Aspects of Seasonal Dynamics of Flooding in the Okavango Delta

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Abstract

Seasonal changes in inundation area and peak flood occurrence in the Okavango Delta are analysed using a multiple regression technique. The multiple regression models developed constitute useful and simple tools for predicting inundation area and peak flood occurrence in the Okavango Delta. The regression model for monthly inundation area achieves a coefficient of determination of 0.80 and standard error of 538 km^2. Explanatory variables in the model are various expressions of long-term and short-term antecedent rainfall and inflow conditions. The model for flood peak occurrence can be used for accurate predictions only in the Jao-Boro distributary, for which it achieves a coefficient of determination of 0.85 and standard error of 15 days, with distance to Delta inlet and an expression of flood size as explanatory variables. Propagation of the flood in the two other analysed distributaries, Maunachira-Khwai and Mboroga-Santantadibe, is complex and its quantitative description appears to be beyond the capacity of a simple regression approach. Additionally, the analyses presented provide insight into the role of storage in the dynamics of flood in the system: hydrological inputs are accommodated in the large system storage, and hydrological response is strongly dependent on the factors affecting (slow!) release from that storage. Based on the analyses, the classic model of kinematic flood wave propagation has been adapted accordingly.

Introduction

The Okavango Delta (Figure 1) is a large wetland pulsed by the annual flood of the Okavango River. The permanent and seasonal flooding creates an ecosystem in stark contrast to the surrounding rain-fed savannah of the Kalahari. This makes the Okavango Delta the basis for subsistence livelihoods of the local population, and the main attraction of Botswana's tourism industry. In 1997 the Okavango Delta was declared a Ramsar site – a wetland of international importance. An important hydrological feature in the Okavango Delta is the difference in timing of local rains and flooding. The flood expands several months after the end of the rainy season, during the dry cold period, which makes water practically available throughout the year. The timing of the flood in the system, i.e. when the flood arrives, achieves maximum extent and subsides, has thus profound consequences for the ecology of the system. Also, it directly affects farming (planting time) and tourism (accessibility).

Predicting flood timing is thus an important issue. However, probably even more important is the understanding of the controls behind the flooding process and its natural variation. Such understanding could be used to elucidate, for example, causes of reduced flooding and late flood arrival. This becomes important in view of increasing development pressure on the Okavango River and the Delta proper, and the common perception of Delta drying due to upstream abstractions.

Complex hydrological models are one of the solutions that can be applied to predict

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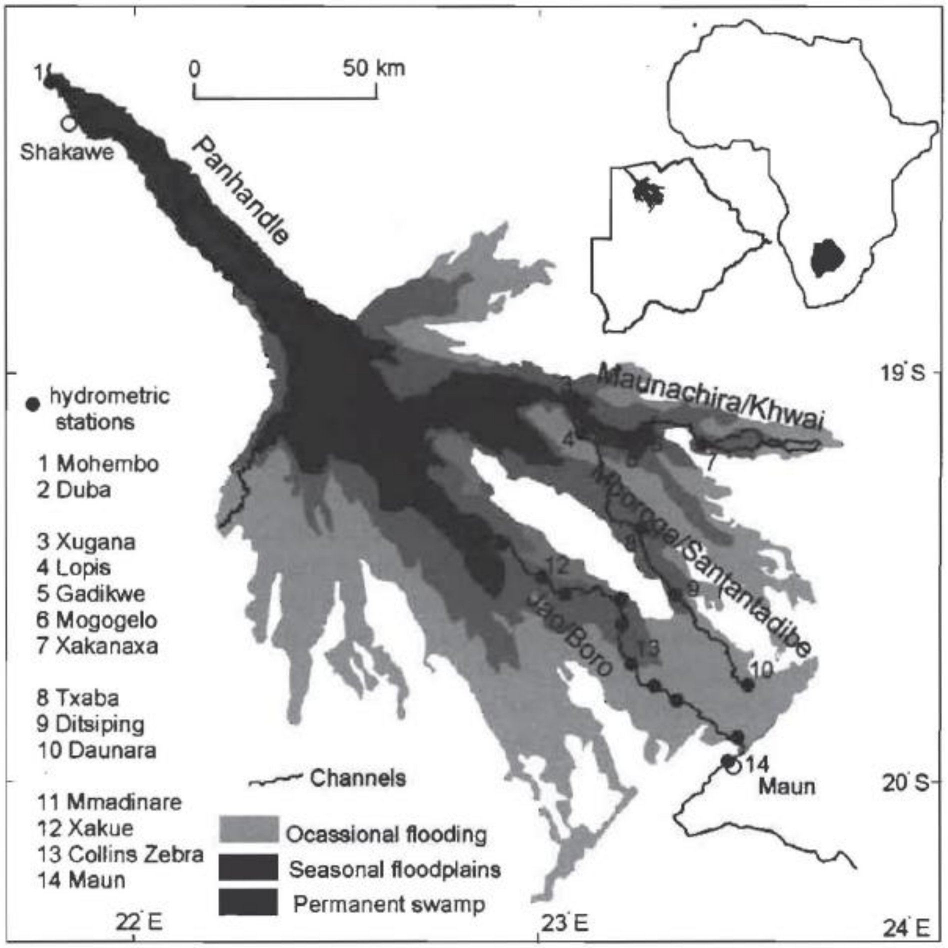

Fig. 1. Location of the Okavango Delta and its principal features.

flood size and timing of flooding. However, simple methods, such as statistical regression-type relationships, are often as useful and helpful in understanding the phenomena. For example, regression models of outflows and flood size run for the annual data were reasonably successful and indicated that the system is relatively well describable using statistical procedures.

This study aims at describing the relationship between the flooding, particularly the seasonal changes in the extent of the flood and timing of peak flood occurrence, and the influencing environmental variables such as inflow, precipitation and evaporation.

Previous Work

A qualitative understanding of processes influencing the hydrology of the Delta has been obtained in the course of past research and is presented in many publications. McCarthy *et al* (1991) described processes of channel–floodplain water exchange, revealing the importance of seepage from the channels through the vegetated banks. This process leads to progressive loss of water from channels. A portion of the water seeping to floodplains evaporates, another portion contributes to the spread of inundated area, while some may be intercepted by downstream systems of channels (Porter and Muzila, 1988). A channel aggradation cycle was described by McCarthy *et al* (1992). In this cycle, the within-channel accumulation of bedload leads to a reduction of channel flow velocities and an increase of channel losses to surrounding swamps. Subsequently, vegetation blockages develop and finally the channel is abandoned. Groundwater behaviour under islands and its role in entrapment of dissolved salts was described by McCarthy *et al* (1993) and McCarthy and Ellery (1995). Modelling work of the floodplain-island groundwater flows was done by Gieske (1996), and recently by Wolski and Savenije (2004). Water balances at the scale of a single floodplain were studied by Dinçer *et al* (1976) at Beacon Island, and by Ramberg *et al* (2005) at Phelo's floodplain on the SW side of Chief's Island. The conceptual understanding of the Delta hydrology obtained from these studies was used to develop and subsequently improve several mathematical models of the system. The most notable efforts are those by SMEC (1990), described also by Dinçer *et al* (1987), Scudder *et al* (1993), WTC (1997) and Gieske (1997). Recently, a distributed MODFLOW-based model was developed by Bauer (2004) and a hybrid reservoir-GIS modelling approach was applied by Wolski *et al* (2005). These latter two models are able to simulate the observed outflow and inundation area relatively well, but are rather complex and computationally intensive.

Apart from the complex models, simple statistical procedures have also been applied in the past to simulate and analyse the observed response of the Delta to the hydrological inputs. A regression model of the Delta outflows at Maun was described in various versions by Dinçer *et al* (1987), SMEC (1990), Scudder *et al* (1993) and McCarthy *et al* (1998). In that model the variation in total annual rainfall, total annual inflow, evaporation and antecedent wetness (previous year outflow) were shown to explain 93% of the observed variability of total annual outflow at Maun.

A regression model of maximum annual inundation area was developed by Gumbricht *et al* (2004). In this model, the maximum annual inundation area derived from satellite images, was related to inflow, outflow, rainfall, potential evapotranspiration and antecedent wetness conditions. The last factor was expressed by maximum area of flooding in the preceding year. The multiple regression model had a coefficient of determination (r^2) of 0.87 with a standard error of 695 km^2 and the potential evapotranspiration variable was shown to be not significant. Additionally, the model was able to predict the maximum area of flooding three months in advance. The predictions are published on the Harry Oppenheimer Okavango Research Centre web site (www.orc.ub.bw).

The Okavango Delta

The Okavango Delta in northern Botswana (Figure 1) is an alluvial fan covering about 22 000 km^2. The Delta is fed from the central Angolan highlands through the Okavango River. Inflow into the Delta at Mohembo peaks usually in April, whereas the outflow in the Thamalakane River as well as inundation extent peak usually in August-September. The average annual discharge of the Okavango River at Mohembo is $1.01 \cdot 10^{10}$ m^3 but is quite variable, ranging from a low $6.0 \cdot 10^9$ m^3 to a high of $1.64 \cdot 10^{10}$ m^3 over the last 60 years. Base flow in the Okavango River sustains 4,000-6,000 km^2 of permanent swamp around the apex of the alluvial fan, but at the peak flood, an additional 2,000-6,000 km^2 of the so-called seasonal and occasional floodplains may be inundated.

Temperatures are generally high during summer months (October-April) with average temperatures of 27°C and 25°C for Maun and Shakawe, respectively. The winter months (May-September) are dry with temperatures averaging at 17°C in Maun and 15°C in Shakawe. The mean annual pan A evaporation (uncorrected) is 2730 mm for Maun and 2460 mm for Shakawe.

Average annual rainfall ranges from 620 mm in the extreme northwest around Shakawe to 460 mm at Maun. About 90% of that rainfall occurs in five summer months from November to March.

Materials and Methods

Inundation Area

Inundation area data were derived from flood maps. The flood maps were obtained earlier by J. McCarthy *et al* (2004). These flood maps cover the period of 1985-2000, and have a spatial resolution of 1 km. The maps were derived by classification of NOAA AVHRR images, and for the details of the procedure, readers are referred to the original publication. The temporal resolution of the maps is 10 days, but numerous gaps are present due to the presence of clouds or unavailability of satellite data. In this study, the area of inundation in the entire Delta was determined for each month for which maps were available. The monthly value of the inundated area was obtained as the average of the inundated areas mapped from images available for that particular month.

Peak Flood Occurrence Data

The date of peak flood occurrence has been determined for a number of hydrometric stations located within the Delta (Figure 1), based on the water level data, which are available since 1970. Flood peak could, however, be identified only for those years during which frequency of measurements was sufficient. For the purpose of the analyses the travel time (number of days) of peak flood between Mohembo and that station during a given year has been calculated for each station.

GIS Data

The along-channel distance between Mohembo and each of the hydrometric stations was obtained by mapping all the channels from satellite images and calculating the distance using a GIS software.

Climate Data

Rainfall and climatic parameters influencing evaporation, i.e. temperature, wind speed, humidity, vapour pressure and radiation, are only available for Maun and Shakawe stations (Figure 1), and were obtained from the Department of Meteorological Services. Potential evaporation for Maun was obtained using the Penman combination equation (Persuad *et al*, 1990).

Statistical Procedures

For the modelling of seasonal variation in flood size as well as the peak flood delay, a multiple linear regression technique was used. The multiple regression procedure relates a dependent variable (Y) to a set of independent or explanatory variables ($X_1, X_2, X_3 ... X_n$) in a linear way:

$$Y = a \cdot X_1 + b \cdot X_2 + c \cdot X_3 + ... + m \cdot X_n \qquad [1]$$

In the procedure, values of regression coefficients $a, b, c ....m$ are calculated. The significance of each regression coefficient is tested using a t-test, and the p-value is calculated, which expresses the probability that the given regression coefficient is equal to 0. By rejecting those variables for which the p-value is higher than the assumed significance level (usually 0.05), the set of explanatory variables can be optimized to include only significant ones. This is often done automatically by statistical software. Here, however, it was done manually in order to have better control over accepting and rejecting variables with p-values close to the significance level of 0.05.

The multiple regression technique was used here not only as a tool for prediction of the dependent variable based on the explanatory variables, but primarily as an exploratory tool enabling selection of the best explanatory variables from a suite of possible ones, thus assisting in understanding the complex hydrology of that system. Considering that objective, and generaly rather poor understanding of drivers of hydrological behaviour of the analysed system and quantitative relationships involved, for the sake of simplicity the analysis was restricted to linear models. It is envisaged that non-linear models might be tested in the future.

Results

Selection of explanatory variables for the regression model of monthly inundation area in the Okavango Delta

Factors to be included in the regression model of seasonal inundation area were chosen to express variation in hydrological inputs and losses: inflow and rainfall, and potential evaporation. Since the annual regression models of flood (Gumbricht *et al*, 2004) and outflow (McCarthy *et al*, 1998) have shown that an expression of antecedent conditions is an important explanatory variable, that factor would also be included.

Inflow

The size of the inundated area in the Okavango Delta depends on the amount of inflowing water, and there is a 3-4 month lag between the inflow at Mohembo and flood expansion. Inflow to the system starts rising in November, while the inundated area starts increasing only in March. Similarly, inflow into the Delta peaks in April/May, while the highest flood extent is achieved only in August/September. Introducing a lag into the relationship between inflow and inundation area seems, therefore, a straightforward way of modelling the monthly inundation area. However, one has to note that there is a considerable storage in the upper part of the Delta (Panhandle and permanent swamp, Figure 1), which accepts the incoming water, and most probably strongly transforms the inflow hydrograph. It is therefore likely that the inundation area in the system responds to the status of that storage rather than to the lagged inflow. To test that hypothesis, Pearson's correlation r has been calculated between the monthly inundation area and cumulative inflow, with various cumulative period lengths (from 1 month to 8 months), and with various lags (0 to 8 months). That lagged cumulative inflow $Q_{(a,l)i}$ [Mm^3] for an i-th month in the data series was expressed as:

$$Q_{(a,l)i} = \sum_{j=i-l-(a-1)}^{j=i-l} Q_j \qquad [2]$$

where Q_j is monthly inflow [Mm^3] during j-th month of data series, a is the cumulating period length and l is the time lag.

The results are presented in Figure 2. The values of correlation coefficient r vary for each cumulating period depending on the lag, but a rather clear maximum is observed. The maximum correlation values for various cumulating periods are similar (r = 0.73 to 0.77). However, the

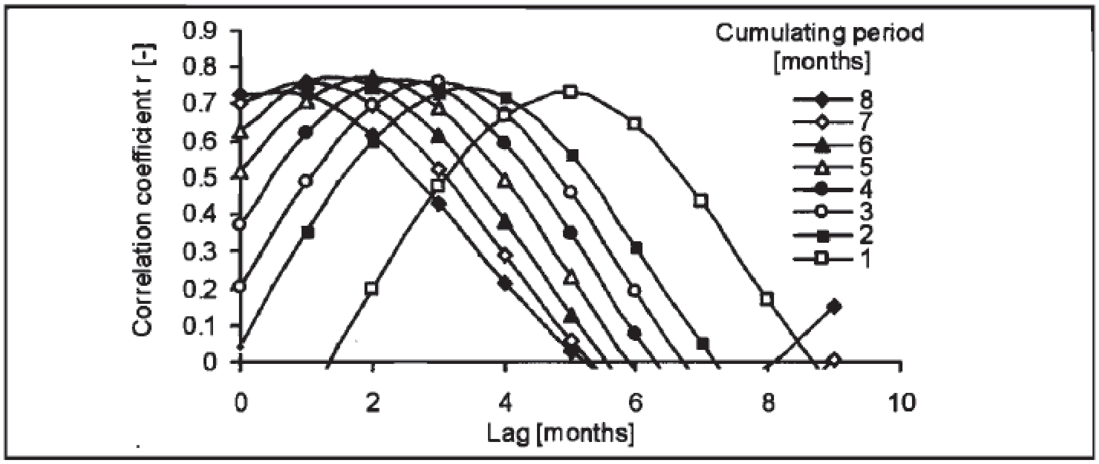

Figure 2. Correlation between inundation area and inflow characteristic $Q_{(a,l)}$ as a function of time lag and averaging period.

monthly inflow (i.e. not cumulated) lagged by 4 months has the weakest correlation ($r = 0.73$), while the best correlation is observed for 5 month cumulative inflow lagged by 2 months ($r = 0.77$). This expression of inflow was used in the regression model.

Rainfall

Flood in the Delta expands in response to the inflow. The rainy season flooding occurs only during years with high rainfall. To account for the high rainfall conditions a cumulative rainfall excess $P_{excess,i}$ has been calculated according to the formula:

$$P_{excess,i} = \max\left[0, P_{excess,i-1} + P_i - E_{0,i}\right] \qquad [3]$$

where P_i denotes recorded monthly rainfall (average of Maun and Shakawe stations) and $E_{0,i}$ potential evaporation for given month (i) or previous month (i–1). In this way, the effect of rainfall was introduced only for months when rainfall exceeded potential evaporation, and that influence could persist for several months after that high rainfall month.

Additionally, rainfall is expected to facilitate inundation by pre-wetting the non-inundated area. To account for that, antecedent rainfall $P_{ant,i}$ was used, calculated as the average rainfall from the previous 10 months, i.e.:

$$P_{ant,i} = \frac{1}{10}\left[\sum_{j=i-9}^{j=i} P_j\right] \qquad [4]$$

Evaporation

Evaporation is expressed as current month E_0. E_0 is calculated from the Penman formula (Persuad *et al*, 1990) based on Maun data.

Antecedent conditions

In the annual regression models the antecedent conditions were incorporated based on the previous year's maximum inundation area (Gumbricht *et al*, 2004) or previous year outflow (e.g. McCarthy *et al*, 1998). Such measures indirectly express how 'wet' the Delta was before the arrival of the current year's flood. Gieske (1997) has shown that the flooding in the Delta responds to long term variation in inputs. He used the so-called cumulative rainfall departure index (*CRD*) to express that long-term variation. Here, we adopted a solution analogous to *CRD*, but with respect to inflow and not rainfall, thus called cumulative inflow departure index.

The cumulative inflow departure index is expressed as:

$$CID_{(m,n)i} = \frac{1}{m}\left[\sum_{j=i-(m-1)}^{j=i} Q_j\right] - \frac{1}{n}\left[\sum_{j=i-(n-1)}^{j=i} Q_j\right] + CID_{(m,n)i-1} \qquad [5]$$

where n is the expression of short-term and m of long-term 'memory' of the system (both in months). Based on the analysis of outflows, Gieske (1997) determined that the long-term memory is 10 years, and the short-term memory is 12 months.

The short-term memory of 12 months seems to be non-controversial. The long-term memory determined by Gieske (1997) is, however, somewhat long. Wolski and Savenije (2004) found that the surface water-groundwater interactions, which are the main cause of long-term memory of the system, are not likely to affect flooding for periods longer than 4-5 years. To find the long-term memory that fits inundation area data the best, a suite of regression models was run that incorporated all the anticipated factors and $CID_{(m,n)i}$ with a long-term memory of 2 to 10 years (Figure 3). A $CID_{(m,n)i}$ with a long-term memory of 4 years (48 months) gave the best correlation between the regression-calculated and observed inundation area. The results of the model with the $CID_{(12,48)i}$ are therefore presented below.

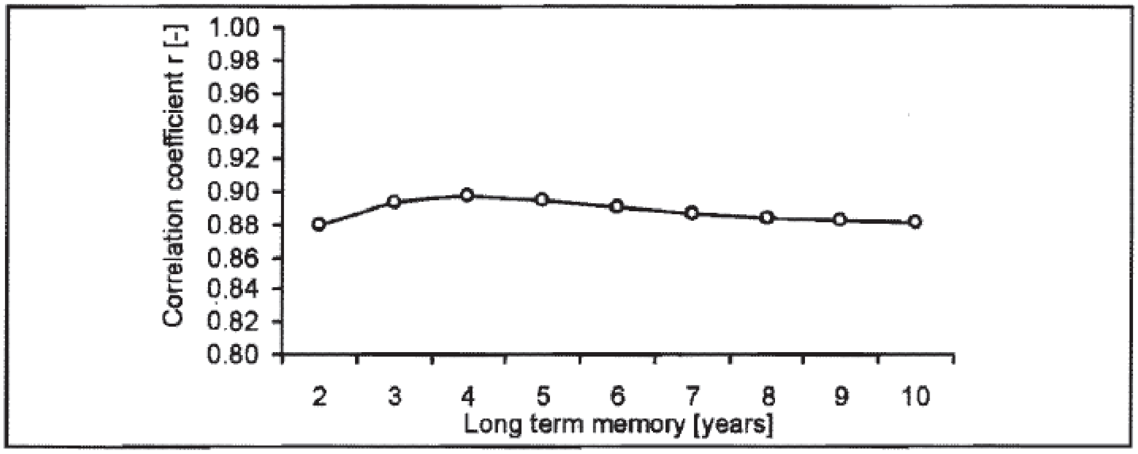

Figure 3. Correlation coefficient for regression models of seasonal inundation area with various long-term memory expressed by CID.

Performance of the regression model of monthly inundation area

The regression model based on the five variables listed above provided a good simulation of the observed seasonal variation in inundation area (Table 1). A correlation coefficient of 0.90 was obtained with a standard deviation of 538 km^2. The influence of the $E_{0,i}$ variable on the dependent variable was statistically non-significant (p-value of 0.29). For the final version of the model this variable was therefore excluded. The final model has the following form: (also Table 1).

$$A_i\,[\mathrm{km}^2] = 2640 + 9.42 \cdot P_{excess,i}\,[\mathrm{mm}] + 2.02 \cdot P_{ant,i}\,[\mathrm{mm}] + Q_{(5,2)i}\,[\mathrm{Mm}^3] + $$
$$+ 35.74 \cdot CID_{(12,48)i}\,[\mathrm{Mm}^3] \qquad [6]$$

Comparison of the observed and calculated inundation areas is presented in Figure 4.

Table 1. Results of multiple regression models for inundation area in the Okavango Delta, n=175.

Full model	Intercept	$E_{0,i}$	$P_{excess,i}$	$P_{ant,i}$	$Q_{(5,2),i}$	$CID_{(12,48)i}$
regr. coeff.	2397	1.22	9.59	2.07	0.15	37.26
p-value	<0.0001	0.29	<0.0001	<0.0001	<0.0001	<0.0001
overall:	p-value < 0.0001		$r^2 = 0.805$		Stdev = 538	
Optimal model	Intercept	$P_{excess,i}$	$P_{ant,i}$	$Q_{(5,2),i}$	$CID_{(12,48)i}$	
regr. coeff.	2640	9.42	2.02	0.16	35.74	
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	
overall:	p-value < 0.0001		$r^2 = 0.804$		Stdev = 538	

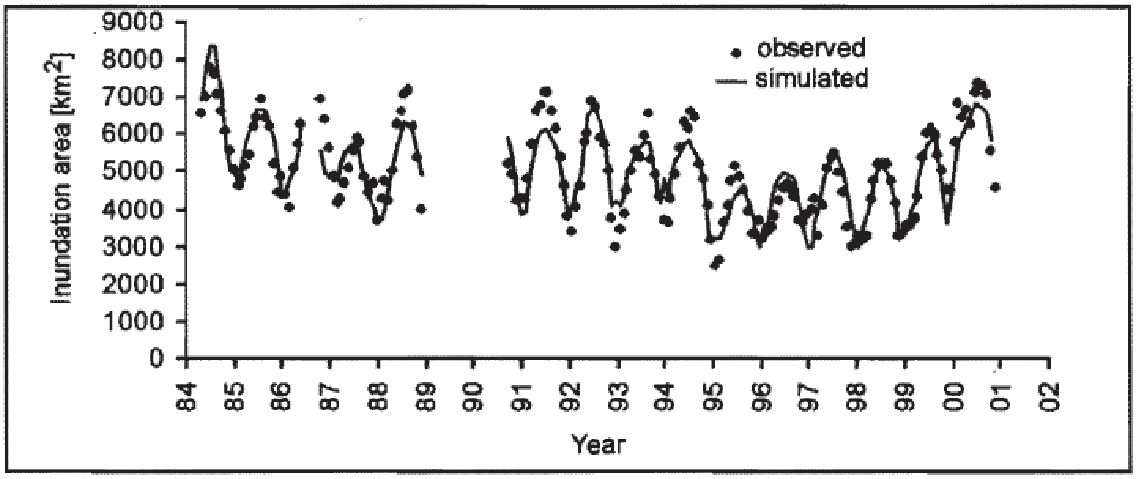

Figure 4. Comparison of observed and regression model simulated inundation area in the Okavango Delta.

Regression model for peak flood occurrence

The delay between peak flood at Mohembo and any given site in the Delta clearly increases with the increasing distance (Figure 5). There is, however, a considerable interannual variation observed at each site. Because the celerity (velocity) of a flood wave increases with the depth of water, on can expect that the variation results from differences in flood size between years. Indeed, when peak flood delay times for stations in the Jao/Boro (J/B) distributary are plotted against the amount of water flowing at Mohembo between the onset of the flood and flood peak

($Q2PEAK_i$, which is one of many ways of expressing flood size) (Figure 6), a rather strong ($r > 0.6$) decrease of delay with increasing water levels is observed. For stations on Maunachira-Khwai (M/K) and Mboroga-Santantadibe (M/S), however, the inverse relationship is either weak ($r < 0.3$), or the delay is directly proportional to the annual inflow volume. Only Xakanaxa and Xugana stations on the M/K display the delay-water level relationship similar to that observed for Boro.

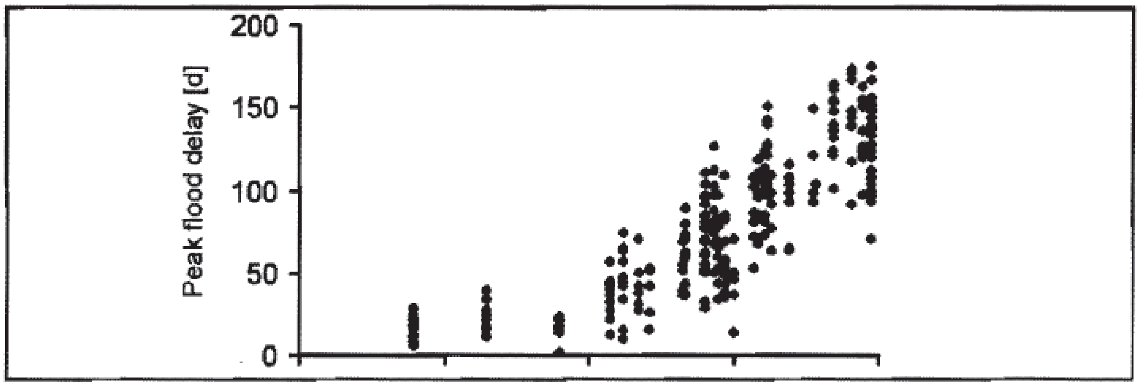

Figure 5. Peak flood delay as a function of distance from Mohembo, all stations.

Delay of flood peak between Delta inlet and any given point in the Delta is, in view of the above, determined by two factors: a) distance between a given point and the inlet to the Delta, which does not change in time, but is different for each of the stations, and b) time-varying conditions that affect the velocity of flood peak movement, which can be considered the same for each of the stations in a given year. The latter can potentially be related to inflow hydrograph characteristics (flood size), total annual rainfall, total annual potential evaporation, and antecedent wetness conditions (i.e. water remaining in the Delta before the arrival of a given year flood).

In the multiple regression model, flood delay time FPD_i [d] determined for each of the stations for all years *i* for which data were available (obtained as described in the Materials and methods section) was the dependent variable. The model included five independent variables:

- distance in km from Mohembo to a given station (*DIST*);
- total annual (July-June) rainfall in mm taken as mean Maun and Shakawe rainfall (P_i);
- total annual (July-June) potential evaporation in mm, taken as a sum of monthly values calculated for Maun based on Penman formula ($E_{0,i}$);
- previous year inflow to the Delta in Mm^3 taken as November-October inflow for the previous flood season ($QLAST_i$); and
- inflow volume from the beginning of the flood to flood peak in Mm^3 ($Q2PEAK_i$).

Table 2 presents the results of calculations for sites in the J/B distributary. In that model variables $E_{0,i}$ and $QLAST_i$ are non-significant, as indicated by high p-values. The "optimal 1" model (Table 1) is obtained by excluding these variables. This model explains 85% of the observed variability in flood peak delay ($r^2 = 0.85$). Removing P_i variable (which has a relatively high p-value of 0.04) results in "optimal 2" model, which still explains 85% of the observed variability in flood peak delay with standard deviation of 15 days.

Table 2. Results of multiple regression models for peak flood delay for the Jao-Boro distributary, n=135.

Full model	Intercept	$DIST$	$Q2PEAK_i$	P_i	$E_{0,i}$	$QLAST_i$
regr. coeff.	-24	0.50	-0.012	0.016	0.007	-0.0001
p-value	0.44	<0.0001	<0.0001	0.03	0.64	0.14
overall:	p-value < 0.0001		$r^2 = 0.860$		Stdev = 15.12	
Optimal model 1	Intercept	$DIST$	$Q2PEAK_i$	P_i		
regr. coeff.	-16	0.50	-0.012	0.014		
p-value	0.097	<0.0001	<0.0001	0.04		
overall:	p-value < 0.0001		$r^2 = 0.857$		Stdev = 15.14	
Optimal model 2	Intercept	$DIST$	$Q2PEAK_i$			
regr. coeff.	-11	0.50	-0.012			
p-value	0.27	<0.0001	<0.0001			
overall:	p-value < 0.0001		$r^2 = 0.852$		Stdev = 15.34	

The "optimal 2" model takes the following form:

$$FPD_i\,[\mathrm{d}] = -11 + 0.50 \cdot DIST\,[\mathrm{km}] - 0.012 \cdot Q2PEAK_i\,[\mathrm{Mm}^3] \qquad [7]$$

Results of the full model for the M/K distributary are presented in Table 3. In that case, all the variables appear significant, but the regression model explains only 33% of the observed variation in peak flood delay. This low explained variation is probably caused by including in the model sites of qualitatively different characteristics, i.e. those with peak flood delay inversely proportional to flood size, and those that do not display that relationship. Table 4 presents results of regression modelling for the two stations of the M/K distributary for which the expected inverse proportionality is present, i.e. Xugana and Xakanaxa. For these two stations the regression model can be reduced to two variables only, i.e. $DIST$ and $Q2PEAK_i$ (Table 4). That model explains 59% of the observed variability in flood peak delay with a standard deviation of 16 days.

Table 3. Results of multiple regression models for peak flood delay for the Maunachira-Khwai distributary, n=36.

Full model	Intercept	DIST	$Q2PEAK_i$	P_i	$E_{0,i}$	$QLAST_i$
regr. coeff.	-505	0.49	-0.011	0.087	0.201	0.007
p-value	0.009	0.027	0.019	0.008	0.016	0.023
overall:	p-value = 0.028		$r^2 = 0.330$		Stdev = 22.61	

Table 4. Results of multiple regression models for peak flood delay for the Maunachira-Khwai distributary, Xugana and Xakanaxa stations only, n=16.

Full model	Intercept	*DIST*	$Q2PEAK_i$	P_i	$E_{0,i}$	$QLAST_i$
regr. coeff.	-424	0.58	-0.012	0.069	0.172	0.004
p-value	0.041	0.002	0.011	0.033	0.056	0.120
overall:	p-value = 0.008		$r^2 = 0.751$		Stdev = 14.51	
Optimal model	Intercept	*DIST*	$Q2PEAK_i$			
regr. coeff.	-38	0.54	-0.007			
p-value	0.443	0.003	0.045			
overall:	p-value = 0.003		$r^2 = 0.594$		Stdev = 16.25	

Table 5 presents results of peak flood regression modelling for the M/S distributary. The full regression model explains only 55% of the observed variability, and only the *DIST* variable appears to be a significant component of that model. The model with *DIST* variable only explains 52% of the observed variability of flood peak delay with a standard deviation of 24 days.

Table 5. Results of multiple regression models for peak flood delay for the Mboroga-Santantadibe distributary, n=36.

Full model	Intercept	*DIST*	$Q2PEAK_i$	P_i	$E_{0,i}$	$QLAST_i$
regr. coeff.	-177	0.66	-0.004	0.001	0.040	0.003
p-value	0.267	<0.0001	0.243	0.983	0.597	0.183
overall:	p-value < 0.0001		$r^2 = 0.553$		Stdev = 24.82	
Optimal model	Intercept	*DIST*				
regr. coeff.	-100	0.66				
p-value	0.003	<0.0001				
overall:	p-value < 0.0001		$r^2 = 0.524$		Stdev = 24.40	

Interpretation and Discussion

The multiple regression models presented here are useful, powerful and simple tools for predicting inundation area and peak flood occurrence in the Okavango Delta. The model for inundation extent, unlike the earlier model of Gumbricht *et al* (2004), which could only estimate the maximum flood, allows for the inundation area to be modelled at any stage with reasonable accuracy. The model for peak flood occurrence is the first of this kind developed for the Okavango Delta, although its application is limited to the J/B distributary.

As such, the models have great potential for practical application by the research community and other users (tourist operators, wildlife wardens, agriculture officers, etc.). To use them, one only needs spreadsheet software, access to long-term inflow and rainfall data (freely available from relevant departments of the Botswana Government) and a basic understanding of regression modelling. This offers a great advantage over comprehensive hydrological models which will always be too complex, expensive and computationally intensive for general use.

Apart from that, the analyses presented here provide some information on how the hydrological system of the Okavanago Delta works, and in particular on how the flood wave propagates in that system.

Firstly, the regression model of seasonal inundation area shows the importance of the storage effects in the system. A rather large part (80%) of the observed seasonal variation in inundation area in the Okavango Delta is explained in that model by variation in hydrological inputs, i.e. inflow and rainfall. To obtain that closeness of fit, input variables had to be presented in a form that reflect the way they are transformed into hydrological output (inundation area), i.e. storage in the system had to be accounted for. When non-transformed input variables are

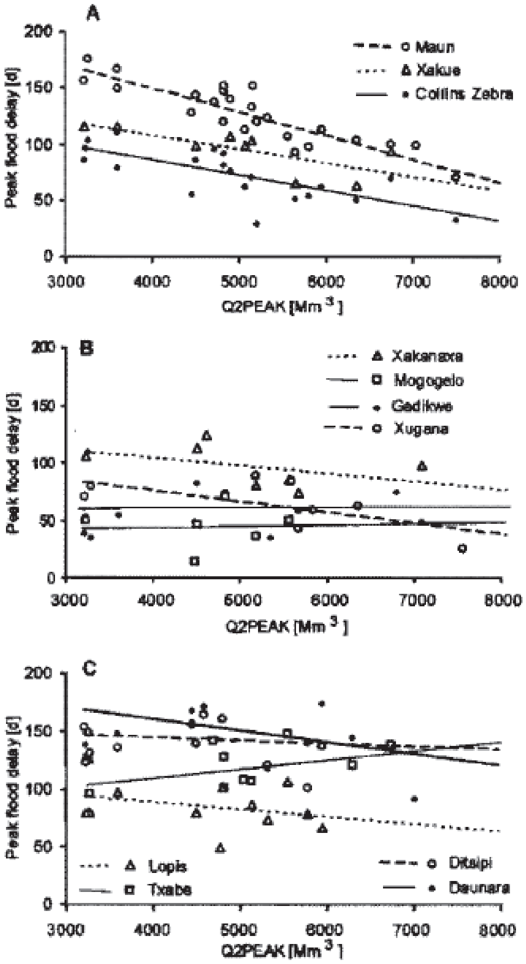

Figure 6. Peak flood delays as a function of annual flood size (Q2PEAK), for stations from a) Jao-Boro b) Maunachira-Khwai c) Mboroga-Santantadibe.

used (i.e. simple lagged monthly inflow and lagged rainfall) a regression model (not presented in this paper for the sake of brevity) explains only 66% of the observed seasonal variation in inundation area. Additionally, it has to be underlined here, that a regression model in its nature relates observed variation in dependent variables to observed variation in explanatory (independent) variables. The fact that an evaporation variable is not included in the model does not therefore mean that evaporation does not affect Okavango Delta waters, but simply that the variation in potential evaporation has a negligible effect on the variation in inundation area.

Secondly, the results of regression of peak flood delay in various distributaries provide information on the complexity of flow paths. The flood peak delay is relatively consistent and well explained by input and distance from Mohembo in the J/B distributary, while in the M/K and M/S that consistency does not occur. Moreover, at several stations in the M/K and M/S distributaries the relation between peak flood delay and inflow to the system is opposite to what would be expected, i.e. peak flood occurs later during larger floods. Some of the variation in the M/S and M/K systems is, undoubtedly, related to poor data – determination of flood peak occurrence from once-monthly measurements cannot be precise. However, we believe that it is mostly related to the complexity of paths through which the flow and flood wave propagate in these systems, with local inherent properties of the floodplain-channel interaction superimposed on the general dynamics of flow in the M/K and M/S systems.

The J/B distributary receives water as over-bank spill from the central part of the permanent swamp, which intensifies in the flood season, and thus is very dynamic, i.e. characterized by strong seasonal variation. As a result, flood propagation is strongly related to its primary determinant-inflow. In contrast, the M/K and M/S systems receive a less varying supply of water, and the flood wave is less pronounced, i.e. the amplitude of flood-induced water level fluctuations is much smaller than in the J/B system. Additionally, flood levels in the M/K and M/S systems respond strongly to local rainfall (Wolski and Murray-Hudson, 2005). As a result, the flood peak occurrence is strongly affected by the complexity of flow paths in the channel-floodplain system of permanently flooded part of these distributaries, and by the status of storages associated with the various parts of the flow path (channels, floodplains, lagoons). Some aspects of that complexity were investigated by Wolski *et al* (2005a), who revealed that, for example, floodplains often form major paths of flow in a distributary, accommodating the bulk of the flood wave, which in this way by-passes channels. Xugana and Xakanaxa, for which the relationship between flood peak delay and hydrological variables is well defined, seem to be located in the main path of flood propagation. Other stations are strongly affected by the by-passes. As a result of all these factors, water level fluctuations at some parts of these distributaries cannot be captured by using a simple relationship to hydrological inputs to the system.

Thirdly, and most importantly, causes of the flood lag can be inferred. The lag between causal rains and flooding is one of the key hydrological and ecological characteristics of this system. The flood expands several months after the end of rainy season (Figure 7b), during the dry cold period, and this makes water practically available throughout the year. This has profound consequences to the ecology of the system, and therefore the process underlying it should be well understood. In the literature pertaining to the Okavango Delta the lag is often attributed to the low topographic gradient in the Delta. However, if we superimpose the flood delay time on the topographic gradient of the system (obtained by McCarthy *et al* (1997)), Figure 8, the peak flood travel velocity (expressed by the slope of delay-distance relationship) appears to be higher in the Panhandle than in the Delta proper, in spite of the lower topographic gradient. It is therefore obvious that it is not only the gradient that causes the lag in the Delta.

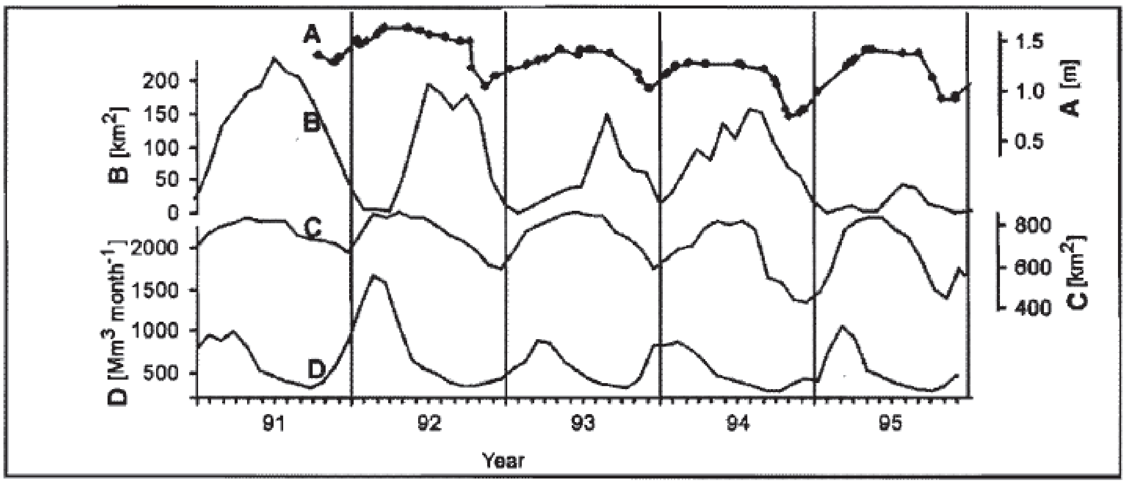

Figure 7. Time series of water levels at Duba (A), inundation area in lower J/B distributary (B), inundation area in Panhandle (C) and inflow at Mohembo (D).

Celerity (velocity) c_k of a kinematic flood wave (effectively flood wave crest) is described by the following equation (Chow *et al*, 1988):

$$c_k = \frac{1}{B}\frac{dQ}{dy} \qquad [8]$$

where B is the width of a channel and y is the depth of flow. For a wide flat channel, this equation can be solved and simplified by introducing Manning's equation, so as it reads:

$$c_k = \frac{5}{3}\frac{\sqrt{S}}{n}y^{2/3} \qquad [9]$$

where S is the topographic slope and n is the Manning coefficient. In the Panhandle, longitudinal slope of the "valley" (it is larger than the channel slope) is $1.95 \cdot 10^{-4}$ [-], n = 0.1 [-] (corresponding to dense floodplain vegetation) and y = 3 [m] (corresponding to the observed depths of water). After substituting these values one obtains flood wave velocity of 41 km · d^{-1}.

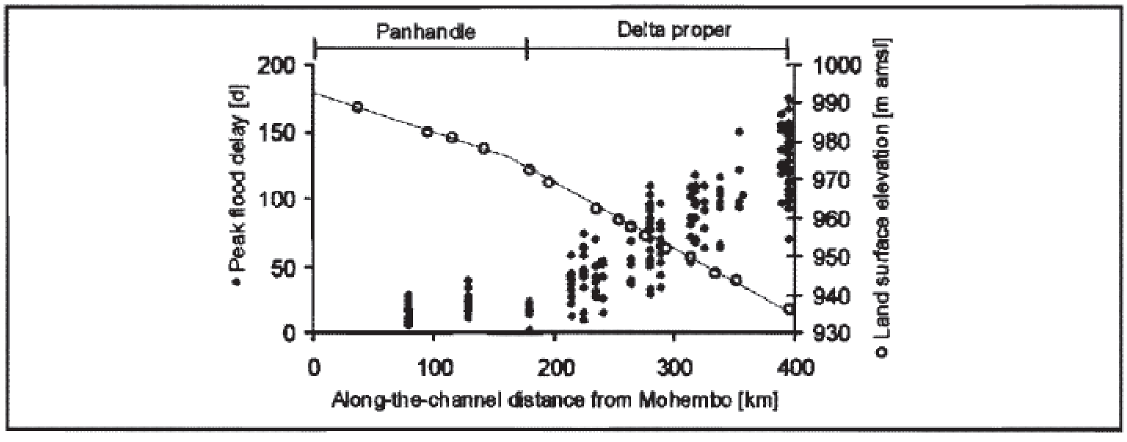

Figure 8. Peak flood delay and land surface elevation in the Panhandle and Jao/Boro distributary. (Elevation data from McCarthy *et al*, 1997.)

For the Delta proper, taking $S = 2.77 \cdot 10^{-4}$ [-] (again, slope along the fan axis, not along the channel), and assuming $n = 0.1$ [-] and $y = 0.4$ [m], one obtains $13\ \text{km} \cdot \text{d}^{-1}$. With these velocities, the flood wave should peak at the end of the Panhandle (95 km downstream of Mohembo along the Panhandle axis) only 2-3 days after peaking in Mohembo, while at the distal parts of the Delta (260 km from Mohembo along the fan axis), peak flood should occur 14-15 days after the peak at Mohembo. Clearly, incorporation of water depth provides a better explanation of differences in flood wave propagation rates between the Panhandle and Delta proper (i.e. deeper water causes faster propagation), than when only gradient is considered. It therefore seems that as a first approximation, the flood lag in the Delta should be attributed to shallow water rather than to low topographic slope.

To explore the issue further, we first note that the observed peak flood delay times (Figure 8) are much longer than the 'theoretical' flood peak travel values. It is possible to obtain peak flood travel times corresponding to the observed delays using the Eq. 9, but it demands applying unrealistic flow depths, i.e. 6 cm for Panhandle, and 2-5 cm for the Delta proper. This suggests a different model of flood wave propagation in the Okavango Delta than the theoretical kinematic wave described by Eq. 8 and 9 and intuitively accepted for the Okavango Delta.

The theoretical kinematic wave model is schematically shown in Figure 9a. In this model the inflow-induced flood (slug of water) moves through a system in the form of a pressure wave. As the inflow reduces, the crest of the flood wave passes downstream. After the flood crest has passed, storage (expressed by water level and inundation area) subsides.

However, the inundation area in the upper part of the system (Panhandle) as well as surface water levels (Duba), shown in Figure 7, do not subside together with the decline in inflow in April or May. Rather, they reach a kind of 'plateau' and subside only in July-September, simultaneously with the decline in inundation area in the entire system, and only slightly earlier than the decline in the distal part of the system (lower Boro inundation area in Figure 7).

Such behaviour of inundation area and water levels in the system can be explained by assuming the model of flood propagation in the Delta as shown in Figure 9b. Inflow at the Delta apex contributes to surface storage, which fills up fast, but the release is slow. The flood wave does not move along the system in the form of a slug of water, but rather spreads across the entire system uniformly. The observed lag in flooding does not therefore depend on the velocity

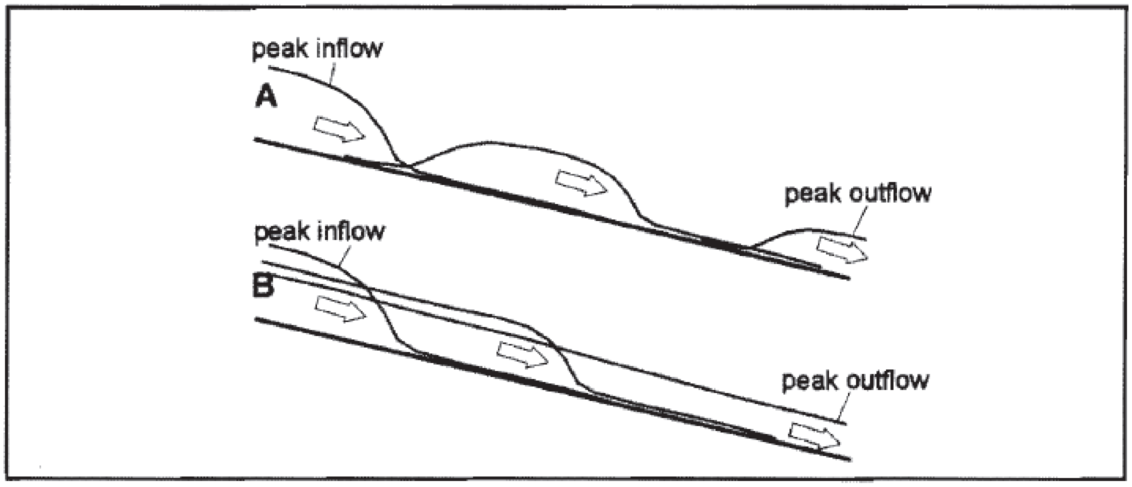

Figure 9. Schematic of flood wave propagation in the Okavango Delta, A – classic kinematic flood wave model, B – refined model.

of flood wave movement *sensu stricto*, but is an apparent effect of the transformation and redistribution of the surface storage of the system. That slow pace of storage redistribution must be caused by the processes at the propagating face of the flood. There, shallow inundation depths cause slow movement of flood front, which is furthermore 'apparently' reduced by the removal of water to fill groundwater storage and inactive floodplain storage (dead-end floodplains).

Acknowledgements

The authors would like to express their gratitude to Department of Water Affairs for providing the data and to J. McCarthy and T. Gumbricht for providing the satellite-derived flood maps.

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