DETECTION AND CAUSAL FACTORS OF CHANGE IN FLOOD DISTRIBUTION IN THE OKAVANGO DELTA, BOTSWANA.

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ABSTRACT

Flooding in the Okavango Delta is very variable both at short and long term time scales. The variation in flooding strongly affect users of water and wetland resources, and the temporal and reversible effects of climatic variation and non-linearity of the Okavango Delta hydrological system are often confused with the effects of system change that are permanent and irreversible. Understanding of causal factors of changes in flooding in the Okavango Delta observed currently and in the past is necessary for determining future prospects and is critical for preventing unnecessary development pressure and for wise management of the world largest Ramsar site. Hydrometric data and satellite-derived inundation areas are analysed here using statistical methods (covariance analysis) to distinguish between temporal and permanent changes in various parts of the Okavango Delta. The results show that statistically significant changes in the input-response relationship occurred in the past in various parts of the Okavango Delta. Depending on the presence and direction of change in neighbouring distributaries, some of these changes are interpreted as effects of system non-linearity, some however, as resulting from physical change in the system. The *high flow* *regime of one of the distributaries, the Boro, observed in 1974-1981, earlier thought to result from physical change in the system was re-interpreted as an effect of system non-linearity, triggered by an exceptionally high rainfall. A physical change in the system is the likely explanation of the relative increase in flooding of one of the distributaries, the Xudum, observed recently. The results suggest that the increase in Xudum flooding took place at the expense of the Thaoge, and not, as previously thought of the Boro.*

Key words: Okavango, wetlands, flood, change

INTRODUCTION

The Okavango Delta (**Fig. 1**) is a RAMSAR site the natural resources of which support a large tourism industry and subsistence of the local population. In the last three decades a general decline of flooding extent occurred, with some parts of the Delta being affected more than the others. So far, the Delta has escaped major human interventions, but technical alterations such as channel clearing are being considered. These proposals are prompted by drying up of floodplains and development of vegetation blockages in channels in the vicinity of settlements and safari camps. Such actions can potentially alter the natural geomorphological dynamics of the system and be harmful to the Delta ecosystem, and they engineering results might not be sustainable. Understanding of the processes causing flood decline and flooding shifts within the Delta is thus absolutely necessary for proper management of its natural resources, and for taking decisions about any technical interventions in particular.

Changes in the flooding within the Okavango Delta results from either variation in hydrological inputs, or changes in distribution of water within the system. Hydrological inputs (inflow from the feeding Okavango river and local rainfall) vary strongly, and in long term the variation is dominated by cyclicity (McCarthy et al., 2000; Wolski et al., 2002) with a well pronounced decline between the 1970s and 1990s (Fig. 2). Additional effects can possibly arise from the non-linearity of the system, i.e. responses not being linearly proportional to inputs, and possible spatial variation in the input-response relationship. As for the change in water distribution within the Delta, historical sources show that major changes occurred in the past. The western distributary, the Thaoge, was delivering water to Lake Ngami during the 1880s, but ceased to do so during the 1920s, and has virtually desiccated (Wilson, 1973). Similarly, a part of Mboroga distributary desiccated in the 1960s (McCarthy et al., 1988). The processes leading to abandonment of a distributary or its part are sedimentation in the channels and a series of feedbacks it initiates, described in details by McCarthy et al. (1992). It has also been suggested that tectonic events can facilitate or even cause shifts of flood distribution (McCarthy et al., 1993).

The important difference between the change in flooding resulting from variation in inputs and that resulting from endogenic processes is the permanency. Reduction in flooding caused by decrease in inputs is reversible – larger floods will come in years of higher rainfall and inflow. Reduction in flooding caused by endogenic processes is rather irreversible – increase in flooding cannot be expected within the geomorphological cycle of aggradation-desiccation, i.e. at least in the period of 150 years and more. It is thus important to distinguish between the two different types of change.

Detection of change in hydrological time series has recently grown to be an important topic in the science of hydrology (Kundzewicz, 2004). Most of the work focuses on analysis of a single time series and development/improvement of statistical tests that allow identification of gradual or abrupt change in mean, standard deviation etc, in a time series characterized by a certain degree of variability and non-normal distribution (Kundzewicz and Robson, 2004). For proper interpretation of detected change, results of such analyses have to be related to auxiliary information on timing and magnitude of possible changes in the system (e.g. changes in land use or trends in rainfall, while analysing catchment discharges). In a situation where there is an internal change within the system, hydrological observations have to be analysed in relation to observations at sites where such a change has not occurred, e.g. inflow to a delta (Polonsky, 1996).

In this paper we address and illustrate the issue of detecting and interpreting internal changes in a hydrological system comprising broad low gradient floodplains, characterized by a strong variation in inputs.

STUDY AREA

The features of the Okavango Delta have been described in detail elsewhere in the literature (e.g. Gieske, 1997; Gumbricht et al., 2004; McCarthy et al., 1998). In brief, the Delta is a large alluvial fan with surface gradient in the order of 1:3700, where water and sediment from the inflowing Okavango River is spread across the conical surface through a system of channels and floodplains (Fig. 1). Channels in the system have permeable banks formed by reeds and sedges (Ellery et al., 1993). The upper part of the Delta, the Panhandle, is a 20 km broad flat-bottomed valley, with a well defined meandering channel. At the apex of the alluvial fan proper, the channel flows through a relatively unbound system of floodplains. Further downstream, chains of islands cause differentiation of relatively separate distributaries, or systems of channels and floodplains. The Chief's Island, the largest land body in the Delta, divides the Delta into eastern and western part. The three major distributaries of the western part, the Thaoge, the Xudum and the Boro (Fig. 1) are of main interest in this paper.

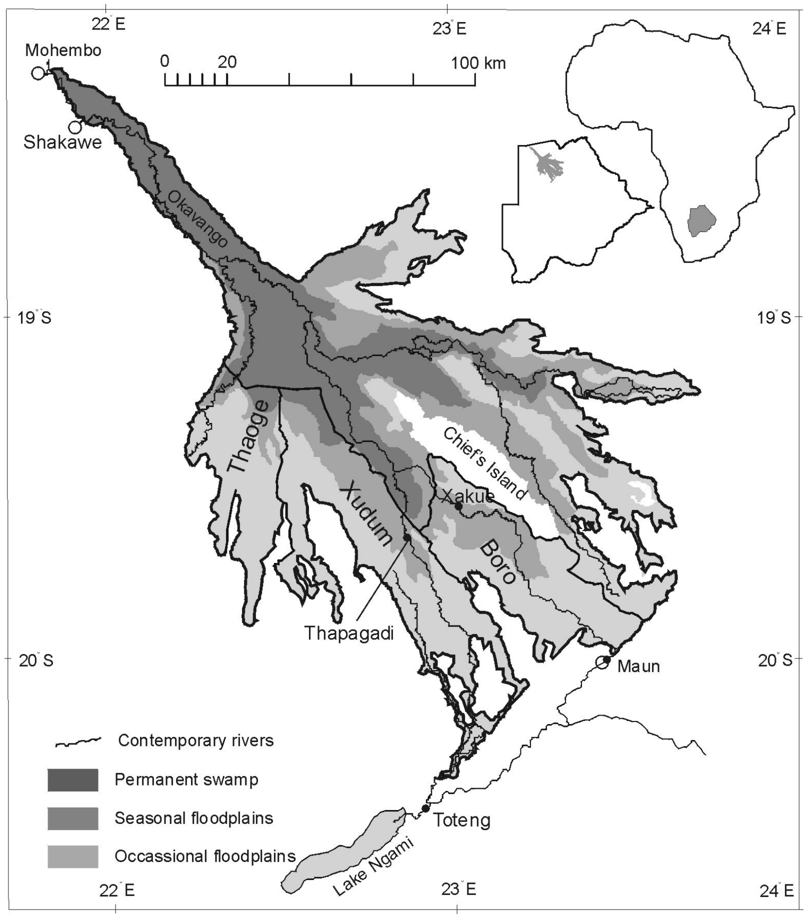

Fig. 1 Main hydrological features of the Okavango Delta.

Annually, in response to the flood wave arriving with the Okavango River, the inundated area expands from the annual low of 3500-6000 km^2 in January/February to the annual high of 6000-12000 km^2 in August/September. This flood event is out of phase with the rainy season which lasts from November to March. This is partly caused by delay of the flood wave on its way from the 600 km distant headwaters of the feeding Okavango River, and partly by slow propagation of the flood in the Delta proper.

MATERIALS AND METHODS

There is a number of hydrometric stations in the Delta where channel water levels and (or) discharges are measured (logistics allowing) once monthly. Data from these stations cover the period of 1970-2004. For this work, two stations in the Boro distributary (Xakue and Maun) and two stations in the Xudum distributary (Thapagadi and Toteng) were selected. The stations were selected based on length and consistency of record, and on location: central and distal parts of each distributary was represented. The satellite imagery-derived flood maps used in this study cover the period of 1985-2004, have spatial resolution of 1x1 km, and temporal resolution of 10 days, but with numerous gaps. Derivation of the maps is described by McCarthy et al. (2004). For the purpose of this study, annual flow series were derived for each analysed hydrometric station and mean monthly inundated area were determined for each analysed distributary. Long-term rainfall data are available only for Maun and Shakawe, and the average annual rainfall from these stations was used.

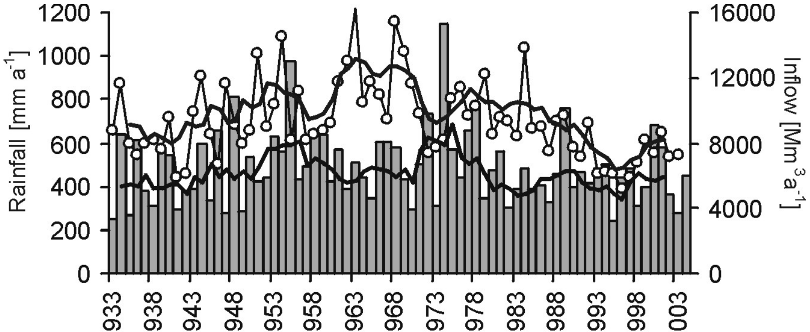

Fig. 2 Hydrological inputs to the Okavango Delta: annual flow at Mohembo (circles) and average annual rainfall at Maun and Shakawe (bars), with 5-year moving average (bold lines).

The time series of inputs, and thus also of responses (water levels, discharges, flood extents) are non-stationary (Fig. 2). To test for change in hydrological responses of the system, a single time series analysis could not be used, as the detected change would reflect the change in inputs rather than the effects of processes occurring within the system. The hydrological responses in the analysed system are influenced by several factors: local rainfall, inflow to the system and antecedent conditions. A change in the system should therefore manifest itself by a change in relationship between given response and its influencing factors. Relationships between hydrological responses and inputs in the Okavango Delta are relatively well expressed using multiple linear regression models both on the annual basis (McCarthy et al. 1998, Gumbricht et al. 2004) and on the monthly basis (Wolski et al., 2005a). In order to assess changes occurring in the system, we use multiple linear regression relationships between inputs and responses in a framework of covariance analysis (Helsel and Hirsch, 1991). In this analysis, a binary variable is introduced into the multiple regression, taking values of 1 for a period when change was expected to occur and 0 for period after/before the possible change. The regression coefficient obtained for this variable reflects a shift (an additive term) in the relationship between explanatory variables and a dependent variable occurring between the periods. Significance of the shift is assessed using a t-test for the regression coefficient of the binary variable, which is equivalent to a partial F-test on the regression with and the regression without the binary variable, as described by Helsel and Hirsch (1991).

For covariance analysis the point of time when change occurs has to be known. This was determined based on exploratory data analyses and results of previous analyses for the Okavango Delta, described in the literature. Also, double mass plots were used.

ANALYSIS

The 1974-1981 "high flow regime" in Boro distributary

In earlier analyses, SMEC (1990) have shown that during 1974-1981 discharges at Maun, reflecting outflow from the Boro distributary, were larger in relation to the inflow into the Delta than before and after that period. The hydrological model prepared by SMEC (1990) failed to simulate the relative increase in outflow during the 1974-1981, and empirical changes in model parameters were introduced in order to represent the shift in flood distribution. SMEC (1990) suggested, that a "physical" change of undefined nature occurred in 1974 at headwaters of Boro distributary, with Boro distributary receiving more water at the expense of Xudum distributary (Fig. 1), and a change in opposite direction, i.e. an increase in Xudum at the expense of Boro, occurred in 1981. This was criticized by Scudder et al. (1993) who suggested that the perceived increase was an apparent effect of data errors. Later, Gieske (1997) explained the increased outflows from Boro distributary as a response of the system to long term antecedent rainfall variation, but his explanation implicitly suggested change in flow distribution. The analyses done by Gieske (1997), Scudder et al. (1993) and SMEC (1990) concentrated on Maun station, and the eventual effects of redirection of flow towards the Xudum were not tested. Here, in order to check whether the increased outflows from Boro distributary resulted from a shift of flood between the distributaries, we have decided to use the available data from Xakue and Maun stations in the Boro and Thapagadi and Toteng stations in the Xudum distributary, and take advantage of the longer available time series. The annual flows at each of the stations (Q_t) were related in a multiple regression model to annual inflow to the Delta ($Q_{in,t}$), annual rainfall (P_t), and previous year flow at given station (Q_{t-1}), i.e.:

$$Q_t = a \cdot Q_{in,t} + b \cdot P_t + c \cdot Q_{t-i} \qquad (1)$$

In the covariance analysis, models described by Eq. 1 were compared to the ones having the general form of:

$$Q = a\cdot Q_{in} + b\cdot P + c\cdot Q_{last} + d\cdot B \tag{2}$$

where the binary variable B took the value of 1 for years of 1974-1981, and 0 for 1970-1973 and 1981-2003. However, for covariance analysis only significant (at 95% significance level) explanatory variables of models described by Eq. 1 were chosen (Table 1). The results of covariance analysis are presented in Table 1, and comparison of observed and simulated annual flows at the four analysed stations, as well as regression residuals are presented in **Fig. 3**. The results indicate that the increase in annual flows during the 1974-1981 period is statistically significant at Maun in Boro distributary and at Toteng in Xudum distributary.

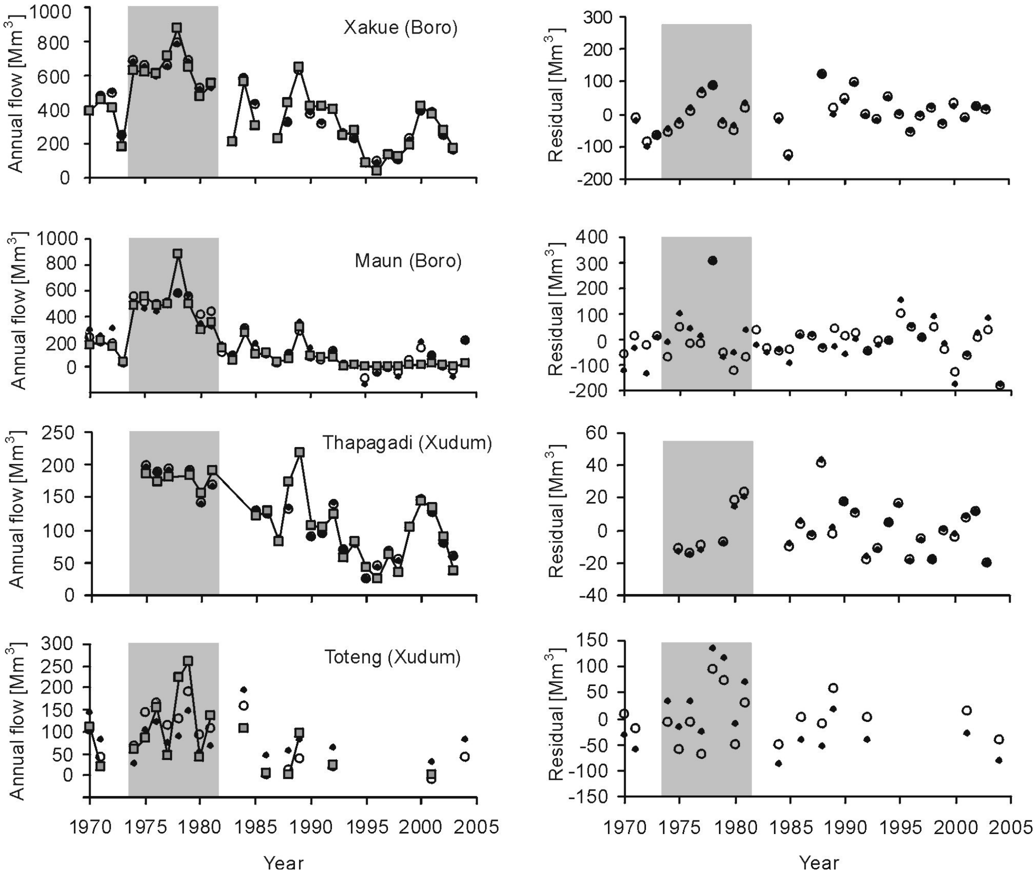

Fig. 3 Annual discharge time series for Xakue, Maun, Thapagadi and Toteng, observed (grey squares) and simulated with a regression model, residuals of the regression (solid dots – without binary variable, open circles – with binary variable).

Table 1

Results of covariance analysis for shift in annual flows between 1974-1981, and 1970-1973 and 1982-2004.

Distrib.	Station	Number of observations (total/period of change)	Variables in regression[*]	Correlation coefficient r (with binary variable/ without)	Shift direction	p-value[**]	H_0 (there is no shift)[***]
Boro	Xakue	29/8	$Q_{in,t}$, P_t, Q_{t-1}	0.97/0.97	Increase	0.42	Not rejected
	Maun	35/8	$Q_{in,t}$, P_t, Q_{t-1}	0.94/0.91	Increase	0.002	Rejected
Xudum	Thapagadi	22/4	$Q_{in,t}$, P_t	0.96/0.96	Decrease	0.60	Not rejected
	Toteng	16/8	$Q_{in,t}$	0.80/0.59	Increase	0.005	Rejected

[*] $Q_{in,t}$ – annual inflow at Mohembo, P_t – annual rainfall, Q_{t-1} – previous year annual flow at a given station

[**] partial F-test on regression with vs. regression without the binary variable

[***] at the 0.05 significance level

Increase of flooding in the Xudum

The 2004 flood caused inflows to Lake Ngami, which is a terminal part of Xudum distributary, that were apparently larger compared to the outflows from the Boro distributary. The effects of comparatively larger flooding in Xudum distributary has been noticed earlier by Gumbricht et al. (2004), who suggested that this has occurred since 1994 at the expense of the neighboring Boro distributary and is caused by tectonic dislocation at a lineament detected earlier by McCarthy et al. (1997).

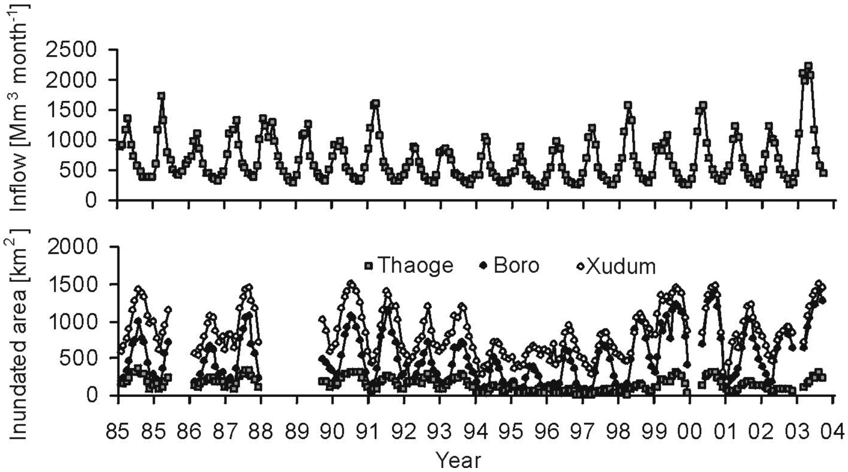

Fig. 4 Mean monthly inflow at Mohembo and mean monthly inundation areas in Boro, Xudum and Thaoge distributaries.

In order to assess the eventual change in the system, we have decided to analyse the relationship between mean monthly inflow and mean monthly inundated area in each of the main distributaries in the western part of the Delta (Fig. 4). Wolski et al. (2005a) have shown that it is possible to establish a good relationship between mean monthly inundation area and hydrological inputs (inflow and rainfall), however, the inputs have to be transformed. Here, based on the exploratory data analysis, mean monthly inflow was lagged by 4 months and log-transformed to obtain a linear relationship mean monthly inundation area. To detect the timing of occurrence of eventual shift in flooding, a double mass plot was prepared of mean monthly inundation area in each of the western distributaries against the transformed inflow at Mohembo (**Fig. 5**).

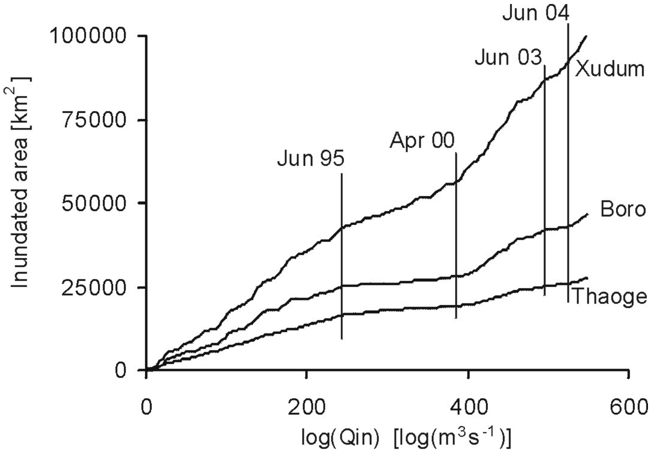

Fig. 5 Double mass plots of mean monthly inundation area in selected distributaries against modified inflow.

Several prominent breaks of slope of the double mass lines occurring concomitantly at all three distributaries could be distinguished: a decline in slope in May 1995, an increase in slope in March 2000, a decline in slope in June 2003 and again an increase in March 2004. Each of these breaks essentially expresses a change in conditions of flooding in the system. However, the periods with lower slope of the double mass lines (1995-1999 and 2003) coincide with the periods of low inflow (Fig. 2). The occurrence of different inflow-inundation area relationship (different flood regimes) can be explained by the way the distributaries are hydrologically linked with the permanently flooded part of the Delta which supplies them, with possible influence of antecedent conditions. The analysed distributaries receive water from upstream through a spill-over mechanism, i.e. only when the water level (or storage) in the upstream feeder exceeds a certain threshold value. During the low inflow years of 1995–1999 as well as in 2003 that threshold was barely exceeded, which resulted in comparably smaller flood extents in the analysed distributaries. The Xudum probably links more directly with the feeding upstream part of the Delta, or the threshold level is lower than that in the Boro and Thaoge, and thus, the decline in flooding in the Xudum was less pronounced (less prominent decline in slope for 1995-2000, **Fig. 5**) than in the other distributaries. At the arrival of larger floods in 2000 and in 2004, all three distributaries displayed relatively larger flooding. The effect of the low flood regime of the 1995-2000 and for 2003 is therefore similar in nature to the high flow regime observed in Boro (and in Xudum) in 1974-1981, described in the previous section. In view of this, the eventual "physical" change in the system should manifest itself through change in the inflow-inundation area relationship between hydrologically comparable periods, i.e. pre-1995 and 2000-2002. The tested regression model was described by a general equation:

$$A_t = a \cdot \log(Q_{in,t-4}) + d \cdot B \quad (3)$$

where A_t is the mean monthly inundated area in a given distribuatary, $Q_{in,t-4}$ is the monthly inflow at Mohembo (*t-4* denotes a 4 month lag), and *B* is the binary variable taking the value of 1 for 2000-2002 period and the value of 0 for 1985-1995 period. The summary of covariance analysis performed on these time-series is presented in Table 2 and **Fig. 6**. The analysis reveals a statistically significant increase in flooding in Xudum, a statistically significant decrease in flooding in Thaoge and a lack of change in Boro. The increase in Xudum flooding is therefore confirmed by the data, and seems to be caused by shift from the Thaoge, and not, as earlier suspected from the Boro. In order to pinpoint the time of eventual shift, cumulative mean monthly inundation area at Xudum was plotted against the cumulative mean monthly inundation are at Thaoge (**Fig. 7**). The distinct change in slope of the line suggests that the shift has taken place in July 1997.

Table 2

Results of covariance analysis for shift in inflow-inundation area relationship between 2000-2002 and 1985-1995.

Distributary	Number of observations (total/period of change)	Shift direction	Correlation coefficient r (with binary variable/without)	p-value[*]	H_0 (there is no shift)[**]
Boro	128/35	Increase	0.78/0.77	0.11	Not rejected
Thaoge	128/35	Decrease	0.77/0.75	0.009	Rejected
Xudum	128/35	Increase	0.86/0.80	<0.0001	Rejected

[*] partial F-test on regression with vs. regression without the binary variable

[**] at the 0.05 significance level

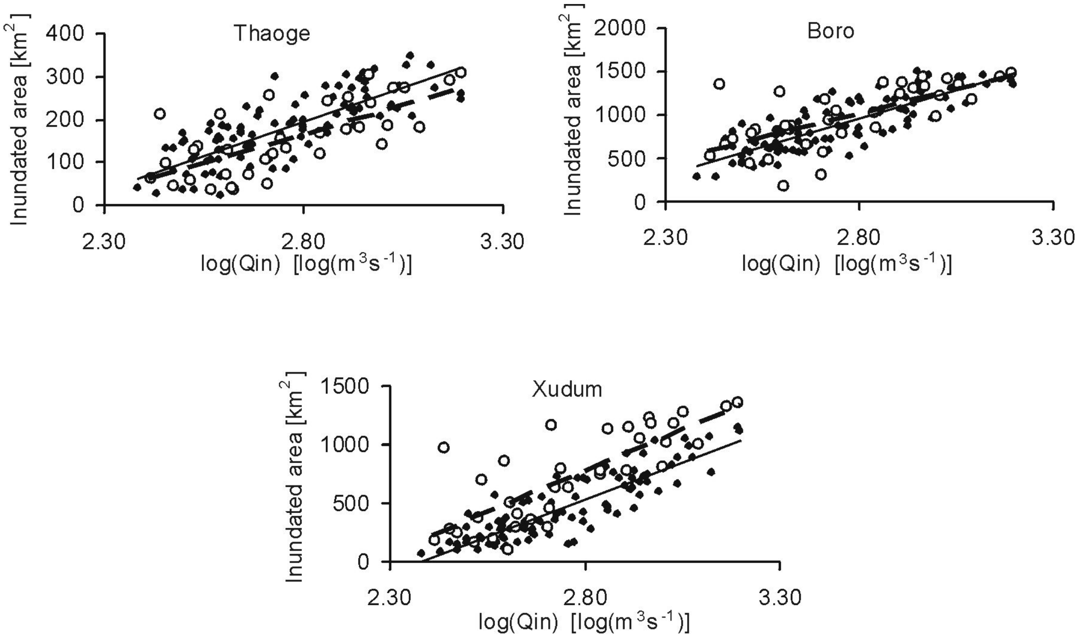

Fig. 6 Relationship between the modified inflow and mean monthly inundation area in Boro, Xudum and Thaoge distributaries for pre-1995 (solid dots and solid line) and 2000-2003 period (circles and dashed line).

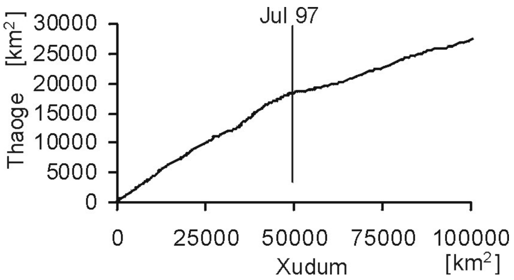

Fig. 7 Double mass plot of mean monthly inundation area in Xudum and Thaoge.

DISCUSSION

The analysis of flow time series from Boro stations revealed that indeed the relative increase in Maun flows observed between 1974 and 1981 was statistically significant. However, similar, statistically significant increase was observed in flows at the terminal station of Xudum distributary, Toteng. It is not, therefore, possible, that the Boro distribuatary increase was caused by redirection of some water from the Xudum, as suggested by Gieske (1997) and SMEC (1990). The onset of the "high flow regime" occurred in 1974 when rainfall of 1145 mm a^{-1} was recorded, which is the highest annual rainfall on record. In a recent hydrological model (Wolski et al., 2005b) the effects of rainfall recharge on groundwater were simulated. The rise in groundwater levels due to the high recharge in 1974 caused reduction of infiltration losses and thus an increase in the amount of water available for outflow from the system. The high groundwater table conditions lasted for several years, and caused the persistence of higher outflows. The effect of increased outflows was simulated not only in the Boro, but in the entire system, and thus also in the Xudum. The results of that modelling study agree with the relative increase in Toteng outflows detected in our study. However, the methods used here did not detect increased flows during the 1974-1981 in the stations in the central Delta. These stations, however, do not capture variability associated with off-channel flows, which could be significant, as the 20-30 m wide channels at both the Thapagadi and Xakue are located within the 500-3000 m wide system of floodplains. In the Maun and Toteng stations, where the increase was detected, essentially entire flow is measured, as flow at these stations is confined in well-defined valleys. The analyses presented by Wolski and Murray-Hudson (2005) reveal strong differences in dynamics of channels and distributaries in the Delta, and thus it is likely that the effects of increased flows in the central part of the system were present, but were simply not revealed by the existing monitoring network.

In view of the above, it therefore seems that the so-called “high flow regime of Boro” is not an effect of change in flood distribution, but results from the high rainfall of 1974, and signifies a non-linearity of the system.

The strong non-linearity of the system is also revealed in the analyses of mean monthly inundation area in the western distributaries of the Okavango Delta. Firtstly, there are periods characterized by different inflow-inundation area relationship (different flooding regimes), possibly responding to prevalent wetness conditions in the system. Secondly, within such periods, the relationship between inundated area and inflow is non-linear. Thirdly, each distributary is characterized by a different inflow-inundation area relationship (different slopes indirectly shown in **Fig. 6**). All these cause the responses of various distributaries to changing inputs to be different, giving an appearance of change in flood distribution. However, we have detected a statistically significant change in hydrological responses that appears to result from a physical change in the system. That change has a nature of a shift in flood distribution between the Thaoge and the Xudum, with the latter receiving more water after 1997 at the expense of the former. The reasons of the shift can only be hypothesized at this stage: it can be either an effect of the aggradation of upper Thaoge, i.e. the process that caused desiccation of Thaoge in the beginning of the century, or it can be a tectonically facilitated redistribution of water. Unfortunately, at this stage no independent data exists that would allow for determination of causal factors of the shift, and confirm that the detected change is indeed the effect of physical change in the system, and not a transient effect resulting from system non-linearity and associated with a specific sequence of inputs.

CONCLUSIONS

The analyses presented here reveal that the hydrological responses of the Okavango Delta are strongly influenced by system non-linearity, and real physical changes rarely occur. The effects arising from non-linearity are temporary, while those arising from a physical change are permanent (within a planning time horizon). Additionally, the non-linear effects are systematic, while the physical change is much less so. It is extremely important to distinguish between these effects, as they have drastically different management implications. For example, the “high flow regime” of Boro, revealed here as a transient and systematic process, was previously thought to be an essentially random process (SMEC, 1990). The study by

SMEC (1990) was done in the context of designing a reservoir. Obviously, the design parameters of an eventual reservoir would be different depending which explanation of the "high flow regime" is accepted.

The important phenomenon revealed here is that the responses in the Okavango Delta are non-proportional to the inputs. Longer periods are present when flood extents and outflows are either considerably higher or lower (flow or flood regimes) than what would be expected considering the magnitude of inflow. The situation of lower flood is often perceived as an effect of permanent change in the system, and this perception results in unnecessary demands of interventions into the system and causes conflicts between the various users (communities, conservationists, safari operators, government departments) who often blame each other for causing the change. A greater understanding of the non-linearity and persistence of hydrological responses in the Okavango Delta is therefore imperative.

A number of comprehensive hydrological models have been developed recently for the Okavango Delta (Bauer, 2004; Jacobsen et al., 2005; Wolski et al., 2005b). Only the last model addressed the issues of presence and persistence of "flow regimes", although only with respect of the 1974-1981 period. Also, simpler regression models exists (Gumbricht et al., 2004; McCarthy et al., 1998; Wolski et al., 2005a). These models are linear and do not account for possible mechanisms causing flow regimes. The analyses presented here provide the basis for improvement of all these models.

LITERATURE

Bauer, P. (2004). Flooding and salt transport in the Okavango Delta, Botswana: key issues for sustainable wetland management. PhD thesis. ETH Zurich, Zurich.

Ellery, W. N., Ellery, K. and McCarthy, T. S. (1993). Plant distribution in islands of the Okavango Delta, Botswana: determinants and feedback interactions. *African Journal of Ecology* 31: 118-134.

Gieske, A. (1997). Modelling outflow from the Jao/Boro River system in the Okavango Delta, Botswana. *J. Hydrol.* 193: 214-239.

Gumbricht, T., Wolski, P. and McCarthy, T. S. (2004). Forecasting the spatial extent of the annual flood in the Okavango Delta, Botswana. *J. Hydrol.* 290: 178-191.

Helsel, D. L. and Hirsch, R. M. (1991). Statistical Methods in Water Resources. USGS, USA.

Jacobsen, T., McDonald, A. and Enggrob, H. (2005). Integrated Hydrological Model. Okavango Delta Management Plan, Department of Water Affairs, Gaborone, Botswana.

Kundzewicz, Z. W. (2004). Searching for change in hydrological data. *Hydrological Sciences Journal/Journal des Sciences Hydrologiques* 49: 3-6.

Kundzewicz, Z. W. and Robson, A. J. (2004). Change detection in hydrological records - a review of the methodology. *Hydrological Sciences Journal/Journal des Sciences Hydrologiques* 49: 7-19.

McCarthy, J., Gumbricht, T., McCarthy, T. S., Frost, P. E., Wessels, K. and Seidel, F. (2004). Flooding patterns in the Okavango Wetland in Botswana, between 1972 and 2000. *Ambio* 7: 453-457.

McCarthy, T. S., Barry, M., Bloem, A., Ellery, W. N., Heister, H., Merry, C. L., Rother, H. and Sternberg, H. (1997). The gradient of the Okavango fan, Botswana, and its sedimentological and tectonic implications. *Journal of African Earth Sciences* 24: 65-78.

McCarthy, T. S., Bloem, A. and Larkin, P. A. (1998). Observations on the hydrology and geohydrology of the Okavango Delta. *South African Journal of Geology* 101: 101-117.

McCarthy, T. S., Cooper, G. R. J., Tyson, P. D. and Ellery, W. N. (2000). Seasonal flooding in the Okavango Delta, Botswana - Recent history and future prospects. *South African Journal of Science* 96: 25-33.

McCarthy, T. S., Ellery, W. N. and Stanistreet, I. G. (1992). Avulsion mechanisms on the Okavango Fan, Botswana: the control of a fluvial system by vegetation. *Sedimentology* 39: 779-795.

McCarthy, T. S., Green, R. W. and Franey, N. J. (1993). The influence of neo-tectonics on water dispersal in the northeastern regions of the Okavango swamps, Botswana. *Journal of African Earth Sciences* 17: 23-32.

McCarthy, T. S., Stanistreet, I. G., Cairncross, B., Ellery, W. N., Ellery, K., Oelofse, R. and Grobicki, T. S. A. (1988). Incremental aggradation on the Okavango Delta-fan, Botswana. *Geomorphology* 1: 267-278.

Polonsky, V. F. (1996). Physicostatistical approach to river delta hydrology. *Journal of Hydraulic Engineering* 122: 333-340.

Scudder, T., Manley, R. E., Coley, R. W., Davis, R. K., Green, J., Howard, G. W., Lawry, S. W., Martz, D., Rogers, P. P., Taylor, A. R. D., Turner, S. D., White, G. F. and Wright, E. P. (1993). The IUCN review of the Southern Okavango Integrated Water Development Project. IUCN, Gland, Switzerland.

SMEC (1990). Southern Okavango Integrated Water Development Project. Department of Water Affairs, Gaborone, Botswana.

Wilson, B. H. (1973). Some Natural and Man-made Changes in the Channels of the Okavango Delta. *Botswana Notes and Records* 5: 132-153.

Wolski, P., Gumbricht, T. and McCarthy, T. S. (2002). In *Conference on Environmental Monitoring of Tropical and Subtropical Wetlands, 4-8 December 2002*Maun, Botswana.

Wolski, P., Masaka, L., Raditsebe, L. and Murray-Hudson, M. (2005a). Aspects of seasonal dynamics of flooding in the Okavango Delta. *Botswana Notes and Records* (in print).

Wolski, P. and Murray-Hudson, M. (2005). Factors affecting flooding in the Okavango Delta in view of analysis and interpretation of 30-year hydrometric record. *HESSD* (accepted).

Wolski, P., Savenije, H., Murray-Hudson, M. and Gumbricht, T. (2005b). Modelling the hydrology of the Okavango Delta, Botswana. *J. Hydrol.* (submitted).