Hydrological Modelling and Resource Management in the Okavango Delta

Peter Bauer, Thomas Gumbricht and Wolfgang Kinzelbach
Institute of Hydromechanics and Water Resources Management, ETH Hoenggerberg
CH-8093 Zürich; bauer@ihw.baug.ethz.ch; Phone: +41-1-6333171; Fax: +41-1-6331061

1.0 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.

2.0 Introduction

In northern Botswana, southern Africa, the Okavango River forms a huge wetland system called the Okavango Delta (Figure 1). Sedimentation into a graben structure that is connected to the East African Rift Valley has built up this large alluvial fan. The waters of the Okavango River (mean discharge ~300 m^3/s) originate in the humid tropical highlands of Angola, flow southward into the Kalahari basin, spill into the Okavango Delta and are consumed by evapotranspiration. The system displays a strong temporal variability, inter-annually as well as during the course of one yearly flooding cycle. A variety of hydrological, geochemical, sedimentological and biological processes acting over different spatial and temporal scales add to the complexity of the Delta (Ellery et al., 1993, Gumbricht et al., 2001, McCarthy and Ellery, 1994, Modisi et al., 2000). The natural system has to satisfy the demands of various users all over the river basin. The structure of the different user groups as well as their mutual relationship is fairly complex in itself. Locally, domestic water supply, mining industry 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 being observed.

The outstanding ecological value of the area as well as the urgent and ever rising water demand from local and regional user groups set a challenging framework for the sustainable management of the Okavango Delta. Sound management of the system calls for a tool for a priori analysis of different management options. This was recognized 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. We feel that this type of model can assist decision-makers in all the affected countries to reach acceptable compromise between the needs of man and nature in this particularly intricate case.

3.0 Description of the hydrological model

3.1 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 and Harbaugh, 1988). In the Delta, surface and groundwater are in close contact and in continuous exchange. The two compartments cannot be reasonably separated from each other and therefore they are 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). In this way, the hydraulic differences between the flow in the swamps and in the major channels are taken into account. The interface between the two horizontal layers is given by the topographic surface.

The coarse spatial resolution of the model (1-2 km) makes it infeasible to accurately predict flow and stage variations at specific points. Rather, the model is meant to capture the regional flooding pattern in the Delta and its temporal variation, inter-annually as well as during the course of the year. The temporal resolution (1 month) is high enough to appropriately resolve the annual flooding cycle.

The only source of water to the model (apart from rainfall, see Section 3.3) is the inflow of the Okavango River at Mohembo (Figure 2). The inflow is simulated by 10 temporally variable well cells along the river valley. On all sides, the model area is surrounded by impervious boundaries. Partly, those boundaries are aligned with physical features (Linyanti system in the North, Makgadikgadi Pans in the South-East), partly they are set arbitrarily, far enough from the Delta to avoid boundary effects that could influence the flooding patterns.

3.2 Effective hydraulic parameters

The spatial resolution of the hydrological model is much coarser than the typical size of terrain features (channels, islands, floodplains 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. This has to be done for channel cells as well as for swamp cells.

3.2.1 Effective k_{st} for channel cells

Flow through a channel cell is governed by Manning-Strickler equation:

$$v = k_{st} \cdot R_{hy}^{\frac{2}{3}} \cdot (\nabla h)^{\frac{1}{2}} \qquad \text{(EQ 1)}$$

v is the flow velocity (m/s), k_{st} is the Strickler coefficient ($m^{1/3}$/s), ∇h is the hydraulic gradient (-) and R_{hy} the hydraulic radius (cross section area / wetted perimeter). In the framework of the finite difference formulation, this equation can be written as

$$v = \frac{Q}{A} = k_{st} \cdot \left(\frac{h-b}{1 + \frac{2(h-b)}{w}} \right)^{\frac{2}{3}} \cdot (\nabla h)^{\frac{1}{2}} \qquad \text{(EQ 2)}$$

where Q is the discharge from one cell to the neighboring cell (m^3/s), A is the cross section area available for the flow between the two cells (m^2), b (m) is the elevation of the cell bottom and w (m) is the width of the cell. For h-b <<w, we can write this as

$$v = \frac{Q}{A} = k_{st} \cdot (h-b)^{\frac{2}{3}} \cdot (\nabla h)^{\frac{1}{2}} \qquad \text{(EQ 3)}$$

In the flow model, the two dimensional cell-by-cell flow equation of the form

$$Q = K \cdot \Delta y \cdot (h-b)^{\beta} \cdot (\nabla h)^{\alpha} \qquad \text{(EQ 4)}$$

applies. As $A = \Delta y \cdot (h - bot)$ in Equation 3, we can identify $K = k_{st}$, $\beta = \frac{5}{3}$ and $\alpha = \frac{1}{2}$. On the one hand, k_{st} can be calculated from the grain diameter 90-percentile:

$$k_{st} = \frac{26}{\sqrt[6]{d_{90}}} \qquad \text{(EQ 5)}$$

Estimating the 90-percentile as 1 mm yields $k_{st} \approx 80 m^{\frac{1}{3}} s^{-1}$.On the other hand, a first estimate of the k_{st} value can be derived from experience: In Mohembo, the Okavango River has a mean slope of ~1/5000. The flow velocity is around 1 m/s and the depth is of the order of 5 m. Solving Equation 3 for k_{st} yields 25 $m^{1/3}$/s.

This 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 Figure 3: 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

$$Q = l \cdot h \cdot v_1 + (\Delta x - l) \cdot h \cdot v_2 \qquad \text{(EQ 6)}$$

If $l v_1 \gg (\Delta x - l) v_2$, the second term in Equation 6 can be neglected and the effective $k_{st,\,eff} = \frac{l}{\Delta x} k_{st}$. Usually, the flow velocity contrast between channel and swamp is 1/10-1/100, which means that the above approximation holds down to a channel width of 10-100m in the 1km resolution model. Channels smaller than this size are not explicitly put into the model but lumped into the hydraulic conductivity of the swamp.

3.2.2 Effective k_f for swamp cells

In the swamp cells of the upper layer, upscaling is applied to derive an effective transmissivity-water table relationship. 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 homogenisation theory can be applied. Homogenisation 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 and Aharony, 1994). The resulting relationship between the thickness of the water body and the transmissivity reads as follows:

$$T_{eff} = K\left(\frac{P(H)-p_c}{1-p_c}\right)^{\mu} \cdot \left.\overline{(H-bot)}^{geo}\right|_{wet} \qquad \text{(EQ 7)}$$

$$P(H) = \int_{-\infty}^{H} p(b)db \qquad \text{(EQ 8)}$$

$$\left.\overline{(H-bot)}^{geo}\right|_{wet} = \exp\left(\int_{-\infty}^{H} \ln(H-b)p(b)db\right) \qquad \text{(EQ 9)}$$

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). If the terrain elevation is assumed to be normally distributed, just one number -the variance of the terrain- is needed to completely determine p(b). The free parameter that is left to describe the hydraulic properties of the swamp (plant cover etc.) is K, which can be different for each cell.

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 (Figure 4). Both curves show reasonably good agreement.

Currently, the hydrological model works with the most simple assumption about the terrain probability density function: Normally distributed and uncorrelated terrain. Therefore, only the terrain variance is needed as an input parameter for the calculation of the effective hydraulic parameter. Topographic transects measured in the field (Figure 5) suggest that the correlation length of the terrain is about 300-500 m, i.e. the grid spacing of 2 km is about 5 times the correlation length. The assumption of uncorrelated terrain elevation is therefore certainly critical, but is useful as a first order approach.

Figure 5 also shows that the terrain variance is highly variable within the area of interest. Therefore a map of terrain variance is needed as an input for the hydrological model. To generate this map, the correlation between the terrain elevation and the landcover classes was used.

A scaled version of the most recent landcover map (McCarthy and Gumbricht, 2002) shows a satisfactory correlation with the terrain elevations measured in the field (Figure 7). This correlation is strongest close to water covered areas (Tshwene, Thata, Monyopi) and declines as one moves into the drylands (Atoll, Tsatsa).

3.3 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.

4.0 Modelling results and implications for sustainable management

4.1 Calibration strategy: comparison with satellite-derived flooding patterns

Thomas Gumbricht and his coworkers have recently derived a time series of the flooded area of the Okavango Delta starting as early as 1973. After 1985 one flooding image is available for almost every month (McCarthy et al., 2002). These flooding patterns display the annual flooding cycle as well as some long-term trends: Starting from the seventies, the Delta was continuously shrinking due to reduced inflow at Mohembo. It is only in the late nineties, that this trend has been reversed (Figure 7).

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 underground, the smaller is the Delta. See Figure 8 A 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. From the observed seasonality of the system, the conductivities can therefore be inferred. If the conductivities are chosen too low, a rather static lake is obtained instead of a pulsating wetland (Figure 8 B). This has important consequences for the management of the system (see next section).
- 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 7 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.

4.2 Typical decision problems and how the model can help

4.2.1 Water abstraction scenarios

One local 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 Thamalakane brings less and less water and the shallow sand aquifers, notably Shashe wellfield, are currently not flooded and therefore overpumped. The two basic options are (i) to build a pipeline around the Delta, taking water from the inflow and supplying it to the downstream population centres; (ii) to install new wellfields in the peripheral sand aquifers, possibly swomewhat further into the wetland to guarantee reliable recharge from the annual floods. The model can help to predict the impacts of both options, but the modelling exercise also revealed how extremely sensitive the water distribution into the different outlet channels reacts on smallest changes in the parameters. This is due to the flatness of the alluvial fan. However, abstractions from the inflow or from the peripheral aquifers do not seem to be critical for the system, as long as the abstracted quantities are small compared to the inflow.

4.2.2 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. Once concrete projects are being discussed, the model can be used to assess the magnitude of the impacts. Scenarios with reduced seasonality of the inflow can be calculated and the effects on the flooded area and its temporal variability can be studied.

4.2.3 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 arising 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 old channels (e.g. Ellery et al., 1993). However, local people maintain, that the blockages are ever increasing and that they have always been cleared by their ancestors 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. However, we do not know if this is just a transition-state before the formation of new major channels or the result of gradually increasing congestion of the Delta. To get a better feeling for this, an estimate of the time-scales inherent in the proposed channel shifting is urgently needed. That estimate would help to perceive the relative importance of channel-clearing projects.

5.0 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 pareto-optimal solutions.

6.0 References

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7.0 Figures

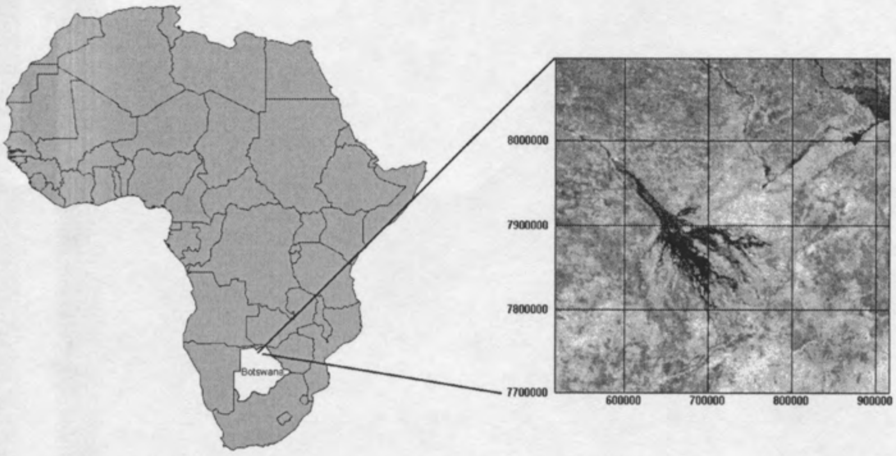

FIGURE 1. The Okavango Delta. Coordinates are UTM Zone 34 S, Cape Datum

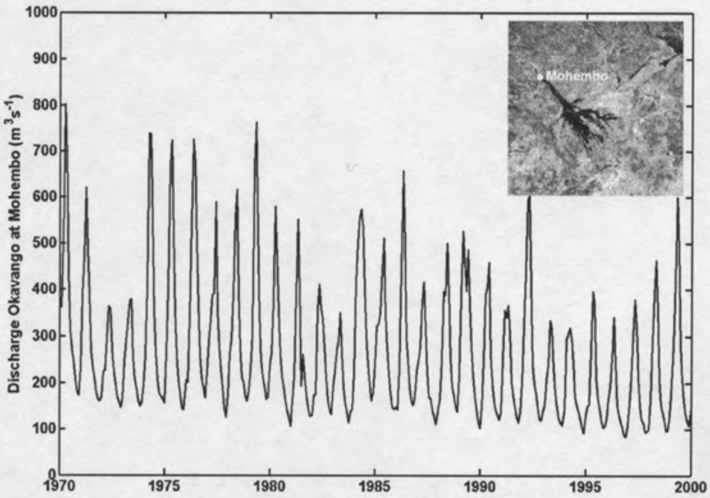

FIGURE 2. Inflow of the Okavango River at Mohembo

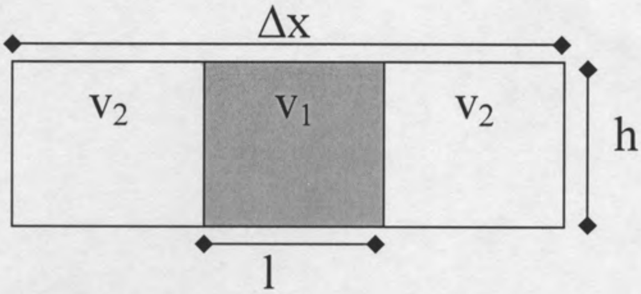

FIGURE 3. Model cell partly covered by channel

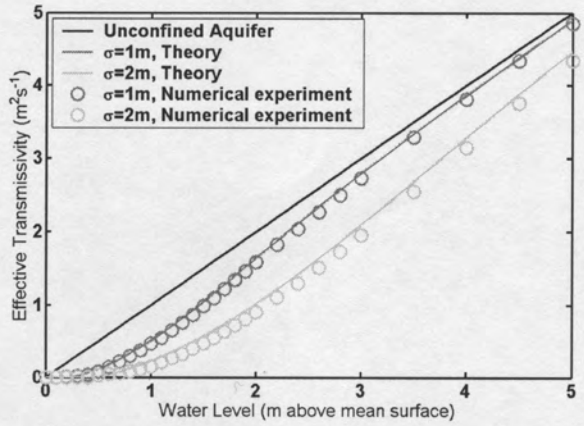

FIGURE 4. Effective transmissivity relationship

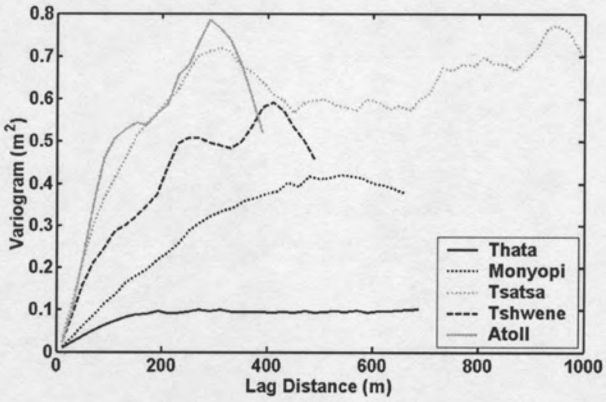

FIGURE 5. Variograms of the topographic surface at different locations in the Delta

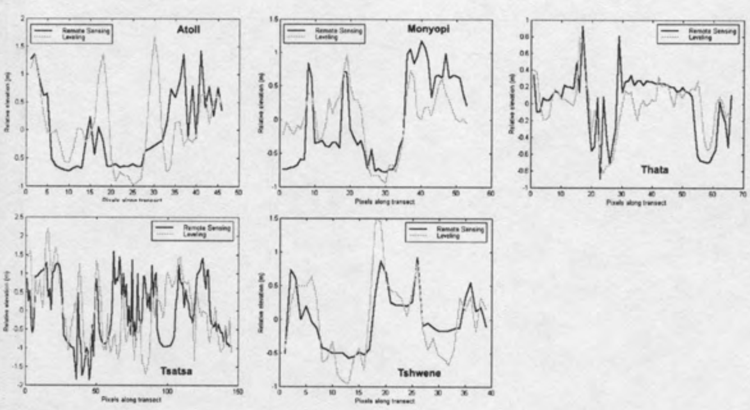

FIGURE 6. Correlation between terrain elevations from the scaled landcover map and from levelling

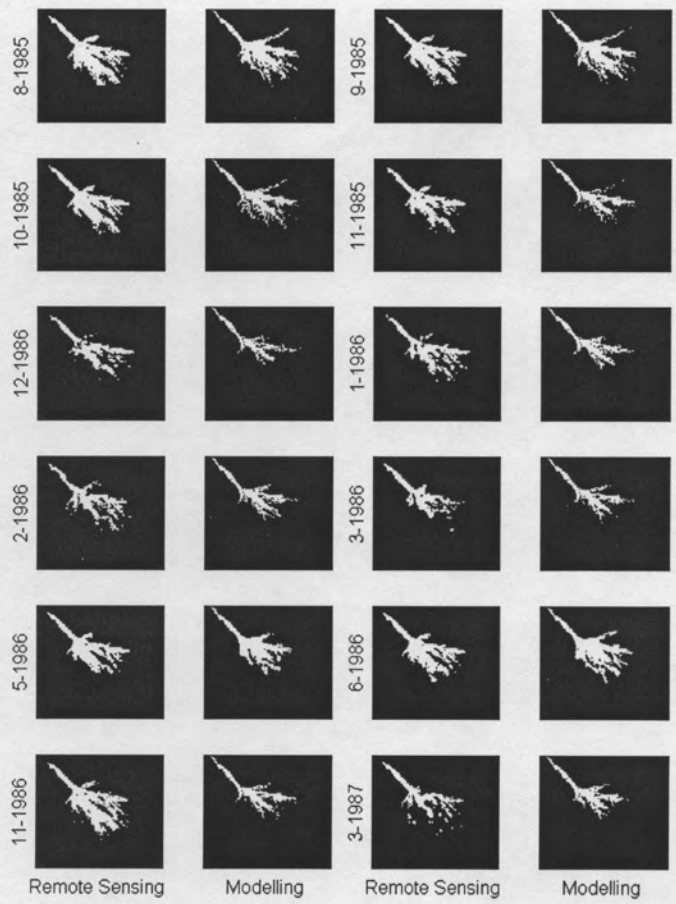

FIGURE 7. Flooded area of the Okavango Delta: Comparison of remote sensing and modeling results

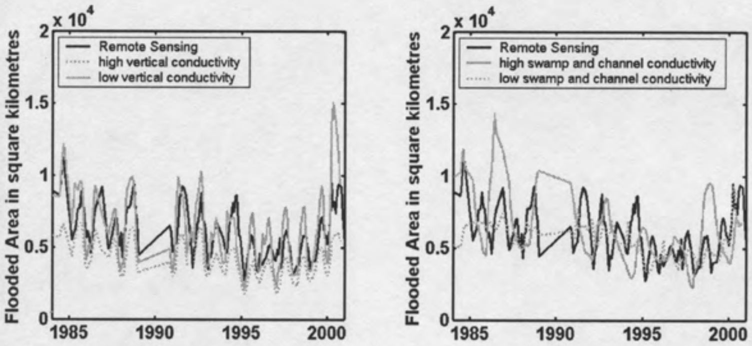

FIGURE 8. Effects of vertical and horizontal conductivities on flooded areas