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Geomorphological Analysis of Change of the Left Bank of the Blue Nile Between Wad Medani and ELKamlin, 1986 and 2020

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Abstract

Erosion and accretion of channels are among the central geomorphological processes that redefine the Blue Nile path, namely with respect to Wad-Medani to El-Kamlin section in Sudan. Such transformations are very dangerous to adjoining agricultural lands, infrastructures, and settlements. This research aims to analyze the geomorphological Change of the Left Bank of the Blue Nile Between Wad-Medani and EL-Kamlin using GIS techniques from 1986 to 2020. The satellite images covering the same span and captured by Landsat satellite were also processed and the Digital Shoreline Analysis System (DSAS) was used to quantify measures of shoreline change. The envelope of shoreline change (SCE) varied 2-1273 m and the net shoreline movement (NSM) varied -719 to 1273 m and the end point rate (EPR) varied -21 m/year (erosion) to +37 m/year (accretion). The maximum accretion rate was recorded as 37.45 m/year whereby the average rate was 5.86 m/year. The mean erosion value was -21.14 m/year with std= 1.55, mean accretion was + 2.5 m/year with std = 0.06 and the average ratio of both erosion and accretion values was -9.06. Predictive analysis also shows that the villages located close to the right bank of the river, with a distance of 4 kilometers, can become more vulnerable in the future due to the current occurrence of bankline migration. The results of this study offer new information about the dynamics of different riverbanks in Sudan and lay the ground to proper management of rivers, planning of land resources, and the development of a disaster mitigation plan of action.

Keywords: Blue Nile River, Channel erosion, Channel accretion, Bankline migration, GIS techniques, Digital Shoreline Analysis System (DSAS).

1. Introduction

The study of the rate of change in a river bank is important to determine hazard areas, erosion impacts, and regional sediment budgets, and to develop predictive modeling of morphodynamic changes (Saadon et al., 2021). It is also important to settle boundaries in river management. The need to delineate riverbank position and assess variation through space and time explains the history of human settlement on or close to it (Smith et al., 2019).

Geomorphological processes of the left bank of the Blue Nile, between Wad Medani and El-Kamlin, and the broader processes of environment and development affecting the riverine landscape of Sudan, can be seen as a reflection of the similar processes on a larger scale (Woodward et al., 2022). This stretch of the river has been relatively subjected to significant morphological change due to the effect of natural processes together with human activities. Coastal management alternates between erosive and depository phases but the Blue Niles hydrological regime happens to be seasonal and during the span of June to September, it has been observed that there is high amount of sediment loading (Frihy & Stanley, 2023). Ethiopian Highlands contribute large loads of sediment to the upstream; however, downstream locations which include the study site lack due attention in the scope of sediment-budget research, or mitigation programs (Gebremichael et al., 2025). The type of soil which is a mixture of a well-balanced sand silt clay and due to the high agricultural activities like banana growing reduces the stability of the soil and enhances the bank erosion (Tilahun & Desta, 2023).

These natural forces are even compounded by anthropogenic forces such as dams, agricultural expansion, or deforestation. since certain processes that boost retreat of the shoreline include the cutting down of trees, uncontrolled agricultural activities that are close to the riverbanks, and

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the ever-increasing migration of settlements (Kerckhof et al., 2016). This recession endangers infrastructure, crops, and the human population located a few kilometers away on the coastline (Kerckhof et al., 2016). This denotes the area is at increasing risk of land degradation, economic losses, and displacement of populations. Spatial heterogeneity in riverbank behavior is found to be significant, as laid out in the GIS-based analysis of the Digital Shoreline Analysis System (DSAS) (Ulain et al., 2022). Some of the sites were observed as undergoing severe erosion, whose inland display style addiction feeds back to sites more than 700 m, while others were seen to accrete up to 1,273m (Abd El-Hamid et al., 2021). Accretional areas were moving at an average of +5.86 m/ yr, and that of the erosional areas averaged at -3.75 m/yr indicating a high degree of geomorphologic instability (Elsayied Abdein, 2021).

Although such transformations, Sudan does not have a system of monitoring the river banks and controlling the erosion. In comparison, Egypt has already implemented a combined management strategy for water and shoreline, which involves a combination of both GIS and protective facilities like embankments and seawalls. In comparisons with Sudan; Egypt is considered since it also depends on the Nile for water security and to assess its monitoring and managing system's advancement. On the contrary, Sudan experiences more dilemma in handling river dynamics and so is the case in terms of erosion and effects of floods (Smit et al., 2021). .

The current weakness of Sudan also indicates that a spatially-oriented planning and intervention is essential. Satellite data, in remote sensing data, including Landsat, covering the period between 1986 and 2020, allow the study of the long-term change in the shoreline dynamics (Riak & Badeng, 2025). The utilization of a present-day trend of erosion and accretion has led to the prediction that in some parts the shoreline will recede or extend by hundreds of meters by 2045, which has the likelihood of altering the landscape and hydrological attributes of the region (González Rodríguez et al., 2025).

A thorough research and control of such alterations is essential in an effort to save the ecological and socio-economic worth of the location and add to the resilience of the general Nile River environment (Sahavacharin et al., 2022). Solid management can combine scientific monitoring, the community-based land-use approaches, and the policy reforms of the institutions focused on riverbank protection, sediment management, and climate adaptation (Walz et al., 2021).

In spite of the larger global and local interest in the problem of the riverbank erosion and sediment control along the major riverways like the Nile, the geomorphological functioning of the Blue Nile in Sudan, in particular, the part located between Wad Medani and El-Kamlin, is rather poorly documented. This region, due to its agricultural productivity, settlements of people and its nearness to Blue Nile and its fluvial processes such as accretion, erosion that were dynamic has been gradually going through a morphological transformation which to date has been mostly unmonitored and under-researched.

Such a gap poses a great threat to the surrounding communities and farmed lands. It is the morphological instability that is characterized by the high levels of erosion (up to -21.14 m/year), accretion (up to +37.45 m/year), is intensified due to human activities, changes in climate combined with lacking well-made infrastructure to protect the riverbank. Those communities located near the right bank of this river (within 4 kilometers) are more exposed to losing the land, damaging the facilities, and leaving the lands. In the absence of local empirical data on erosion and accretion dynamics, policymakers and planners are not able to create the right measures to protect the livelihoods of rural people, control sediment outflow and ensure navigability of rivers.

Section of the Blue Nile between Wad Medani and El-Kamlin (whereby the majority of the downstream material is sourced) has limited research, despite its strategic significance about the stability and control of the riverbanks. There is no measurable measure of the processes of erosion and accretion in this area, so the protection of riverbanks and overall scarcity measures of sediment management are still lacking.

1.1 Research Questions

- How has the shoreline position, accretion rates, and erosion evolved between Wad Medani and El-Kamlin from 1986 to 2020 in the Blue Nile?

2. Theoretical background

2.1 Importance of Shoreline Change

Riverbank change has driven communities to fix shoreline positions; however, this under-observed (Risha, 2024). To effectively tackle the challenges presented by coastal erosion risk and future sea-level change, it is important that appropriate data is acquired and robust methods are adopted to both delineate the shoreline and accurately measure and represent shifts in its position

(Darwish, 2023).

Such behavior of the Blue Nile riverbanks and shores is a critical indicator of the river geomorphological processes and the overall state of the socio-environmental situation (El-Asmar & Taha, 2022). Additional factors affect these processes locally including the coarse combination of sand, silt, and clay in the soils together with intense banana plantation techniques (Alghamdi et al., 2023). When combined with high soil exploitations in the area create an extreme and severe change in the bank instability (El-Sanat et al., 2017). Such local erosion processes put at risk farmland, infrastructure and navigation safety in addition to reducing the total amount of sediment carried over to downstream (Anwer & Hassan, 2025). The resultant decrease in the supply of sediments increases the rate of coastal erosion in the Nile Delta, an area, which has already lost 10 m/yr of coast Indian Beach Ocean Shore to the shoreline erosion after the construction of Aswan Dam (Elkotby et al., 2023).

Therefore, careful observation and regulation of the shoreline morphological changes is crucial, not only in order to protect riparian human populations, but also to maintain the sediment balance, through which delta stability and crops productivity down the river is sustained.

2.2 Shoreline Change Analysis

Shoreline change analysis (SCA) is a broad descriptor that has been used since the 1970s to express the methods and approaches used to define and quantify change in the location of shorelines (Janda et al., 2025). It is not limited to coastal environments, and studies have applied SCA to lake shorelines, particularly in larger systems such as the Great Lakes (Janda et al., 2025; Murray et al., 2023). Considerable thought had been given to shoreline dynamics in much earlier geoscience accounts of the 19th century. The majority of the literature on shoreline topics was published in the USA, followed by India and Spain (González Rodríguez et al., 2025). Also, the trend of the shoreline change study has increased over time. Given the importance of shoreline dynamics, it is essential to continuously monitor and detect spatiotemporal changes in shorelines to keep track of the changes and understand the vulnerability and risks associated with natural disasters (Hastuti et al., 2024). In addition, adopting measures for sustainable planning, decision making, and better management practices for the communities impacted by riverbank erosion, and coastal erosion, globally (Dede et al., 2023).

It is essential to take proactive measures and adopt appropriate adaptation and mitigation plans for flood management, dam construction, estimation of erosion and accretion rates (Ankrah et al., 2022). Modeling of sediment budgets, and predictive modeling of coastal morphological dynamics (Rahman et al., 2022).

The dynamics of coastal regions in the Blue Nile river, specifically those found in the downstream of the Ethiopian highlands, have received special attention in the recent times, because of related studies based on remote sensing (Ewunetu et al., 2021). Geographic Information System (GIS) and system like the Digital Shoreline Analysis System (DSAS). Another interesting study involved a land-use/land-cover (LULC) and flood-hazard dynamics leading to the confluence of Blue and White Nile in 2014 till 2020 (Ewunetu et al., 2021). The result suggests that the agricultural, huge settlement and water body segments located on the Blue Nile have gone through a comparatively low change (0.3-7.3%) between this period, but the equal parts on the White Nile have undergone prominent changes (5.6-21.4%) which shows increased vulnerability of flood (Ewunetu et al., 2021).

Another study that was undertaken utilized geospatial methods along the Blue Nile corridor, which included Berber, Es-Sileit, and Dongola settlements. Major erosion and accretion were highlighted by the findings: Berber experienced about 60 50.0 ha/year in erosion, Es Sileit 50 50.0 ha/year, and Dongola registered net accretion (+288.0 ha). Berber and Es-Sileit lost land amounting to 317 and 199 ha, respectively (Belay & Mengistu, 2021).

2.3 Geomorphological changes and effects

Dams have a determining impact on rivers and often, the natural flow regime is altered and reset by dams (Chong et al., 2021). The morphology of rivers can be significantly changed with the building of huge water retention dam, for example, the Grand Ethiopian Renaissance Dam (GERD), on the Blue Nile, which can impact the riparian states downstream cases (Luna et al., 2024). The sediment upstream of reservoirs is in most cases entrapped and this reduces the amount of the sediment that is transported past the dam leading to the narrowing of the channel and also degrading the river bed (Ahmed et al., 2024).

In the meantime, the accumulation of sediments in reservoirs provides such environmental damage as harmful changes in aquatic systems, decreased transport of sediments to oceanic areas and considerable regression of

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deltas (López et al., 2016). Although flushing of sediments during the regular intervals may help to mitigate some of the effects, the reduced number of high-discharge events cause the accumulation of sediment that leads to channel aggradation (Islam et al., 2021; Kondolf et al., 2014). As an example, the Cachi dam in Costa Raised the riverbed by a small amount some 250000 tonnes in a 30-kilometre stretch because of depositing the fine sediment (Bing et al., 2022).

A complex temporal study of Blue Nile processes in the area of GERD construction and operation has shown a dramatic change of the surface cover of water, especially the periods of filling the dam (Hassan et al., 2023). The changes that occurred between 2011 and 2018 were attributed mostly to improvements of the Roseires Dam but those experienced between 2018 and 2019 were attributable to the climate variability (Alrajoula et al., 2016). Most decisive alterations were noticed in 2020-2022 when alterations majorly took place in the areas located upstream of the GERD where water reservoir was heavily expanded (Eldeeb et al., 2023). Roseires Dam is however functioning as a hydrological buffer and this helps in reducing effects that occur downstream and also supplies water to communities that rest at lower terrains (Alrajoula et al., 2016). Upstream of the GERD at a distance of not more than 30 km, there has been no significant changes in surface area and in channel morphology. Beyond that, however, there has been increasing sediment deposition as it has shifted from a minor event in 2020 to the point of apparent deposition in 2022 (Li et al., 2022). It is contrary to the reduction and narrowing with the formation of upstream reservoirs. Such results indicate that the manner in which the management conducts the developments on the Roseires dam is very crucial in enhancing sedimentation (Ahmed et al., 2025).

2.4 Dynamics of Land-Use/Cover in Blue Nile Headwaters

Land-use/cover (LULC) change is one such issue that is ongoing and global and Africa has been majorly affected due to a lot of transition such as the grassland, woodland and other vegetative land being turned to agricultural and settlement land (Ahmed et al., 2025). Sudan in particular has to deal with massive land degradation and reduced ecosystem services: between 1981 and 2003, 26 % of the total land of Sudan was degraded which means the lives of about 30 % of the population was affected (Yasin et al., 2023). Deforestation has continued to occur and it is bringing about loss of biodiversity, climatic change, desertification and soil erosion. In Sudan, the forest cover of more than 40 % in the start of the twentieth century recorded a very low figure of 2.36 % in the year 2000 and this has been attributed primarily by population growth (Yasin et al., 2023).

Blue Nile (Abbay) basin, which is the location of the main tributary of the Nile located in western highlands inhabited by Ethiopia, doubles as an important agricultural area. Biophysical condition of the change of the basin has been recorded in remote-sensing and GIS studies (Ewunetu et al., 2021). According to land-use/cover data analysis that was conducted in North Gojjam sub-basin using data of 1986, 1994, 2007 and 2017 agriculture increased by 21.4 % and plantation forestry increased by 368.8% (Bekele et al., 2019). At the same time the water bodies decreased by 50.0 %, bare land by 7.9 %, grassland by 41.7 %, forest by 28.9 %, bush and shrub land by 38.4 %. At the 31-year period, the amount of landscape that experienced at least one LULC transition were 34.6% (Abebe et al., 2022).

The agents of these changes are complex and site-specific being under the influence of socio economic and biophysical factors. Inhabitants of North Gojjam cited population expansion. (Abebe et al., 2022). As a result of such an expansion, there exists a constant lack of supplied land used to cultivate crops and graze animals. Poverty emerged as the second-strongest force because of the fact that a great number of communities survive on subsistence farming (Hall et al., 2017). In addition, the use of biomass energy due to the lack of access opportunity to rural electrification or any other forms of renewable energy supply.

The sale of firewood, dung cake, and charcoal has thus led to the commercialization of energy sources by farmers in rural areas and the urban community, which is increasing the rate of degradation of forests (Bazgir et al., 2024). The lack of awareness about the environment, the mention of resources as the possession of the government, and the poor enforcement of the regulations regarding the environment also lead to the forests deterioration (Bazgir et al., 2024). The rate at which the grazing lands and agricultural areas spread. Moreover, the infrastructural works, e.g., schools, health centres, and road network, promote settlements in communal grazing areas and hence conversion to settlements.

3. Literature Review

Spatial and Temporal Variability of Bank Erosion during the Period 1930–2016: Case Study—Kolubara River Basin (Serbia) (Dragićević et al., 2017). The fluvial process is characterized by an intense meandering riverbed. This study aimed to perform a reconstruction of the lateral migration of a 15 km length of an active meandering river during the period 1930–2016. River morphological changes were analyzed and quantified from cadastral maps and aerial photographs and by geodetic survey and GIS. Hydrological characteristics and extreme hydrological events were evaluated in relation to bank erosion rate and the maximum annual rate of bank erosion during 2010–2016 varied between 0.3 and 11.5 m (Uddin et al., 2011). It is very likely that in the period from 2010, frequent discharge variations and rapid change of its extreme values caused more intensive bank erosion. These research results can be deemed valuable for river channel management, engineering (soft and hard engineering), and planning purposes (predicting changes in river channel form) in the Kolubara River Basin.

3.1 Global trends within Shoreline Dynamics

Initial methods of studying shoreline dynamics originated in the nineteenth century, but it was not until the 1970s that the term shoreline change analysis emerged to become the key in this research area (Hunt et al., 2023). The United States continues to have the largest share of scholarship in the region in terms of persons contributing to scholarship, and India and Spain stand as the second-largest contributors to scientific output (Faghri & Bergman, 2024). The increasing interest in conducting SCA research is one of the pieces of evidence hinting at the strategic relevance of continuous monitoring of the shorelines in an effort to achieve the sustainable management of the land and the water.

A review of the shoreline processes reveals some common factors that drive these processes whereas in case of the river banks of the Blue Nile in Sudan the same drivers are present, that is, climate variability, anthropogenic land use, and hydrological engineering (Anwer & Hassan, 2025). Climate change has increased rate of precipitation extremes and changed flow regime that enhanced episodic erosion and accretion globally (Anwer & Hassan, 2025). At the same time, anthropogenic activities upstream, namely clearance of the land cover (deforestation), expansion into the agricultural sector and the creation of dams, have significantly altered sediment inputs. Dams hamper sedimentation, weaken downstream lines and increase the recession rate of banks a factor that has already been cited on many rivers including the Nile (Warrick et al., 2023).

The results obtained in this international study allude to findings evidenced in the Sudanese Blue Nile where literature indicates episodic collapse of the bank, spatially non-homogenous areas of erosion, accretion hotspots and net land loss about Berber and Es-Sileit.

3.2 Flood and Coastal Management in Sudan

Since Sudan is dependent on the river Nile and most of the coasts are low-lying especially in the Mediterranean Sea, the control of floods and coastal operations is a national priority (El Raey, 2022). The government has embraced integrated management of water resources that involves building dams other than the Grand Aswan High Dam, building embankments, and creating drainage systems to reduce the risks of floods (Olson & Kome, 2024).

Sudan also faces the emission along the shores, caused by rising sea levels and beach erosion especially in the Nile Delta (Mohamed & Abd-El-Mooty, 2023). To resolve such issues, coastal protective shields are implemented to prevent destruction of infrastructure. This includes agricultural land through installation of seawalls, breakwaters and nourishment of coastlines (Zehro, 2021). More recent efforts are also aimed at using satellite information and GIS tools so as to enhance the early warning systems and sustainable plans of land use.

4. Material and Methods

4.1 Material

Due to improved availability of aerial photography in coastal zone, a protocol of standard method or technique of measuring shoreline location and computing shoreline change was developed (Topah et al., 2022). Since then the methodological basis upon which the analysis is constructed at the time has been improved and many other types of data have been inputted into shoreline change analyses.

DSAS computes rate-of-change statistics for a time series of shoreline vector data. DSAS version 5.0 (v5.0) was released in December 2018 and has been tested for compatibility with ArcGIS versions 10.4 and 10.5 (Ankrah et al., 2022).

Digital Shoreline Analysis System (DSAS) is a free software tool which runs on ESRI Geographic Information System (ArcGIS). DSAS 5.0 that was released in December 2018 has passed through a series of compatibility testing with ArcGIS 10.4 and 10.5 versions (Himmelstoss et al., 2021). The application is now operating on the windows 7 and windows 10 operating systems and is meant to cover assessment of coastal dynamics mostly in the coast

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protection of coastal populations.

There was hence an imperative to make sure that the geospatial that existed such as national maps and aerial photographs should be well utilised in the process of analysing the coastal behavior and also to introduce a definite method where the position of the shores can be easily compared and a trend of the changes could be established (Siyal et al., 2022).

As far as ERIS (Earth Resources Information System) is concerned, information pertaining to preprocessing of data/images, resolution, and error margins is scant in the stipulated text. In the document, it is stated that when the images are captured remotely, there are fewer chances that the images would require geometric corrections because of distortion that has been created by a number of issues like the curvature of the Earth, refraction of the atmosphere, and the satellite's orbit. These distortions are either systematic or random, or they are both, hence rendering the geometric correction process complicated. The text also briefly mentions the topic of accuracy of elevation information and mentions that a 1-meter vertical error can cause the horizontal error to range up to 20 meters at a 3-degree slope. Though there is no exact data on the approaches of the preprocessing methodology, numerical solutions (e.g., spectral, temporal), or an elaborate error margin related to ERIS images.

The recent versions of shoreline change analysis are based on these previously made advancements, with the inclusion of improved analytical steps, more advanced systems of error management, and the utilization of multiple numerical and statistical methods of interrogating shoreline change data (Apostolopoulos & Nikolakopoulos, 2021). In the current research, DSAS v5.0 is used, which was performed at the ArcGIS v10.4, with the SCE, NSM, and EPR rate types. The Digital Shoreline Analysis System (DSAS) is a freely available software application that works within the Esri Geographic Information System (ArcGIS) software (Himmelstoss et al., 2021).

4.2 Methods

4.2.1 DSAS Workflow

The digital shoreline Analysis System (DSAS) that

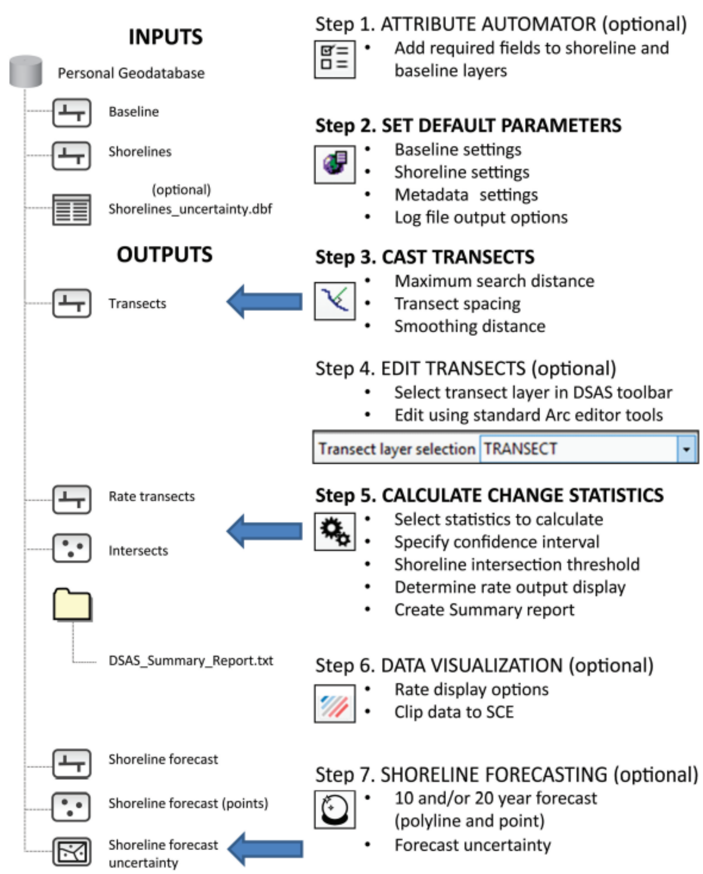

Figure 1 DSAS Workflow

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was used to discuss this study adopts a workflow-based structure in order to evaluate the changes in morphology in the left bank of the Blue River. The selected extent of work begins with the preparation of the type of shoreline data sets taken out of the georeferenced Landsat satellite images that were retrieved in 1986, 1991, and 2000, 2010, 2020 b. Shoreline dates used are 1/24/1986, 1/6/1991, 2/16/2000, 1/26/2010, 1/22/2020. These shorelines are then compiled and brought into ArcGIS in which a reference line, i.e. baseline, is produced parallel to the shorelines but situated away towards the landward direction to be utilized as the basis of measuring the change and for shoreline forecasting as well (figure 1).

After this, perpendicular transects which are automated are then cast across the area under study at the same uniform time across the study area and cut across the shore-lines at the sections of the same time-periods. The system in turn runs the statistics of changes in each of the transects and produces the following main output: Shoreline Change Envelope (SCE) that registers a total distance between the furthest shorelines; Net Shoreline Movement (NSM) that reports about a distance between the initial and the final shorelines;

End Point Rate (EPR) that calculates the ratio of shoreline movement over an annual period of time. This algorithmic process makes the quantification of the dynamic structure of the shoreline or riverbanks accurate as well as consistent.

5. Results

5.1 SCE

- Bank: right bank of Blue Nile between south of Wad- Medani to the north of ELKamlin cities reach from (14 20 00N) to (15 10 00N) (map,1, fig. 2)

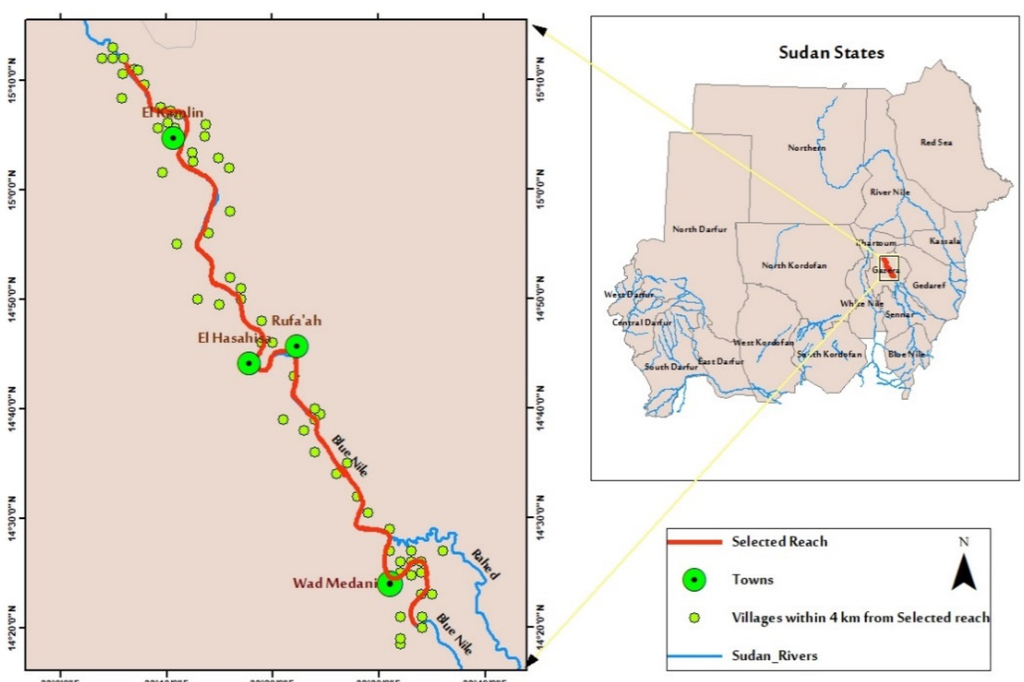

Figure 2 Map of the selected reaching of the study area

Blue Nile's left bank, as shown in Figure 2, is between Wad Medani and El-Kamlin, and that is marked by the unique red of the selected reach here. Overall, this tract is superimposed with a number of small green circles marking villages smothered within a range of 4km, as also filled up larger green circles denoting Wad Medani, El-Hasahisa, and El-Kamlin. The geographical configuration of this area proves that most of the rural settlements and towns are situated in this area of the country that is most likely to erode and accrete banks (Das et al., 2014). Since these points are distributed just adjacent to the moving shoreline, it follows that any recession or protrusion of the shoreline is going to influence the infrastructure of the community and the utilization and cultivation of the agricultural lands.

It was also shown on the map that the river was highly sinuous and it was highly bent at Ruf a 233m and El-hasahisa where it exerts a lot of morphological activity in the river.

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Such locations coincide with locales where seaward shore instability was high as determined by the DSAS findings, which further supports the premise that meandering loops make banks more vulnerable. The high exposure is further enhanced by the concentration of villages around these bends: during episodes of rapid erosion the surrounding livelihoods and water transport systems along the river are instantaneously endangered.

5.2 NSM

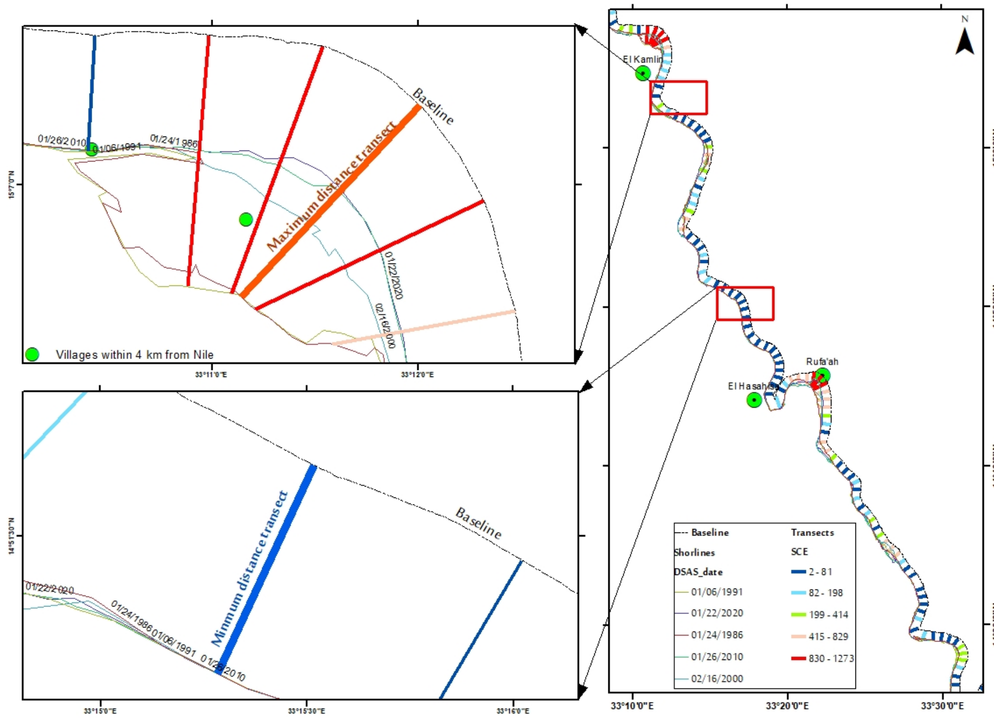

Figure 3 Blue Nile's path between El Kamlin and Wad Medani

The main picture is the graphical representation of the course of Blue Nile between Wad Medani and El Kamlin with particular groups of colors distinguished by the successive interval classes within the Shoreline Change Envelope (SCE) in meters. Every color strip defines area of measured shoreline shift at each era. Areas of greatest SCE-red indicate severe morphological shifts, and those areas colored in blue exclusively point out to places of little or no change. The most geomorphologically active territorialities of the study area are marked by two large boxes (with red frames) located in close vicinity of El Kamlin and in between El Hasahisa and Ruf stimulating the development of the activity. The generous lateral transport that is clearly seen along these reaches point to erosion or accretion processes which were going on.

To reinforce these dynamic and stable regions of the river two enlarged insets are provided on the left side of the main diagram. The top inset gets magnified by a hotspot near El Kamlin, where a number of red transects converge at sequential positions of the shoreline, which were observed on different dates. All the transects point to a different direction and are perpendicular to a reference baseline which implies that there is massive dispersion in lines and, subsequently, in lateral erosion of riverbank throughout the study period. Orange transect that is at the highest level of SCE suggests the part on the river bank that has been the most shifted between 1986 and 2020. This region hence forms a risky zone in which erosion or deposition has triggered great rearrangement of the channel which may affect the surrounding uses of land and settlements.

The lower inset, however, represents a relatively steady interval identified by blue transect that bulges heavily on consecutive shoreline locations that change every year. The small distinction between these lines, there is little change during the course of the study always pointing out that the study area has not been changing significantly over time. The identification of such stable reaches is also highly relevant on the results that they form more stable where prophylactic reinforcement does not take priority.

5.3 Shoreline Change Statistics Equations

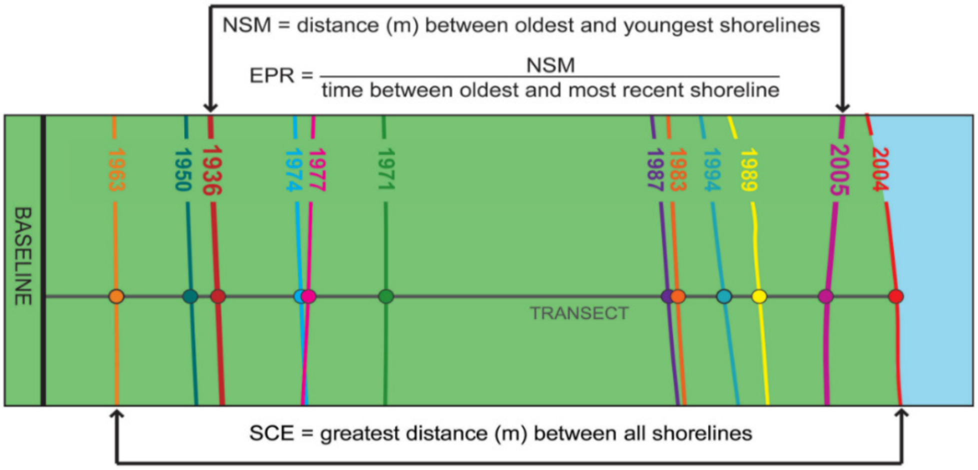

Figure 4 Shoreline change statistics equations

Shoreline change statistic rates calculated:

5.3.1 Distance: SCE (Shoreline Change Envelope, m)

The shoreline change envelope (SCE) reports a distance (in meters), not a rate. The SCE value represents the greatest distance among all the shorelines that intersect a given transect (figure 4). As the total distance between two shorelines has no sign, the value for SCE is always positive. SCE overall averages show: that the total number of transects is 140, the average distance is 230.7, the maximum distance is 1273.01 and the minimum distance is 1.62 as shown in table (1).

The graphical description characterizes the key propitious shoreline-change metrics, namely, Net Shoreline Movement (NSM), End Point Rate (EPR), and Shoreline Change Envelope (SCE), at the center of the non-study on the geomorphological changes of the Blue Nile left bank located between Wad Medani and El-Kamlin in 1986 and 2020. NSM refers to the straight-line distance between the oldest and the latest position of the shorelines and provides reflection of the magnitude and the direction of the shoreline migration with time. Respectively, with regards to the Blue Nile, the band of NSM values (correlation with erosion to accretion) was between 1,273 meters (accretion) to negative (erosion) 719 meters, which denotes there exists spatial variation on the stability of riverbanks.

By dividing NSM by the years to the two dates at shorelines, one gets EPR which gives the rate of change per year on average. Throughout the period of studies, the values of EPR were as high as 37.45 meters per year in the regions of strong accretion and as low as = -21.14 meters per year in regions of intense erosion. Maximum distance of any two positions of the shorelines, known as SCE, defines total dynamic range of change between any position of the shore during several years and allow hotspots of erosion and deposition to be identified as criteria of critical importance. All these identifiers allowed to conduct a very specific, time-sensitive analysis of the shoreline processes, as such, they have provided the scientific foundation of the land-use planning, the protection of the riverbank, and the mitigation of the flood risks of the area in the future.

5.3.2 Distance: NSM (Net Shoreline Movement, m)

The net shoreline movement (NSM) is the distance between the oldest and the youngest shorelines for each transect; therefore, units are in meters. NSM

Table 1: SCE overall averages

The Value For SCE	**Total Distance**
Total Number Of Transects	140
Average Distance	230.7
Maximum Distance	1273.01
Minimum Distance	1.62

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overall averages: The Negative distance where the total number of transects is 140, the average distance is 59.27, the number of transects with negative distance is 60, % of all transects that have a negative distance is 42.86%, maximum negative distance: -718.64 and the average of all negative distances: -127.39 the Positive distance where the number of transects with positive distance is 80, % of all transects that have a positive distance is 57.14%, maximum positive distance is 1273.01 and the average of all positive distances: 199.27 as shown in tables 2 and 3 and also figure 4.

Table 2: NSM overall averages: Negative distance

NSM overall averages	Negative distance
Total number of transects	140
Average distance	59.27
Number of transects with negative	60
The %age of all transects that have a negative distance	42.86%
Maximum negative distance	718.64
Average of all negative distances	127.39

In the current Net Shoreline Movement (NSM) analysis of the left bank of the Blue Nile between Wad Medani and El Kamlin, the current paper provides necessary information about the amount and range of riverbank erosion that occurs during the study years 1986 to 2020. Out of the total transects measured, 60 of them had the negative value of NSM which means that around the 42.86 percent of the whole riverbank has eroded over the years. The average NSM of all transects was 59.27 m, but in the case of negative values, the average retreat was 127.39 m, and this is a particularly high displacement weight to an adjacent system of rivers and at the same time such displacement has obvious consequences regarding settlements and crops.

Moreover, retrogression was 718.64 m and this is the area of wild erosion whereby the river has made a lot of ground going inland. This flow testifies to the active water processes, and probably some human influence, such as the change of land use, cutting of forests, or banks destabilization due to construction or agriculture. NSM outcomes demonstrate that significant part of the riverbank is in the state of instability and vigorous erosion.

Therefore, villages as close as 4 km to the river and particularly those villages in these erosive hot spots are much exposed to the dangers of land wastage, displacement, and destruction of infrastructure. Cumulatively, this analysis confirms the spatial variability of erosion and determines particular areas that require immediate geomorphological intervention and monitoring.

Table 3: NSM overall averages Positive distance

NSM overall averages	Positive distance
Number of transects with positive distance:	80
The %age of all transects that have a positive distance:	57.14%
Maximum positive distance:	1,273.01
Average of all positive distances:	199.27

The data of the Net Shoreline Movement (NSM) of positive distances on the left side of the Blue Nile Hypothetical course between Wad Medani and El Kamlin allow to represent this accretion, which is the outward growth of the bank of the river, during the 1986-2020 year. Eighty transects (or 57.14 %) of the analyzed measurements were positive NSM, that is, in the majority of the analyzed areas of the river banks, either the deposition of the sediments or the lateral shoreline expansion was observed. A large positive maximum NSM of 1273.01 m was interpreted to mean that a significantly high amount of accretion occurs at specific locations and it could be a result of deposition of the sediments in the event of floods or due to the way the channel has migrated with a preference of

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deposition in the outer bends and point bars. Mean positive NSM was 199.27 m, and this showed that the riverbank has been extending outwards over the years in many parts of the area under study hence affecting the morphology of the land and therefore may affect land use pattern, ecosystem formation and water flow among others.

The results found are significant in locating the zones of accretion, though they are not of an imminently devastating nature in comparison with erosion, but might lead to the emergence of navigation problems and alteration of the floodplain regime and water distribution patterns in times of the flood. Together with the data on erosion, the current accretion analysis presents a complete picture of the dynamic behavior of the Blue Nile. It demonstrates the complexity of shoreline phenomena in terms of space. Some parts of the river lose territory to erosion, and some gain land due to the processes of depositing material, which shows the complexity of the shoreline development along the river.

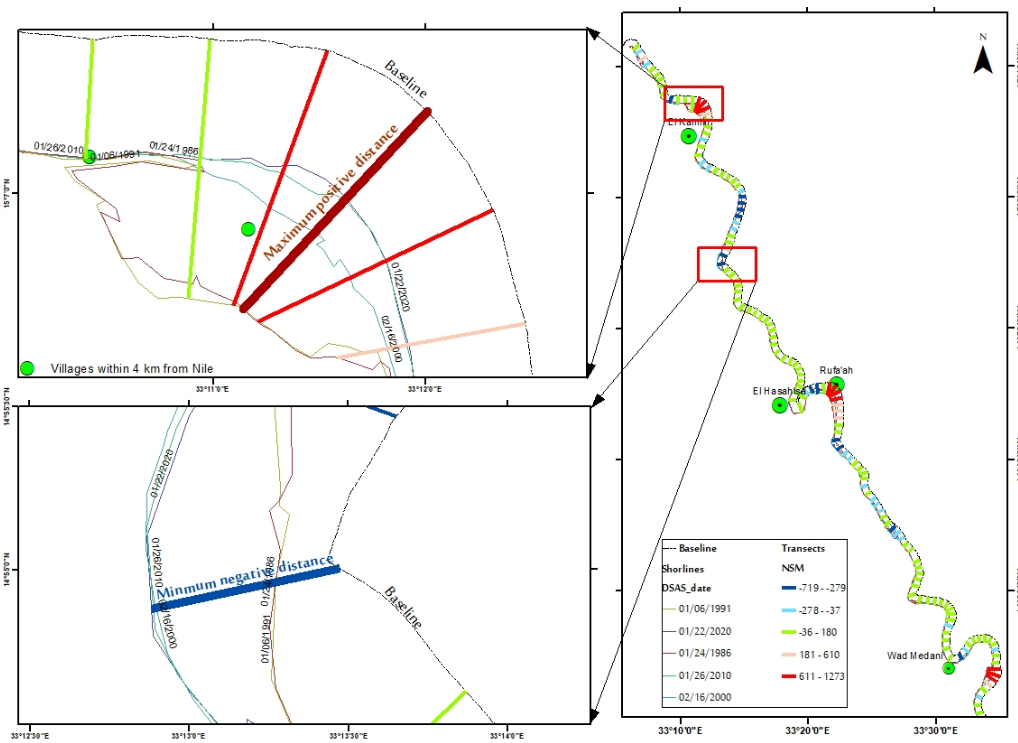

Figure 5 NSM for selected reach

The end point rate (EPR) is calculated by dividing the distance of shoreline movement by the time elapsed between the oldest and the most recent shoreline. The major advantages of the EPR are the ease of computation and the minimal requirement of only two shoreline dates as denoted in Figure 5. The disadvantage is that in cases where more data are available, the additional information is ignored. Data are available, the EPR overall averages of Erosional transects the total number of transects is 140, average rate is 1.74, number of erosional transects is 60,

Table 4: Erosional transects

EPR overall averages	Erosional transects
total number of transects:	140
average rate:	1.74
number of erosional transects:	60
% of all transects that are erosional:	42.86%
maximum value erosion:	-21.14
average of all erosional rates:	-3.75

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% of all transects that are erosional is 42.86%, maximum value erosion is -21.14 And the average of all erosional rates is -3.75 The Accretional transects: The number of accretional transects is 80. % of all transects that are accretional is 57.14% And the maximum value accretion is 37.45 the average of all accretional rates is about 5.86 as shown in tables 4, 5 and figure 5.

The detailed analysis of End Point Rate (EPR) of erosional transects in Blue Nile indicates the useful information about the rate and magnitude of shoreline retreat between the reference data in 1986 and 2020. Negative EPR values were recorded in 60 transects (42.86 %) out of the total number of 140 transects sampled and thus the study showed that a large area of the river bank has experienced sustained erosion. On all the transects, the mean rate of movement of shorelines was found as 1.74 metres per year including erosional and accretional areas. But in case of the erosional transects alone, the average rate of the bank retreat was -3.75 meters per year and this highlights a uniform and alarming erosion of river bank materials.

The highest annual rate of erosion was -21.14 meters per year and this is a very high value which is an indication of an extremely unstable area with the river having invaded a neighboring land to a very fierce degree. This kind of rate implies that with the passage of time those vital places close to the bank of the river particularly the agricultural land and rural villages might majorly suffer in case no measures are put in place to mitigate the situation. These observations refer to extreme geomorphological action, which is promoted by seasonally occurring floods, the lack of the vegetative cover, disproportionate supply of sediments, and perhaps the impact of humans on a riverbank.

This process of erosion is of great significance to the aims of the study; i.e., finding out a vulnerable spot, and knowing way of river management. It supports the importance of constant observation, control of land use and erosion control because more deterioration must be stopped before it destroys the lives of people living along the Blue Nile.

Table 5: Accretion transects

EPR overall averages	Accretional transects
the number of accretional transects:	80
% of all transects that are accretional:	57.14%
Maximum value accretion:	37.45
average of all accretional rates:	5.86

Carrying out an End Point Rate (EPR) test on accretionary transects sited along the left bank of Blue Nile between Wad Medani and El Kamlin resulted to the recognition of some significant areas where the riverbank is upgrading due to the deposition of sediments. Out of the 140 transects analyzed, 80 transects (57.14 %) reveal positive results on EPR values and this means that the majority of the study region was subjected to net accretion between the periods of 1986 and 2020. The discovery highlights a widespread impulse of banks accretion in certain areas hence helping in the changing morphology of the river corridor.

Such data is essential for the understanding of the spatial variability of the riverbank processes in the study area. Whereas erosion poses the risk of land loss in some of these locations, accretion causes land gain in other places, which may change the land use pattern, ease of navigation, and the flood scenario. The identification of accretional zones is a great contribution to the goal of the study, which is to make a thorough evaluation of the geomorphological change, and also as a contribution of significant insights to such processes as land-use allocation, management of sediment, and infrastructure development along the Blue Nile.

5.4 End point rate (EPR)

End point rate (EPR) is a measure of shoreline change adopted in the current study to determine the speed of the riverbank migration in the left bank of the Blue Nile between Wad Medani and El Kamlin in the duration of 1986-2020. It is calculated as a ratio of the distance between the oldest and the most recent positions of the shoreline to the time range between the dates (as shown in figure 6). The process has the following benefit mainly when there are only two shore measurements because this provides straightforward method of estimating the average

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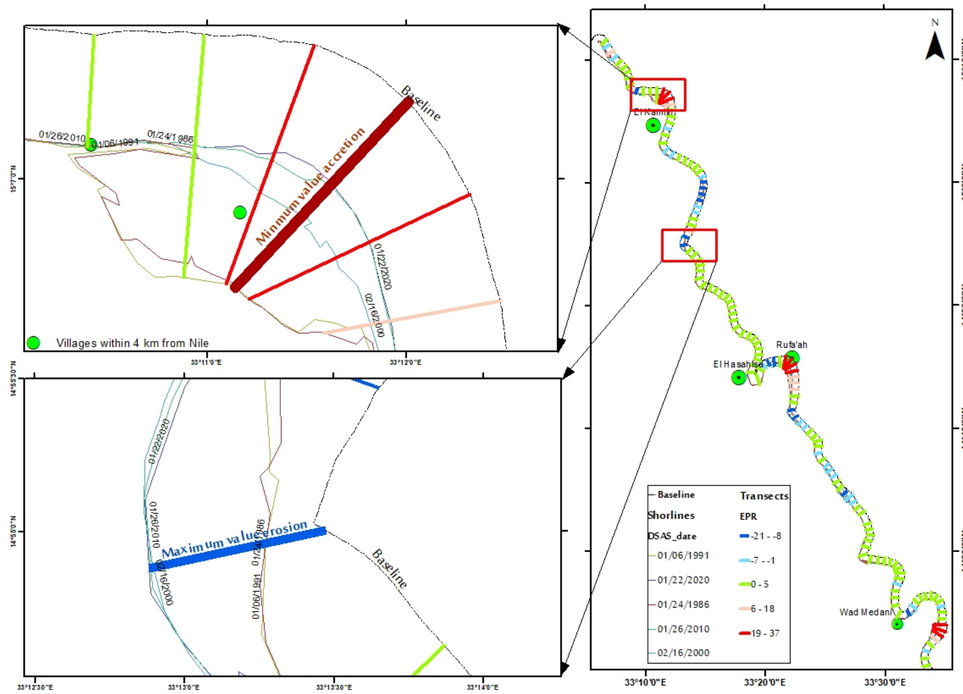

Figure 6 EPR

annual movement of the riverbank.

There are erosion and accretion patterns as seen in the data in the 140 transects that were studied. Sixty transects (42.86 %) show indications of erosion with the highest recording rate of −21.14 meters per year and the overall one of -3.75 meters per year. The findings show the high extent of the land loss in some of the reaches which is most probably because of the meandering of the river together with some seasonal flooding and anthropogenic activities including deforestation and uncontrolled agricultural practices along the river bank.

On the other hand, 80 transects (57.14 %) have accretion where the bank protruded into the land by means of the deposition of sediment. The highest accretion was 37.45 meters per year with an average of 5.86 meters per year which implies that some areas showed significant accretion and this may be due to characterized by reduced velocity of water, suitable channel geometry and seasonal supply of sediments at high water season.

5.5 Forecasting

A geomorphological alteration due to the filling of the left bank of Blue Nile between the Wad Medani and El Kamlin is expected to take place in the near future ten and twenty years. Analysis of the current end point rates (EPR) depict that Erosional zones, which covers 42.86 per cent of the transects, are likely to draw back an average of about 37.5 meters by 2035 and 75 meters by 2045 in case the erosion rates sustain at the current rate. States in the areas of maximum EPR, greater than 21.14 meters per year, have a possibility of the riverbank recession prevailing at 210 and 420 meters, respectively, in a decade and two decades, which may threaten the security of farmlands, infrastructure, and the settlements around riverbanks as shown in figure 7.

On the other hand, the accretional zones which is 57.14 % of the transects is predicted to project seaward. These sectors have got an average rate of accretion that is 5.86 meters per year, this means that over the next 10 years, these sectors will have shifted an estimated 59 meters and in 20 years by an estimated 118 meters. Along the regions of the highest accretion rate of 37.45 meters/ year, the shoreline is bound to prograde beyond 370 meters in a decade and 740 meters in two decades and such amount of sediment overload can overhaul the messages of any river and even contribute in the flood plains activity and water flow patterns.

6. Discussion

A long-run change of the shoreline, which is embedded in the chronological sequence of the erosion and accretion of the coasts, offers a base to understand

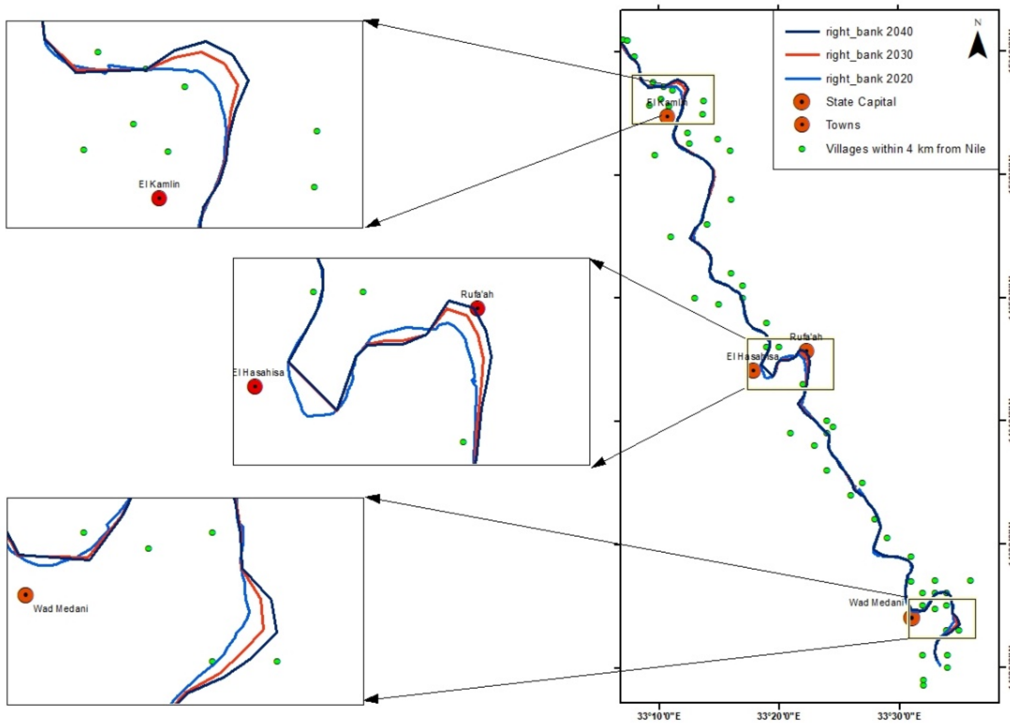

Figure 7: Forecasting reach after 10 years and 20 years

the future rise of sea level (Bekele et al., 2019; Belay & Mengistu, 2021). In the current study, the data on historical shorelines, which were captured on 1/24/1986, 1/6/1991, 2/16/2000, 1/26/2010, and 1/22/2020, are utilized in order to assess the rate of site-specific shoreline change. Figure 4 is an example of long-term erosion and accretion on the right bank of the Blue Nile in Wad Medani, where the 1986 baseline marks the extent of erosion and accretion (Woodward et al., 2022). The northern basin, between south of Wad Medani up to Rufaah, has a great emphasis on net accretion, and the Blue Nile right bank, between Rufaah and the areas of Eihassahisa and Eikamlin, has undergone a great erosion rate of more than 10 m per annum (El-Asmar & Taha, 2022). Therefore, the right bank of the Blue Nile between El-Hasahisa and El-Kmlin has submerged over 21 m, which is a rare aberration, and this has been acclaimed as one of the adverse outcomes of human activity.

The inset that shows the boundaries of the states of Sudan and river network locates the reach of the Blue Nile within the context that is wider in both hydrologic and administrative spheres. It reveals that the origin range of the sediment transport in this reach is part and parcel of the downstream dynamics like sediment deficits that are experienced in the Nile Delta. In such a way, major objectives of the study quantification of spatial variability on shoreline and its linkages with human and hydrological impacts and definition of high risk zones that should be used as a target of management attention are directly covered by the map.

The long-term spatial change of the shoreline is measured in terms of the temporal Landsat ETM+ + images from 1986 to 2020. Figure 5 gives the accretion-erosion zoning on the right bank of the Blue Nile River between Wad Medani and southern Sudan. The changes in deposition. Conversely, in the Wad Medani area and in the proximal Arabian Gulf, deposition has resulted in highly linear accretion patches (sand spits, sand beaches, beach ridge systems, and dunes) upgrading up to 1 km inland.

These results reinforce the un symmetric nature of fluvial processes on the riverbanks of the study reach where the erosion was promoting threats whereas the other reaches were physically modified by accretion (Topah et al., 2022). The estimates however are based on the assumption of a linear trend and failures to consider future expected hydrological changes, future developments of infrastructure and climatic variability (Smith et al., 2019). Therefore, although they provide an excellent point of reference, continuous monitoring and state-of-the-art modelling methods, like Kalman filtering or scenario-based coastal ocean prediction, should also be utilised in order to enhance and improve the projections and serve an active management of the riverbanks and land planning activity.

7. Conclusion

The present study is geomorphological character study of the left bank of river Blue Nile between Wad Medani and El-Kamlin in Sudan since 1986 to 2020 using GIS analysis and Landsat satellite images in order to evaluate the changes in the riverbanks. This study highlighted about the geomorphological changes that occur both naturally and through human interventions and these occurrences subject the agricultural fields, the built structures and structures to risks.

The research measured change envelope shoreline (SCE) of -719 to 1273 meters on the Digital Shoreline Analysis System (DSAS) and net shoreline movement (NSM) of -719 up to 1273 meters as well as end point rates (EPR) of -21 m/year and +37 m/year (erosion and accretion instances). It was found that the highest value of an accretion rate was 37.45 m/year but the average speed was 5.86 m/year whereas, the mean erosion rate was -21.14 m/year. Predictive analysis implies that villages located within 4 kilometers of the right bank are going to be vulnerable to the bankline migrations in the future. This is because the results present key information concerning the river processes in Sudan in a manner that can be used to enhance river management, land resource planning, and possible strategies to deal with disasters that may occur as a result of river processes.

8. Limitations and Future Implications

The future implications can be provided based on the results regarding significant geomorphological changes on the left bank of the Blue Nile covering the area between Wad Medani and El-Kamlin with the high exaction and significant accretion can be witnessed during the past 34 years of observation and measurement period. More than 42 percent of the transects have eroded some 0.7km inland whereas nearly 57 % of the transects have accreted up to 1,273 m offshore. The erosion rate at present indicates that in the course of the next 20 years there is a threat to lose even villagers which are within 4 km range along the banks of the river, as well as there will be destruction of even infrastructures and moving of the populations.

a. Limitations

There are also a number of restrictions that are observable on this study and in the data recording of the Blue Nile in terms of its geomorphological operation that covers Wad Medani and El-Kamlin area, there exist a huge shortage in recording such the procedure, especially the matter of the erosion on the riverbank and the stabilization of sands. Even though the region was very productive and populated in agricultural lands, the active state of flowing rivers, building, and tearing down the banks was not monitored and studied extensively, thus becoming a menace to society and its farmlands. Its morphological unsteadiness, which is manifested by the high rates of erosion and accretion, is also highly augmented by anthropogenic impact, climate variation, and insufficient strong infrastructure that could be used to protect river banks. The lack of local empirical information on the processes of erosion and accretion only makes it difficult to formulate effective methods of protection of the livelihood of various rural communities, stream of sediment release, and river navigability by policy makers and planners. Moreover, there is not much facility and information about the data and image preprocessing, resolution, and overall margin of error of ERIS (Earth Resources Information System) images in the text presented.

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