Analyzing the effects of historical and recent floods on channel pattern and the environment in the Lower Omo basin of Ethiopia using satellite images and GIS

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Abstract Previous accounts and recent observations indicate that the pattern and geometry of the Omo River meanders in the Lower Omo basin of Ethiopia had already been established in earlier times by large floods that took place after extended periods of drought. The cross-sectional changes resulted from floods in the nineteenth and twentieth centuries, were then simply limited to small degree channel widening and entrenchment, and floodplain erosion and deposition. The effects of the August 2006 flood, although widespread and destructive for the environment, were also modest as far as adjusting the channel pattern is concerned. Changes in channel profiles at short-term scales usually come in the form of aggradation and degradation. Interpretations of satellite images taken before and after the flood showed the accumulation of coarse sediments in the channel. There are also some sporadic indications for an increase in channel width. Widening in response to high amount of discharges can generally be expected during floods. Besides, signs of channel shortening were observed in some places. Apart from these minor changes, the dimension of meandering segments or the outline of the entire meander belt, and the basic morphology of the channel remained unaffected.

Keywords Omo River · Flood · Lake Turkana · Meandering · Ethiopia

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Introduction

In Ethiopia, floods occur occasionally in all parts of the country, either as flash floods in the cities and highlands or in the form of downstream floods in large basins and lowlands. The fact that the floods occur in certain period of the year and often proceeded or succeeded by drought is probably consistent with the prediction and theory of global climate changes (Wood and Lovett 1974; Knox 1993; Verschuren et al. 2000).

May be the worst flood disaster in the recent history of Ethiopia has occurred in August 2006 following heavy rains across East Africa. During this time, most parts of the country had flood incidents of a certain proportion. Dry streams in the east became full to a record level and the Omo River in the south ran out of its banks and inundated the surrounding regions. Several cases of flood occurrences and flood hazards were also reported from northwestern Ethiopia. While the floods were important to replenish soil nutrients, recharge soil moisture, and encourage high agricultural activity in many parts of the country, overflows in the Lower Omo basin killed 364 people, inundated 14 villages, and destroyed farmlands.

Following the floods, efforts aimed at dealing with disasters under emergency situation began immediately by local and international organizations. But, disaster management is effective when it is supplemented by a complete study on the long-term environmental effect of floods including hydrological investigations, fluvial geomorphology, floodplain mapping and analyses, monitoring and forecasting, and possibly mitigation and control.

Floods occur on all timescales and with a continuous range of spatial extents. While measuring absolute as well as relative flood magnitude is a hydrological and meteorological endeavor, to understand and be able to predict the

causes, frequencies and effects requires comprehensive and interdisciplinary research in terms of incorporating historical records as well as secondary remote sensing data and various geological and topographical information.

This study, was designed to bring together data from results of previous researches in the Lower Omo basin, recent observations, and remote sensing, to evaluate the effect of historical and recent floods on the environment in general and fluvial geomorphology (channel pattern and meander geometry) in particular. While previous studies were useful to assess the history of flooding and lake level rise in the area, recent observations and satellite images were found to be important to determine the spatial extent of the August 2006 flood in a GIS. Besides, post-flood satellite images allowed investigating the scale of channel adjustment in semi-quantitative terms. This helps to predict the balance between erosion and deposition in the channel after large floods, and the long-term cumulative effect on meander geometry.

The Omo River basin

As shown in Fig. 1, the Omo River starts in central and western highlands of Ethiopia and has a total length of approximately 930 km. Unlike the Blue Nile, with which it shares high relief drainage divides, the entire course of the Omo River is contained within the boundaries of Ethiopia. Starting a little downward from these divides, the river gathers its pace and flows to the south through deep, forested gorges. Side creeks and waterfalls appear at every drop and perennial streams flow into its course from different directions. In this locality, however, it is known as the Gibe River. The name Omo becomes familiar further downstream.

After traversing about 200 km through a slightly curved, deeply incised channel, the river starts to rotate first to the east and then the southwest. From the high relief areas until it reaches this locality, the river drops roughly 900 m. Consequently, it is a high energy river which can transport abundant bed loads. From this point downstream, it begins to mellow and twist, and drains much to the southwest constrained largely by the geology and narrow valley.

At approximately 480 km mark, the canyon opens up and the river flows straight to the south with less speed and turbidity. It winds a little at some places but maintains a stable course until the southern end of Nkalabong Ridge, where it makes a large bend to the east (Fig. 1). Then, it flows with many twists to the north and rotates back to the south when it reaches the lower limit of the Mago basin. The floodplain widens when it emerges onto a broad tectonic depression, roughly 20 km downstream from the end of the Mago basin. The Omo River continues to flow south,

before it turns to the west and form a broad S-shaped loop. Finally, it manages to meander south again and empty into Lake Turkana.

Based on topographical and hydrological aspects, the Omo River system is divided into three basins (Fig. 1). The upper reach with hilly and comparatively steep slopes is called the Gibe basin. It has an extent of about 14,340 km². There is no problem of flooding in this basin, although water rapids and cataracts are common. Apart from its own discharge, the Omo (Gibe) River in this region collects water from a major perennial stream, called the Gilgel Gibe. This stream has recently been dammed and is being used for hydropower generation.

The middle part, known as the Upper Omo basin, is the largest with an area of 34,100 km². This basin is confined in a valley and has also no history of flooding. The main tributary that has an influence on the drainage system in this basin is the Gojeb River, which rises in the highlands south of Jima (Fig. 1). Although it shares water divides with Gilgel Gibe, this river is powerful enough to control the discharge of the Omo River in downstream localities.

The lower part of the drainage system is a flatland, and is often subjected to flooding. It is referred to as the Lower Omo basin and covers an area of about 18,880 km². Even during periods of low precipitation, the middle and lower parts of this basin, are flood prone and suffer from occasional inundation because of the rains in the highlands. There are some tributaries joining the Omo River in this region including the Mago River (Fig. 2). But, all of them are seasonal, and their contribution throughout the year is negligible.

In general, the above three drainage basins of the Omo River can be seen as an upper zone of sediment production by erosion, a middle zone of sediment transport with simultaneous erosion and deposition, and a lower zone of sediment deposition. The actual situation is often a little different, because local geological controls, the level of Lake Turkana and an increase in the discharge of the river produce local erosional zones in the Lower Omo basin.

The study area

The study area constitutes the middle and lower part of the Lower Omo basin where much of the flood disaster in 2006 has occurred (Fig. 3). It is a semiarid to arid lowland with a minimum elevation of 362 m, but surrounded by a range of hills as high as 1,200 m. Its areal extent stretches over a distance of about 124 km north–south and has a width of up to 66 km.

The area is dry for much of the year and annual rainfalls are generally less than 500 mm. Most of these rainfalls come in the form of thundershowers between March and
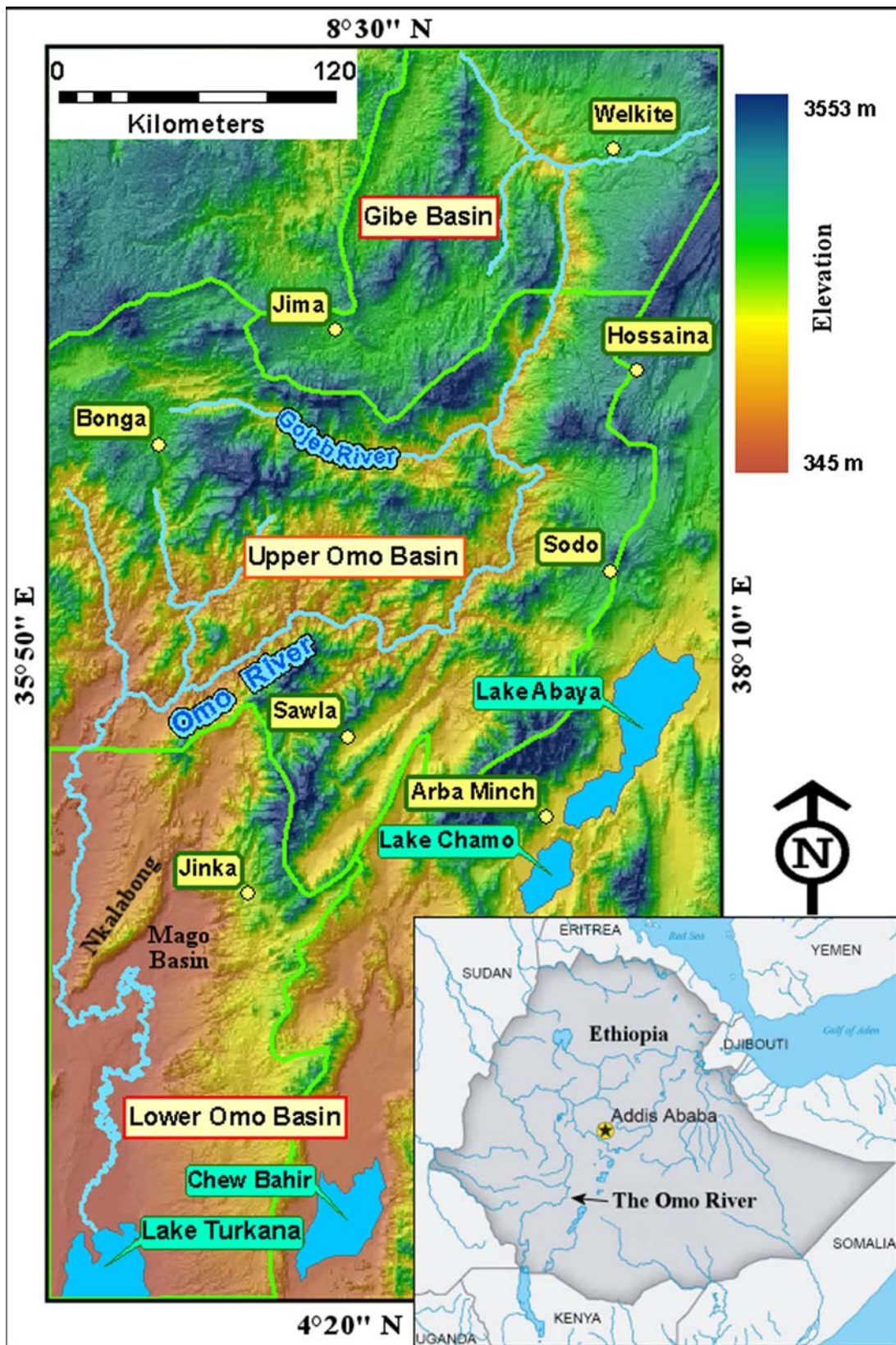
Fig. 1 Regional setting of the Omo River and its drainage basins

Fig. 2 The confluence of the Omo and Mago rivers

April and from October to November. The mean monthly temperature varies from 17°C in August to over 40°C in January and February. Access to the study area is using a gravel road that goes from Jinka (Fig. 1). This road normally goes to national parks and tourist attractive villages, and there is a need to drive on grasslands with no real tracks to go to the Omo River banks. The area is inaccessible at times of rainfall and during periods of flooding.

In response to the rainfalls from the high relief areas at its source, the Omo River begins to rise in the Lower Omo basin in April and reaches its maximum level in August or September. Once reached its peak, the river recedes again rapidly during September and October. It is at its lowest level by December and January, exactly in the middle of the dry season in the highlands. The contribution of the Mago River and other small streams, although not enough to change the main discharge significantly, is also high in August and September. At present, warmer temperatures cause Ethiopian rivers to carry a heavier flow and sediment load during rainy seasons, and trigger floods like the one observed in August 2006. During dry periods on the other hand, river flow reduces much and results in water shortages and drought.

Vegetation conditions along the lower part of the Omo River as a whole have changed appreciably during the past century, due to a period of reduced rainfall and river flow, and a drop in the level of Lake Turkana at the river's terminus (Carr 1998). Generally, the study area is characterized by a grassland and shrub Savannah. Vegetation in the immediate vicinity of the river banks varies between large forest trees and shrub grassland, with closed canopy woodland and forest predominate on fore levees in meandering segments.

Geologically, the Lower Omo basin is a volcano-sedimentary environment developed as a result of a widespread rift activity, followed by repeated flooding and river meandering, and alternating changes in the level of Lake Turkana (Butzer 1971a). According to Butzer and Thurber (1969), sedimentary sequences had begun to develop in the basin 4.18 million years ago. The oldest deposition is known as the Mursi Formation, laid down north of the meandering section of the Omo River adjacent to Nkalabong ridge. This formation contains horizontal loams of deltaic to fluvio-littoral origin, inter-bedded with sands and lenses of clay (Butzer 1971a). The next oldest rock unit is the Nkalabong Formation which is exposed along Nkalabong ridge. It is composed of fluvial basal beds and primary eolian tuffs. Another depositional sequence found immediately north of Karodus village is the Usno Formation. It represents a fluvial deposition in channel, floodplain, and marsh environments.

All the above formations, the Mursi, Nkalabong and Usno, together with Shungura Formation and other rock units found a little north of Lake Turkana are collectively called the Omo Group. Their ages range from Upper Pliocene to Lower Pleistocene (De Heinzelin et al. 1971), and formed about 850 m thick fluvial, deltaic, littoral, and lacustrine sediments in the lower and middle part of the Lower Omo basin (Butzer and Thurber 1969; Butzer 1971a). The time from Mid-Pleistocene to Mid-Holocene is represented by Kibishi Formation which covers the Bongozo, Gulugo, Lokulan plains and the region west of the study area. With a thickness of about 130 m, the various members of this formation contain delta plain, delta fringe and fluvial layers of sand, clay, silt, and reworked tuffs (Butzer et al. 1970).

The recent history of the basin is marked by the deposition of alluvial sediments in flat areas and adjacent to the Omo River banks. These semi-consolidated sediments are predominantly sands and silts with marked lateral variations. They are subject to periodic inundation by the river and their deposition in general was episodic reflecting submergence and emergence conditions. Soils from the highland areas are also part of the contemporary history of sediment deposition in the basin. Often, the Omo River and its tributaries erode residual clay soils from the source

Fig. 3 The location of the study
area in the Lower Omo basin
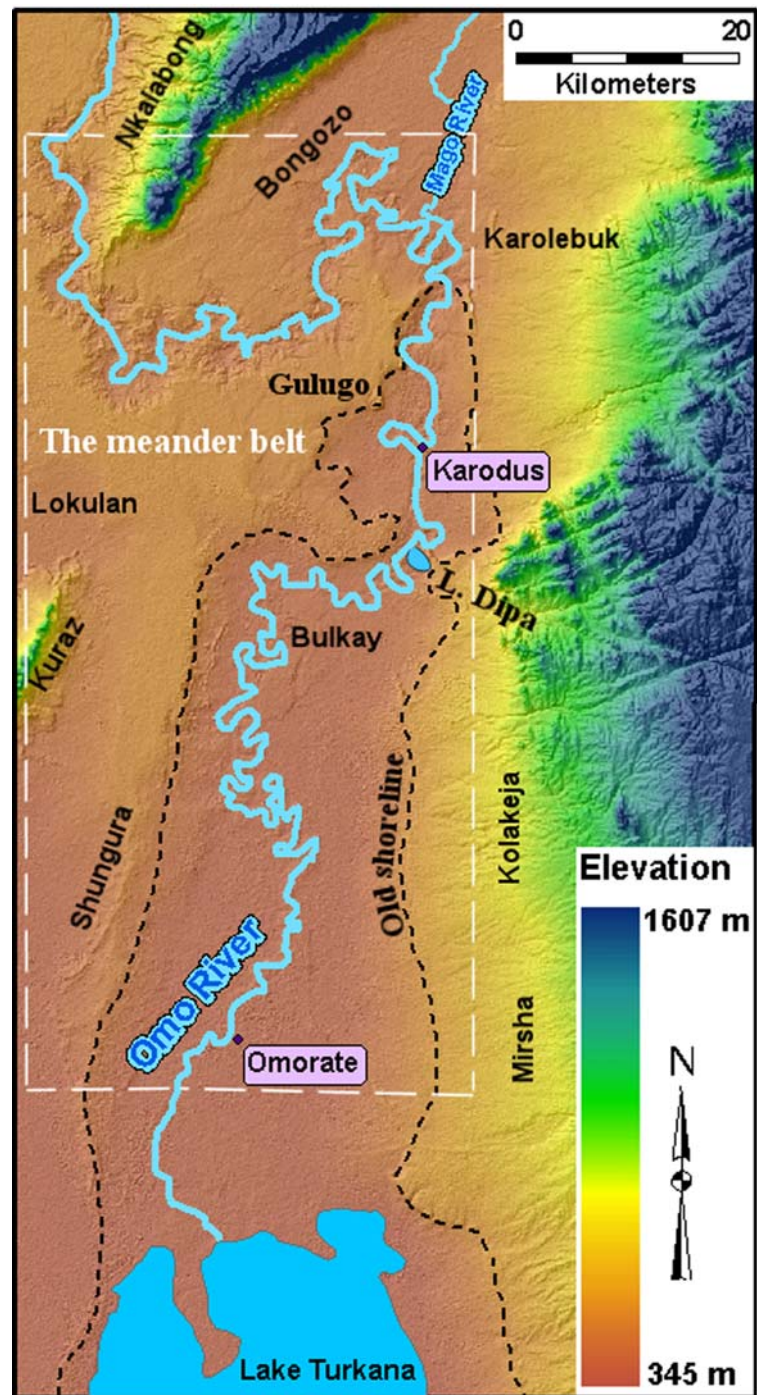
areas and transport them downstream as suspended loads. These soils ultimately settle down in Omo delta or in the nearby areas as floodplain deposits.

The level of Lake Turkana and the origin of river meandering

As shown in Fig. 3, the Omo River meanders strongly from the southern ends of Nkalabong ridge to the town of Omorate for a distance of about 291 km. This traverse is roughly 30% of the entire length of the river. The meander belt that was formed as a result is shown in Fig. 3 delineated by white broken lines. It has a straight horizontal width of approximately 38 km and a north–south stretch of 85 km. In the S-shaped loop alone, the Omo River meanders for about 204 km. The characteristic of meandering vary from stretch to stretch because of the variation of the resistance of bank materials. However, the meandering process, like any other meander belt, had

Fig. 4 Lake Dipa and seasonally or permanently saturated back-swamps

created alluvial flats, point bar deposits, oxbow lakes and back-swamps.

Actually, the action of twisting and bending of the Omo River starts in the middle part of the Upper Omo basin. But in this region, the valley is narrower, gradients are still steeper, riverbanks are often covered by hard rocks, and channels are occasionally constrained by geological structures. With all these conditions in place, the river is unable to meander much, and long straight courses are common in between twists and bends. The degree of sinuosity increases in the upper part of the Lower Omo basin, where the valley becomes wider. But even here, the river winds with short amplitudes and wavelengths, and it is possible to say that the river course has remained essentially straight and laterally stable.

The evolution of the meander belt in the middle and lower part of the Lower Omo basin together with the history of the Omo delta and the formation of delta flats and fringes was studied by Butzer (1970, 1971a, b) as part of an extensive research on geology and geomorphology of the region. As an extension to the work of Butzer, Haack (1996) investigated the change in the size of the Omo delta since 1960 using satellite images.

Generally, Butzer (1971b) divided the Omo delta and the depositional trough north of it into eight morphologic units using rectilinear margins and structural lineaments as boundaries. Among these, the meander belt constitutes the places, where the river channel winds strongly with associated natural levees, oxbow lakes, clay plugs and restricted flood basins. It was subdivided further into three subunits: northern, central and southern. The northern subunit corresponds to the S-shaped loop, the central fits with the river course across Bulkay plain in Fig. 3, and the southern refers to the meander belt close to the Omorate town. According to Butzer (1971b), while the northern and southern subunits of the meander belt are markedly convex, the central part is flat with well developed point bar ridges and swales.

In literature, many explanations have been proposed for the creation of meanders, including changes in river stages, local obstructions, slope adjustment, rotation of the earth, enlargement of previous bends, and energy dissipation (Yang 1971; Sakalowsky 1974). Matthes (1941) suggested four variables which appear to be essential factors in river meandering: valley slope, bed load, stream discharge, and bed resistance. Similar interpretations of meandering as a mechanism for restoring balance between transport capacity and sediment supply have been proposed after studying river responses to differential increases in valley slope by tectonics (Schumm 1963; Ackers and Charlton 1970; Gomez and Marron 1991).

Definitely, the above explanations are also applicable for the formation of meanders in the Lower Omo basin in general. However, the causes of meandering might be different from stretch to stretch as evidenced by the shape of river channels, the degree of sinuosity and the concentration of oxbow lakes and bar deposits. Exactly from where the river begins to meander (the southern end of Nkalabong ridge) to the southern periphery of the Mago basin, the alluvial tract is about 2 km wide, and the maximum sinuosity is 2.3. However, meanders are not free to move here and the channel exhibits the features of a typically confined, laterally stable river. Point bar sequences are limited (Butzer 1971b), and floodplains are either absent or restricted to a narrow belt immediately adjacent to the channel.

The origin of river meandering in this region can historically be connected to the location of the Omo delta and the level of Lake Turkana. According to Butzer and Thurber (1969) and Butzer (1971a, b) the Omo River mouth was situated 90–120 km north of the present delta during the deposition of the Mursi Formation because of cold climates. The last Nkalabong unit marks the highest Late Cenozoic transgression about 3.9 million years ago. By contrast, the interpretation of the Shungura and Usno Formations suggests that the Omo delta was situated less than 50 km north of its present position (Butzer 1971a).

On the basis of the studies of Butzer (1971b), the earliest sediment sequences of the Kibishi Formation indicates a lake level of 60–70 m above present, with the Omo delta located 70–100 km north of the current position. Moreover, Lake Turkana was relatively low between 35,000 and 9,500 years ago when it shrank to about its current dimension. It rose again around 7,500 years before present. The youngest member of Kibishi Formation preserves a transgressive sequence, with an increase in the lake level by 65–70 m until 4,400 years ago. Following a temporary regression, the final transgression occurred 3,000 years ago and increased the lake level by about 70 m. According to Butzer (1971b), Lake Turkana had been relatively low since that time dropping rapidly in accordance to the Nile flow system.

Generally, the presence of sediments near the current southern part of the Mago basin allows to infer that the northern limit of Lake Turkana in ancient times was probably around this area, as shown in Fig. 3 by black broken lines. In addition to these sediments and their depositional records, the present morphology indicates that the floor of much of the middle and lower part of the Lower Omo basin was once an extension of the lake. In fact, if it were not because of the effects of regressions, the tectonic depression and the morphological setup of the region were amenable enough for Lake Turkana to advance even further north.

Based on the above analyses, the Omo River had made a major bend to the east near the southern end of Nkalabong ridge dictated probably by the position of Lake Turkana and the topography of Kibishi Formation. However, the short, horizontal distance from Nkalabong to the southern limit of the Mago basin (as a former boundary of Lake Turkana) implies that the river has to meander and embed strongly to reduce its energy and erosive power. This means, while most of the energy the river has gained by falling more than 900 m vanishes in Gibe and Upper Omo basins because of incision and lateral erosion, anything in excess dissipates by frictional resistance around bends and by cutting around 50 m into the sediments of the Lower Omo basin. Generally, meandering in this setting was necessary as a mechanism for restoring a balance between river energy and the level of Lake Turkana.

A little down to the south, the area around the current confluence with Mago River was probably the entry point of the Omo River to the old lake. The extension of the Omo River further downstream and the shape of the river channel were then linked to the regression and transgression of the lake. Hence, for every decline in the level of Lake Turkana, a corresponding meander channel was formed close to the river terminus. Straight segments between large bends like those found near Karodus village were results of fast regression. Besides, channel incision

can be related to an increase in stream gradient because of a decrease in the lake level. On the other hand, any interruption in regression or some form of transgression was responsible for the formation of dense meanders in Bulkay plain.

In the process of shifting, the river had also produced oxbow lakes, seasonally or permanently saturated backswamps, and occasional ridge and swale structures, which are still remained as visible scars on the landscape (Fig. 4). The presence of two oxbow lakes in Bulkay plain especially indicates that meander cutoffs were part of the processes of channel migration in earlier times. Besides, the current geometry of these oxbow lakes illustrates that they were probably formed by a process called neck cutoff, which occurs when the upland between opposing segments of meanders is eroded away and the river abandons the entire loop to shorten the length of the channel appreciably (Lewis and Lewin 1983; Hooke 1995). During the dry season, desiccation and cracking is common in the Lower Omo basin, although some of the back-swamps retain water or remain wet, particularly after periods of peak discharges. In addition to meander cutoffs and backswamps, evidence of major relocation of the Omo River in the form of an abandoned course is present further downstream, where the channel has switched from the east to the west (towards the town of Omorate).

Recent history of the Omo delta and the meander belt

The recent history of the Omo River meander belt started at around 1888, when information on the state of the delta and the level of Lake Turkana began to appear by travelers. By this time, much of the regression had stopped and the adjustment of meander geometry had been largely completed. However, the level of Lake Turkana has continued to vary in the range of 20 m and this was associated with minor modifications in the details of the meander belt (Butzer 1971b). In literature, such modifications are linked with an increase or decrease of either water or sediment load provided to the channel (Gregory and Walling 1973).

Generally, from 1888 to 1970, two phases of lake level rise and one long-term reduction were reported by Butzer (1971b). The first increase was in the time between 1888 and 1900, when Lake Turkana had expanded by about 15 m. This was followed by a major decline in the lake level which lasted up to 1962 and resulted in a fall of 20 m. Thereafter, there was a rapid rise by about 4 m, and this had brought the lake to a level close to the mark in the 1970s. The rises or expansions of Lake Turkana were related to the increase in the discharge of the Omo River because of highland rains. On the other hand, the decrease

in its level was linked to an increase in aridity and temperature, which encourage evaporation.

Besides, an increase in the size of the Omo delta by over 500 km^2 since 1960 was reported by Haack (1996) with the help of satellite images and low altitude flights. According to this study, the growth of the delta appears to be primarily a result of decreased lake levels following repeated droughts. However, like any other river in Ethiopia, the sediment load of the Omo River has also increased in recent times because of anthropogenic factors, such as intensive cultivation, overgrazing and deforestation, and contributed a lot to the expansion of the delta. There was a reduction in the level of Lake Turkana in 1973–1974 and 1984–1985 following prolonged and widespread droughts in Ethiopia and East Africa. Then, high amount of rainfalls came in 1993–1994, and led to a lake level rise in 1995 by 1.5 m. Much did not change in the delta area between 1996 and 2006, although minor lake level rise in the year 1998/1999 and a significant reduction from 2003 to 2005 were reported.

Substantial changes in the details of the meander belt implied by lake level fluctuations or the increase in Omo delta occurred during periods of prolonged rainfall and subsequent floods. Butzer (1971b) noted times of intense precipitation in between long dry spells or extreme droughts. The effect of global climate change in Ethiopia has probably started in the middle of the nineteenth century when the "somewhere drought, somewhere flood" picture of contrasts had become the norm of the country's weather condition. Since then, the dual tests of dry runs and showers come and go, and the country has repeatedly lurched from drought to flood.

Hence, following periods of drought at the start of the twentieth century, large floods occurred in the Lower Omo basin from 1918 to 1919 because of unusually wet climatic conditions in western Ethiopia (Butzer 1971b). These floods initiated months of increased bank erosion and sediment remobilization, both upstream and downstream of the meander belt. The process of sediment erosion and deposition itself had brought about minor adjustments in channel width. It had also increased meander-bend amplitudes, and led to point bar development, streambed scouring, and aggradation (Butzer 1971b). Although, it is difficult to quantify these changes using old maps, there are evidences currently along the river, which indicate an increase in channel width by up to 10 m in places where bank materials are loose. As channel width enlarges, the alluvial deposits were constantly reworked and the floodplain widened.

As far as the stability of the meander belt is concerned, the implications of the 1962–1965 lake level rises were even more significant than 1918–1919 rains. During this time, much of the Omo delta was submerged and the

shoreline had advanced northward for an average distance of 12 km (Butzer 1971b). Parts of the Shungura and Bulkay plains were covered by water and the area around Omorate town was completely inundated. These large volumes of floods had resulted in more erosive conditions in the upper reaches of the Omo River and massive sedimentation in the lower part. Hence, the aggradations of silt berms within the river channel were the first symptom of a pending readjustment of stream gradient in meandering channels to a renewed rise of the lake level (Butzer 1971b). Later, silts dropped from retreating water were trapped by vegetation and leveled floodplain surfaces. Since then, channel instability, represented by minor changes in meander outline, is common in the basin.

However, all of these adjustments are considered normal and the channel was described as stable since it had established an average meander geometry (width, depth, and gradient) and pattern (sinuosity) in earlier times (Butzer 1971b). The maps produced at the end of the nineteenth and the beginning of the twentieth centuries accurately depict this and contain all meander features including many of the lakes and back-swamps. As channel migration rates and instability are strongly controlled by valley width, lithology, stream power, bank erosion resistance, bank height, meander-bend geometry and channel width, in addition to sediment load and stream power (Hickin and Nanson 1984), the various lake level fluctuations in the twentieth century were simply ineffective to provoke major changes in the form of the entire meander belt.

The August 2006 flood

As mentioned in the introduction, unusually high amounts of rainfalls fell in the highlands of Ethiopia in August 2006, and caused several rivers to burst their banks and overflow, resulting in extensive floods in many sectors of the country and subsequent loss of life. According to the Ethiopian National Meteorological Agency, the monthly total rainfall in August 2006, has exceeded the average value by about 100 mm in central and western Ethiopia where the Omo River starts. Similarly, the summer was wetter than the previous three summers. In the Lower Omo basin, above average rainfalls were registered for two (2005–2006) consecutive years. The amount of rainfall in August 2006, in the basin was about 150 mm, almost one-third of the mean annual precipitation falling in the area.

Flooding, by coming right after droughts or dry spells, is evolving into a major disaster in Ethiopia. Normally, floods are common in the country from June to September when rains peak during the main wet season. In the Lower Omo basin, floods generally damage neither crops nor human settlement. In fact, they provide fertile silts, and vital

moisture to floodplain farms. But, the 2006 overflow was destructive because it inundated villages, was unexpected, and lasted long (August 8–13) in a basin where floods recede very rapidly.

Environmental effects

The immediate impact of the August 2006 flood was the inundation of around 14 villages and the subsequent death of 364 people. As the inhabitants of the area are pastoralists, they normally live close to the river or within the floodplain, where there is enough grass for animals. They were then suddenly caught by rising water levels unaware of the high amount of rains that fell in the upper part of the Omo River. In the process, many cattle and wild animals were stranded and parts of the basin became inaccessible. Much of the damage was concentrated in the upper part of the meander belt (around Karodus village), where the river overflowed its banks (Fig. 5), and back-swamps and oxbow lakes became full.

Although flooding is not only a function of terrain configuration, the topography, the large S-shaped loop, and the meander geometry of the river could be the major reasons for the occurrence of a large overflow in this locality. After flowing within the valley throughout the straight part of the course, the flood water gushed out of the channel onto the landscape, where the river makes a strong turn to the east near the southern limit of Nkalabong ridge. The levees at this particular place rise in the range of 1–1.5 m above the level of alluvial deposits (Butzer 1971b) and could not hold the rapidly moving mass of water.

Next, there were only small amounts of overflows at each bend of meanders until much water was running out of the channel again in the area where the river turns to the south, a little upstream from the confluence with Mago River. Then, after inundating Karodus village and the surroundings of Lake Dipa, the flood water poured out straight to the west, at the inflection point of the S-shaped loop, where the channel rotates to the south. Flooding continued downstream, and overflows were reported in the meanders of Bulkay plain, although the problem was not as severe as in the upper part of the meander belt because of a decrease in discharge and speed. Finally, as an ultimate location of deposition, the Omo delta and the surrounding regions were also equally affected by large sediment accumulation.

Spatial extent

As an attempt to know the aerial extent of inundation and to investigate subsequent changes in meander geometry, satellite images in dry and flooded conditions, were used in this study together with sporadic ground observations. It is known that during the last two decades, data acquired by satellite-borne sensors has been used to carry out many environmental studies. Especially, satellite images are found to be useful for flood hazard analysis as demonstrated in the studies of Harun and Pramanik (1993); Islam and Sado (2000); Puech and Raclot (2002); van der Sande et al. (2003); Sanyal and Lu (2005) and Forte et al. (2006).

Advantage of satellite images in flood hazard analyses comes in a way that they provide instant depiction of inundated areas in places where stream gauges are unavailable like the Lower Omo basin. The images are useful to determine the level of water, and spatial extent of the flood. They are also helpful to detect and quantify

Fig. 5 An aerial view of the effect of the August 2006 flood of the Omo River

changes in river morphology. The two major problems which restrict the use of images for the study of floods are cost and cloud. Despite of the advance in photography and satellite technology, the cost of high resolution images is still high, and limits their use for environmental studies. Clouds normally stay over flooded areas for some time and appear on satellite images covering the ground surface. This makes interpretation and subsequent image classification very difficult.

For this study, SPOT4 satellite images acquired in January and March 2006, were used to delineate the river channel during the dry period when the volume of discharge was low. Flood affected areas on the other hand were extracted from SPOT5 images taken on 13th and 19th of August 2006. Separating land from water using SPOT images was possible with the help of tonal differences and other image segmentation and classification techniques. IKONOS images obtained some days after the flood were also important to supplement the effort of defining the water–land boundary because of their higher resolution.

As mentioned in the previous section, much of the flood problem was concentrated in the upper part of the meander belt where the river forms a broad S-shaped loop. Hence, only this locality was considered for analyses. It has a total extent of 2,268 km^2, about 40 km^2 of which, is occupied by the river channel. The size of the floodplain in this locality is 735 km^2. In general, the landscape inundated by the flood covers approximately 246 km^2 of the area considered for analyses (Fig. 6). Roughly 110 km^2 of this, lies within the floodplain and experiences occasional flooding. The remaining part with an aerial coverage of 136 km^2 was affected by overbank flow probably for the first time in recent history. As shown in Fig. 6, much of this area includes the landscape between the two inflection points of the S-shaped loop where the high energy flood surged out of its channel because of sharp curvatures.

Based on the accounts of Butzer (1971b), the location of the 2006 flood is different from those inundations occurred in 1888–1895, 1918–1919, and 1962–1965. While the recent flood has affected the upper part of the meander belt,
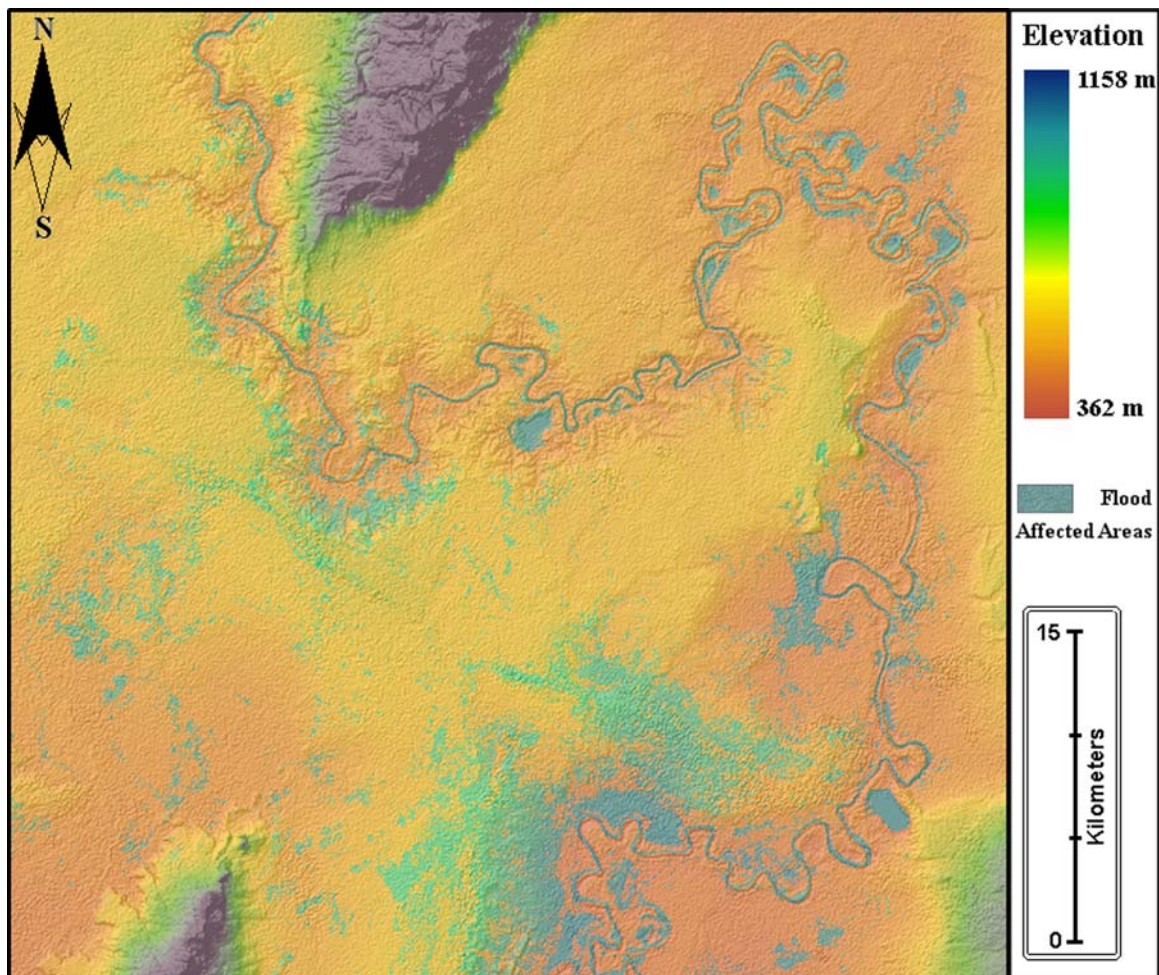

Fig. 6 Spatial extent of flood affected areas in the upper part of the meander belt

those in early times were located in the region close to the Omo delta. Even during the 1967–1968 floods, when around 350 km^2 of the delta was inundated, only limited tracts of the floodplain in the upper part of the meander belt were flooded, primarily by seepage rather than overbank flow (Butzer 1971b).

Channel adjustment

In addition to assessing the impacts of the flood on the environment, its instantaneous effect on the river channel and meander geometry was investigated in this study. As the landscape of the area under investigation is relatively flat, comparisons of the channel position in satellite images rectified to remove distortion, allowed quantification of changes in meander geometry after the occurrence of the flood. Oxbow lakes, back-swamps and other landform elements visible in images, were also useful to interpret channel morphology. Besides, the mass of sediments deposited in the surroundings of the delta provided some indication of the natural bed load transport capacity of the Omo River and were helpful as an approximate surrogate to predict the balance between erosion and deposition throughout the river course.

Generally, comparison of satellite images acquired before and after inundation indicated a shift in waterway within the river channel at various places. Significant shifts were especially observed in the straight portion of the river course, between the Mago confluence and Lake Dipa. There are also some sporadic indications for an increase in channel width. Apart from these minor changes, the dimension and outline of each meandering segment or the entire meander belt, and the basic morphology of the channel remained unaffected.

However, the Omo River is known for transporting a large amount of sediment from the highlands to Lake Turkana. This was witnessed after the occurrence of the 2006 flood. Following dry spells in previous years, the sediment load has increased during the August 2006 flood, presumably due to enhanced erosion of the highly denuded catchments. IKONOS images taken on 4 September 2006 show the accumulation of sediments within the channel in the lower part of the meander belt (Fig. 7), although those acquired on similar date at meanders near Bongozo and Lake Dipa depict no signs of deposition. This indicates a large decrease in stream power and a free dissipation of energy onto floodplains due to overflows.

As shown in Fig. 7, most of the sediments were accumulated in the riffle portion of the channel, although some were laid down in the pool areas. The development of the riffle-pool sequence indicates the transportation of coarse sediments in significant proportion up to this point of the river course. The sediments could be either from the source areas of the river or the pool portion of the meanders. But, since deposition had also occurred in the inside part of pools, it is safe to think that much of the sediment load was supplied from the highlands.

Apart from sedimentation, signs of channel shortening were also observed in meanders of Bulkay plain, near the oxbow lakes, after the August 2006 flood (Fig. 8). Levees are frequently breached by the Omo River at the time of

Fig. 7 Images showing the accumulation of sediments in the lower part of the meander belt after the flood in 2006

Fig. 8 Signs of river breach during the 2006 flood and the effect of evaporation on oxbow lakes and back-swamps

flooding (Butzer 1971b). Especially in the middle and lower parts of the meander belt, where levees dip gently and meanders are relatively free to move, the Omo River can easily breach its banks. The result of this process as shown in Fig. 8 was the creation of back-swamps and lakes. With time, if the levees and alluvial deposits are completely eroded, the river will abandon its course and

flow through or around back-swamps and lakes. In the process, channel length, sinuosity and amplitude will decrease, and the mender belt will get another pattern and geometry.

In the feature, there is a possibility for the river to assume a new route by cutting off many of the bends in the middle and lower part of the meander belt. The fact that the

basin is broad in these regions plus the reduction in the level of Lake Turkana because of the increase in aridity and evaporation, the decline in the normal discharge of the Omo River, the increase in sediment load (bed load), and the change in global climate (that results in long dry spells and sudden floods), makes this rather possible. If the lake level decreases, the river traverses long and erodes much. By doing so, it straightens the channel to create a proper gradient and a corresponding ability to transport coarse sediments. The effect of aridity on the lake level can be inferred from the excessive reduction of the intake of oxbow lakes and back-swamps, 3 weeks after the occurrence of the 2006 flood as shown in Fig. 8. As temperatures rises, the atmosphere absorbs more water vapor, raising the likelihood of rainstorms and occasional floods, during which meander cut-off and channel straightening will take place.

The river could also modify the channel pattern in the upper part of the meander belt. But, this would not be beyond an increase in channel width as the river banks in this locality are made up of old, relatively strong rocks. In the long feature, the river may, however, try to connect the two inflection points of the S-shaped loop by cutting slowly into the landscape in between. This is a difficult task, but if occurred, will shorten the channel length by about 150 km.

Conclusion

Floods occur occasionally in Ethiopia after long, dry periods. In 2006, rains in the highlands caused many streams to swell and led to the heaviest floods in recent periods. During this time, the Omo River in the far southwestern corner of the country, burst its banks and brought about damages both in property and loss of life. Normally, the drainage basin of the Omo River is divided into three: Gibe, Upper Omo, and Lower Omo. Floods are common in the Lower Omo basin where the channel has formed a meander belt, a floodplain, and a delta.

In this study, satellite images and ground observations were used to evaluate the effects of the 2006 floods on channel pattern and the environment in the Lower Omo basin. The evolution of the river course and the impact of floods in the nineteenth and twentieth centuries on meander geometry, together with the accompanying fluctuation of the level of Lake Turkana were largely inferred from previous studies. Generally, the development of the meander belt had largely been completed before historical records began to appear in the nineteenth century. Since then, the average meander geometry and pattern (sinuosity) have stayed the same, although depositional and erosional records indicated the occurrence of some adjustments in

cross section of the channel as a result of severe floods and long-term lake level reductions.

The 2006 flood was large enough and lasted long to incur environmental effects. But, like previous floods, it was too brief to initiate major changes in channel pattern. Hence, many of the adjustments were only in the form of minor increments in channel width and meander-bend amplitudes. However, the sediment load of the river had increased at the time of flooding because of the erosion of highly denude catchments. Images taken after the flood showed the accumulation of sediments in the lower part of the meander belt. Naturally, stable streams must be able to transport the sediment load supplied by the watershed. The inability of the Omo River to transport the sediments down to the delta area leads to instability or channel pattern adjustment as excessive deposition causes the river bed to rise. This problem will increase if additional sub-catchments see considerable removal of vegetation cover. In addition, as a sign of channel shortening, the river had breached its levees in the middle part of the meander belt, which could lead to a change in meander geometry in the long feature.

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