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ARTICLE

Multi-Temporal Analysis of Avulsion and Channel Dynamics: A Case Study of the New Channel in the Kwando River, Botswana

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Abstract

Channel modifications and avulsions through time and space have a big impact on how streams flow and how wetlands develop. The objective of this study is to identify the factors that cause the Kwando channel to avulse in Botswana territory and to explain the spatiotemporal sequences that accompany this movement. The study, which was conducted in 2016, used Garmin-GPSMap 62S to collect the coordinates of the split New Channel from the trans-boundary Kwando River's west bank. By looking through the Google Earth photographs from 1985 to 2017 on a desktop computer with the selected images from July 1985, May 2002, December 2011, December 2013, and December 2017, the multi-temporal fluctuations in the New Channel spatial position are given and discussed. The map was created using ArcMap GIS 10.2 relying on field-tracked coordinates that are comparable to the well-defined New Channel for approximately 45km. The formation of the New Channel might be linked to three factors: i) 547mm of above-average rainfall between 2004 and 2015; ii) increased inflows into the Kwando River between 2008 and 2015, and iii) the presence of paleochannels and flood plain sloughs in the system. According to analyses of historical Kwando River flow data series, 51% of inflows in 1986–1994 travelled to Shummamorei station whereas 53% of inflows in 2017–2020 went to James Camp station on the New Channel, indicating that a sizeable portion of Kwando River flows were diverted to the New Channel. Between 1995 and 2010, channel blocks and aggravation forced the flow to be diverted to the Linyanti Swamp by bank spill, which disrupted the flow pattern at Shummamorei. The New Channel has an impact on the outflow rivers, Savuti and Selinda Canal. The New Channel is concentrated on downstream wetlands in Botswana and might have an impact on the Linyanti Swamp region in Namibia.

Keywords: Avulsion; Bates inflow; James Camp; Kwando River; New Channel; Linyanti Swamp

Introduction

Avulsion is the process by which flow from an existing channel is diverted onto a nearby floodplain or fan surface, eventually creating a new channel belt. Avulsions can be created by humans in addition to being natural (Pierik *et al*. 2018). According to Slingerland and Smith (2004), avulsions can sometimes cause fatalities and property damage that affects millions of people in fluvial and deltaic-coastal ecosystems. For instance, the Yellow River in northern China has experienced seven significant eruptions in its approximately

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2000-year history, each of which affected 250,000km^2 and disrupted the lives of 8–14 million people by causing fatalities and property destruction over that period (Soong and Zhao 1994). Avulsions, however, may also be advantageous for expanding wetlands that have been the focus of theoretical and experimental investigations (Stouthamer and Berendsen 2001; Edmonds *et al*. 2009; Hoyal and Sheets 2009) and opening up new shipping routes.

Sediments are important in the channel avulsions, and bifurcations disseminate both water and sediment. Increased sediment input from the catchment causes a significant rise in avulsion frequency in the Late-Holocene Rhine-Meuse Delta, and crevasse-splay complexes are composed of sandy substrates that encourage scour and avulsions (Aslan *et al*. 2005; Gouv and Erkens 2007). Crevassing and avulsions were more frequent upstream than downstream in the upper Columbia River in western Canada as a result of an excessive bed-load input (Abbado *et al*. 2005; Makaske *et al*. 2001 and 2009). The terrain, sedimentation, water table, elevation, vegetative cover, resistance to erosion, and existence or absence of pre-existing channels are only a few of the variables that affect the amount of avulsion floods and subsequent channel construction (Bristow 1999). Avulsion can be brought on by tectonic activity either immediately by earthquakes or gradually by changes in river and floodplain gradients (Jones and Schumm 1999; Stouthamer and Berendsen 2000 and 2001). Although it only involves a little amount of displacement, neotectonic movement is thought to be the primary factor in the Okavango Panhandle's avulsion (Smith *et al*. 1997).

The majority of alluvial low-relief rivers have overbank flooding which happens sporadically when the bank full discharge is surpassed. Sediment deposition, which can fill or obstruct the channel and force the flow to forge a new path, or bank erosion, which will cause the flow to be diverted, are two possible causes of channel avulsion (Kleinhans *et al*. 2008). Avulsion happens when there is an imbalance between the sediment load and sediment-carrying capacity of two bifurcation channels. According to Singherland and Smith (2004) and Kleinhans *et al*. (2008), erosion or deposition in one or both channels may alter the discharges, slopes, and cross sections of the channels, hence altering the flow capacities.

The system as a whole includes river adjustments, which are cumulative responses to flow-related events (Brierley and Fryirs 2005). Although they are frequently visible in the Okavango Delta (Kurugundla 2021), such river changes have not yet been noted in the Kwando-Linyanti River system, which borders Botswana and Namibia. The river channel winds and meanders inside the flat topography floodplains, shifting back and forth through time. According to local studies (Corenblit *et al*. 2007; van Dijk *et al*. 2013), riparian vegetation improves bank resistance, combats bank erosion, and reduces channel migration, which results in erosion at sharper bends. The current study demonstrates how the running water, slope, and path of least resistance in Botswana land have been taken into account in the development of a 'New Channel' as a bifurcate from the west of the Kwando River by relying on the existing alluvial land structure and behaviour of water flows.

The outside bends or meanders often create high water speeds before becoming weaker. Over time, the channel shifts laterally, strengthening one side while degrading the other. Due to the river's natural desire to follow the downstream path of least resistance, bends enlarge until they are completely blocked off by new channels (Nelson 2015). Long-term observations of the creation of new channels and the widening of streams that have been there for a long time into larger channels have been made in a number of wetlands, including the Okavango Delta (Porter and Muzila 1989; McCarthy *et al*. 1992).

Recent field research employing modelling and the application of satellite imagery have identified the reasons of avulsion. This essay discusses how the trans-boundary Kwando River's west bank in Botswana helped build the New Channel. Second, we looked into how the New Channel's avulsed flows differed from the main Kwando River's historical flow data. The hydrology of the Kwando-Linyanti River system has not received as much research as the Okavango Delta.

Materials and Methods

Study area

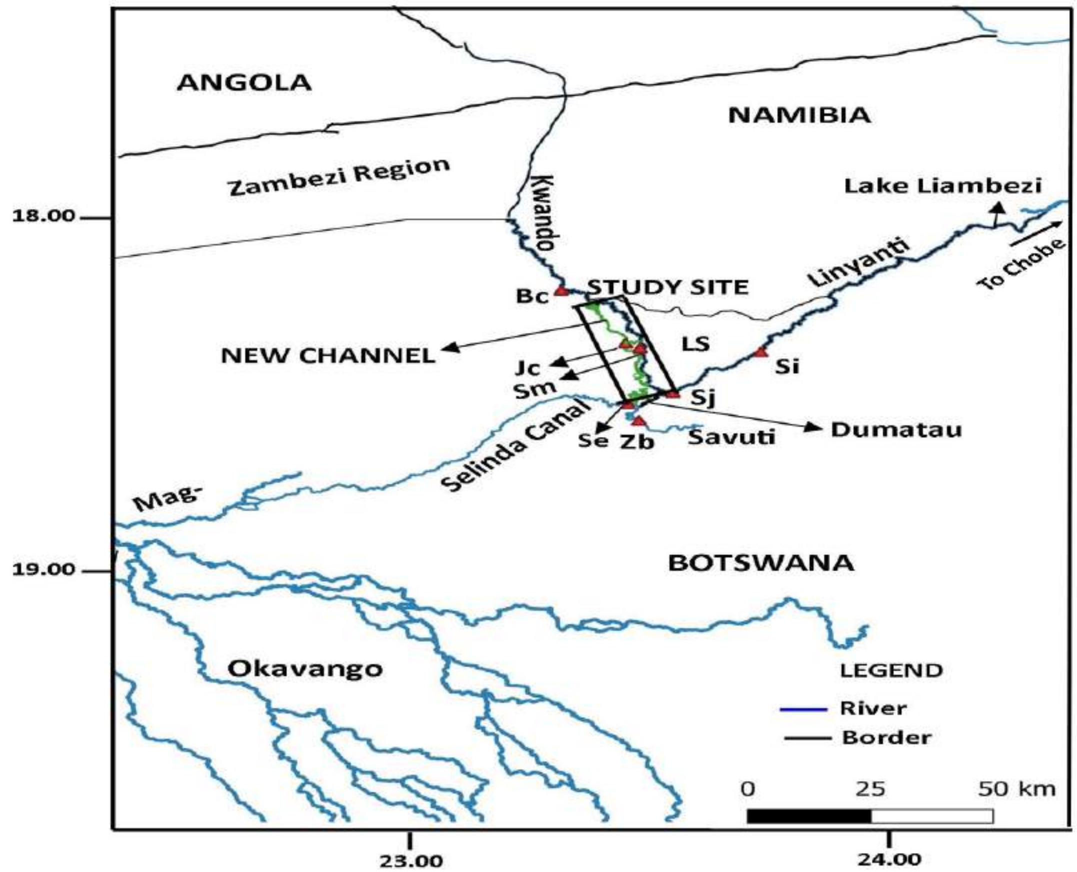
The Cuando River, as it is known where it originates in Angola, rises in Angola's central plateau and flows along the country's border with Zambia before turning southeast (Figure 1). Over this portion, it travels via a system of channels in a swampy corridor that is 5–10km wide. Following its south-easterly course, the Cuando forms the border between Namibia and Botswana after crossing the Zambezi Neck (formerly known as the Caprivi Strip until 2013). The Linyanti River receives the Kwando River's discharge before it is diverted east to the ephemeral 'Lake Liambezi' where the Chobe River joins the Zambezi River close to Kazungula. A series of cross-flow canals link the Linyanti Swamp (LS) in Kwando (Lat. -18.223680, Long. 23.920750) and Linyanti (Lat. -18.236000, Long. 23.457800). The system's southernmost points, however, the Dumatau and Zebadianja Lagoons in Botswana, were made by Kwando and Linyanti. A portion of the Kwando River and the New Channel in Botswana are included in the study area (Figure 1). If the Kwando/Linyanti Rivers' flow paths change, disputes over trans-boundary and water-sharing concerns between Botswana and Namibia may develop.

The Okavango River's Magweqgana (Selinda Spillway) spilled to the Linyanti River via the Selinda Canal nearly 30 years later, between 2009 and 2013, when Mohembo inflows were above 10,000 annal million cubic meters (MCM) (Kurugundla *et al*. 2018). This linked the Okavango, Kwando, Linyanti, and Chobe basin river systems. The catchment area for the Okavango River system begins in central Angola's Bihe Plateau, while the Kwando River starts on Mount Tembo's mountainside. The Zambezi River originates in the Mwinilunga District, northwest region of Zambia.

James Camp since 1986

James Camp is accessible via a bridge that the Botswana Defence Force (BDF) constructed in 2019 and is situated near the riparian margins of the New Channel (Figure 1). The Department of Water and Sanitation (DWS) of the Kasane Regional Station has used the Camp as a base facility since 1986 to monitor the hydrological and biological control of the Kariba weed *Salvinia molesta* Mitchell and water lettuce *Pistia stratiotes* L. James Camp was inaccessible between 2009 and 2015 as a result of severe flooding in the Kwando River, which was aided by above-average rainfall (an average of 509mm) during that period. As a result, there was no hydrological data collecting for the Kwando River from October 2010 to September 2016. When the upstream Kwando River was finally accessible in September 2016, the DWS team discovered a well-defined channel or river that was about 12m wide and was located to the west of the James Camp. This significant finding led to the tracking of the Kwando River's New Channel in order to determine its origin and create hydrological scenarios from its bifurcation.

Figure 1: 'Study site' is on the Kwando River - Bc - Bates Camp (Bates), James Camp on the New Channel, Sm – Shummamorei, Se - Selinda, Zb – Zibadianja just after the Zibadianjia Lagoon, Sj - Sajawa and Si - Simaa. LS = Linyanti swamp.



Tracking the New Channel

Two surveys were conducted at the research site location (Figure 1) while an air boat was used to monitor the New Channel. On 20 July 2016, the New Channel was tracked from 'James Camp' to an upstream 'Bates Camp station' (hereafter referred to as 'Bates'). On 12 October 2016, a second survey was completed that followed the 'New Channel downstream from James Camp' all the way to its confluence with the Kwando River. A log of the coordinates was created throughout the tracking using the Garmin GPS-Map 62 series.

Historical channel avulsion: A desktop study

Google Earth images from 1985 to 2017 were visually analysed on a desktop computer covering the Study site (Figure 1). The images from July 1985, May 2002, December 2011, December 2013, and December 2017 were picked for examination because they showed the 'New Channel's' significant development in terms of its multi-temporal changes and spatial position. Since there were no additional channel paths in 1985, it served as a benchmark for how the additional New Channel would develop in the selected years. The 2016 field-collected point coordinates for the fully completed New Channel in 2017 were combined with ArcMap GIS 10.2 Desktop to develop a map. The size of the 'Small lagoon' in July 1985 and its relative expansion into the 'Big lagoon's size in December 2017 at the New Channel origin were also depicted using Google Earth pictures. Pictures taken in May 2002, December 2010, December 2013 and December

2017 were used to identify and characterise the New Channel (channel commencement, evolution, and geographical position) in the James Camp area. We estimated the size of the wetland and its delineation in the region from the point of the 'Big lagoon' along the New Channel and up to the 'Dumatau-Selinda Canal' in Botswana from the Google Earth images taken in July 1985, May 2002, December 2011, December 2013, and December 2017.

Data use, hydrological measurements and analyses

As of 2016, there were 23 stations in the hydrometric network of the Kwando/Linyanti River. Seven of them were either abandoned or difficult to access due to vegetation barriers and, therefore, they were not in use. The stations chosen for the hydrological assessments between 1986 and 2020 are listed in Table 1. In October 2016, Selinda station on the Selinda Canal was restored, and a new station called 'James Camp' on the New Channel was launched (as it is close to James Camp). The stream flow discharges in cubic metres per second (m^3/s) were computed using a current metre and the two-point technique (World Meteorological Oganisation 2010). When employing the two-point method to assess velocities, observations are made in each vertical at 0.2m and 0.8m below the water's surface at predefined interval lengths across the river. The average of these two statistics is then used to calculate the mean stream velocity.

Table 1: Selected hydrometric stations on Kwando/Linyanti Rivers for hydrological analyses from 1986 to 2020.

Rivers	Stations	Longitude, E	Latitude, S
Kwando	Bates Camp inflow (Bates) – Outside study site	23.39967	-18.20550
	Shummamorei – Study site	23.55306	-18.37217
Kwando-New Channel	James Camp – Study site	*23.52503*	*-18.35850*
Linyanti	Sajawa – Outside study site	23.61736	-18.50156
	Simaa - Outside study site	23.78778	-18.38386
Outflow Rivers			
Savuti	Zibadianja - Outside study site	23.55075	-18.58194
Selinda Canal	Selinda - Outside study site	23.52993	-18.53405

The DWS provided the historical flow data for the Kwando and Linyanti Rivers from 1986 to 2020. By calculating the average monthly flows in m^3/s and the average cumulative MCM, the data was categorised into four scenarios: Scenario 1 (1986-1994), Scenario 2 (1995-2000), Scenario 3 (2001-2010), and New Channel Scenario (2017-2020). The normal rainfall periods in Botswana are from October to March, but in most cases it could be from November to March. The Okavango and Kwando systems are dominant in the northern region, where the study used rainfall data. The period from 1 October to 30 September of the following year is referred to as a hydrological year. For instance, the hydrological years 2019–2020 and 2020 correlate to one another. Observations of stream discharge and water level are necessary for establishing long-term links between rivers and wetlands; in many situations, data gaps make it clear that routine monitoring is not being done.

Gauge zeros, channel widths and depths

The 5m contours used to create the Digital Elevation Model (DEM) were provided by the Department of Surveys and Mapping (DSM), Botswana. The DEM was used to interpolate a hydrologically accurate raster surface from point, line, and polygon data using the Topo to Raster geoprocessing tool. Elevations were extracted from the DEM (raster) using the extract to point tool, which extracts the cells of a raster based on a set of coordinate coordinates The maximum 'river depth' in metres from the 'water surface' was ascertained by reading HY-Data sheets in order to estimate the gauze zeros in the raster surface elevation.

Results and Discussion

Kwando-New Channel Development, July 1985–December 2017

A river's flow initially overflows sporadically onto a floodplain before leading to a well- defined new channel that eventually carries all or part of the discharge. As the flow proceeds down the floodplain slope, it seeks path-connecting areas of lowest elevations until it eventually intercepts another channel, perhaps a tributary or a downstream reach of the parent channel (McCarthy *et al*. 1992; Schumm *et al*. 1996; Smith *et al*. 1997; Mohrig *et al*. 2000, Kleinhans *et al*. 2013). The selected images from July 1985 (Figures A and B), May 2002 (Figures 2C and 2D), December 2010 (Figure 2E), December 2011 (Figure 2F), December 2013 (Figures 2G, 2H, 2I, 2J), and December 2017 (Figure 2K) explain the spatial-temporal sequences of the New Channel evolution from the west bank of the trans-boundary Kwando River by making reference to the July 1985 image that showed no channel paths other than a very small stream (the existing channel of 1985, Figure 2B). As described in other river systems (Collins *et al*. 2003; Collins *et al*. 2012), the New Channel formation probably exhibits behaviour ranging from reoccupying relict channel systems (ie. paleochannels, floodplain sloughs, etc.) to creating new paths and finally re-joining the parent river after about 45km downstream in Botswana. According to Smith *et al*. (1997), four channels that diverged from the Okavango trunk channel finally reconnected with it 26km downstream within the graben. Such new course channels in lowland floodplains eventually display an anastomosed pattern (Kleinhans *et al*. 2013).

Slower rivers deposit material on the inside of bends whereas faster rivers deposit material on the outside, changing the course of the river (Nelson 2015). However, some riverbank bends include weak spots, and at periods of the maximum water velocity, erosion is greatest on the outside bends (Brooks and Warddrop 2013). According to geological time scale, the Kwando River should have been gushing over six (6) outer bends or meanders (Figures 2A and 2K) to the east of Linyanti Swamp in Namibia. It should be noted that Kwando had a less range of 4.83-32.61 m^3/s flow velocities in 1986-2020. However, over a prolonged time of low velocity, the flood also caused material to accumulate in the inside bends (Figures 2A and 2K), weakening the west bank and allowing water to overflow into Botswana. Because of this, it is reasonable to assume that the New Channel avulsion on the west bank portion may have poor drainage or seams of easily erodible soil material within the bank profile with erodible bank-vegetation, a situation documented by Konrad (2012) in the avulsion process. Surprisingly, the east and west banks of Namibia's Linyanti Swamp (Lat. -18.23472, Long. 23.45917) and Botswana's New Channel (Lat. -18.23791, Long. 23.45838) are roughly opposite each other where they originate.

Spilling at the Botswana side of the Kwando River's vulnerable section should have begun prior to 1985, forming a small lagoon (Figures 2A) with c. 2km 'Existed channel' (Figure 2B). Between 2002 and 2017, a big lagoon was created by carving flow paths as a result of overbank flow velocities (Figures 2C and 2K). Our ground measurements clearly showed that 'Big lagoon' was connected by cutting small alluvial streams with resilient lips in the levees on the left bank of the river. Our 2016 survey also revealed that the New Channel appeared outflows to the main Kwando channel via 'Lagoon-Marsh or Reed-Marsh' with two treacherous-looking, 0.5–1m-wide streams (Figures 2J and Figure 3). However, according to our most recent observations of the 2023 Google Maps, the New Channel attempts to connect the tiny water bodies towards Dumatau Lagoon downwards of the Lagoon-Marsh/Reed-Marsh indicating that it is moving forward. Breakouts within a few flood seasons, supported by frequent large-flow events (Sinha *et al*. 2005), rivers flowing well above the level of the floodplain (Nelson 2015), and new and unpredictable flow paths when flow oscillates among the channels indefinitely (Reitz *et al*. 2010) all contribute to the formation of a new stream or channel. Figure 2C shows the New Channel developed in most its length except at 'Marsh'.

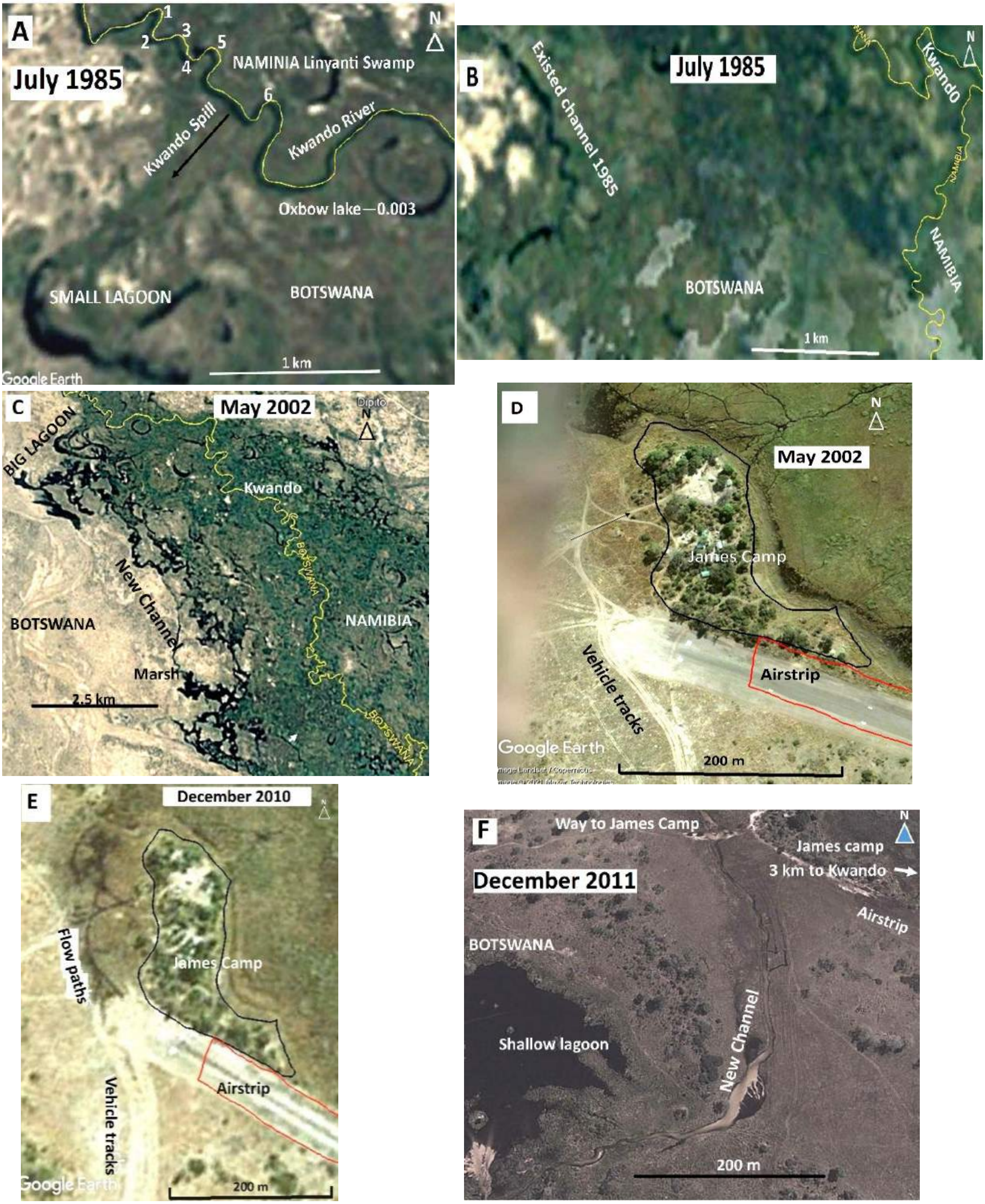
New Channel in Botswana was built during a 15-year period between 2002 and 2017, but more primarily between 2011 and 2017. The west side of James Camp, where sandy terrains and vehicle tracks were typically seen during our frequent visits to the camp before 2002, did not have any flow routes visible. However, there were little spills north of James Camp in 2002 (Figure 2D), despite the airstrip and vehicle tracks being easily visible. These spills were most likely caused by a greater inflow of 532 MCM at Bates in 2002. On the west of the James Camp, however, distinct 'flow paths' were discovered in December 2010 (Figure 2E), which were successively crevassed and revealed sediment deposits on their journey downstream, forming into a shallow lagoon (Figure 2F). Meandering rivers frequently favour flooding and sediment deposition during channel building (Kleinhans *et al*. 2006; Valenza *et al*. 2020), and this is why the commencement of overbank sedimentation in the reaches is linked to the establishment of a connection between the connecting channels via avulsion (Makaske *et al*. 2008). By 2013 a distinct and well-developed New Channel had formed to the west of the James Camp (Figure 2G), which was likely due to a probable higher inflow and increased local rainfall of 758 mm in 2011 (Figure 4). In 2013, the downstream portion of the New Channel that followed was still developing and had discontinuities in some places (Figures 2H, 2I, and 2J). However, by 2017 the 'Big lagoon' had distinct features (Figure 2K), and all of the New Channel's features—aside from 'Reed-Marsh'—exhibited clear flow and navigability (Figure 3). Other river systems have experienced channel incisions similar to those seen in the James Camp area's New Channel as a result of higher flows, heavy rains, and sediment loads (Smith *et al*. 1998; Collischonn *et al*. 2001; Pittaluga *et al*. 2003).

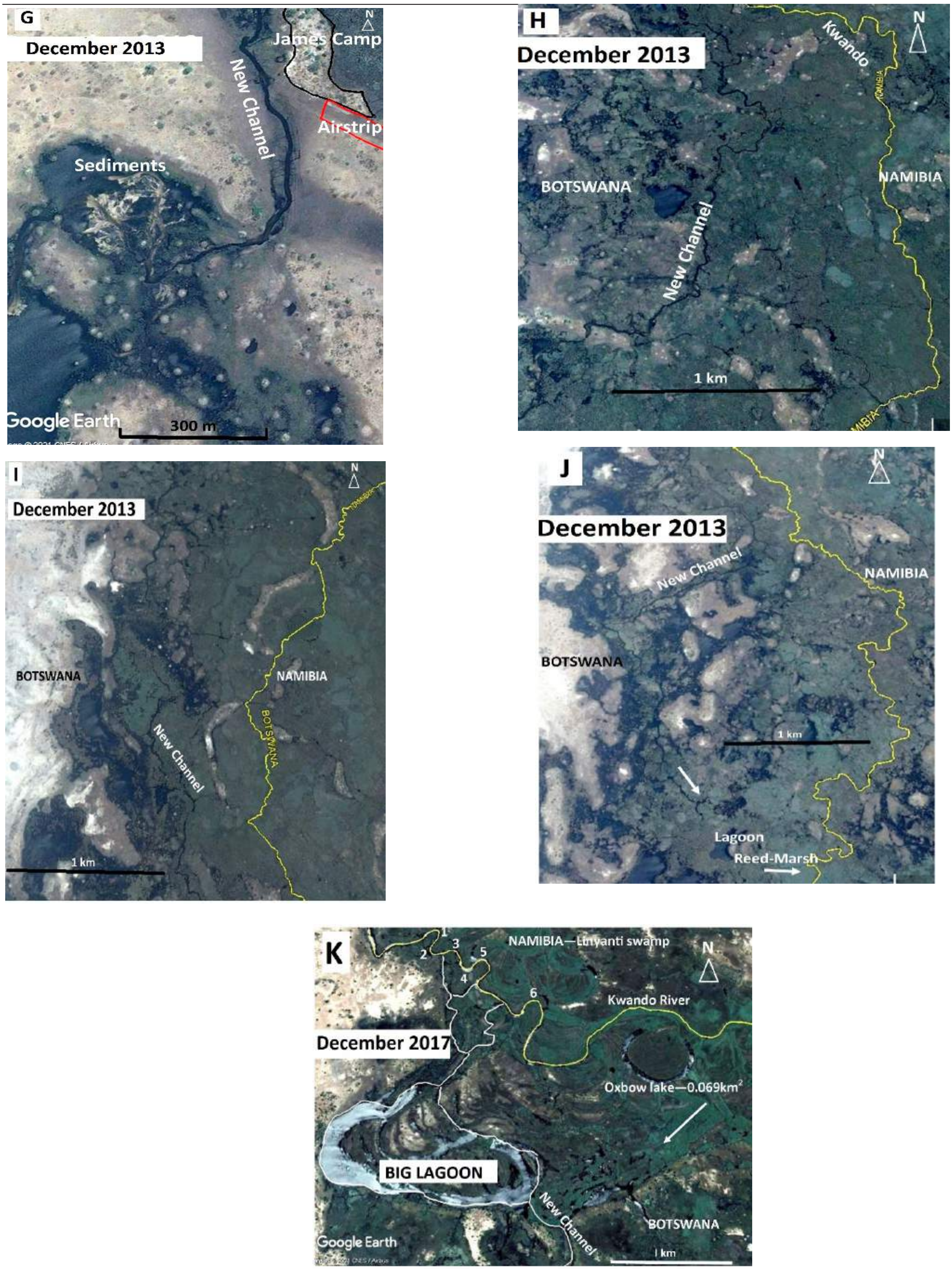
When there is a sizable channel belt that influences the establishment of crevasses and results in an increase in wetland areas, avulsions are preferentially triggered by high-magnitude floods (Makaske *et al*. 2012 and 2017). The wetland area of Botswana's New Channel determined using Google Images, all along the west bank of the Kwando River, increased from 105.9km^2 in July 1985 to 141.1km^2 in December 2013 (Table 2). Due to heavy deposition, Kwando, a low-relief zone, was obliged to cut a new channel across the floodplain and encourage gradation.

Table 2: New Channel resulted in increase in wetland area in Botswana.

Year	**Increased wetland area, km^2**
July 1985 (Reference)	**105.9**
May 2002	**100.3**
December 2011	**140.0**
December 2013	**141.1**
December 2017	**123.8**

Figure 2: Study Site showing avulsion of New Channel from the west bank of the Kwando River and its subsequent evolutionary images' sequences (see text for each image description).

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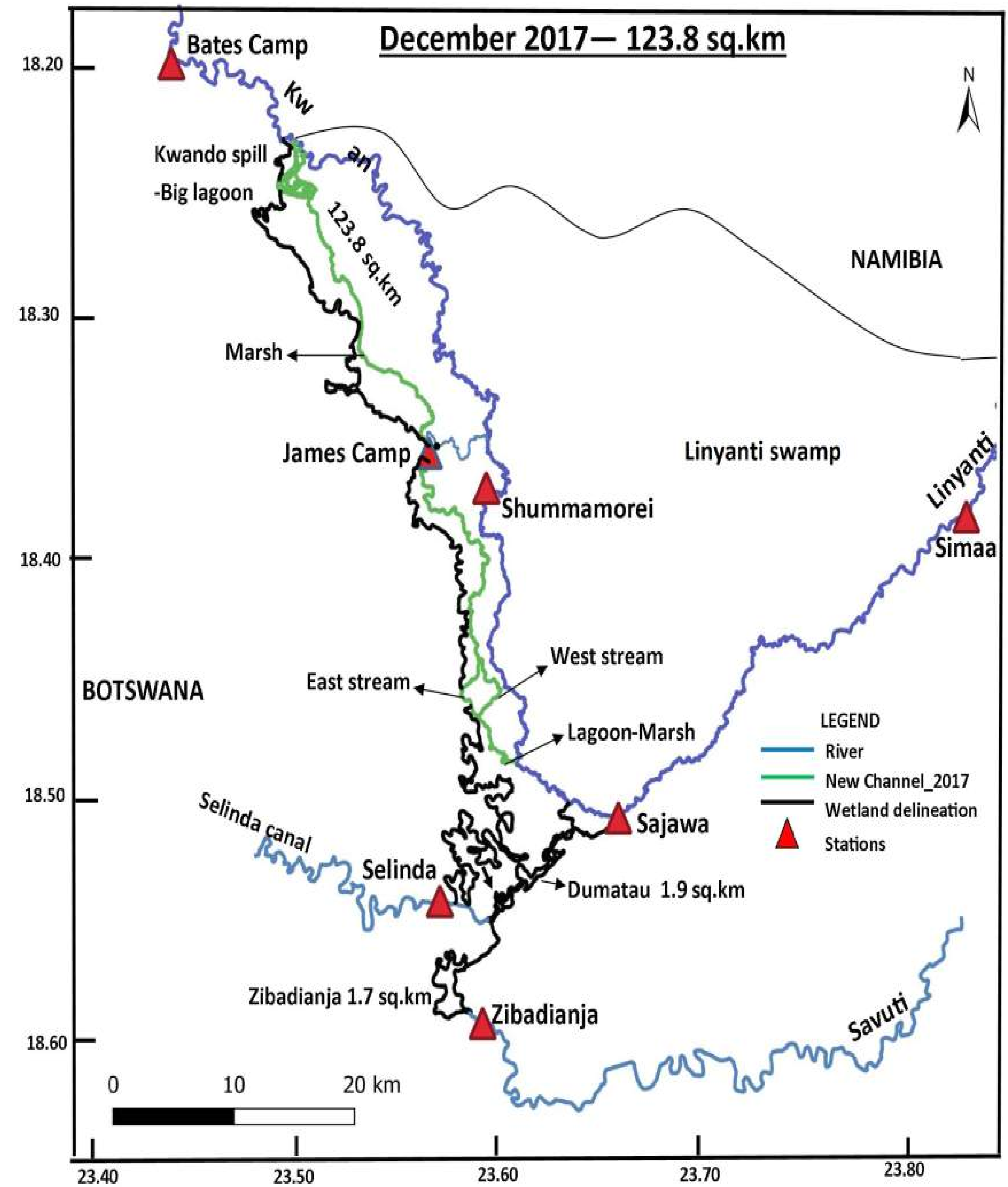
1 km
Lagoon
Reed-Marsh
K
1
2
3
4
5
6
NAMIBIA—Linyanti swamp
Kwando River
December 2017
Oxbow lake—0.069km²
BIG LAGOON
New Channel
BOTSWANA
Google Earth
1 km

Figure 3: Well-defined New Channel (green line) from Kwando River. Hydrostations from Bates to Simaa with new station James Camp on the New Channel. 'Kwando spill-Big lagoon' in Botswana sharply defined. New Channel for ~45km except at one place with two streams (East and West streams) join together downstream. No clear channel at the 'Marsh' upstream James Camp and at 'Lagoon-Marsh or Reed-Marsh' area that connects the main Kwando River. Wetland was 123.8km² in Botswana.



Hydrology: Kwando River versus New Channel

The annual mean rainfall in Botswana's north was about 450mm. However, the region's rainfall between 2004 and 2012 was above normal at 547mm (Figure 4). Between Bates and Shummamorei, three distinct flood scenarios are sketched from 1986 to 2020, and they are provided with average m^3/s (Figure 5) and also in annual quantities (Table 3). In scenario 1 of 1986-1994, the mean monthly flows between Bates (mean =16.81 m^3/s, range =10.32-29.48 m^3/s) and Shummamorei (mean = 8.97 m^3/s, range = 6.62-14.91 m^3/s) appeared normal with their losses to Linyanti Swamp probably little to Botswana wetlands; in scenario 2 of 1995-2000, the flow passage to Shummomorei (mean = 5.35 m^3/s, range = 2.95-8.43 m^3/s) was obviously unaffected despite lower monthly inflows at Bates (mean = 8.66 m^3/s, range = 5.42-12.89 m^3/s); and in scenario 3 of 2001-2010, the monthly flows at Bates in 2001-2010 was a mean of 16.49 m^3/s and in a range of 5.13-32.61 m^3/s, but with significant declines in a mean of 2.58 m^3/s and a range of 0.76-5.22 m^3/s at Shummamorei ($R^2 = 0.8849$ $p<0.005$, Figure 5) indicating greater losses to Linyanti Swamp. Due to these reductions, the Zibadianja Lagoon actually dried up in 2003 (Kurugundla *et al*. 2010). The flood reached James Camp at a mean of 6.76 m^3/s with a range of 2.03-11.44 m^3/s in 2017-2020 in the New Channel scenario, which is reminiscent of Scenario 1. This is an interesting difference from the flows at Bates (mean 12.67 m^3/s, range 4.83-24.32 m^3/s) in 2015-2020 (Figure 5).

We provide a potential scenario of a high flood throughout the period of 2011–2016 with the following supporting evidence because there were no pertinent hydrological data available at that time: i) Similar to the Okavango, Kwando River should have recorded with a comparable high flood of Okavango (Kurugundla 2018); ii) Kwando was inaccessible due to expanded wetland area indicating higher inflows, and Magwegqana or Selinda Spillway typically discharges water into the neighbouring Linyanti River (Gieske 1997), however it is unclear how much this condition affects the river's health; and iii) Simaa station on the Linyanti, which gets its spill from the Kwando over the Linyanti Swamp across, experienced greater floods between 2011 and 2015 that ranged from 102-181 MCM (Figure 7). As a result, the following three possibilities could explain the development of the New Channel: Rainfall increased by 547mm above average between 2004 and 2012; Bates station likely sustained greater Kwando inflows similar to the Okavango River in 2008–2015; and fossil streams provided possible routes for flow paths.

Figure 4: Annual rainfall in the northern region of Botswana

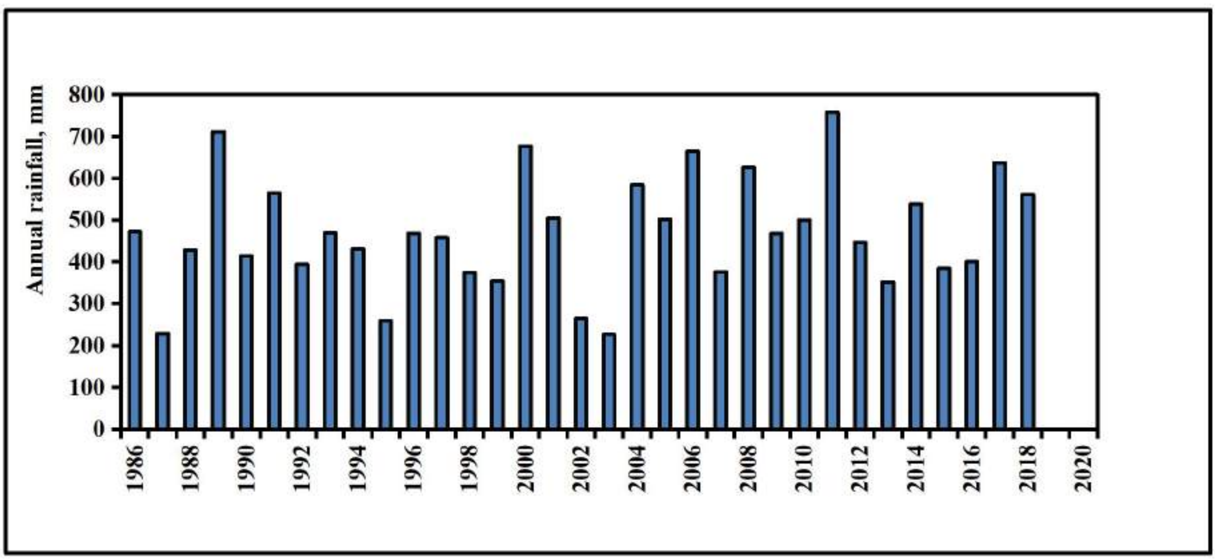
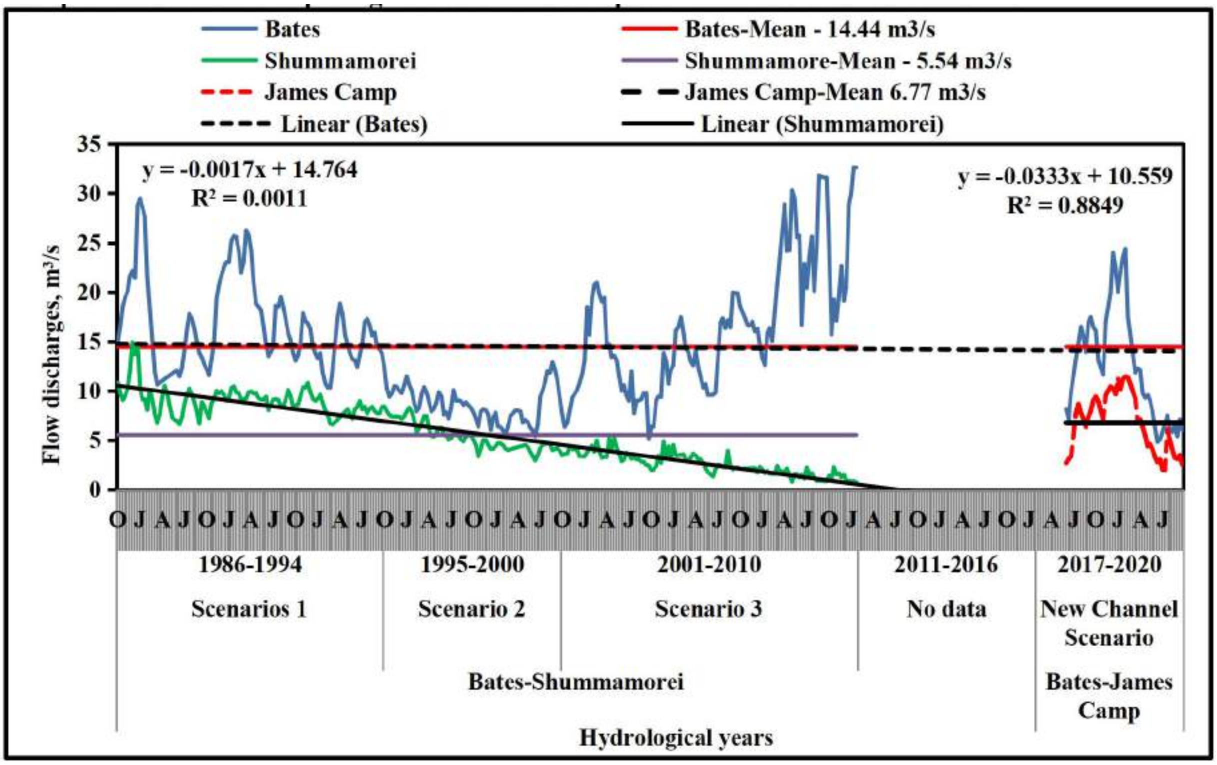


Figure 5: Monthly flow discharge series at Bates inflow, Shummamorei on Kwando River and James Camp on New Channel depicting three scenarios compared with New Channel Scenario..



The flow discharges at Shummamorei in 2001–2010 for 10 years in scenario 3 revealed considerable decrease, with just 16% arriving to the station after losing 84% to the Linyanti Swamp-Namibia and little to Botswana (Table 3). As a result of consolidated vegetation and aggradation in the Shummamorei area, flood diversions and losses by east bank spills of the Kwando River to Linyanti Swamp were noted after the 1980s (Smith 1987). This supports the claim that DWS removed obstructions in the region between 1998 and 2006 (Kurugundla *et al*. 2010) (Table 4). Due to a lack of funding, these certifications were later stopped. In the upstream Shummamorei, where we conducted surveys in 2016, we also noticed that hippo grass had outgrown the surface water while papyrus was used as fringe. This led to high hydraulic conductivities, which encouraged water loss from channels towards Linyanti Swamp and caused sediment deposition within channels.

It is obvious that vegetation significantly influences channel hydraulics because channel width is predominantly a result of vegetation processes at the channel edge, particularly the growth of the papyrus (Ellery *et al.* 2003). Accordingly, it is proposed that channel switching is the result of a combination of erosional and depositional processes (Ellery *et al.* 1993). The historical observations of the Okavango Delta (Wilson 1973; McCarthy *et al*. 1992; Kurugundla *et al*. 2021) suggest that flow diversions can result from the destruction of old channels caused by vegetation and aggradation. Indicated by the arrival of 53% flood at James Camp in 2017–2020 as opposed to 51% at Shummamorei in 1986–1994 (Figure 5, Table 3), the floods in the New Channel scenario and scenario 1 were more or less comparable.

Table 3: Scenarios presented in mean volumes in MCM between Bates, Shmummamorei are compared to New Channel-James Camp Scenario. Mean volumes and percentages arrived at Shummamorei and James Camp and to swamps of Botswana & Linyanti Swamp.

Years	Mean volumes, MCM, Bates inflow	Mean volumes, MCM and % arrival (Station)	% to Swamps – Linyanti swamp & Botswana
1986-94 Scenario 1	550 (100%)	278, 51% (Shummamorei)	49%, Major % Linyanti Swamp
1995-00 Scenario 2	273 (100%)	169, 62% (Shummamorei)	38%, Major % Linyanti Swamp
2001-10 Scenario 3	492 (100%)	80, 16% (Shummamorei)	84%, Major % Linyanti Swamp
2017-20 New Channel scenario	375 (100%)	199, 53% (James Camp)	47%, Major % to Botswana wetland

Table 4: Blockage clearances in Kwando River in the Shummamorei area (Source: Kurugundla et al. 2010).

From	To
21 March 1998 22 April 1998 June 1998 19 July 1998 27 November 1998 25 September 1998	**31 March 1998 29 April 1998- - 25 July 1998 30 November 1998 12 October 1998**
9 August 2000 June 2000 (with monthly offs) June 2001 (with monthly offs) May 2002 (with monthly offs) 2 February 2004 6 March 2004 12 October 2005 20 March 2006	**12 September 2000 December 2000 November 2001 September 2002 24 February 2004 31 March 2004 17 October 2005 24 March 2006**

While the bypassed older channel segment still exists (Makaske 2001), the vulnerability of floodplain surfaces to chute incision depends on point bar growth, floodplain texture, floodplain gradient, and vegetation cover, which limit channel sinuosity (Dunne *et al*. 2010). The New Channel connects the parent Kwando River by passing through two floodplains that have been transformed into marshy areas, one above the James Camp and the other near Lagoon-Marsh/Reed-Marsh, which is dominated by reed *Phragmites australis* (Cav.) Steud and papyrus *Cyperus papyrus* L (Figure 3). The bank vegetation along the New Channel, which was brought about by the floodplain, is another intriguing aspect. Local water-surface elevations were first enhanced by avulsion flooding, which deepened tiny already-existing fossil lakes and produced new shallow lakes on the surface of the floodplain (Perez-Arlucea *et al*. 1999). The wire-leaf daba grass (*Miscanthus junceus* (Stapf) Pilg.) banks the open canal that follows the lagoons, and papyrus appears to establish itself in scattered stands for about 3km. This follows the downstream, which is wide in some places and small in others, with dominant hippo grass *Vossia cuspidata* (Roxb.) Griffith. Water circulation in the lagoon-marsh area appeared to be more or less stagnant, although a sizeable spill appears occurred in the direction of Dumatau and Selinda Canal (Figure 3).

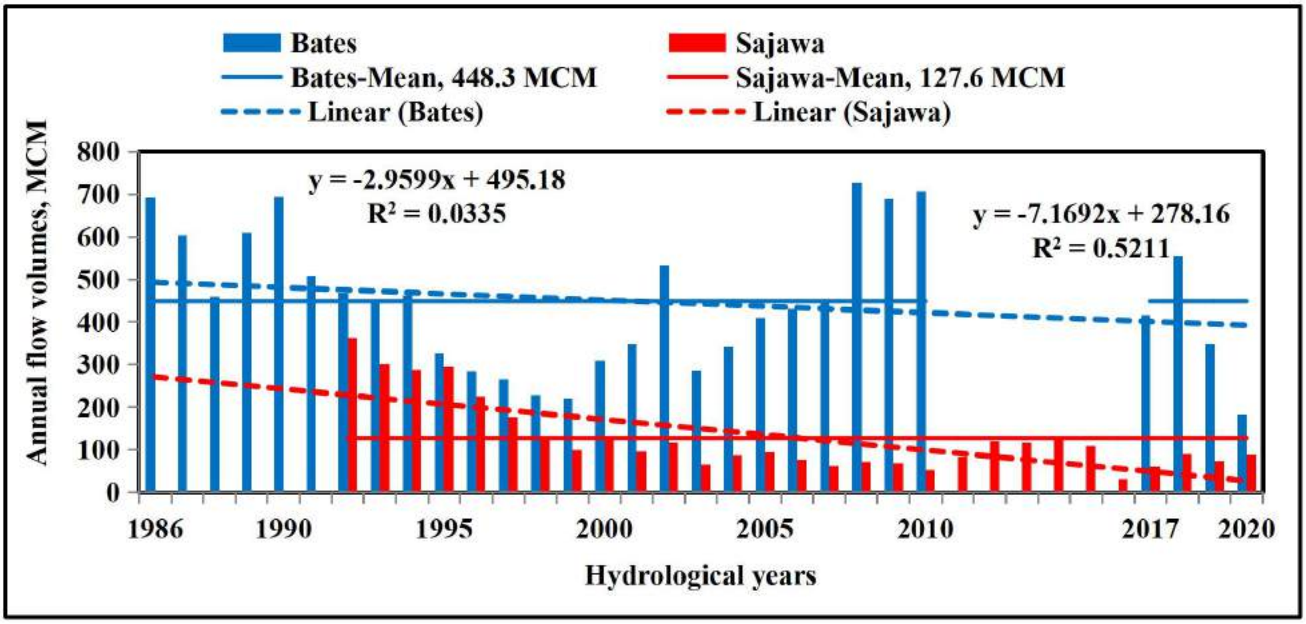
In October 2016, the New Channel at James Camp was 12m wide; by 2020, it had grown to 15m, and it is likely to get wider again. In comparison to the parent Kwando channel (for example, Shummamorei 1.237 m^3/s in May 2009; channel width 6m, depth 2.3m), the New Channel bifurcate had larger flow discharges, width, and depth (for example, James Camp 11.202 m^3/s in September 2018; channel width 15m, depth 2.52m) (Table 5). The presence of an upstream meander benefits the width-depth ratio (Kleinhans *et al*. 2008), which favours one bifurcate with more sediment and the other bifurcate with greater discharge. Because the new channels are cut deeper than their counterpart main rivers, they are likely to grow deeper over time (Brooks and Warddrop 2013). We draw the conclusion that the replacement of Shummamorei station on the Kwando with James Camp station on the New Channel, begun in October 2016, for hydro-monitoring, is warranted based on the assessments of flow discharges and channel width-depth connections discussed above.

Table 5: Subtraction of the deepest depth in meters from river-surface in meters (DEM) above msl at the discharge stations to obtain gauge zeros (channel elevation) in meters above msl; also channel width in meters.

River-Station	River surface elevation-Raster value, m	River deepest depth, m (with month & year)	River surface elevation, m above msl-River deepest depth, m	Gauge zeros, m above msl	Channel width, m
Kwando-Bates	953.492	1.51 (04/2009)	953.492 - 1.51 =	951.982	26
Kwando-James Camp	947.864	2.52, (09/2018)	947.864 - 2.52 =	945.344	15
Kwando-Shummamorei	950.000	2.30, (05/2009)	950.000 - 2.30 =	947.70	6
Savuti-Zibadianja	944.644	2.62, (07/2018)	944.644 - 2.62 =	942.024	18
Selinda Canal-Selinda	944.708	2.18, (04/2018)	944.708 - 2.18 =	942.528	64

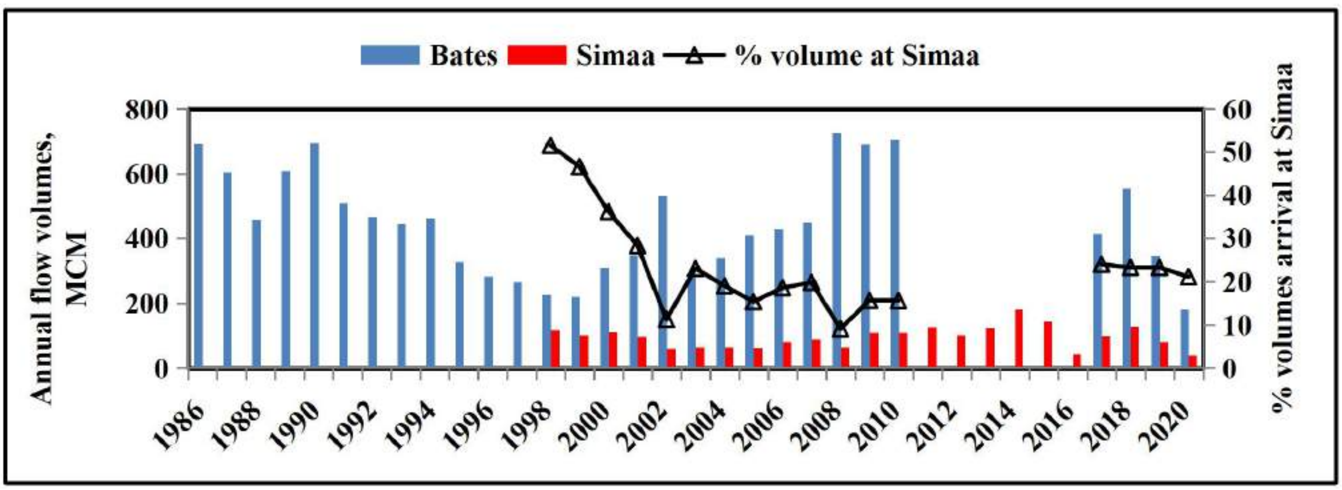
In the early era of record, the trends in flow volumes at Sajawa were hardly significant (R^2 = 0.5211), dropped in 1995-2000, and likely increased afterwards (Figure 6). This explains why the losses brought on by the growing papyrus obstruction upstream of Sajawa after 2000 had a minor impact on the Kwando River's flow carrying capacity. According to Mr. Tapson Bombo of DWS (in a personal communication on 7 March 2018), whatever the losses in the section might have been transferred to Dumatau Lagoon, which is shared by the Savuti River and Selinda Canal. His view is supported by our 2016 surveys, and for about 5km, the river in the upstream Sajawa was progressively becoming blocked here and there.

Figure 6: Annual volumes at Bates in 1986-2020 and Sajawa in 1992-2020. The linear rends are with respect to mean volumes at the stations.



One question that can come up is whether the Linyanti River's flow pattern at the Simaa hydro-station will change if the New Channel is developed as its flow is diverted on the Botswana side. There are a number of minor streams and tributaries that enter the Linyanti River from the east bank of the Kwando River and get around 50% of the Kwando inflow to Linyanti River (Kurugundla *et al*. 2010). It is demonstrated that despite differing trends at Bates inflow (missing data between 2011 and 2016), the flows at Simaa were largely unchanged since 1998. Unknown factors may have contributed to the Simaa flow pattern's comparable behaviour as the Bates inflow fluctuated and grew considerably from 2000 to the present (Figure 7).

Figure 7: Annual volumes at Bates and Simaa. Data gaps and poor data collection at the station. Note 2016 is absolutely not right.



Flow Partition

The gauze zeros of the Kwando River, New Channel and outflow channels, Savuti and Selinda Canal indicate the smooth partitioning of the flood (Table 5). While the flood was different throughout Selinda Canal and Savuti River represented by Selinda and Zibadianja stations respectively, the Kwando River flood wave at Bates roughly correlates to the New Channel flood wave in 2017-2020 (Figure 8). The flows in the Savuti River were substantially more or less steady, in contrast to Selinda Canal, which had flood dips during non-flood months (Figure 8). This is mostly attributable to the Zibadianja Lagoon's flood threshold intensity lessening, which led to the nullification of peaks. Selinda station on the Selinda Canal is situated at a higher altitude above mean sea level (942.528m) than the Zibadianja station (942.024m) (Table 5) on Savuti river, but the former has floodplain characteristics and is 64m wide, giving it the advantage of receiving spillage from the "Lagoon-Marsh/Reed-Marsh" of the New Channel as well as from the Dumatau Lagoon, which results in higher flows (Figures 8 and 9). James Camp (945.344m) has a lesser elevation than Shummamorei (947.70m), which clearly got stronger flows for the New Channel while Shummamorei's lower volumes may be due to the aggradation of the main river.

Long-term flows in the New Channel are anticipated to rise, which would reduce spills into Namibia's Linyanti Swamp. Compared to their counterpart main rivers, channelised streams formed by deepening and widening have more recurring floods. The typical hydroperiod of wetlands and streams is maintained through long-term surface water flow and storage across months and years (Brooks and Warddrop 2013).

Figure 8: Comparison of flood waves between Kwando River and New Channel and between Selinda Canal and Savuti River.

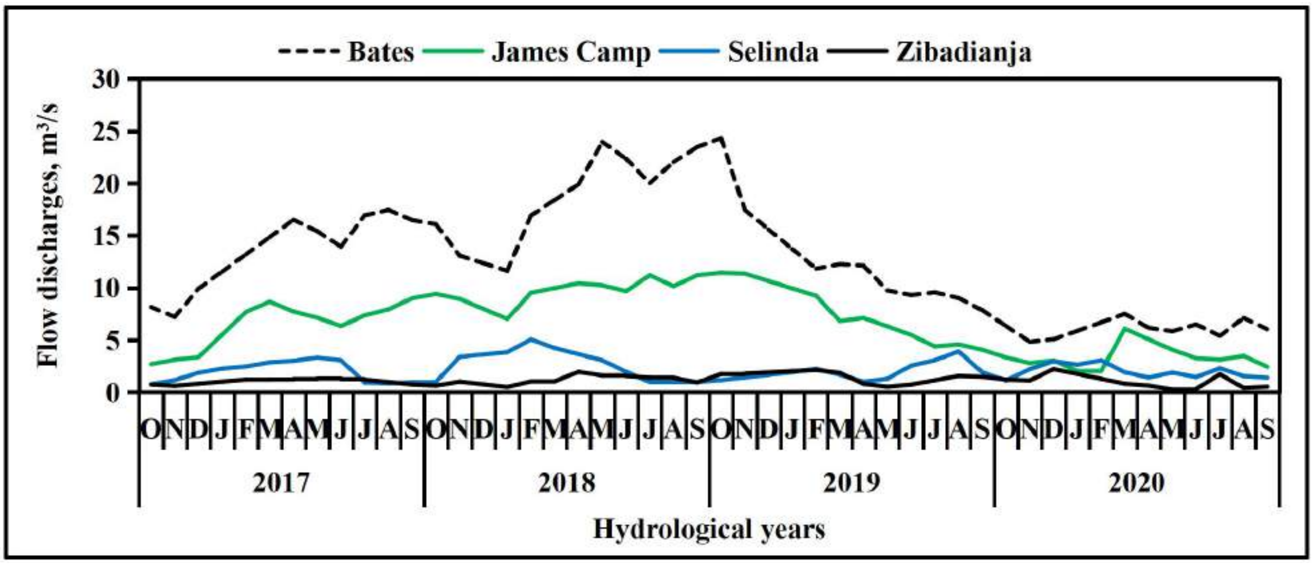
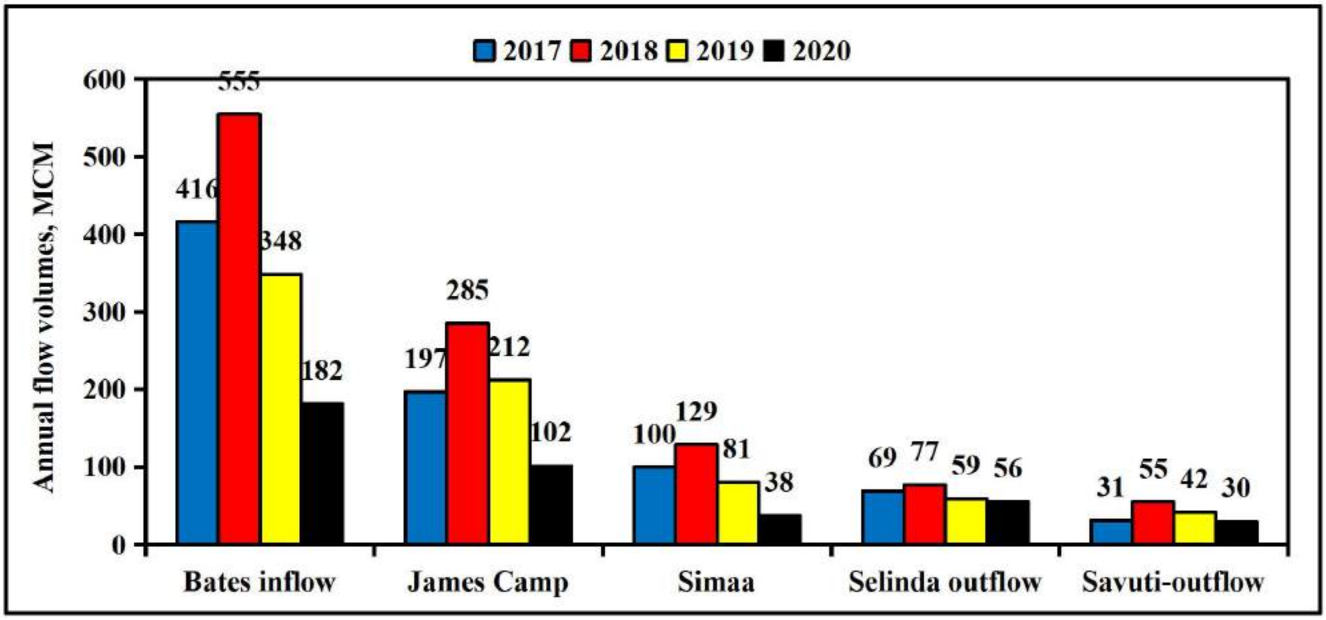


Figure 9: Passage of inflow from Kwando-Bates to the New Channel-James Camp and flow partition to outflow rivers Linyanti at Simaa, Selinda Canal at Selinda, and Savuti River at Zibadianja.



Conclusion

The reoccupation of pre-existing channels during floods in response to local aggradations, lateral erosion, and hydrological variability (mostly flood magnitude) appears to be the most likely mechanism of avulsion in the study area. However, it is more likely that bank instability and hydrological changes are to blame for numerous landslides in the area. In the future, the Linyanti Swamp in Namibia and the wetland region in Botswana may also be impacted by the New Channel. As a result, in order to comprehend the hydrological conditions and channel configurations, we encourage Botswana and Namibia jointly to investigate the Kwando River up to Shummamorei and the split New Channel.

For James Camp to monitor changing water levels, a baseline with a stage is necessary. The bifurcation of the Kwando River, which occurred without major environmental changes, cannot be attributed to climatic or other environmental changes without additional evidence. We arrive to the conclusion that the avulsion of the New Channel and the expanding wetland zone in Botswana are analogous, and that further major flooding may dramatically change the configurations of the New Channel.

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