Vegetation Blockages and their Influence on the Channel Flow Dynamics in the Okavango River Alluvial Fan, Botswana

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Abstract

The vegetation blockages in the Okavango Delta tributaries have been a concern among the local communities, water managers and in tourism industry. The objective of this study is to update historical vegetation blockages reported in 1970s in the Okavango channels and to assess the blockage influences on the channel flow dynamics. The blockages were determined by boat in 2002 in three river systems namely Ikoga-Thaoge, Nqoga-Maunachira and Mboroga-Gomoti Rivers and further assessed at four-to-five-year intervals until 2018. The collected coordinates using GARMIN GPSMAP 62S at the start and end points of the blockages were added to the Okavango Delta feature dataset to ArcMap GIS 10.2 software to map and measure the blockage lengths in km. 'Papyrus' is the dominant species blocking the channels while the 'hippo grass' is a fringe vegetation. Five types of blockages were categorised based on their growth and spread in different flood regimes. The hydrological data analysis showed that the 'Intermittent rooted emergent papyrus' and 'Emergent papyrus rafts' in Thaoge River held large volumes of water in the upstream Qaaxhwa and Weboro Lagoons from 2005 onwards causing some flow diversions to Boro River. The 'Surface blockage debris' in the origin of Maunachira River did not have significant influence on its downstream flow because of added flows via Khiandiandavhu channel. The Bokoro and Dxerega Lagoons on the blocked Maunachira were reduced in their water surface area by 28.7% and 45.2% respectively between 1984 and 2011. The hippo grass in Mboroga and Gomoti Rivers do not have much impact on channel flow. It is recommended that efficient management of blockages through the engagement of local communities and safari operators in the areas of concern would improve the flow distribution for community resource use and tourism development.

Keywords: Botswana; Okavango Delta; World Heritage site; blockages; Thaoge; Maunachira; Gomoti.

Introduction

The Okavango River originates in the southern Angolan highlands as two rivers, the Cuito and Cubango, flowing through eastern parts of Kavango region in Namibia and finally flowing into the Okavango Delta, Botswana. The annual flood wave arrives at Botswana-Namibia border two months later than the rainy season in Angola. It takes further five to six months to flood downstream of the Okavango (Greater Maun area), mostly by May to July depending on the flooding condition and rainfall in the Delta. The mean inundated area is around 5,000km^2 but the intermittently inundated area exceeds 12,000km^2 (Milzow *et al.,* 2009). In the period of 85 years (1932-2016), the average annual inflow at Mohembo was 9316 million cubic meters (MCM) with a range of 5331(1996) to 16047(1967) MCM and the annual Delta rainfall ranged from 217(1942) to 923 (1974) mm (Kurugundla *et al.*, 2018). Approximately 97% of the total inflow

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is evaporated in the Delta (Anderson *et al*., 2003). The low topographic gradient of the Delta (1:3470) causes low flow velocities. The flow takes place through meandering channels and associated vegetated floodplains with overbank spills that often join downstream (Gumbricht *et al*., 2001 and Anderson *et al*., 2003).

The Okavango Delta is a protected Ramsar site, the 1000th World Heritage site and an iconic tourist destination. It is the most abundant natural source of perennial surface water system in Botswana encompassing extensive savannah woodlands with rich biodiversity. The Delta supports water supply, farming, wildlife, tourism and the livelihoods of local communities. Any change in the flooding pattern resulting from natural and/or anthropogenic interventions would have a significant impact on the Delta and the associated sectors as stated above.

Plant species namely papyrus *(Cyperus papyrus* L.), fen sedge (*Cladium mariscus* (L.) Pohl.) (Family Cyperaceae); hippo grass (*Vossia cuspidata* (Roxb.) Griff.), reed grass (*Phragmites australis* (Cav.) Steud.), and wire-leaf daba grass (*Miscanthus junceus* (Stapf) Pilg.) (Family Poaceae) are generally involved in blockage formations in African wetlands (Denny 2012). Eight plant communities have been recognised in the Okavango: 1) fountain grass (*Pennisetum glaucocladum* Stapf & CE Hubb.); 2) reed grass (*Phragmites mauritianus* Kunth) (Family: Poaceae); 3) *Cyperus papyrus;* 4) Mixed *Cyperus papyrus* and *Miscanthus junceus*; 5) *Miscanthus junceus*; 6) cotton wool grass (*Imperata cylindrica* (L.) Raeusch.) (Family: Poaceae); 7) tiger sedge (*Pycreus nitidus* (Lam.) J. Raynal) (Family: Cyperaceae); and 8) Mixed bog community (Ellery *et al*., 2003). Of these species, papyrus is the dominant species capable of quickly growing over water bodies, along the edges of channels and into flowing water, eventually blocking them either by floating or anchoring (Denny 2012 and Gaudet 2014).

Papyrus grows up to 5m in height forming dense stands from submersed rhizomes. It is common in low to moderate water levels and usually dominates in situations where the meristems are permanently submerged (Ellery *et al*., 2003). Hippo grass can either be associated with papyrus along the shorelines of rivers or may form vast meadows on pool/lagoon sides and other wetland areas. It tolerates strong water currents and copes well with unstable hydrological regimes (Wietse *et al*., 2010). The other common channel fringe plant species in the Delta is *M. junceus* (Smith 1976) which requires solid banks for its anchorage but not in flowing channels (Hutchings and Bradbury 1986).

There are 20,000km^2 of papyrus floodplains in Africa but it occupies less than 20% of total *Phragmites* spp. in the Okavango Delta (Denny 2012). Hydrological models suggest that morphological changes brought about by dredging of channels and removal of vegetation have a pronounced effect on the distribution of flood waters in the Delta (Bauer *et al*., 2006 and Okavango Delta Management Plan, ODMP 2006). The blockages in channels frequently prevent accessibility to the hydrometric stations thus affecting the quality of data collection by independent researchers and government institutions. The problem of channel-papyrus-blockage in the Delta has been a concern for a long time among the local communities, water managers and people in the country's tourism sector. The communities living around the Delta believe that blockages in the channels decrease water flows from reaching their settlements as well as contributing to drying up of certain peripheral/seasonal areas where flood recession farming is common.

The impact of vegetation on the hydrology and geomorphology of aquatic ecosystems has been studied for river basin management (Wietse *et al*., 2010; Mulahasan and Stoesser 2017; Liu *et al*., 2017; Marcinkowski *et al*., 2018). Aggradation process triggers the decline in flow velocity resulting in the invasion of the channels by aquatic plants and causing their failure and loss of water (McCarthy *et al.,* 1992). Channel blockage and abandonment of lower Nqoga in the Okavango Delta has been postulated to be caused by either a combination of encroachment of papyrus from the channel banks into the channels, or the development of papyrus debris blocking in the lower reaches of major distributary channels (Ellery *et al*., 1995).

The flow impacts of submerged and emergent vegetation in natural wetlands and man-made rivers have attracted significant attention of researchers and engineers over time. Ellery (1988) outlined the papyrus rafts blocking the rivers in African swamps. The possible role of papyrus and other vegetation debris blockages in the evolution of major distributaries of the Okavango Delta is well documented (Wilson 1973; McCarthy *et al.,* 1991 and 1992; Ellery *et al.,* 1995; McCarthy and Ellery 1997; Ellery *et al*., 2003). The impacts of the vegetation blockages on the channel flows have, however, scarcely been assessed. The blockage history and their clearances undertaken between 1930 and 1970 in the Delta have been described in detail in Wilson (1973),but have not been updated or reviewed since then. Therefore, the present study aims to update the historical vegetation blockages with their extensions in the channels of the Okavango Delta and to determine whether the blockages have any effect on the flow distribution in the channels.

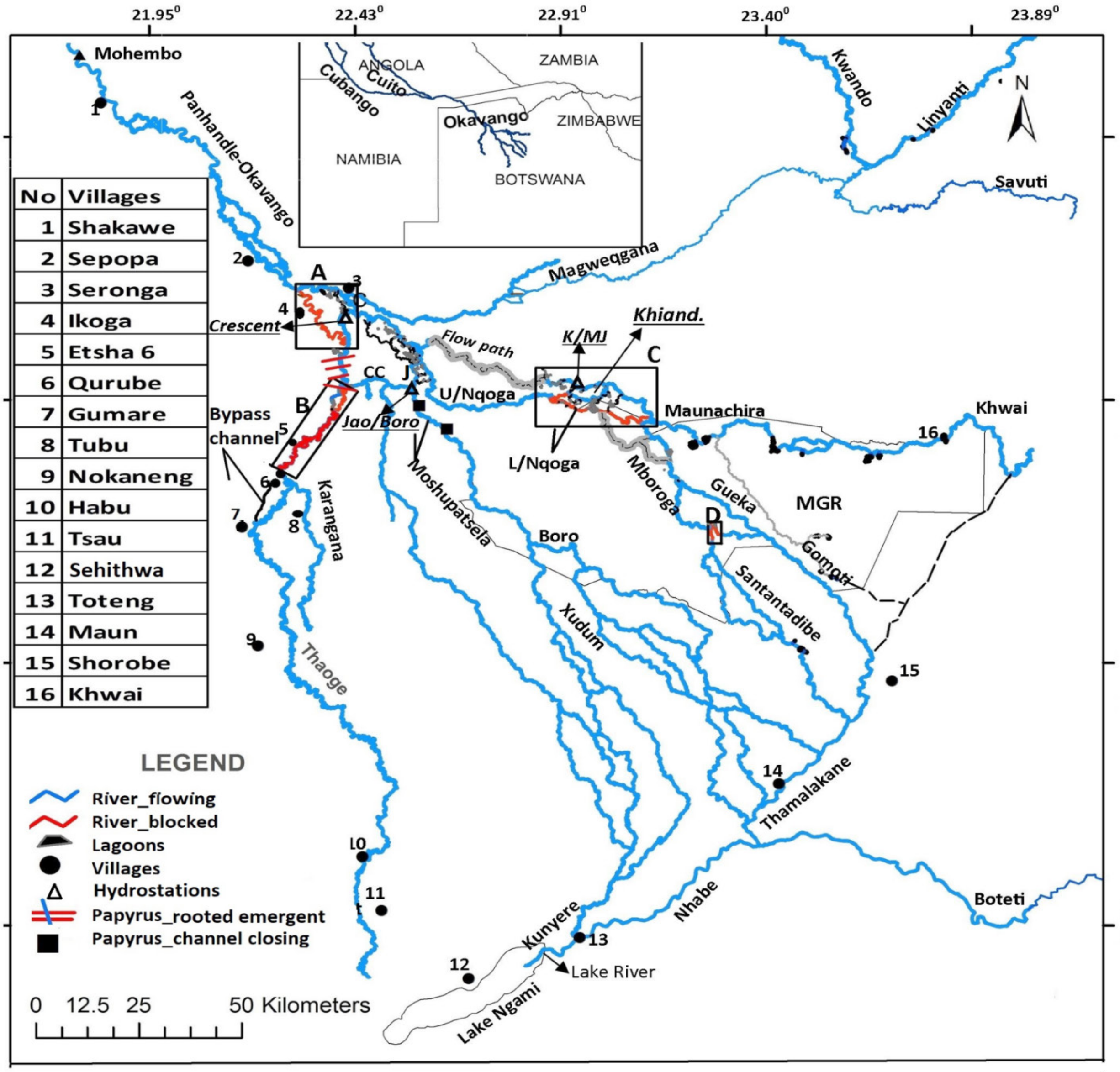
Materials and Methods

Site description

Below the Panhandle, five major distributaries can be distinguished (Figure 1). The most easterly Magweqgana (Selinda Spillway) originates from the Okavango River near Seronga, reaches the Linyanti wetland, which happened during the recent period (2011-2015) when the Mohembo inflows were above 10,000 MCM (van des Sluis *et al.,* 2017). The most westerly branch, the Thaoge River, twists south westerly as the Crescent channel (Snowy Mountains Engineering Corporation, SMEC 1987) receiving the flows of Ikoga River to form Thaoge River proper.

Most of the water has been carried by the Upper Nqoga (U/Nqoga) River since the last 100 or more years, bifurcating into Lower Nqoga (L/Nqoga) and Maunachira-Khwai Rivers. The Jao (J) River takes-off from the U/Nqoga and continues as Boro River spilling into Xudum system in south-westerly and finally reaching the Lake Ngami via Kunyere-Lake Rivers. The Boro continues to flow into Thamalakane River, which bifurcates into Boteti and Nhabe Rivers in the Maun village region. Nhabe River outflows to Kunyere River in high flood events only (Kurugundla *et al*., 2018). The Khiandiandavhu (Khiand.) River collects U/Nqoga bank spill via flow paths (Figure 1) and meanders to join the proper Maunachira River. Maunachira sends out its spills to Mboroga and Santantadibe Rivers, which rarely outflows to the Thamalakane River. Thus, the flow of the Okavango River is partitioned within the Delta (Kurugundla *et al.,* 2008).

Figure 1: Hydrography of the Okavango Delta showing the vegetation-blocked channels in the boxes. (A) Ikoga River; (B) Middle reaches of Thaoge River; (C) Origin of Maunachira River (Smith Channel or Papyrus filter) and its downstream; (D) Origin of Gomoti and Santantadibe Rivers. CC = Cross Channel, J = Jao, *K/MJ* = Khiandiandavhu (*Khiand.*)/Maunachira Junction, L/Nqoga = Lower Nqoga, MGR = Moremi Game Reserve, U/Nqoga = Upper Nqoga.



Vegetation blockage collection process

Kurugundla (2003) explored all the five major tributaries in the Okavango Delta by boat in July and December 2002. The blockages were identified and located in three river systems namely Ikoga-Thaoge, Nqoga-Maunachira, Santantadibe and Gomoti Rivers. The coordinates were then collected at the start and end points of the blockages using GARMIN GPSMAP 62S (Kurugundla 2003). The observations were replicated by subsequent surveys at four-to-five-year intervals to determine whether the length of the blockages had changed over the period from 2002 to 2018. The last survey to the blockage points was in June 2018.

The coordinates were incorporated in ArcMap GIS 10.2 software, and then merged into the

Okavango Delta feature dataset. The river-blocked sections were styled in red color and displayed in boxes. The approximate lengths of the blockages in km were determined within ArcMap GIS 10.2 software using 'Measure Tool'. Similarly, the length of the Lower Nqoga from its take-off point to *'1983 upper limit of blockage'* blockage (Figure 3) was measured using Google Earth engine images of the Okavango Delta as the river was inaccessible. The blockage points were cross-checked with 2002 aerial photographs and Google Earth images.

Data source and hydrological measurements

The hydrological data were obtained from the selected hydrometric network of the Delta and from the temporary stations that were introduced for the study (Table 1). The coordinates, the channel depths (deepest channel point is the gauge zero) above mean sea level (msl) in meters (m) at the stations were sourced from the Botswana government's Department of Water and Sanitation (DWS) as shown in Table 1. The stream flow discharges (Q) in cubic meters per second (m^3 s^{-1}) were measured using a current meter (Brand-SEBA, Model-A-OTT 162398, Propeller No. HO8887, Counter number Z215) by a two-point method (Wisler and Brater 1978 and World Meteorological Organization, WMO 2010). In the two-point method of measuring velocities, observations were made in each vertical at 0.2m and 0.8m of the depth below the surface water at selected interval distances across the river. The average of these two observations is used as the mean velocity in the vertical.

The water flow discharges at Crescent, Jao/Boro, and Khiandiandavhu/Maunachira Junction (K/MJ) stations and their elevations above msl in relation to Mohembo were compared to establish the flow partition among Thaoge, Boro and Maunchira Rivers.

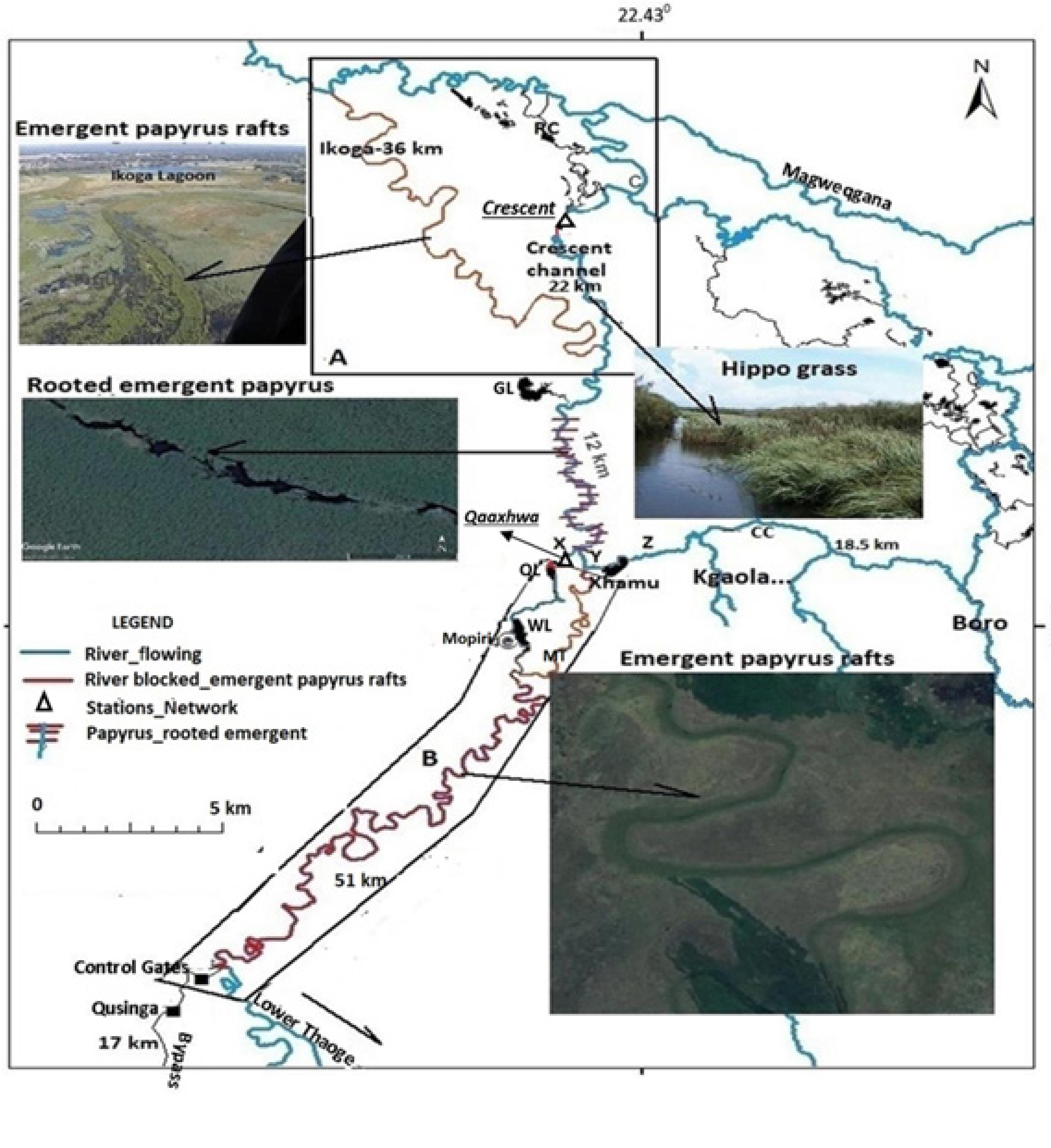
Table 1: Flow measurements and gauge zeros of the stations from hydrological network and stations introduced for the study.

Permanent stations-Hydronetwork			Temporary stations-Introduced	
Rivers	**Stations - Gauge zero, m**	**Latitude, Longitude**	**Stations**	**Latitude, Longitude**
Okavango	Mohembo – 992.882	-18.17834, 21.73633	-	-
Thaoge	*Crescent – 975.565	-18.88043, 22.39029	-	-
	Qaaxhwa – 971.525	-19.04745, 22.39087		
Boro	*Jao/Boro – 968.170	-19.05850, 22.55588	-	-
U/Nqoga	Gaenga - 963.948	-19.06831, 22.82030	-	-
	Hamoga (H) – 962.823	-19.07015, 22.87870	-	-
Maunachira	*Khiandiandavhu/ Maunachira Junction (K/MJ) – 953.231	-19.03504, 22.87849	Khiandiandavhu Inflow (KI) Smith Inflow (SI) Smith Outflow (SO)	-19.06253, 22.87952 -19.06763, 22.88136 -19.05521, 22.91743
Mboroga	Dxaaba – 948.393	-19.36879, 23.23320	-	-
Gomoti	Gomoti – 943.101	-19.54031, 23.55180	-	-

*Stations used to determine flow partition among three river systems

The water flow discharges at Crescent and Qaaxhwa on Thaoge were analysed to describe the influence of papyrus blockage at the upstream Qaaxhwa and Weboro Lagoons (Figure 2). The 'Papyrus filter' at the take-off point as well as the adjacent swamp of Maunachira was so named because papyrus grows in entangled mass and its erect culms act like pores through which the flow diffuses favouring slow deposition of sediments. The section was also called 'Smith channel' since Peter Smith, Chief Technical Officer in then Department of Water Affairs cut the link between the headwaters of Nqoga and Maunachira channels at Hamoga Island in 1973 (close to Hamoga station) to facilitate boat passage (McCarthy *et al*., 1992; Ellery *et al*., 1993; Smith 1995). The Maunachira River where the surface blockage started was named 'Smith Inflow' (SI) and its outflow at the end of the channel that closed with papyrus rafts was named 'Smith Outflow' (SO). The Khiandiandavhu Inflow (KI) channel opened only for 0.7km distance at the time of the study. Thus, KI, SI, and SO are the temporary stations introduced in October 2003 to determine the influence on the flow pattern at Papyrus filter with respect to Hamoga (H) station.

Figure 2 Expanded from Figure 1: (A) Upper Thaoge: Blocked Ikoga River with 'Emergent papyrus rafts' (aerial photograph), Crescent channel with fringe of hippo grass, 'Rooted emergent papyrus' (intermittent blockage) (Google Earth Image) from downstream GL (Guma Lagoon), (B) Middle Thaoge: Blocked with 'Emergent papyrus rafts' (Google Earth Image) up to 'Bypass channel'. CC = Cross Channel to Boro; Crescent = Crescent Island station; MT = Main Thaoge; Kgaola… = Kgaolalefatshe; QL = Qaaxhwa Lagoon; Qaaxhwa = Qaaxhwa Upstream station; RC = Relict Channels; WL = Weboro Lagoon; 'X, Y and Z' = Cut channels.



We also compared Gaenga on U/Nqoga and K/MJ on Maunachira to show whether the clogged surface blockage in between had any influence on the flows of Maunachira proper (Figure 3). Channel flow discharges at Dxaaba in Mboroga River and Gomoti station on Gomoti River were used to determine the effects of the hippo grass blockage in Gomoti River (Table 2 and Figure 4). The hydrological stations are tied with their corresponding rivers in graphical figures. The years 1984 (10780 MCM) and 2011 (13852 MCM) when Mohembo recorded above 10,000 Mm^3 inflow were selected to determine the changes in the water surface area of Bokoro and Dxerega Lagoons by using December 1984 and December 2011 Google Earth Images.

Table 2: Types of blockages with their approximate lengths in km in the rivers of the Okavango Delta, Botswana

Type of blockages	Rivers: Blockage sections	From Latitude; Longitude	To Latitude; Longitude	Length, km
(1) Rooted emergent papyrus	Upper Thaoge: Guma Lagoon (GL) to 'X' section of the channel	-18.98931; 22.39301	19.03965; 22.39887	~12.0
(2) Emergent papyrus rafts	Upper Thaoge: Ikoga	-18.81151, 22.29933	-18.93925, 22.40818	~36.0
	Middle Thaoge	-19.09938, 22.37264	-19.24536, 22.25204	~51.0
	*Lower Nqoga: Take-off point to '*1983 upper limit of blockage*'	-19.07014, 22.87861	-19.09810, 22.95065	~13.4
(3) Surface blockage debris	Maunachira: Smith Inflow (SI)	SI -19.06763, 22.88136	_	~0.2
(4) Closing papyrus rafts	Boro: Moshupatsela Maunachira: Smith Inflow (SI) to Smith Outflow (SO)	-19.10906, 22.57341 SI -19.06763, 22.88136	-19.11764, 22.59119 SO-19.05521, 22.91743	~3.5 ~6.0
(5) Hippo grass	Thaoge: Crescent channel	At intervals	_	-
	Santantadibe	-19.37608, 23.25064	-19.42493, 23.27648	~4.3
	Gomoti	-19.37522, 23.25072	-19.40652, 23.28727	~4.8

*Approximate start and end points determined using Google Earth images (not surveyed due to inaccessibility)

Flow discharge analyses

Daily inflows at Mohembo and monthly flows in other stations in $m^3\ s^{-1}$ were converted to annual cumulative MCM in Excel. Percentage (%) storage denotes the difference in volumes that probably stay between the stations in a hydrological year excluding evapotranspiration and percolation (Kurugundla *et al*., 2018). One hydrological year means the period from 1 October to 30 September of the following year, that is, year 2017 means 2016/17 hydrological year and so on. Stream discharge and water level measurements are important for understanding river-wetland relationships in long-term scales and in many cases the lack of regular monitoring is evident from data gaps.

Results and Discussion

A delta normally exhibits oscillation of alluvial channels, a permeable boundary composed of erodible sediment with vegetation, meandering belts, a free water surface, active aggradation, degradation of floodplains and sediment deposition supplied by a river channel (Bridge 2003 and Miall 2014). In the high velocity of primary channels, the vegetation (mostly papyrus and hippo grass) supports the bank stability while in the low velocity channels sedimentation in combination with vegetation could reduce the current velocity, which may be the cause for channel decline (Ellery *et al*., 1995). This decline initiates a series of mechanisms involving invasion of the channels by aquatic plants and debris, accelerating blockage and aggradation, which triggers the rate of water loss from the channels (McCarthy *et al.,* 1992). Papyrus and hippo grass that have historically invaded some channel sections of the Okavango Delta were updated in km in this study as well as their influence on in-stream flow is discussed. The four areas of channel blockages identified in 2002 in the Okavango Delta and further updated until 2018 are (Figures 1): A) = Ikoga River on the Thaoge system; B) = Middle Thaoge River from downstream Qaaxhwa Lagoon to Bypass Channel; C) = Origin of Maunachira River at Hamoga Island 'Papyrus filter' (Smith 1995) and D) = Origin of Gomoti and Santantadibe Rivers. Five types of papyrus and hippo grass blockages were categorised in the above rivers based on their growth, anchorage, habitats, and intensity of their spread in different flood regimes. All the blockage points recorded remained the same in the rivers in the period from 2002 to 2018 except in Maunachira where the blockage was extended upstream to Upper Nqoga for about approximately 700m preventing to reach the Hamoga hydrostation for regular measurements (Figure 3).

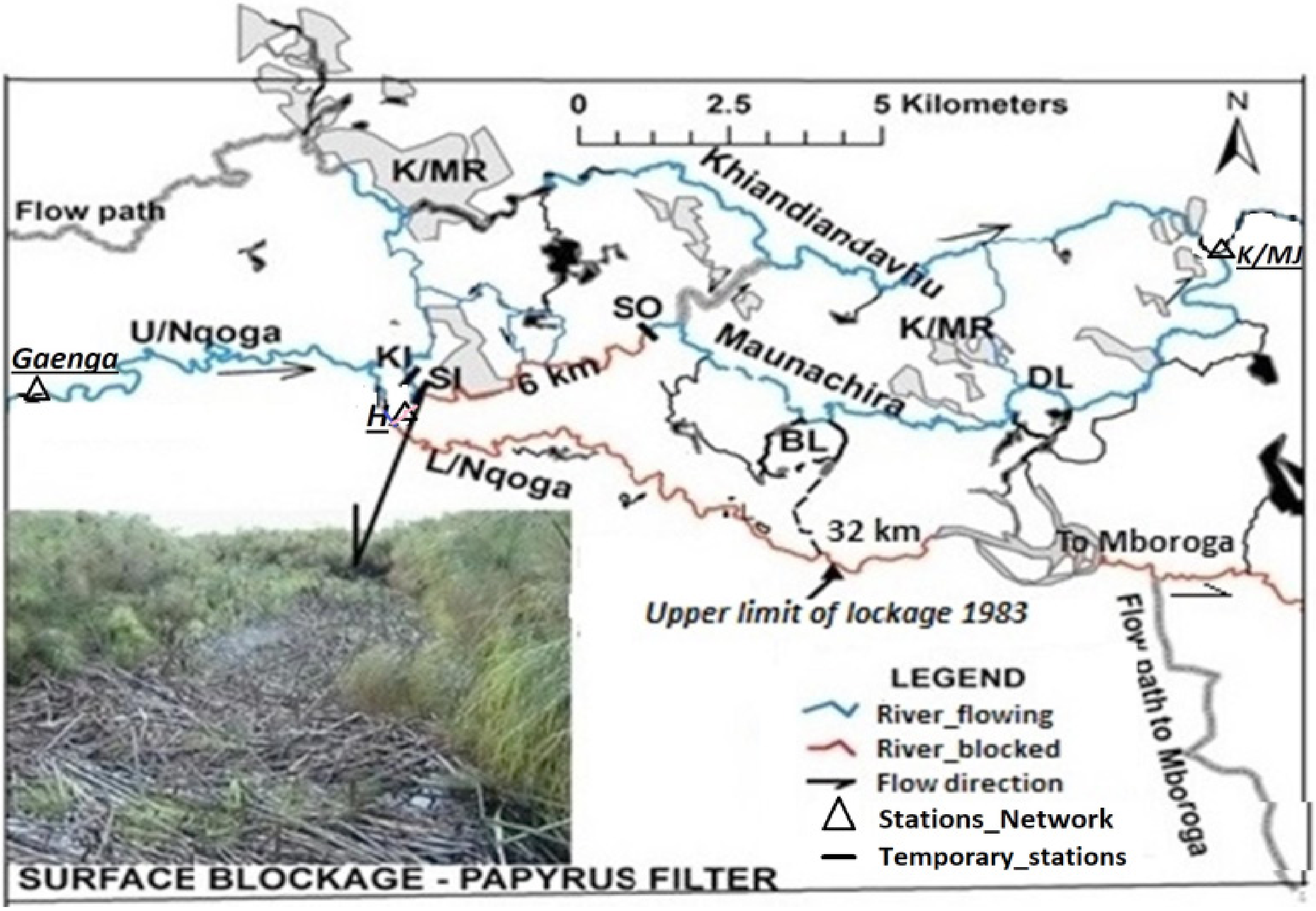
1. *Rooted emergent papyrus*

Papyrus gets rooted strongly in less velocity channel beds. This was observed intermittently from Guma Lagoon (GL) to 'X' section of the channel (Table 2, Figure 2 – Rooted emergent papyrus). Brind (1955) stated that under conditions of very low flow, a previously floating papyrus becomes rooted in the channel floor, supporting the development of permanent blockages in Thaoge River (Brind 1955; Wilson 1973; Ellery *et al*., 1993), which are a consequence and not a prior cause of reduced flows (Ellery 1988). Although the rooted papyrus is difficult to manage in the channels, DWS cleared them at frequent intervals between 1993 and 1996 in the section.

2. *Emergent papyrus rafts*

Emergent papyrus rafts are generally composed of interwoven masses of submerged rhizomes with roots hanging in the water. This occurs in Ikoga, in the middle reaches of Thaoge (Figure 2, Table 2), in L/Nqoga up to '*1983 upper limit of blockage'* (Table 2 and Figure 3) (Ellery 1988; Ellery *et al*., 1989; Ellery *et al.,* 1995). Flood diffuses through papyrus rafts and spills through the vegetated channel banks (Wolski and Murry-Hudson 2006) and floating papyrus in river fringes enables sediment deposition leading to aggradation (Ellery 1988).

Figure 3: Expanded from Figure 1 (C). Maunachira, L/ Nqoga and Khiandiandavhu Rivers. H = Hamoga hydrostation, KI = Khiandandavhu Inflow, SI = Smith Inflow, SO = Smith Outflow. BL = Bokoro Lagoon, DL = Dxerega Lagoon, K/MJ = Khiandiandavhu/Maunachira Junction, K/MR = Khiandiandavhu/Maunachira Reservoir



3. Surface blockage debris

After the clearance of papyrus rafts for a length of ~100 m in 1973 at Hamoga Island to connect U/Nqoga (Ellery *et al*., 1993, Smith 1995), the section had been navigable up to 1998. By 2000, the Maunachira from its take-off has been clogged for a length of ~0.2 km with 'Surface blockage debris' (Table 2 and Figure 3). The papyrus plants in higher water velocities get separated by elephants and hippopotami while grazing. These separated plants drift out downstream with vegetative debris and get clogged over a period in the narrow sections of rivers affecting the flows (Wietse *et al*., 2010) as observed in the study (Figure 3 and Table 5).

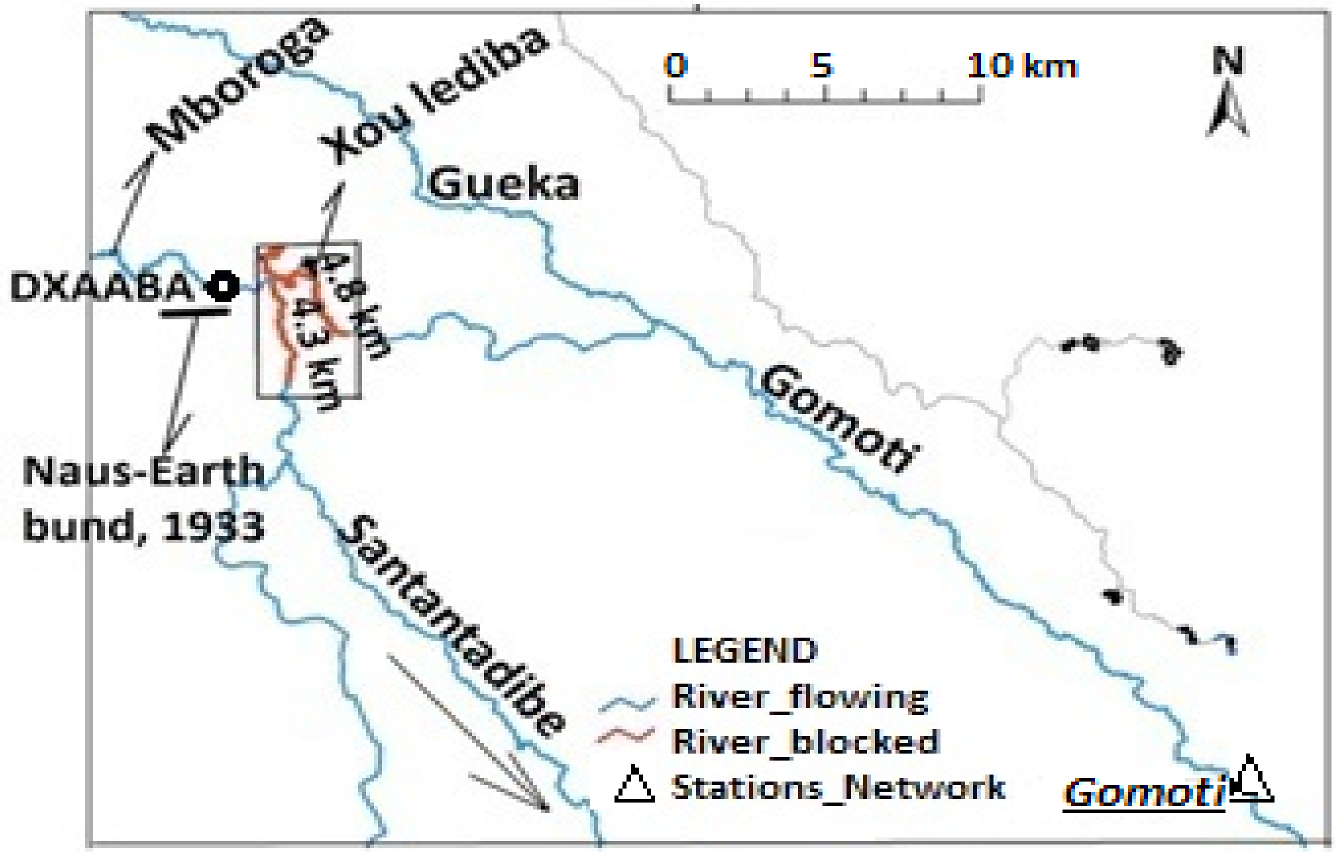
4. Closing papyrus rafts

Papyrus rafts closing above the surface channel is common in Boro River at Moshupatsela as well as in the downstream "Surface blockage debris' in Maunachira River (Figure 1, Table 2). The encroachment of papyrus was limited by a high current velocity, which forced rhizomes to oscillate backward towards the bank in high flood events while in low floods, they move to the centre of channels resulting in the channel closure (Ellery 1988; McCarthy and Ellery 1998).

5. Hippo grass

Hippo grass grows densely in the fringes of channels of less flow velocity in Crescent channel of Thaoge (intermittently), in Santantadibe and Gomoti Rivers as meadows (Table 2, Figure 2 and 4) restricting the normal flows. It was observed that the encroachment of hippo grass (Kurugundla 2003) may be replaced by papyrus overtime, and it is a symptom of channel aggradation and failure, with sustained water loss from the channel (Ellery 1988; Alonso and Nordin 2003). Comparison with avulsions described in other river systems indicates that the influence of aquatic plants in the Okavango River system is exceptionally strong (McCarthy *et al*., 1992).

Figure 4: Expanded from Figure 1(D). Santantadibe and Gomoti Rivers' blockage from their take-off points of Mboroga River



Elevation and flow partition

Elevations of the deepest channel beds (gauge zero) above msl at the flow partitioning stations of the three river systems clearly indicate that the Thaoge is more elevated than the Boro and Maunachira implying that the latter river is in low gradient while Boro is in between (Table 3). Therefore, the monthly flow discharges in each hydrological year from 2005 to 2017 (Figure 5), and mean volumes with their range in the period (Table 3) was relatively lesser in Thaoge-Crescent than in the other two flow sharing systems.

Figure 5: Partitioning of channel flows among Thaoge, Boro and Maunachira Rivers at their respective stations (see Figure 1) in relation to Mohembo inflow on Okavango River from 2005 to 2017.

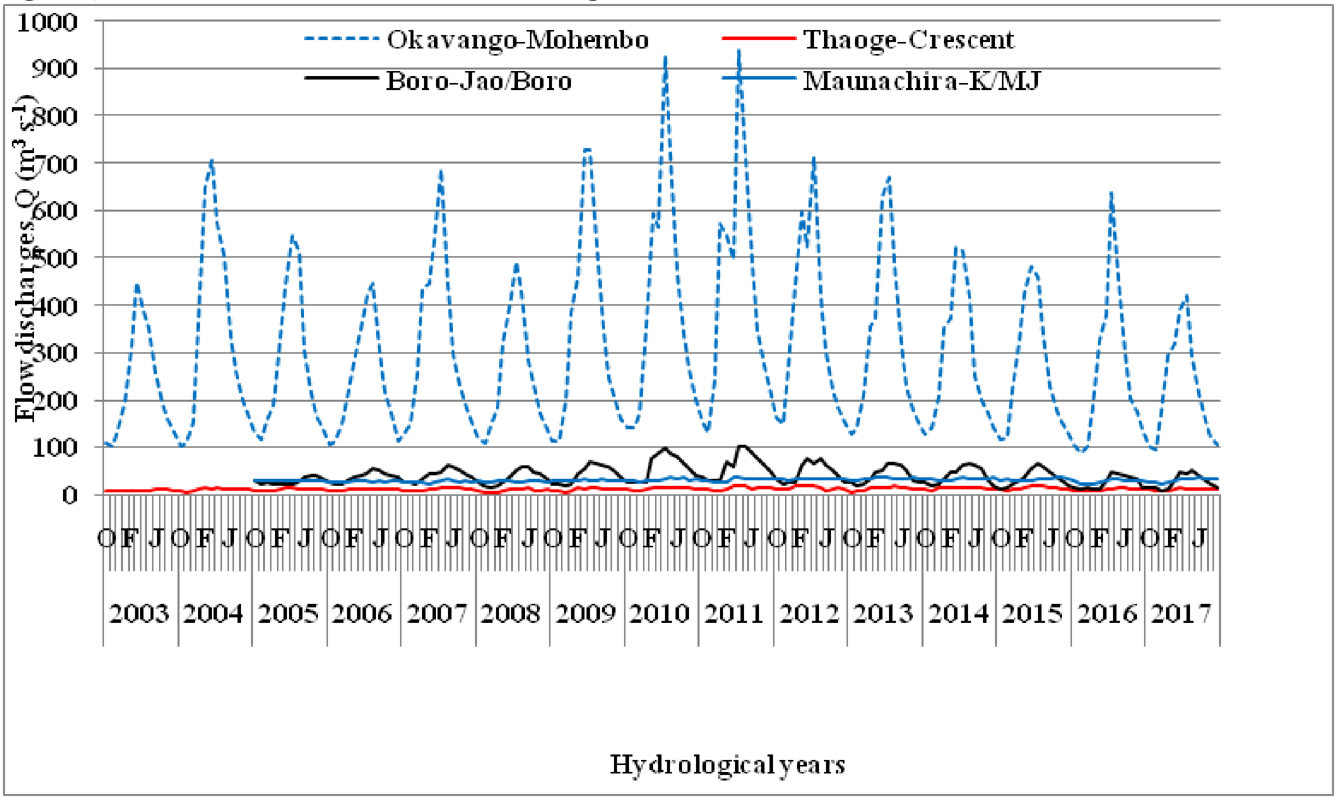


Table 3: Elevations of channel bed above msl at Mohembo, Crescent, Jao/Boro and K/MJ stations and mean flows for the period 2005-2017 with minimum to maximum flow range of discharges in the parentheses.

Measurements	Okavango-Mohembo	Thaoge-Crescent	Boro- Jao/Boro	Maunachira- K/MJ
Elevation, m	992.882	975.565	968.170	953.231
Mean flow ($m^3 s^{-1}$)	303 (86-937)	12 (5-18)	41 (9-102)	31 (24-38)

Low water levels with seasonal fluctuations in downstream of Qaaxhwa and Weboro Lagoons in Thaoge had been observed for longtime (Porter and Muzila 1989), which could have been facilitated by the establishment of papyrus blockage (Smith 1976). Thompson *et al*., (1979) reported that extensive papyrus swamps are associated with large and shallow basins. The flood peaks at Mohembo in Okavango correspond to the flood peaks of Boro River at Jao/Boro station (Figure 5). Such comparable flood peaks are the result of the southern bank spill of Nqoga River between Thaoge and Jao-Boro Rivers which arrive at Jao/Boro station as wetland flows during flood peak periods in the Okavango (Kurugundla *et al*., 2008 and 2009).

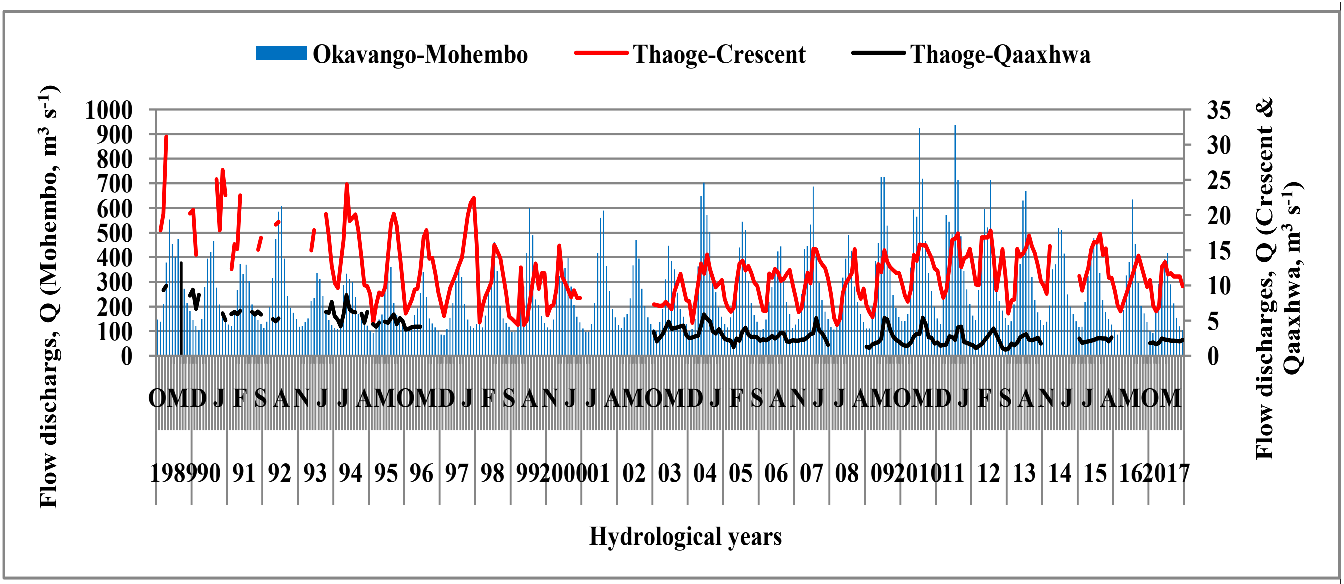
Thaoge River system

Upper Thaoge

Ikoga River, part of the Upper Thaoge, started blocking since the beginning of the eighteenth century (Wietse *et al*., 2010). Our ground surveys revealed that the 'Emergent papyrus rafts' were dense both upstream and downstream of the overflow or outflow channel from the Ikoga Lagoon as well as in the lagoon outflow section connecting to the Thaoge River proper (Figure 2). Further, our helicopter reconnaissance in 2005 and 2011 indicated that the papyrus rafts were well established in several parts of the river and small portions were still opened. Comparison of 1969 and 1983 aerial photography confirms that the blockages were progressing in the Ikoga River (Porter and Muzila 1989). A low velocity Crescent channel is fringed with hippo grass at frequent intervals (Figure 2) which could reduce the channel width and impeding flow (McCarthy *et al*., 1992; Alonso and Nordin 2003).

As shown, Thaoge River is in higher elevation above msl than the other two systems (Table 2) and is a very low relief system from upstream to midstream. The difference between Upper Thaoge-Crescent (975.565m above msl) and Middle Thaoge-Qaaxhwa (971.525m above msl) stations was 4.040m (975.565-971.525 = 4.040). Therefore, Thaoge shares lesser Mohembo inflow, and the flow average was 12 $m^3 s^{-1}$ (range = 5-31 $m^3 s^{-1}$) at Thaoge-Crescent and 4 $m^3 s^{-1}$ (range = 0.9-10 $m^3 s^{-1}$) at Thaoge-Qaaxhwa between 1989 and 2017 (Figure 6). Similar lesser % flow discharges in relation to Mohembo inflow were reported between Crescent and Qaaxhwa in 2005-2007 (Kurugundla *et al*., 2008). After all, the Delta is a low topographic gradient (1:3470) and causes low flow velocities (Anderson *et al*., 2003).

Figure 6: Monthly flow discharges at Thaoge-Crescent station (Upper Thaoge) and Thaoge-Qaaxhwa station (Middle Thaoge) compared to Mohembo.



The time series discharge data at Crescent and Qaaxhwa compared to Mohembo inflow (Figure 6) shows that the flow pattern declined systematically in Thoage from 1989 to about 2004, but after that the flows seemed to rise and then remained constant. In other words, the mean flow volumes of 178 MCM at Qaaxhwa were higher in 1989-2004 when Mohembo recorded less inflows of 7495 MCM than in 2005-2017, which had 75 MCM at Qaaxhwa but with higher inflow of 9607 MCM (Figure 7 and Table 4). Given that sedimentation, vegetation, and other factors play a role, Qaaxhwa should have received higher volumes when Mohembo had high range of inflows in 2005-2017 as compared to 1989-2004 (Figure 7, Table 4). 'Rooted emergent papyrus' at frequent intervals between Guma Lagoon (GL) and 'X' section of Thaoge appeared established right from 1999 onwards and could have considerable influence on the channel flows in 2005-2017. It must be noted that Kurugundla navigated the Thaoge River with some difficulties from Crescent channel up to Qaaxhwa Lagoon in 1999 and inaccessible afterwards. Spills onto southern fringe of the Guma Lagoon and along its downstream are probably due to 'Rooted emergent papyrus' that resulted in the flood accumulation in papyrus-reed swamps. This accumulated flood could penetrate as far as Qaaxhwa Lagoon which plays an important role in intercepting swamp flow to distribute southwards (Porter and Muzila 1989). The backing up of flows upstream Qaaxhwa and Weboro was also possible as the result of 'Emergent papyrus rafts' for ~51 km in Middle Thaoge. Despite some backups, some losses of water also would take place via surface flow to the other areas of wetlands (for instance, to the Boro River) through Cross Channel (CC, we observed significant flow in flooding events) bypassing Kgolalefatshe, which has been blocked for a long time. The channel blockages back up water in low topographic floodplains creating, in some cases, large swamps (Shankman and Smith 2004).

Figure 7: Annual cumulative volumes in Mm³ at Crescent and Qaaxhwa and % storage volumes between Crescent (Upper Thaoge) and Qaaxhwa (Middle Thaoge) stations.

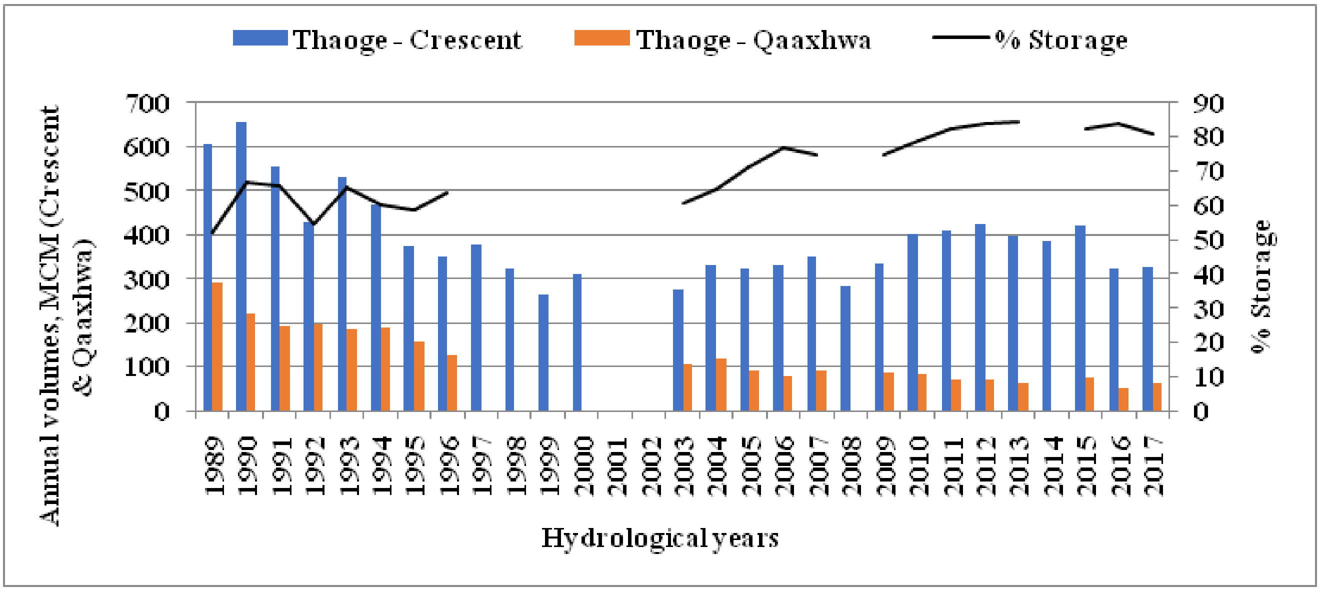


Table 4: Summary of Figure 7 showing mean flow volumes and the ranges in MCM in the periods 1989-2004 and 2005-2017 at Mohembo, Crescent and at Qaaxhwa stations.

	1989-2004	2005-2017
	Average (Min.-Max.)	Average (Min.-Max.)
Okavano-Mohembo, MCM	7495 ((5331-9945)	9607 (7034-13852)
Thaoge-Crescent, MCM	417 (262-654)	361 (281-424)
Thaoge-Qaaxhwa, MCM	178 (108-292)	75 (52-92)
% Storage between Crescent & Qaaxhwa	61 (52-66)	79 (71-84)

Extreme end of Upper Thaoge and Middle Thaoge

The lower most Upper Thaoge had been phenomenally changed since 1970s. The main Thaoge (MT) River (Figure 2,) between Xhamu and Weboro Lagoons has been totally blocked by 'Emergent papyrus rafts' since long time ago (Wilson 1973). The connecting cut section 'X' (~2 km) between the main Thaoge and Qaaxhwa Lagoon was opened by tourist operators after 1980s, did not exist in the 1969 and 1983 aerial photographs (Porter and Muzila 1989) and this was reconfirmed with the aerial photographs and Google Earth images in the study. In effect, the 'X' section has not changed since its creation, and it acts as the main supply to the Middle Thaoge passing through Qaaxhwa and Weboro Lagoons. By scanning the Google Earth images from 1969 to 2002, it is evident that the section 'Y' (Figure 2) was clearly visible in the 1995 Google images and is believed to have been cut by tour operators before 1994 for *mokoro* (canoe) use. The cut section 'X' was freely navigable while the cut section 'Y' has been under regular management by DWS to reach the data collection platforms in flood events. A small cut channel, 'Z' (Figure 2) was also opened to the east of the Xhamu Lagoon for safari operations, and it was conveying 6.4 m^3 s^{-1} from the Thaoge to Kgaolalefatshe (Porter and Muzila 1989), which finally resulted into a Cross Channel (CC) by 2002 as the result of continuous motorboat navigation from Khamu Lagoon to Boro River. The connecting channel between Qaaxhwa and Weboro Lagoons was navigable and had a strong flow prior to 1989 (Porter and Muzila 1989), but papyrus developed in due course. This was cleared by Mopiri Camp (Figure 2) in 2014 (Personal Communication with Manager, Mopiri Camp, January 2019) and is navigable now. Presently, the CC (Figure 2) is being continuously used and maintained by DWS to reach data collection platforms, as well as by tour operators and communities for tourism activities. Thaoge has been ever changing since 1880s. For example, until 1850, Middle Thaoge used to convey large volumes of water to Lake Ngami (Shaw 1983; Kurugundla *et al*., 2018), but ceased to flow into the Lake from 1880 (Wilson 1973) and the papyrus got stabilised by the twentieth century (Porter and Muzila 1989; MaCarthy *et al.,* 1992). Therefore, we believe that ~51 km stretch of Middle Thaoge is completely dominated by 'Emergent papyrus rafts' in shallow water levels and water seeping through the swamp only in flood events.

Lower Thaoge

Towards the end of Middle Thaoge close to 'Control Gates' of the 'Bypass channel' (Figure 1 and 2) there exists marshy peats, which on drying resulted in nutrient rich areas that favor forage resources for cattle (Ellery *et al.,* 1989). The communities also cultivate sugarcane, tropical fruits, and vegetables in these areas because of the elevated soil fertility (Kurugundla 2003; Alonso and Nordin 2003). Further downstream, the river is opened towards Tubu village in high flood events and rarely flows beyond Tsau as observed between 2009 and 2012 (Figure 1). The 'Bypass channel' dug by DWS from the Thaoge River in Qurube area to Gumare village (~17 km) for irrigation of 500 hectares and for Gumare water supply (Scudder 1993) (Figure 2) was a failed project as the blocked Middle Thaoge could not supply sufficient flood to Lower Thaoge.

The papyrus blockage removal and management of Thaoge River undertaken between 1930 and 1960 is documented in Wilson (1973). The recurrent blockages in Thaoge were cleared by DWS, safari Operators and local communities from 1993 to 1996, in 2003 and in 2007 (Kurugundla 2003). We conclude that the length of the blockages in km (Figure 2) is the testimony of the present-day condition of hippo grass, papyrus, and other vegetation diversity in the Thaoge River.

Nqoga-Maunachira-Khiandiandavhu system

The Okavango-Nqoga River is ~100 m wide for a length of ~270 km from Mohembo, and it gets progressively narrow downstream at Hamoga Island. McCarthy *et al.,* (1991) reported that most of the incoming bed-load depositions occur on the upper portion of the fan in a meandering and anastomosed channel system, but on the mid-fan, deposition of bedload occurs by channel-bed aggradation, at a rate of up to 5cm yr^{-1}. Therefore, it is believed that apparent gradual rise in water level could be expected at Hamoga Island by the deposition of bedload and for this process Ellery (1988) conceptually proposed a model by combining sediment deposition and vegetation growth to account for the blockage and abandonment of L/Nqoga.

Flow distribution to KI (340.8 MCM) was relatively higher spilling northwards than to SI (176.3 MCM) of Maunachira where the clogged 'Surface blockage debris' (~0.2 km) might obstruct the stream flow with respect to Hamoga station (597.8 MCM)(Table 5). A marginal difference in flows at SI and SO in 2004-2006 (Figure 8 and 9) with a mean loss of 1.2% in the period between SI and SO in a length of ~6 km was insignificant indicating likely standing water in the swamp section. The loss of 13.5% between H and KI+SI in a length of less than ~600m (Table 5) provides active distribution of flows with likely rise in water levels at Hamoga Island swamp area. A difference in water level of approximately 1.5m across the small island was evident at the time of excavation and clearance of papyrus triggered the rushing of water from the Upper Nqoga into the eroded wide channel (McCarthy *et al.,* 1992). This channel still exists,and it is closed now but rise in water levels would be a recurrent phenomenon. The mean volumes of 57% at KI (Table 5) were relatively directed to the northern floodplains being added to the oncoming north bank spills of U/Nqoga (Flow path, Figures 1 and 3) and consequently redirected to Maunachira River (Wolski *et al.,* 2005). The flow variations in blocked channels have a large effect on the morphology and dynamics of rivers (van Dijk *et al.,* 2013; Vesipa *et al*., 2017). The KI channel width was higher (15.0m) than SI (6.1m) concurs with higher flows at KI while the difference in depth at SI (4.7m) and SO (2.8m) was evident showing the topography of Maunachira River (Table 5). One-dimensional, steady-flow model used by Macrcinkowski *et al.,* (2018) showed that there is an influence of macrophytes on water flow distribution during the whole year.

Figure 8: Monthly flow discharges at Upper Nqoga-Hamoga station (H), Khiandiandavhu Inflow (KI), Smith Inflow (SI) and Smith Outflow (SO) on Maunachira River compared to Mohembo inflows. Khiand. = Khiandiandavhu.

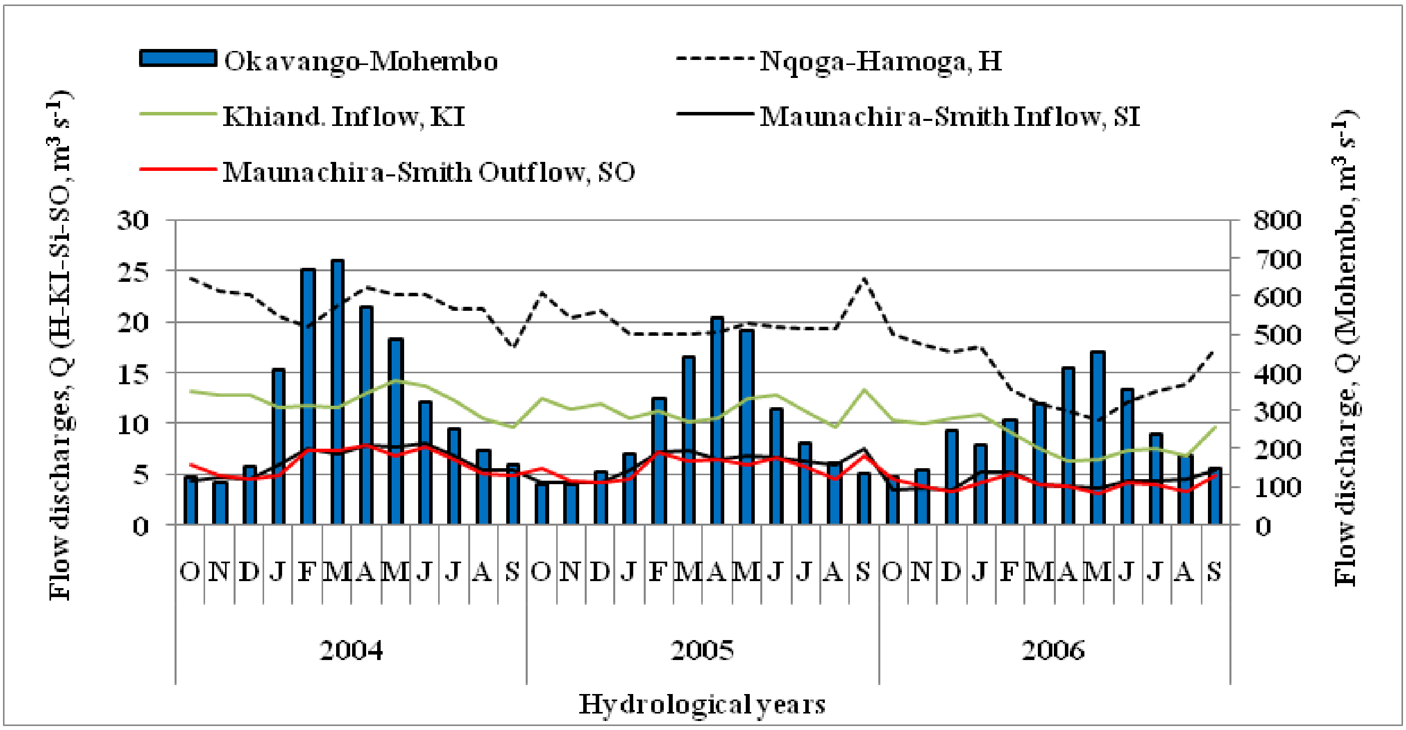


Figure 9: Mohembo inflow and comparative analysis of the cumulative volumes recorded at the blocked points of Nqoga-Maunachira-Khiandiandavhu section in 2004, 2005 and 2006 hydrological years. Khiand. = Khiandiandavhu.

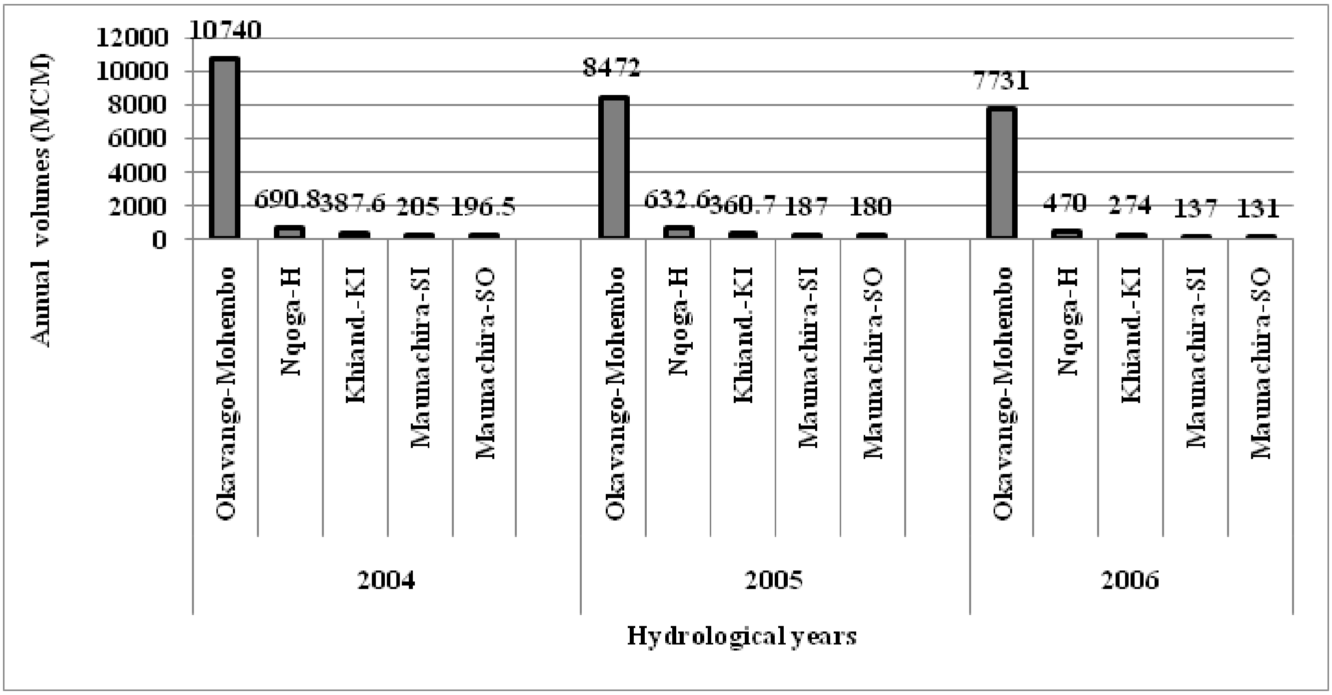


Table 5 Summary of Figure 9 showing average volumes of 2004, 2005 and 2006 hydrological years at the blocked points of the stations on Nqoga-Maunachira-Khiandiandavhu section with respect to Hamoga flow volumes; also, the mean width and depth of the channels at the stations. (Khiand. = Khiandiandavhu).

Years - 2004, 2005, 2006	**Hamoga-H**	**Khiand. Inflow-KI**	**Smith Inflow-SI**	**Loss in flow between H & (KI+SI)**	**Smith out-flow-SO**	**Loss in flow between SI & SO**
Mean volumes, MCM (%)	597.8 (100%)	340.8 (57.0%)	176.3 (29.5%)	597.8-(340.8+176.3) = 80.7 (13.5%)	169.2 (28.3%)	(29.5%-28.3%) = (1.2%)
Mean width/depth, m	12.0/5.6	15.0/4.7	6.1/4.7	-	6.2/2.8	-

Monthly flows at Gaenga seem relatively constant from 2003 to 2011, after which flows declined consistently. Nevertheless, the monthly flows and annual cumulative volumes in MCM at K/MJ show relatively marginal increases from 2013, which could be the result of antecedent flood above 10,000 MCM recorded in 2009-2013 (Figure 10 and 11). Thus, Maunachira-Khiandiandavhu section can hold large quantities of incoming flows in large ponds and pools in high flood events, hence called K/MR (Khiandiandavhu/Maunachira Reservoir) as shown in Figure 3. The losses in volumes were relatively less in a distance of ~37.4km between Upper Nqoga-Gaenga and Maunachira-K/MJ (Figure 11). Our data, therefore, confirms that the Papyrus filter in Maunachira did not significantly affect the water transfer between U/Nqoga and Maunachira Rivers because of the support of the Khianadiandavhu Channel and K/MR which sustain the Maunachira-Khwai flows. Similar flow relationships between Khiandiandavhu and Maunachira were reported by Smith (1995) and in later periods by Ellery *et al.,* (1993) and Wolski *et al.,* (2005).

Figure 10: Monthly flow discharges at U/Nqoga-Gaenga and Maunachira-KMJ between 2005 and 2017 compared to Mohembo inflow.

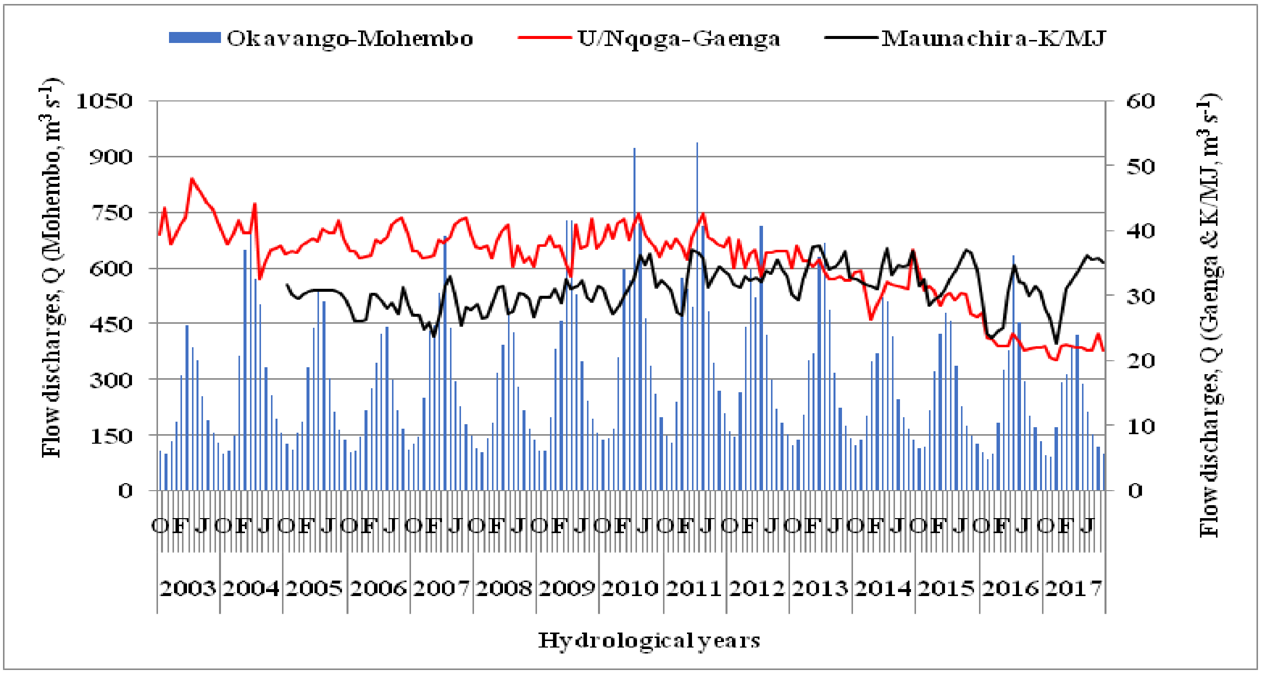
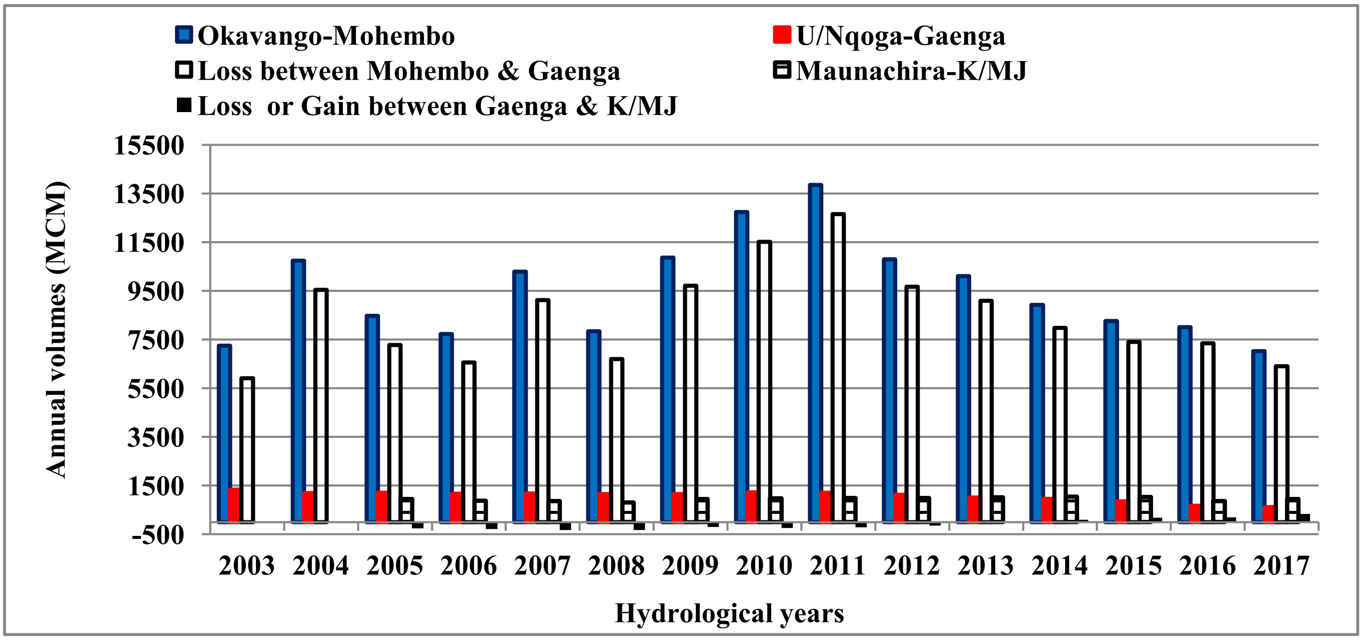


Figure 11: Annual cumulative volumes at Okavango-Mohembo, U/Nqoga-Gaenga, Maunachira-K/M Junction with losses between Mohembo and Gaenga; losses and gains between Gaenga and K/M Junction



Source: Google Earth

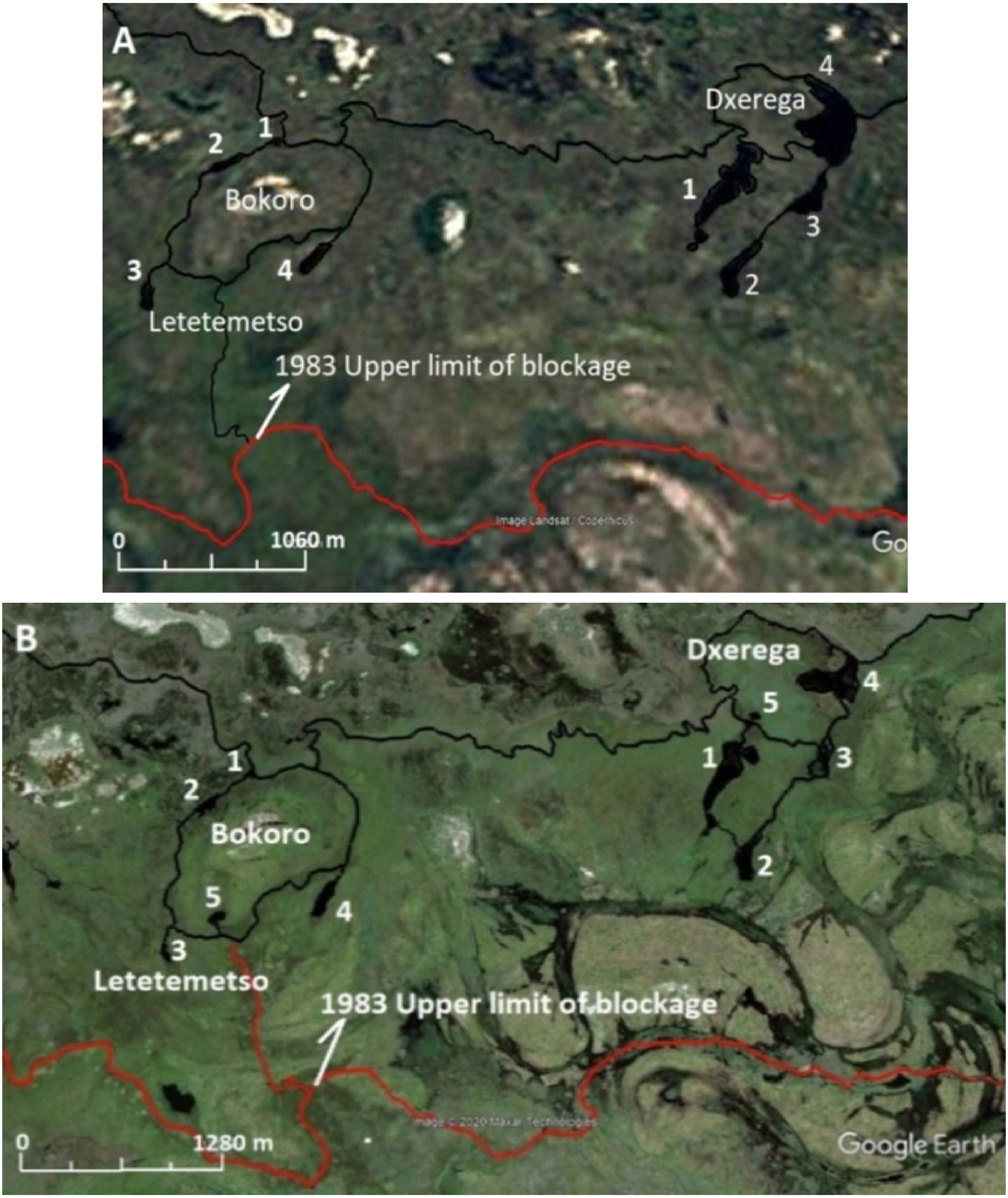
Numerous hydraulic models have been developed to understand and quantitatively assess the influence of instream macrophytes on channel's hydraulic dynamics (Marcinkowski *et al*., 2018). The models of the Delta developed by Dincer *et al*., (1987); Scudder *et al.,* (1993); Gieske (1997) and others have helped to explain the flow distributions in the Delta. However, simulations for channel papyrus clearances using a large-scale (1km^2 grid) coupled surface water/groundwater model (Bauer *et al*., 2006) in the Nqoga area suggested increased floods in the Maunachira-Khwai systems whereas the Boro system loses water. In the scenario of non-clearance of blockages, water levels usually rise and redistribute into the Boro system while the downstream Khwai and most notably the Santantadibe regions lose a significant amount of water. Through MIKE SHE-Mike 11 model, the clearance of blockages in Maunachira showed that the normally flooded zone at papyrus filter were reduced by an average of 0.17m, while the downstream water levels in the rarely flooded zones of Khwai and Santantadibe areas increased by 0.11m (Okavango Delta Management Plan, ODMP 2006). Such redistribution of water in flat topographic deltaic systems is a common feature (Allanson *et al*., 1990).

The lagoons normally could display full capacity when inflow at Mohembo records above 10,000 MCM annually. The years 1984 and 2011 that recorded inflow of 10780 MCM and 13852 MCM respectively showed phenomenal changes in water surface area of Bokoro and Dxerega Lagoons on Maunachira River. These two lagoons exhibit channel like features linked to distinct water bodies. There were four water bodies in Bokoro and Dxerega Lagoons in 1984 but they increased by one in each lagoon in 2011, thus making a total of five water bodies (Figure 12A and B). The Letetemetso channel that was opened to L/Nqoga in 1984 from Maunachira (Figure 12A) is currently blocked (Figure 12B). From 1984 to 2011, the surface area of water bodies 2 and 3 in Bokoro Lagoon were reduced by 40.3% and 72.7% respectively while water bodies 1 and 4 in Dxerega Lagoon were reduced by 43.6% and 57.8% respectively with overall reduction of 28.73% and 45.23% (Table 6). Ellery (1988) reported the surface area reductions for water bodies of Dxerega Lagoon: water body 4 reduced by 27% while 1, 2+3 together shrunk by 3% and 7% respectively from 1969 to 1983. These gradual shrinkages have been due to vegetation debris load carried directly from the inlet main channel as well as papyrus growth expansion into the water bodies over a course of time (Ellery *et al*., 1993). The cross-link of the Dxerega Lagoon was not seen in 1984 (Figure 12A) however, appears developed in 2003 and established in due course (Figure 12B). Papyrus encroachment leads to a reduction in open water bodies in many African lakes (Thompson 1985). Kurugundla reached 1 and 2 water bodies of Bokoro Lagoon and 1, 3 and 4 water bodies of the Dxerega Lagoon in the June 2006 survey.

Table 6: Surface water area measurements of Bokoro and Dxerega Lagoons using Google Earth Images

Water bodies	**Bokoro Lagoon**			**Dxerega Lagoon**		
	December 1984	**December 2011**	**% Reduction of independent water bodies**	**December 1984**	**December 2011**	**% Reduction of independent water bodies**
1	0.254	0.196	**22.8**	10.439	5.888	**43.6**
2	1.505	0.898	**40.3**	3.785	2.867	**24.3**
3	0.921	0.251	**72.7**	3.371	3.133	**7.1**
4	1.786	1.612	**9.7**	19.395	8.190	**57.8**
5	**-**	0.226	**-**	**-**	0.189	**-**
Total area, hectares	**4.466**	**3.183**	**-**	**36.99**	**20.261**	
Overall area reduction (%)	**4.466-3.183 = (1.283*100/4.466) =28.73**			**36.99-20.261 = (16.729*100/36.99) = 45.23**		

Figure 12 Bokoro and Dxerega Lagoons of December 1984 (A) showing 4 water bodies and December 2011 (B) with 5 water bodies extracted from Google Earth.



Source: Google Earth (2021)

The blockages in Maunachira were cleared by the DWS from 1994 to 2003, in 2005 and 2006 in Hamoga Island and upstream SO blockage point was located by Kurugundla (2003). Kurugundla navigated the entire Maunachira River on 2 April 1998 from Maunachira to U/Nqoga but failed in 2006 because of the blockage consolidation.

Maunachira-Mboroga-Gomoti Rivers

Maunachira River spills onto Mboroga River which bifurcates into Gomoti and Santantadibe Rivers, both blocked at their origin (Figure 4). Santantadibe is a floodplain-induced river with hippo grass and Gomoti River is blocked with vegetation debris and floating papyrus at its origin.

Gomoti was regarded as a major channel system to the Thamalakane River in the early nineteenth century (Stigand 1925), then it suffered a dramatic decline in water flow due to blockages in the 1960s and has been mostly seasonal after 1970s (Wilson 1973). The flow volumes in MCM were higher in Gomoti-on-Gomoti River than at Dxaaba-on-Mboroga River (Table 7) which could be attributed to Gueka that presumably emerged in the 1980s as an important major channel supplying flood to Gomoti River sourcing from the Mboroga upstream (Porter and Muzila 1989). The Santantadibe River last flowed into the Thamalakane in 1979 (Mpho 2004) and scarcely flowed in 2011.

Table 7 Cumulative volumes in MCM at Okavango-Mohembo, Mboroga-Dxaaba, Gomoti River-Gomoti with percentage volumes arrived at Dxaaba, Gomoti and gains in volumes at Gomoti compared to Dxabba.

Hydro-year	Mohembo-MCM	Dxaaba-MCM	% volumes at Dxaaba	Gomoti-MCM	% Volumes at Gomoti	% Gains in volumes at Gomoti
2006	7726.1	76.14	0.99	141.02	1.83	+0.84
2007	10297	65.54	0.64	*18.23	*0.18	*0.46
2008	7835.6	74.2	0.95	86.2	1.10	+0.15
2009	10858	74.6	0.69	104.3	0.96	+0.27
2010	12786.5	73.4	0.57	216.6	1.69	+1.12

*Irregular data collection at Gomoti in general, but more pronounced in 2007. No data after 2010.

Naus constructed an earth bund of ~320m length by ~4m height in December 1933 (Lat.19.38843, Long.23.22663) in Dxaaba (Wilson 1973) to dry out and burn the blocked vegetation in the downstream (Figure 4). Our surveys to this area are regarded as a minor blockage area where several blocked ‘outlet channels’ are found to connect the Santantadibe and Gomoti Rivers. The channel blockage played a part in the desiccation of Gomoti, and water levels declined right from the 1930s in Gomoti and Santantadibe (Wilson 1973; Bernard and Moetapele 2005). These declines were a result of the failures of the L/Nqoga with its junction of Mboroga (McCarthy *et al.,* 1991 and 1992) and Lower Thaoge and Santantadibe dried due to blockages by debris and papyrus (Wolski and Murray-Hudson 2006). Wilson (1973) suggested that the vegetation blockages in the Okavango system are inevitable, and we do not need to postulate climate changes or the interventions of man to account for them. We agree with the assertion that sedimentation causes channel elevation favouring blockage formations, which are the symptoms in the Delta (Wilson 1973; McCarthy *et al*., 1986; McCarthy and Ellery 1997).

We suggest that the indigenous management activities such as burning of vegetation in drying channels and continuous clearing of small blockages as employed by local communities, safari operators and DWS are the best practice for channel maintenance in the Okavango Delta.

Conclusion

We conclude that papyrus can grow as rooted emergent, floating emergent rafts, surface debris material resulted in blocking the channels that impede normal flow in the channels. Hydrological data at the critical points of blockages in Thaoge and, Maunachira indicate that papyrus might not influence the channel flow, except at the Qaaxhwa and Weboro section of Thaoge where papyrus holds certain volumes of water despite some flows diverting to Boro system.

The study confirms the predictions of McCarthy *et al.,* (1986) that the Santantadibe River would dry from its terminal end because of the dying of the L/Nqoga while Maunachira could be activated with the flow supply via Khiandiandavhu channel, which is true today as the latter has become a primary channel to Maunachira River. Blockages impact river navigation resulting in poor data collection at few hydrostations, the use of channels by the tourists' and community could affect the socioeconomics.

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