Assessment of Channel Planform Adjustments in the Mubi Section of River Yedzeram, Adamawa State, Northeastern Nigeria

Ezekiel Yonnana, Mohammed Sayd Dzarma and Kadmiel Oliver

Department of Geography, Adamawa State University Mubi, Adamawa State, Nigeria
Email: ezekiel97@adsu.edu.ng

Abstract

Recent changes in the channel planform of the Mubi section of River Yedzeram were examined using field studies and Geographical Information System Analysis. Changes resulting from channel widening, incision, meandering and lateral migration processes in the channel section were examined over a period of 13 years (2006 to 2019). Impacts of the occurring changes on riparian land uses were also assessed. Results showed an average channel widening of 8.48m; meandering (sinuosity) range of 1.51 to 1.58; meander bend lateral migration rates of 32.38m at 5.40m/year (from 2006 to 2012) and 27.80m at 3.97m/year (from 2012 to 2019). A short term (2016 to 2019) channel incision rate of 0.32m/year was also observed within the embanked section of the channel. Major affected land uses were irrigation farmlands and residential structures. Riparian buffer zones mapping and restriction policies against encroachment within the zones were recommended.

Keywords: Channel bend lateral migration; Channel Incision; Channel Meandering; Channel Widening and Riparian land uses.

Introduction

River channels are bound to morphological adjustments owing to certain internal and external adjustments including human activities (Downs, 1995). Such adjustments tend to pose diverse impacts on riparian and in-streams land uses and ecosystems. A prominent form of such adjustments is channel migration. Channel migration is the process by which stream channels move and shape floodplains through time (Wolman & Leopold, 1957; Legg & Olson, 2014). It is an indicator of stream channel instability which can either occur gradually as a river erode its bank and deposits sediment along the other or abruptly as a sudden shift of the channel to a new location (avulsion), which may happen during a single flood event (Knighton, 1998; Larsen, 2007, King County, 2018).

Although the migration of stream channels across their flow paths is a natural process, it is of significant relevance to people making livelihood or to organizations planning or maintaining infrastructure within the migration zones (U.S Department of the interior Bureau of reclamation, 2008). This is because of the serious threats the migration processes pose on riparian land uses, infrastructure and human livelihood (King County, 2018). Channel migration has also been regarded as a natural phenomenon presenting challenges for engineers, scientists, and managers on how to best accommodate societal needs with the structure and processes of nature (Giardino & Lee, 2011). Legg and Olson (2014) further buttressed that human development in riverine areas liable to stream channel migration are often faced with adverse economic impacts associated with property loss and costs of erosion protection measures. They further added that stream channel migration poses threats not only to human infrastructure and farmlands but also to the ecological status of the river system by temporal disturbance and displacement of aquatic habitats and live forms. Walling *et al* (2003) also noted that channel migration into developed areas can introduce waste and contaminants into channels which impact water quality far downstream.

The three major processes through which channel migration occurs are channel widening, gradual bend migration and avulsion (Knighton, 1988). Although these processes differ in their physical mechanisms, they are often intertwined by their modes of operation such that sudden changes as avulsions at meander bends are results of gradual bend migration (Legg & Olson, 2014).

Channel width is among the major variables that control the hydraulic geometry of river systems. The relationship between channel width and other hydraulic variables have been examined by many scholars (Leopold & Maddock, 1953; Schumm & Lichty, 1963; Richards, 1976; Andrews, 1982; Parker *et al*, 2007; Alcantara, 2014). Changes in river channel width by widening or narrowing normally occur as the river undergoes adjustments towards a state of equilibrium owing to changes in other controlling hydraulic geometry variables (Simon & Collison, 2002; Parker *et al,* 2011). However, channel widening or expansion is considered as one of the major processes of channel migration (Knighton 1988; Legg & Olson, 2014). It can occur episodically in response to floods (Schumm & Lichty, 1963; Konrad, 2012) or as a long term channel modification owing to increase in stream discharges as influenced by climate change (Legg & Olson, 2014). Channel widening can also result from depletion of riparian vegetation (Brooks *et al*, 2003; Eaton, 2006)

Natural channels hardly exhibit a straight planform pattern for distances greater than about ten channel widths (Arkers & Charlton, 1970). Consequently, meanders are bound to develop along the planform owing to some inherent stream forces as explained in the conceptual models of stream meanders by Dietrich *et al* (1979) and Frothingam and Rhoads (2003). Sear *et al* (2010) further clarified that Meandering channels are those with a sinuosity greater than 1.2 and are characterized by a series of bends and intervening sinuous sections. They further noted that although the planform may be meandering, it is important to recognize that this does not mean that the river is actively eroding the outer bends and migrating across the floodplain. Thus meandering channels can be usefully divided into those that are actively meandering and those that are passively meandering, depending on the degree of bank erosion and lateral movement.

Gradual lateral channel migration which is most common along meander bends is dependent on the flow conditions within the channel and the ability of the bank to resist erosion by stream flow (Nanson & Croke, 1992). Giardino and Lee (2011) further clarified that lateral channel migration is influenced by a number of variables including land cover, hydrologic regime, bank composition and underlying geology, among others. From a similar view point, the U.S Department of the interior Bureau of reclamation developed the Sedimentation and River Hydraulics-Meandering (SRH-Meander) model which simulates river channel migration and associated bank erosion as a function of the channel bend radius of curvature, stream discharge, river channel dimensions, sediment transport capacity, and bank material properties (reclamation). Hickin (1983) observed that the rate of progressive migration is generally assumed to increase with channel centerline curvature up to some threshold, as such channel centerline curvature (an indicator of meander intensity) is assumed to be related to the spatial distribution and the magnitude of channel migration (Hooke & Harvey 1983; Johannesson & Parker 1989; Furbish 1991; Larsen 2007). Furthermore, considering the influence of river hydraulics, the rate at which channels migrate laterally generally increases with stream power (Nanson & Hickin, 1986; Richard *et al*, 2005).

Confined streams can also be subjected to channel incision (deepening) and migration if there is a change in geomorphic controls. This is capable of destabilizing stream banks and posing threats on buried pipelines, bridge abutments, and road embankments (Legg and Olson 2014).

Identification of Channel Migrating Zones (CMZs) helps tremendously in reducing the risk of property or casualty loss due to stream bank destabilization, rapid stream incision, stream bank erosion, and shifts in location of stream channels (King County, 2018). It is on the basis of this view that this study attempts to examine the nature and pattern of the recent migration of the Mubi section of the Yedzeram River channel and the associated implications on the riparian infrastructure and land uses.

Description of Study Area

The studied river channel section is located between latitudes 10°16'N and 10°18'N of the equator and between longitudes 13°14'E and 13°16'E of the Prime Meridian. It forms part of the middle course of the Yedzeram main channel which cuts across Mubi town as well as the lower section of the upper Yedzeram sub-basin. The channel section extends from Shuware Bridge to Wuro Sati settlement, covering a planform length of about 8km (Fig. 1). This length tends to slightly vary over time owing to periodic channel meandering and migration behaviour.

Mubi town is characterized by the tropical wet and dry climatic type with distinct wet season from May to October and dry season from November to April. While the wet seasons contribute to the channel's flow characteristics, the dry season is responsible for its ephemeral nature. As such its fluvial behaviour is mainly confined to the wet seasons. Over the last 14 years (2005 to 2019) of measurements and data gathering for the studied section of the channel, a mean flow velocity of $1.60ms^{-1}$; mean peak discharge of $42.21m^3s^{-1}$; mean stream bed shear stress of $26.17Nm^{-2}$ and mean specific stream power of $42.53Nm^{-2}$ have been observed.

The riparian zones of the studied channel section serve several socioeconomic and domestic purposes among which are consistent irrigation agriculture (market gardening and sugar cane plantations), residential functions, water supply (bore hole) and solid waste disposal. Major human settlements along the channel section include part of Mubi town (Shuware, Yelwa, Wuro Gude), Wuro Yuguda, Wuro Harde, Yaza, Wuro Hoba and Wuro Sati among others.

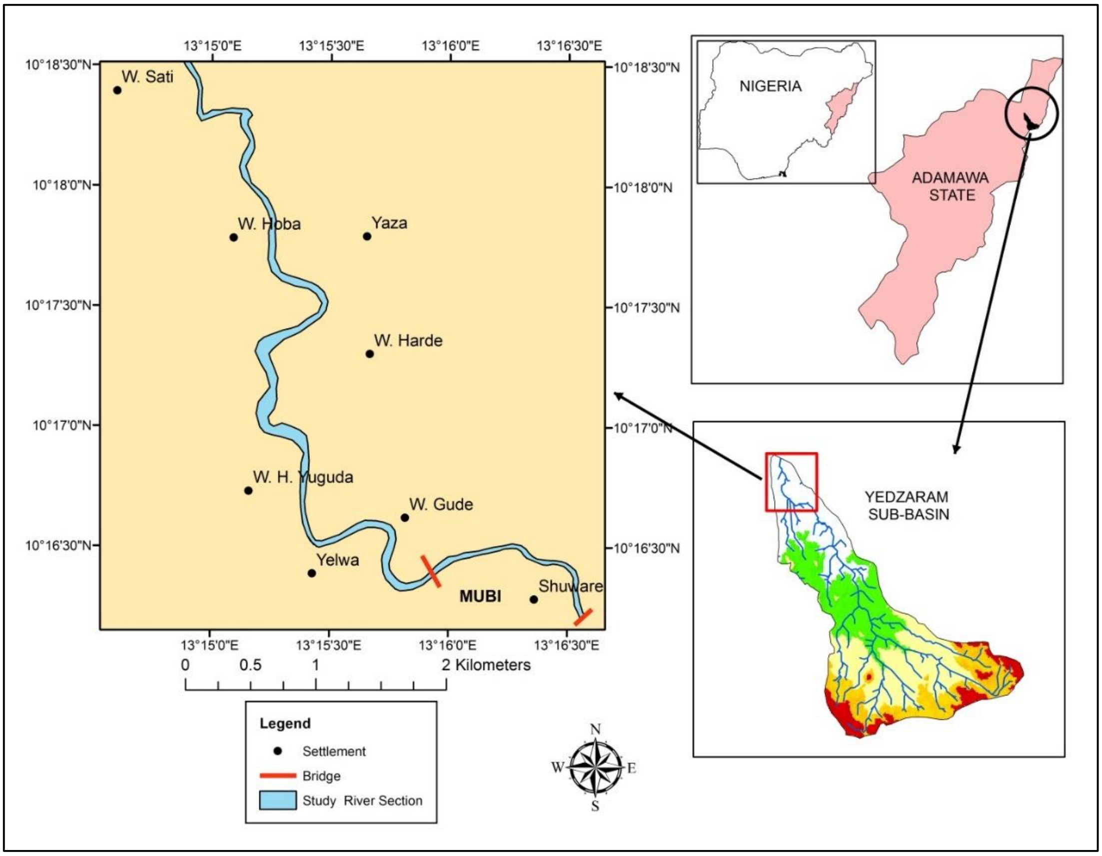


Fig. 1: The Study Area

Materials and Methods

The study employed the use of an integrated approach of Remote Sensing (RS), Geographic Information System (GIS) and field survey in assessing changes in the channel width changes, short term channel incision rate, meandering characteristics, channel migration pattern and associated impacts on riparian infrastructure and land uses from 2006 to 2019. This short term (13 years) study period was adopted on the basis of availability of required data.

High resolution Google Earth Images of the study area for 2006, 2012 and 2019 were obtained online and processed in the Arcmap environment of ArcGIS 10.3. In this activity, the respective images were Georeferenced and the studied channel section from each period was digitized to obtain the channel area polygon as well as the left and right bank line shape files. The centerlines of the channel for the three periods were then created using the 'collapse dual lines to centerline' tool of Cartography-Generalization components of the Arc toolbox as suggested by Giardino and Rowley (2016). This is because the Centerline Length (L_c) also known as the mid channel length serves as a very vital parameter for determining the Active Channel Width (ACW) or simply Average Channel Width (Alcantara, 2014; Kou *et al*, 2017) as well as a more preferable parameter for computing river channel sinuosity (Friend and Sinha, 1993; Larsen, 2007) and the creation of channel migration polygons (Alcantara, 2014; Giardino & Rowley, 2016; Das & Pal, 2016).

Assessment of Channel widening

Channel widening was assessed over two time intervals or periods (2006 to 2012; and 2012 to 2019). The Active Channel Width (ACW) for the periods (2006; 2012; and 2019) were established by digitizing out from each image the channel area polygon and determination of the channel length from the centerline. The Channel Area (A_c) for each period was then calculated using the Geometry Calculator in the Attribute Table window of ArcMap 10.3. The Active Channel Width also known as the Average Channel Width is expressed as the ratio of the Channel Area to the Channel Length which is a measure of the Centerline Length (Alcantara, 2014; Kou *et al*, 2017):

$$ACW = \frac{A_c}{L_c} \qquad (1)$$

Where ACW is Active Channel Width, A_c is Channel Area and L_c is Centerline Length.

Changes in channel width were determined by differences in dimensions between previous and recent ACWs. Furthermore, percentage changes in channel widths from 2006 (n1) through 2012 (n2) to 2018 (n3) were then computed as suggested by Alcantara (2014) in equation 2 or as recommended by Kenton (2019) in equation 3:

$$R_c = \left[\left(\frac{ACW_{n2}}{ACW_{n1}}\right) - 1\right] \times 100 \qquad (2)$$

$$R_c = \left(\frac{ACW_{n2} - ACW_{n1}}{ACW_{n1}}\right) \times 100 \qquad (3)$$

Where R_c is Percentage Change in channel width, ACW is Active Channel Width, n1 is initial year of measurement and n2 final year of measurement.

Annual rainfall, Peak discharge and Specific Stream Power data for the river channel section over the study period (2006 to 2019) were obtained from the Department of Geography Adamawa State Mubi.

Assessment of Channel Incision

Short term channel incision assessment was conducted mainly by field measurement procedures. In February 2016, the bed level of the studied river channel section was re-established by a levelling survey procedure involving the use of an automatic levelling instrument, a levelling staff and eTrex Global Positioning System (GPS). The exercise was conducted as an initial routine for assessing the rate of channel incision at the Shuware Bridge Gauging Station. The three years channel incision data obtained was analyzed with respect to section channel width stability over the period.

Assessment of Meandering Characteristics

Sinuosity indices of the studied river channel for 2006, 2012 and 2019 were calculated as the ratio of the respective stream channel length to the valley length as presented by Rosgen and Silvey (1996), expressed as**:**

$$S.I = \frac{Ls}{Lv} \qquad (4)$$

Where ***S.I*** is Sinuosity Index, ***Ls*** is Stream Channel Length and ***Lv*** is Valley Length. Categorizing sinuosity indices, Yong et al (2018) suggested four class types as presented on Table 1.

Table 1: Class types of sinuosity indices

Sinuosity Index	Channel class type
<1.05	Straight
1.05 – 1.30	Sinuous
1.30 – 1.5.	Moderate Meandering
>1.50	Meandering form

Adopted from Yong et al., (2018)

Assessment of Lateral Migration

Using the channel centerlines for the three periods of study, migration polygons between 2006 and 2012 as well as those between 2012 and 2018 were created using the ‘feature to polygon’ tool of the feature component in the data management tools of Arc GIS 10.3 Arc Toolbox. From the attribute tables of the two sets of migration polygons created, the area and corresponding perimeter of each polygon was calculated using the Geometry Calculator of ArcMap 10.3. The data were then copied to Microsoft Excel environment where the Total Rate of Migration (R_t) and Yearly of Migration (R_y) of the channel section over the study time intervals (period) were computed using the formulae provided by Giardino and Rowley (2016) expressed as follows;

$$R_t = \frac{A}{\frac{1}{2}(P)} \qquad (5)$$

$$R_y = \frac{R_t}{N} \qquad (6)$$

Where, $\boldsymbol{R_t}$ is Magnitude of Migration, $\boldsymbol{R_y}$ is Rate of Migration ***A*** is area of each polygon, ***P*** is the corresponding perimeter of the polygon and ***N*** is the number of years in the study time intervals. Spatial errors associated with digitizing and resolution of the Google earth images used were minimized by eliminating $\boldsymbol{R_t}$ values that are less than 6.0m, as suggested by Giardino and Rowley (2016). The mean total and yearly rates of the channel's lateral migration for the two time intervals (2006-2012 and 2012-2019) were then computed.

Result of the Findings

Based on field studies and GIS analysis, channel widening and gradual lateral migration were identified as the major processes of channel migration occurring in the studied channel section as no any form of channel avulsion was observed. However, another channel adjustment activity noticed was short term channel incision at the protected bank section of the channel.

Result of the findings revealed that the studied river channel section was subjected to both channel widening and lateral migration processes within the 13 years period of study (2006 to 2019). These processes were strongly tied to the increasing trends in the area's rainfall, stream discharge and specific stream power characteristics as presented in Table 2, as well as tied to by anthropogenic disturbances within the channel and its riparian zones.

Table 3: Annual rainfall and stream regime data of the river channel

Year	Annual Total Rainfall (mm)	Annual Peak Discharge (m^3s^{-1})	Annual Mean Specific Stream Power (Nm^{-2})
2006	981.80	49.93	58.61
2007	719.60	35.54	40.27
2008	845.00	45.27	36.67
2009	896.00	47.87	41.15
2010	779.50	33.69	32.16
2011	643.80	23.01	23.49
2012	1342.90	45.80	45.64
2013	848.80	36.19	35.00
2014	964.40	37.16	37.16
2015	1001.60	44.84	40.32
2016	1150.40	40.08	41.64
2017	1265.00	47.13	42.63
2018	913.30	57.22	59.97
2019	1900.90	102.55	107.48

Channel Width Changes

Geographic information system analysis revealed increasing widening of the studied channel section within the study period, though at varying rates. An increase in the channel Active Width (average width) from 42.39m in 2006 to 50.58m in 2019 was observed (Table 3). Between 2006 and 2012, the channel got widened by an active channel width increase of 8.19m with a percentage change of 19.32%. This channel widening effect was connected to the combined direct impacts of the area's rainfall regime and the stream flow characteristics as well as the indirect effects of anthropogenic disturbances of the river channel section. This finding buttresses the assertion of Alcantara (2014), in which he noted discharge as one of the main drivers of channel widening. Anthropogenic activities such as year round irrigation agriculture on the riparian lands, human settlement encroachment, and excessive sand mining tend to actively trigger and enhance failure of the channel banks, while solid waste disposal enhances meandering and bend migration.

Table 3: Channel width changes

Year	Channel Polygon Area (m^2)	Channel Length (m)	Active Channel Width (m)	Change in Mean Width (m)	Percentage Change (%)
2006	350000	8256.32	42.39		
2012	420000	8303.36	50.58	8.19	19.32
2019	410000	8059.1	50.87	0.29	0.58

The increasing channel width effect notwithstanding, a very low increment in the Active Width (0.29m by 0.58%) was observed between 2012 and 2019 (Table 3). Although increase in rainfall and stream flow trends of the channel were still observed, the decrease in channel widening compared to the previous period (2006-2012) was connected to observable local control measures practiced by land users along the channel riparian zones. Another eminent driver was the 2016 to 2019 channel banks protection project embarked by the Ecological Fund Programme of the Federal Government of Nigeria. The project covered only 1.3km section of the studied channel (from the Shuware Bridge to the Wuro Gude Bridge).

Channel Incision

A new process of channel incision (deepening) was observed at the recently protected channel section of the banks. The banks protection project which aimed at controlling channel widening and meander bends migration in the channel section resulted in triggering the new process of channel incision in the section. This is because the lateral erosion effect on the channel banks, which was tending towards enhancing energy balance in the channel section was transformed into a form of vertical erosion that initiated and enhances the incision process. The three years channel incision measurements (2016 to 2019) at Shuware Bridge Gauging Station revealed that the protected section of the channel was recently deepening at a rate of 0.32m year^{-1} (plate 1). With this new development, the Shuware Bridge is currently at a risk of structural disturbance as the channel has deepened below the pile footings exposing substantial parts of the piles (plate 1). Besides, a form of distortion in the channel section's width/depth ratio is initiated, and as the incision process advances, the width/depth ratio will continue to decrease until it creates a low friction loss that will be translated into large erosive forces that are bound to disturb the channel protected banks in the future as noted by Baird *et al* (2015).

Plate 1: Channel incision between 2016 and 2019

In Addition, advance in the incision process is bound to subject the non-protected banks sections downstream (from the Wuro Gude Bridge) to severe channel widening and lateral migration effects in the near future. This finding is in agreement with the assertion of Legg and Olson (2014), that Reaches downstream of those experiencing incision will experience elevated inputs of bed load (gravel-sized) sediment which can accelerate lateral migration.

Meandering behaviour of the channel

Field observation confirmed that the meandering behaviour of the studied channel section is active. This confirmation is based on the noticeable bank failure and fresh meander bend cut off scars created on annual bases within the channel section. Sinuosity indices of the channel within the period of study ranged between 1.51 and 1.58 (Table 4). This indicates that the river channel is meandering going by the sinuosity index categorization of stream channels presented by Yong *et al* (2018) and Sear *et al* (2010). It was also observed that the channel sinuosity increased by 0.3 from 2006 to 2012 owing to the channel stream flow behaviour over the years (Table 2). However, in 2019 the channel exhibited a decrease in sinuosity by 0.3 notwithstanding the sharp increases in the area's rainfall, discharge and stream power. This was to greater extent connected to the recent Ecological Fund channel modification and banks embankment project in which some meander bend sections were modified and channel banks protected.

Table 4: Sinuosity indices of the stream channel within the period of study

Period	Stream Channel Length (m)	Valley Length (m)	Sinuosity Index	Channel class type
2006	8,256.32	5,319.86	1.55	Meandering form
2012	8,414.96	5,319.86	1.58	Meandering form
2019	8059.09	5,319.86	1.51	Meandering form

Based on field observations and GIS analyses, severe bend cut-offs that posed serious threats to adjacent land uses were identified and mapped out (Figure 2). It was observed that, there were more hazardous bend cut-offs in 2006 and 2012 compared to 2019 despite the high flow behaviour of the stream observed in 2019. The drastic decrease in the number of hazardous bend cut-offs was also tied to the channel modification and banks protection project from 2017 to 2019.

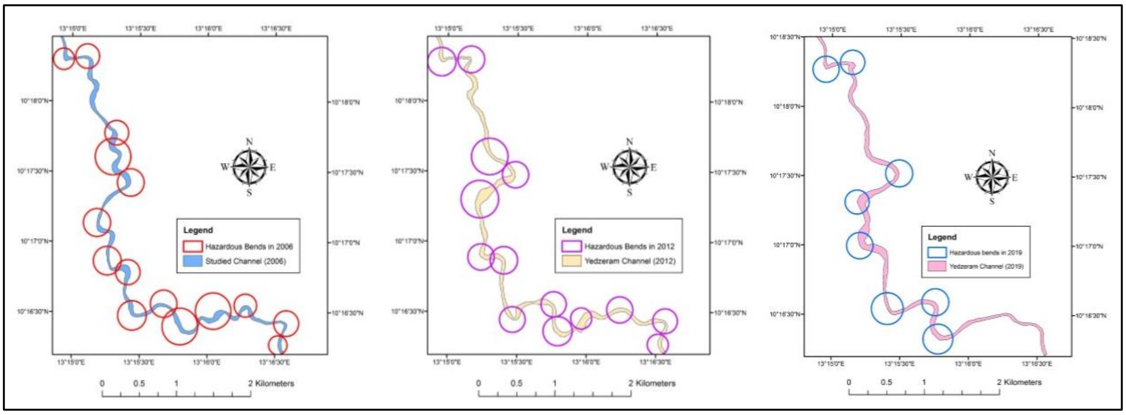


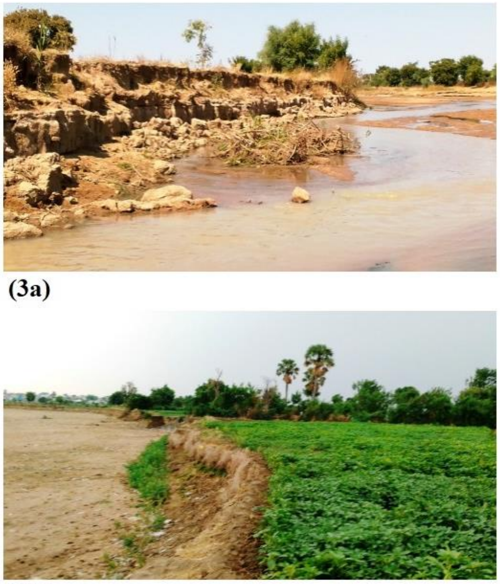
Figure 2: Hazardous meander bend cut offs in 2006, 2012 and 2019

The devastating effects of the bend cut offs on adjacent land uses are shown in plates 2, and 3. Most affected land uses were farmlands and residential structures at Shuware, Wuro Gude, Yelwa, Wuro Harde and Yaza areas.


(2a)

(2b)

Plates 2a and 2b: Impacts of channel bend cut-offs on residential structures


(3a)

(3b)

Plates 3a and 3b: Impacts of channel bend cut-offs on Farmlands

However, the channel banks protection activity which involved the combination of Stone Riprap as well as Gabion and Mattresses methods, covered only a planform length of 1.3km (Shuware Bridge to the Wuro Gude Bridge) of the studied channel section. As such, the channel sections from Wuro Gude to Wuro Sati are still exposed to the adjustment threats.

Lateral migration of the channel

Results of lateral migration rates showed that 32 and 31 migration polygons were generated for the two time intervals (2006 to 2012; and 2012 to 2019), respectively (Figures 3). The total and yearly rates of channel migration for the two studied time intervals are presented on Table 5.

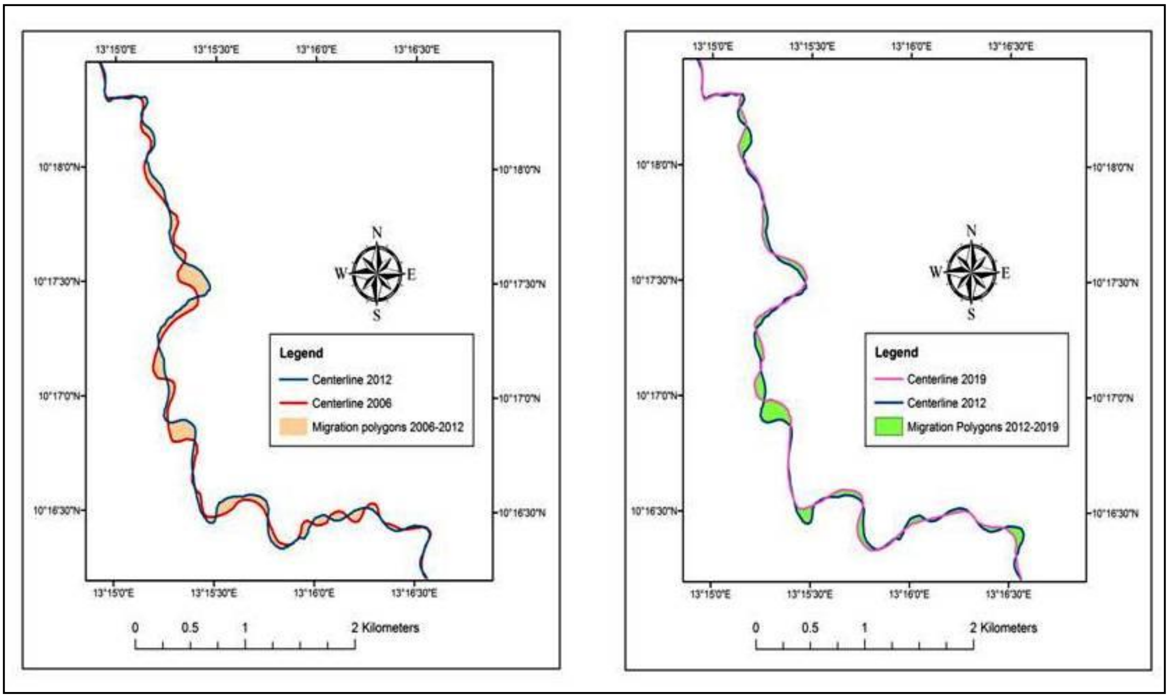


Figure 3: Channel migration pattern and polygons for 2006 – 2012 and 2012 - 2019

Table 5: Total and Yearly Channel Migration Rates

Period	Total Rate of Channel Migration (R_t)	Yearly Rate of Channel Migration (R_y)
2006 - 2012	32.38m	5.40m
2012 - 2019	27.8m	3.97m

The channel had a total lateral migration rate of 32.38m from 2006 to 2012 at 5.40/year and 27.80m from 2012 to 2019 at 3.97m/year. The results showed a slight and insignificant rate decrease in lateral migration of its meander bends; an indication of persistent channel meandering, banks instability and continual erosion of concave meander banks.

Conclusion

On the basis of the results and discussion presented, it was discovered that the studied channel section is under serious natural and anthropogenic disturbances. Consequently, it is exhibiting some forms of morphological instability and adjustments owing to persistent channel widening, gradual incision, meandering and temporal meander bend lateral migration. The effects of the morphological changes on riparian land uses are enormous and devastating, while efforts made towards managing the changes seem to be less effective and inadequate.

Recommendation

Based on the findings of the study, the following recommendations and made;

i. A mega and more effective channel modification and stabilization project that will cover the entire length of the studied channel section be carried out by concerned agencies.
ii. There is an urgent need to map out and reclaim the stream channel’s flow corridors through such procedures as infrastructure relocation and setback, conservation easements, vegetation buffer zones, longitudinal bank lowering, and addition of side channels among others.

References

Alcántara, M. A. S. (2014). Channel Adjustment and Channel-Floodplain Sediment Exchange in the Root River, Southeastern Minnesota. A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Watershed Science, Utah State University Logan, Utah.

Arkers, P. and Charlton, F. G. (1970). The Geometry of small meandering streams. *Inst Civ. Eng. Proc. 1970 suppl.* (xii); 289-317.

Andrews, E. D. (1982). Bank stability and channel width adjustment, East Fork River, Wyoming, *Water Resour. Res.* 18 (4): 1184-1192.

Brooks, A. P., Brierley, G. J., and Millar, R. G. (2003). The long-term control of vegetation and woody debris on channel and flood-plain evolution: insights from a paired catchment study in southeastern Australia: *Geomorphology,* 51; 7–29.

Das, S. and Pal, S. (2016).Character and Cardinality of Channel Migration of Kalindri River, West Bengal, India. *International Research journal of Earth Science,* 4(1); 13-26.

Dietrich, William E. Smith, D. J. and Dunne, T. (1979). Flow and Sediment Transport in a Sand Bedded Meander. *The Journal of Geology*, 87(3); 305-315

Downs, P. W. (1995). Estimating the probability of river channel adjustment. *Earth Surface Processes and Landforms.* 20(7); 687-705. https://doi.org/10.1002/esp.3290200710

Eaton, B. C. (2006). Bank stability analysis for regime models of vegetated Gravel Bed Rivers: *Earth Surface Processes and Landforms,* 31; 1438–1444.

Friend, P. F. and Sinha, R. (1993). Braiding and meandering parameters. *Geological Society London Special Publications* 75(1):105-111. DOI: 10.1144/GSL.SP.1993.075.01.05

Frothingham, K. M. and Rhoads, B. L. (2003). Three-dimensional flow structure and channel change in an asymmetrical compound meander loop, Embarras River, Illinois. *Earth Surface Processes and Landforms. 28(6);* 625-644. https://doi.org/10.1002/esp.471

Furbish, D. J. (1991). Spatial autoregressive structure in meander evolution. *Geological Society of America Bulletin* 103:1576-1589.

Giardino, J. R. and Lee, A. A. (2011). Rates of Channel Migration on the Brazos River. Final Report Submitted to the Texas Water Development Board.

Giardino, J. R. and Rowley, T. M.S. (2016). Evaluating channel migration of the lower Guadalupe River: Seguin, Tx, to the San Antonio river confluence. *Final Report.* Contract No. 1548311790.

Hickin, E. J. (1983). River channel changes, retrospect and prospect, in Collinson, J.D., and Lewin, J. (eds). *Modern and Ancient Fluvial Systems*: International Association of Sedimentologists Special Publication 6, p. 61–83.

Hooke, J. M. and Harvey, A. M. (1983). Meander Changes in Relation to Bend Morphology and Secondary Flows: In Collinson, J. D. and Lewinm, J. (Eds). *Modern and Ancient Fluvial Systems.* John Wiley and sons. https://doi.org/10.1002/9781444303773.ch9

Johannesson H. and Parker G. (1989). Linear Theory of River Meanders, *American Geophysical Union, Water Resources Monograph,* 12, 181-213.

Kenton, W. (2019). Percentage Change. *Investopedia.* Retrieved on January, 16, 2020 from www.investopedia.com.

King County (2018). Channel migration hazards. Retrieved January 3, 2019 from *https://www.kingcounty.gov/services/environment/water-and-land/.../migration.aspx*

Knighton, D., (1998). *Fluvial forms and processes: a new perspective.* Arnold, Hodder Headline, PLC.

Konrad, C.P. (2012). Reoccupation of floodplains by rivers and its relation to the age structure of floodplain vegetation: *Journal of Geophysical Research*, 117, doi: 10.1029/2011JG001906.

Kuo, C., Chen, C., Chen, S., Yang, T. and Chen, C. (2017). Channel Planform Dynamic Monitoring and Channel Stability Assessment in Two Sediment-Rich Rivers in Taiwan. *Water,* 9(84). Doi: 10.3390/w9020084

Larsen, E. W. (2007). Predicting Modes and Magnitude of River Channel Migration and Chute Cutoff Based on Bend Geometry, Sacramento River, California, USA**.** *Technical Report for United States Department of the Interior Bureau of Reclamation Technical Service Center, Denver, CO*. Pp 3-5

Legg, N. T. and Olson, P. L. (2014). Channel Migration Processes and Patterns in Western Washington: A Synthesis for Floodplain Management and Restoration. *Shorelands and Environmental Assistance Program Report, State Department of Ecology publication.*No.14-06-028. https://fortress.wa.gov/ecy/publications/SummaryPages/1406028.html

Leopold, L. B., Maddock, T. J. (1953). The hydraulic geometry of stream channels and some physiographic implications. *USGS Professional Paper,* 252; 57

Nanson, G. C. and Hickin, E. J. (1986). A statistical analysis of bank erosion and channel migration in western Canada: *Geological Society of America Bulletin,* 97; 497–504.

Nanson, G. C. and Croke, J. C. (1992). A genetic classification of floodplains: *Geomorphology*, 4; 459–486

Parker, G., Shimizu, Y., Wilkerson, G. V., Eke, E. C., Abad, J. D., Lauer, J. W., Paola, C., Dietrich, W. E. and Voller, V. R. (2011). A new framework for modeling the migration of meandering rivers. *Earth Surface Processes and Landforms.* 36: 70-86.

Parker, G., Wilcock, P. R., Paola, C., Dietrich, W. E., and Pitlick, J. (2007). Physical basis for quasi-universal relations describing bank full hydraulic geometry of Single-Thread Gravel Bed Rivers. *J. of geophys.res.* 112, F04005.

Richard, G.A., Julien, P.Y., and Baird, D.C. (2005). Statistical analysis of lateral migration of the Rio Grande, New Mexico: *Geomorphology,* 71; 139–155.

Richards, K.S. (1976). Channel width and the riffle-pool sequence. *Geol. Soc. Am. Bull.* 87 (6): 883-890.

Rosgen, D. L. and Silvey, H.L. (1996). *Applied River Morphology*. Wildland Hydrology Books, Fort Collins, CO

Sear, D. A., Newson, M. D. and Thorne, C. R. (2010). *Guidebook of applied fluvial geomorphology.* London, Thomas Telford Limited. Pp 50-53

Schumm, S. A. and Lichty, R. W. (1963). Channel Widening and Flood-Plain Construction along Cimarron River in Southwestern Kansas. *Geological Survey Professional Paper 352-D.* Retrieved January 02, 2020 from *https://pubs.usgs.gov › report*

Simon, A. and Collison, A. J. C. (2002). Quantifying the mechanical and hydrologic effects of riparian vegetation on stream bank stability. *Earth Surface Processes and Landforms.* 27: 527-546.

U.S Department of the interior Bureau of reclamation (2008). Channel Migration Model Predicts Meandering of Rivers. *Western Water and Power Solution Bulletin* No. 15

Walling, D. E., Owens, P. N., Carter, J., Leeks, G. J. L., Lewis, S., Meharg, A. A., and Wright, J. (2003). Storage of sediment-associated nutrients and contaminants in river channel and floodplain systems: *Applied Geochemistry,* 18; 195–220.

Wolman, M. G., and Leopold, L. B. (1957). River flood plains: some observations on their formation: *US Government Printing Office Geological Survey Professional Paper* 282-C, 87–107 p.

Yong, N. S., Mahammad, I. N. and Lee, W. (2018). Experimental Study on River Meander Planform Pattern. *International Journal of Engineering and Technology,* 7(3.11); 214-217.