Flow Partitioning Within the Okavango Delta – A Pre-requisite for Environmental Flow Assessment for Human Livelihoods and Sustainable Biodiversity Management

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Abstract

The sustainable management of water resources of the Okavango Delta requires balanced water allocation to various users (e.g. water supply to the villages and settlements, fishing and agriculture, tourism and biodiversity), through the engagement and participation of all key stakeholders. The process involves the characterization of water flowing into representative streams so as to determine relationships between flow extension and ecological processes. The Mohembo inflows were analyzed to determine sharing and partitioning patterns for three major rivers systems in the Delta: Thaoge, Boro and Maunachira by the application of MKE SHE-MIKE 11 Integrated model. To better understand wetland storage areas, which are significant in maintaining the integrity of the Delta's biodiversity, hydrometric data collected at the critical flow stations in the channels and the simulated results of the model were used for the study. The observed and simulated discharge data in the improved monitoring confirms that Thaoge River receives lesser flows due to its elevation, while competition exists in flow-sharing between Boro and Maunachira Rivers. The hydro dynamics reveal that Maunachira River has an advantage of being perennial all along its terminal Khwai River while the Boro River exhibits seasonal patterns. The model output results show that the marginal increases/declines in the flow discharges in Thaoge, Mboroga and Maunachira systems is related to the stability in inundation while the dynamism in the velocity of flows are noticed only in the Jao-Boro system in the high flood events. The intensity of inundation and topographic slope are the important characteristics guiding the flow sharing and distribution among the three major tributaries. The systematic partition of inflows driven by Panhandle Reservoir into the seasonal Jao-Boro Reservoir and into the Khiandiandavhu Reservoir determines the environmental flow requirements for the various sectors in the Okavango Delta.

Key words: Okavango delta, flow sharing, Maunachira, Thaoge, channels

Introduction

An understanding of relationships between ecological processes and flow regimes is a pre-requisite for maintaining a desirable state that ensures continued availability of goods and services from riverine systems. A flow regime that ensures maintenance of a river system in a desirable state is referred to as an instream-flow requirement, environmental flow, or environmental flow requirement. Allocation and maintenance of an environmental flow requirement is considered as part of an integrated flow management which enables achievement of economic development, social justice, and ecological integrity. Parties to the Ramsar Convention are encouraged to determine and ensure that environmental flow requirements for the respective wetlands are provided for. The knowledge of flow dynamics, and relationships between flow regimes and fluvial, ecological, and socio-economic process is important for estimation of environmental flow requirements of wetlands.

The Okavango Delta is one of the largest wetlands with the annually flooded area varying from 5,000 to 12, 000 km^2 and highly variable channel morphology, flow regimes, and ecosystems. Channels within the delta have been classified into upper or primary channels, distributary channels and outlet channels (Gumbricht *et al*. 2004). The delta can also be classified in terms of flow regime and habitat; permanent swamps, seasonal swamps, occasionally flooded areas, and drylands (McCarthy *et al.* 1988; Murray-Hudson *et al.* 2006). The upper part of the delta, commonly referred to as the Panhandle, consists of a 10-15 km wide and 150 km long valley within which the main channel meanders through. The Okavango River in the Panhandle splits into the western distributary, the Thaoge River. and continues to the eastern part as Nqoga River, which eventually becomes Maunachira and Khwai Rivers. Jao River originates from Nqoga River and subsequently separates to form the Boro and Xudum Rivers while Maunachira splits to form Mboroga and Santantadibe Rivers (Figure 1). Flow of the Okavango River is therefore partitioned within the delta. Over-spilling of flow from channels onto adjacent floodplains is a common feature within the delta during the high flow period, and in some cases the spilled water joins the same or different channel (Wolski and Murrary-Hudson 2006). Of the three main distributaries, the Thaoge River in the west terminates in a series of lagoons and extensive floodplains near its upper end. The Boro upstream flows through lagoons and floodplains and is a single more or less confined channel in the downstream discharging into Thamalakane River. The Khwai River in the east has wide permanent flood plains in its middle reaches and discharges to less defined floodplains in the downstream. Channel banks are very porous as most of them are made of papyrus. The substratum of channels is very permeable resulting in substantial exchange of water between channels, floodplains, and groundwater.

The partitioning of Okavango River flows among channels of the delta changes over time as is evident from the currently dry Thaoge River which used to be the main outlet some 120 years ago. Wolski and Murray-Hudson (2006) have shown the Xudum River (Figure 1) seems to be gaining flow at the expense of the Boro River. The estimation of the partitioning of flows into the channels and flood inundation within the Okavango Delta is important and a challenge for determining environmental flow requirements of this system. Previous hydrological modelling considered partitioning of flows between linear reservoirs assumed to describe flow through the delta (Dincer *et al*. 1987; SMEC 1989; Gieske 1997; Wolski and Savenije 2006; Wolski *et al*. 2006). The study by Wolski and Murray-Hudson (2006) examined changes in water levels and discharges along the Nqoga and Jao/Boro Rivers, while Murray-Hudson *et al* (2006) examined possible effects of flow upstream abstraction, impoundments, and climate change on areas of delta under different flooding regimes. The examination of the observed flows with the existing hydrometric network being followed still reveals that there is lack of satisfactory understanding of the flow distribution into the major tributaries and the floodplain water base flows that join the rivers. The floodplain flows show a great deal of influence on the in stream flows and some areas have high base flows and some have relatively small seasonal variations

Aims of the study

1. To assess and understand the flow discharges at critical junctions where the floodplain flows join the rivers/tributaries using improved hydro monitoring in the Okavango Delta

2. To develop a quantitative hydrological model of the Delta with improved hydrological data input

3. To model water flows in the rivers, using Mike She-Mike 11 driven by Mukwe hydrostation in Namibia in the upstream of Mohembo inflows in Botswana.

4. .To identify the areas of floodplain reservoirs that governs the ecological integrity of the Delta.

Methods

The study used discharge measurements made at 14 hydro stations (Figure 1) at the inlet and within the Okavango Delta. Of the 14 stations used for the present study, the stations such as Etsatsa, Duba, Jao/Boro, KM-Junction (Khiandiandavhu-Maunachira Junction) and North Gate were introduced in the improved monitoring of the Okavango Delta in July 2003 (Kurugundla 2005). Observed discharge measurements were made once a month from 2005 to 2007 hydro years in the stations except at inflow station in Mohembo where the flow discharges were collected on daily basis using the current meter method. Figure 1 shows the locations of the hydrological stations used for the study. Years 2005, 2006 and 2007 represent the hydro years that run from October to September .

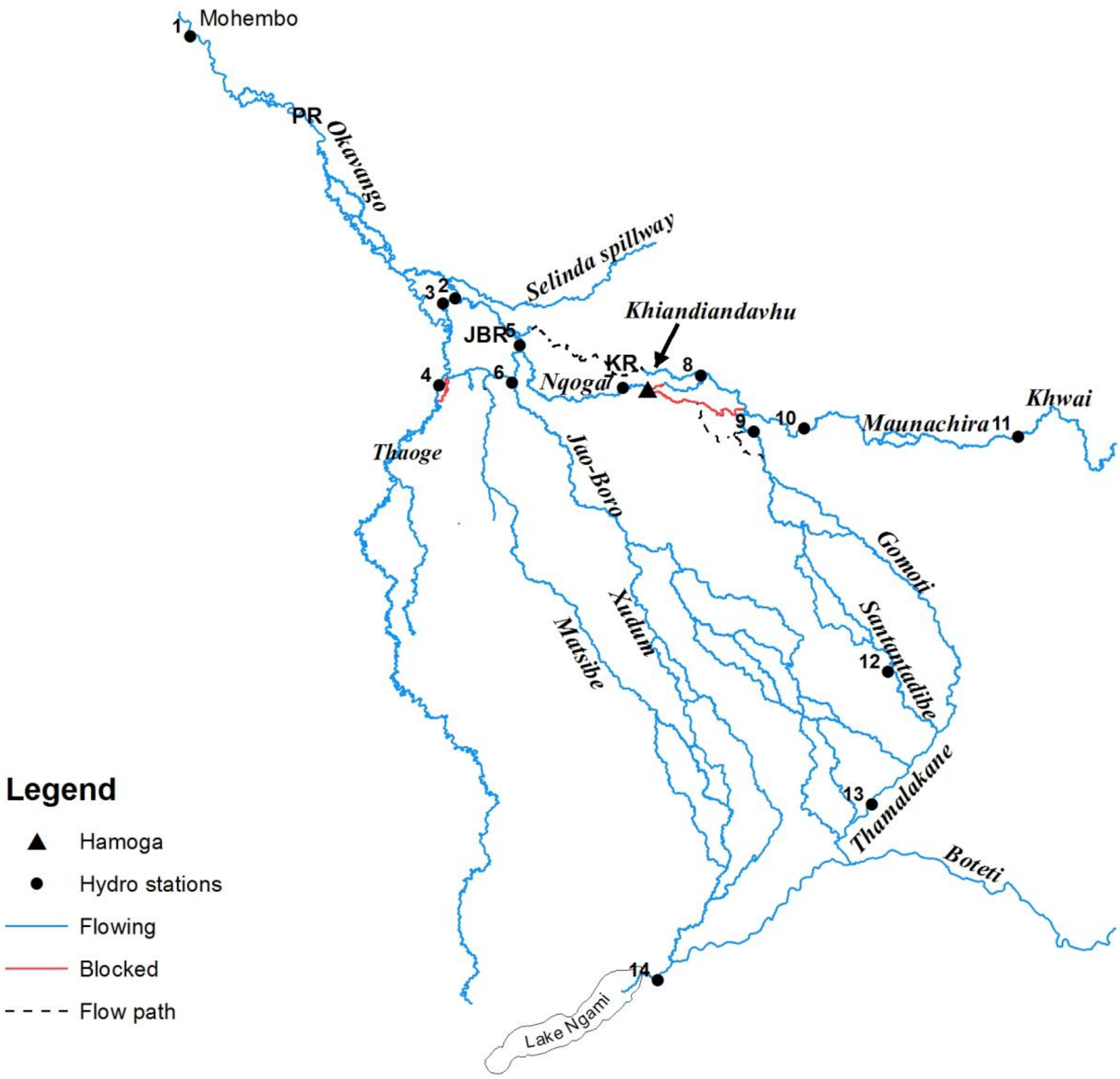

Figure 1: Inflow, flow sharing stations and outflow stations in the Okavango Delta.

Station locations are numbered 1 to 14. 1 = Mohembo, 2 = Etsatsa, 3 Crescent, 4 = Qaaxhwa, 5 = Duba, 6 = Jao/Boro, 7 = Gaenga, 8 = Khiandiandavhu-Maunachira (K/M) Junction, 9 = Lopis, 10 = Gadikwe, 11

= North Gate, 12 Ditshipi, 13 = Maun bridge, and 14 = Mogapelwa. PR = Panhandle Reservoir, JBR = Jao-Boro Reservoir, KR + Khiandiandavhu Reservoir

MIKE SHE Modelling system

MIKE SHE modelling system is a deterministic, distributed and physically based model system, which can model all the major processes of the land phase of the hydrological cycle. It can be applied on spaces with scales ranging from single soil profiles to regional watersheds. The Integrated Hydrologic Model for the Okavango Delta was developed under the Okavango Delta Management Plan (ODMP) project (ODMP 2005) and later transferred to Department of the Water Affairs for its application. The model was developed by the Danish Hydrological Institute (DHI) Water and Environment, Denmark.

The MIKE SHE model used in this study is to estimate the inflows arriving at Mohembo and the inflows that get shared and partitioned to the three major river systems of the Delta. The model results are compared with the physical flow measurement analysis. In the model set up, the surface water flows depend on the topography and channel cross sections and 1-D (1 Dimensiona) and 2-D (2 Dimensional) diffusive wave Saint Venant equations that describe channel and overland flow, respectively. (Figure 2). "The surface waters of the Delta are described by a fully hydrodynamic representation of the flows in the main river and channels, together with a distributed kinematics representation of the flows over the flood plains and swamps" (ODMP 2006). For the estimation of flows the channels and flood plains are fully coupled representing one dimensional flow through the channels, spreading and distribution of storage over the flood plains (Figure 2). The model results was extracted to Microsoft excel to compare the observed discharges with that of model simulated discharges at the specified hydrometric stations.

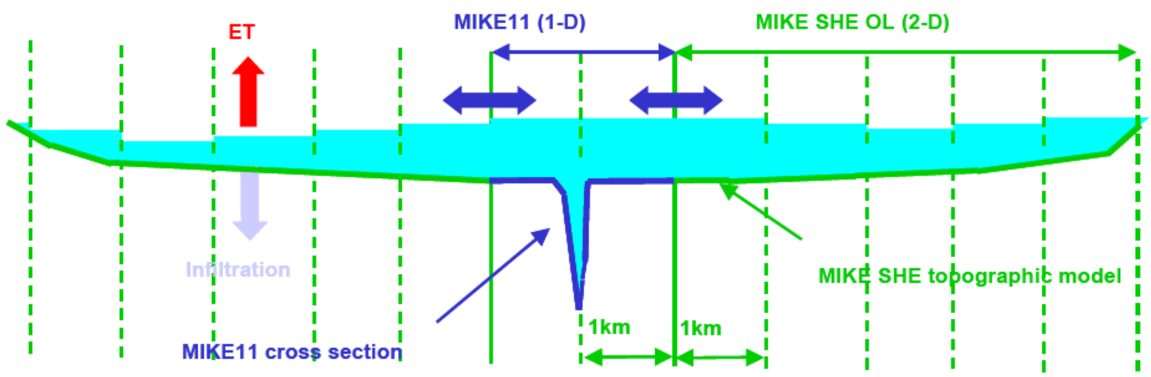

Figure 2: Channel and flood plain coupling (ODMP 2006)

Results and Discussion

Understanding the controls of the flooding process and flood distribution in the Okavango Delta and its natural variation depends on the topography, precipitation, evapotranspiration, infiltration and vegetation distribution. Okavango Delta is a low topographic gradient system. The altitudes of the at Mean Sea Level (MSL) in meters extracted from the topographic model showing the channel beds (Figure 3) at the inflow Mohembo point, at the three flow sharing hydro stations and at outflow stations indicates the sloping of the Okavango delta in easterly direction to facilitate the smooth movement of flows.

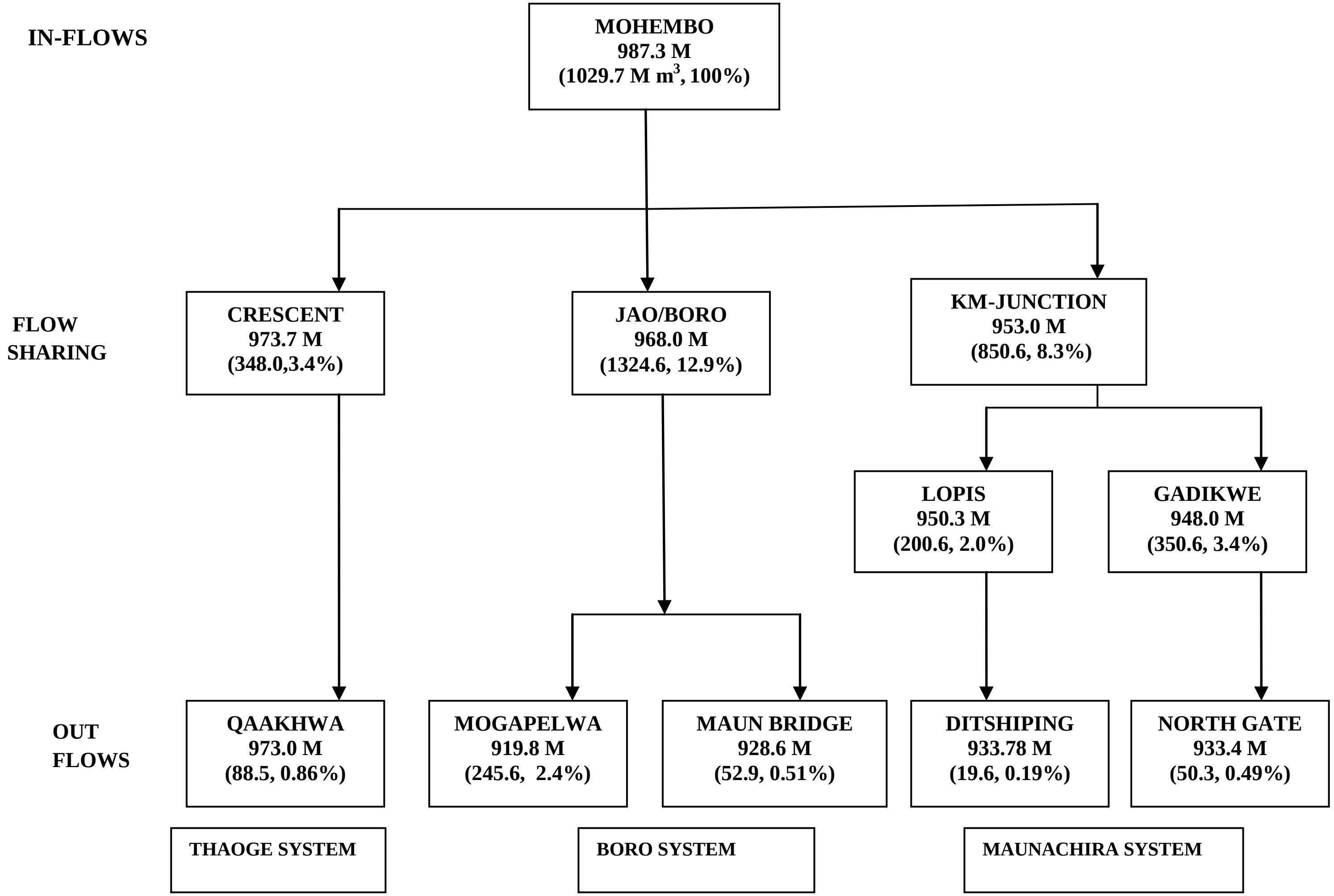

Figure 3: Altitudes of different hydro stations extracted from topographic model at the inflow point of Mohembo, the flow sharing stations and at outflow stations in the Okavango Delta. Figures in the parentheses are the total annual observed flows in Mm^3 and % flows at each station calculated with respect to the total annual observed inflows at Mohembo for the 2006/07 hydrological year

Etsatsa 972.62m, duba 969.02 m, gaenga 961.02 m

The simulated discharge results obtained using MIKE SHE Model at Mohembo shows a good model fit with the observed flow discharges. However, the higher simulated discharges (Figure 4) in the peak flood season compared to the observed explain that the floodplain flows do bypass at Mohembo. The Okavango River at Mukwe in Namibia and at Mohembo in Botswana is more or less confined with defined banks. Dikgola (2007) using MIKE SHE model obtained very close response of simulated discharges to those observed in the Havelse Catchment in Northern Zealand, Denamark and Anderson *et al.* (2003) using the Pitman Model for the Okavango River Basin at Mukwe showed a good model fit for the simulated discharge compared with the observed.

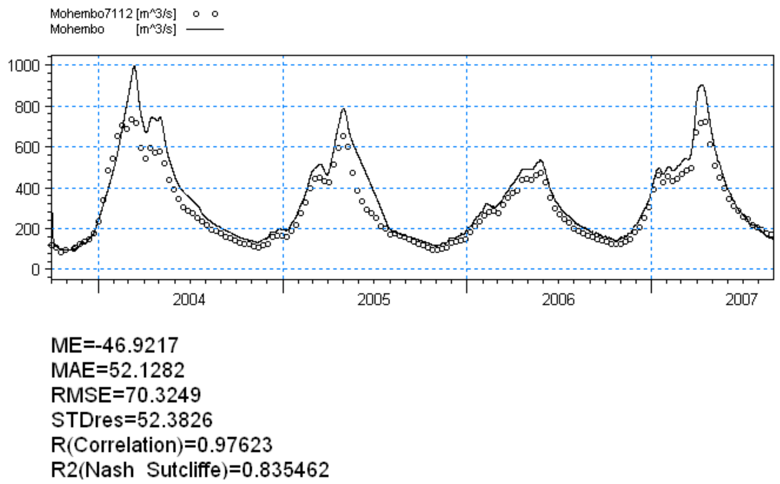

Figure 4: Model simulation results showing discharges at Mohembo hydro station compared to the observed in m^3/s

Hydrometric data collection in the Okavango Delta is measured only in the channels. Wolski and Murray-Hudson (2005) show that channel flow dynamics usually does not reflect the dynamics of the distributary flows. This is clearly illustrated by the comparison between observed discharges in the channels and simulated results of the model for all stations (Figures 5-9) and the same is reflected in the overall annual flows in Mm^3 for the three hydrological rears, 2005, 2006 and 2007 (Table 1). The model simulated discharge estimates are evidently higher than the observed in Etsatsa, Jao.Boro, Gaenga, KM-Junction (Khiandiandiandavhu-Maunachira Junction), Gadikwe and Lopis (Table 1) as there are contributions from the flood plains and swamps. The flow paths are defined by cross sections rather than river channels (Figure 2). The cross sections were extracted from the topographic model extending over kilometres in length covering large flood plains and swamps and therefore resulting in relatively higher simulation discharges compared to the observed.

Thaoge River system

In the elevation model (Figure 3) Thaoge River system surprisingly shows that the Thaoge River at Crescent Island and at Qaaxhwa had more or less similar depths of 973m above MSL. There is no larger difference between the simulated and the observed flows either at Crescent or at Qaaxhwa (Figure 5 and Table 1) in the Thaoge River and therefore certain levels of water should have been maintained in this section in relation to topography of the overland flooded area. It should be noted from the elevation model that the altitude of Thaoge River at Crescent Island (973.7m) hydro station is slightly higher than the Okavango River at Etsatsa (972.7m) indicating the Okavango River Section allows smooth passage of water into the easterly direction. Upper Thaoge used to receive the flows larger than the Nqoga until about the middle of the 19th century, when it blocked completely (Wilson and Dincer 1976). The deposition of sediments and the growth of vegetation could change the channel configuration quite appreciably as described in channel aggradation cycle (McCarthy *et al*. 1992).

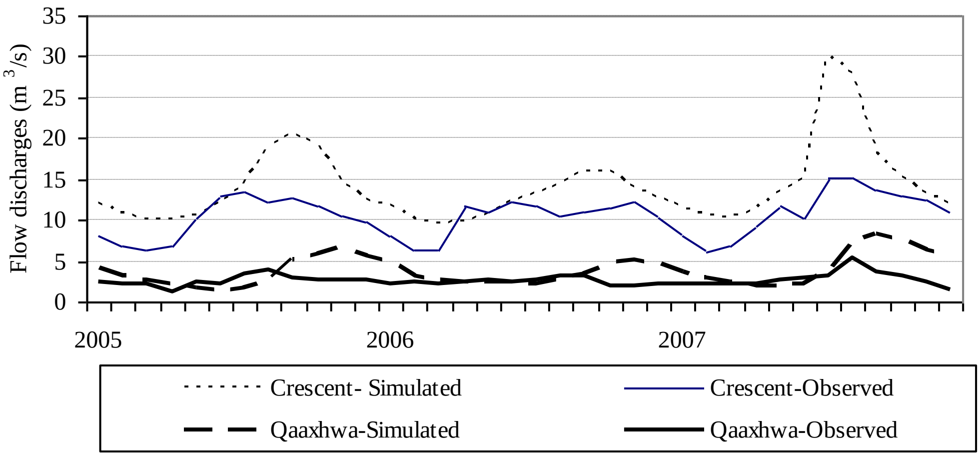

Figure 5: The simulated and the observed flow discharges in Thaoge River at Crescent and Qaaxhwa stations

Table 1: Comparison of observed and simulated annual flows in Mm^3. Figures in the parentheses indicate the % flows with respect to total inflows at Mohembo

	Mohembo		Crescent		Etsatsa		Duba		Jao/Boro		Gaenga		KM Junction		Gadikwe		Lopis	
Year	**Obs**	**Sim**	**Obs**	**Sim**	**Obs**	**Sim**	**Obs**	**Sim**	**Obs**	**Sim**	**Obs**	**Sim**	**Obs**	**Sim**	**Obs**	**Sim**	**Obs**	**Sim**
2005	8536.4	**10476.2**	320.4 (3.8)	**435.3 (4.2)**	4061.6 (47.6)	**6744.1 (64.4)**	2740.9 (32.1)	**2862.9 (27.3)**	920.7 (10.8)	**2789.3 (26.6)**	1202 (14.1)	**1527.1 (14.6)**	935.8 (11.0)	**1450.5 (13.8)**	347.5 (4.1)	**627.0 (6.0)**	170 (2.0)	**393.6 (3.8)**
2006	7720	**8825.7**	331.1 (4.3)	**395.7 (4.5)**	4070.6 (52.7)	**6030.4 (68.3)**	2673.7 (34.6)	**2675.4 (30.3)**	1173.1 (15.2)	**2567.0 (29.1)**	1168.1 (15.1)	**1558.4 (17.7)**	876.4 (11.4)	**1546.3 (17.5)**	349 (4.5)	**763.9 (8.7)**	230.3 (3.0)	**464.3 (5.3)**
2007	10297	**11460.5**	348 (3.4)	**492.0 (4.3)**	4769.2 (46.3)	**7522.0 (65.6)**	2715.3 (26.4)	**3130.5 (27.3)**	1324.6 (12.9)	**3228.9 (28.2)**	1176.6 (11.4)	**1692.9 (14.8)**	850.6 (8.3)	**1622.8 (14.2)**	350.6 (3.4)	**697.1 (6.1)**	200.6 (2.0)	**421.9 (3.7)**

Obs = Observed, Sim - Simulated

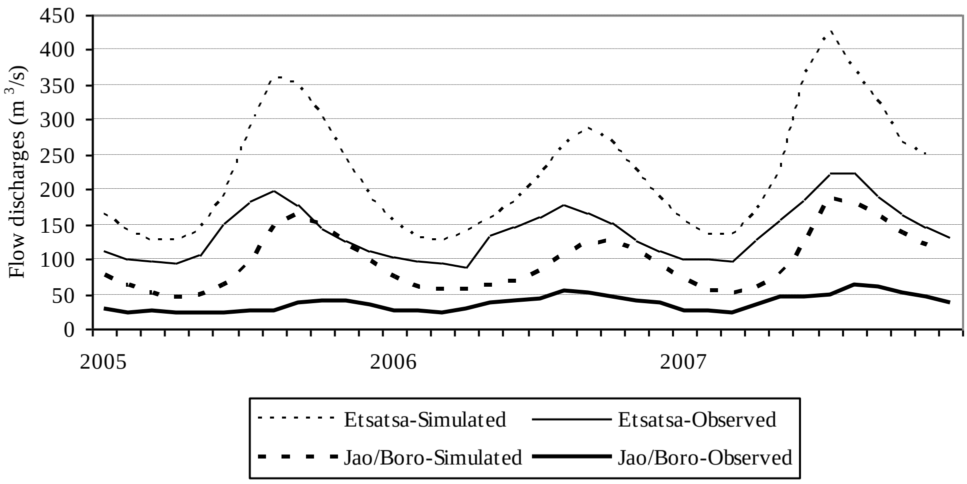

Figure 6: Differences between the simulated and the observed flow discharges at Etsatsa (Okavango River) and at Jao/Boro in Jao-Boro distrbutary system

Jao-Boro river system

The trends in the combined flow distribution of the floodplains and the main channel are directly correlated between the simulated and the observed at Etsatsa and Jao/Boro although the simulated discharges have been higher than the observed particularly in the peak flood events, invariably between March and June of hydrological years (Figure 6 and Table 1). Wolski *et al.* (2005) using regression model, shows how the flood wave propagates in Jao-Boro distributary and provides the importance of storage effects with inputs of inflow and rainfall. The Jao-Boro distributary receives water as over-bank spill between Etsatsa (972.7m) and Duba (968.7m) (Figure 1) and intensifies in the flood season, thus characterised by strong seasonal variation as compared to the other distributary systems in the Delta. Almost similar volumes of flows are observed by simulation in Jao/Boro (968.0m) compared to Duba (968.7m) (Figure 7, Table 1), even though Jao/Boro is in the downstream of Duba and however, both the sites lie at the same altitudes. The swamp storage is gradually released in subsequent months on the west of Jao and water levels there fall, resulting in minimum discharges in the area to support the part of Boro system even during the off flood season. Various distributaries in the Delta are characterised by a different flood events. The Boro river, for instance, is thus very dynamic, with a significant difference between the annual minimum and annual maximum simulated discharges (minimum to maximum: 2005 = 139.4 to 360.3 m^3/s, 2006 = 125.4 to 286.9 m^3/s, 2007 = 133.5 to 425.9 m^3/s) in the flows (Figure 7) resulting in the extension of floodplains and water levels. The amount of volumes arriving at Etsatsa in every year (Table 1) is so great and much of the spills activate the ponds, pools and relict channels (Porter and Muzilla 1988) on the west of Jao River thus acting as a large seasonal reservoir. The Jao-Boro seasonal reservoir, as it may be called, not only feeds the Boro River and its associated floodplain but also the Matsibe distributory system and out flows to Thamalakane /Boteti Rivers and Lake Ngami seasonally (Figure 1).

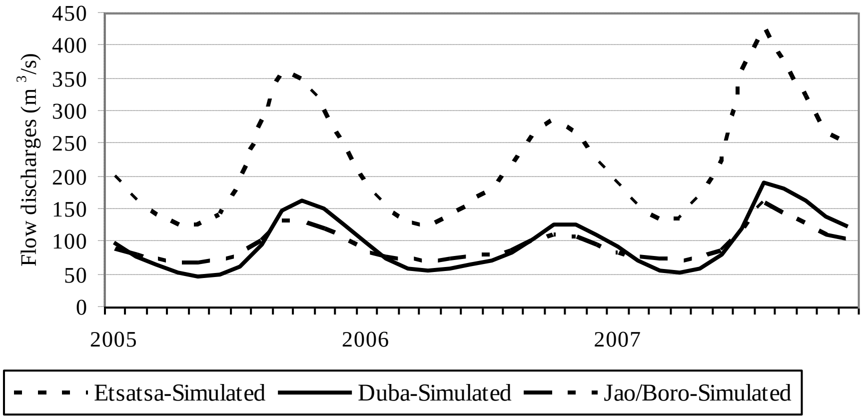

Figure 7: Comparison of Simulated discharge of the three stations, Etsatsa and Duba in the Okavango River and Jao/Boro in Jao-Boro distributary system

Maunachira River System

Lagoon type of water bodies is found in the origin of Khiandiandavhu channel, which curves as a loop to join Maunachira at KM-Junction (Figure 1). Although Gaenga (952.1m) is in the upstream of Khiandiandavhu (953.0m), there is no significant difference in the simulated flows between Gaenga and KM-Junction (Figure 8) because a flow path (Figure 1) adjacent to Nqoga River carries much of the filter flows to Khiandindiavhu channel, which eventually joins the KM-Junction. The peaks in the simulated flows represent the flood events in the section of Nqoga river (Figure 8) and Maunachira as well, even though the intensity is not that high in ranges. Kurugundla (2005) reported that ca. 56% total flows at Hamoga (Figure 1) in Nqoga River were diverted towards Khiandiandavhu wetlands between July 2003 and July 2004 apparently due to blockages and sediment build up process. This shows that the bulk of water accession to Maunachira is through bank filtration all along Nqoga section and the blocking of channel at Ham,ogal do not significantly affect the water flows between Nqoga and Maunachira Rivers (Wolski *et al.* 2005). It may be noted that observed discharges at Gaenga and KM-junction remain relatively constant as the Nqoga and Maunachira channels have a very definite conveyance capacity due to papyrus fringes. Maunachira area at KM-junction is deeper (Figure 3) (953.0M) than Jao-Boro section (968.0m) indicating higher volumes of water should be flowing in the eastern distributary.

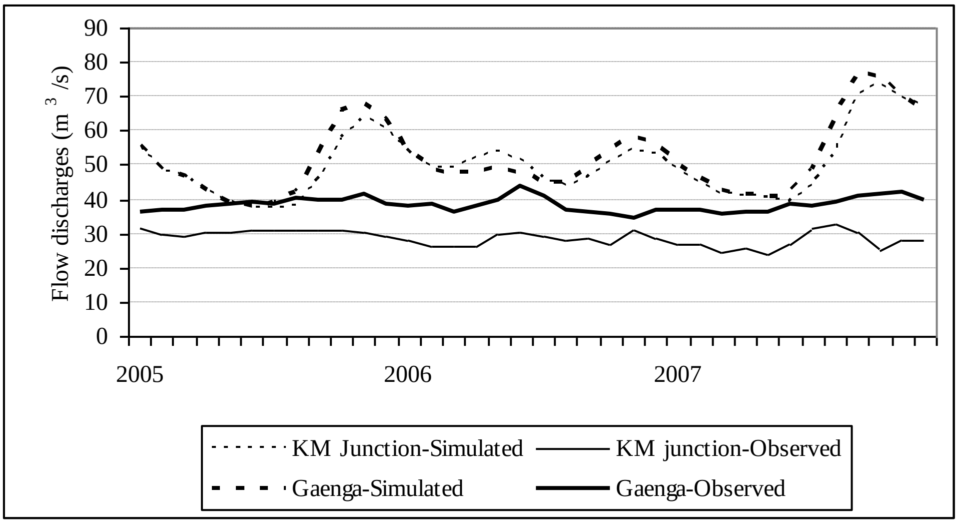

Figure 8: Comparative account of flow discharges between the simulated and the observed at Gaenga (Nqoga) and at KM- Junction (Maunachira)

The hydrometric station, Gadikwe representing Maunachira proper receives the flows rather efficiently than Lopis on Mboroga River (Figure 9). Maunachira always receives higher volumes of flows as compared to the Mboroga River as the lower Nqoga feeding the Mboroga in the earlier periods became desiccated about more than thirty years ago (Ellery *et al*. 1993), With the result, a secondary channel, the Khiandiandavhu River activated to become a primary channel, possibly by direct connection to the main Maunachira River (McCarthy *et al*, 199, 1992 and 1993).. Thus Maunachira River facilitates the smooth distribution of water flows in the easterly direction to reach Khwai River all the times of the years

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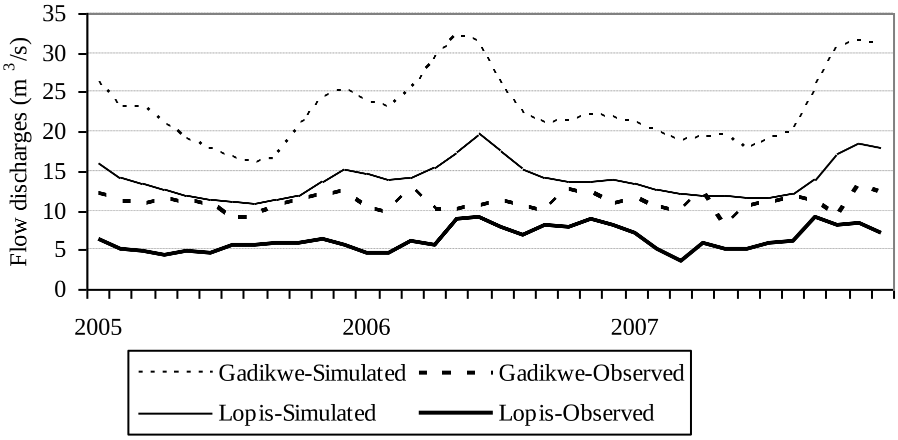

Figure 9: Comparative account of flow discharges between the simulated and the observed at Gadikwe (Maunachira River) and Lopis (Mboroga River)

Several models of conceptual character were developed to explain the hydrological process in the Okavango Delta. Some are successful in their application and some are criticised in their representation. In the earlier periods, hydrological models were applied to know the floodplain-ground water flows (Gieske 1996), and water balance at the scale of a single floodplain at Beacon Island (Dincer *et al.* 1976). Recently a distributed MODFLOW-based model was developed by Bauer (2004) and Wolski *et al.* (2005) in a hybrid reservoir-GIS model have shown that infiltration and ground water flow processes are explicitly represented with a set of reservoirs for the Okavango Delta. An attempt is made in the present study to apply MIKE SHE model to know the flooding distribution in the Okavango Delta. MIKE SHE Model integrates and simulates the overland flow distribution in two dimensional pattern through swamps and floodplains coupling with MIKE 11, which describes water levels and flows through the main river channels of the Delta.

The channel and floodplain discharges can't be obtained separately in the model. Rather, the model simulates the sum of these two fluxes across unit boundaries as distributary flows. The magnitude and seasonal dynamics of channel flows differ considerably from that of the entire distributaries (Wolski *et al.* 2006). Similar differences between the observed and the simulated discharges across the hydro stations of major distributaries in the upper part of the Delta are obtained in the study.

The strong seasonal variation in the flooding and storage in Jao-Boro distributary as compared to Mboroga and Maunachira systems (Wolski *et al.* 2005; Wolski *et al.* 2006) supports with MIKE SHE model floodplain-channel simulated flow discharges. The amplitude of flood – induced water discharge fluctuations in Mboroga and Maunachira is less pronounced as compared to the Jao-Boro system. The present analysis concurs with the observations of Wolski *et al.* (2005) that the propagation and distribution of flood in Mboroga and Maunachira is mostly related to the complexity of paths with inherent properties of floodplain-channel interactions, coupled with slow and gradual increase/decrease of flood. Wolski *et al.* (2006), in their model displayed less flood variation due to inundated deep areas and flood expansion in response to the rainfall and arrival of flood wave. Thus MIKE SHE Model is able to reproduce the similar dynamics of the flooding representative of flow discharges in the eastern distributaries of the Delta. The complexities in the flow paths describes the continuous inundation in the systems and provides the sustainability for biodiversity and ecological integrity.

The behaviour of inundation area and water levels in the Okavango Delta system can be explained by assuming the model simulated results representing the three flow sharing stations of the major tributaries. Inflow at Mohembo contributes to the surface storage in Thaoge, which fills up fast, and the release is slow as there is not much variation in the flow discharges in the hydrological years (Figure 5, Table 1). The flood wave moves fast onto the west of Jao River in the peak floods, fills up slowly and releases gradually to Boro and Xudum systems. The flood pulse in Maunachira also fills up slowly due to the stability in vast inundation characterised by ponds, lagoons, small streams etc., at the mouth of Khiandiandavhu, releases slowly even though the water levels decline in the Okavango river probably up to the upstream of Duba area. Active storage is the one that is replenished by inflow from upstream and determines the outflow to the downstream areas (Wolski *et al.* 2006) and the phenomenon is well displayed by the model in Jao-Boro distributary. In contrast, the passive storage is mostly shallow floodplain storage that floods over a large extent but does not convey much water and which is represented in Thaoge River system. Wolski *et al.* (2005) suggested that the flood lag in the Delta should be attributed to shallow water rather than to low topographic slope. The movement of flood is dependent on the scale of inundation in a year and slope in the topography of the Delta.

Conclusion

This paper has demonstrated that the channels within the Okavango Delta lose and gain flows due to spilling of water onto floodplains, and some of this water flowing back to the same or other channels. The Okavango Delta has very low gradient (1:3700) and highly permeable Kalahari sands and therefore no significant runoff from floodplains into the delta channels occurs. Thus the increase in channel flows is due to water that would have spilled onto the floodplains flowing back into channels. The presence of lagoons along some channels such as along the Khiandiandavhu Channel north of Nqoga River results in substantial supply of water to channel flows in every hydrological year.

A major challenge is to establish thresholds at which channel spill onto and from the floodplains. Spilling of water onto floodplains affects habitats, for example for small and large herbivores. Permanent switching of flow from one channel to another is a characteristic feature of the delta in long-term time scale. There is as yet an incomplete understanding of causes of the switching. Switching of flows has major effects on flow distribution as is evident from the Thaoge River which some 120 years ago was perennial. In addition the switching of flows changes habitats, goods and services provided by rivers including livelihoods (Kgathi et al, 2007). Further work aimed at improving understanding of how flow partitioning affects hydro-ecological linkages, and prediction of flow partitioning is required as this is critical for environmental flow estimation.

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