INFLUENCE OF SHALLOW GROUNDWATER LEVELS ON OUTFLOW FROM THE OKAVANGO DELTA - BOTSWANA

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The Okavango Delta[1-8], a vast expanse of swamps, lagoons, floodplains and river channels, lush with vegetation and abundant in wildlife, is fed through the Okavango River by rains falling in the Angolan Highlands. Outflow is through the Thamalakane and Boteti rivers to the Makgadikgadi Pans, the lowest point of the Kalahari Basin. This outflow is of great importance for the water supply of Maun and downstream areas along the Boteti, where groundwater is scarce and usually saline.

A severe problem is the extreme variability of the outflow. Predictions have been based on two numerical models[2,3], outflow from the Delta being considered as a function of inflow, precipitation and evapotranspiration. Both have shown remarkable vagaries - so-called regime shifts - in the Delta's outflow. Attempts were made to interpret these in terms of flow changes inside the Delta[2], for example, channel diversion resulting from blockages by vegetation and sedimentation, or simply systematic errors in rainfall measurement[3].

It is shown here that substantial model improvement is achieved when the effect of recharge, by rain, on groundwater levels is taken into account. High groundwater levels reduce surface water infiltration to the shallow groundwater, creating favourable runoff and throughflow conditions, while infiltration losses are much higher when groundwater levels are low. Both timing and magnitude of the flow regimes then emerge as a natural consequence of groundwater recharge processes, particularly in the lower Delta.

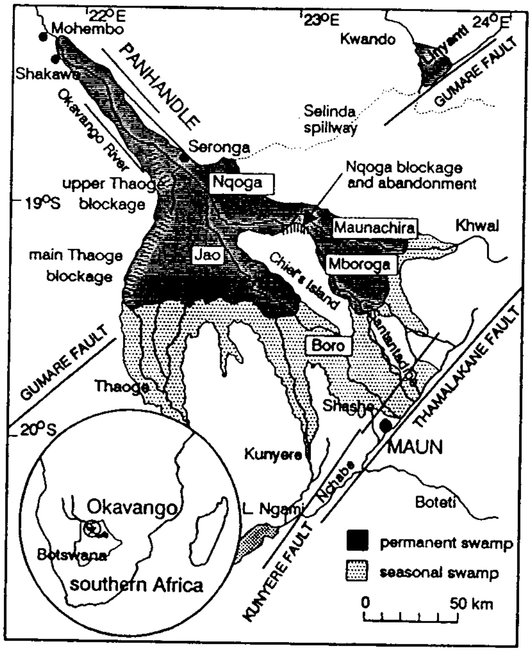

FIG. 1 Simplified map of the Okavango Delta[1,4] showing seasonal and perennial swamps. Modelling of outflow through the Jao/Boro river system to the Thamalakane and Boteti rivers is the subject of this study.

Records of river flow at Mohembo (near Shakawe) and Mukwe (Namibia) are available from 1933, whereas river levels at Maun have been monitored since 1950. Reliable flow records at Maun, however, only date from 1968. Average annual inflow at Mohembo is 11×10^9 m^3 while the average outflow at Maun is in the order of 300×10^6 m^3. With an annual precipitation of about 5×10^9 m^3, the average Maun outflow corresponds to about 2% of the total input. Flood peaks in Mohembo (Fig. 2) generally occur in April but vary according to rainfall patterns in the upper Angolan catchment. River stage levels at Maun usually peak in August, five months later than at Mohembo. The average flow statistics obscure the extreme variability of the outflow. During the wet period of the 1970s, it was possible to travel by boat 200 km down the Boteti to Orapa, almost reaching the Makgadikgadi pans, whereas outflow during the last five years hardly reached the Boteti and the river was reduced to a virtually "fossil" state. The outflow hydrograph in Fig. 3 represents a more realistic pattern.

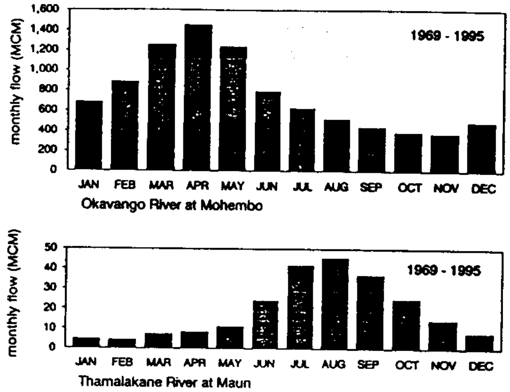

FIG. 2 Hydrographs of average monthly flow at Mohembo and Maun from 1969-1995.

The first Delta outflow model[2] was developed into the SMEC model[9] which in turn led to the alternative IUCN model[3]. Both the SMEC and IUCN models use inflow at Mohembo, rainfall and evapotranspiration data to model outflow through the Thamalakane, Shashe and Boro rivers near Maun. They divide the Delta into a number of cells through which the water is routed. For each cell a monthly water balance is calculated. A set of distribution parameters determines the flow from each cell into neighbouring cells. Area-volume relationships, losses to groundwater and the nature of the hydraulic links between the cells are also modelled.

With the early SMEC modelling it was found that Thamalakane flows were reasonably well predicted for a number of years, after which the model began to overestimate or underestimate the flows. Explanation was attempted in terms of so-called "regime shifts" in the Delta; channel changes, resulting from sedimentation and blockage by vegetation, were supposed to re-distribute the floods to different parts of the Delta. It was proposed that the time series should be divided into three different regimes (Fig. 3): medium flow from 1969 to 1974, high flow from 1975 to 1982 and low flow from 1982 to 1989, the end of SMEC's modelling period. Fig. 4 illustrates the need for this subdivision by means of a double mass curve of cumulative Mohembo inflow versus Thamalakane outflow. The SMEC modelling was forced therefore to (a) incorporate the empirical dates of regime shifts and (b) use a different set of distribution parameters for each of the three segments in the time series.

The alternative IUCN model tried to resolve the issue from a different perspective. Through double mass analysis of the Maun and Shakawe rainfall records and those of other stations in the region, it was concluded[3] that both the Maun and Shakawe records needed correction and, finally, that "good simulation accuracy was obtained without modifying parameters relating to the physical nature of the

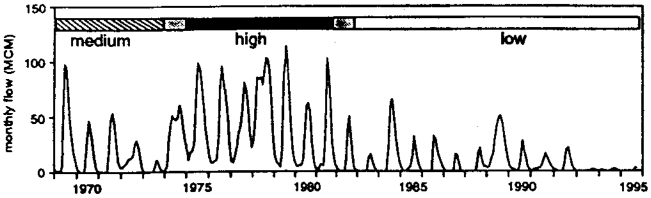

FIG. 3 Hydrograph of the observed monthly flow through the Thamalakane (Maun Bridge) from 1969-1995. The bar indicates the low-medium-high flow regimes[2,9].

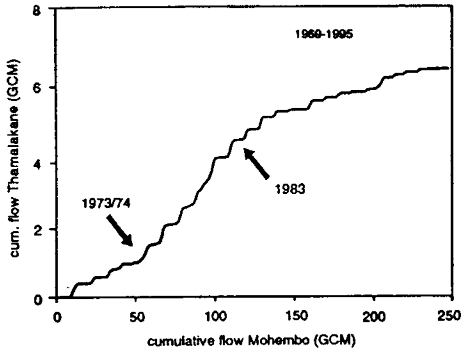

FIG. 4 Cumulative flow through the Thamalakane plotted against cumulative inflow at Mohembo. The Delta's changing response to inflow is indicated by the two kinks in the curve.

Delta. This demonstrates that a reasonable explanation of the 'regimes' is that these were an effect caused by errors in the measurement of rainfall". Table 1 summarizes the results obtained with the IUCN and SMEC models. For option A (Table 1) the uncorrected rainfall and PET data were used, with only one parameter set, leading to a monthly standard error of 16.47 MCM with a correlation of 0.84. Use of the "corrected" rainfall and potential evapotranspiration data (PET) resulted in a standard error and correlation of respectively 13.48 MCM and 0.889 (result B), which was considered IUCN's final result[3]. In obtaining results C,D and E various forms of regime shifts were used. It should be noted that the SMEC and IUCN models used different modelling periods (Fig. 5). Nevertheless, it is clear from Table 1 that empirical regime shifts improve model performance.

Study of the pattern underlying these regime shifts, prompted the development of a new model, more fully described elsewhere[10]. The comparison of SMEC and IUCN modelling focuses on the Jao/Boro River system, because outflow from the Delta takes place mainly through the Boro system where calibration data are also best. A four-cell model was therefore developed for this river system only, with a structure very similar to that of SMEC, differences being that more recent PET data from Maun were used, that deep groundwater losses were considered zero as in the IUCN model and that the modelling period now extended from 1969-1995. Moreover, application of the non-linear optimization routine by Marquardt[11] made it possible to optimize all parameters.

The model is a simplified version of the SMEC model, with the total number of parameters reduced to eleven. The results obtained (Table 1, F), however, are very similar to IUCN alternative A. Now, instead of introducing ad hoc regime changes or altering rainfall data, use was made of a groundwater recharge transfer function.

Transfer modelling is closely related to ARIMA methods of time series analysis[13-15] and to lumped parameter recharge modelling[16,17]. Although similar results have been obtained with a lumped parameter model, the transfer function selected here proved to be most convenient. It was recently introduced as the Cumulative Rainfall Departure (CRD) method[12], defined as

TABLE 1 Comparison of modelling results

	source	standard error (MCM)	monthly correl.	comment
A.	IUCN	16.47	0.840	uncorrected rain and PET
B.	IUCN	13.48	0.889	corrected rain and PET, final model
C.	IUCN	12.92	0.908	two regimes, extra PET correction
D.	IUCN	12.90	0.900	two regimes, two parameter sets
E.	SMEC	17.90	0.860	three regimes, three parameter sets
F.	here	16.61	0.781	basic model, no regimes
G.	here	11.45	0.902	CRD function implemented
H.	here	9.59	0.932	heuristic algorithm for peak events

$$CRD_i = \frac{1}{m}\left[\sum_{i-(m-1)}^{i} R_j\right] - \frac{1}{n}\left[\sum_{i-(n-1)}^{i} R_j\right] + CRD_{i-1}$$

where R_j is the rainfall in month j, where m is the number of months indicating short memory antecedent conditions and n is the number of months indicating long-term memory. The great advantage of this method is that it only uses rainfall records. The CRD can be calibrated to groundwater level fluctuations through transformations requiring the aquifer storage coefficient and adjustment of the short and long memory parameters m and n. Although neither groundwater level records nor aquifer storage coefficients are available for the Delta, the method can be applied here. Using a short memory of 12 months and a long term memory of 120 months, the CRD's for Maun and Shakawe records were calculated and normalized. Fig. 5 shows the two CRD functions together with the bar of high-medium-low flow regimes[2,9]. The correspondence between the CRD function and the regime changes is remarkable, particularly for the Maun data. Positive values of the normalized CRD correspond to high flow regimes and negative values to low flow regimes. The Shakawe record exhibits the same pattern with lower amplitude.

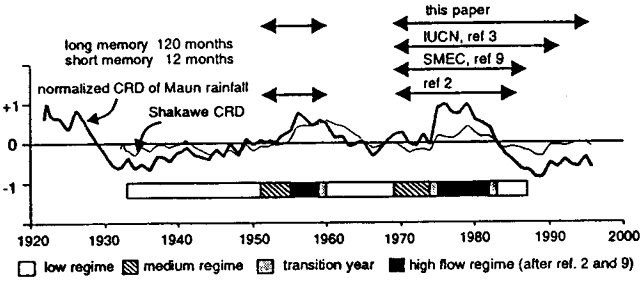

FIG. 5 The normalized CRD functions of Maun and Shakawe rainfall for the period 1922-1995. The bar indicates changes in flow regimes[9]. The modelling period 1952-1960 is discussed elsewhere[2,10].

It was found earlier[2] that regime shifts could easily be taken into account by adjusting distribution parameters of cells three and four. These parameters were now changed by multiplying them with the factor $[1+\lambda(\exp(CRD)-1)]$, where parameter λ is the twelfth parameter to be optimized.

Incorporation of the Maun CRD into the basic model resulted in a monthly standard error of 11.45 MCM (result G, Table 1) which is the best in terms of the standard error, a clear indication of the strength of this approach. Moreover, these results have been obtained with a simpler model, with less parameters, without any data alteration and without the need for empirical regime boundaries. Fig. 6 illustrates results F and G (Table 1) in a cumulative flow diagram. In the absence of long-term records of groundwater levels many different choices for the CRD function seem possible. Therefore, fifteen CRD functions were generated with long-term memories ranging from 5 to 20 years. Optimization then produced the result illustrated in Fig. 7, where the monthly standard errors, annual and monthly correlations

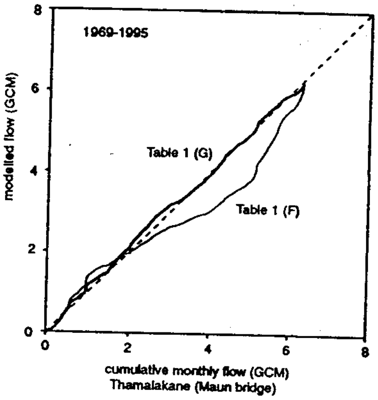

FIG. 6 Cumulative modelled monthly flow against the observed Thamalakane flows. Note the improvement from the basic model (Table 1, F) to the model with the CRD transfer function (Table 1, G).

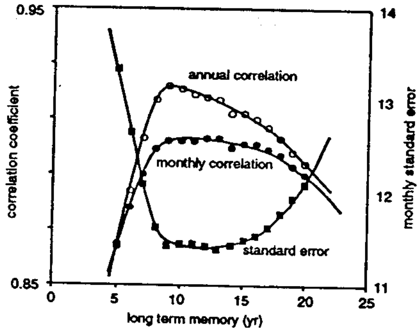

FIG. 7 Standard error, annual and monthly correlations plotted against the "long term memory" parameter n of the CRD function. The overall best value seems to lie at about 10 yr.

are plotted against long-term memory. The short-term memory was kept constant at 12 months. The figure shows that values from 10 to 15 years are possible. However, because the annual correlation is better for a memory of 10 yr, it was decided to maintain the long-term memory at this value.

Finally, study of the residuals showed that systematic deviations occurred during peak rain and flood events. The introduction of a heuristic algorithm[10] to model these peak events, further reduced the standard error to 9.59 MCM with a correlation of 0.932 (Table 1, H). Notwithstanding this additional improvement, however, the success of the CRD function clearly points to the controlling influence of groundwater levels on surface outflow. The fact that the Maun rainfall data gives the best results, as opposed to the Shakawe rainfall or inflow data, suggests that Delta outflow is influenced more by recharge events in the lower than in the upper Delta.

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ACKNOWLEDGEMENTS. The permission of the Director of the Botswana DWA to make use of Botswana data is gratefully acknowledged, as is the assistance by Mrs Jane Prince Nengu (DWA, Maun). The author thanks M. McFarlane, F. Sefe and J. Gould (all UB) for critical comments and long discussions.