase in river runoff in the study area. Expansion along the banks of the Niger, Benue, and post-confluence rivers is low and non-uniform, signifying resistance of the banks to erosion due to the vegetated nature of the banks. These decadal changes in confluence planform were triggered by dislodgment and erosion of parts of the confluence, upstream erosion, and downstream migration of bars. Decadal morphological changes observed at the confluence of the River Niger and Benue are important for sustainable planning and for understanding river confluence dynamics in and around major rivers worldwide.

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In this study, time-lapse data covering 35 years record (1987-2022) of publicly available Landsat imageries and shuttle radar topography mission DEM are used to investigate the changes in planform morphology at the confluence of River Niger and Benue in West Africa. The confluence is flanked by high elevation areas, with the Niger, bordered by ca. 400 m high plateaus and low-lying floodplains on its western bank. Intra-channel and bank-attached bars are abundant in the Benue compared to the Niger. The confluence is segmented, and its tip records a net downstream migration of about 880 m in the last 35 years. With the confluence angle significantly reduced from ca. 175° in 1987 to ca. 50^0 in 2006 and ca. 16° in 2022. The abrupt drop in confluence angle between 1987 and 2006 reflects a marked increase in river runoff in the study area. Expansion along the banks of the Niger, Benue, and post-confluence rivers is low and non-uniform, signifying resistance of the banks to erosion due to the vegetated nature of the banks. These decadal changes in confluence planform were triggered by dislodgment and erosion of parts of the confluence, upstream erosion, and downstream migration of bars. Decadal morphological changes observed at the confluence of the River Niger and Benue are important for sustainable planning and for understanding river confluence dynamics in and around major rivers worldwide.

Keywords: Decades, River, morpho-dynamics, migration, Niger, Benue, confluence.

Key Points

- Downstream migration of confluence within a 2.2 km wide zone with a net migration of ~ 880 m in 35 years mapped from Landsat imagery.
- Change in confluence angle from ca. 154° in 1987 to ca. 16° in 2022.
- More significant channel expansion along the tributary relative to the main river.

Plain Language Summary

A key goal of river confluence geomorphology is to understand the morpho-dynamic changes occurring at confluences over different time scales. In this paper, we discuss the morpho-dynamic changes that have taken place at the confluence of two tropical rivers, the river Niger and Benue, which are two of West Africa's most important rivers, using Landsat data covering a period of 35 years (1987 to 2022). We reveal significant downstream migration of the confluence within a 2.2 km wide zone with a net migration of ~ 880 m at the confluence tip in 35 years and a change in confluence angle from ca. 154° in 1987 to ca. 16° in 2022. We further discuss likely controls on bank processes and confluence morphology in the area, which are important to understand in the face of ongoing climate change and the need for risk assessment and sustainable planning globally.

1. Introduction

River confluences are some of the most captivating morphological features on earth. Their occurrences and morphologies typically characterize both large and small rivers and are key in dictating the sedimentological (Best, 1988; Sambrook Smith et al., 2019), ecological (Benda et al., 2004; Rice et al., 2008), hydro-geochemical characteristics (Guinoiseau et al., 2016; Maurice-Bourgoin et al., 2003) and morphological transformation of landscapes (Dixon et al., 2018). River confluences represent zone of complex hydrological and sedimentological convergence (Rhoads & Kenworthy, 1995), where points of intense incision into underlying substrate downstream of the confluence are known (Miall & Jones, 2003; Mosley, 1976). Incision at river junctions often leads to the formation of scour holes and sediment bars (Best and Rhoads, 2008), which are important morphological features at river confluences (Best, 1988; Mosley, 1976).

In terms of morphological variation, the location of confluences and confluence planform of several rivers have been shown to change e.g., Ganges/Jamuna Rivers confluence in Bangladesh, while others remain stagnant over decades e.g., Congo and Kasai Rivers confluence in the Democratic Republic of Congo (Dixon et al., 2018). While Shit and Maiti, (2013) argue that the up-and downstream migration of gully confluences, at least at a small-scale is related to sediment deposition. Consequently, several studies have shown that sediment deposition at river junctions located downstream of dams can create local bed aggradation patterns that may promote lateral and longitudinal movement of the junction location (Grant et al., 2013; Phillips et al., 2005). These processes can be accompanied by episodic bank erosion and changes in bar formation processes at river confluence because of flooding events (Ettema, 2008). Moreover, confluences respond to discharge ratio i.e., ratio of the discharge of the tributary river to that of the main river that make up a confluence. The discharge ratio in turn modulates scour hole morphology (Best, 1988; Mosley, 1976), migration of tributary bars (Best & Rhoads, 2008), bar morphology (Boyer et al., 2006), sediment load, and migration rate of the channels (Dixon et al., 2018). Mosley et al. (1976)'s classical work on experimental study of channel confluences also showed that the morphology of confluences changes overtime in response to variations in flow and sediment supply in the confluent channels or rivers. These processes directly impact the nature, extent, and type of changes at the confluence, especially as it relates to their morphology, unless certain factors such as vegetation, geological controls such as bedrock presence, and anthropogenic controls such as land use and river damming are active (Grant et al., 2013; Hackney & Carling, 2011; Knox, 2008). The morphology of scour holes and tributary mouth bars is controlled by the confluence angle (Sambrook Smith et al., 2019). The formation of bars around the confluence in tributary channels and within post-confluence rivers may also enhance bank erosion, leading to the widening of channels and subsequent changes in confluence morphology (Mosley, 1976).

Laboratory and field studies of the morpho-dynamics of river confluences are abundant (Best, 1988; Mosley, 1976; Rice et al., 2009; Shit & Maiti, 2013). Research in this field has been strengthened immensely by recent advances in technology, permitting the incorporation of satellite imagery and other techniques for a greater understanding of morphological changes (Costard & Gautier, 2008; Dixon et al., 2018; Hackney & Carling, 2011; Lewin & Ashworth, 2014). The use of satellite data or remote sensing techniques allows these processes to be studied in detail (Dixon et al., 2018) even where ground truth, discharge, sediment load, and other information are unknown. Despite the extensive studies done on morphological changes at confluences, knowledge of the extent of these changes and their controls, especially for tropical rivers, is sparse.

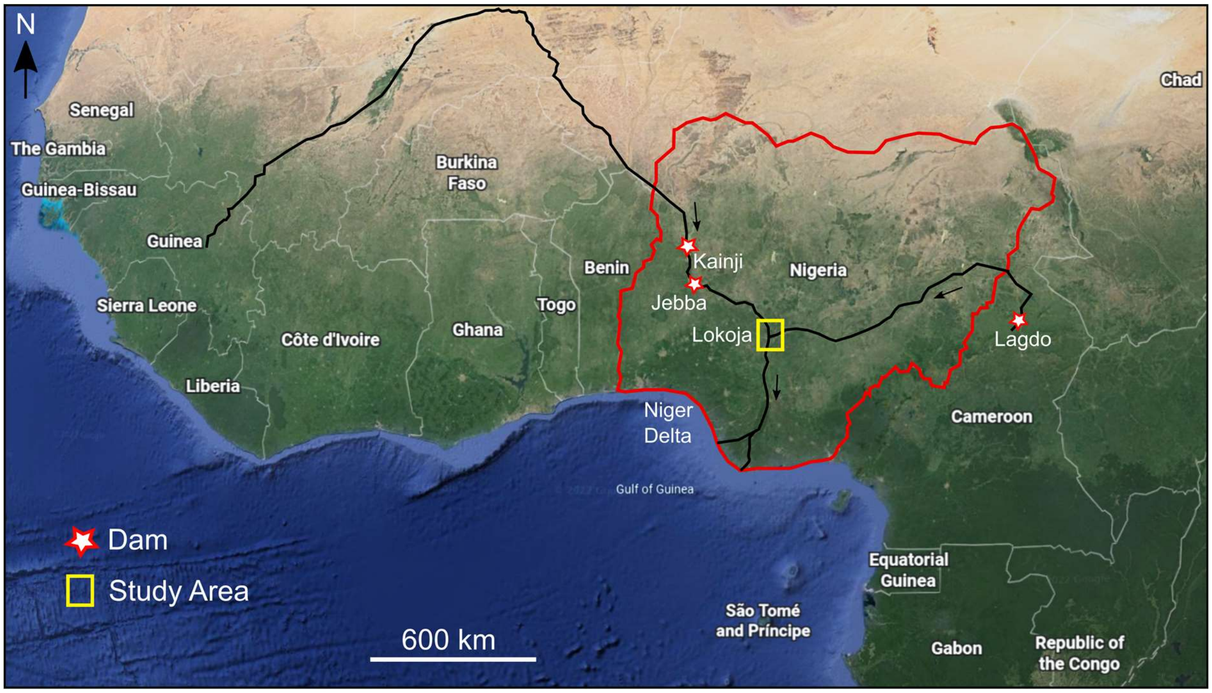

Fig. 1. Map showing the extents of the main segments of River Niger and Benue, and the location of the study area at the confluence of the two rivers in Lokoja, West Africa. The post-confluence river flows downstream and empties into the Niger Delta and into the Gulf of Guinea at its southern limit. Dams along the rivers are shown in white-filled stars with red outline, while flow direction is shown in black arrows. The map of study area map was obtained from Google Earth Engine: https://earth.google.com/web/.

This is likely due to lack of interest, unavailability of important data such as discharge and sediment load, and lack of technical know-how, technology, and competence. For this reason, there is an impetus to investigate the morpho-dynamics of tropical rivers and their confluences. Additionally, such investigation is important because knowledge of the morpho-dynamic behavior at river confluences is valuable for planning, risk evaluation and sustainable management of aquatic resources, including drinking water, hydro-electricity, food, and habitat, for the society (Andersen et al., 2005; Richter et al., 2003).

The aim of this study is to investigate the decadal morphological changes and dynamics at the confluence of major rivers and to evaluate the extent of mobility and planform changes at the confluence. For this purpose, the morpho-dynamics of the confluence between Rivers Niger and Benue, two of West Africa's most important rivers, are investigated. River Niger converges with River Benue, its largest tributary, at Lokoja, a city in northern Nigeria (Fig. 1), where the Niger River enters its lower segment. This study shows the planform morpho-dynamics of the confluence of the two rivers, estimates the probable spatial extent and mobility of its planform, describes the morphological changes in the confluent rivers, and highlights the potential controls on the morphological changes at the confluence over a 35-year period.

2. Geographic and geologic settings

Rivers Niger and Benue are two of West Africa's most important rivers, though they remain extremely poorly studied. The Niger River is Africa's third longest river, with a length of ca. 4,200 km (Fig. 1) and together with the Benue River, the two rivers have remained important to the livelihood of millions of people across Africa. The Niger-Benue Basin (Fig. 1) is home to about 100 million people in 9 different countries - Benin, Burkina Faso, Cameroon, Chad, Cote d'Ivoire, Guinea, Mali, Niger, and Nigeria (Andersen et al., 2005). The Niger River has its source in the Guinea Highlands in southeastern Guinea (Fig. 1; Abrate et al., 2013), from where it meanders across several countries before entering Nigeria through the Niger Republic (Andersen et al., 2005). In Nigeria, the Niger River meanders downstream, and is dammed at Lake Kainji and Jebba (in western Nigeria) some 400 km northwest of Lokoja (Fig. 1). The Benue River on the other hand has a total length of ca. 1400 km and its source in the Adamawa Plateau. It is dammed at

Lagdo Gorge in Cameroon (Fig. 1). In Nigeria, the Benue River is joined by several tributaries before it links up with the Niger to form an extensive floodplain in Lokoja (Laë et al., 2004). The post-confluence river formed by the two rivers meanders downstream or southwards for about 350 km before emptying into one of the world's most prolific hydrocarbon provinces i.e., the Niger Delta and onwards into the Gulf of Guinea (Fig. 1).

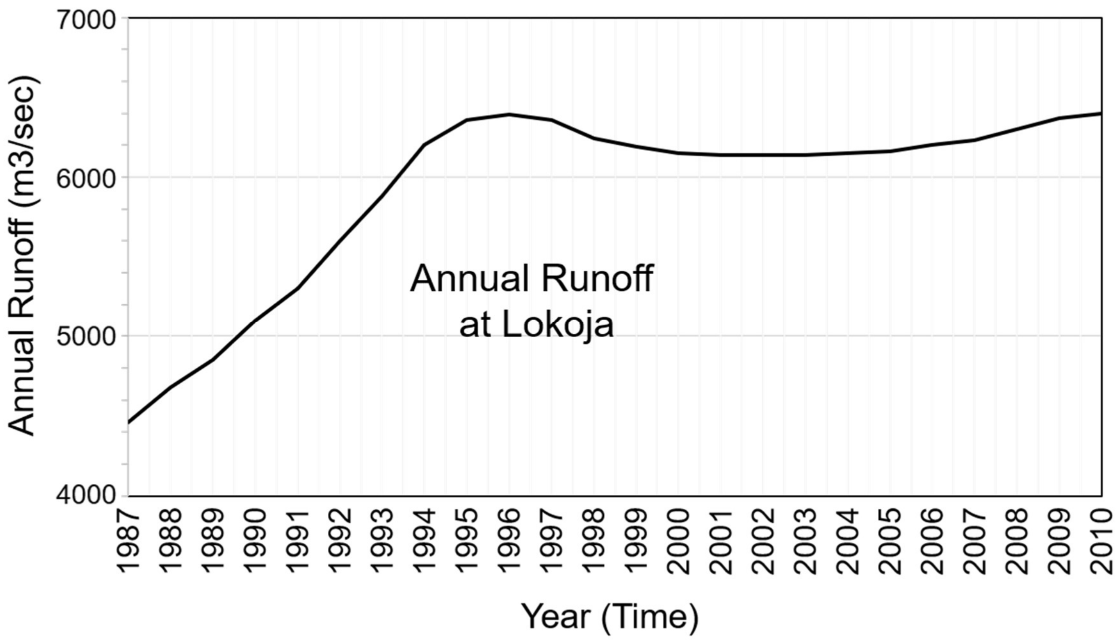

Fig. 2. Plot showing variation of annual runoff (m^3/s) versus time (years) at the confluence of River Niger and Benue in Lokoja between 1987 and 2010. Reference: Dada et al. (2018).

The study area has a warm continental type climate and average daily wind speed is ca.3.0 to 4.6 knots in the south-south westerly direction in June/July and 1.5 to 3.7 knots in the north-easterly direction in December/January (Olivera et al., 1995). Average annual temperature is around 30.7°C, while relative humidity is 30% in the dry season and about 70% in the wet season (Olivera et al., 1995).

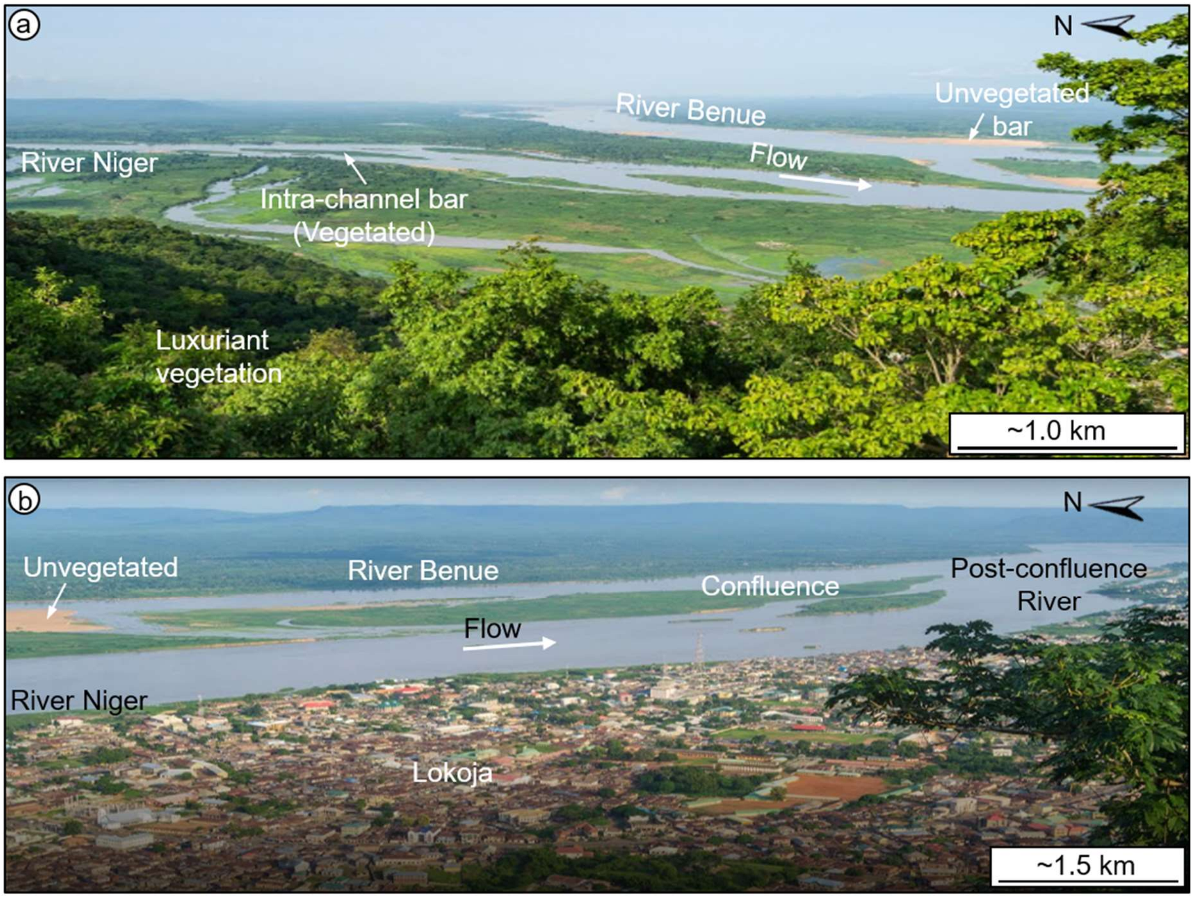

Fig. 3. Images showing the confluence of Rivers Niger and Benue. The acute-angled confluence tip planform, bars, and segmented nature of the confluence as well as the highly vegetated nature of the area are discernable (a, b). Along the western floodplain of the Niger River is the city of Lokoja (b). Images were taken in 2017 from the top of Mount Patti. Source: Adapted from Google Arts and Culture; https://artsandculture.google.com/story/mount-patti-a-spectacular-viewpoint/AwJydnJcqNFkJA.

Lokoja is characterized by Guinea Parkland savannah vegetation type, with tall grasses and trees that are green in the wet season and dried-up in the dry season. Annually, rainfall begins around March/April, ceases in October/November, with a short break in August (Olatunde & Adejoh, 2017). This rainfall pattern contributes to the seasonal floods and increased river flow experienced seasonally in Lokoja and its environs. The floods are mainly attributed to the opening of the Lagdo and Kainji dams located upstream of Lokoja along the Benue and Niger Rivers respectively (Laë et al., 2004). Available data (Fig. 2) indicate annual runoff at the confluence increased from 1987 to 2010, with a sharp increase from the late 1980s to early-mid 1990s (Dada et al., 2018). The study area, including the confluence, and banks of Rivers Niger, Benue and Post-confluence are densely vegetated (Fig. 3). An exception is the western bank of River Niger, which hosts the city of Lokoja. In this area, patches of vegetation are observed along the riverbank and around buildings.

The stratigraphy of the Niger Basin ranges from ancient Archean formations to recent alluvial deposits, through which the river flows and erodes, contributing to its yearly sediment load (Andersen et al., 2005). From Jebba to Lokoja (Fig. 1), the floodplains of River Niger are composed of a mixture of organic-rich, coarse Quaternary alluvial deposits, while the deposits become sandy and form recent sandbars along the river channels, with weathered lateritic soils present in adjoining areas (Adojoh & Dada, 2015; Olatunde & Adejoh, 2017). The alluvial deposits on the plain extend to the Benue valley and all the way to Chad (Andersen et al., 2005). The confluence area is underlain by Precambrian basement complex rocks, which stretch as far as SW Nigeria and other parts of northern Nigeria. At the confluence, the basement rocks are uncomfortably overlain by Upper Cretaceous sediments (Adojoh & Dada, 2015; Andersen et al., 2005). Along the river channels, low-lying basement rock outcrops are observed owing to river incision and erosion of the Cretaceous sediments by the rivers (Adojoh & Dada, 2015). Furthermore, the confluence area is bordered in the northwest by the Agbaja Plateau. Further south of this plateau and closer to Lokoja is Mount Patti, which is relatively smaller than the former. South of the confluence is a similar system of plateau that has a SW-NE trend and up north between the arms of the Niger and Benue Rivers is the Katon-Karfe plateau (Adojoh & Dada, 2015).

According to Adeleye, (1973), the systems of plateaus are composed of Campano-Maastrichtian sediments that are capped and preserved by a thick bed of lateritic, pisolitic and oolitic sediments, dropping steeply to the crystalline basement.

3. Data and research methods

Elevation map of Rivers Niger and Benue confluence area was computed using shuttle radar topography mission digital elevation model (SRTM DEM) with a spatial resolution of 30 m (1-arc second). The DEM was provided by the United State Geological Survey, downloaded via https://dwtkns.com/srtm30m/ and loaded into Esri's ArcMap software. The downloaded SRTM DEM is ready-to-use, was not processed further and the three-dimensional representation was generated in Esri's ArcScene software. The DEM was also used to generate cross-sections to understand the planform morphology of the rivers and confluence area. Georeferenced Landsat images of 1987, 2006, 2013, 2015, 2018, and 2022 (collectively standing for a 35-year period) were also analyzed to reveal the planform dynamics of the confluence. The images have 30-megapixel resolution and were generated and downloaded using Esri's Landsat Explorer application that is available at https://livingatlas2.arcgis.com/landsatexplorer/. Rivers Niger and Benue have km-scale widths, making it easy to find them and delineate planform changes along them and their confluence. All the images were downloaded on January 28, 2022. To avoid problems which could arise from seasonal variations in discharge and unavailability of data for the same month, December data was used for the specified years, except for 2022, for which we used January data. December and January are regarded as off-flood months in which discharge has reduced tremendously and reached normal threshold in the study area (NIHSA, 2021). Using data from these periods helped to reduce errors that could arise in the identification of morphological features such as bars (Dixon et al., 2018). Furthermore, data for some years, including 2012 are unavailable on the Landsat Explorer platform. To avoid visibility problems, which could hinder our analysis, images with cloud cover ranging from 0 to 10% were downloaded and used. Preference for lowest cloud cover images also limited image availability.

To understand the variations in confluence or junction angle within the 35-year period, the approach of Hackney and Carling, (2011) was adopted to measure the junction angle from one year to the other. The approach involved drawing centerlines within Rivers Niger and Benue and the post-confluence river to three channel widths from the confluence and measuring the angle formed at the intersection of the centerlines of the two rivers. To understand the overall changes in channel course and location of the riverbanks (i.e., expansion or contraction) between 1987 and 2022, a shapefile of 1987 planform was cautiously prepared, digitized and superimposed on the 2022 image. Additionally, shapefiles of the confluence area were made for all available years and compared with themselves to understand changes in confluence planform. Measurement error arising from the digitization is ±5 m, which is small considering the hundreds of meters-scale changes observed in the area. The separation between the 1987 and 2022 riverbanks was measured at specific locations to estimate how much the riverbank has changed or expanded. This was complemented by using the Landsat Explorer's *Change detection* tool (https://livingatlas2.arcgis.com/landsatexplorer/) to automatically compute the changes between the two dates i.e. an earlier and a later date. The computed changes were rendered in geology mode to highlight all locations where changes in planform exist between the two years. Subsequently, the changes were computed by assigning colors, say purple and green to planform features from the two different years and superimposing them to detect sites of possible changes. All the images were then extracted and exported as georeferenced high-resolution TIFF files from Landsat Explorer and were imported into ArcMap for further analysis.

Analyses performed include estimating bar migration rate, river channel expansion, and the area of the eroded part of bars. In this study, the rate of bar migration explains how far a bar has migrated or moved from a reference point over a specified period, while river channel expansion reveals increase in the width of a river channel at specific locations over a specified period. To estimate the rate of bar migration between two dates, the separation between the location of the bar in a previous year and its location in a more recent year was measured and divided by the difference of the two years. The distance was measured from the center point of the bar in an earlier year to its center point in a later year. In this work, the area of eroded part of a bar is explained as the surface area of the missing or eroded part of a bar as determined from the comparison of the planform of the bar on an earlier date to its morphology on a later date. Where the area of eroded or dislodged part of a bar was estimated, polygons were created around the area and the area of this polygon was calculated in ArcMap and taken as a representation of the surface area of the eroded portion of the bar.

4. Result

4.1 Planform morphological characteristics.

In the study area, Rivers Niger, and Benue display north-south and northeast-southwest trajectories, respectively (Fig. 4). In their upstream sections, they have a separation of up to 7.8 km, which declines southward until it pinches-out at the tip of a Y-shaped confluence, forming a post-confluence river at Lokoja (Fig. 4). Rivers Niger, Benue, and their flood plains are located in low-lying areas that are flanked by high elevation areas (Fig. 4). Upstream, River Niger is flanked on its western border by a prominent, extensive, irregularly-shaped, and NW-SE trending ridge that is up to 428 m high (above sea-level) and extends for more than 8 km southward into the study area (Figs. 4 and 5) i.e. the Agbaja Plateau (Adojoh & Dada, 2015; Omada & Owadi, 2009).

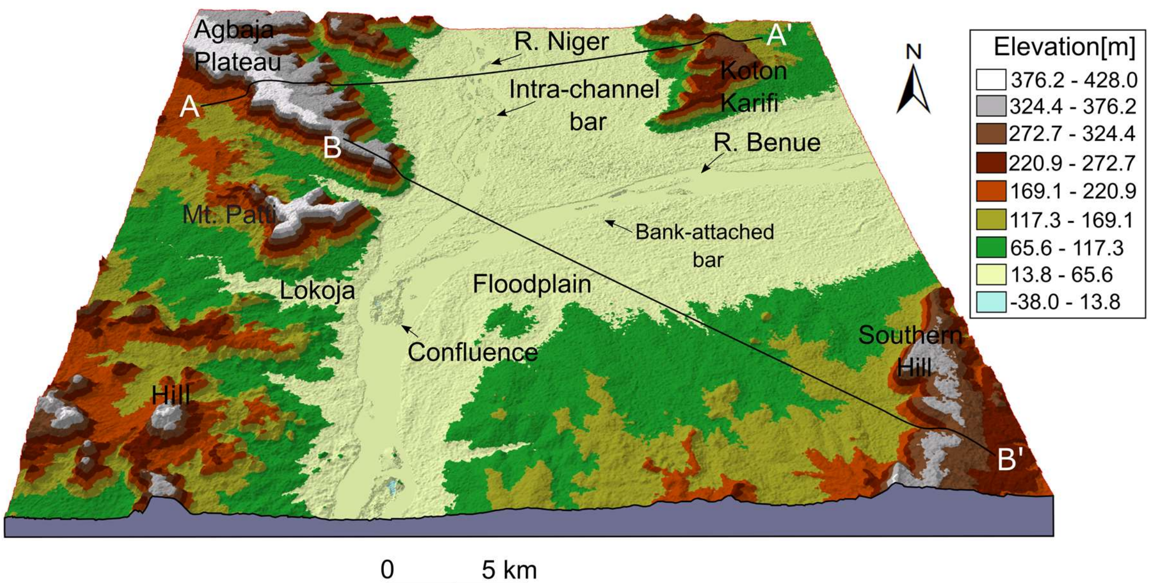

Fig. 4. 3D view of the confluence between River Niger and Benue as derived from shuttle radar tomography mission (30 m resolution) digital elevation model of the area. Hills, including the Agbaja Plateau, Mt. Patti and Koton Karfe surround the confluence. Black lines indicate the outlines of profiles shown in Fig. 5.

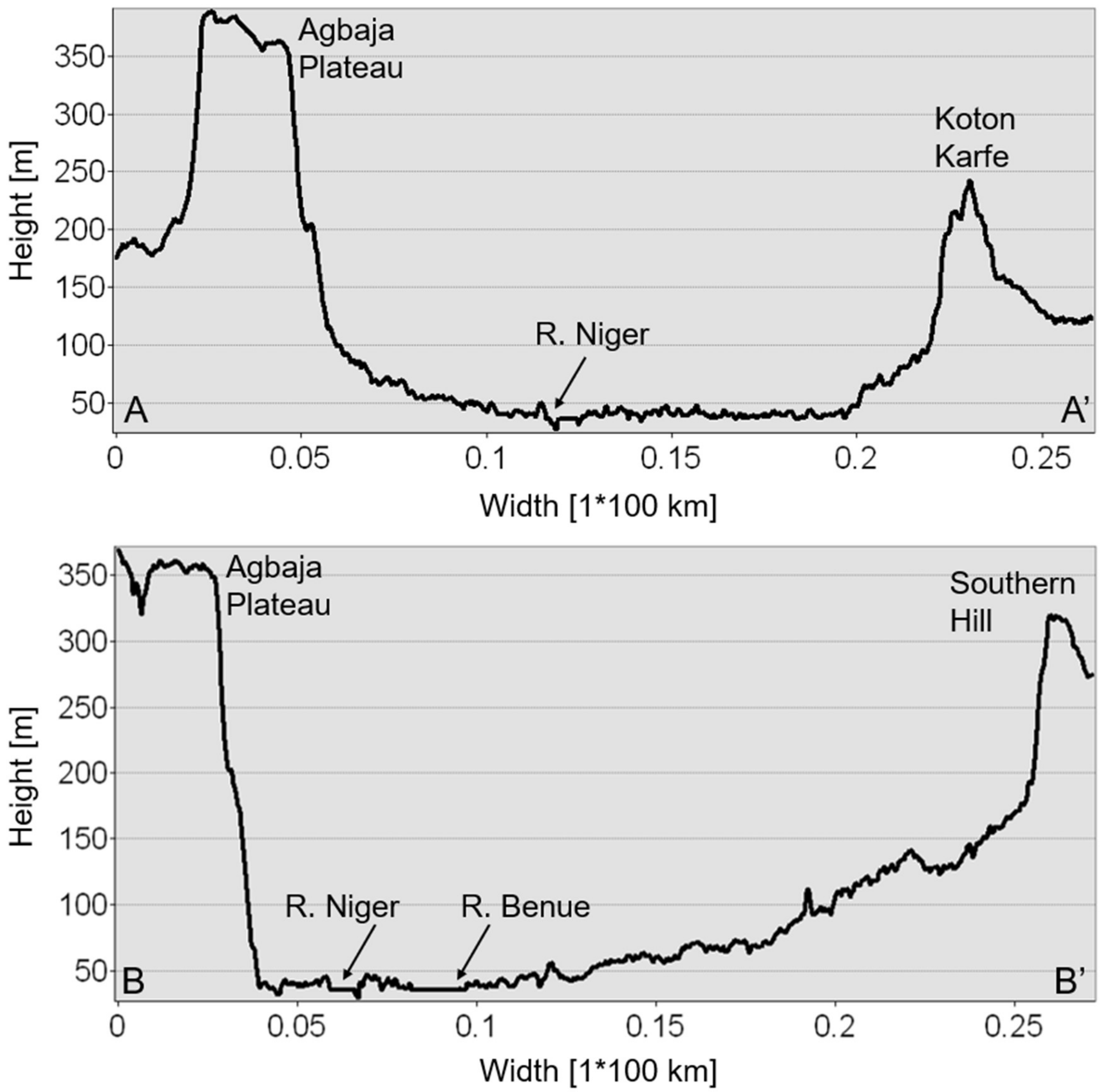

Fig. 5. Cross-sections showing the topography across the study area, mainly between ridges. (Top) Agbaja Plateau to Koton Karfe through River Niger. (Bottom) Agbaja Plateau to Southern Hill through Rivers Niger and Benue. *Location of the topographic profiles is shown in Fig. 4 as transects A-A' and B-B'.*

The trajectory of River Niger exhibits a slight bend at the location of the Agbaja Plateau (Fig. 4). This is in response to the occurrence of the ridge, indicating that River Niger is relatively younger than the ridge and that the ridge impeded the flow of the Niger, forcing it to adjust its flow path downstream. Further south at the confluence, River Niger is flanked on its western side by an up to 428 m high (above sea-level) ridge i.e., Mount Patti. This ridge is star-shaped at its southern end, NW-SE trending, and extends for more than 3 km into the study area (Fig. 4). South of Mount Patti and west of the post-confluence river is another system of ridges that is up to 350 m high and irregularly shaped. Ridges in the western part of the study area appear to be dissected by the floodplains of River Niger and the post-confluence river, which extend for several kilometers westward i.e., landward (Fig. 4).

Another system of ridge, referred to as southern hill in Fig. 4, flanks the southern bank of River Benue. The elevation of this ridge is about 50 m close to the river and up to 350 m further south (Fig. 5). The floodplains of the post-confluence river along its eastern flanks reach adjoining areas at the bottom of this hill. Further north, the Koton Karfe Plateau, found in between Rivers Niger and Benue is up to 300 m high and irregularly shaped (Figs. 4 and 5). Like the others in the study area, these ridges are flat-topped and have steep margins (Fig. 4). Rivers Niger and Benue are further characterized by regularly to irregularly shaped, up to 800 m wide and 42 m high bars (Figs. 3 to 6). These bars are either attached to the channel flanks or located within the channel. Upstream, the estimated width and depth of the Niger and Benue Rivers are ca.1.40 km, ca.36 m and ca.1.7 km, 35 m, respectively (Figs. 4 and 5). At the confluence, the widths of the two rivers are ca. 1 km. Depth and width of the post-confluence river are >37 m and 1.24-1.73 km, respectively. The width of the post-confluence river is in the same range as that estimated for the post-confluence river of the Orinoco and Meta Rivers in Columbia (Dixon et al., 2018).

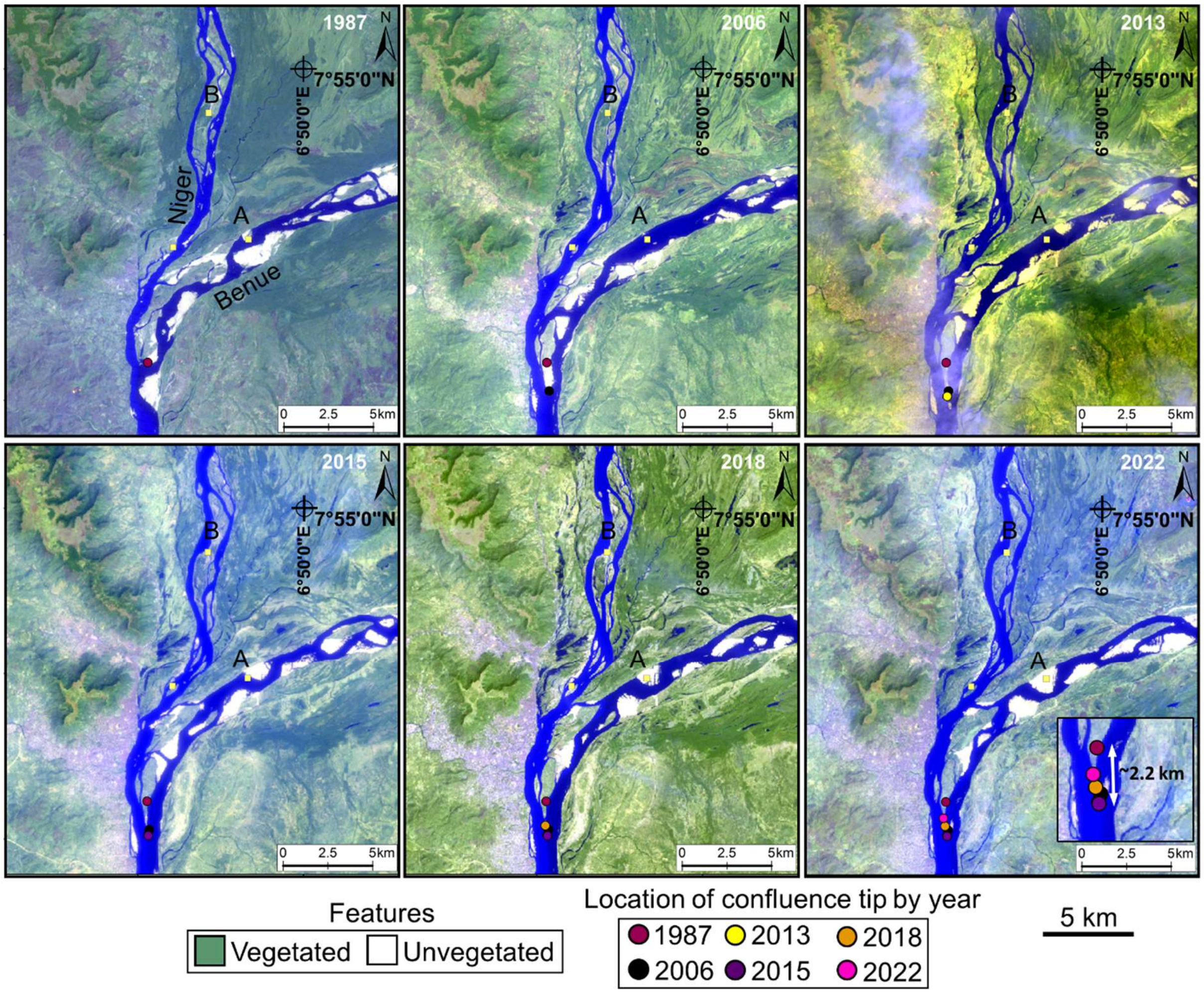

Fig. 6. Landsat images (1987-2022) revealing planform changes at the confluence of the Niger and Benue Rivers. The position of the confluence and its tip shifts over time as bars are formed, displaced, and eroded within the two rivers. The position of the tip of the confluence changes from year to year within a narrow zone that is up to 2.2 km wide. Yellow polygons and alphabets (A, B) are used to infer bar erosion and migration in places within the study area.

4.2 Upstream-downstream confluence migration and changes in confluence angle and form.

The images presented in Fig. 6 reveal southward (downstream) and northward (upstream) changes in the location of the tip of the confluence. The downstream extension is observed between 1987 and 2013. No net change in the location of the tip was observed between 2013 and 2015. Between 2015 and 2022, the tip location moved upstream, showing that the confluence tip has experienced upstream migration. Collectively, this shows upstream and downstream migration of the confluence tip within a zone that is about 2.2 km wide between 1987 and 2022 (Fig. 6). This 2.2 km estimate is twice the widths of Rivers Niger and Benue at the confluence, ca. 1.6 times the upstream width of River Niger, and ca. 1.3 times the upstream width of River Benue in this area. Moreover, the confluence angle also changed over time from ca. 175° in 1987 to ca. 50° in 2006, ca. 30° in 2013, ca. 27° in 2015, and a ca. 16° in 2018 and 2022 (Fig. 7).

The morphology of the downstream tip of the confluence changed from near flat in 1987 through a semi-pointed tip morphology in 2006 to a pointed sharp-edged morphology in 2022 (Figs. 6 and 7). The change in morphology is accompanied by a limited lateral expansion of the confluence within a zone that is ca. 3.5 km wide in the upstream part of the confluence (Fig. 8a) i.e., ca. 2.5 times the upstream width of River Niger and ca. 2.16 km wide in the middle of the confluence. The change is further linked to the erosion or dislodgment of parts of the confluence (Figs. 6-8). For instance, the western edge of the confluence is eroded inward by about 0.71 km between 1987 and 2022 (Fig. 8a). This edge extends outward into the river channel on the 1987 image (Figs. 6-8), when it would probably have been an obstruction to flow, rendering it susceptible to erosion or dislodgment from the main confluence as flow impacts on it. Hence, it is missing on the post-1987 images (Figs. 6-8).

An overall reduction in width along the confluence is also noticed from 1987 to 2022 (Fig. 8). Within this period, the location of the external banks of the rivers is relatively fixed, except for a few changes observed upstream of the confluence along the two rivers and within the Benue, near the confluence (Fig. 8a). In addition, Fig. 8b reveals significant reduction in the width of the confluence by up to 0.4 km from 2006 to 2013 albeit the changes are mostly concentrated in the

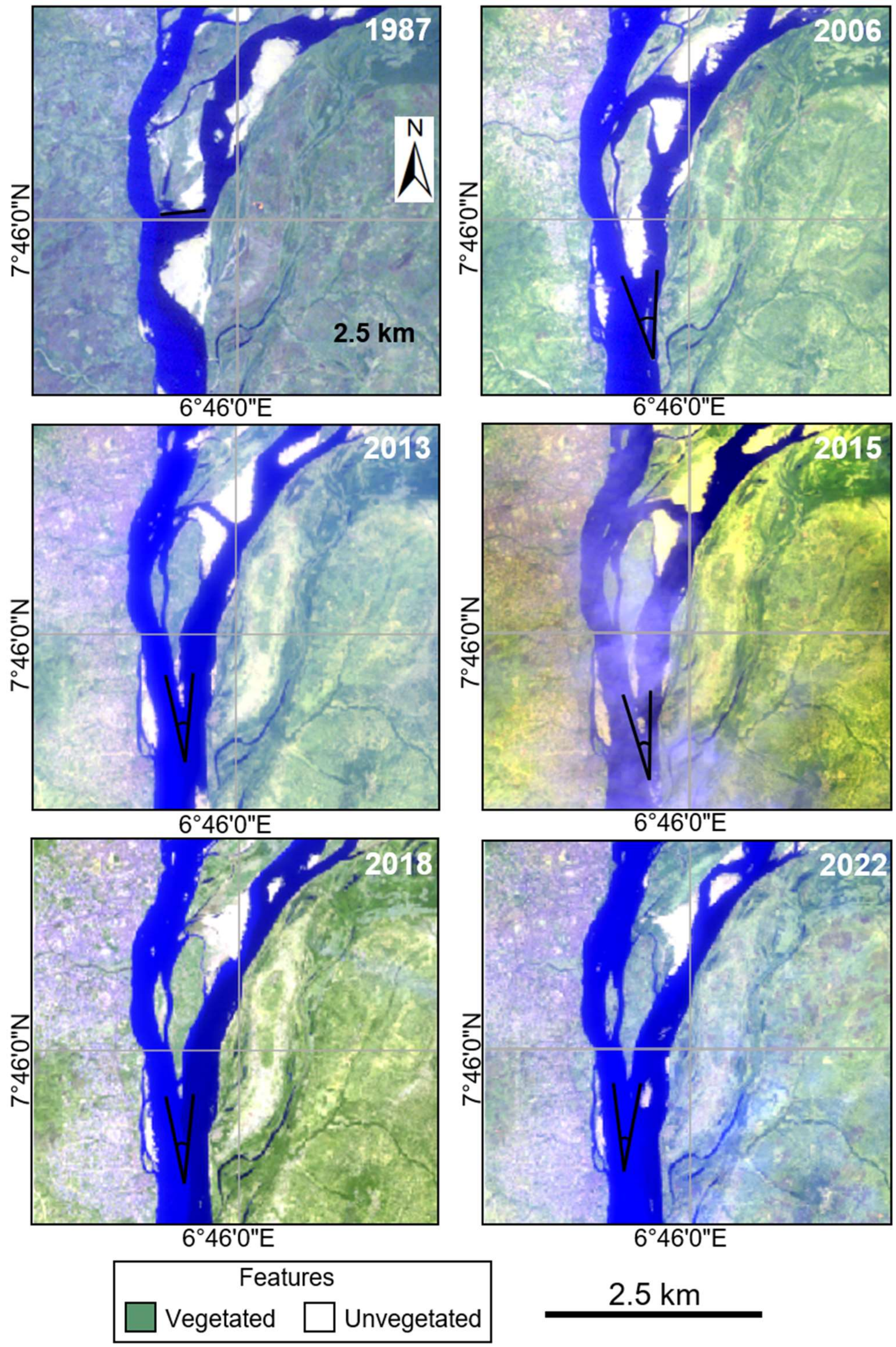

Fig. 7. Detailed view of Landsat images from 1987 to 2022 showing changes in morphology and confluence angle. Images also show segmentation of the confluence.

River Benue portion. The position of the external banks of Rivers Niger and Benue remained fixed within this period (Fig. 8b). A striking feature of the confluence is its segmented nature, which was more clearly seen in the post-1987 images (Figs. 6 to 8a-d). Two major segments are visible on the 2006 image, three on the 2013 and 2015 images, and two that are ca.0.24 km apart on the 2018 and 2022 images (Figs. 6 and 7). The confluence segments are also found on the ground truth images from 2017 (Fig. 3). Where the segments changed from three to two, we observe that two segments are joined by unvegetated sediments/bars, indicating recent deposition of sediments (Figs. 6 and 7). Overall, there is a net downstream/southern extension of the confluence tip by about 880 m in the study area between 1987 and 2022 (Fig. 8d).

4.3 Intra-channel and bank-attached bars.

Figs. 5 and 7 show the presence of multiple bars upstream of Rivers Benue and Niger and at the confluence. While the intra-channel and flank-attached bars are observed within the two rivers, the flank-attached bars are more common in the Benue River. Intra-channel bars within the Niger and confluence area, are commonly vegetated while flank-attached and intra-channel bars within the Benue are commonly unvegetated (Figs. 6 and 8a-c). Consequently, a reduction in the sizes of some intra-channel bars upstream of the confluence over the 35-year period is observed. For instance, in the location marked B upstream of River Niger, a north-south oriented vegetated intra-channel bar is identified (Figs. 6 and 8d). Although the position of the bar remained relatively fixed between 1987 and 2022, there is a marked reduction in the size of the bar in 2022 relative to 1987 (Figs. 6 and 8c-d). Estimated surface area of the missing portion is 5.86 km^2. Furthermore, at the upstream portion of River Benue near the confluence, a decrease in the separation of a bar and a reference point to its northeast (yellow dot near point A) was observed between 2013 and

2022 (Fig. 6). Estimated distance between the dot and the center of the bar was 1.05 km in 2013. In 2018, the distance between the two points reduced to 0.19 km, while in 2022, the bar widened, and its center coincides with the location of the dot. This indicates that the bar grew and migrated downstream over ca.1.05 km between 2013 and 2022 i.e., at an average rate of ca.120 m/year.

4.4 Marked evidence for river channel expansion.

Although the locations of the vegetated external banks of the rivers remained relatively fixed as changes were observed at only a few places, mainly along the western bank of River Niger in the upstream part of the confluence (Fig. 8c). Despite this, local, but significant increases in width were observed along the channels of Rivers Niger and Benue and the post-confluence river between 1987 and 2022 (Fig. 8c-d). At the eastern flank of the post-confluence river, a local increase in channel width of about 1.2 km was estimated due to the erosion of a bank-attached bar. The increased width is accompanied by the occurrence of a smaller but linear bar just next to this location on the western flank of the river (Figs. 6 and 8). The net result of this is an increase in channel width in that location. Upstream of the same river, its 1987 western bank was observed to have moved landward by ca. 0.1 km, signifying landward expansion of the Niger River channel due to bank erosion in this area (Fig. 8c). This expansion is confirmed by the change detection image computed for the period (Fig. 8d). Apart from these changes, there appears not to be any more significant landward bank expansion in the area between 1987 and 2022. At the eastern bank of River Niger near the confluence, a reduction in the width of the confluence along its western flank by ca. 0.67 km was estimated, promoting the expansion of the Niger channel in that location (Fig. 8c-d). Evidence of increasing river channel width is found in several locations along the eastern flank of River Benue, including at its upstream, intermediate, and downstream parts, between 1987 and 2022 (Fig. 8c-d). Downstream of the river channel, an increase in width was identified owing to the erosion of an ca. 0.52 km wide bank-attached bar that extended into the river on the 1987 image (Fig. 8c-d). Midway along the confluence, where it divides into two segments on the River Benue axis on the 2022 image (Fig. 8c-d), the initial (1987) channel width has widened on the present-day (2022) image due to the erosion or dislodgment of parts of the confluence. Upstream of the same river, a localized increase in the width of the channel by ca. 0.52 km is noted due to the erosion of an unvegetated bank-attached bar (Fig. 8c-d). No evidence of lateral migration or avulsion of the rivers was observed over the 35-year period in the study area.

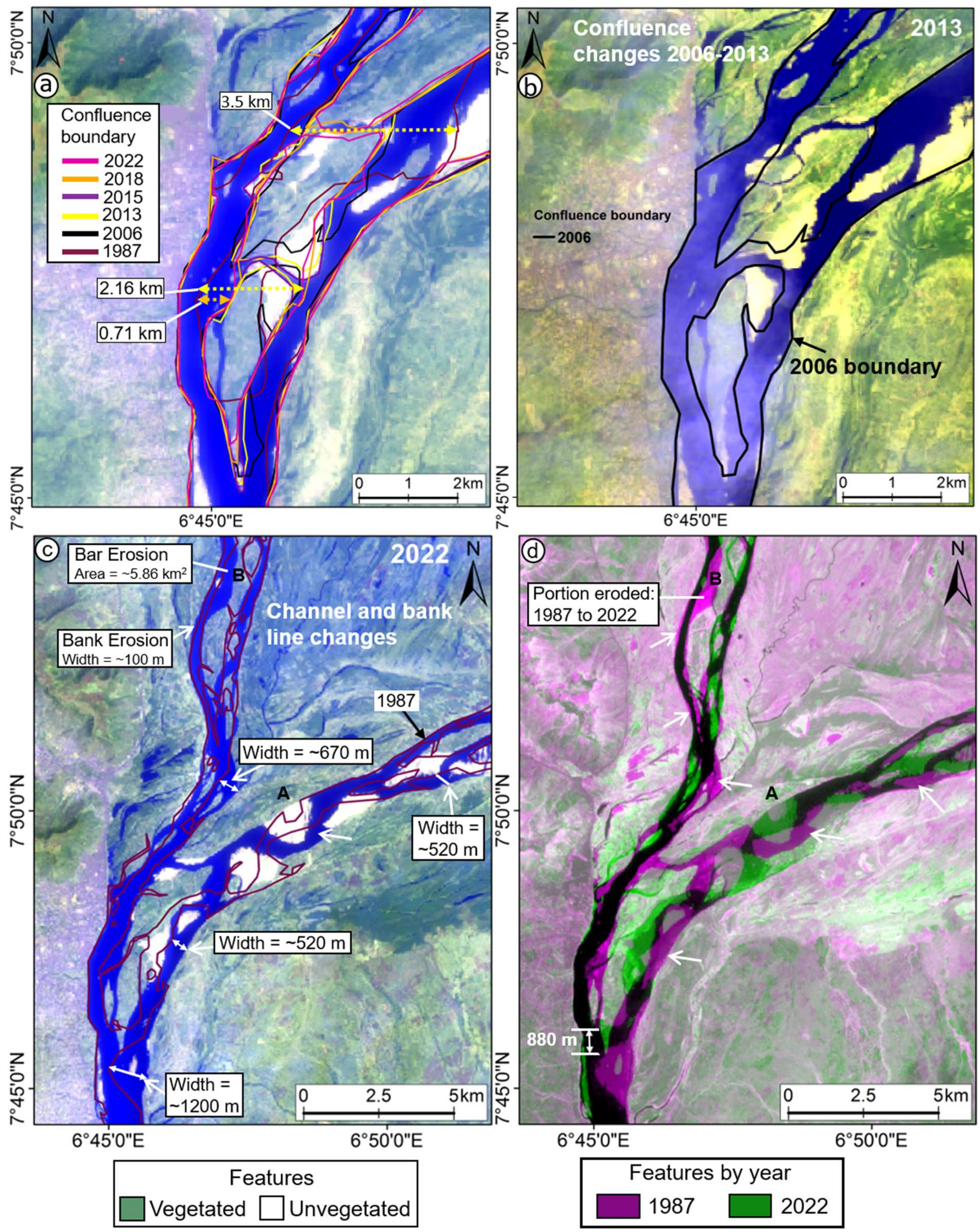

Fig. 8. Planform changes at the confluence of Rivers Niger and Benue between 1987 and 2022. (a) Shapefiles of the various years superimposed to show morphological changes in the confluence area. (b)

Shapefile of 2006 morphology superimposed on the Landsat image of 2013 to show morphological transformation within the period. (c) Shapefile of 1987 confluence morphology is placed on the 2022 Landsat images to show overall changes in planform over the 35-year period. (d) Change detection image showing morphological changes at the confluence and rivers between 1987 and 2022. White arrows indicate locations where changes in river channel width were observed.

5. Discussion

5.1 Architectural changes in planform morphology from 1987 to 2022

Results of this study show that the Rivers Niger and Benue confluence is undergoing drastic changes to its planform morphology. These changes are primarily indicated by variations in confluence angle and form, changes in channel widths of the Niger, Benue, and post-confluence river, and bar migration over a 35-year period. A 2.2 km confluence migration window was estimated in the study area. This estimate is significant when compared to a similar tropical confluence at the junction of the Congo and Kasai Rivers in the Democratic Republic of Congo that exhibited no migration between 1984 and 2014 (Dixon et al., 2018), and probably till date. However, it is less significant in comparison with the 12-14 km estimate at the confluence of the Ganges and Jamuna Rivers in Bangladesh between 1973 and 2014 (Dixon et al., 2018; Sambrook Smith et al., 2019). In addition, confluence migration has been linked to shifts in scour location in the direction of confluence migration (Ashmore & Parker, 1983; Dixon et al., 2018; Sambrook Smith et al., 2019). Based on this, it is suggested that the upstream and dominant downstream migration of the confluence tip allows a northward and dominant southward shift in scour location in the study area. Moreover, dominant downstream confluence migration as observed in the Niger-Benue confluence (Fig. 6) is likely to promote sediment deposition or bar formation downstream of the scour hole and within the post-confluence river (Best, 1986).

A significant decrease of over 150° in confluence angle from ca.174° in 1987 to ca.16° in 2022 is shown in the study area (Fig. 7). These estimates are greater and smaller than the upper and lower limits of the angles (100^0 - 60^0) estimated for the Orinoco-Meta Rivers confluence (1973 - 2014) (Dixon et al., 2018), where post-confluence channel width (1-2 km) estimate is like the present study area. In the study area, decreasing confluence angle over the 35-year period is likely to have caused a decrease in scour depth and promoted a change in scour pattern in front of the confluence as water and sediments arrive (Best, 1988; Mosley, 1976). Therefore, the very wide confluence angle of 1987 would have resulted in remarkable scouring. As Mosley, (1976) reveal there is no appreciable scour up to a confluence angle of 15° and scour depth increases rapidly just above this value, it is argued that present-day scour in the Rivers Niger and Benue confluence may not be significant due to a low confluence angle of around 16°. Past research (Ashmore & Parker, 1983; Best, 1986) also shows that decreasing confluence angles push the scour zone to change from basin- to trough-shaped morphology. Consequently, scouring in the study area is likely to have moved from changing a broad basin-shaped area around 1987 to changing a small trough-sized area at the front of the confluence today. However, the unavailability of bathymetric data for this study means we are unable to verify the exact morphology of the present-day scour hole. Wide confluence angles may further indicate higher slope of the tributary relative to the main river, while a small confluence angle signals nearly equal slopes (Howard, 1971). It is therefore likely that the decrease in confluence angle over the 35-year period in this area corresponds to a decrease in the relative slope of the Benue compared to the Niger near the confluence.

This study reveals that the confluence is segmented, ranging from two to three segments and that the spacing between segments can be about 0.24 km (Figs. 6-8). These observations prove multiple confluence junctions rather than one, promoting complex and changing flow dynamics within the study area. Based on the observations, the likelihood of the existence of varying scour patterns that are associated with the migration of the confluence segments (cf. Dixon et al., 2018) and sediment deposition and erosion at each junction is suggested. Moreover, where three confluence segments become two within the study area, unvegetated bars are observed at their junctions, promoting the bridging of confluence segments and changes in confluence morphology. Past research (Costard & Gautier, 2008; Dixon et al., 2018) has also revealed a similar multi-junction/segment confluence consisting of multiple migrating bars at the junction of the Aldan and Lena Rivers in Russia.

5.2 Erosion and migration of bars

Within the confluence area, bars formed and are eroded over the period 1987–2022 and are emergent during low flow as seen on the Landsat images (Figs. 6-8). It is therefore suggested that these features are linked to sediment supply and deposition within the rivers due to waning flow velocities and low downstream sediment transport ability. Further downstream of the present study area, the development of bars has been attributed to damming or impoundment of Rivers Niger and Benue (Abam, 2001; Dada et al., 2018). This has been revealed to cause a significant drop in discharge at the confluence from 7000 m^3/s in the pre-dam years to 3000 m^3/s in the post-dam years (Abam, 2001), which is likely to encourage sediment deposition. In addition, bar development seems to be more effective in the Benue than in the Niger due to the abundance of bars in the former (Figs. 6-8). Roy and Sinha (2007) show that bar formation in the confluence area of the Ganga-Ramganga streams confluence is related to a decrease in the slope of the Ramganga (tributary) relative to the Ganga (main). The abundance of bars, especially the unvegetated bank-attached types in the confluence area in the Benue relative to the Niger is perhaps related to a decrease in the slope of the Benue relative to that of the Niger and reduced flow over the years, favoring widespread bar growth in the Benue River side of the confluence. This inferred decrease in slope also aligns with the reducing confluence angle observed between 1987 and 2022 in the study area. The occurrence of bars within the rivers, particularly the unvegetated nature of many of the bars within River Benue makes them susceptible to erosion and disintegration, allowing further downstream transport of sediments and addition of materials to confluence junctions. Hence, the formation and erosion of bars within and at the mouth of the rivers coupled with flow promoted downstream addition of sediments to the confluence, causing changes to its morphology.

In addition, the occurrence of bars within the Niger and Benue Rivers and the segmented nature of the confluence as discussed above points to the possibility that the confluence formed from multiple downstream migrating bars, which are potentially mainly sourced from the Benue. The presence of these bars generally dictates channel width within the two rivers and the post-confluence river and play a significant role in influencing the direction of flow. This has consequently limited efficient transportation of people and goods along major sections of the two rivers (Andersen et al., 2005). This study further reveals reduction in the surface area of a vegetated bar by up to 5.86 km^2 in the upstream section of River Niger. This reduction probably occurred due to erosion and dislodgment of sediments at the western flank of the bar, forcing the eroded or dislodged materials to migrate downstream towards the confluence. Moreover, the static state of the bar over the 35-year period may be linked to its vegetated nature, which is likely to have enhanced its stability and resistance to erosion (Knox, 2008). Furthermore, the ca.120 m/year migration rate estimated for a bar at the upstream part of the Benue River (near the confluence) indicates appreciable migration rate for the bar. Bar migration in this area is likely to have been driven by the appreciable sediment supply and water discharge that accompanies floods in the area as such pulses can account for the ca.120 m/year bar migration rate inferred within the Benue River. Therefore, downstream bar migration that would enhance sediment supply to the confluence and confluence erosion could explain changes in its morphology from a wide-angle confluence of 1987 to a small-angle confluence in 2022.

5.3 Possible controls on bank processes and morphology of the confluence

Availability of erodible materials

Confluences in areas with important geological and other controls may show varied morphological changes over decadal timescales (Dixon et al., 2018). The confluence of the Niger and Benue Rivers is perhaps an example of this type of environment. Results have shown landward bank expansion of up to 100 m at the western bank of River Niger, with expansion in other places being less significant. The most significant channel expansion was recorded at the location of bank-attached unvegetated bars along the eastern bank of the Benue and post-confluence Rivers, while it is limited along other banks. This observation suggests the unvegetated bank attached sandbars are susceptible to erosion. Furthermore, paucity of bank-attached bars along other banks coincides with the lower rate of channel expansion observed along those banks, thus indicting that those banks are likely to contain less erodible materials. As most of the river banks in the study area are vegetated, their resistance to erosion is expected as this is most likely contributed by their highly vegetated nature, significantly enhancing their stability and increasing their resistance to erosion (Knox, 2008). Therefore, the presence of erodible materials and occurrence of vegetation along the banks are important controls on channel and bank expansion in the study area.

Occurrence ridges and bedrock control

Another factor that may have contributed to the limited expansion along the western bank of the Niger and post-confluence Rivers may be the restriction exerted by the existence of the large ridges or plateaus which mainly flank the western bank of the Niger River and its flood plain. Ridge control was evident as the Niger River bends around the extensive Agbaja Plateau in its upstream portion (Figs. 4 and 6). The occurrence of ridges, particularly along the western flank of the Niger River is expected to exert a restraint on that flank of the river, thereby limiting its ability to expand. However, because expansion is generally limited along all the river banks in the study area, even along those that are not flanked by ridges, it is suggested that the occurrence of ridges along River Niger is not the primary factor limiting expansion along its bank. Adojoh and Dada, (2015) reveal that the floodplains of the Niger and Benue Rivers are made up of organic-rich Quaternary to Recent alluvial sands, while the river channels are characterized by recent alluvium, sandbars, and ancient basement outcrops. These generally mean that the rivers should be able to adjust their planforms easily at least because they have erodible floodplains and can flow easily above the basement rocks. However, the rivers show no evidence of migration within 35 years, and this could potentially point to a generally reduced flow capacity of the rivers over the years. Moreover, the basement rocks are expected to exert a strong bedrock control and would limit the ability of the rivers to carve into them, thereby limiting the depth of the rivers.

Discharge, runoff, and sediment load

Given the marked reduction in discharge and flow experienced in the area following the construction of dams (Abam, 2001; Dada et al., 2018), we envisage that the reduced flow in the area must have contributed to the limited expansion experienced along the banks of the rivers.

Lower discharge and flow generally reduce river bank erosion and increase bar development in the rivers (e.g., Abam, 2001). Importantly, a sharp increase in annual runoff from about 4200 m^3/s in the late 80s to about 6400 m^3/s around the mid-90s and returning to about 6400 m^3/s in 2010 has been revealed at the confluence (Fig. 2). The period of enhanced runoff from late 80s to 2010 in fact corresponds to the period in which drastic changes (from large angle-1897 to acute angle-2010) in confluence angle began in the study area. Consequently, it is suggested that enhanced runoff in the confluence area is a primary factor driving morpho-dynamic changes at the confluence.

Considering the reduced discharge and runoff at the confluence are accompanied by reduced sediment load (Abam, 2001; Dada et al., 2018), we suggest the reduced sediment load must have played a key role by limiting the amount of sediments available and deposited for bar formation at the confluence. Hence limiting the rate of migration of the confluence and forcing a drastic change in its angle between 1987 and 2022. Past researches (e.g., Dixon et al., 2018) have shown that sediment load is an important factor influencing morpho-dynamic changes at confluences. The Niger/Benue Rivers confluence area experiences annual/recurrent, but seasonal floods which come with huge water and sediment discharge (Buba et al., 2021; Dada et al., 2018; Odunuga et al., 2015). These events are generally triggered by the release of water at the Kainji and Lagdo dams located upstream of the Niger and Benue rivers, respectively (Fig. 1). Complementing flooding is regionally variable (Conway et al., 2009), but significant annual water contributions from an average rainfall of 1,185 mm in Nigeria (FAO, 1997). Recurrent floods, including record floods of September 2012 (31,696 m^3/s combined flood flow, 12.84 m water level) and 2020 (23,459 m^3/s combined flood flow, 11.89 m water level) within the study area usually generate high river flow power and discharge before dropping to off-flood values which can be around ca.5,327 m^3/s: ca.2.7

m water level in December (NIHSA, 2021). The significant change in confluence morphology between 2006 and 2013 (Fig. 8b) may be related to the 2012 flood, the impact of which has been documented within the Lower Niger segment (Dada et al., 2018).

Higher river flow power during floods would lead to the erosion of sandbars and river banks (Pal & Pani, 2019), causing channel expansion as inferred in places within and away from the confluence area (Fig. 6). The yearly flood-enhanced pulses of increased sediment supply would also lead to the development and emergence of bars and shrinkage of floodplains when water level lowers (Rice et al., 2009). Worth mentioning is the impact of discharge ratios of the two rivers on the morphology of the confluence. Although discharge data at the confluence is not available for this study, based on the morphological changes observed at the confluence, it is suggested that the reducing confluence angle from 1987 to 2022 points to an overall decadal-scale decrease in the discharge ratio of the rivers (e.g., Best, 1988, 1986). Considering the present-day confluence is acute-angled, it is expected that the present-day runoff is still within the 2010 range or perhaps higher.

Anthropogenic activities

Anthropogenic activities in the study area may include dredging, which was carried out along the lower segment of River Niger from September 2009 to 2012 (Dada et al., 2018; VanDerBurg, 2010) and increased land use compelled by urbanization. These activities are likely to have contributed to the limited expansion along the banks, erosion, disappearance and decrease in size of some of the bars within the study area, thereby impacting the dynamics of the rivers and confluence planform. Dredging along this segment of the river has been suggested to trigger coastline erosion and subsequent shoreline recession in the Niger Delta region between December

2007 and April 2012 (Dada et al., 2018) and is therefore a potential contributor to morpho-dynamic changes in this area.

6. Conclusions

In this study, we show detailed analyses of the morpho-dynamic changes at the confluence of River Niger and Benue over 35-years. Our results show that the River Niger and Benue confluence area is bordered by up to 400 m high flat-topped ridges that have high slopes at their margins and are commonly separated by the floodplains of the rivers. The confluence has migrated predominantly downstream within a 2.2 km wide zone with a net migration of about 880 m in 35 years. A change in confluence angle from ca. 154° in 1987 to ca. 16° in 2022 is observed. The most significant change in confluence angle occurred between 1987 (154°) and 2006 (50°) because of increase in runoff from the late 1980s to 2010. This study also highlights changing segmentation patterns of the confluence, ranging from two to three segments in different years. While analyses show less significant landward bank expansion for Rivers Niger and Benue and the post-confluence river, we identify significant channel expansion along the Benue relative to the Niger. This observation is linked to the occurrence or paucity of vegetation along the rivers. Our results present significant morpho-dynamic changes at the confluence and have wider implications for understanding river and confluence dynamics and evolution, particularly for tropical rivers with low sediment load, on a global scale. The changes in confluence planform are compelled by the dislodgment and erosion of parts of the confluence, upstream erosion, and downstream migration of bars, which promoted sediment deposition and morpho-dynamic changes at the confluence. Downstream bar migration in this area is shown by the ca. 1.05 km migration of a bar within River Benue towards the confluence between 2013 and 2022.

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