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Scenarios of the impact of local and upstream changes in climate and water use on hydro-ecology in the Okavango Delta, Botswana

Michael Murray-Hudson *, **Piotr Wolski**, **Susan Ringrose**

Harry Oppenheimer Okavango Research Centre, University of Botswana, Private Bag 285, Maun, Botswana

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Summary Changes in hydrological inputs to the flood-pulsed Okavango Delta result in changes in such flooding characteristics as floodplain water depth, inundation duration and frequency. A mathematical model is used to assess impacts of changing hydrological inputs on flooding in the Okavango Delta. Future conditions are simulated by superimposing simulated abstractions, upstream developments and climate change effects on the observed time series of hydrological inputs. The effects of change in inputs are then determined by comparing hydrological characteristics such as inundation duration and frequency derived from the original and modified time series of model outputs. Simulations show that upstream abstractions are likely to have small short-term effects on the flooding pattern in the Delta, while other upstream developments such as damming or deforestation have more pronounced effects. All of these effects are relatively small, however, when compared to changes resulting from existing climatic variability, and those from the possible effects of future climate change. The combined effects of human abstraction and climate change, manifested as increased temperatures, decreased rainfall, and reduction in river flows, may result in significant Delta drying. The simulated hydrological changes affect the Delta floodplain ecosystems, with anticipated changes in the area and proportions of permanent swamp, areas covered by sedge and grass vegetation (seasonal floodplains) and floodplain grasslands (intermittently flooded areas). These will have varied effects on ecological processes in the Delta, in particular vegetative succession, primary production, and relationships of floodplains with the surrounding woodland and savannah. Additional ripple effects up trophic levels can also be expected. There may also be downstream

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* Corresponding author.
E-mail address: mmurray-hudson@orc.ub.bw (M. Murray-Hudson).

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impacts on tourist facilities presently on the fringes of the seasonal swamps as a result of reduced or increased flooding. As a result of altered flood regime, some effects are also anticipated with respect to the recharge of aquifers, which are currently used for drinking water supply around the Delta.

Introduction

The Okavango Delta is the distal part of the endorheic Okavango basin drainage system. The annual flood pulse resulting from seasonal rain in the headwaters in Angola causes an expansion and contraction of flooded area, and is a primary driver of the vegetation ecology of the Delta (Smith, 1976). The water balance of the Delta is dominated by river inflows and evapo-transpirative loss (McCarthy and Metcalfe, 1990; Scudder et al., 1993; SMEC, 1986). The Delta consists of permanent and seasonal floodplains, channels and islands of varying sizes (Gumbricht et al., 2004a). The vegetation of the Delta is described in Smith (1976), SMEC (1989) and Ellery and Ellery (1997). Here a very brief summary is given of the major floodplain communities which are relevant to this study. The channel fringe and floodplain vegetation is dominated by emergent graminoid macrophytes: sedges and grasses, all of which vary in their tolerance of flooding both in terms of frequency and duration. Higher frequencies, and longer durations, of flooding favour obligate wetland species (such as the giant sedge *Cyperus papyrus*, the reed *Phragmites australis* and other strictly aquatic species). These communities are classed as ''Perennial Swamp'' by SMEC (1989). Under lower inundation frequency and duration, obligate species are replaced by facultative wetland species (able to tolerate some dry periods), which include significantly a *Cyperus articulatus*/*Schoenoplectus corymbosus* sedge community characteristic of areas which are regularly flooded on a seasonal basis. SMEC (1989) classed these communities as ''Seasonal Swamp''. This class of floodplains is extensively used for flood recession farming in the peripheral parts of the Delta, and constitutes an important contribution to the subsistence livelihoods of rural people. Under drier conditions, various grassland communities prevail (Bonyongo et al., 2000); these may be termed facultative upland species, which are tolerant of some flooding and are classed as ''Flooded Grassland'' under the SMEC (1989) nomenclature. The floodplain grasslands of the Okavango Delta support densities of herbivores that are seasonally considerably higher than those in the surrounding woodland and savanna (Paterson, 1976; SMEC, 1989). Dryland in close proximity to water in the Delta supports a diverse and productive riparian woodland; this is entirely dependent on groundwater supplied from the adjacent floodplain or channel. Ringrose (2003) found that the species composition and structure of riparian woodlands in the distal parts of the Delta were related to drying trends of distributary systems and to salinity of groundwater, as a reflection of change in the number of recharge events.

There have been several previous attempts to assess potential change in the Delta due to upstream development or climate change through hydrological modelling (Dinçer et al., 1987; Gieske, 1997; Gumbricht et al., 2004b; Scudder et al., 1993; SMEC, 1990; WTC, 1997). These models focused purely on quantitative assessment of hydrological changes, which were defined in terms of reduction of flows in the terminal rivers of the system and through ''loss of flooded area'' determined for a single flood. The latter term, although reflecting some aspects of flooding conditions in the Delta, does not reflect the primary hydrological variables that result from the seasonal and inter-annual variation in hydrological inputs to the system, which determine the ecology of the system: the extent, distribution, frequency and duration of inundation. As a result, these models had no means to relate modelled hydrological changes to potential changes in ecological processes such as primary production, succession or effects at higher trophic levels.

This study relates changes in hydrological inputs, simulated from various possible upstream development and climate change scenarios (Andersson et al., this volume), to changes in extent, distribution, frequency and duration of inundation. It evaluates the effects these changes might have on the ecology of the Delta as a wetland system by relating these changes to floodplain vegetation communities. It must be emphasised that this assessment deals only with effects related to change in temporal distribution of water and magnitude of inputs.

Materials and methods

Approach

The assessment of effects of possible future changes in hydrological inputs on the hydrological characteristics of the Okavango Delta was done by modifying the past time series of inflows and rainfall inputs to reflect possible future changes, and running a hydrological model of the Okavango Delta (Wolski et al., this volume) using these modified inputs. The simulated hydrological characteristics were then compared with those of the unmodified time series. The assumption underlying the adopted approach was that we were interested in obtaining indices of change in relation to past and contemporary conditions, rather than to explicitly simulate future conditions. Such an approach was possible since the characteristics of the hydrology of the system are not defined as pertaining to a single flood, but rather to conditions prevailing over several years (average), and these are reflected well in the past time series. In this setting, comparison of various scenarios is relatively straightforward.

The available observed time series of hydrological inputs to the Delta, both river inflow and local rainfall, is non-stationary. This non-stationarity is caused by the presence of sequences of wetter and drier years, and is often described as following a quasi 80-year cycle (McCarthy et al., 2000; Wolski et al., 2002), the persistence of which over the last

3000 years has been indicated by palaeoclimatic data (Tyson et al., 2002). This cyclicity has not yet been resolved by global/regional climate models, and a discussion of its veracity and driving forces is beyond the scope of this paper. Such sequences have been observed in wetlands elsewhere in Africa, and globally, and are referred to as pluriannual wet and dry periods by Junk (2002). The Delta has been subject to three general wetness regimes in the recent past which we have called wet (1974—1985), transitional (1985—1990) and dry (1990—2000). The wet and dry periods were of sufficient duration and consistency to result in the establishment of a particular distribution of wetland herbaceous communities. Irrespective of the cause of these regimes, neither can be considered a reference ''normal'' situation (both are normal, yet different). If the assumption of the climatic cyclicity is true, both are likely to repeat themselves in the future. Given this situation, our assessment of future change was undertaken separately for wet and dry conditions.

Assessment of the hydro-ecological effects of simulated future changes comprised five steps.

Step 1. Determination of change in hydrological inputs to the Delta and in climatic conditions in the Delta resulting from postulated upstream development and climate change.

For development scenarios (Table 1), the modified inflow time series obtained from Andersson et al. (this volume) was applied. These are all upstream in the catchment as no developments in the Delta proper were simulated. For climate change scenarios, the future change in hydrological inputs was imposed on the observed past time series using the concept of change factor in a variable Var, i.e. Δ(Var), where:

$$\mathrm{Var}_{\mathrm{average,future}} = \Delta(\mathrm{Var}) \cdot \mathrm{Var}_{\mathrm{average,past}}$$

The values of Δ(Var) were derived from climate models for rainfall, air temperature and humidity for both the catchment of the Okavango River and the Okavango Delta separately (Andersson et al., this volume). The Δ(Var) for the Okavango Delta were applied to modify the observed time series of Okavango Delta rainfall and variables used for calculating local potential evaporation for each time step:

$$\mathrm{Var}_{\mathrm{scenario}} = \Delta(\mathrm{Var}) \cdot \mathrm{Var}_{\mathrm{past}}$$

Implementation of Δ(Var) for the Okavango catchment was done in the catchment model as described by Andersson et al. (this volume). The output of the catchment model for each of the scenarios was then taken as the input to the Delta. Several scenarios of future climate were considered here. These scenarios were simulated by three global climate models (HadCM3, CCC and GLFD) for different scenarios of greenhouse gases emissions (A2 and B2) and pertained to the periods of 2020—2050 and 2050—2080. For detailed description of the models and methods used see Andersson et al. (this volume).

Table 1 List of simulated development scenarios

Scenario code	Impact type	Impact details	Prognosed for year
Low abs	Low intensity abstractions	Water use (domestic, livestock, tourism):	2015
Low dam	Low intensity damming	Dams (primarily for hydropower)	
High abs	High intensity abstraction	Irrigation	
Low def	Low intensity deforestation	Deforestation 1 km from rivers	
Low com	Low intensity combined	Irrigation and water use + deforestation 1 km from rivers (no dams)	
High com	High intensity combined	Dams, irrigation and water use + deforestation 1 km from rivers	
Low abs	Low intensity abstractions	Water use (domestic, livestock, tourism):	2025
High dam	High intensity damming	All potential dams	
High abs	High intensity abstractions	Irrigation (5% of potential Land around Menongue and Cuito-Cuanavale and at least 15% of potential irrigable land downstream)	
High def	High intensity deforestation	Deforestation 2 km from rivers	
High abs	High intensity abstraction	Pipeline to Windhoek	
Low com	Low intensity combined	Irrigation + water use + deforestation 2 km from rivers + Windhoek pipeline (no dams)	
High com	High intensity combined	Dams + irrigation + water use + deforestation 2 km from rivers + Windhoek pipeline	

Step 2. Determination of size of inundated area and distribution of inundation using a semi-lumped hydrological model.

A time series of inundated area was determined for baseline conditions and for each scenario using a semi-lumped hydrological model. The hydrological model used is described in detail by Wolski et al. (this volume). The model simulates flooding in the Delta using a linear reservoir concept. Hydrological inputs (inflow and rainfall) are routed through a set of interlinked reservoirs representing major distributaries in the Delta. Apart from surface water fluxes the model simulates fluxes between surface water and floodplain groundwater and between floodplain groundwater and island groundwater. The model accounts for rainfall recharge to groundwater both within floodplains and islands, and evaporation from inundated areas, as well as from groundwater within non-inundated floodplains and islands. Values of inundated area as well as fluxes in and out of the surface water and groundwater reservoirs are obtained for each distributary at a monthly time step. The model was calibrated against observed discharges at one of the Delta outlets, the Boro, (period of 1973–2003) and against observed inundation area (period of 1985–2000) in each of the distributaries. The calibrated model achieved correlations between observed and simulated outflows of 0.95 on an annual basis and 0.91 on a monthly basis, and between the observed and simulated inundation areas of 0.76 for the Boro distributary and 0.72 for the entire Delta. A comparison of observed and simulated inundation area in the entire Okavango Delta is presented in Fig. 1.

The lumped value of inundation area in distributaries obtained from the hydrological model was used as an input to a GIS model (Wolski et al., this volume) in which the spatial distribution of that flood was determined based on a 15 year time series of flood maps. Although the spatial resolution of the hydrological model is very coarse (units vary in size from 500–2000 km^2), the GIS model provides the distribution of flood at a much finer spatial resolution, 1 km × 1 km. Flood maps show some variation in flood distribution for floods of similar size from different periods. The available data do not permit distinction between possible causes of this variation, such as mis-classification and mis-registration of satellite images used to derive flood maps, and natural variation in inundation extent. Therefore, flooding at the 1 km × 1 km pixel size was described in a probabilistic manner: for each of the pixels, the probability of being inundated by a flood of size x was described by a probability distribution function $F(x)$ corresponding to the normal distribution. Parameters of $F(x)$ were derived for each of the pixels based on the analysis of the flood map series. Although the GIS model allows for performing analyses in a probabilistic manner (i.e. deriving a suite of flood characteristics for a pixel together with their associated probabilities), for the sake of simplicity we decided to work with the most probable situation only.

Step3. Determination of size and distribution of functional floodplain classes.

SMEC (1989) distinguished four classes of floodplain in the Okavango based on frequency of flooding with minor subdivisions based on duration based on analysis by the project hydrologist (J. Porter). These classes were correlated as far as possible with major plant communities as derived from the compilation of earlier studies with long-term personal observations by the

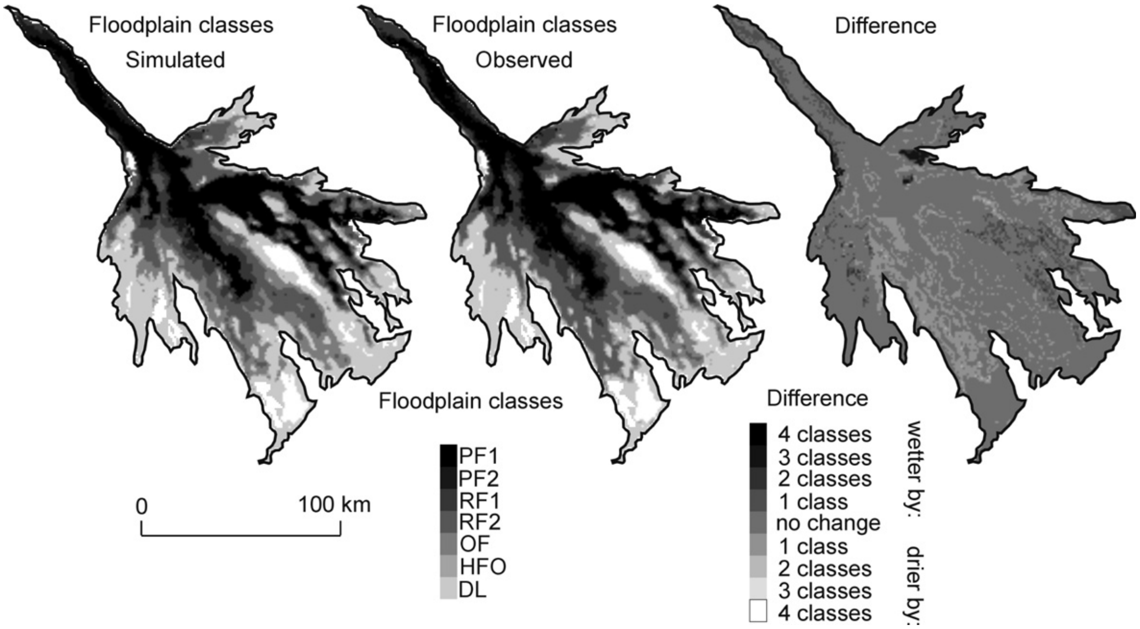

Figure 1 Modelled and observed distribution of Functional Floodplain classes for the period 1985–2000.

vegetation ecologist (P.A. Smith). This was the first classification scheme to relate the occurrence of different vegetation communities in areas with different flooding characteristics in the Delta, and in the absence of a statistically based derivation for plant community-hydroperiod relationships, we have used a modified version of the system in this study (Table 2).

Inundation frequency and duration were derived for 1 km × 1 km pixels by analysing the stacked maps of the most probable inundation distribution for each of the months in the modelled time series of inundation extents. Each of the major functional floodplain classes shown in Table 2 is characterized by a specific combination of inundation frequency and duration. By classifying the inundation duration and frequency maps it was thus possible to obtain maps showing the distribution of the functional floodplain classes, hereafter referred to as floodplain classes. The above analysis was performed on the time series of inundation area simulated by the model for the past (baseline) conditions, for which observations were available and for which the model was calibrated.

Step 4. Determination of change in size and distribution of functional floodplain between each of the scenarios and (simulated) baseline conditions.

The extent of change was assessed by calculating the areas for which change in floodplain class occurred between the given scenario and the baseline simulation. Differences were also calculated on a pixel to pixel basis and expressed by the number of classes towards drier or wetter conditions (as illustrated in the figure). Model-simulated baseline conditions were used as the reference with respect to which scenarios were assessed, instead of observed conditions, so that the uncertainty and error of the two models used (i.e. the Okavango River catchment model and Okavango Delta model) do not affect the indices of change obtained for each scenario. Maps showing the distribution of floodplain classes for baseline conditions and for each of the scenarios carry the error of the hydrological modelling, illustrated in Fig. 1. However, that error largely cancels in the difference maps.

Step 5. Assessment of ecological consequences of hydrological change.

Ecological consequences were assessed by translating change in functional floodplain class area into change in successional status of floodplain vegetation based on the relationships given in Table 1. The implications of the different extents of vegetation communities on primary production and upward effects on trophic linkages were then derived from the literature, and related to potential management objectives.

Results and discussion

The various development scenarios are modelled discretely, although clearly their effects will probably occur in combination in a continuous rather than a quantum manner over time. The hydrological model, however, allows quantitative comparisons of the flood change effects to be made between scenarios and against two sets of ''baseline'' conditions (wet, and dry) in terms of changes in area of functional flood classes. It should be noted also that the development scenarios are hypothetical at this time. For example, in all likelihood, land clearing (deforestation) in the Angolan catchment will be very slow due to the prevalence of land mines and the effects of land clearing on inputs into the catchment rivers currently appears minimal.

Results are presented in the form of graphs showing areas corresponding to each of the floodplain classes under each scenario (Fig. 2, development, and Fig. 3, climate change), in which changes are shown as proportions of the floodable area made up by the various floodplain classes, and can be compared to wet and dry baseline conditions. Maps showing the spatial distribution of floodplain class units (Figs. 5 and 6) are also presented. These include ''difference'' maps showing areas where change occurs, and the number of floodplain classes constituting that change. The hydrological effects are described in terms of change in the areas of floodplain classes under various development or climate change scenarios. These changes in area are then

Table 2 Hydrological characteristics and vegetation communities of functional floodplain types (after SMEC, 1989)

Floodplain class	Sub-class	Class code	Flood frequency	Flood duration (months/year)	Vegetation communities
Permanent floodplain	Proper	PF1	1	12	Perennial marsh
	Fringe	PF2	1	8–12	Perennial marsh
Regularly flooded seasonal floodplain	Annual	RF1	1	4–8	Seasonal marsh
	>Biennial	RF2	0.5–1		Seasonal marsh
Occasionally flooded seasonal		OF	0.1–0.5	1–4	Flooded grassland
High floods only		HFO	<0.1	<2	Forbland/grassland
Dryland		DL	0	0	Dryland communities

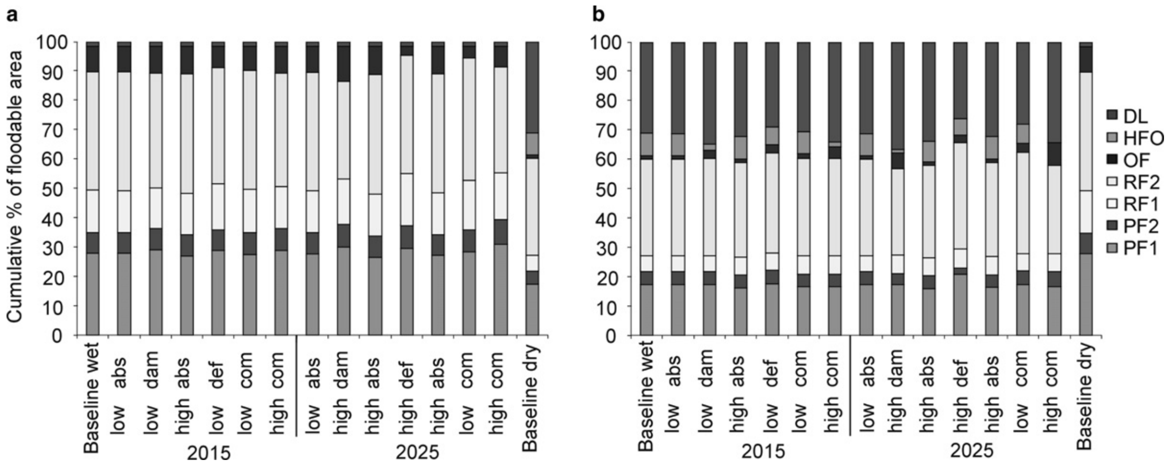

Figure 2 Class composition of Okavango Delta floodplains simulated for hydrological inputs reflecting high (''high'') and low (''low'') intensity of abstractions (''abs''), damming (''dam'') and deforestation (''def'') or combination of these (''com'') in the Okavango basin, as obtained from potential development scenarios for 2015 and 2025. (a) Wet conditions and (b) dry conditions. Floodplain classes as in Table 2.

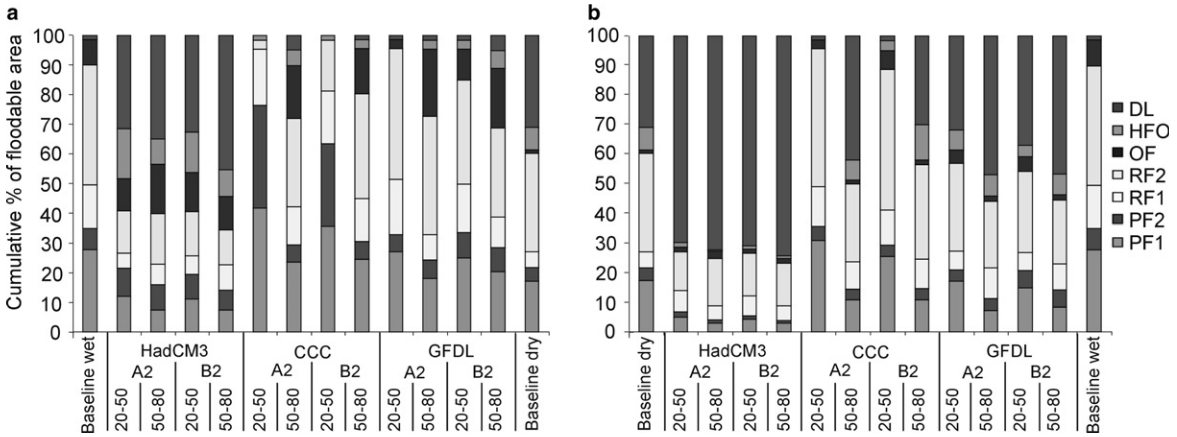

Figure 3 Class composition of Okavango Delta floodplains simulated for hydrological inputs obtained from various climate models (HadCM3, CCC, GFDL) for various greenhouse scenarios (A2 and B2) and for different future time windows (2020—2050 and 2050—2080). (a) Wet conditions and (b) dry conditions. Floodplain classes as in Table 2.

related to the vegetation ecology of the wetland in terms of potential loss or gain, and the implications of these changes are discussed in terms of processes, trophic links, and biodiversity.

In general, during wet sequences, the total area permanently flooded increases as a result of increased inflow volumes, as does the area subject to regular, long duration flooding (comparing baseline dry with baseline wet, Fig. 4). The areas subject to less frequent, shorter flooding (dryland, or DL and high flood only, HFO) under dry sequences revert to occasionally flooded (OF) and regularly seasonally flooded (RF) classes during wet sequences. It is important to bear in mind that within these wet and dry sequences, there is still great variability in size and characteristics of the inflow. Change from the wet conditions of the 1970s and 1980s to the dry conditions of the 1990s caused an average reduction in the mean extent of perennially flooded (PF) of 1700 km^2, and of the RF/OF/HFO by 2365 km^2. It is also clear from the difference maps in Figs. 5 and 6 that the potential effects of climate change are an order of magnitude greater than the potential effects of human development in the basin, but similar to the difference between wet and dry periods.

Hydrological responses to development scenarios

The development scenarios (Figs. 2 and 5) were divided into four qualitatively different types (Table 1); (i) degrees of abstraction (called ''low'' and ''high abs''), (ii) differing intensities of catchment deforestation (''low''/''high def''), (iii) upstream damming (''low''/''high dam'') and (iv) combinations of these (''low''/''high com''). The result of abstractions is to reduce inflows both during low flow as well as during high flow periods. As a result, there is a reduction in the size of the permanently inundated area (by 4 km^2 for low abstraction to 165 km^2 for high abstraction), and an increase in the area of dry land. The total size of the seasonal (RF) and occasional floodplains

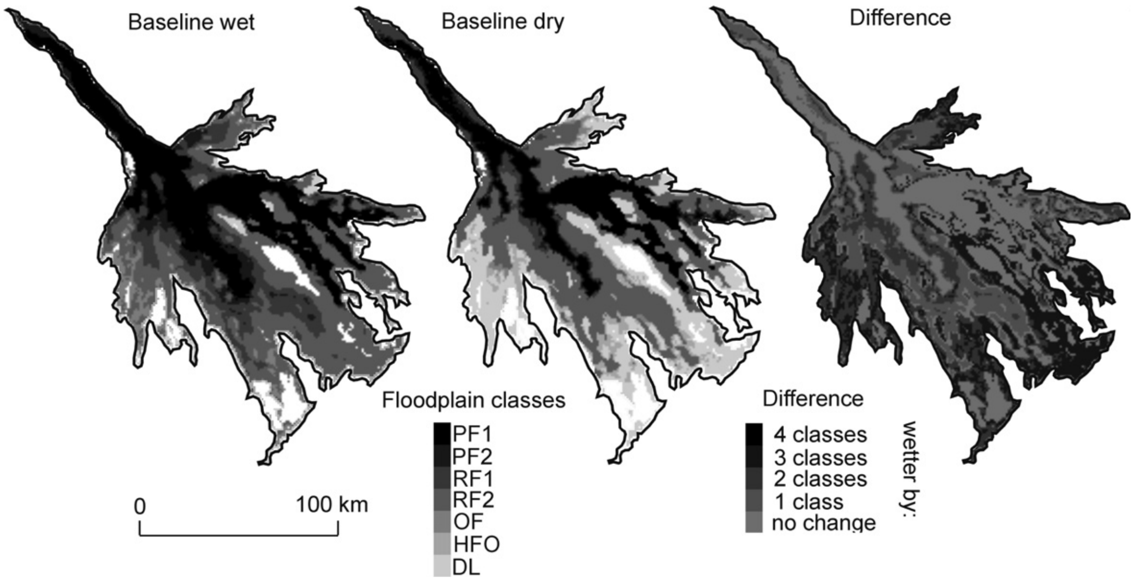

Figure 4 (a) Baseline distribution of floodplain classes during wet (1970—1985) and dry (1985—2000) conditions as simulated by the hydrological model of the Okavango Delta and (b) change in floodplain classes between the wet and dry conditions.

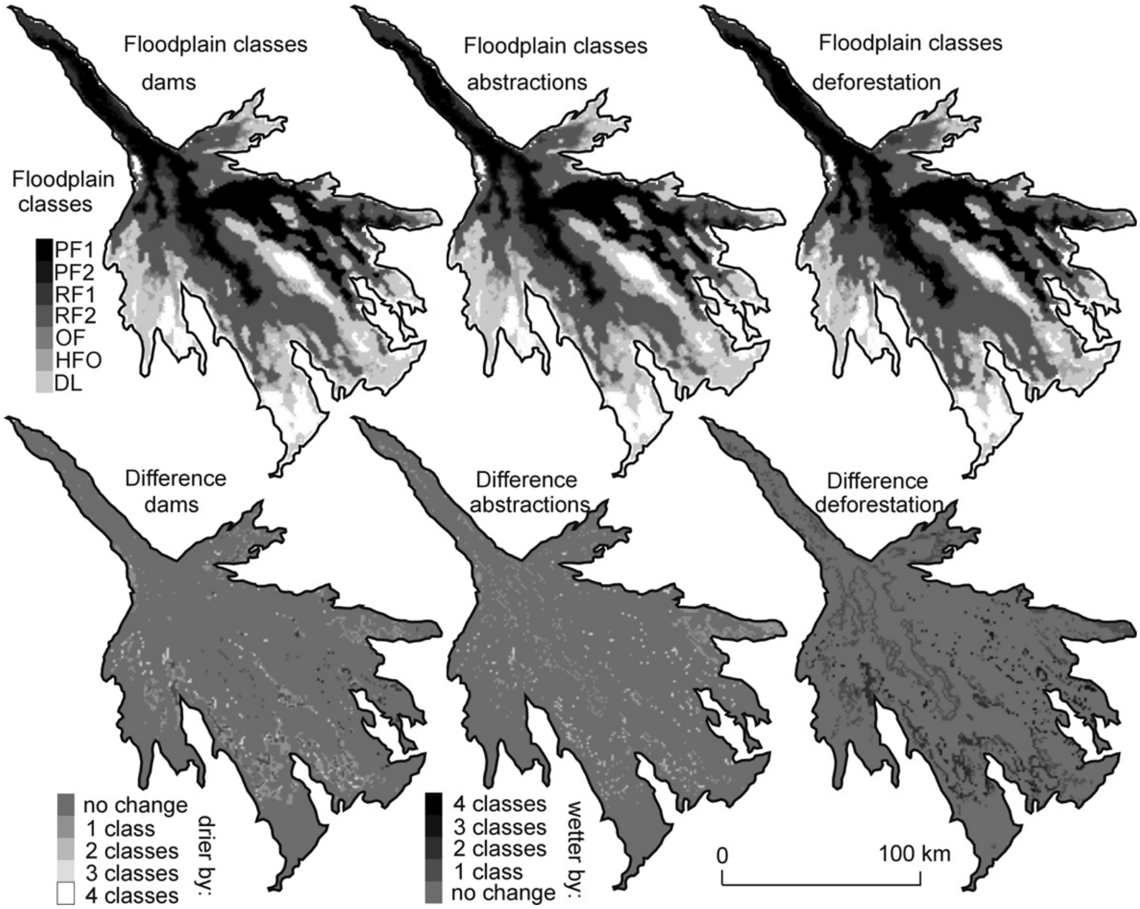

Figure 5 Effects of high intensity development scenarios on the Okavango Delta under dry conditions: (a) distribution of floodplain classes and (b) change in floodplain classes with respect to baseline dry conditions (as presented in Fig. 4).

(OF) remains approximately the same, but the zone occupied by them retreats towards the centre of the Delta. The effect of damming is to reduce peak flows and increase low flows. However, due to the way the dams operate, these effects are strongly manifested during wet periods, and during transition from wet to dry, but less during dry

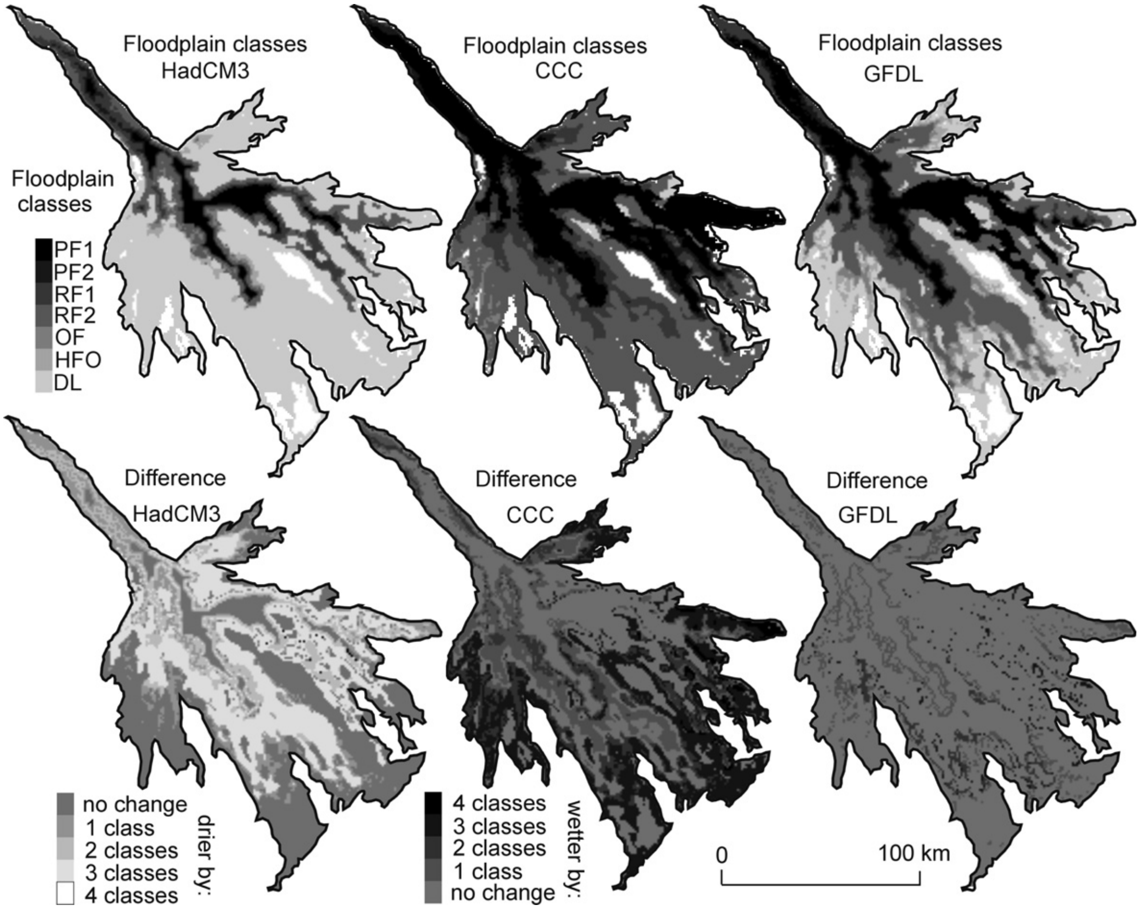

Figure 6 Effects of change in hydrological inputs on the Okavango Delta as obtained from various climate models (HadCM3, CCC and GFDL) under A2 greenhouse gases scenario for 2020—2050 period. Dry conditions: (a) distribution of floodplain classes and (b) change in floodplain classes with respect to baseline dry conditions (as presented in Fig. 4).

periods. During wet years, the effects of damming cause an increase in the size of PF (from 130 km^2 for low damming to 300 km^2 for high damming) and reduction in the size of RF (by 230 km^2—660 km^2, respectively). The extent of dry land (DL) increases by 70—200 km^2, respectively. The difference maps (Fig. 5) show that these effects are largely manifested in the margins of all flood zones: for example, the fringes of the perennially flooded parts of the Panhandle dry by up to 4 flooding classes — these floodplains may change from class PF1 to OF. The overall differences produced by damming and abstraction scenarios are broadly similar: a drying trend throughout the Delta including the Panhandle.

The result of deforestation is to increase inflows throughout the year, with stronger effects seen during peak flood. As a result, there is an increase in size of all the floodplain classes except the dry land. This increase is strongest for the permanent floodplains (PF), where it amounts to 190 km^2 for low deforestation and to 400 km^2 for high deforestation, while for seasonal floodplains the changes are 85 and 165 km^2 respectively. The zones occupied by each of the units, obviously, shift towards the peripheral parts of the Delta. The difference map (Fig. 5) shows an increase in flooding class affecting the peripheral Delta.

The combination scenarios integrate all the above factors. Since the ''pure'' scenarios sometimes induce effects opposite to each other (e.g. deforestation causes increases, while abstractions cause decreases in inflows to the Delta), there is no clear direction of change in the case of combination scenarios, and actual effects vary between dry and wet years. For scenarios which combine deforestation and abstractions, there is a reduction in PF area during dry years (by 50 km^2 for low and 30 km^2 for high) and no change (for low) or increase (by 80 km^2 for high) during wet years. There is a consistent increase in the area of RF by 40 km^2 for low to 140 km^2 for high. When all three factors are introduced simultaneously, the effects of dams largely cancel the effects of deforestation causing more regular flooding with a virtual cessation of the effects of high floods (<0.1 frequency).

Hydrological responses to climate change scenarios

Different global climate models (GCMs) predict future conditions in the Okavango Basin ranging from drier than present to wetter than present, and there are differences in both degree of change and direction of change between the Okavango river catchment area and the Okavango Delta proper (Andersson et al., this volume). The subtle interplay of change in the catchment and change in the Delta proper as obtained from GCMs produces a wide spectrum of possible future conditions in the Delta. It is beyond the scope of this paper to assess which of the climate models and scenarios for greenhouse gases concentrations are most realistic. What is important here is that there is a large uncertainty about future climatic conditions, and that the modelled effects of climatic variation on the hydrology of the Delta are much stronger than those of development.

Wet sequence

Under the A2 greenhouse gas scenario (Fig. 3), the HadCM3 model outputs produce large increases in DL, HFO and OF, with similar large decreases in PF1 and RF1 in both analysed time periods. RF2 and PF2 both increase. The HadCM3 B2 greenhouse gas scenario outputs produce similar effects, but slightly more pronounced. CCC model outputs for scenario A2 produce an initial (2020—2050) large increase in perennially flooded area (PF1 and PF2) with losses of all OF, HFO and DL in the area currently susceptible to flooding. The 2050—2080 period produces a reversion to conditions close to current baseline, although with more extensive area in the OF and HFO classes. The B2 scenario also produces wetter initial conditions, with a loss of DL and reduction in RF2, and an increase in both PF classes. In the 2020—2050 period, areas subject to regular seasonal flooding (RF2) increase significantly, with some increases in OF, while PF classes shrink to close to baseline. The GFDL model under the A2 scenario produces initial conditions very close to the wet baseline. During 2050—2080 there is a reduction in RF1 and PF1, and an increase in OF area. Under the B2 scenario, initial conditions show a slight increase in OF and HFO, with reduced RF2 compared to wet baseline. Subsequently (2050—2080) a large increase in seasonally flooded classes and dryland occurs. Losses of PF1 and RF1 occur. These conditions are still not as severe as the difference between wet baseline and dry baseline conditions.

Dry sequence

Under dry sequence conditions, both HadCM3 and GFDL outputs produce significantly reduced areas of flooding compared to the baseline, especially in the latter half of the century. The HadCM3 effects are to greatly reduce all flooded areas, with a large (more than double) increase in the area of DL; GFDL effects only produce large increases in DL in the 2050—2080 period. Differences between greenhouse gas scenarios are not pronounced, but are larger in GFDL outputs than with the HadCM3 model. Neither of these models produces the increases in seasonal or occasional flooding that are found in the wet sequence. The CCC model differs considerably here, in that initially, conditions are significantly wetter than the dry baseline for both A2 and B2 scenarios. Areas subject to regular seasonal flooding and perennially flooded areas (RF2 and both PF classes) increase, with a significant loss of dryland and areas inundated at high floods only. In the subsequent 2050—2080 period, significant drying occurs, with conditions under greenhouse gas scenario A2 being slightly drier than under the dry baseline. Under the B2 scenario there are slightly greater areas of seasonal and occasional flooding than the dry baseline. These changes are shown graphically in Fig. 6 for greenhouse gas scenario A2 and the period 2020—2050 with differences related to the dry baseline. The drier conditions under the HadCM3 scenarios are clearly manifest throughout the Delta, including the Panhandle, with changes of up to four classes affecting large areas of the more seasonal (central and western) distributaries in particular. Wetter conditions produced by CCC and to a lesser extent by GFDL outputs are shown affecting peripheral OF and dry land areas, with extensive areas showing an increase in flooding of between 2 and 3 classes. Increases of 4 classes occur in localised areas, particularly at the distal end of the eastern distributary. The Panhandle is relatively unaffected, with small increases along the very periphery.

Potential ecological responses to hydrological change

Because hydrology is a primary determinant of the floodplain vegetation, the ecological effects of hydrological changes from upstream development will be similar to those of climate change, varying only in degree. Few woody species are adapted to flooding (Cronk and Fennessey, 2001). This holds true in the Delta where floodplains are maintained as sedge or grasslands by regular or intermittent flooding (Smith, 1976). Vegetation succession trends in Delta floodplains, as conditions become increasingly drier, consist primarily of substitution of obligate wetland species by facultative species and ultimately by woody, flood intolerant, species, (SMEC, 1989; Smith, 1976). Cessation of flooding for a period of a decade or more results in the establishment of woody species on the floodplain (often the early colonisers are *Acacia* spp., or *Combretum imberbe*, depending on seed bank, soil type and other conditions). This trend has been documented in the lower reaches of the Boro where dredging has prevented floods from inundating floodplains since the early 1970s (Ellery and McCarthy, 1998), and can be observed on the terraces of the currently ephemeral Lake Ngami and elsewhere in the distal Delta. Flooding in effect arrests this succession, resetting the system and favouring the short life-cycle herbaceous species (Junk, 2002; Odum, 1971). In the Delta, new flooding (of sufficient duration) of dry land areas kills the woody components, and results in the re-establishment of sedge or grassland. This effect is primarily related to duration, and secondarily to frequency: one inundation of several months is sufficient to kill all the woody species and re-set successional processes; these must be maintained in an arrested state by subsequent flooding at sufficient frequency. This mechanism, for example, maintains the HFO floodplain class as an open grassland.

Frequently, the result of maintaining ecological succession at an early stage is to maintain the primary productivity at a high rate under the given nutrient, energy and offtake conditions (Odum, 1971). Another important effect of flood pulsing is a rapid and repeated change of redox conditions in the soils of seasonal floodplains (Mitsch and Gosselink, 2000). In the seasonal floodplains of the Boro distributary of the Okavango, Hoberg et al. (2002) found elevated levels of dissolved nitrogen and phosphorus relative to the channel. The change from aerobic to anaerobic redox status effectively slows the pace of nutrient cycling in floodplain soils as it becomes predominantly microbially mediated, and nutrients exist in their reduced form essentially unavailable to plants (Mitsch and Gosselink, 2000). Under these conditions, Okavango floodplains act as nutrient sinks, with active sequestration of nitrate and phosphate in the floodplain sediments, and some transport in the groundwater. When the flood recedes, conditions become aerobic and nutrients become available to plants in their oxidised form. The graminoid plants in particular are capable of very rapid growth, and available nutrients are quickly bound up in plant tissue. In the Okavango, maximum flood generally occurs in mid-winter; flood recession takes place just before the advent of seasonal summer rains and higher temperatures. This timing serves to amplify the effects of the pulse-driven switching of nutrient pathways. Thus, ecologically, maximum biomass production is likely to be concentrated in those floodplain classes which are subject to alternating flooding and drying (RF, OF and HFO, or seasonal marsh and flooded grassland communities). Similarly, plant species richness is highest in those areas which are regularly flooded on a seasonal basis (Alonso and Nordin, 2003). Dryland, if completely removed from the area subject to flooding, reverts to a rainfall-driven savanna biomass production model (Coe et al., 1976), and long-term successional trends there will ultimately favour a browser-dominated fauna, similar to that extant in the large areas of Mopane (*Colophospermum mopane*) and *Acacia* woodland which form the ecological hinterland for the Delta. Increases in dryland area can thus be considered undesirable under a management regime which seeks to maintain or improve biological diversity and eco-tourism value (National Conservation Strategy Coordinating Agency, 2004, 2005). Development scenarios involving damming (D2, D5, D8 and D13) result in the loss of OF and HFO (grasslands) and will have a negative effect on wildlife habitat, herbivore diversity and the extensive eco-tourism development based on these two factors. Similarly such losses will result in the loss of arable potential for these floodplain classes in the peripheral parts of the Delta, with subsequent negative effects on subsistence livelihoods. In addition, some loss of biological productivity can be expected with the reversion of these classes to woodland. The climax community in such areas if no reflooding occurs is likely to be dominated by *Colophospermum mopane* or an *Acacia erioloba*/*Terminalia sericea* community (depending on soil type). This is observed in the fossil delta landscapes in the dry land portions of the Delta. Such trends can be expected under the damming scenarios. Reduction in areas flooded in the OF and HFO floodplain classes in the distal parts of the Delta has the potential to result in decreased recharge to the shallow aquifers currently being developed to supply the District capital Maun with domestic water.

In general, modelled potential developments in the basin do not greatly affect the extent of permanently flooded marshland, with the exception of extensive deforestation in the catchment. This results in an increase in the fringe PF class which includes those areas which are flooded in all years but may experience a dry spell of up to 4 months. This increase occurs during both dry and wet sequences. This would be a result of more peaked flood hydrographs and an increase in overall inflow volume resulting from increased runoff from decreased vegetative land cover in the catchment.

Trophic linkages

In general, the aquatic components of the Delta system appear to be less at risk than the components dependent on the seasonally and infrequently flooded areas. These latter importantly include the preferred habitats of endangered species such as wattled crane (*Grus carunculatus*), and a wide diversity of water-dependent and specialist grazing mammals such as lechwe (*Kobus leche*), tsessebe (*Damaliscus lunatus lunatus*) and Cape buffalo (*Syncerus caffer*). Similarly adverse effects can be expected for the predators of these grazers, such as cheetah (*Acinonyx jubatus*) and wild dog (*Lycaon pictus*), both of which are presently endangered and require the maintenance of open savannah habitats.

The permanently flooded areas in the Delta constitute important refugia for many of the fish species (Merron and Bruton, 1995), including the commercially important cichlids. However, the pattern of usage of the seasonally flooded areas for breeding and forage (Merron and Bruton, 1995) indicates that there is likely to be a significant flow of nutrients from the seasonally to the permanently flooded areas. The movement of fish-acquired nutrients up the trophic scales occurs when water levels in the seasonal floodplains start to drop and small fish species leave the floodplains and enter the permanent channels, where they are exposed to intense predation by larger fish species, birds and crocodiles (Merron, 1993). These linkages do not appear to be threatened by any of the development scenarios, except possibly under deforestation scenarios, where a slight decline in productivity of the fishery as a result of reduction in area of OF and HFO areas may be expected.

Modelled hydrological effects of climate change will induce ecological changes similar to those described above for basin development; the extent in spatial terms and the magnitude in terms of production and nutrient cycling will obviously be much greater. Scenarios indicating drier conditions result in pronounced increases in the total area of dry land in both wet and dry sequences. Effectively this represents a very substantial decrease in the functional size of the Delta, and will result in encroachment of woody species onto the new dry land areas, which will ultimately support a climax woodland community, with a concomitant decrease in grazers and increase in browsers. Viable habitat size and contiguity may fall below the minimum for some wetland and grazing species (and consequently for their predators), which will be lost from the system. The available habitat will be considerably reduced, and thus populations will decline. Here, in particular, Wattled Crane, Cheetah and Wild Dog are at great risk, as the Okavango populations are some of the largest globally, and they are all already on IUCN Red Data lists (IUCN, 2004).

Conclusions

Spatial modelling of flood extent in combination with a functional definition of floodplain classes appears to be a useful step in moving from a channel-discharge hydrology-based understanding of a large wetland system towards a spatial dynamic ecological model. This approach has enabled a quantitative assessment of changes in extent of flooding characteristics that are the primary determinants of floodplain vegetation based on inflow characteristics. It represents a tool which has improved our ability to conceptualise impacts of hydrological change in an ecological framework rather than a strictly hydrological one, and allowed conjectural predictions about how such changes might be manifest in higher trophic levels in the system. Other important ecological parameters such as sediment load and more importantly, water quality (nutrient content) are potentially much stronger instruments of ecosystem change in the Delta (Ellery and McCarthy, 1994) than flooding characteristics. Their variation and role in ecosystem processes in the Okavango Delta are not yet understood to a degree sufficient to allow their incorporation in mathematical models.

Here we have been able to predict in quantitative terms potential changes in spatial distribution of floodplain plant communities, and to use the spatial qualities of these modelled outputs to predict possible impacts on current and future ecosystem services provided by the Okavango Delta, a large relatively pristine wetland in an arid, resource poor country. Since change is inevitable in the Okavango Delta from both developments in the basin and climate change, the pursuit of improved techniques and information to refine this approach is considered critical for land and resource managers, and policy makers. Early steps towards this would include the development of a statistical basis for a vegetation community-based floodplain classification system, an increase in the resolution of the GIS flooding model, and ultimately the incorporation of sediment and nutrient expressions in the model.

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