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Hydrological modelling and resource management in the Okavango Delta

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Abstract The Okavango Delta in Botswana is one of the world's most fascinating wetland systems. A hydrological model of the Delta is presented, which is based on a finite difference formulation of the relevant flow processes (surface water and groundwater). Spatially distributed input data include rainfall, evapotranspiration and microtopography. The model results are compared to flooding patterns derived from remote sensing. Some questions concerning the sustainable water use and management of the Delta are discussed in view of the modelling results.

Key words hydrological modelling; remote sensing; sustainable management; wetlands

INTRODUCTION

In northern Botswana, southern Africa, the Okavango River forms a huge wetland system called the Okavango Delta (Fig. 1). The waters of the Okavango River originate in the humid tropical highlands of Angola, flow southward into the Kalahari basin, spill into the Okavango Delta and are consumed by evapotranspiration. A variety of hydrological, geochemical, sedimentological and biological processes are shaping the Delta over different spatial and temporal scales (Ellery *et al.*, 1993; Gumbricht *et al.*, 2001; McCarthy & Ellery, 1994; Modisi *et al.*, 2000). The natural system has to satisfy the water demands of various users all over the river basin. Locally, domestic water supply, mining and tourism compete with the ecosystem and its spectacular wildlife for the scarce water resource. Internationally, the classic conflict between countries located upstream (Angola, Namibia) and downstream (Namibia, Botswana) is observed.

Sound management of the system calls for a tool for *a priori* analysis of different management options. This was recognized a long time ago and several modelling efforts have been carried out (Dincer *et al.*, 1987; Gieske, 1997; SMEC, 1987). However, the previous models were designed as box models and could not reproduce the spatially distributed flooding patterns in the Delta. Recent progress in remote sensing technology provides time series of flooding patterns, which can be used to calibrate a spatially distributed hydrological model (McCarthy *et al.*, 2002). To take advantage of these new developments and to generate a more reliable and flexible tool, a spatially distributed hydrological model of the Okavango Delta is being developed together with Botswana's Department of Water Affairs.

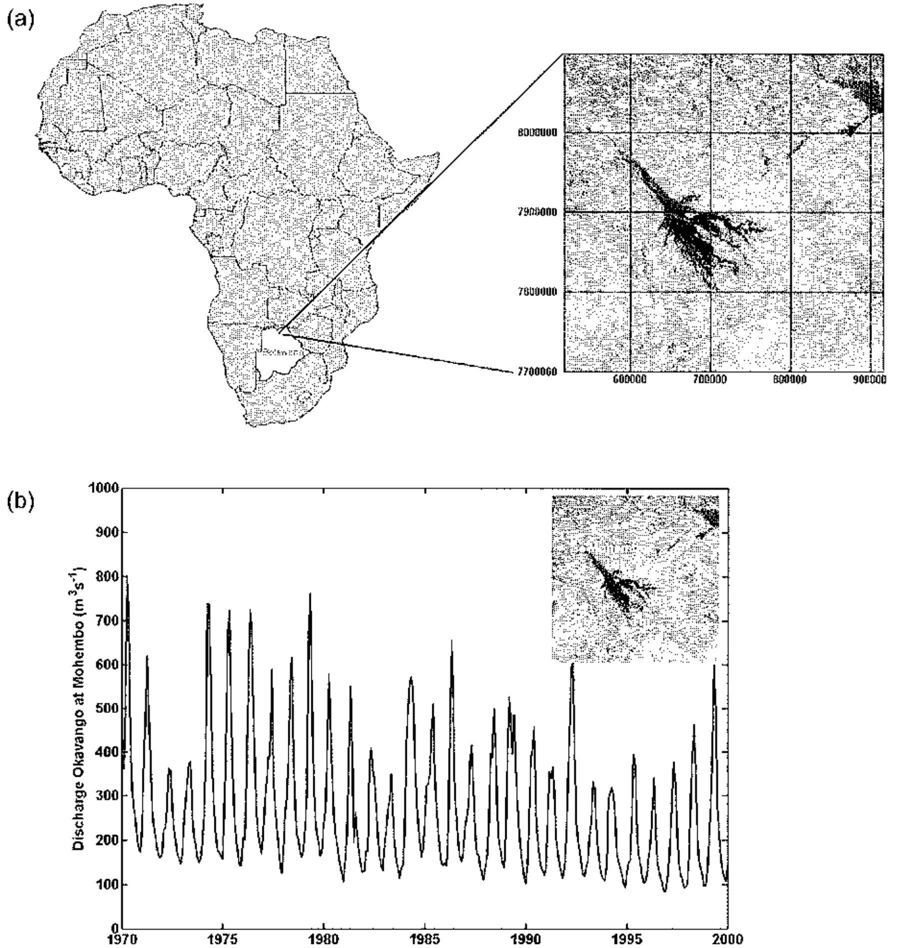

Fig. 1 (a) The Okavango Delta. Coordinates are UTM Zone 34 S, Cape Datum. (b) Inflow of the Okavango River at Mohembo.

DESCRIPTION OF THE HYDROLOGICAL MODEL

Modelling approach The hydrological model of the Okavango Delta is a finite difference surface and groundwater flow model, based on the groundwater modelling software MODFLOW (McDonald & Harbaugh, 1988). In the Delta, surface and groundwater are in close contact and in continuous exchange. They are therefore represented in the model as two interacting horizontal layers. The lower layer represents the underlying sand aquifer. In this layer, water flows according to Darcy's law. In the upper layer, which represents the wetland, the model provides two optional flow laws, which can be assigned individually to every cell in the layer: Darcy flow and normal discharge (Manning-Strickler equation). The interface between the two horizontal layers is given by the topographic surface.

Effective hydraulic parameters The spatial resolution of the hydrological model is much coarser than the typical size of terrain features (channels, islands, flood plains, etc.) in the Okavango Delta. The representation of the flow processes on such a coarse grid is only possible, if the local hydraulic parameters are upscaled to the grid scale to yield effective parameters.

Effective k_{st} for channel cells Flow through a channel cell is governed by the Manning-Strickler equation:

$$v = k_{st} \cdot R_{hy}^{\ 2/3} \cdot (\nabla h)^{1/2} \tag{1}$$

v is the flow velocity [m s^{-1}], k_{st} is the Strickler coefficient [m$^{1/3}$ s^{-1}], ∇h is the hydraulic gradient [–] and R_{hy} the hydraulic radius (cross-section area wetted perimeter). Simplification of this equation leads to the cell-by-cell flow equation in the finite difference model (b is the elevation of the layer bottom):

$$Q = k_{st} \cdot \Delta y \cdot (h - b)^{5/3} \cdot (\nabla h)^{1/2} \tag{2}$$

The local value of k_{st} has to be modified to take into account the small size of the actual channel as compared to the grid resolution. Consider the set-up of Fig. 2. The average flow velocity in the channel is v_1. Outside the channel, in the swamp, the average flow velocity is v_2. The total discharge can be calculated as:

$$Q = l \cdot h \cdot v_1 + (\Delta x - l) \cdot h \cdot v_2 \tag{3}$$

If $lv_1 >> (\Delta x - l) \cdot v_2$, the second term in equation (6) can be neglected and the effective $k_{st,eff} = \frac{l}{\Delta x} k_{st}$.

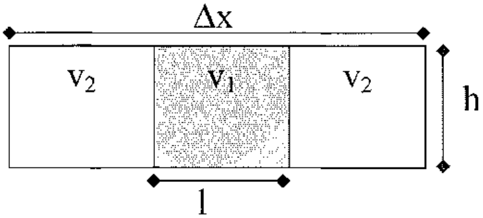

Fig. 2 Model cell partly covered by channel.

Effective k_f for swamp cells If the terrain is uncorrelated, i.e. if the cell size is large compared to the intrinsic correlation length of the topographic surface, a combination of percolation theory and homogenization theory can be applied. Homogenization theory gives the effective parameter as the problem approaches the limiting case of an unconfined aquifer with a rough bottom, where the size of the roughness elements is small compared to the overall thickness of the aquifer. Percolation theory describes the effective parameter as the thickness of the water layer tends to zero and the connectivity of the flooded areas within one model cell becomes important (Stauffer & Aharony, 1994):

$$T_{eff} = K\left(\frac{P(h) - p_c}{1 - p_c}\right)^{\mu} \cdot \overline{(h-b)}^{geo}\Big|_{wet} \tag{4}$$

$$P(H) = \int_{-\infty}^{h} p(b)\,\mathrm{d}b \tag{5}$$

$$\overline{(h-b)}^{geo}\Big|_{wet} = \exp\left(\int_{-\infty}^{h} \ln(h-b)\,p(b)\,\mathrm{d}b\right) \tag{6}$$

where K is the hydraulic conductivity, b is the topographic elevation, p_c is the percolation threshold and h is the water table elevation. The characteristics of the terrain are now summarized in the probability density function $p(b)$.

The validity of this theoretical approach was checked with a series of numerical experiments. A synthetic aquifer with varying bottom elevation was created. The bottom elevation was normally distributed and independent at every site. A fixed hydraulic gradient was applied across the synthetic aquifer and the throughflow was calculated. The resulting value for the effective transmissivity was compared to the theoretical predictions (Fig. 3). Both curves show reasonably good agreement.

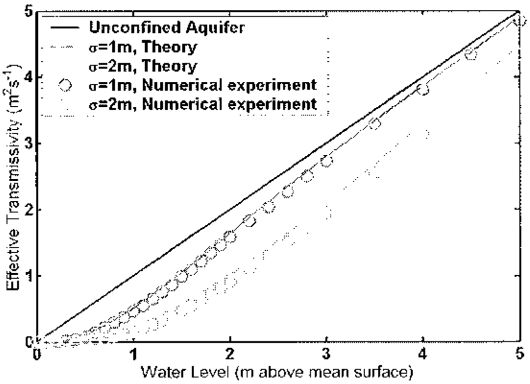

Fig. 3 Effective transmissivity relationship.

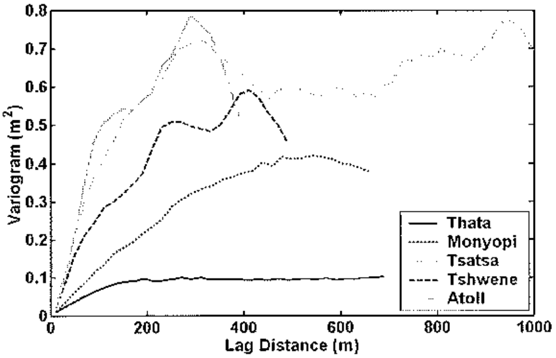

Fig. 4 Variograms of the topographic surface at different locations in the Delta.

Currently, the hydrological model works with the simplest assumption about the terrain probability density function: normally distributed and uncorrelated terrain. Topographic transects measured in the field (Fig. 4) suggest that the correlation length of the terrain is about 300–500 m, i.e. the grid spacing of 2 km is about five times the correlation length. The assumption of uncorrelated terrain elevation is therefore certainly critical, but is useful as a first order approach.

Spatially distributed input parameters: rain and evapotranspiration The exchange of water between land and atmosphere, i.e. the balance of rain and evapotranspiration is parameterized as a function of the depth to the water table only. This concept is covered in more detail in Bauer *et al.*, 2002. The net exchange of water (rain – *ET*) can be quantified for the wetland situation (depth to water table equal zero), using remote sensing techniques. For the deep groundwater situation, the chloride method can be used to derive an estimate for the net exchange. In between these two points, the net exchange is interpolated linearly.

MODELLING RESULTS AND IMPLICATIONS FOR SUSTAINABLE MANAGEMENT

Calibration strategy: comparison with satellite-derived flooding patterns

McCarthy & Gumbricht (2002) have derived a time series of the flooded area of the Okavango Delta starting in 1973 (Fig. 5). The flooding patterns are used to calibrate the hydrological model. If the net exchange of water with the atmosphere is assumed to be known, the model output is most sensitive to the following three parameters:

- Vertical hydraulic conductivity. This parameter controls the overall size of the Delta: the faster the water infiltrates into the ground, the smaller is the Delta. See Fig. 6 for the effect of this parameter.
- k_{st} of the channel cells. Together with the k_f value of the swamp, the k_{st} determines the temporal response of the Delta. If the conductivities are either too big or too small, the annual fluctuation in the flooded area is completely suppressed, or the amplitude of that fluctuation is too small (Fig. 6).
- k_f of the swamp cells. In addition to the overall effect of the conductivity, the ratio between the channel and the swamp conductivity determines the shape of the Delta. In the case of high channel conductivity but relatively low swamp conductivity, flooding keeps to the rivers and does not invade big areas next to the channels. In the opposite case, more uniform flooding over the whole area results.

Figure 5 shows the correspondence between flooding patterns derived from remote sensing and modelled flooding patterns for some selected times. Modelled and observed flooding patterns still differ significantly. This is due to the fact that so far, all the parameters are uniform for the whole model area. To accurately model the flood, one probably has to take into account variations in the horizontal swamp conductivity. Nevertheless, the effect of blocking existing channels or opening new ones can already be studied. The location and the status of the various channels is the key factor determining the shape of the flooded area. The channels are not stable over time but keep on shifting around (e.g. Ellery *et al.*, 1993). The time scale of those

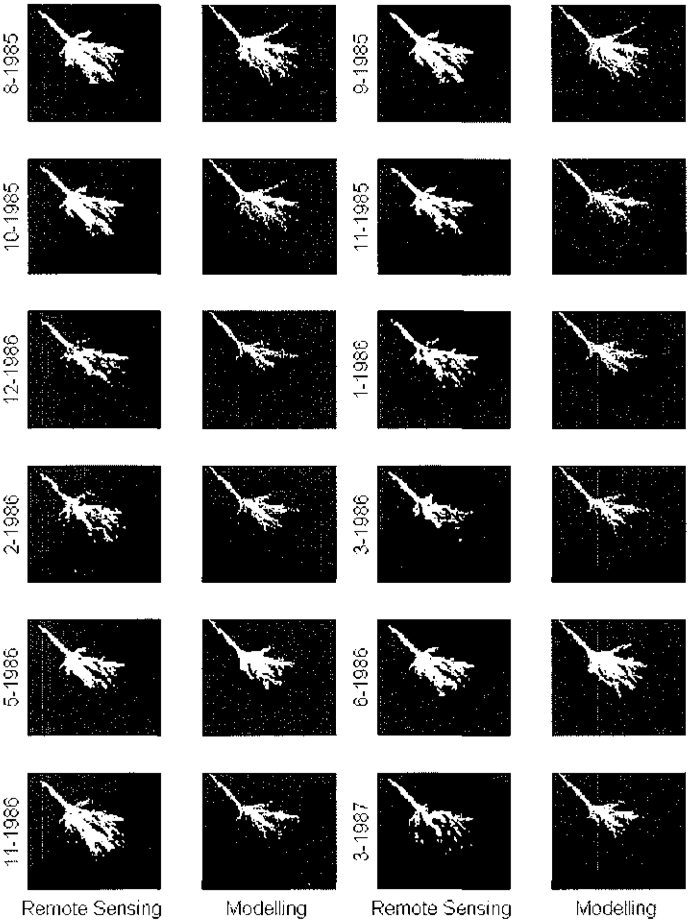

Fig. 5 Flooded area of the Okavango Delta: comparison of remote sensing and modelling results.

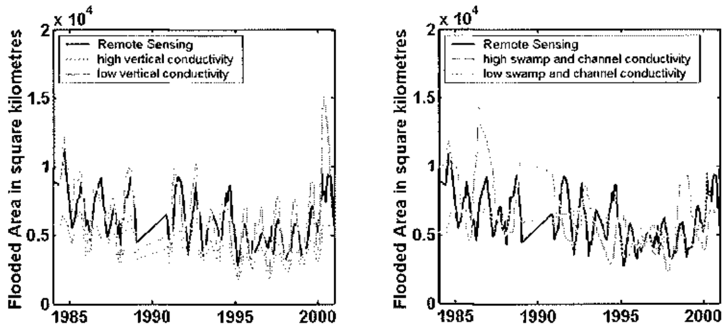

Fig. 6 Effects of vertical and horizontal conductivities on flooded areas.

shifts is not very well understood but is probably related to sedimentation. At the present stage, channel shifts have to be externally specified. However, at a later stage, coupling of a sedimentation model to the flow model may make it possible to internalize channel dynamics.

Typical decision problems and how the model can help

Water abstraction scenarios One water-related problem in the area is how to supply the growing population of the town of Maun and the surrounding rapidly developing areas. Maun is located at the downstream end of the Delta and water supply has so far relied on the shallow sand aquifers in the wetland's periphery as well as surface water flowing seasonally in the local outlet channel, the Thamalakane River. However, decreasing inflow and consequently smaller flooded areas in the nineties have shown the vulnerability of Maun water supply. The two basic options are: (a) to build a pipeline around the Delta, taking water from the inflow and supplying it to the downstream population centres; and (b) to install new wellfields in the peripheral sand aquifers, possibly somewhat further into the wetland to guarantee reliable recharge from the annual floods.

Dam building and abstraction in the upstream countries Dam building and abstraction in the upstream countries will certainly have more serious impacts. The problem here is not so much the abstracted amount of water, but the changes in the river's seasonality, which have to be expected from such projects. The vast areas of seasonal swamp are an integral part of the Delta ecosystem and probably its most diverse habitat.

The problem of blockages One problem, which is currently causing a lot of controversy in Botswana, is the problem of channel blockages. The channels in the Delta are blocked by floating swaths of papyrus (*Cyperus papyrus*) causing the channels' inaccessibility by boats and possibly shifts in the water distribution patterns. The question is whether these blockages should be cleared or not. In the long-term observation of the Delta, the blockages have been identified as an integral part of the system dynamics, triggering the formation of new channels and finally obliterating the obsolete channels (e.g. Ellery *et al.*, 1993). However, local people maintain, that the blockages are ever increasing and that their ancestors have always cleared them to keep the channels open. They feel that the amount of water reaching the settlements and villages in the downstream areas is decreasing whereas in the upstream areas, the water is withheld and water levels reach record elevations. The model supports these observations. Decreased conductivities in the swamp do in fact decrease the seasonality of the system, drying up the peripheral seasonal swamps.

CONCLUSIONS

It has been shown that the flooding dynamics of the Okavango Delta can in principle be understood and modelled in the framework of a two layer finite difference flow model. The model is calibrated with spatially distributed information on flooding derived from remote sensing data. Once calibrated and extensively validated, it can be used to assess the impacts of different management scenarios on the hydrological system. It is particularly useful to study long-term changes that result from different development scenarios. Decision-makers in Botswana and in the whole river basin are facing intricate water distribution problems in which the model may help to approach optimal solutions.

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