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Humans Reshape Wetlands: Unveiling the Last 100 Years of Morphological Changes of the Mara Wetland, Tanzania

F. Bregoli[1], A. Crosato[1,2], P. Paron[1], M. McClain[1,2]

[1] Department of Water Science and Engineering, IHE Delft Institute for Water Education, Westvest 7, 2611 AX, Delft, the Netherlands.

[2] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Building 23, Stevinweg 1, 2628 CN, Delft, the Netherlands.

Corresponding author: Francesco Bregoli (fr.bregoli@gmail.com)

Abstract

The Lower Mara River and Wetland, Tanzania, is an important ecosystem and unique water resource for a vast semi-arid area. The river, an affluent of Lake Victoria, and the wetland are experiencing morphological and vegetation changes resulting in channel avulsions and wetland expansion. This study analyses the changes over the last 100 years and investigates natural and anthropogenic behaviors to explain the increase of the Mara Wetland area. We collated historical topographic maps and satellite images. We conducted two field surveys in low and high flow condition with an unmanned aerial vehicle, a sonar and an ADCP. We mapped selected areas as well as the bed topography in some stretches of the river, measured discharges, and collected river bed and suspended sediment samples. The analysis of the sediments shows that the wetland system, dominated by papyrus *sp.*, is very efficient in trapping sediment, releasing clear water to the Lake Victoria. The historical reconstruction using topographic maps, satellite images and a multivariable analysis including hydrology and land cover, shows that 4 major avulsions occurred in the last 70 years due to a combination of natural behaviors, hydrological fluctuations and anthropogenic factors such as basin deforestation, farming and grazing along the river banks and in the wetland. Each avulsion led to substantial expansion of the wetland. Combined, they increased the wetland area by a factor of 3.6. Describing the Lower Mara River dynamic behavior, this work provides relevant information for sustainable future water and sediment management in order to preserve wetland habitats and natural resources.

Keywords

wetland expansion; river avulsion; wetland sedimentation; Lake Victoria; East Africa; Mara River.

1 Introduction

Wetlands are inundated or saturated areas that host important habitats for species, perform natural water purification, carbon storage, flood protection, and provide water resources and recreation opportunities among other ecosystem services (Woodward and Wui, 2001; Zedler and Kercher, 2005). Water abstraction, dams and other hydraulic infrastructure for irrigation, water supply and power generation, land use and climate changes are among the pressures that modify and can endanger riverine (Sabater et al., 2018) and wetland (Van Asselen et al., 2013) systems. Freshwater wetlands in African semi-arid climates are fundamental for the support of wildlife, humans and their activities such as grazing, farming and fishing (Schuyt, 2005; van Dam et al., 2014). Deforestation, grazing and farming have direct effects on runoff, soil erosion and sediment transport in river basins (Foley et al., 2005; Lal, 1985; Pimentel et al., 1995). Wetlands act as natural filters receiving and retaining suspended sediments, nutrients and pollutants, and releasing clean water downstream. Therefore changes in river flow and sediment transport regimes may alter their physical and ecological equilibrium (Houlahan and Findlay, 2004; Maclean et al., 2011). Floodplain vegetation plays an important role on river morphodynamics (Crosato and Saleh, 2011; Tal and Paola, 2010) and particularly in trapping sediments in wetlands (Arboleda et al., 2010; Johnston, 1991). In the swamps of Lake Victoria, overgrazing and overharvesting of papyrus (the dominating plant) for charcoal production and land reclamation are recognized issues that degrade wetlands (Kassenga, 1997; Osumba et al., 2010; Pacini et al., 2018).

Globally, inland wetlands area is heavily decreasing in the last century due to land conversion to crops and grazing fields, water abstraction and lack of sediment input which is retained in reservoirs (Davidson, 2014; Dixon et al., 2016; Hu et al., 2017). Wetlands area decrease is posing serious concerns for wetlands conservation in various areas of the world (Fang et al., 2019; Orimoloye et al., 2018; Qu et al., 2018). However, the Mara Wetland in Tanzania is instead expanding (Mati et al., 2008). We have considered this site as a key study: finding the causes of the Mara Wetland expansion might help to find solutions to preserve this and other similar wetlands natural functions. The Mara River Basin is a transboundary catchment occupying territories of Kenya and Tanzania, including wide areas of the Maasai Mara and Serengeti ecoregion (Figure 1a). The basin lies in the migration path of millions of wild animals and supports the livelihood of nearly one million of inhabitants (McClain et al., 2014). It is thus a strategic area for nature conservation and economic development. Before flowing into the Lake Victoria in Musoma Bay, Tanzania, the Mara River forms a large wetland. Wetland rapid expansion may occur in the presence of sediment excess in the river inputs (Kirwan et al., 2011; Woodward et al., 2014). A considerable expansion of the Mara Wetland is reported in past studies such as Mati et al. (2008), who found sediment inputs linked to land use changes to be the major driver of wetland expansion in the last decades. High suspended sediment transport, up to 4 g L^{-1}, have been measured in the Mara River, as described in the GLOWS-FIU report (2007) and by Dutton et al. (2018). The latter study attributes the recent increase of suspended sediments to unregulated livestock overgrazing, conversion of land into agriculture and large wildlife populations in the upper area of the basin. There are now plans to construct a dam immediately upstream of the wetland. This will potentially further stress the river system (Kingsford and Thomas, 2004; Yang et al., 2005; Zhang et al., 2012).

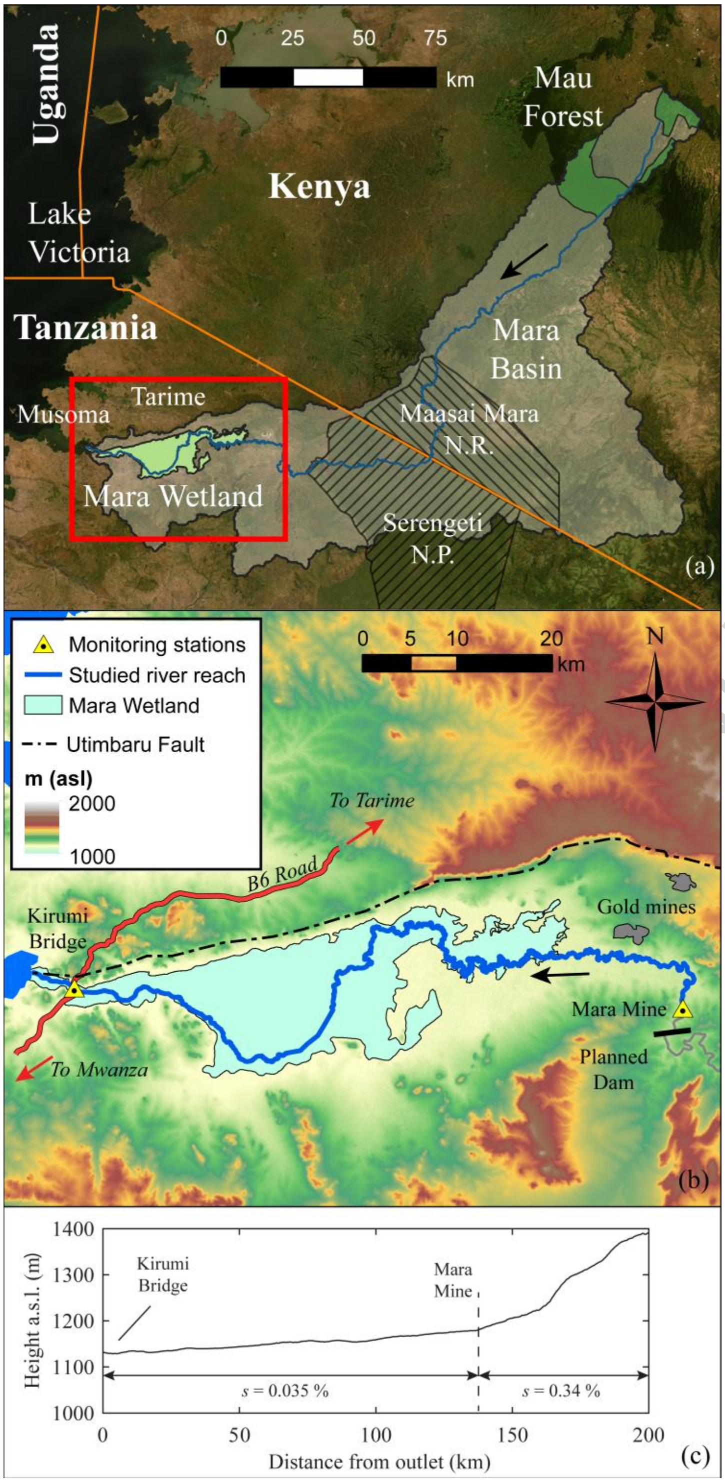


Figure 1. The study area: a) the Mara Basin, which includes wide areas of the Mau Forrest, the Serengeti National Park and the entire Maasai Mara National Reserve; b) the studied river reach and wetland; c) the longitudinal profile of the current Lower Mara River extracted from the digital elevation model ASTER GDEM version 2 (2011). Black arrows indicate river flow direction.

Dynamic features in floodplains, deltas and wetlands are river bifurcations and, particularly, river avulsions. At bifurcations the flow divides in two downstream branches (Kleinhans et al., 2013) being formed by natural or anthropogenic causes. A bifurcation may lead to river avulsion when the flow is completely (or almost completely) diverted out of the established channel into a new or preexistent channel, which becomes dominant, on the adjacent floodplain (Slingerland and Smith, 2004). An avulsion is a result of multiple factors such as local river bed accretion, tectonic movements, climate changes and anthropogenic interference, the latter playing an important role in the last centuries in both urbanized and rural areas (Heyvaert et al., 2012; Hudson et al., 2008; Stouthamer and Berendsen, 2000). In some cases wildlife, such as hippopotamus, can also play an important role in incising new channels and creating diversions of water and sediments as happened in the Okavango Delta of Botswana (McCarthy et al., 1998). Once a river bank breach (also called crevasse) occurs, physical processes may cause the sedimentation and abandonment of the river channel and the widening and stabilization of a new channel (Herrero et al., 2015), which is further promoted when a topographic gradient advantage exists between the river channel and the adjacent floodplain (Lewin and Ashworth, 2014).

Avulsions are infrequent and are difficult to observe or experimentally investigate (Smith et al., 1998). However, they can involve serious economic, social and ecological implications. Some historically relevant examples of avulsions are the ones of: the Yellow River, China, where, in the last 2000 years, seven major avulsions disrupted the lives of tens of million people with countless loss of life and property damage (Slingerland and Smith, 2004); the Kosi River, Nepal and India, where, in 2008, an avulsion relocated the river by about 60 km to the east, abandoning and drying hundreds of villages on one side and flooding thousands of people and croplands on the other side (Chakraborty et al., 2010); the Karkheh River, Iran, where in the last 2000 years a combination of human-induced factors (e.g. weakening of the river levees and high sedimentation rates), led to several avulsions (Heyvaert et al., 2012); and the Patia River Delta, Colombia, where in 1972 a human-induced water diversion for commercial purpose triggered an avulsion that shifted abruptly the active delta with great social and ecological consequences (Bateman et al., 2009; Restrepo and Kettner, 2012).

This study investigates morphological changes that have occurred in the Lower Mara River during the last 100 years, focusing on the natural and anthropogenic mechanisms that led to the observed expansion of the Mara Wetland. The research aims to explain the causes of the most recent river avulsions and identify the major factors responsible for wetland expansion. The work includes a quantitative description of the present and on-going dynamics of the wetland, which will allow identifying the possible effects of the planned dam and the mitigation measures for a future sustainable basin resources management.

2 Materials and Methods

2.1 Study site

The Mara River originates from the forested highlands of the Mau Escarpment, Kenya, at about 3,000 m a.s.l. and flows downstream through croplands, rangelands and the Maasai Mara National Reserve. After crossing the Tanzanian boarder and the Serengeti National Park, the river meanders through cultivated and grazed fields before entering the Mara Wetland. It finally discharges into Lake Victoria at Musoma Bay, Tanzania, at 1,120 m a.s.l. (Figure 1a). The basin occupies an area of 13,500 km^2. Mean annual rainfall varies spatially within the basin, ranging from 1,750 mm y^{-1} in the highlands to 600 mm y^{-1} of the southeast area (Alemayehu et al., 2017). The rainfall regime is bimodal, with “short” (October – December) and “long” (March – May) rainy periods. Based on records between 1901 and 2009, the highest daily rainfall measured in the basin was 170 mm (31/05/1980) and the highest monthly rainfall was 684 mm (08/1961) during the so-called Independence Rains (Wenninger and Venneker, 2017). River discharge patterns in the Lower Mara reflect the bimodal rainfall regime with an annual mean discharge of 47.2 $m^3 s^{-1}$, a recorded minimum discharge of 1.5 $m^3 s^{-1}$ and a maximum of 921 $m^3 s^{-1}$ at Mara Mine gauging station, based on analysis of data between 1969 and 2012 (Dutton et al., 2018; McClain et al., 2014).

The study site of this research is the Lower Mara River from the Mara Mine (MM) gauging station (UTM 36M 672906E, 9828804S, water surface level at 1163 m a.s.l. on 12/05/2018), around 30 km upstream of the wetland, and the Kirumi Bridge (KB) gauging station, in the proximity of the river outlet at Lake Victoria (UTM 36M 608482E, 9830962S, water surface level at 1120 m a.s.l. on 11/05/2018). The total length of the studied river reach is 130 km and includes the Mara Wetland (Figure 1b). The river longitudinal slope in the study area is approximately 0.035 % (Figure 1c). The wetland is an asymmetric basin with the southern boundary more gently sloping and punctuated by several inselbergs that are isolated remnants of granitic hills. The northern shores are characterized by a sharper escarpment that is bounded by a geological normal dip-slip fault, buried under the wetland (Figure 1b). Therefore, the wetland may experience subsidence. The fault is known as Utimbaru Fault (Kabete et al., 2012; Kazimoto and Ikingura, 2014). The upper part of the wetland, where the floodplains are temporarily inundated in the rainy periods, is mainly composed of marshes with herbaceous vegetation. In the middle and lower parts, the wetland is permanently inundated and consists of a papyrus (cyperus papyrus) swamp (Figure 2).

The Mara Basin is poorly gauged and access difficulties complicate the logistic of field measurements. Particularly, systematic measurements are lacking in the lower part. Therefore, it has been often necessary to rely on interviews with local people, previous reports and literature review. Through this work, it has been possible to retrieve a useful number of data. Specifically, in order to describe the Lower Mara River system dynamics in the last 100 years and to link the documented avulsions and wetland expansions to their possible causes: (1) historical topographic maps and (2) available data on rainfall, water surface level (WSL) and flow discharges have been gathered; (3) selected satellite images have been analyzed; and (4) detailed field work has been conducted in the last two years.

2.1 Historical topographic maps

The use of historical topographic maps is considered a very good reference for historical conditions of wetlands (Dickens et al., 2017). Fortunately, for this study area, a few good quality maps dating back to the 19th century exist. The first available topographic maps of Tanzanian territories are the German maps of Stieler (1891) with a scale of 1:10,000,000 and Dantz (1902) with a scale of 1:2,000,000. Unfortunately, their scale and level of detail are not sufficient to properly observe the Mara River basin. The first suitable map is the German map of Reimer (1911) having a scale of 1:1,000,000, followed by the British maps (GB Army Map Service, 1946) having a scale of 1:1,000,000, the Tanzanian maps of 1963 (Tanganyika Governament, 1963) having a scale of 1:250,000 and the Tanzanian maps of 1976 (Tanganyika Governament, 1976) having a scale of 1:50,000. The maps rely on previous topographic surveys. Therefore, for the purposes of this study, the year of reference is related to the topographic survey as identified in the original maps and reported as basemap year in the Table S1 (Supplementary Material). The suitable maps contain details on the Lower Mara River course and branches as well as the swamp to observe the evolution of river and wetland from 1911 to 1975, when satellite images were not available (Supplementary Material, Figure S2).

2.2 Remote sensing

Satellite images from 1975 onwards have been retrieved including Landsat Level-1 series 1-3, 4-5, 7 and 8 (retrieved from United Station Geological Survey at https://earthexplorer.usgs.gov) and Sentinel-2 (retrieved from European Space Agency at https://scihub.copernicus.eu/dhus/#/home). Landsat 1-3 multispectral images have resolution of 60 m, Landsat 4-5, 7 and 8 multispectral images have resolution of 30 m. The corresponding panchromatic band of Landsat 7 and Landsat 8 have a resolution of 15 m. Sentinel-2 multispectral images have 10 m resolution in the red, green, blue and near-infra red bands (Band 8). Pansharpening, a technique used to increase the spatial resolution of multispectral images merging them with the panchromatic band, has been applied to Landsat 7 and 8 images in order to enhance images resolution from 30 m to 15 m and visualize narrower river channels. False color composites (FCC) assigning near-infrared, red and green to the Red-Green-Blue (RGB) channels has been used. The FCC images particularly facilitate the visual analysis of river courses, other water bodies and vegetation cover. Visualization and analyses of satellite images have been performed with ESRI ArcGIS 10.3. Google Earth pro was used for time comparison of Google Earth images from 2005 onwards. Satellite images helped to determine the position and timing of river bifurcations, avulsions, meander cuts, bank breaches and other features such as human and livestock walk paths and crops placed on river banks, being the possible causes of the bank weakening. Digital elevation models (DEMs) of the study site have been obtained from the global DEMs SRTM V3 released in 2015 and ASTER GDEM V2 released in 2011, both having 1 arc-second resolution (about 30 m resolution at equator).

2.3 Discharge, water surface levels and rainfall historical data

Major changes in the river morphology are triggered by intense flood events (Costa and O'Connor, 1995; Fitzpatrick and Knox, 2000; Nardi and Rinaldi, 2015). Therefore, discharge data are important to date the morphological changes and relate them to the river momentum. While the Lower Mara is poorly gauged, available data of WSL and rainfall are still useful to date flow peaks. Discharge and WSL daily data from the MM measuring station and WSL daily data from the KB measuring station have been obtained from the Lake Victoria Basin Water Office (LVBWO) of the Tanzanian Ministry of Irrigation and from previous works (Hulsman et al., 2017; McClain et al., 2014). WSL data from MM are available for the period 1969 – 2018, having gaps in the periods 1991 – 2005 and 2008. WSL data from KB range from 1969 to 2018, with a gap from 1979 – 2006. Discharge data for MM are calculated from the rating curve being calibrated by LVBWO. Discharges at KB are not available. For this reason, it was measured a few times for this study (see section 3.4.2). Available daily and monthly rainfall data covering the time between 1901 and 2009 have been gathered from 25 stations along the entire basin (Dessu et al., 2014; Dessu and Melesse, 2013; Hulsman et al., 2017; Wenninger and Venneker, 2017). Monthly data range from 1901 to 2009 and daily data from 1959 to 2009. Both monthly data and daily data have scattered gaps.

2.4 Field work

The site was visited in two occasions: during low flows in October 2017 and during high flows in May 2018. Multidisciplinary field work was conducted in order to obtain data on terrain morphology of the river and floodplains, vegetation distribution, river hydrodynamics and sediment transport. The first visit was devoted to observe the floodplains, otherwise inundated during high flows, and to measure discharge and suspended sediments in low flow condition. The second visit was devoted to measure high flow discharge, suspended sediments and sediment granulometry along the river reach from MM to KB. A total of eleven locations were visited. A list of locations and performed field measurements are reported in Table 1 and Figure 2.

Table 1. List of field works locations and performed field measurements. HF is high flow, LF is low flow.

SITES				**FIELD MEASUREMENTS**				
Name	Acronym	Coordinates	Distance from KB (km)	Discharge	Suspended Sediment	Bed granulometry	UAV	Sonar
Kirumi Bridge	KB	-1.5483, 34.5542	0	HF	HF	HF	LF	LF, HF
Lower Wetland	LW	-1.5043, 34.5255	6.76	-	HF	HF	-	HF
The Rock	TR	-1.4967, 34.4963	8.06	-	-	-	LF	-
Kyamanyaka	KY	-1.4598, 34.3202	13.70	LF	-	-	LF	LF
Buhenche	BU	-1.4723, 34.2767	20.10	-	LF	-	LF	-
Kongoto	KO	-1.5780, 34.1107	29.20	-	-	-	LF	-
Bisarwi	BI	-1.5409, 34.0422	52.62	LF, HF	LF, HF	HF	LF	HF
Sioux Lake	SL	-1.5451, 34.0792	60.22	-	LF	-	LF	-
Pump Station	PS	-1.5291, 33.9752	112.32	-	HF	-	-	HF
Meander Cut	MC	-1.6007, 34.1819	118.09	-	-	-	LF	HF
Mara Mine	MM	-1.5387, 34.0303	130.00	LF, HF	LF, HF	HF	LF	HF

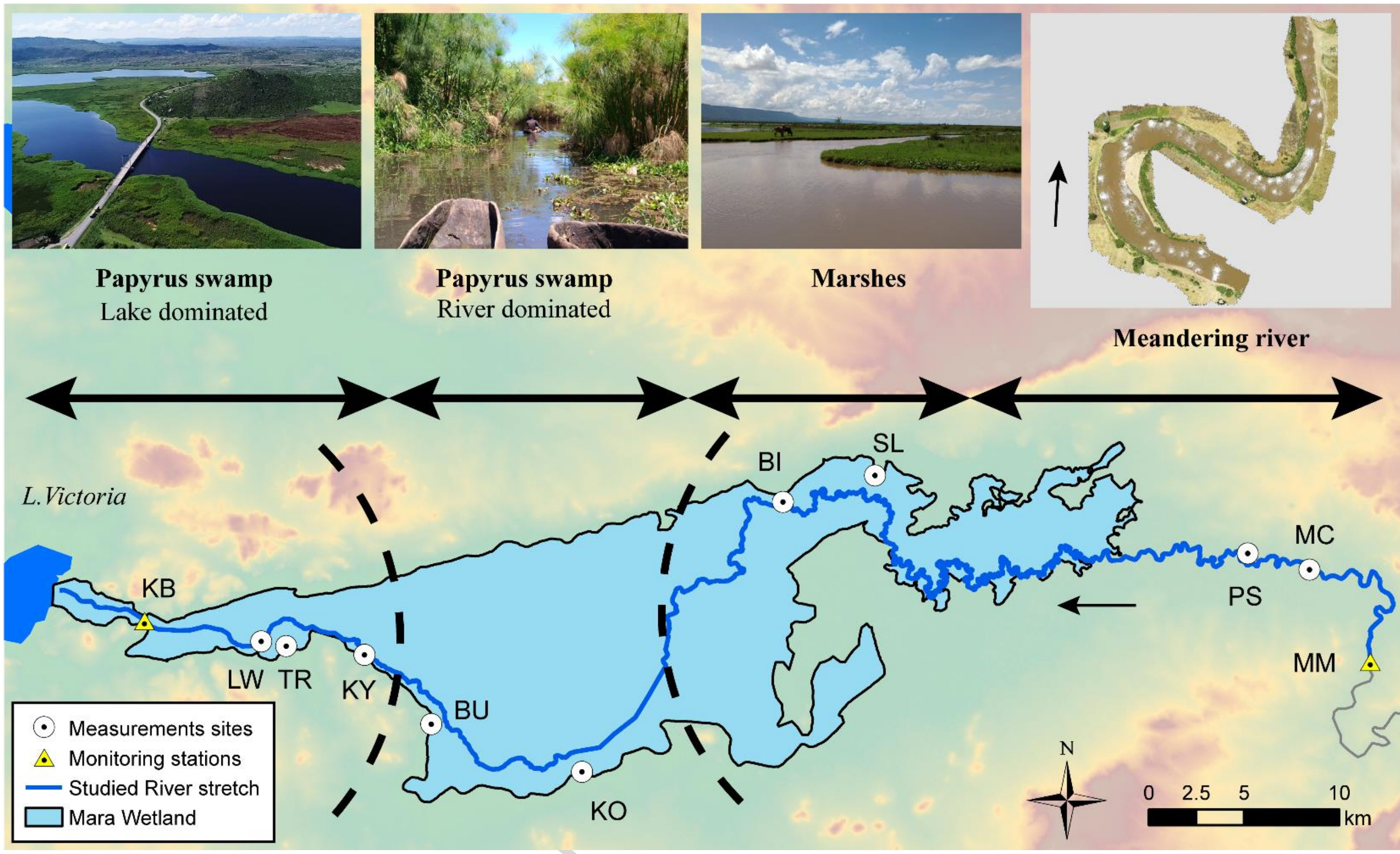


Figure 2 Study area characteristics and visited points (acronyms as in Table 1). Pictures from left to right are: UAV footage of the papyrus swamp at KB area; papyrus swamp at BU area; marshes at BI area; UAV-derived orthophoto mosaic of the meandering river at PS measurements site.

2.4.1 Surveys with unmanned aerial vehicle, GPS RTK and sonar

A multicopter DJI Phantom 4 Pro, carrying a 20MP camera with 1 inch sensor CMOS with a Field Of View of 84.4° and a lens of 8.8mm equivalent to a 24mm (https://www.dji.com/phantom-4-pro/info#specs), was deployed in selected areas of the study site with the objectives of obtaining terrain morphology, vegetation distribution as well as observations in unreachable areas. Ground control points as well as terrain features in selected areas were surveyed employing two GPS RTK Emlid Reach RS. A sonar Humminbird 798ci HD

SI Combo operated from an inflatable boat, was used to map the bathymetry of some stretches of the wetland and of the river.

Applying structure-from-motion photogrammetry processing with Agisoft Photoscan v1.3.3, the aerial images were rectified with ground control points (GCPs) and orthophoto mosaics and DEM have been obtained. The 16 resulting orthophoto mosaics and DEM have respectively 5 cm and 20 cm resolution (see example in Figure 3). The placement of GCPs was complicated by the inaccessibility of a great part of the territory, meaning that result accuracy is low compared with the potentiality of the methodology. However scarce GCPs or even direct georeferencing in structure-from-motion produces acceptable accuracy at least for qualitative approaches (Carbonneau and Dietrich, 2017; James et al., 2017).

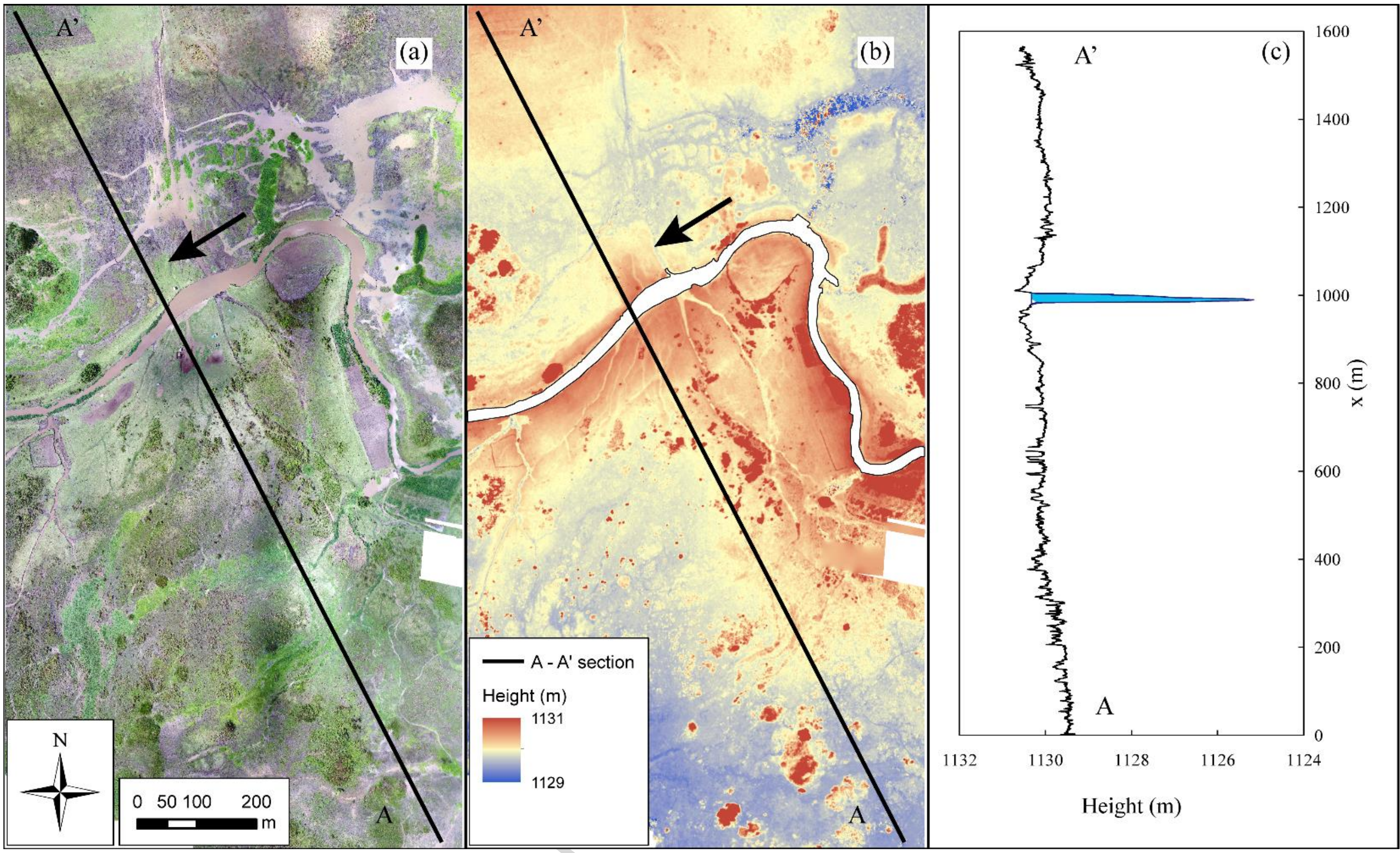


Figure 3 Survey with the UAV at Bisarwi location during the low flow period in October 2017: a) orthophoto mosaic with a resolution of 5 cm; b) DEM with a resolution of 20 cm; c) flow measurement's transversal section A-A' including the floodplains (derived from the DEM) and the river with wetted area being marked in blue (measured by ADCP during flow measurement). Arrows indicate the flow direction

2.4.2 Discharge, suspended sediment and bed material granulometry

During the missions, the Mara River discharge was measured at 4 locations along the main river stream at low and high flow conditions (see Table 1). The employed measuring devices are an ADCP OTT Qliner2 for deep river sections (h > 1.3m, being h water depth) and a current meter for shallow river sections ($h \leq$ 1.3m). Suspended sediments were sampled at 7 locations during low and high flows (see Table 1). The suspended sediment samples were collected in bottles at three different vertical depths (0.2, 0.6 and 0.8 of the water depth) along the river thalweg and in certain cases also near the left and right banks in order to observe the sediment mixing. The samples were successively analyzed in the water quality laboratory at the LVBWO in Mwanza, Tanzania, to get the total suspended solid concentration. The analysis consisted of filtering a defined volume of water samples with a standard cellulose membrane of 0.45 μm pores and weighing of the residues after drying in an oven at 103°C for 1 hour and exsiccate for 15 minutes. Depending on sediment concentration, the filtered water volume ranged between 50 and 500 ml. Bed material was collected with a dredge-type sampler. The granulometry of the river bed material was obtained by dry sieving in the laboratories of IHE Delft.

3 Results

3.1 Field observations and measurements

Analysis of data obtained from field observations, surveys carried with UAV, GPS RTK and sonar and the analysis of satellite images, permitted to delineate the main river and wetland morphological features and vegetation cover in the study area at specific locations. The river between Mara Mine and Bisarwi is meandering (Figure 2) and it has an average depth of 1.45 m with maximum depths of about 7 m just upstream Bisarwi (recorded on 12/05/2018 by cruising the river with sonar) at high flow conditions (discharge of 153 m^3/s). The river bankfull width drops gradually from 60 m at Mara Mine to 20 m in Bisarwi. For extended parts of this river reach, banks lack riparian vegetation and crops occupy the majority of banks and floodplains. Livestock roam the floodplains during the dry season, drinking from the river, and thus destabilizing the banks or even lowering their elevation. This situation has induced accelerated bank erosion and therefore meandering migration and cutoffs (Figure 4a). Levee breaches are frequent during high flows and are enhanced by local bank weakening due to adjacent crop fields (Figure 4b and c), paths and fords incised by livestock and wild animals.

Figure 4 Human activities on river banks lead to bank breaches: a) orthophoto map taken by UAV in November 2017 at CM point showing an old meander cut, heavy farming and no riparian vegetation; b) meandering Mara River near the Pump Station (PM) in 17/01/2010 (Google Earth image); c) same area of b) in 24/09/2010 showing a crevasse in correspondence of a pre-existent crop.

Moreover, some of the breaches are reported to be opened artificially for irrigation and fishing pools. The more relevant artificial water diversion led to the formation of the Sioux Lake in

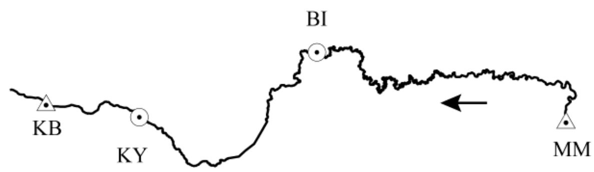
2000, visible in Landsat images, in the upper part of the wetland (private communications with local water users). The diversion channel is currently widening from 5 m in 2010 (Google Earth images of 17/01/2010) to 13 m in 2017 (UAV-derived orthophotos of 01/11/2017). Further downstream, at Bisarwi, the river has frequently breached lateral levees which are formed by cohesive sediments. UAV-derived DEM reveals floodplains that are clearly lower than river levees and water surface level (Figure 3). With this condition, natural or human induced breaches can trigger avulsions, which are further enhanced by a positive gradient from river to floodplains. Past avulsions occurred downstream are further reported in this article. Avulsion causes could be similar to the ones leading crevasses in the meandering reach.

Downstream of Bisarwi, the river turns abruptly to the south and flows through the papyrus swamp. After few kilometers of narrow channel (10 m width), the main stream disappears in the dense vegetation and likely divides in a few hidden channels. Unfortunately the area is inaccessible by boat and UAV footage was also not possible. Likewise satellite images do not permit a clear observation of the river. The stream is recognizable again after 7 - 8 km, in the proximity of Kongoto, and flows through an established channel along the South-West wetland boundary. Remarkably, the river between Kongoto and Kyamanyaka is narrow (about 20 m wide) and deep with an average depth of 2.20 m and maximum depth of 5.4 m during low flows as it was measured during the field work of October-November 2017. The wetland narrows from 14 km at its maximum width in Kongoto to 1.5 km of width in Kyamanyaka. Downstream of Kyamanyaka the river widens to more than 50 m and forms lakes in the proximity of the Kirumi Bridge. The flow is forced by the terrain morphology through the Kirumi passage, where, at the bridge, the water depth exceeds 8 m. Although, Kirumi Bridge is potentially a good location for water level and discharge measurement, the Lake Victoria backwaters jeopardize the measurements for low river discharges. At the time of field work in October – November 2017, the water in Kyamanyaka was clearly flowing downstream and the Lake Victoria backwater effect was not witnessed. Although it needs to be further investigated, the backwater effect seems to be limited to 10 km upstream of KB, an estimation that might change depending on the seasonal water level and river discharge.

Water level and discharge are fairly systematically monitored at Mara Mine. However, no systematic monitoring has been performed downstream of Mara Mine and the only values available for this research are based on the field measurements of this work and on past literature. A comprehensive picture of the measured flows is reported in Figure 5. During the low flow condition of October – November 2017, the flow fully conveyed into the main channel with substantially no lateral outflows in floodplains (Figure 5a). The reduction of discharge in Kyamanyaka can be associated to non-measured flow spreading in the papyrus swamp, and to the strong evapotranspiration and water uses. Discharge at Kirumi Bridge was not detected due to the Lake Victoria backwaters. During the high flow condition of May 2018, the lateral outflows were remarkable between Mara Mine and Bisarwi: more than 70% of flow was outflowing in the floodplain and only the 30% of the flow conveyed into the main channel. Those percentages have been evaluated by comparing the measured discharge at Mara Mine and Bisarwi (Figure 5). At Kirumi Bridge the discharge exceeded 1.5 times the discharge measured in Mara Mine after considering a water travel time of 1.5 days (Figure 5b), showing a substantial input from the lower sub-catchments and the emptying of the surface and subsurface water storages in the wetland system due to previous floods and rainfalls.

a)

01/11: Q measured = 14.00 m^3/s at BI



03/11: Q measured = 10.30 m^3/s at KY

	Distances (km)	Travel time (days)
MM to BI	77.38	0.90
BI to KY	38.92	0.45
BI to KB	52.62	0.61
MM to KB	130.00	1.50

Measures at MM

Day (dd/mm)	Q read (m^3/s)	Q measured (m^3/s)
26/10	15.50	
27/10	15.40	
28/10	15.20	
29/10	18.50	
30/10	17.00	
31/10	16.30	
01/11	15.70	16.08
02/11	15.10	
03/11	14.70	
04/11	14.40	
05/11	14.10	
06/11	14.10	12.00

b)

13/05: Q measured = 44.00 m^3/s at BI

11/05: Q measured = 365.00 m^3/s at KB

14/05: Q measured = 228.00 m^3/s at KB

Measures at MM

Day (dd/mm)	Q read (m^3/s)	Q measured (m^3/s)
09/05	234.00	
10/05	136.00	
11/05	99.00	
12/05	143.00	153.00
13/05	124.00	
14/05	94.00	
15/05	123.90	
16/05	148.50	

Figure 5 Flow measurements at (a) low flow in October – November 2017 and (b) at high flow in May 2018. Q_{read} *is the reading of the monitoring station,* $Q_{measured}$ *is the measured discharge as described in chapter 3.4.2, travel distance is roughly estimated by assuming a velocity of flow v = 1 m/s.*

Sediment transport plays an important role in the wetland system. Particularly, suspended sediments carried by the river are efficiently trapped by papyrus swamps (Boar and Harper, 2002; Ryken et al., 2015), promoting the wetland accretion. Unfortunately, we could not perform a systematic monitoring of suspended sediment. However, the few obtained data are important to understand the suspended sediment fate along the wetland. Measurements during low flows show that total suspended sediment concentration (TSC) is constant between Mara Mine and Bisarwi with values of 350 mg/L and dramatically drop by 10 times to the 35 mg/L measured at Buhenche, 32.5 km downstream Bisarwi (Figure 6a). During high flows, suspended sediments, which include sand, settle already in the river reach between Mara Mine and Bisarwi, where the outflow and deposition in floodplains is large. TSC drops in high flow from 600 mg/L measured in Mara Mine, to 195 mg/L in Bisarwi (3.6 times less than Mara Mine) and to an average of 63 mg/L at Kirumi Bridge (3 times less than Bisarwi), after the total 130 km of the observed river reach. Therefore, the suspended sediment behavior in high flows shows overall the same reduction observed in low flow, but with the major TSC reduction located in the meandering reach between Mara Mine and Bisarwi. During high flows the total suspended load (TSL) shows very high values of the order of 100 kg/s at Mara Mine. TSL is reduced to 20 kg/s at Kirumi Bridge (Figure 6b). Comprehensively, the measured fate of suspended sediments reveals the remarkable trapping and filtering efficiency of the river system and the wetland, with a release of clearer water to Lake Victoria.

Samples of bed material show a river bed composed by medium sand with the presence of fine gravel at Mara Mine (d_{50} = 0.482 mm, d_{16} = 0.178 mm, d_{84} = 4.216 mm) and by silt with the presence of fine sand in Bisarwi (d_{50} = 0.022 mm, d_{16} =0.006 mm , d_{84} = 81 mm) and Kirumi Bridge (d_{50} = 0.026 mm, d_{16} = 0.008 mm, d_{84} = 0.151 mm) (Figure 7c).

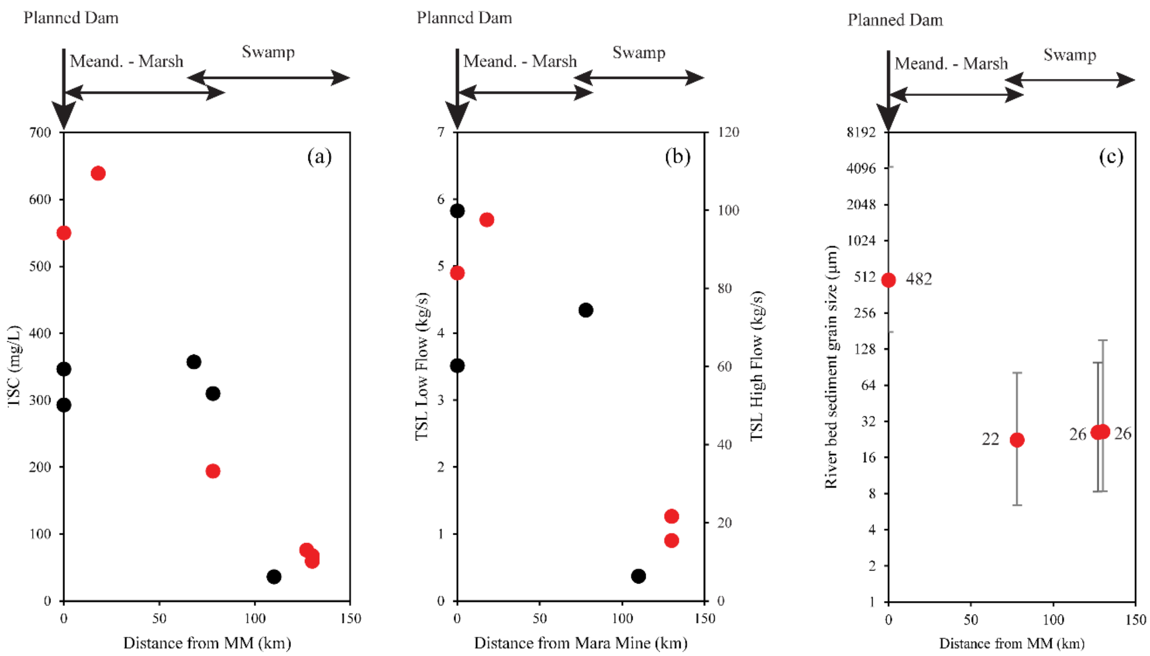


Figure 6 Suspended sediment and grain size of bed material along the main river reach: a) total suspended sediment concentration (TSC) for low (black) and high (red) flow conditions; b) total suspended sediment load (TSL) for low (black) and high (red) flow conditions; c) grain size of bed material for high flow condition (dots and values correspond to the d_{50} diameter, bars represent values included in the interval between d_{16} and d_{84} diameters).

3.2 Historical reconstruction of river and wetland evolution

Supported by the previously described field observations and measurements, interviews, available literature and maps, the historical reconstruction of river and wetland morphological evolution was performed. The overall results are reported in Figure 7 and Figure 8.

The wetland area extension has been measured for selected years. The first suitable data dates back to 1911 when the wetland depicted in the German map (Reimer, 1911) had an extension of 113 km^2. The wetland did not change in area till the 1950 decade, when it started to increase in size, measuring 270 km^2 in 1963 and 288 km^2 in 1973. Increasing wetland area has been further observed from selected Landsat images of 1984 (213 km^2) and 2002 (344 km^2) and from Google Earth images of 2017 (388 km^2) (Supplementary Material, Figure S3). The recent data taken from sediment cores performed in the Mara Wetland by Dutton et al. (2019) show accelerating sedimentation. Reading their results (in Figure 7 and Figure 8), the accretion rate of the last 100 years shows constant low values till the 1940 decade and a tangible increase starting from the 1950s.

The upper and middle parts of the wetland form an alluvial fan having a slope of 0.23 ‰. Here the river, due to aggradation and sediment clogging, is prone to avulsions toward bank breaches, tributaries or ancient channels. Important channel avulsion toward the south has been depicted in the available topographic maps (Supplementary Material, Figure S2). The maps of 1911 and 1943 show the main channel flowing clearly along the northern wetland boundary, where nowadays the path is still recognizable and wetted during high flows. Successively, the map of 1957-1959 depicts a formation of a network of channels towards south (marked as A and B in Figure 7) and the initial development of Kubigena Lake, which was reported to be persistent during the Independence Rain of November 1961. The map of 1975-1976 shows the consolidation of the avulsions A and B (Figure 7) and the definitive abandonment of the Old Mara reach. The following period was analyzed with Landsat images, showing a progressive parent channel abandonment toward upstream until the establishment of Avulsion C evolving from 1988 to 1992, as visible in Landsat 4 (e.g. image 07/02/1990 in Supplementary Material,

Figure S4). The Avulsion C has been visited in February 2019. Pictures of this area are reported in Supplementary Material, Figure S5 – S8. Particularly Figure S6 shows woody debris that, together with sediment, clogged the old channel. The main channel is often narrower than the images resolution. However, starting from 1999, the pansharpened images of Landsat 7 and 8 (e.g. Landsat 7, 12/09/1999 in Supplementary Material, Figure S4), and Sentinel images are particularly helpful to spot the channel migration toward south. Avulsion D is firstly observed in 2004 (e.g. Landsat 7, 20/05/2004 in Supplementary Material, Figure S4) and the main channel has been not substantially changing until nowadays, except for the disappearance of Lake Kubigena in 2007. Nevertheless, around the Bisarwi area and upstream, various bank breaches have happened in the last decade (Figure 7). Recent breaches (some of them observable in Figure 3) could potentially lead to future avulsions, promoted by a positive gradient toward the floodplains.

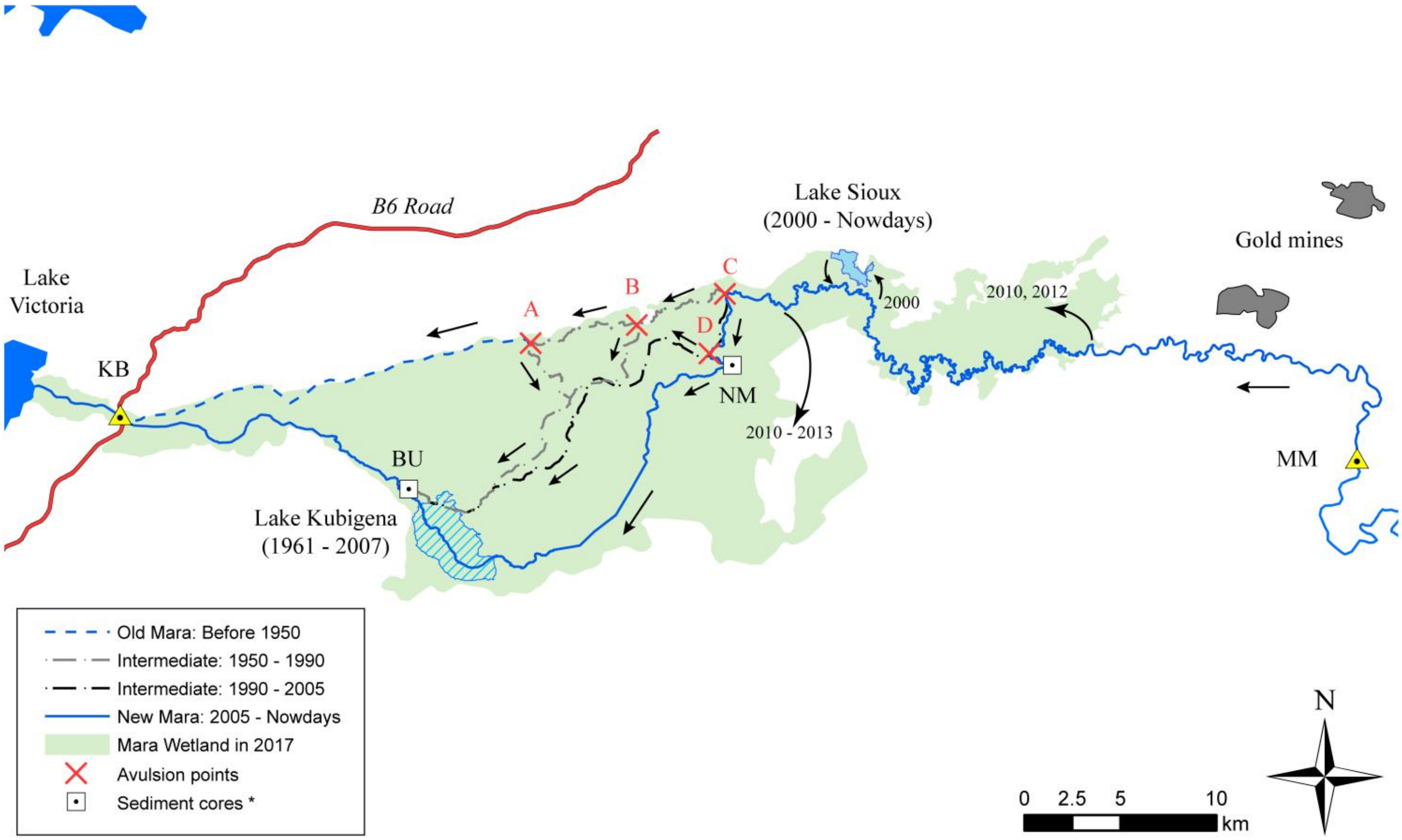


*Figure 7 Observed main river channel avulsion in the Mara Wetland: straight arrows indicate flow direction; curved arrows indicate relevant outflow/inflow in/from floodplains or lakes occurred in reported years. * - Sediment cores locations as in Dutton et al.* (2019).

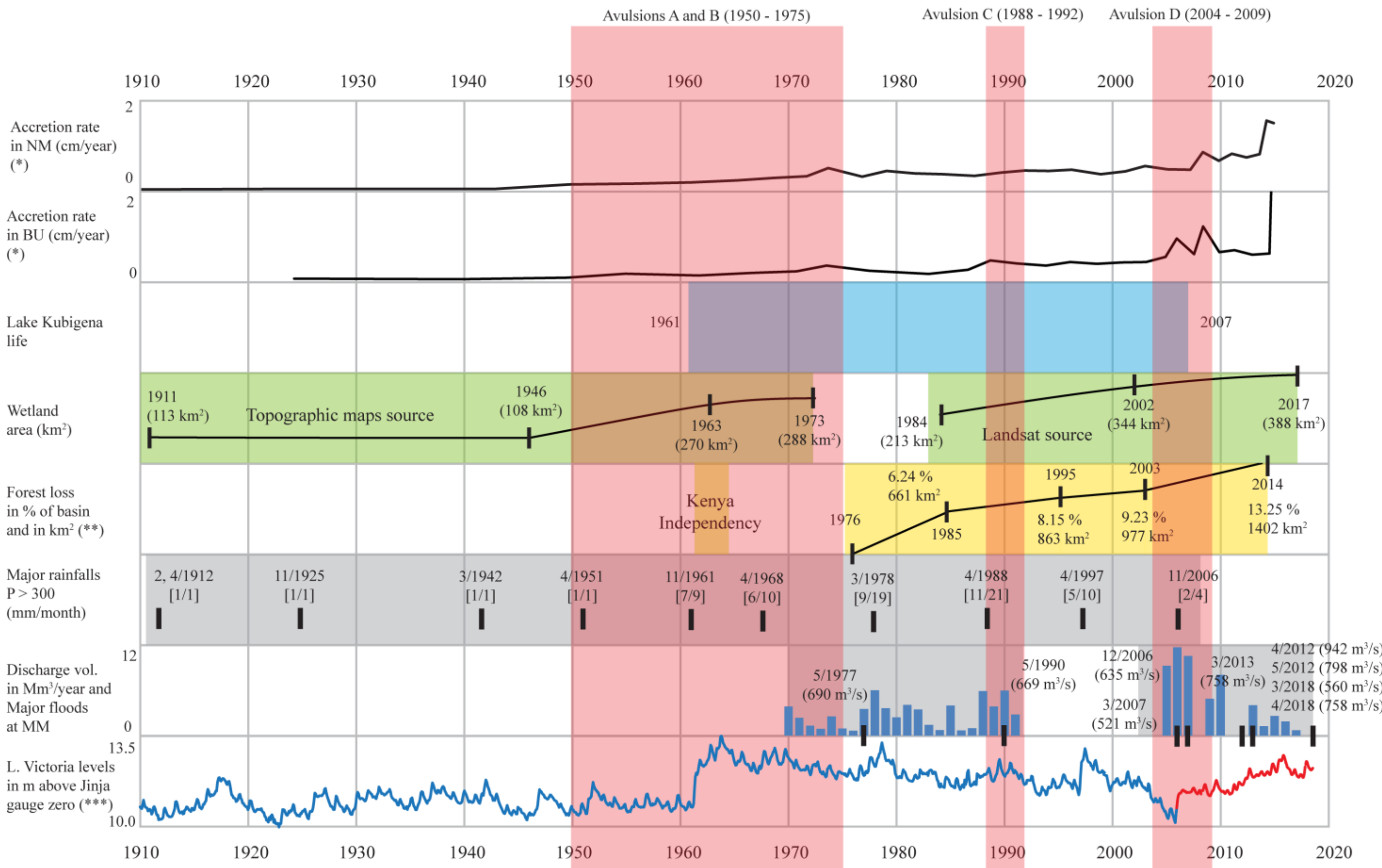


*Figure 8 Time evolution of eight variables influencing the avulsions observed in the Mara Wetland. * - Dutton et al.* (2019)*; ** - Mwangi et al.* (2018)*. *** - blue data series is taken from Sutcliffe and Petersen* (2007)*, red data series is lake water level shifted to Jinja gauge zero from TOPEX/POSEIDON/Jason-1 and Jason-2/OSTM altimetry (US Department of Agriculture, Foreign Agricultural Service,* https://ipad.fas.usda.gov/ *, accessed the 15/01/2019). Values in squared brackets are [# of gauges where rainfall exceeds 300 mm/month / # of operative gauges in the study area]. Shaded areas mark the time windows of available data. The periods in which the avulsion events occurred are marked with vertical pink bands.*

4 Discussion

Before 1950 the Old Mara stream was flowing along the north side of the wetland likely due to the local geomorphological setting: the normal dip-slip fault forms a depression in the northern part, where the river used to flow. Recently, important climatic and land use changes enhanced sediment transport in the river and deposition in the wetland. Figure 8 shows the temporal variation of eight variables: bed level accretion rates measured by Dutton et al. (2019) at New Mara (NM) and BU; the life spam of the Lake Kubigena; the wetland surface area; the forest loss as in the Mara River Basin as assessed by Mwangi et al. (2018); the major recorded rainfall events; the yearly volume of the Mara River discharge at MM; the major floods events and; the Lake Victoria water level fluctuation.

Wetland area and upper basin forest cover loss show a direct correlation in time. Sedimentation and main river channel clogging during the last 70 years forced the river to relentlessly shift toward the south, as stated in the previous section. Interviews of local inhabitants confirmed that the Old to New Mara transition and the vegetation shifting from savannah and forest to marshes and swamps of the Lower Mara Floodplains were initiated in the 1950s (Bogers, 2007; Mturi, 2007). Peaks of sedimentation, major floods and rainfall events, and peaks of yearly river discharge in the wetland support the assessment of the timing of avulsions and wetland size change (Figure 8). Dating Avulsions A and B is complicated due to scarcity of observations. However, the accretion rate increase in BU shows that avulsions A and B started in 1950. The heavy Independence Rain of November 1961, coupled with the recorded increase in Lake Victoria water levels (Sutcliffe and Petersen, 2007) and the extensive deforestation immediately after the Kenya independency (1963), promoted changes in the river system. Indeed, avulsions are intrinsic mechanisms resulting from strong floods and high sediment deposition during the receding phase of the flood wave. The reported wetland expansion in the period 1950 - 1970 might have been triggered by Avulsions A and B which have caused the river channel to progressively shift to the south, but also by the rise of Lake Victoria (+1.5 m in 1964), which inundated a part of the lower wetland and pushed upstream the backwater effect, enhancing sediment deposition. In the period 1988 - 1992 a new avulsion (C) happened. Major rainfalls of 1988 and 1990 and high discharge volumes of that period are among the causes of this new avulsion. The accretion rate peak of 1988 in BU confirms this hypothesis. The avulsion event is visible in the Landsat image of September 1990 (Supplementary Material, Figure S4) after a major flood recorded in May 1990 which, accordingly with local interviewed persons, clogged the old river channel with woody debris and sediments. More recently, peaks of accretion rate in 2006 and in 2008 in BU appear related to the floods and peaks of discharge volumes of the same period and to the occurrence of Avulsion D in the New Mara channel. Avulsion D consolidated in 2008, the year when the accretion rate in NM doubled in value, proving the river avulsion in NM channel. Interestingly, the Lake Victoria water level dropped by 1.2 m over the years 2000 – 2006 due to over-abstraction. This has been attributed to the turbine operation of the new Kiira Dam in Jinja, Uganda, overriding the known Lake Victoria Agreed Curve outflows (Sutcliffe and Petersen, 2007). The re-establishing of the Agreed Curve outflows contributed to the subsequent rise of the lake level. Thus, Lake water level rise could not trigger Avulsion D, but a direct correlation between lake level and wetland area seems to exist, at least for the 1950-1960 period. Further remote sensing analysis on wetland extent in the last decades could help to define the relation between wetland area, lake level and the other involved variables.

Systematic monitoring of water flow and water level is scarce and related only to two monitoring stations having scattered data: Mara Mine and Kirumi Bridge. Additionally, the reading of the Kirumi Bridge station is affected by the Lake Victoria water level. For these reasons, dedicated studies on the water balance of the Mara Wetland, so far absent in literature, are of primary importance. However, the field data obtained thanks to this study, permitted to shed some light on the current wetland water balance. In Figure 5 we described two examples of the measured river discharges along the study area for low flow and high flow conditions. For low flow conditions all the water is conveyed in the main channel. The little discharge reduction from Mara Mine to Kyamanyaka can be attributed to water uses and evapotranspiration (Migadde, 2019), which are particularly high in the dry season. Remarkably, the wetland northern boundary, where the river channel is almost abandoned, and the center parts of the wetland remain wet enough to support the papyrus life. Lacking data of groundwater, we can speculate that a certain water storage and possibly baseflow groundwater input from lateral sources exists. Flow measurements in high flow conditions showed a different behavior of the wetland system with respect to low flow conditions. Nearly 70% of the water discharge measured at Mara Mine is outflowing in the floodplains through levee breaches. Only 30 % of the flow is conveyed by the main river channel in Bisarwi. However, at the same time, the discharge measured at Kirumi Bridge was 150% of the Mara Mine discharge. We can speculate that lateral input from lower catchments and the empting of the water stored in the wetland pounds contributed to the increased discharge measured at Kirumi Bridge. It can be immediately seen that further studies on the wetland water balance should be addressed to understand the resilience of the wetland ecosystem.

In order to demonstrate the mechanism and causes of avulsions in the Mara Wetland one would need dedicated past field observations which are unfortunately nearly absent. Observations in the wetland are very limited due to difficult access to many locations because of poor road conditions in the wet season and navigation blocked by floating papyrus and water weeds. Historical satellite images, although useful to capture the avulsions occurrence, lack sufficient resolution to observe detailed behaviors. Beyond the limitations of the study, looking to the relatively large avulsion angles (around 90°) in the Mara Wetland, three observations can be made:

- natural large bifurcation angles occur in cohesive banks where a weaker bank part can breach (Blanckaert, 2011; Ferguson et al., 2003; Kleinhans et al., 2013);
- avulsions in the study area can be initiated where walking paths (population and livestock), fords and crops weaken the river banks, as explained earlier and already observed in similar studies as, e.g., Heyvaert et al. (2012);
- bank breaches reported to be opened artificially for irrigation and fishing pools can trigger avulsions which are further promoted by positive gradient from river to floodplains.

The final effect is due to the combination of the three causes above. Additionally, past studies show that the majority of the documented avulsions moved the water flow into pre-existing channels (Jerolmack and Paola, 2007; Slingerland and Smith, 2004). This has likely happened for Avulsions A and B, where the newly formed channel seems to flow through the tributaries depicted in the topographic maps of 1911 and 1946 (Figure S2, Supplementary Material).

Observing the avulsion positioning it is possible to describe a trend of upstream-moving avulsion regression and simultaneous increasing of wetland size. Avulsion A is located 24 km upstream of Kirumi Bridge and Avulsion B 7 km further upstream. Associated wetland size increased from 108 km^2 to 288 km^2. Avulsion C is located 6.4 km upstream Avulsion B, and together with Avulsion D increased the wetland size to 388 km^2. Thanks to the formation of the new channels, the river system distributes the same amount of water over a wider alluvial fan. New inundated area means wetland expansion, vegetation and habitat changes, but also less water volume per unit area and increasing of evapotranspiration, with possible social and ecological implications in the preexisting inundated area. As an example, in the period 2006-2009, when Avulsion D likely occurred, the yearly water volume entering the wetland (Figure 8) was sufficiently big to inundate the whole wetland area. However, in the current decade, the record shows a considerably smaller yearly water volume (Figure 8) and implies potential water scarcity in some parts of the study area, such the ones abandoned by the river flow. Since the wetland has not shrunk in the area close to the northern boundary during the current relatively dry decade, it is possible that baseflow, non-quantified lateral surface or subsurface inflow feed the abandoned river channel sufficiently enough to support the wet ecosystem. The Thigithe Creek, a permanent northern tributary, appears to be an important, and yet non-quantified, water input to the northern and upper part of the wetland. This shows once again the need of the water balance assessment and further field measurements in order to understand the interaction between wetland, aquifer and lateral inflows.

Due to hydrological changes, land use change and other human activities, the Lower Mara Wetland is suffering substantial alterations. A barrage is planned to be constructed at Mara Mine, about 28 km upstream of the wetland, for irrigation and hydropower. The barrage will have gates that can be fully open to allow water and sediment flowing through during high flows. According to the project design, the reservoir will have a storage volume equivalent to 5 days of average flow. Therefore, flow peak alteration will be likely small. However, the dam will certainly trap part of the sediment due to backwater effects and upstream river channel widening related to the reservoir. Sedimentation is expected during low flows, when the water is retained in the reservoir and abstracted for irrigation. Moreover, hydropower operations will probably trigger fast flow fluctuations which can destabilize banks (Cushman, 1985; Khan et al., 2014). Water fluctuations, as well as water abstraction and sediment retention, can generate additional stresses to the river and wetland ecosystem. Therefore, the management of dam releases will be of primary importance for the wetland health and its conservation and for the quality of the water being released to the Lake Victoria. For this reason, further consistent monitoring of suspended sediment is critically important and recommended to better understand the wetland system in order to target a proper conservation strategy and sustainable dam operation.

The analysis carried out in the framework of this study is affected by the scarcity of data. In particular, it has not been possible to thoroughly describe the hydraulic behavior of the system river-wetland-lake. For this, the description of the water balance appears as the first necessary step, but its achievement requires new and systematic field and monitoring data on discharge, water level and groundwater flow in different part of the study site. The same data would be necessary to set up a numerical model which would finally allow quantifying the contribution of the different factors governing the hydraulic functioning of the system. Specifically, the following key factors still need to be quantified: Lake Victoria backwater area extension and its variations, wetland water storage and release, contribution of groundwater and lateral surface and sub-surface inflows. Additionally, consistent sediment transport data would allow the set-up of a hydro-morphodynamic model of the Lower Mara River and Wetland. This would strongly improve the understanding of the role of sediment, vegetation and flow regime under different scenarios, including dam operations, on the river and wetland system. Further studies, including new data acquisition and numerical modelling, are thus strongly recommended.

5 Conclusions

Supported by recent multidisciplinary field surveys and previous available data, a number of conclusions are reached regarding the mechanisms causing channel avulsions in the Lower Mara River and Mara Wetland expansion.

- The dense papyrus vegetation of the wetland traps suspended sediments very efficiently. This behavior, together with the backwaters induced by the fluctuation of the Lake Victoria water level, enhanced sedimentation in the wetland area.
- Bifurcations and levee breaches often occurred due to a combination of natural and anthropogenic bank weakening, such as persistent grazing and farming on the river margins.
- Increased sediment input due to upstream deforestation for land reclamation, farming and grazing and particularly wet periods in the Mara Basin, accelerated the clogging of the main river channel and reinforced the water flow through the bifurcations and breaches, establishing river avulsions.
- The identified avulsions of the Lower Mara River have promoted wetland expansion: the events occurred between 1950 and 1975 increased the wetland surface by a factor of 2.7, while the most recent ones by a factor of 1.8. Avulsions distribute the water flow over a larger area but are not sufficient to explain the wetland expansion alone, since sufficient water volume is needed to maintain a wider area wet. The water volume brought in by the river and the relatively low Lake Victoria levels of the last decades do not seem sufficient to support the extended Mara Wetland in the current years. Therefore, the non-measured water

volumes from subsurface flow and lateral inflows from relevant wetland tributaries could be the additional water contributors that are necessary to maintain a wet ecosystem.

- In this context, the flow and sediment flux management of the dam that has been proposed upstream of the wetland will be of primary importance for the wetland health and conservation and for the quality of the water being released to the Lake Victoria.

We found that river channel avulsion is a key mechanism that supports the Mara Wetland expansion. Beyond the scientific importance for the case study of the Mara Wetland, this finding offers the possibility to explore solutions based on imposing river avulsions for the conservation of both expanding and shrinking wetlands.

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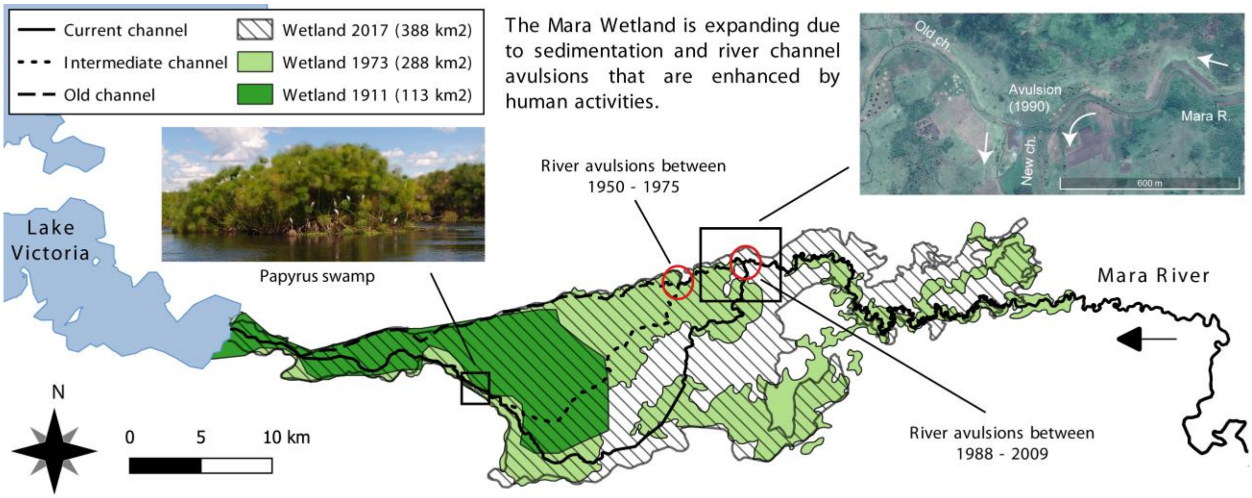
Graphical abstract



Highlights:

- The Mara Wetland provides fundamental ecosystem services in a semi-arid area
- Field and historical data analysis shows wetland morphological alterations
- River avulsions and sedimentation increased by 3.6 times the wetland area
- Causes are hydrological fluctuations, deforestation, grazing and farming