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ORIGINAL ARTICLE

Hydrogeomorphic Dynamics of Gumara River at the Lacustrine Plain of Lake Tana (Ethiopia)

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ABSTRACT

River bank erosion has become a pressing issue in Ethiopia, demanding immediate attention. This problem is having a detrimental impact on farmland, infrastructure like bridges and homes, and is also altering the physical characteristics of many rivers and streams. The main objective of this study was to investigate the in-channel deposition of the Gumara River and evaluate the effects of bank erosion on the overall sediment load at the river's reach. Additionally, the study aimed to estimate the rate of river bank expansion in the lacustrine plain of Lake Tana using historical aerial imagery. Methodologies such as suspended sediment concentration (SSc) measurements, aerial photograph assessments, field observations, and discussions with local residents were employed to analyze river bank erosion and in-channel deposition. The analysis utilized the Environment for Visualizing Images (ENVI 4.2) and ArcGIS 10.7.1 software to assess the erosion and deposition processes. Findings from the sediment analysis indicated a decrease in sediment yield from the upper reaches to the lower reaches during periods of high flow, while an increase was observed during low flow conditions. Specifically, the sediment load at the upper reach of the Gumara River was recorded at 5.9 million tons (46.7 t ha-1), surpassing the lower reach's load of 5 million tons (38.8 t ha-1) during high flow, based on measurements taken over three months (June 7 to September 2, 2012). These results suggest that the primary source of sediment during high flow originates from the upper watershed, with 0.9 million tons of sediment deposited between the two gauging stations. Under low flow conditions, the upper reach recorded a sediment load of 0.96 million tons (7.6 t ha-1), while the lower reach had a load of 2.3 million tons (17.8 t ha-1), indicating that 1.34 million tons of sediment originated from the river channel during the same timeframe. An evaluation of aerial photographs from 1957 compared to recent Google Maps imagery from 2014 revealed an increase in the river's surface area by 3.7 ha over 57 years, resulting in an average annual expansion of 0.065 ha. Based on these results, it can be concluded that bank erosion and deposition pose a significant concern.

Keywords: *River morphology, Sedimentation, Sediment yield, Aerial photograph, Gumara watershed*

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1. Introduction

In the highland of Ethiopia, particularly in the Lake Tana basin, sheet, rill, and gully erosion are the most prevalent erosion processes [1-3]. Although evidence about river bank erosion in Ethiopia is limited, it is increasingly becoming a significant issue [4-6]. This has led to a notable transformation in the morphology of many rivers, becoming a key cause of flooding. However, there is inadequate research on the impact of river bank erosion on the overall erosion rate and in-channel deposition in the Tana basin. Rivers play a crucial role not only in transporting water, but also in conveying erosion products such as boulders, gravel, sand, silt, and clay from their watershed and channels. Any alteration in the river's water flow or the construction of reservoirs can affect its transportation capacity, leading to sediment deposition [7-9]. Notably, a substantial portion of the eroded material, such as sediment, is deposited in reservoirs, diminishing their effective capacity [10]. The improper handling of certain depositions can be detrimental. Many reservoirs in Ethiopia are experiencing a shortened life cycle due to excessive sedimentation, often because upstream sediment supply is disregarded or the seriousness of this process is underestimated due to insufficient data. Changes in sediment yield, caused by alterations in land use in upstream watersheds, lead to harmful sedimentation. For instance, inappropriate land use practices, inadequate management systems, and a lack of proper soil conservation measures have led to significant soil erosion and land degradation issues in Ethiopia [11-15]. According to [16-19], Lake Tana and its watersheds are currently at risk, with sediment yields as high as 84 t ha-1, exceeding permissible values of 1–16 t ha-1 [20-23]. Given the lake's average depth of only 9 m, erosion from its watershed decreases its depth by an average of 8 mm/yr (Lemma et al., 2020), impacting fisheries activities, tourist transportation to historical island monasteries, and other commerce dependent on the lake. Addressing this issue, this study marks the first attempt to assess the relative contribution of river bank erosion to total erosion and in-channel deposition in the Lake Tana Basin (LTB). The Gumara River and other rivers in Ethiopia undergo constant changes in their shape due to erosion and sediment deposition [24-28]. Erosion of river banks leads to various drawbacks, such as frequent destruction of crops and fertile lands near the river during floods without warning. Additionally, it results in significant damage to bridges and other structures situated near or across the rivers [29-32]. The loss of agricultural lands, either through soil erosion or washing away of soils by the river's flow, is also a major concern [33-34]. Hence, a thorough understanding of the hydrological and hydraulic processes in the Gumara watershed is essential for successful water management and environmental restoration The main goal of this research is to explore the in-channel deposition of the Gumara river and the impact of bank erosion on the overall sediment load around the Gumara River mouth in the lacustrine plain of Lake Tana. This study aims to achieve three specific objectives: 1) estimating the sediment load contribution from upland and bank erosion of the Gumara River in the lacustrine plain of Lake Tana, 2) determining the expansion rate of the river bank at two different time periods (1957 to 1982 and 1982 to 2014), and 3) assessing the sediment yield of the watershed at the Wanzaye and lower Gumara gauge stations (downstream of the bridge).

2. Materials and Methods

2.1 Description of the Study Area

Gumara River is located in northern-western Ethiopia and drains its content into Lake Tana at 11053’N and 37031’E coordinates. The watershed may be described as a flat to gently sloping plain. During field visit, a vast plain with a majority of the watershed area reaching an elevation of 3709 m above mean sea level was observed. The watershed characterized by a slope of 1/5000 towards the Lake Tana shore. The total watershed area of Gumara is 2586 km^2. It has 21 tributaries and the total length of the river is about 99.6 km. This study considered only about 20 km length of the river between Wanzaye and lower reach. Based on the Ethiopian Ministry of Water and Energy (MoWE) data (1994 to 2009), the river has a daily average streamflow rate of 38.2 m^3/s. The elevation of the watershed ranges from 1786 to 3709 m a.s.l. in the lower part and upper part of the river respectively. The annual rainfall of the watershed varied from 1145 mm in 2004 to 1660 mm in 2006 with mean annual rainfall of 1474mm. The rainfall of Gumara watershed is a Unimodal, in which the four rainy months (i.e. June, July, August and September) accounted for 85% of the total annual rainfall of the watershed whereas the dry season (i.e. from October to May) has 15% of the mean annual rainfall of the watershed [35-37]. The temperature of the watershed varies from minimum temperature of 2.8 ^{o}C in Debre Tabor station, to a maximum of 34 ^{o}C in Woreta station. The humidity of the watershed ranges between 70% in December and 88% in August. Based on Debre Tabor station, the sunshine duration of the area is between 6- and 6.5-hours during July and August which is the lowest duration in a year in the watershed. The soil of Gumara watershed is deep in the lower part of the watershed (i.e. in the flood plain) and shallow in the upper part of the watershed. Based on the FAO soil classification, the watershed is characterized by six common soil types, namely Haplic Luvisols, chromic Luvisols, Lithic Leptosols, Eutric Vertisols, Eutric Luvisols and Chromic Cambisols [38-40]. According to [41-43], the spatial distribution of soil in LTB is in typical Nitisol-Vertisols sequence. In Gumara watershed, three quarter of the land is intensively cultivated and Teff, Maize, Barley and Wheat are the common crops in the watershed [44] but currently, rice is becoming common crop in the floodplain part of the watershed.

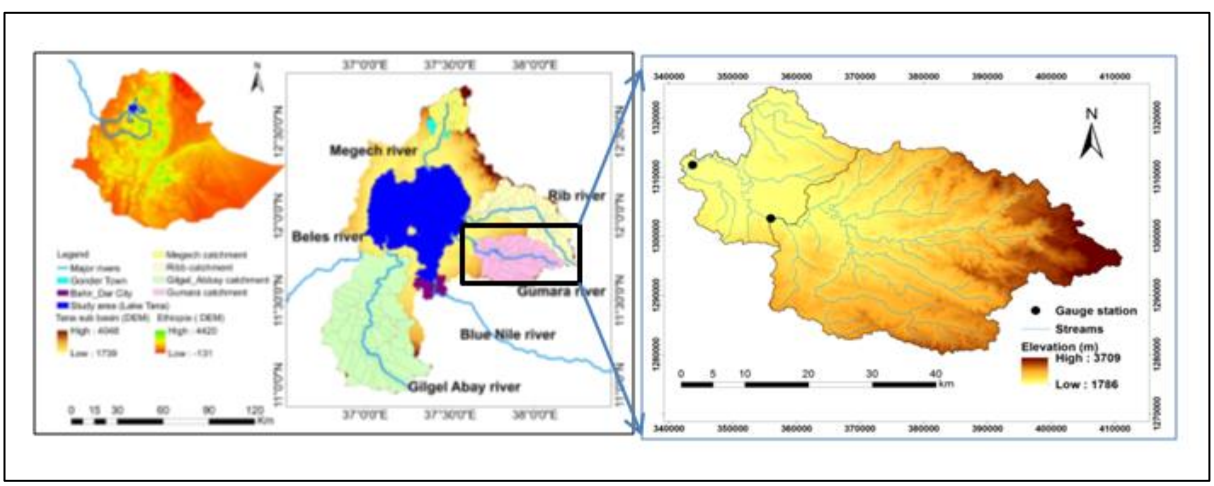

Figure 1. Map of the study area, Gumara watershed, in Tana Basin, Ethiopia

2.2 Data Collection and Sources

Primary data have been collected from the field. The collected primary data were watershed and sub-watershed outlets and GPS positions of lateral stream flow inputs and different known point (such as Churches) and hydraulic properties of river bank at field monitoring sections i.e. qualitative data (bank sliding, collapsing, impacts of meandering, vegetation and straight parts of the river). Secondary data have been collected from WASE-TANA (Water and Sediment Budgets of Lake Tana for Optimization of Land Management and Water Allocation) research project such as River discharge, River cross-sectional data at inlet and outlet reach of the river, and Sediment Concentration (input and output sediment concentration). Aerial photographs in the years of 1957, 1982 and 2014 were collected from Ethiopian Ministry of Water and Energy. To achieve the objective, sediment and stream flow rate and gage height data were taken from lower and upper reach of Gumara River (Wanzaye and downstream of the bridge). The suspended sediment data was collected with filter paper method from water samples and analyzed in laboratory. The suspended sediment load was measured in mg/l. It was used to analyze the spatial pattern of sediment load distribution along some part of the Gumara River and to investigate channel erosion and in-channel deposition. The data collection was especially done in one summer season (2012). To compute the sediment load in the watershed, the measured sediment concentration data was converted in to sediment load. The stream flow data was collected with duration of two hours and six hours for **high** stream flow (in July and August) and 24 hours for **low** stream flow. The sediment concentration data was taken two or four times in a day according to the stream flow condition i.e., **high** stream flow and **low** stream flow.

2.3 Analyzing of river bank erosion using aerial photographs

Historical aerial photographs, starting from 1950's of the Gumara floodplain were used to determine changes in channel area over time. A time series of aerial photos of 1957, 1982 and 2014 were assembled for the Gumara River floodplain. For 2014, the Google earth has been used. The aerial photos were not geo-referenced and they were not accessible for ArcGIS. To make, the aerial photos accessible for ArcGIS, ENVI 4.2 software, was used. The step for image analysis had different procedure (Figure 2).

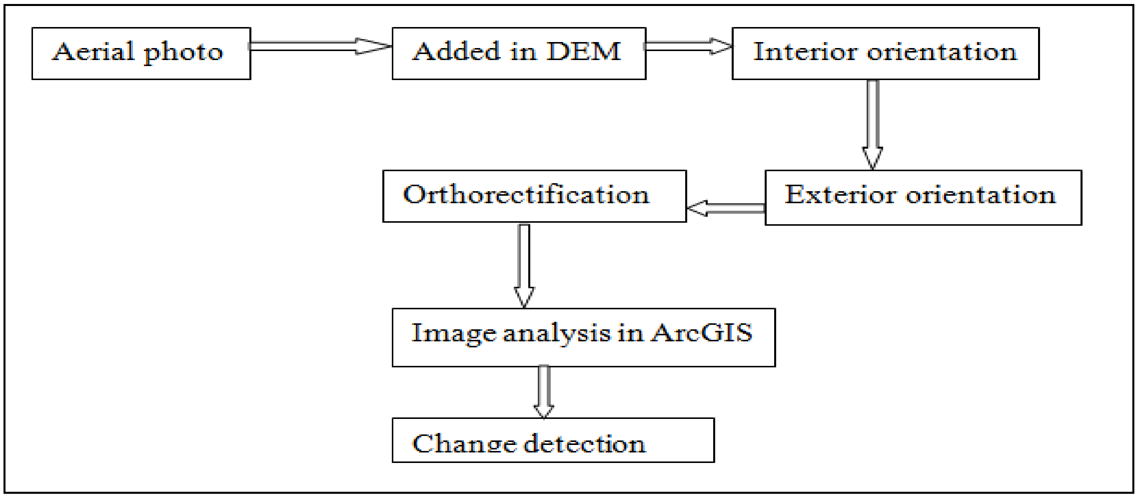

Figure 2: Main steps in image analysis using ENVI 4.2.

From Figure 2, the scanned aerial photo of 1957 was processed with ENVI4.2 software for interior and exterior orientation and finally the photo was orthorectified. In this work, the first step was the interior orientation which establishes the relationship between the camera model and aerial photograph image. This process used tie points between the aerial photograph and camera fiducial marks and the camera focal length. Interior orientation enabled the aerial photo to be calibrated internally using the fiducial points and the camera focal length. To calibrate the aerial photo eight fiducial points were used and the camera focal length was 153.046 mm. The second step was exterior orientation. Building Air Photo Exterior Orientation was used to relate points in the aerial photograph to their known map coordinates and elevations. The exterior orientation was built by selecting eight ground control points (GCP) and entering the corresponding map coordinates. The GCP includes not only the geographical XY coordinate systems but also elevation data on each GCP.

3. RESULTS

3.1 Sediment load analysis

To see the pattern of the sediment load in the watershed, the measured sediment concentration data was converted into sediment load using a relation which is explained in the methodology part.

Table 1: Watershed area and value of sediment yield

Watershed	**Area (ha)**	**Sediment load**		**Sediment yield**	
		At low stream flow (in M tons)	At high stream flow (in M tons)	At low stream flow (t ha^{-1})	At high stream flow (t ha^{-1})
Upper reach	122725.4	0.96	5.9	7.6	46.7
Lower reach	160946.8	2.3	5	17.8	38.8

Table 1 explained that sediment yield in this study season was decreased as we travels from the upper to lower part of the river reaches. Generally, Generally, the value of the sediment yield was in the range of 7.6 t ha^{-1} and 46.7 t ha^{-1} in the study season. The sediment load at the upper reach of Gumara River is higher than the lower reach of the river for daily **high** stream flow. The sediment load in the gauge stations at **high** daily stream flow has been estimated as 5.9 million tons and 5 million tons respectively. This result indicates that the main source of the sediment is the upper watershed and 0.9-million-ton sediment load deposited on the river banks and in the floodplain area along the river. For **low** flow condition, the sediment load at the upper reach was 0.96 million tons and at the lower reach was 2.3 million tons. It indicates that 1.34 million tons of sediment loads comes from the channel of the river.

3.2 River bank erosion using Arial-photograph

After accomplishing of the all steps described in the methods part, the image was digitized for the river surface area and finally the shape area of the river was found to be 13.6 ha and its shape length was 8355 m. These results were used as initial dimension for comparison of the Gumara river bank expansion in different time series periods. For 1982, the same procedure had been used to find the required results. In this process, the focal length was 152.82 mm. The shape area of the river had been found 14.9ha and its shape length had been found 8468 m. The shape area change between 1957 and 1982 was 1.4 ha and the river bank expansion rate was 110.4% in 25 years. For the shape area of the river had been found 17.2 ha and its shape length (perimeter) was 8701 m. The shape area change between 1957 and 2014 was 3.7 ha and the river bank expansion rate was 127.4% in 57 years (Table 2).

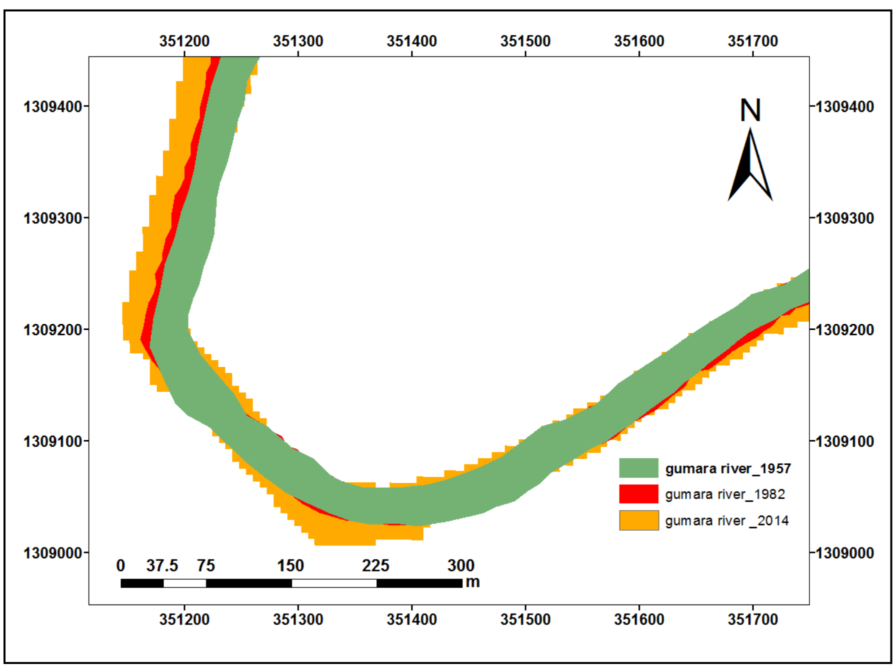

Figure 3: Overlaid studied section of Gumara River in different time periods (1957, 1982 and 2014).

Figure 3 showed that the river is shifting towards left in the majority of the river and sediment deposition occurred on the right and this is becoming the main cause of flood hazard on the people who are living on the left side of the river.

From field observation and the peole's experience, the river shifts to the left by filling the right with its sediment (deposition).

Table 2: Surface area change of Gumara River in the study site (1957–2014)

Year	Surface area (ha)	Areal Change (ha)	% Increment	Perimeter (m)	Perimetr Change	% Increment
1957	13.5			8355		
1982	14.9	1.4	110.4	8468	113	101
2014	17.2	3.7	127.4	8701	346	104

4. Discussion

4.1 Sediment load analysis

For **high** stream flow rate, the sediment load transported at the lower reach was lower than upper reach because sediment from upper was deposited and much of the runoff infiltrates as it stream flows toward the outlet [46-47]. The result indicates that the soil erosion in the upper reach was high during **high** stream flow rate. For this condition the sediment load in the lower reach was estimated about 5 million tons and for the upper reach it was estimated about 5.9 million tons. From this result 0.9 million tons of sediment was deposited in between the two reaches i.e., either in the channel or in the flood plain but from field observing the channel deposition was significant (Figure 4).

For **low** stream flow the value of the sediment load in the lower reach was higher than the sediment load in the upper reach. This result indicates that when there is no rainfall (flood) from the watershed, the sediment coming from the watershed is negligible, and sediment load difference between the lower and the upper reach comes from the channel i.e., it might be from the bank, from the deposited material (sediment remobilization) or from the bed of the river channel (scouring). From this result about 1.34 million tons was contributed by the channel in the lower reach. It should be understood that this sediment load does not mean from the river bank but in Gumara case, as it is seen in Figure 4, there is high sediment deposition. The significant amount of the sediment might come from this deposited material. Another interesting point in case of river bank erosion during field observation and discussion with the local people was observed that there are different human induced activities in the river and along the river which facilitates the river bank to be eroded. The river is becoming wider and shallow (discussion with local people).

From the result, the value of the average sediment yield is 31 t $ha^{-1}yr^{-1}$ in the study season and it is exceeding the tolerable soil loss rates 1–16 t ha^{-1} found by [19]. These values are not exceeding the maximum average value i.e. 84 t $ha^{-1}yr^{-1}$ found by [47]. In previous studies in Lake Tana basin and Blue Nile Basin, part of the Ethiopian Highlands, reported soil losses vary from 1 to over 400 t ha^{-1} yr^{-1} [48-50]; with an average of 7 t ha^{-1} yr^{-1}. The other previous study in Gumara watershed indicates that the sediment load was ranging between 11 t ha^{-1} yr^{-1} and 22 t ha^{-1} yr^{-1} [51].

Figure 4: Sediment deposition in Gumara river (January, 2014 image).

4.2 River bank erosion using Arial-photographs

In this method, it is found that the river widening by 1.4 ha and 110.4 % increment rate for the first 25 years and 2.3 ha and 127.4 % increment rate for the overall study periods of 57 years. From 1957 to 1982, the surface area of the river expanded in average 0.056 ha in each year. and from 1957 to 2014, the surface area of the river expanded in average 0.065 ha yr^{-1}. This result indicated that the expansion of the river was insignificant. The river changed its course towards the left and on the right sediment deposition occurred. This is becoming the main cause for flood hazard to the people who are living on the left side of the river and the river balances its erosion and deposition i.e., sediment is deposited at the right side and changes it's course to the left by eroding the left side of the river bank (Figure 3). Even thought the river bank erosion is insignificant in Gumara river, the meandering part and some places where cattles drink water, places where high human induced activities are practicing are facing with sever river bank erosion problem. The river may change its course towards the left at the hot spot bank erosion river meandering areas (Figure 5)

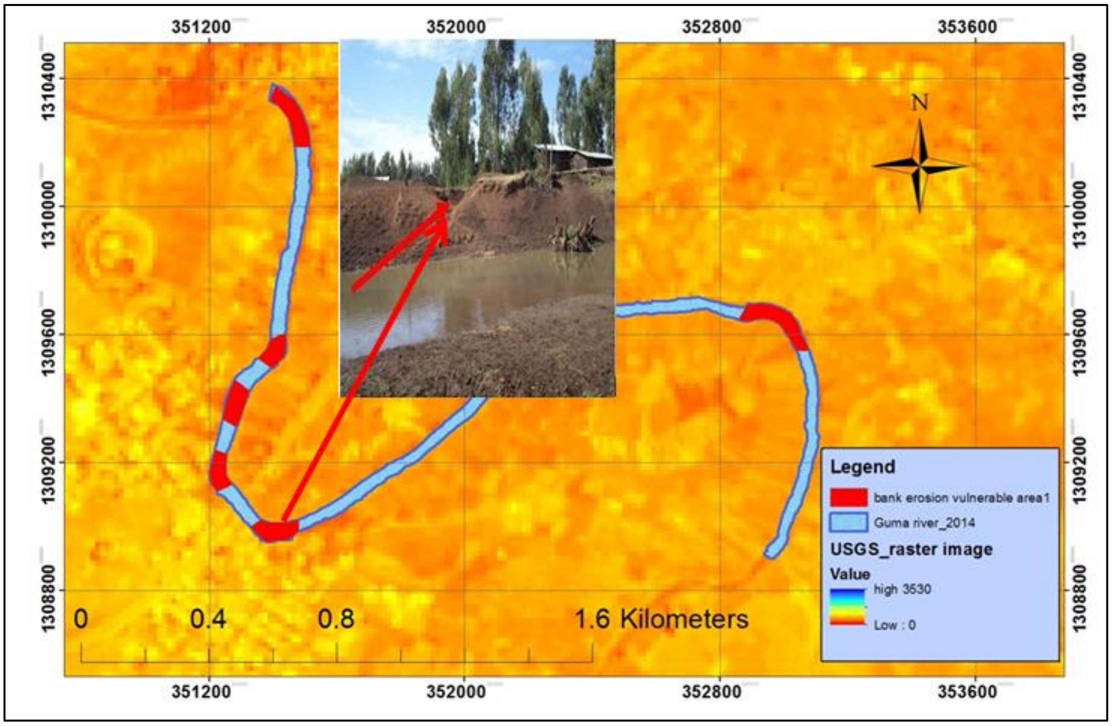

Figure 5: The place where Gumara River will have a probability to change its course to the left near the small village and River bank erosion hot spot areas.

5. Conclusion

From sediment sampling, image analysis, and field observing methods, different but with the same perspective results have been found. The dominant factors for river bank erosion are meandering, irrigation activities, cultivation and sand mining of the river bank and bed. The spatial pattern of sediment load in Gumara watershed decreased from upper to lower reach. The river supplied significant amount of sediment to the Lake Tana from June to July (Gumara river has a considerable amount of sediment and sediment carrying capacity). Sediment deposition in Gumara River was significant and it is the dominant features of the river especially on the flood plain area. River width expansion within 57 years was insignificant. It deposits its sediment on the right side and shifts its position in the left side of the river i.e., balances bank erosion and sediment deposition. The rate of expansion of the river surface area in two-time series photos due to erosion had been the same. In the river, the contribution of river bank erosion to the total sediment budget is insignificant but during the rainy season, the river deposits sediment on the bank and in other time this deposited sediment being transported by the stream flow (sediment remobilization). So, the amount is not only from the original bank material but also from the deposited sediment material (i.e. sediment remobilization) and the bed of the river (scouring). The river depth decreases by sediment deposition and its capacity to carry the stream flow is reducing and becomes flood hazard during the August. In the meandering part of the river and '**Arkebers**' (places where cattle drink water), river bank erosion is becoming severe. Unless different measures have been taken along the River in the flood plain, flooding hazard will have a tendency to be increased because the river's bank is filling with sediment and reducing the carrying capacity. The sediment coming from the upper watershed is significant. The sediment concentration of the river is high at beginning of the rainy season and starts lowering after the beginning of August. The sediment that comes from the watershed of the upper Gumara does not directly inter to Lake Tana but significant amount of the sediment is being deposited on the channel in the flood plain. So, the floodplain used as a buffer zone to prevent the direct entrance of sediment to Lake Tana. At **high** stream flow rate, in-channel deposition is high because during this stream flow sediment inflow from the upper watershed is high.

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