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Geomorphic parameters infer the 65 years of meander evolution from the upper Yom River, Phrae, northern Thailand

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Abstract

The Yom River, one of the Chao Phraya River tributaries, shows the meandering process in the Phrae Basin within a narrow meander belt. This paper analyzed the geomorphological change of the upper Yom River in Phrae Province by assessing aerial photographs and satellite images from 1954 to 2019 (65 years). Identified geomorphological landforms included, paleo-channels, oxbow lakes, and meander scars that help to evaluate the channel migration. The upper and middle sections of the research site were characterized by a flat and wider floodplain area, exhibiting more remnants of cut-offs compared to the lower section where the floodplain is narrowed by mountainous areas. To compare the changes, five geomorphic metrics were used, i.e., 1) channel width (W), 2) channel length (L), 3) sinuosity index (SI), 4) radius of curvature (RC), and 5) channel migrations. The width (W) underwent significant alterations due to increased bank deposition. Changes in land use were found to have various impacts on runoff and sediment supply. The channel's length and sinuosity index (SI) decreased, indicating frequent cut-offs at the neck and chute during floods. Decreasing erosion rates were observed to be lower in the upper and middle portions of the Yom River due to previous cut-offs, while the lower portion exhibited active bending as evidenced by migration rates versus Rc/W values. Lower Rc/W values corresponded to slower rates of bend migration.

Keywords: Geomorphological change, Sinuosity index, Yom River, Meander, Meander belt

1. Introduction

Rivers have a significant impact on how the topography of the earth is shaped. They take action in a variety of methods, including removing material from its confines, transferring it, and dumping it in distant locations. Even over relatively short periods of time, river paths cannot be considered stable. Glover and Johnson (1974) provided evidence of the river channels being abandoned in several cases in very short periods of time. There are two ways that material might be removed from the confining channel by flowing water: either the channel is being scoured out, deepening it, or the removal takes place on the lateral.

Typically, meander processing in floodplains creates concave on the erosion side and convex on the oppositional deposition side. Rising erosion and deposition rates can alter the channel balance's geometry, increasing migrations and sinuosity (SI).

Since geomorphological features can be seen on avulsion plains, meander processes will leave traces of evidence of channel modifications, such as oxbow lakes and meandering scars, on floodplains (Choowong, 2011). Specifying river meander behavior and the forms they take has benefited in recent years from various important developments. Current studies are revealing certain characteristics in meander behavior, and lengthy ideas about the evolution of equilibrium forms and regular meander morphology are currently being investigated. The diversity of measurement and analysis techniques has also increased. For these reasons, it is helpful to look at the most relevant views and information on meander changes (Yousefi et al., 2016).

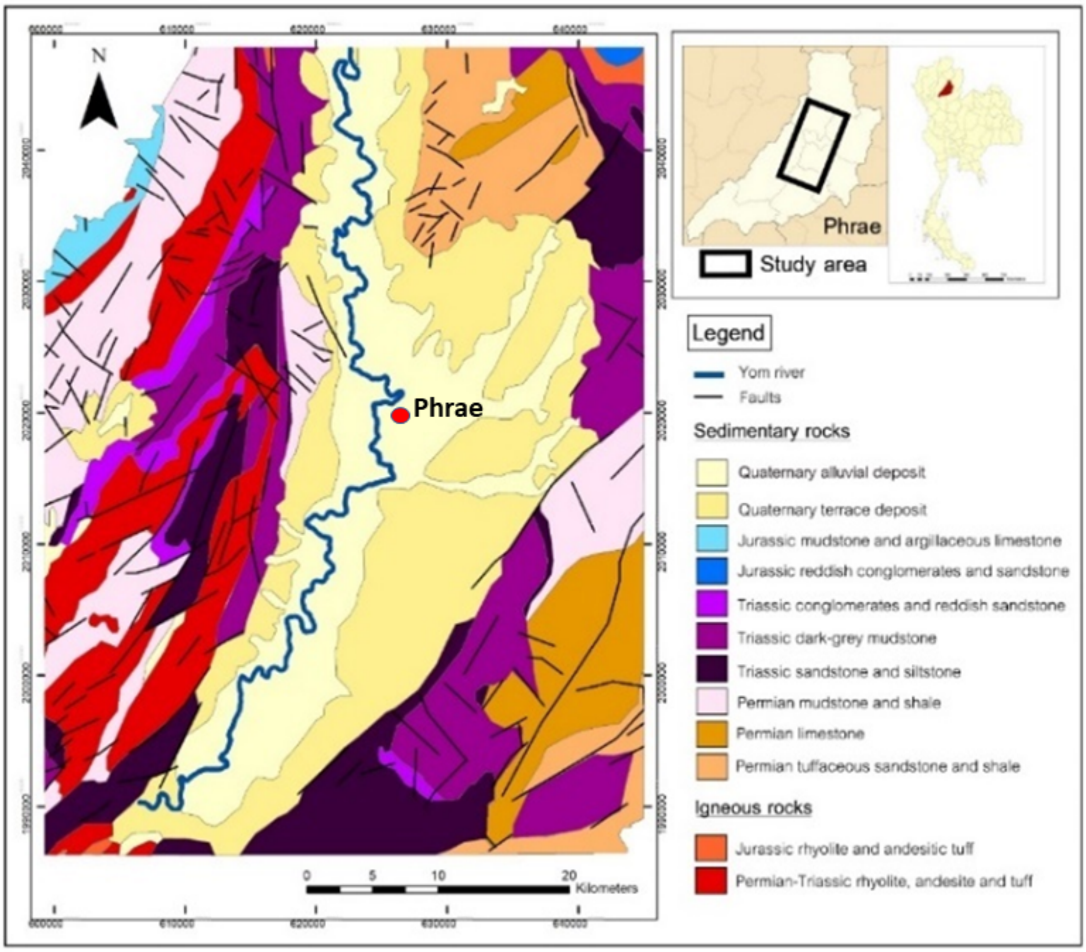

Figure 1 Geological map of the upper Yom River basin, Phrae province. The study area shows in the top right (square box) (Modified from Department of Mineral Resources, 2007).

The Yom River is the main tributary of the Chao Phraya River, which flows from north to south. In the province of Phrae, the upper Yom River passes through a basin between two mountains. The purpose of Upper Yom River was chosen for this study due to its meandering in an active basin, which has the potential to significantly migrate and modify landforms. Furthermore, since this region periodically experiences both flooding and drought, the Office of the National Water Resources began a Yom-Long project to decrease the risk of both events by managing and reserving water at oxbow lakes and meander scars. (National Office of Water Resources, 2020). As a result, this river is a fascinating location to research sediments, paleochannel structure, river mechanics, and river evolution. This study will analyze aerial photos, satellite images, and topographic maps from various time periods to examine the geomorphological changes in the location. The differences in the geomorphology change over a 65 years period were assessed using geomorphological criteria. This research will focus on channel sinuosity (SI), bend radius of curvature (Rc), width (W), length (L), and channel migration rates that can assist in comprehending the natural processes of the river (Leopold, 1960; Williams, 1986). The research objective of this study was to examine the geomorphological changes of the Upper Yom River within Phrae Province.

2. General geology

The Yom River, which flows mainly from north to south through the Phrae basin, has significant tributaries from the northeast and east that transport sediments there. The Phrae Basin, which covers an area of 1,100 square kilometers and is the largest basin in northern Thailand, is comprised of a layer of Cenozoic sediment with a thickness of nearly 2 kilometers. This basin was a triangle-shaped form that was located in a north-northeast to south-southeast direction. Its longitudes and latitudes are 18º 00' N to 18º 30' N and 100º 05' E to 100º 20'E, respectively. The Triassic Lampang Group, which consists of shale, mudstone, and limestone, surrounded the basin in the majority; Carboniferous-Permian rocks can also be found in some places. To the east and west, Permian limestone, shale, and chert are less widespread. (Fig. 1).

The Phrae basin encountered five tectonic events in total, along with five sedimentary cycles in a stratigraphic sequence, according to Srisuwan (2000). This research used co-analyzed boreholes, outcrop, and seismic data in the basin. Each cycle begins with the beginning deposition of braided channels and floodplains, which gradually transitioned to shallow swamp-lake and lake margin deposition, which was followed by the deposition of crevasse splays. Doi Khun Yuam in the Phi Pan Nam Mountain Range where the Yom River has its beginnings. It is located in Amphoe Pong and Amphoe Chiang Muan, Phayao Province. The Yom River initially flowed through a valley with a very steep slope; there are narrow plains along the river in some places. Afterward, it flowed into the plains of Phrae Province. Then, it flowed into the western valley. Finally, it flowed in a southern direction into the plains of Sukhothai Province, Phitsanulok, Phichit, and Nakhon Sawan then flowed to converge with the Nan River at Ban Koei Chai, Chum Saeng District, Nakhon Sawan Province. The river runs for around 735 kilometers in total length. (Fig. 2).

3. Methodology

3.1 Aerial photographs and satellite image interpretation

For the objective of interpretation, a variety of satellite pictures and aerial photographs encompassing the area were collected. We applied the air-photos recorded in 65 years from the Royal Thai Survey Department in 1954, 1970, and 1989 to create geomorphological maps with a scale of 1: 50,000. A mirror stereoscope was used to analyze a collection of grayscale aerial photographs in three dimensions and scan images to create digital files. Each picture was corrected using 5 to 6 ground control points (GCPs) located throughout the photos in accurate landmarks such as road intersections or man-made construction to obtain the low root mean square error (RMSE). The geomorphic correction was carried out using software from ESRI ArcGIS 10.4.1. For this investigation, an RMSE value of less than or equal to 10 is acceptable. In addition, utilized 3 m- resolution satellite pictures from Google Earth in 2012 and 2019. Each year's images were characterized as the geometries of channel landforms in the past and present, and alterations in the ArcGIS software were compared to them.

3.2 Delineate the geomorphic characters

3.2.1 Geomorphic mapping

A series of aerial photographs were processed into digital files for comparison with Google Earth satellite imagery. All images were identified as the geometries of channel landforms in the past and modern ages of each year and contrasted with various alterations using the ArcGIS. From photos to shifting geomorphological features, the boundaries of geomorphic characters including channels, paleo-channel traces, oxbow lakes, meander scars, scroll bars, and floodplains will be defined.

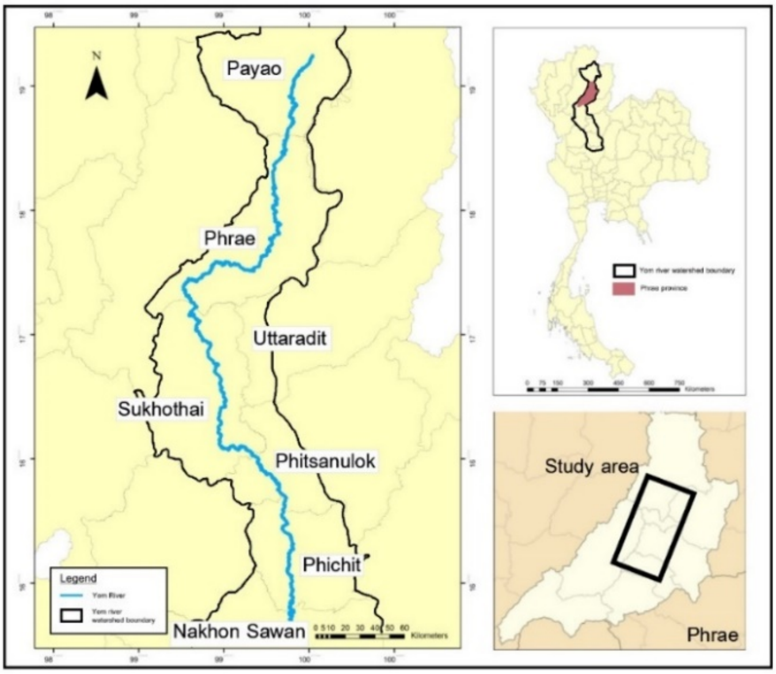

Figure 2 The Yom River initially flowed through Payao, Phrae, Sukhothai, Phitsanulok, Phichit, and Nakhon Sawan Provinces. The river runs for around 735 km in total length.

3.2.2 Geomorphic Criteria Calculation

Channel width (W), channel length (L), sinuosity index (SI), the radius of curvature (Rc), and channel migrations are five geomorphic parameters that were used to analyze trends. Each criterion has its own resources and details that have been beneficial for determining how geometry has changed throughout time. In order to compare recent channels and abandoned channels, the sinuosity index (SI), the radius of curvature (Rc), channel width (W), and channel migration rate were measured using the measure tool for distance measurement on ArcGIS 10.4.1. Channel length (L.) was produced by channel centerlines from the temporal vector layer of river courses. Moreover, 53 cross-sections made across various river sections were measured in order to determine the river's width. These cross-sections represent the lateral movement of centerlines (channel migrations).

4. Results

4.1 Geomorphological map

Comparing geomorphological changes throughout the previous five periods was achieved using ArcGIS 10.4.1 software (1954, 1970, 1989, 2008, and 2019). Channel migration, neck cut-offs, oxbow lakes, and meander scars are examples of how geomorphology has changed over the past 65 years (from 1954 to 2019) in aerial photographs and satellite imagery. There are several meander changes in the upper and middle parts, but there are only a few geomorphological remnants in the lower area.

4.2 Geomorphological criteria analysis

4.2.1 Sinuosity Index (SI)

Given the SI measurements used in this study, they varied from 1.95 to 1.50 from 1954 to 2019. The sinuosity value was significantly highest in 1954 at 1.95, and the lowest in 2019 was 1.50. As the total sinuosity values of the Yom River have decreased over time, as seen in Figure 3, it is plausible to assume that the river had erosion and deposition between 1954 and 2019. Moreover, SI values from the past to the recent illustrate in meander river type (SI of the meander is 1.25 to 2).

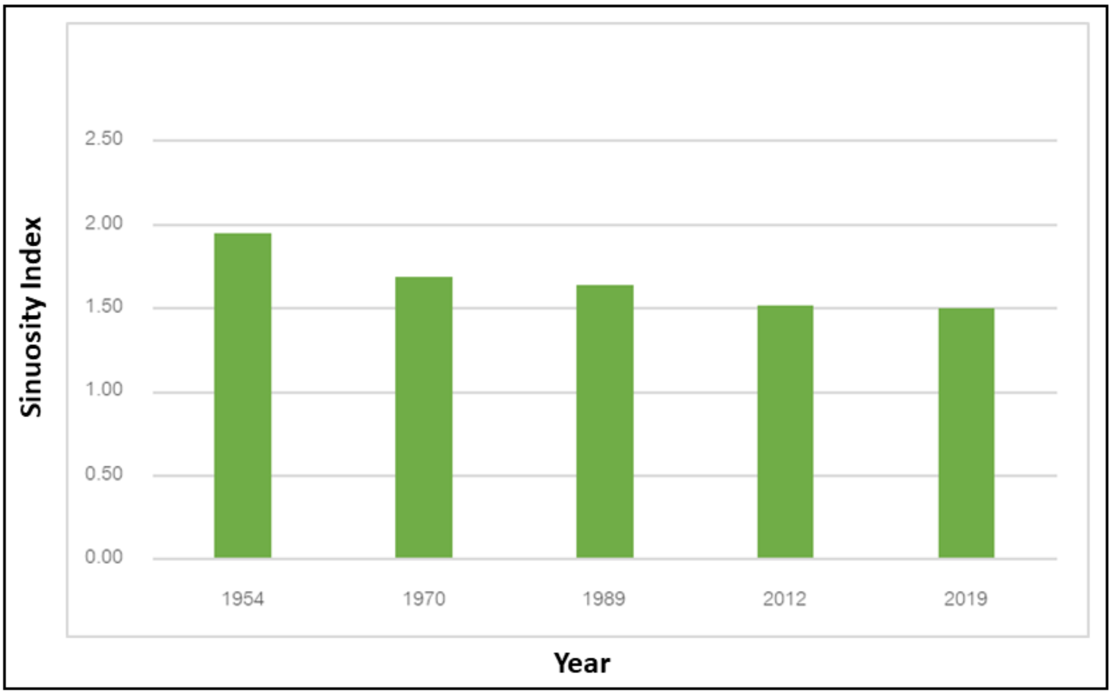

Figure 3 Graph shows SI values from 1954 to 2019 was drop from 1.95 to 1.50.

4.2.2 The Radius of curvature (Rc)

The Rc is the thickness value of the bend; if the value is high, the river bends will be close to each other. A wider bend, on the other hand, will have a low Rc value. Areas 1 and 3 of the curve, which were recorded throughout 5 periods (1954 to 2019), are the only fully complete bends that will be measured in this research. Area 2 was only monitored during specific years due to cut-off channels. According to Figure 4, RC had measurements from three distinct locations that the measurement able bends covered the whole research area. From 1954 to 2019, all RC values, Rc/W and Migration rate versus Rc/W in areas 1, 2 and 3 are shown in Figure 5.

4.2.3 Channel width (W)

According to the results of measuring 53 values along the river in 5 periods (Fig. 7), the average channel width in 1954, 1970, 1989, 2012, and 2019 is 59.70 m, followed by 64.72 m, 58.13 m, 59.14 m, 58.25 m, and 58.23 m, respectively. The width of Yom channel has been slightly reduced from 1954 to 2019 but when compared to paleo-channel width, it has changed dramatically from 90.10 meters to 58.23 m. In addition to the width of this channel is medium size from past to recent (20-200 m) (Miall, 2013).

4.2.4 Channel length (L)

The midpoint between the left and right banks of the channel polygon is where the Yom River's channel length was measured. The largest channel length for the whole research period was in 1954 (127.93 km), while the shortest was in 2012 (110.19 km). In overall, the length of the river decreased by 17.74 km from 1954 to 2012 and then slightly 2.02 km longer than 2012 in the year 2019 (Fig. 5d).

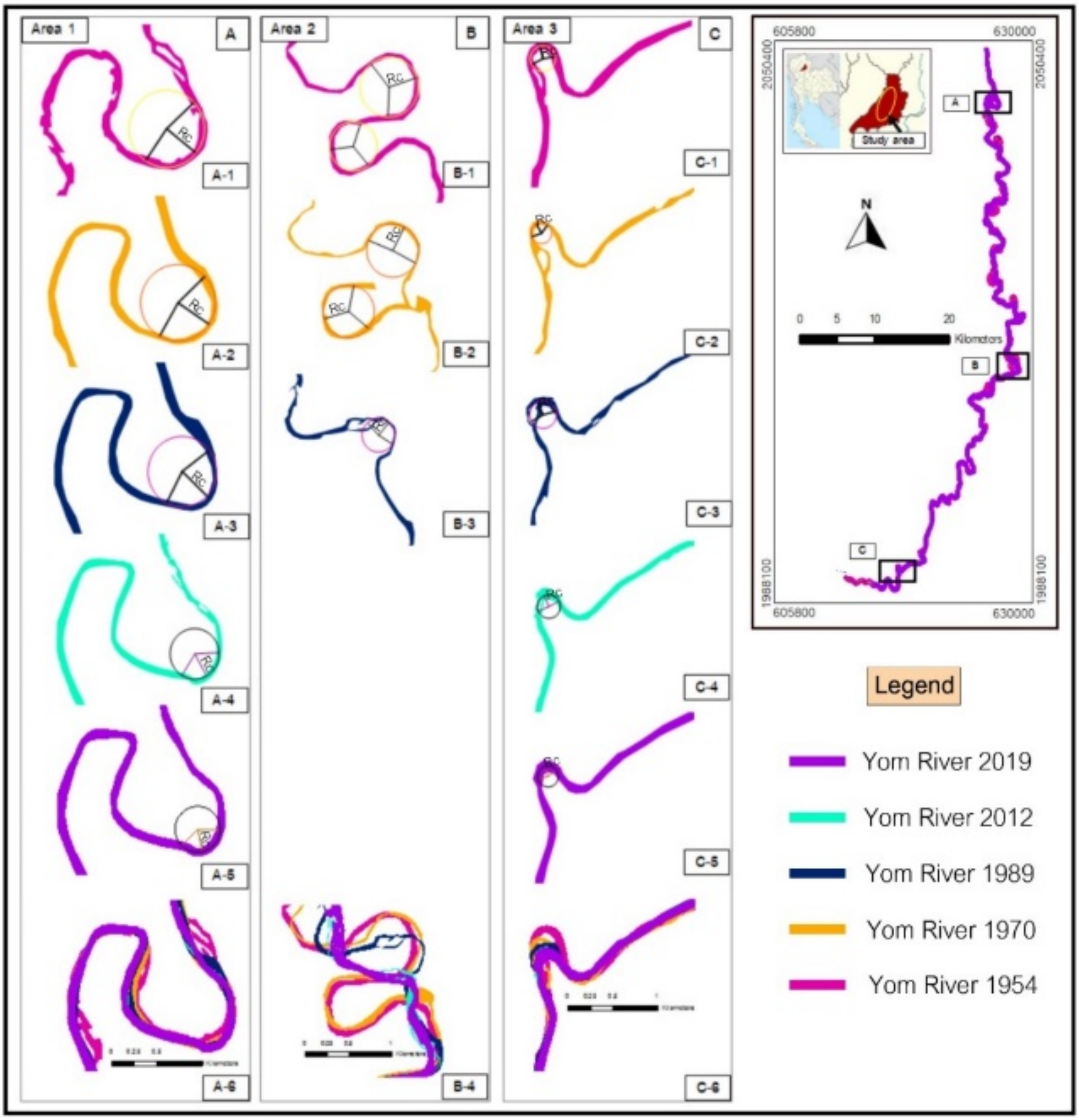

Figure 4 The Rc measurements from 3 locations from 1954-2019.

4.2.5 Channel centerline migration from 1954 to 2019

The centerline lies halfway between the left and right banks. From 1954 through 2019, the global centerline migration rates each year has varied. The centerline moved eastward at a rate of around 0.46 m per year between 1954 and 1970 (Left side of the river). On the other hand, the centerline changed to the west (right bank of the river) throughout the time periods 1970 to 1989, 1989 to 2012, and 2012 to 2019, respectively, as indicated by the graph in Figure 6.

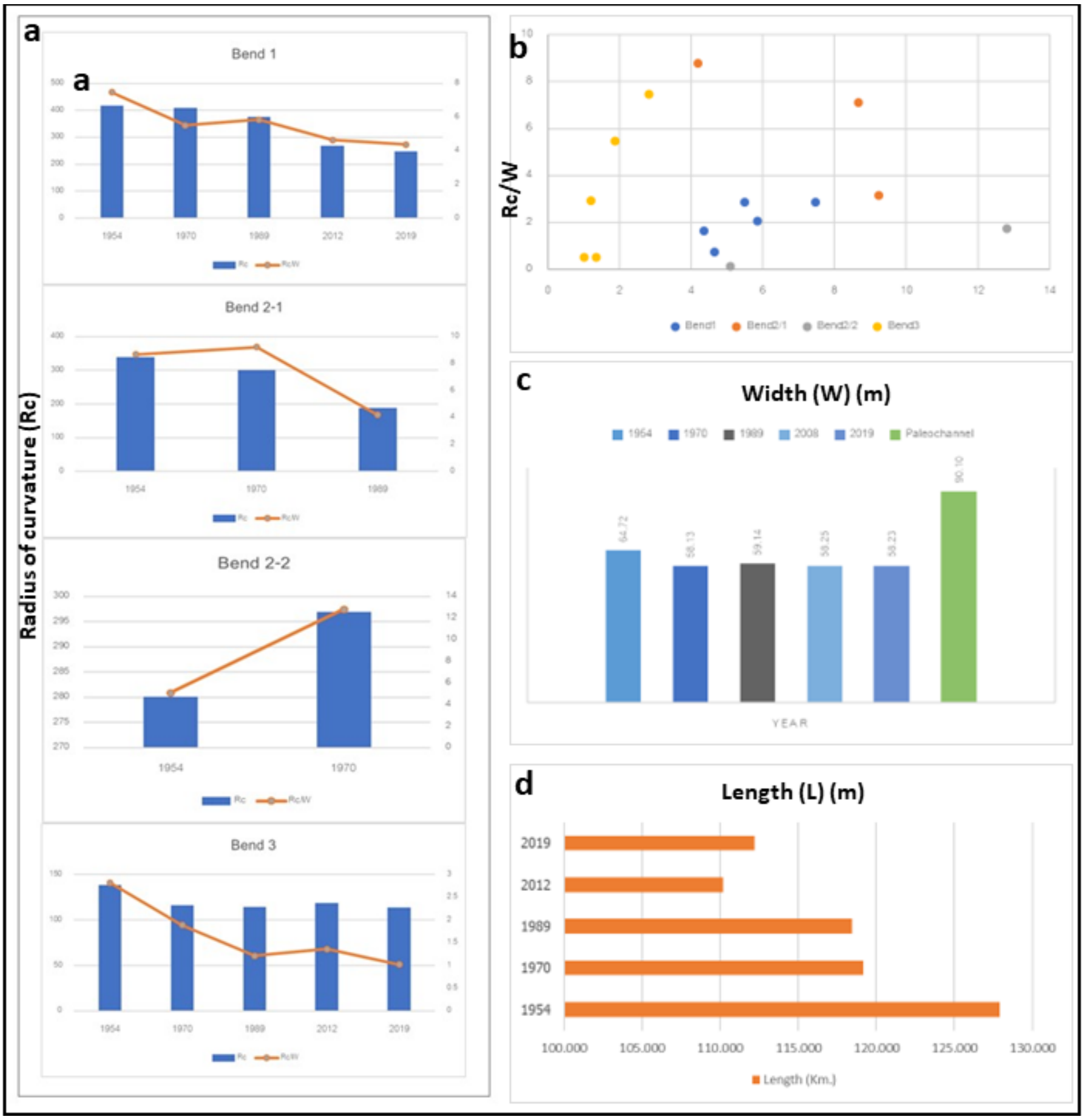

Figure 5 (a) All Rc values and Rc/W in 3 Bends. (b) Meander migration rate versus bend curvature (Rc/W), a number that falls between 1 and 2 indicates that the bend will either cut off the neck or the chute. Bends will erode quickly if values are between 2.5 and 4. Bends will have a low erosion rate if values increase by more than 5. Bends 1 and 2 have a value rise of more than 4, which indicates low erosion rate, and bend 3 trends to cut off (active bend). (c) The width of Yom channel has been slightly reduced from 1954 to 2019 but when compared to paleo-channel width, it has changed dramatically from 90.10 m to 58.23 m. (d) The graph shows the comparison in the length of Yom River from 1954 to 2019 that was dropped due to neck cut-off and chute cut-off.

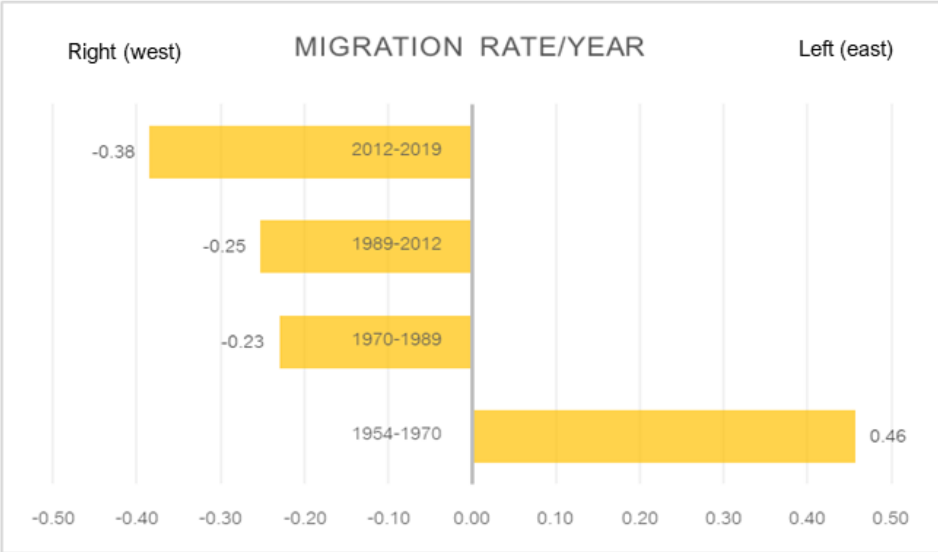

Figure 6 River migration to the west (right bank of the river) from 1970 to 2019, In contrast to 1954 to 1970, the river was migrated to the east.

5. Discussions

5.1. Geomorphological map

In order to compare the geomorphological changes across the previous five time periods (1954, 1970, 1989, 2008, and 2019), ArcGIS 10.4.1 was utilized. Between 1954 and 2019, channel migration (lateral migration) was visible in aerial photographs and satellite photos as a result of the oscillation of the meandering river produced by erosion and deposition along the riverbank, which led to chute cut-off and neck cut-off to maintain balance. The chute cut-offs often have higher stream power, trace close to the meandering discrimination limit, and are linked with more noticeable spatial width changes (Kleinhans and van den Berg, 2011). As a result of their propensity to meander over their floodplain, meandering rivers frequently leave behind a pattern of scroll bars and cut-off lakes (Parker et al., 2011).

The expression "floodplain" refers to an alluvial landform that is relatively flat, near a river channel, and occasionally flooded. In addition, meander bends in the same channel do not necessarily have characteristics in common with one another (Schmudde, 1997), and differences in bank dynamics can occur both within rivers as well as between them (Hooke, 2007; Alho and Mäkinen, 2010). According to Lotsari et al (2014), the sites of bend erosion change across meander bends of various planform types, and depending on whether the floodplain is flat or steep-sided, the topography of the surrounding area can affect the creation of numerous channel remains.

The upper and middle areas exhibited more cut-off remnants than the lower part due to the floodplain area being flat and broader than the lower in all five prior times, as seen by the meander scars and oxbow lakes. Maps and cross-sections of the floodplain at the upper, middle, and lower sections are given for comparison shown in Figure 7, whereas the lowest part has a small floodplain and human habitation close to the Yom River, which is the reason for limiting the flow of the river and lack of remnants.

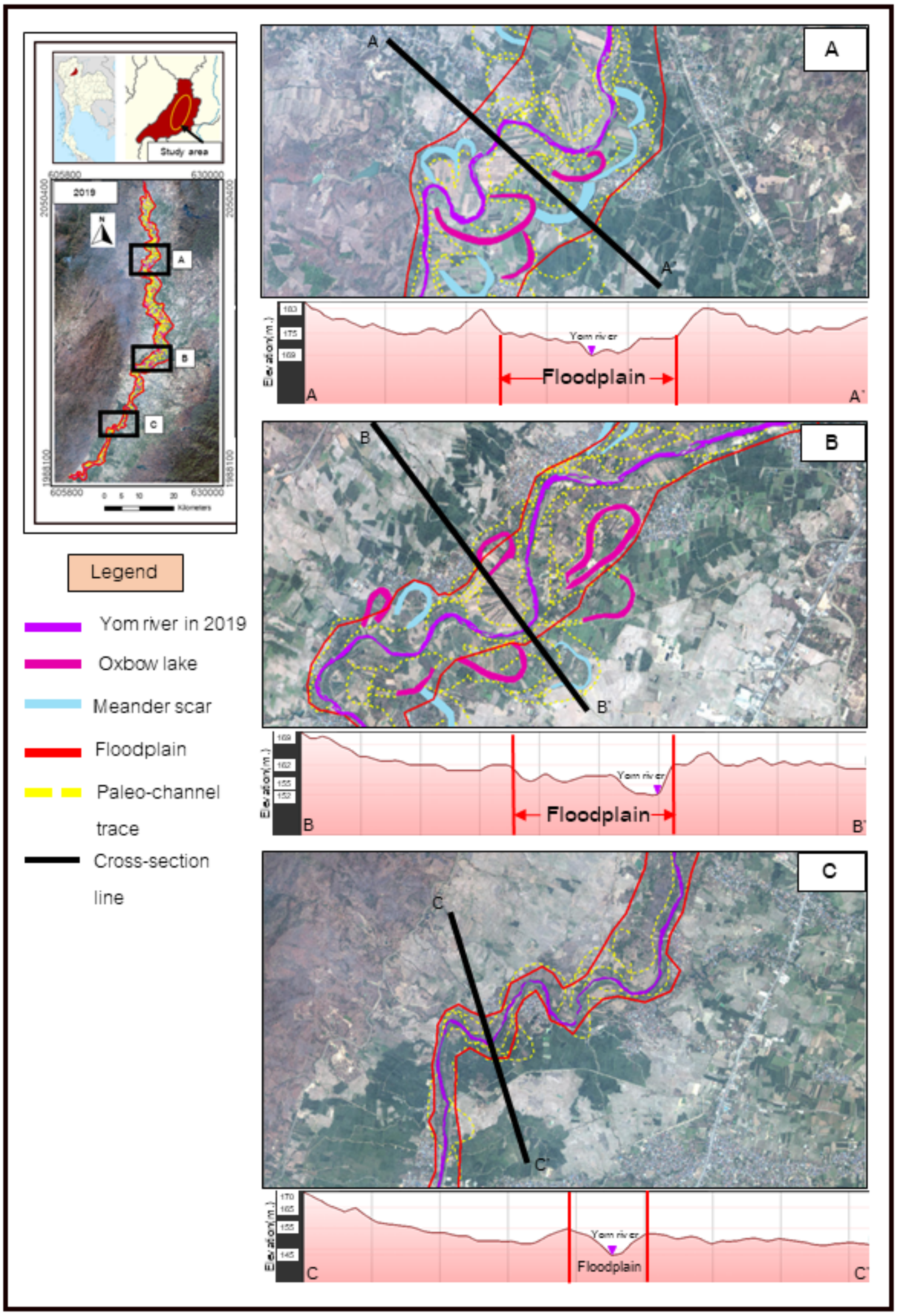

Figure 7 The maps and cross-sections of the floodplain at the upper, middle, and lower sections are given for comparison.

5.2. Change in geomorphic criteria

The meander planform of affected rivers has been the subject of several additional investigations. In terms of causes, a variety of other human impacts have been identified, such as reservoir construction and land-use modifications in the catchment and/or the floodplain that result in changes to the controlling variables (flow and sediment discharge) (e.g., Kiss, Fiala and Sipos 2008; Ollero, 2010; Magdaleno and Fernández-Yuste, 2011; Yousefi et al., 2016). For example, Kiss and Blanka (2012) and Suizu and Nanson (2018) found that fluctuations in hydrological regimes associated with climate changes or indirectly associated with human influences may have significant effects on meander shape. However, because the interpretation of cause-and-effect relationships of cumulative impacts is frequently constrained, it is typically challenging to distinguish between natural and human causes (Downs and Piégay, 2019).

The five parameter planforms of channel width (W), length (L), sinuosity index (SI), the radius of curvature (RC), and centerline migration rate/year (M/Y) will be discussed in this study's discussion of the causes of these changes. The measure could take notice of changes to channel behavior and development (Williams, 1984). From the past to the present, all parameters have tended to decline. These specifics are described..

1. *Channel width (W)*

The channel width is reduced by bank accretion, but bank erosion has the reverse effect. Hence, the equilibrium river width can only be achieved if opposite bank accretion and bank erosion are balanced out. Bank erosion happens during or soon after flood events, whereas bank accretion occurs during high flow stages (deposition) and low flow stages (consolidation and plant cover) and is typically significantly slower. The width of the Yom channel has been slightly reduced from 1954 to 2019 but when compare to paleo-channel width, it has changed dramatically caused of bank deposition increasing from time to time by human activities e.g. land-use changes may have many potential effects on either sediment supply or runoff. Deforestation may increase the sediment supply through augmentation of soil erosion, and decrease runoff because of higher evapotranspiration, whereas the opposite patterns generally occur during periods of reforestation (García-Martínez and Rinaldi, 2022). Based on previous studies (Boonyawat and Susanpoontong, 1996; Department of Water Resources [DWR], 2005; Royal Irrigation Department [RID], 2010), land use in the Yom River basin was classified into four major groups including agricultural, forest, urban, and water-covered. Most of the land use areas are agricultural areas and forests. During the period 1973 to 1993, the agricultural area increased from 24 to 44% of the total area (1.02% per year). Meanwhile, the forest area decreased from 75 to 54% (1.05% per year). These reasons are the main cause of changing in width of study area.

2. *Changing in length (L) and sinuosity index (SI)*

These two parameters can provide changes in a river caused by chute cut-off and neck cut-off. Chute cutoffs in meandering rivers can develop in a variety of ways, including swales on the floodplain surface that can redistribute overbank flows and incise until producing a cutoff and an embayment upstream of a point bar that forms by localized bank erosion, often during floods, causing downstream extension of the embayment ultimately leading to cut-off (Van Dijk et al., 2012**.** Earlier studies accomplished in 1981, 1995, 2006, and 2011 indicated that severe flood occurrences were correlated with significant sediment loads in the Yom River (Namsai et al., 2020). As a result, there are no records of flood events in the studied area before 1981.

Rainfall plays a major role in rainfall-runoff interactions, which is essential to the evaluation of floods and droughts (Chattopadhyay and Edwards, 2016). Based on Kunkel et al (2003), the increased frequency of severe precipitation events in the

United States may have contributed to hydrological flood events. In addition, in between 1921 and 2015, annual rainfall data were discovered in the upper and lower reaches of the Yom River basin to have an insignificantly rising trend (Mama et al., 2018). The Yom basin's rainfall trends between 1921 and 2015 show an increase in rainfall, according to the research. There may be flood occurrences, which are predicted to produce flood events, but which are not recorded and analyzed between 1954 and 1981. The Yom River in the study area was cut off as a result of this.

3. *Relationships between Rc/W and channel migrations*

The important ratio of the radius of channel curvature to channel width (Rc/W), which is reached by an increasing meander bend, influences controls on the ensuing direction and rate of meander migration, was identified by Hickin (1974). Furthermore, the tightness and looseness of a bend could be determined by the relationship between the radius of curvature and channel width(Rc/W). Lower numbers clarify the tight bends, whereas higher values specify the loose bends. The study demonstrates a direct correlation between migration rate and the tightness index (Rc/W), with lower tightness values corresponding to slower rates of bend migration (Bag et al., 2019). When migration rates are plotted versus Rc/W, a number that falls between 1 and 2 indicates that the bend will either cut off the neck or the chute. Bends will erode quickly if values are between 2.5 and 4. Bends will have a low erosion rate if values increase by more than 5 (Nanson and Hickin, 1983). According to the graph (Fig. 5) other bends have a value rise of more than 4, which indicates low erosion rates, and bend number 3 may be cut off. According to the information in Figure 6, the Upper and middle portions of the Yom River in the research region have decreasing rates of erosion since these sections have already cut themselves off, whereas the lower portion has been actively bending.

6. Conclusions

This research concludes that the channel migration, neck cut-off, oxbow lakes, and meander scars are landform indicators of the changing geomorphology that has occurred during the past 65 years (from 1954 to 2019). Due to the flatness and broader of floodplain area, the upper and middle portions of the research site had more cut-off remnants than the lower section. The width (W) of the Yom River's paleochannel has altered dramatically in recent years because of continuous increases in bank deposition brought on by human activities. Changes in land use might have a variety of impacts on runoff or the supply of sediment. The channel's longest length was 127.93 km in 1954, while its shortest length was 110.19 km in 2012. Between 1954 and 2019, it varied between 1.95 and 1.50 according to SI measurements. In 1954, the sinuosity rating was its greatest (1.95), while in 2019, it was at its lowest (1.50). Yom River's total length and sinuosity measurements reflect a downward tendency from the past to the present, indicating that it was frequently cut off at the neck and chute during several floods. In addition, the upper and middle portions of the Yom River in the research region have decreasing rates of erosion because these sections have already cut themselves off, whereas the lower portion has been actively bending due to the migration rates versus Rc/W values. Rc/W shows lower tightness values corresponding to slower rates of bend migration.

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References

Alho, P. & Mäkinen, J. 2010. Hydraulic parameter estimations of a 2D model validated with sedimentological findings in the point bar environment. *Hydrological Processes,* 24**,** 2578-2593.

Bag, R., I. Mondal & Bandyopadhyay, J. 2019. Assessing the oscillation of channel geometry and meander migration cardinality of Bhagirathi River, West Bengal, India. *Journal of Geographical Sciences,* 29**,** 613-634.

Chattopadhyay, S. & Edwards, D. R. 2016. Long-term trend analysis of precipitation and air temperature for Kentucky, United States. *Climate,* 4**,** 10.

Choowong, M. 2011. Basic Geomorphology *Tienwattana Printing, Co., LTD***,** 202 p.

Downs, P. W. & Piégay, H. 2019. Catchment-scale cumulative impact of human activities on river channels in the late Anthropocene: implications, limitations, prospect. *Geomorphology,* 338**,** 88-104.

García-Martínez, B. & Rinaldi, M. 2022. Changes in meander geometry over the last 250 years along the lower Guadalquivir River (southern Spain) in response to hydrological and human factors. *Geomorphology,* 410.

Glover, B. & Johnson, P. 1974. Variations in the natural chemical concentration of river water during flood flows, and the lag effect. *Journal of Hydrology,* 22**,** 303-316.

Hickin, E. J. 1974. The development of meanders in natural river-channels. *American journal of science,* 274**,** 414-442.

Hooke, J. M. 2007. Spatial variability, mechanisms and propagation of change in an active meandering river. *Geomorphology,* 84**,** 277-296.

Kiss, T. & Blanka, V. 2012. River channel response to climate-and human-induced hydrological changes: Case study on the meandering Hernád River, Hungary. *Geomorphology,* 175**,** 115-125.

Kiss, T., K. Fiala & Sipos, G. 2008. Alterations of channel parameters in response to river regulation works since 1840 on the Lower Tisza River (Hungary). *Geomorphology,* 98**,** 96-110.

Kleinhans, M. G. & Van den Berg, J. H. 2011. River channel and bar patterns explained and predicted by an empirical and a physics-based method. *Earth Surface Processes and Landforms,* 36**,** 721-738.

Kunkel, K. E., D. R. Easterling, K. Redmond & Hubbard, K. 2003. Temporal variations of extreme precipitation events in the United States: 1895–2000. *Geophysical research letters,* 30.

Leopold, L. B. 1960. *Flow resistance in sinuous or irregular channels*. US Government Printing Office.

Lotsari, E., M. Vaaja, C. Flener, H. Kaartinen, A. Kukko, E. Kasvi, H. Hyyppä, J. Hyyppä & Alho, P. 2014. Annual bank and point bar morphodynamics of a meandering river determined by high-accuracy multitemporal laser scanning and flow data. *Water Resources Research,* 50**,** 5532-5559.

Magdaleno, F. & Fernández-Yuste, J. A. 2011. Meander dynamics in a changing river corridor. *Geomorphology,* 130**,** 197-207.

Mama, R., K. Jung, B. Bidorn, M. Namsai & Feng, M. 2018. The Local Observed Trends and Variability in Rainfall Indices Over the Past Century of the Yom River Basin, Thailand. *Journal of the Korean Society of Hazard Mitigation,* 18**,** 41-55.

Miall, A. D. 2013. *The geology of fluvial deposits: sedimentary facies, basin analysis, and petroleum geology*. Springer.

Namsai, M., B. Bidorn, S. Chanyotha, R. Mama & Phanomphongphaisarn, N. 2020. Sediment dynamics and temporal variation of runoff in the Yom River, Thailand. *International Journal of Sediment Research,* 35**,** 365-376.

Nanson, G. C. & Hickin, E. J. 1983. Channel migration and incision on the Beatton River. *Journal of Hydraulic Engineering,* 109**,** 327-337.

Ollero, A. 2010. Channel changes and floodplain management in the meandering middle Ebro River, Spain. *Geomorphology,* 117**,** 247-260.

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

Schmudde, T. H. 1997. FLOODPLAINFlood plain. In *Geomorphology*, 359-362. Berlin, Heidelberg: Springer Berlin Heidelberg.

Srisuwan, P.,Elders, C. F. & Nichols, G. J. 2000. Structure, stratigraphyand sedimentology of Phrae Basin, Northern Thailand. *International Conference on Applied Geophysics*. Chiang Mai University,Chiang Mai, Thailand, 219-248.

Suizu, T. M. & Nanson, G. C. 2018. Temporal and spatial adjustments of channel migration and planform geometry: responses to ENSO driven climate anomalies on the tropical freely-meandering Aguapeí River, São Paulo, Brazil. *Earth Surface Processes and Landforms,* 43**,** 1636-1647.

Van Dijk, W., W. Van de Lageweg & Kleinhans, M. 2012. Experimental meandering river with chute cutoffs. *Journal of Geophysical Research: Earth Surface,* 117.

Williams, G. P. 1984. Paleohydrologic equations for rivers. *Developments and applications of geomorphology***,** 343-367.

Williams, G. P. .1986. River meanders and channel size. *Journal of hydrology,* 88**,** 147-164.

Yousefi, S., H. R. Pourghasemi, J. Hooke, O. Navratil & Kidová, A. 2016. Changes in morphometric meander parameters identified on the Karoon River, Iran, using remote sensing data. *Geomorphology,* 271**,** 55-64.