Regional review: The hydrology of the Okavango Delta, Botswana – Processes, data and modelling

Article *in* Hydrogeology Journal · September 2009

DOI: 10.1007/s10040-009-0436-0

Christian Milzow
AF-Consult Switzerland Ltd

Lesego Kgotlhang
Debswana Mining Company

Philipp Meier
Eawag: Das Wasserforschungs-Institut des ET…

Wolfgang Kinzelbach
ETH Zurich

Regional review: the hydrology of the Okavango Delta, Botswana—processes, data and modelling

Christian Milzow · Lesego Kgotlhang ·
Peter Bauer-Gottwein · Philipp Meier ·
Wolfgang Kinzelbach

Abstract The wetlands of the Okavango Delta accommodate a multitude of ecosystems with a large diversity in fauna and flora. They not only provide the traditional livelihood of the local communities but are also the basis of a tourism industry that generates substantial revenue for the whole of Botswana. For the global community, the wetlands retain a tremendous pool of biodiversity. As the upstream states Angola and Namibia are developing, however, changes in the use of the water of the Okavango River and in the ecological status of the wetlands are to be expected. To predict these impacts, the hydrology of the Delta has to be understood. This article reviews scientific work done for that purpose, focussing on the hydrological modelling of surface water and groundwater. Research providing input data to hydrological models is also presented. It relies heavily on all types of remote sensing. The history of hydrologic models of the Delta is retraced from the early box models to state-of-the-art distributed hydrological models. The knowledge gained from hydrological models and its relevance for the management of the Delta are discussed.

Keywords Wetlands · Groundwater/surface-water interactions · Water-resources conservation · Regional review · Botswana

Received: 1 February 2008 / Accepted: 19 January 2009

C. Milzow · L. Kgotlhang · P. Meier · W. Kinzelbach (✉)
Institute of Environmental Engineering, ETH Zurich,
8093, Zurich, Switzerland
e-mail: Kinzelbach@ifu.baug.ethz.ch
Tel.: +41-44-6333066
Fax: +41-44-6331061

L. Kgotlhang
Department of Water Affairs,
Government of Botswana,
P/Bag 0018, Gaborone, Botswana

P. Bauer-Gottwein
Department of Environmental Engineering,
Technical University of Denmark,
2800, Kgs. Lyngby, Denmark

Introduction

The Okavango wetlands, commonly called the Okavango Delta, are spread on top of an alluvial fan located in northern Botswana, in the western branch of the East African Rift Valley. Waters forming the Okavango River originate in the highlands of Angola, flow southwards, cross the Namibian Caprivi-Strip and eventually spread into the terminal wetlands on Botswanan territory covering the alluvial fan (Fig. 1). Whereas the climate in the headwater region is subtropical and humid with an annual precipitation of up to 1,300 mm, it is semi-arid in Botswana with precipitation amounting to only 450 mm/year in the Delta area. High potential evapotranspiration rates cause over 95% of the wetland inflow and local precipitation to be lost to the atmosphere. Only a small percentage flows into regional groundwater.

Seasonal flooding in the Okavango Delta is the result of a complex interaction of local, regional and basin-wide influences (McCarthy et al. 2000). The discharge from the basin is quite variable from year to year and within a year. It is characterised by a flood peak in April at the entry to the “Panhandle” (see Fig. 1). The movement of the flood wave across the Delta is slow, taking about 3–4 months to travel the 250 km from Mohembo to Maun. During that time, wide areas of the Delta are flooded. The seasonal flood spreads in channels and by overland flow. The outflow of the Delta at Maun is a good indicator for the extent of seasonal flooding. A high discharge at Maun is an indicator for widespread inundation. Another interesting indicator is the occurrence of flooding at Lake Ngami, an event which only happens as a result of large floods.

Being located in the Kalahari Desert, the Okavango wetlands are the only perennial water body for hundreds of kilometres. The mean inundated area is around 5,000 km^2 but the intermittently inundated area exceeds 12,000 km^2. It is crossed by migration routes of wildebeest, zebra and other animals. Besides the presence of water as such, it is the variability of hydrological conditions over the year which makes these wetlands unique. The combination of a highly seasonal inflow and local dry and wet seasons result in an ever-changing flooding pattern. A multitude of different environments and ecological niches have developed accordingly. The

DOI 10.1007/s10040-009-0436-0

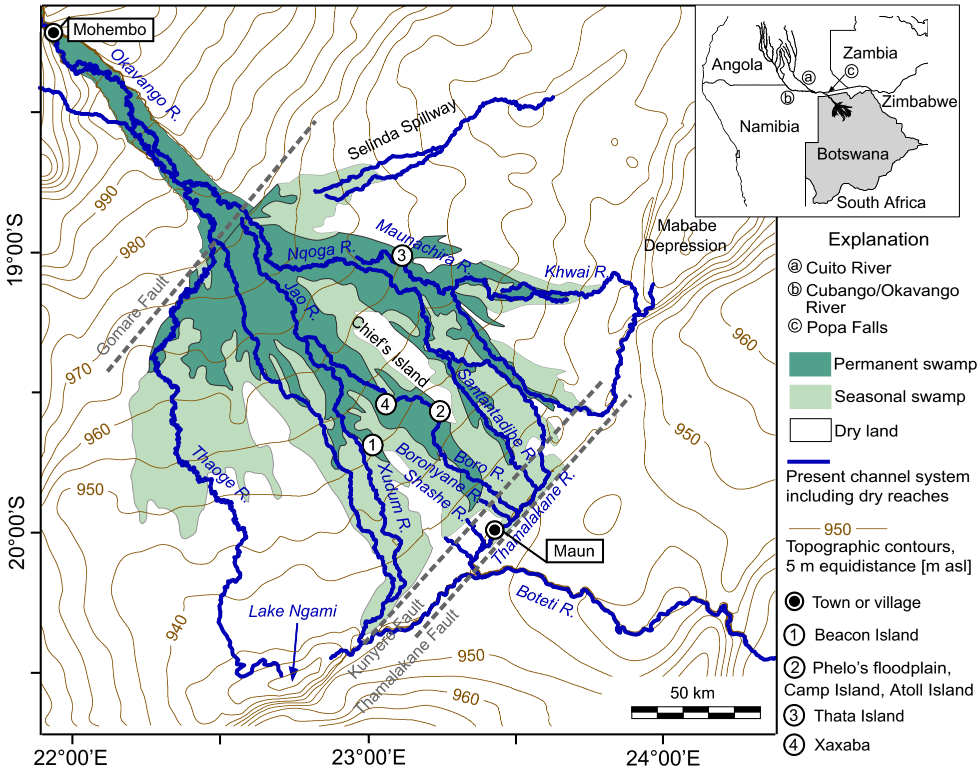

Fig. 1 The Okavango wetlands (commonly called the Okavango Delta) covering the so-called Panhandle on the northwestern side of *Gomare Fault* and parts of the Okavango Fan. The extent of the permanent and seasonal swamps is plotted from data of the Sharing Water Project (RAISON 2004). The channel network includes reaches that are not currently active

biodiversity found in the wetlands is large and can be primarily attributed to the special hydrological setting. Ramberg et al. (2006b) list the number of identified species as 1,300 for plants, 71 for fish, 33 for amphibians, 64 for reptiles, 444 for birds, and 122 for mammals. With upstream activities still minor, the Okavango presently remains one of the largest virtually pristine river systems on the African continent. The Okavango wetlands with a recorded area of 5,537,400 ha were included in the Ramsar List of Wetlands of International Importance (UNESCO 1971) in 1996. A number of future threats to the wetland are apparent. These are linked mainly to the development of the upstream basin and to climate change. Other large African wetlands included in the Ramsar list are for example the Niger inland delta in the Republic of Mali, the Sudd swamps in the Republic of Sudan, and the Bahr Aouk et Salamat floodplains in the Republic of Chad.

The Okavango River Basin is an international basin, with conflicting interests of the riparian states. Angola has a large potential both for hydropower and irrigated agriculture. The land area suitable for irrigation is estimated at 104,000 ha (Diniz and Aguiar 1973, in Andersson et al. 2006). Agricultural intensification and its detrimental impact on the Okavango Delta with respect to both water quantity and quality are to be expected.

Namibia suffers from severe water scarcity and is highly interested in the Okavango waters. Within the Central Area Water Master Plan (CAWMP), the abstraction of 120 million m^3/year from the Okavango River at Rundu, Namibia to supply the Eastern National Water Carrier of Namibia was originally proposed (JVC 1993; Pallett 1997). The project was later redimensioned to meet only immediate water consumption needs in an emergency situation, which were anticipated at 17 million m^3/year, equivalent to an average flow of 0.54 m^3/s (Water Transfer Consultants 1997). For comparison, the mean river discharge since the beginning of the record in 1933 is 292 m^3/s and the lowest monthly average was 83.2 m^3/s. Even though the impacts anticipated by a feasibility study (Water Transfer Consultants 1997) were found to be relatively minor, the scheme was not constructed due to international protest. The same is true of a study to build a 20 MW hydropower dam in the Caprivi-strip (NamPower 2003).

In Botswana, a population of about 125,000 was counted in 2001 in the larger Okavango Delta area (Ngamiland District). Of these, slightly less than 2,700 lived in the wetlands proper and about 50,000 in the city of Maun at the downstream end of the wetlands (RAISON 2004). Household water is supplied either directly from the river or from groundwater. The latter was pursued in the Maun Groundwater Development Project (Water Resources Consultants 1997). Large-scale agriculture is not practiced in the Delta area. For Botswana, the wetlands generate a considerable income through tourism. In 1996, tourism contributed 4.5% to the GDP of Botswana (Mbaiwa 2005a), with a large part being derived from the Delta area.

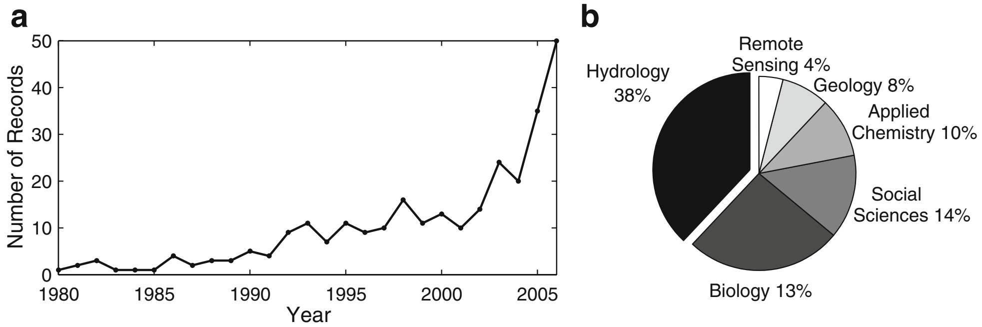

Fig. 2 **a** Yearly number of records found for the term Okavango in the Web of Science. **b** Classification of the 50 records of 2006 into main research areas

In 1994, Angola, Botswana, and Namibia jointly established the Permanent Okavango River Basin Water Commission, OKACOM, to "promote coordinated and environmentally sustainable regional water resources development, while addressing the legitimate social and economic needs of each of the riparian states" (Pinheiro et al. 2003).

Scientific interest in the Okavango Delta wetlands has been growing considerably over the last few decades. As an indicator for this interest, the number of records found for the term Okavango in the Web of Science can be used. In 2006, the yearly number of records reached 50, a large part of which dealt with the hydrology of the Delta. Other important fields of research are biology, social sciences and applied chemistry (Fig. 2).

The geological setting of the Okavango Delta

Regional tectonic setting

The Okavango Delta straddles both the northeast trending Ghanzi-Chobe Belt to the southeast and the Damara Belt to the northwest (Fig. 3). These two belts are tectonically the same, and are commonly referred to as the Damara Belt in the literature. However, in Botswana, the rocks marking the southeastern edge of the belt (Fig. 3b–e) are known as the Ghanzi-Chobe Belt. The Damara belt formed during the collision of the Kalahari and Congo Cratons, with the Kalahari Craton subducting northwards below the Congo Craton during the Neo Proterozoic Pan African Damara Orogeny (Passchier et al. 2002; Kampunzu et al. 1998). Rock exposures in this belt are quite scarce in Botswana. However, they are well delineated in airborne magnetic data maps. On the other hand, their correlatives are well exposed in Namibia and hence their tectonic evolution is mainly based on evidence from exposures in Namibia and a few outcrops in the near vicinity of the delta.

Stratigraphic description

The geology below the Okavango Delta is virtually masked by a thick blanket of Cenozoic Kalahari sands and recent Okavango Swamp sediments, grouped together as Kalahari Beds (Hutchins et al. 1976; Reeves 1978; Thomas and Shaw 1991; McCarthy et al. 1993b; Modisi et al. 2000). Hence, geological rock descriptions are derived mainly from rock outcrops in the nearby areas and their spatial distribution below the Delta is mainly inferred from airborne magnetic survey and gravity data. Borehole data (where available) supplement these two data sets. The main aquifer of interest in hydrogeological modelling of the Okavango Delta—the Kalahari Beds—is the very blanket that obscures the geology.

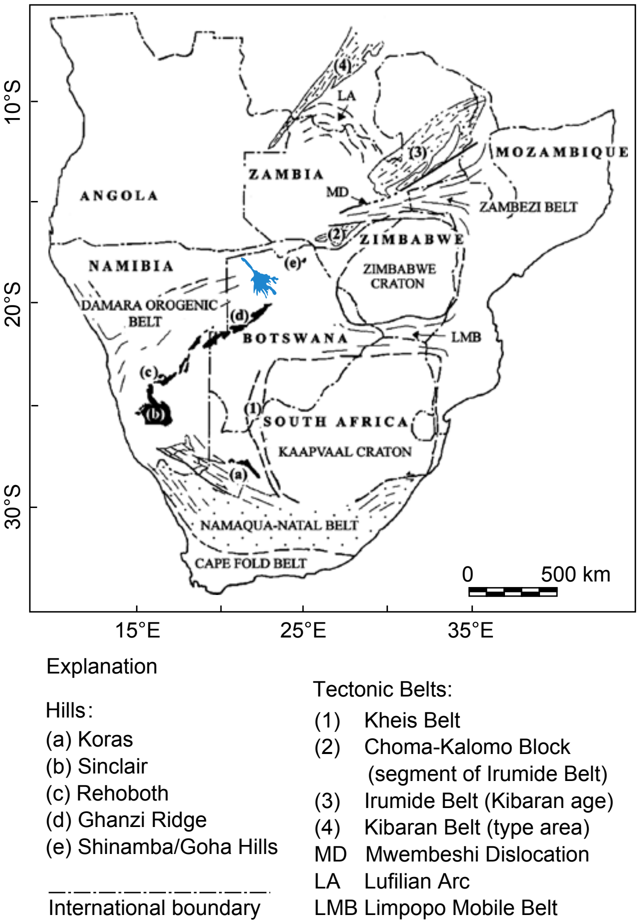

Fig. 3 Regional tectonic setting of southern Africa (after Kampunzu et al. 1998). The *blue area* is the Okavango Delta

The geological units underlying the sand-cover are, in order from youngest to oldest:

1. Sedimentary and volcanic Carboniferous to Jurassic Karoo sequences
2. Neoproterozoic siliclastic and carbonate sequences of the Ghanzi-Chobe/Damara rocks
3. Mesoproterozoic metavolcanics and metarhyolites of the Kgwebe Formation

Kalahari Beds

Overlying the bedrock are vast expanses of deltaic and windborne, medium to fine-grained sands and silts of Cenozoic age collectively known as the Kalahari Beds. Hutchins et al. (1976) estimated the thickness of these sediments to be of up to 300 m, but probably on average considerably less. These mainly unconsolidated to semi-consolidated detritus deposits are associated with hard concretionary lenses of calcrete and silcrete duricrusts. Duricrusts are mainly found in the distal parts of the delta and beyond. They occur both in the near subsurface (within an average of 20 m below surface) and as outcrops along drainage channels and pools. The confinement of duricrusts to the distal parts is attributed to the enrichment of silica and carbonates in the surface water down the flow gradient due to evapotranspiration processes (McCarthy and Ellery 1995; Shaw and Nash 1998). Surface duricrusts form due to cementation of the host lithologies (sands) by silica and carbonate rich pore waters. However, subsurface duricrusts form in the vadose zone very close to the water table. Water table fluctuations lead to alternating saturated and unsaturated conditions, which in turn lead to variation from relatively low to high pH values. Calcrete precipitates in the former conditions while silcrete precipitates in the latter ones (Shaw and Nash 1998).

The Kunyere Fault (Fig. 1) acts as an important lithologic divide in the Kalahari Beds (Department of Water Affairs, DWA 2004). North of the fault, the sediments are primarily deltaic and consist of sands and clays associated with the Okavango Alluvial Fan. To the south of this divide (between the Kunyere and the Thamalakane faults), the lithologic character of the sediments is more variable and originates from deltaic, aeolian and pan type deposits. The older non-deltaic deposits are often diagenetically altered through the precipitation of silica to form silcrete beds, which are well exposed along the Thamalakane River bed. Calcretes are a common sight around the vicinity of Maun Village and occur either as continuous beds or disseminated nodules within the predominantly sandy lithologies.

Reeves (1978) found that the Kalahari Beds are around 500 m thick towards the northeastern part of the Kunyere Fault on the down-dip side (northwest). By using a three-dimensional Euler Deconvolution Technique on aeromagnetic data, Modisi et al. (2000) and Atekwana et al. (2003), working mainly on the Okavango Rift Basin, found an average thickness of 300 m along the graben with the greatest thickness occurring along the Kunyere Fault. Applying the same technique, Brunner et al. (2007) estimated the thickness of these sediments over the entire Delta and determined an average of 150 m for the entire area, an average of about 250 m between the Gomare and the Kunyere faults, and a thickness of about 500 m in the near vicinity of the Kunyere Fault around Lake Ngami in the southwest and the Mababe Depression in the northeast (Fig. 4, see also Fig. 1 for the location of the faults).

Descriptive summary of spatial distribution of basement rocks from airborne magnetic images

Figure 5 shows total magnetic intensity (TMI) data that have been acquired over the Delta by the Department of Geological Surveys, Botswana. Blue tones represent low magnetic rocks; red tones represent high magnetic rocks while yellowish-green tones indicate rocks of intermediate magnetic strength. A swarm of closely spaced highly magnetic northwest trending lineaments cutting the image through the southwestern branch of the Delta are Karoo dolerite dikes. The lower southeastern edge of the Delta consists mainly of the Kgwebe and Ghanzi rocks with the elongated highly magnetic zones of the Kgwebe rocks being flanked by low magnetic Ghanzi rocks. This is more visible along the Okavango Rift Zone (ORZ) as referred to by Modisi et al. 2000 and Atekwana et al. 2003. The ORZ is a fault bounded, northeast trending zone (~55±5 km wide), clearly visible around Maun Village where the bounding faults cross cut the dolerite dike swarm. The area north of the ORZ is mainly occupied by foliated metamorphic (high magnetic) and low to intermediate magnetic rocks (quartzites and dolomitic marbles) of the Damara Formation.

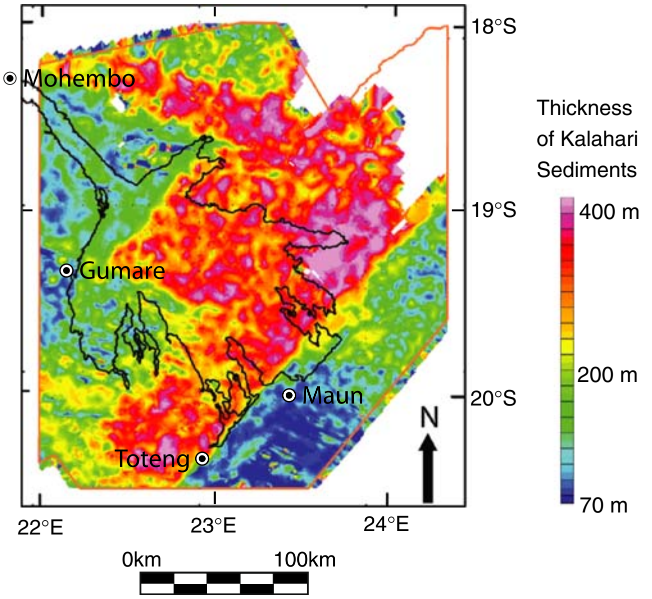

Fig. 4 Spatial distribution of Kalahari Beds' thickness as estimated from airborne magnetic data (after Brunner et al. 2007)

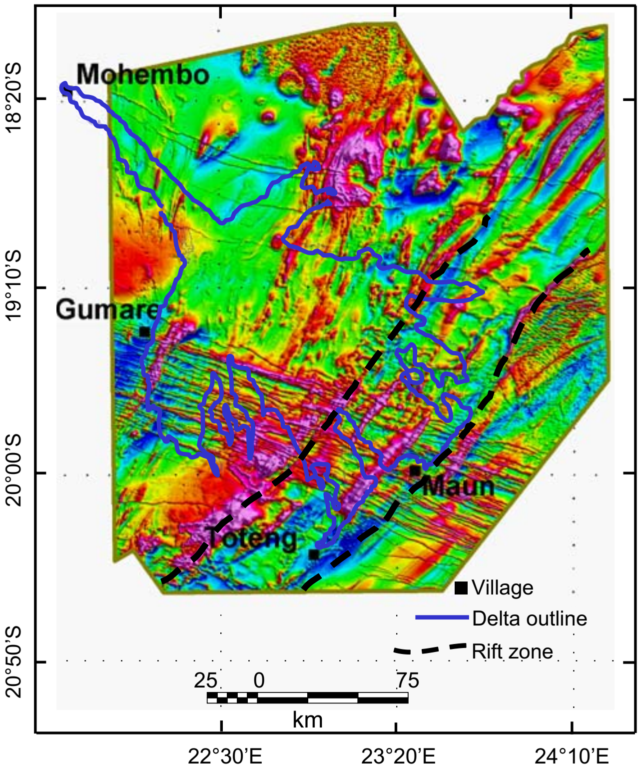

Fig. 5 Total magnetic intensity (TMI) image. *Blue tones* represent low magnetic rocks, *red tones* represent high magnetic rocks while *yellowish-green tones* indicate rocks of intermediate magnetic strength (data provided by Department of Geological Surveys, Botswana, 2000)

Okavango rifting

Du Toit (in Hutchins et al. 1976) was the first investigator to suggest that the Okavango Delta had a tectonic connection to the East African Rift System (EARS). The tectonically active nature of the region was realised from the high incidence of earthquakes (McConnell 1959, in Hutchins et al. 1976). Large earthquake events were recorded during the May 1952–May 1953 period, with magnitudes ranging between 5.0 and 6.7 on the Richter scale. The 6.7 magnitude earthquake on 11 October 1952 was reported to have caused considerable damage to buildings in Maun Village (Hutchins et al. 1976). Reeves (1972) plotted 38 earthquake events within Botswana for the period from September 1965 to August 1971, 28 of which clustered below the Delta swamps in a narrow northeast-southwest trending zone bounded by the Thamalakane and Gomare faults to the southeast and northwest respectively. The spatial distribution pattern of these seismic events led Reeves (1972), Scholtz et al. (1976), and Hutchins et al. (1976) to postulate that rifting was occurring below the Delta.

A micro-earthquake investigation carried out by the Department of Geological Surveys (Botswana) in 1974 showed that the Maun-Toteng area was the most seismically active, with most activity associated with the northeasterly trending Kunyere and Thamalakane faults at the distal end of the Delta (Hutchins et al. 1976). A fault plane solution by Scholtz et al. (1976) to these events indicated normal faulting with the nodal plane dipping 60° to the northwest. Scholtz et al. (1976) propose a NW–SE crustal extension. McCarthy et al. (1993b) suggest that rifting in the NW–SE directions was inconsistent with the northwest striking lineaments in the Okavango, which are more compatible with the E–W extension. The E–W extension implies a component of strike-slip in the NW–SE directions. Reeves (1978) suggests that the apparent lack of strike-slip motions in the NW–SE direction along the Thamalakane and Kunyere faults in the aeromagnetic data is not a contradiction to this view but rather that the total movement along these faults is on the order of a few hundreds of metres. This E–W extension has reactivated the north-easterly basement fabric to form oblique-slip faults, producing a divergent strike-slip system (McCarthy et al. 1993b). Experiments have shown that antithetic faults develop in such systems (Wilcox et al. 1973, in McCarthy et al. 1993b). The antithetic faults are dominated by the formation of grabens due to the overall extensional nature of the tectonic regime. In the Okavango Delta area, these fault systems correspond to the northeast striking faults such as the Kunyere, Thamalakane, Gomare and others. The apparent increase of the sediment thickness in a southeasterly direction towards the Kunyere-Thamalakane fault pair (Reeves 1978) implies a half-graben system (McCarthy et al. 1993b). Figure 6 illustrates the proposed tectonic setting of the Delta as postulated by DWA (2004).

High resolution airborne magnetic data (collected at 250 m line spacing) has added more evidence to the postulations by different authors that indeed there is rifting below the Delta. Modisi et al. (2000) and Atekwana et al. (2003) used these data to reveal an unprecedented view of the rifting. This is shown by the cross cutting between the Karoo Dike Swarm and the reactivated Proterozoic northeasterly fault systems.

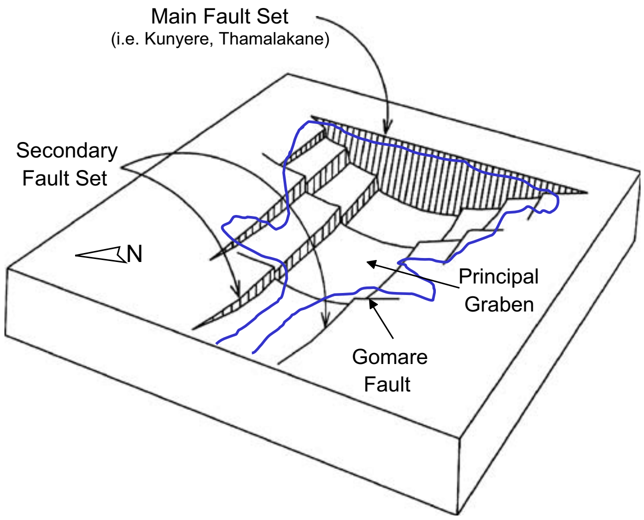

Fig. 6 A schematic diagram of the Okavango Graben (modified after DWA 2004). The *blue line* shows the approximate outline of the Delta

DOI 10.1007/s10040-009-0436-0

Clearly, the tectonic activity did not only influence the position of the Delta but continues to influence flow by the resulting fault lines. The NE–SW trending Kunyere and Thamalakane faults in the distal part of the Delta are two prominent examples. The Okavango waters pond against their scarps and are redirected to flow parallel to them. At some locations, a fault induced break along the lengths of these major faults allows flow across them. This occurs for instance where the Shashe and Boronyane rivers cross the Kunyere Fault. The Gomare Fault governs the lateral expansion of the wetlands where the river flows out of the Panhandle. With faults acting as guides for flow, seismic events and consecutive tectonic movement can therefore also play a major role in the shifting of flow paths within the Delta. This is further discussed in a later section.

Processes driving the hydrology of the Okavango Delta

The hydrology of the Okavango wetlands is governed by a series of drivers which influence the hydrologic system over different time scales. As a result, the flooding patterns are highly seasonal and differ from year to year. In the long term, these drivers include sedimentation which is responsible for the formation of the fan over geological timescales, sedimentological and biological processes maintaining the roughness of the fan surface and driving the positioning of channels, and the climate.

In the short term (i.e. in periods on the order of a decade, time scales relevant for water-management actions) the fan-shaped surface overlain by small- and large-scale topographic features can be considered a fixed setting. Also, vegetation cover which, given the flat topography, has a strong influence on the hydraulic roughness in floodplains takes several years to adapt to new conditions. The set of processes driving the short-term variability of the flooding patterns are meteorological processes and anthropogenic impacts.

Tectonics movements are difficult to classify as short- or long-term drivers. Tectonic movements occur in the short term, while it takes quite a long time for the erosional processes to counter balance the effects of their displacement.

Variations in the hydrology of the wetlands are best documented for the eastern branches of the wetlands—the Nqoga, Maunachira, and Khwai systems—with discharge and water level data available since 1970 (Wolski and Murray-Hudson (2006b). In these systems, important recent changes have occurred which are due partly to human interventions and partly to the natural fluctuations of the wetlands.

Sediment inputs and transfers

The massive alluvial fan, on top of which the Okavango wetlands lie, consists of riverine and aeolian sediments. As McCarthy et al. (1991b) note, the date of initiation of the fan is still unknown. The Okavango River system may have flown already at pre-Cretaceous times (Thomas and Shaw 1988, in McCarthy et al. 1992), but tectonics have influenced the course and endpoint of the river several times (McCarthy et al. 1992). At present, 870,000 tonnes of sediment are deposited on the fan annually (Garstang et al. 1998). This sediment deposit consists of approximately 50% from solutes contained in the inflowing water, 22% from particle sediment (mainly bedload and some suspended load), and 28% from aeolian inputs. The amount of solutes entering the delta can be assessed using laboratory analyses of water samples and thus is known precisely. The situation is different for bedload. Laborious sampling has been undertaken with pressure difference samplers but given the uncertainty of the method, derived amounts remain approximate. The very low suspended load has been estimated using turbidimeters. A source of error is the varying organic content of the water. The estimations on the aeolian input cannot be considered to give more than the order of magnitude of the input.

Both particle and solute sediments (200,000 and 420,000 tonnes/year respectively, Garstang et al. 1998) enter the wetlands through the inflow channel but because of the different transport processes, the locations where they are deposited are different. Channels are typically flanked by dense aquatic vegetation (reeds or *Cyperus papyrus*) through which water filtrates to the surrounding floodplains. Flow velocities in the channels are in the range of 0.5–1.5 m/s and only on the order of a few cm/s in the floodplains. As a result, bedload is transported in the channels only and the small suspended fraction in the channels is filtered by the flanking vegetation. Solutes are deposited as calcretes and silcretes in places where water evaporates or is transpired by vegetation, i.e. on islands and drying floodplains. Even though with 35 mg/l of total dissolved solids (Dincer et al. 1978), the water is relatively fresh at its inflow to the Delta, one has to keep in mind that the Okavango wetlands are a terminal system where most of the solute inputs are deposited (with a small amount leaving the system by a limited flux towards the regional groundwater system). Solutes account for as much as 50% of deposited sediments. The importance of dissolved salts and their implication in biological processes is discussed in the section Salt transport and deposition.

Particulate sediments represent less than a quarter of the sediment input but because of their concentrated deposition on channel bottoms, they play an important role in the geomorphology of the Delta. Aggradation of channels is faster than morphological change in floodplains and the resulting channel shifting determines which floodplains are going to be inundated (e.g. McCarthy et al. 1992).

The third component of sediment input, aeolian sediments, differs from the two others as deposition is more or less uniform over the Delta regardless of the short-term water distribution. The long-term water distribution, however, is important as it is a driver for the distribution of vegetation, which then acts as a filter removing aerosols from the air. Vegetation cover also diminishes remobilisation of aerosols thus ensuring a net accumulation. Garstang et al. (1998) estimate the yearly input of aerosols to be 250,000 tonnes/year. The amount results from an average anticyclonic circulation transporting aerosols with

DOI 10.1007/s10040-009-0436-0

a rate of 38.0 kg/ha/day (Tyson et al. 1996). It can be assumed that a constant fraction is continuously deposited on the wetlands while the near surface aerosol layer is recharged from higher layers. By comparison with measurements by Swap (1996), the fraction or depositional rate is estimated to be 1.5% of the transport by anticyclonic circulation. This leads to a deposited load of 0.57 kg/ha/day, which considering a wetland area of 12,000 km^2, amounts to an input of 250,000 tonnes/year.

An export of particles from the Delta occurs through fires which are a common process in the wetlands. Most frequent are fires on dry floodplains, followed in frequency by fires on drylands where biomass production is lower (Heinl et al. 2006). Less frequent are peat fires along abandoned channel reaches. To date, no studies have been carried out to quantify the related losses of mass from the system.

On a smaller scale, Krah et al. (2004) examined the importance of airborne transfer of locally generated dust inside the Okavango wetlands. Passive wet dust collectors were installed along cross sections ranging from floodplains to islands. Measurements at different elevations above ground showed a rapid decrease of dust transport with height. The major part of the dust transport occurs in the lowest 3 m. The amount of dust collected decreases towards the islands. Simultaneous measurements showed that wind speeds also decrease towards the islands. Therefore it is argued that dust is produced on the open floodplains by relatively strong winds that can develop there. As the wind reaches the vegetated fringes of the islands, its velocity decreases and dust is deposited. The islands' centres are composed of open grasslands or salt pans but are shielded by the surrounding vegetation fringe. The amount of dust collected in the island centres was even smaller than at the fringes. Krah et al. (2004) therefore concluded that island growth through dust accumulation occurs laterally, not vertically.

Topographic roughness

On a large scale, the Delta is a regular fan with a low gradient of about 1:3550 (Gumbricht et al. 2001). However, deviations from a perfect conical surface exist on various scales. Large-scale deviations over horizontal distances of tens of kilometres lie in a range of plus to minus two meters in the vertical. It is remarkable that the distribution of water is not clearly correlated with these deviations. Gumbricht et al. (2001) show that some channels flow in topographic lows, whereas others lie on topographic highs. Channels can remain in a topographically unstable location because of stabilising vegetation flanking the channels. The authors further note that the most sensitive zone for water distribution is the floodplain area at the end of the Panhandle where minor topographic differences and vegetation growth may have a significant impact in directing the flows.

A small-scale micro-topography with a standard deviation of typically around 50 cm along kilometre-long transects is superimposed on the large-scale structures (Gumbricht et al. 2005). Although of low amplitude, this topographic roughness is of great hydrological and ecological importance. It is the key parameter for the small-scale distribution of dry and wet areas, of islands and lagoons. The topographic roughness originates from and is preserved by several transport processes usually combining physical and biological mechanisms.

Starting from a flat surface, islands are initiated by two different mechanisms. Termites (*Macrotermes michaeleni*) accumulate fine-grained material to build termitaria which are often several metres in height. Termitaria constructed in seasonal floodplains will generally be tall enough to stick out of the water during seasonal flooding and vegetation types differing from those of the floodplain can eventually colonise the termitaria. (Dangerfield et al. 1998; McCarthy et al. 1998c). The second type of island initiation is related to bedload transport in channels of the fan. Infiltration to floodplains and evapotranspiration cause a decrease of channel discharges in the downstream direction as well as an associated decrease of the bedload transport capacity. Bedload is thus deposited on the channel bottoms, leading to aggradation. Channels are flanked by a thick layer of peat and vegetation, which stabilises the bed and filters suspended sediment. These stable side walls allow the channels to rise to a higher level than the surrounding floodplains. At some point the elevation difference is such that the channel dries out by leakage through the peat layer or a new channel develops, leading towards the lower lying floodplains. The peat that was flanking the channel dries, contracts and can eventually burn (Ellery et al. 1989). What remains are elongated topographic enhancements which just like the termitaria are above the seasonal flood level and can host dryland vegetation types. This mechanism of channel aggradation and eventually topographic inversion was first described by McCarthy et al. (1986a). The conceptual model of the life cycle of channels was later revised by McCarthy et al. (1992) and Ellery et al. (1993b).

The growth process of islands is identical regardless of the initiation type. Matter is accumulated preferentially on the shores of the islands leading to a lateral rather than a vertical expansion. Due to the high salinity on island centres (described in the section on salt transport), vegetation is limited to the fringes. Transpiration of local groundwater by plants accumulates solutes and favours precipitation at the fringes. In addition, airborne particles preferentially settle in the vegetated fringe. During the growth process several islands can coalesce. Which mechanism initiated an island is apparent because islands tend to preserve their elongated or circular shape when growing. Also, past termitaria can be detected—even when abandoned and eroded—as an accumulation of fine grained material (McCarthy 1992).

Channel type and positioning

The life span of channels in the fan is governed by sediment transport, whereas the exact positioning of the onset of new channels depends on minor characteristics and is often influenced by hippopotamus paths (McCarthy et al. 1998b). Historical records show that the switching of water distribution from the Thaoge to the Nqoga and finally to the Maunachira took place over a period of approximately 100 years (McCarthy et al. 1986a, 1988). However one must be cautious in drawing conclusions regarding the life span of channels in the entire system based on findings on a single channel. Underlying topography in the range of decimetres may have a significant impact on the life span and thus it should not be expected that similar channel systems necessarily have similar life spans.

Channels of the Panhandle region upstream of the Gomare Fault differ considerably in type from those of the fan region downstream of the fault (Tooth and McCarthy 2004). On the Fan, where the overall gradient of 0.00029 is noticeably steeper than in the Panhandle (0.00018), channels tend to be of straight ($P<1.5$) to stable sinuous type ($1.5 < P<1.75$). P is the ratio of channel length to straight-line valley length. In the Panhandle, channels have higher sinuosity ($P>2$) and two sections of the Panhandle present anastomosis (Smith et al. 1997). The Panhandle channels are actively meandering while rates of meander migration are below 0.5 m/year on the Fan. Bank vegetation plays a major role in the change of channel types. Tooth and McCarthy (2004) analyse the channel type transition based on the ratio of channel width w to channel depth d. Relatively wide channels ($w/d>10$) present active meandering because scouring of unconsolidated sediment at the bank base is strong enough to undermine the flanking vegetation, thus enhancing meandering, whereas in relatively narrower channels ($w/d<10$) the vegetation resistance exceeds the scouring forces and channels are stable. While currently flowing channels of the fan region are not actively meandering, vegetation structures visible on satellite imagery clearly indicate that active meanders have in the past existed in the Fan region.

During peat fires, the ground level in the affected areas can drop by several meters. Reflooding of areas that were lying dry for several years then becomes possible in a short period of time (Ellery et al. 1989). Depending on the location of the peat fires, the resulting redistribution of flows is either only local or can affect the wetlands at a larger scale.

Climate

Another important driver of the hydrology of the Okavango wetlands is climate. Climate plays a dual role, as it is a driver for the upstream basin and for the Delta itself. At present conditions, approximately two thirds of the water input comes from channel inflow while the remaining one third originates from precipitation over the wetland area. Climatic conditions of the past 50,000 years can be reconstructed using radiocarbon methods. Thomas and Shaw (1991) conclude from the analysis of several studies that the period from 35,000 BP to 22,000 BP was marked by generally humid conditions in the Kalahari region. A second humid period from 17,000 BP to 12,000 BP was detected in the region with the exception of the southeast corner of the Kalahari. The study of past shorelines of Lake Ngami at the south-western end of the wetland system (see Fig. 1) reveals the presence of a large lake along the Thamalakane Fault during the second wet period and also around 2,000 BP (Shaw 1985). Shaw calculates that to maintain such a lake under present climatic conditions (except for a change in precipitation) and with present inflow to the wetlands through the Okavango River, annual precipitation would need to increase by 160–225%, depending on the assumed outflow from the lake. Because changes in the flows generated in the catchment are neglected, these figures represent absolute maximum values of necessary precipitation increase. Proof of wetter conditions is also found in the presence of stromatolites 1–1.5 m above the present level of Ukhwi Pan in the central Kalahari of southern Botswana dated 17,000–15,000 years BP (Lancaster 1979).

Meteorology and inflow

Precipitation in the upstream catchment generates the inflow, while precipitation over the Delta itself contributes to a more spatially distributed water availability and to the recharging of the aquifer. At the inflow to the Panhandle at Mohembo, the Okavango River has a strongly seasonal regime with low flows in October–November (between 100 and 200 m^3/s) and high flows in April–May (between 400 and 1,000 m^3/s). The mean flow for the period of 1933–2006 was 292 m^3/s. The strong inter-annual variation of peak flows contributes to the yearly variability in seasonal flooding. A long-term cyclic behaviour pattern appears in the inflow data with a maximum in the 1960s and a minimum in the late 1990s (Fig. 7). The cause for this is still unknown but it was found to be statistically significant by Mazvimavi and Wolski (2006). A cyclic component with a period of 65.4 years best fits the average annual flow at Mohembo. Accordingly, a series of relatively wet years are to be expected in the near future.

Local precipitation is important as it raises groundwater levels, thus determining how fast a flood can propagate through the wetlands. This is described in detail in the section Groundwater-surface water interactions in the Okavango Delta.

Tectonics

A further natural and fast driver is tectonic movement. Its relative importance in shifting the flows compared to sedimentation processes is still under discussion. Pike (1970) suggested that the earthquakes of 1952 caused a change in the drainage pattern of the Delta. McCarthy et al. (1993b) and McCarthy et al. (1997) hypothesise that graben development in the northern Nqoga system led to the flow increase in the Maunachira system. Their work concludes that neotectonic movements initiated the changes by creating interconnected graben systems, which then diverted water flow while sedimentation in the channels accentuated the process of redistribution.

Regarding the flow distribution at the scale of the entire Delta, Gumbricht et al. (2001) argue against the hypoth-

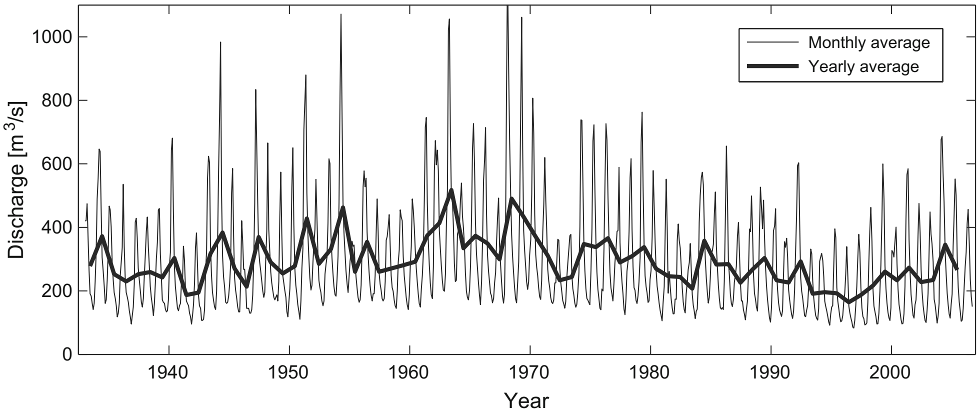

Fig. 7 Monthly and annual averages of discharge measured at Mohembo (data acquired by the Department of Water Affairs, Botswana, 2007)

esis that a regional tilting may have shifted flows from the western Thaoge system which received the major part of flows in the middle of the nineteenth century, when David Livingstone visited the Delta, towards more easterly located flow systems. They note that given the characteristics of channels to remain stable on relative topographic highs, tilting with elevation changes on the order of tens of metres over the whole Delta would be required to change channel positions. What is overlooked is that already changes of much smaller amplitude could have a significant impact on the water distribution within the existing channel network without changing the channels' position. In a sensitivity analysis, Bauer et al. (2006a) tilted the topography of their distributed hydrological model by an angle of 0.00014° along an axis running through the centre of the Panhandle. Over the approximate 30 km of width of the end of the Panhandle this corresponds to an elevation change of 0.075 m. Over the entire width of 300 km of the conical surface an elevation change of 0.75 m is created. These 0.75 m would hardly have been detected as anomalous on the diverse profiles as shown by Gumbricht et al. (2001). Still, they induce a noticeable change in the flood distribution. However, the study by Bauer et al. (2006a) remains a sensitivity analysis and does not try to quantify changes in flooding patterns resulting from specific tectonic events. McCarthy et al. (1993b) demonstrated that tectonic movements are at least on a small scale responsible for initiating water diversions. On a SPOT 2 satellite image showing the flood of 1991 in the Maunachira area, it can clearly be observed that the shoreline of the flood is linear over long distances. These lineaments are aligned with known fault systems. However the question whether and to what extent tectonic movements have contributed to the large-scale shifting of the flows away from the Thaoge system until now remains open.

Anthropogenic impact

The anthropogenic impact on the flow distribution is significant and cannot be neglected. It consists mainly of dredging of channels and clearing of papyrus blockages to promote flow to specific areas. Intensive dredging of the lower Boro was carried out from June 1971 to December 1974 to ensure water availability for the Orapa Diamond Mine situated 200 km southeast of the Delta along the Boteti channel. Its repercussions over two decades were studied in detail by Ellery and McCarthy (1998) at the request of Debswana Diamond Company. During the 3.5-year period, the last 17.5 km of the Boro River (upstream of its junction with the Thamalakane River) were deepened by approximately 1 m. In the lowest 4.5 km, the deepening was up to 3.5 m and the channel was partially straightened. Low earth dikes were constructed at various locations over the entire 17.5 km to prevent flows to the floodplains. The impact on vegetation was large. Floodplains isolated by earth dikes were colonised by terrestrial communities. Aquatic vegetation in the channels was destroyed by excavation and was unable to recover as a result of increased flow velocities. Due to increased sediment transport towards the deeply dredged reach, channel beds in sections upstream of the dredged reach were consecutively eroded and aquatic vegetation was destroyed. Over the two decades between the dredging and the study by Ellery and McCarthy (1998), a 10.5 km long section of the channel upstream of the deeply dredged reach was affected by erosion.

Groundwater-surface water interactions in the Okavango Delta

The important role that local groundwater flows play in the hydrology of the Okavango Delta wetlands has been pointed out and studied increasingly over the last 30 years. The generally accepted theory is that, as the flood front advances into the Delta, a large fraction of the surface water infiltrates through the highly permeable soil and the groundwater level rises to the surface before flooding is possible. Hydraulic conductivity of the soils has been estimated in the range of $1.2 \cdot 10^{-4}$–$3.5 \cdot 10^{-4}$ m/s and porosity at 0.30 by Obakeng and Gieske (1997, in McCarthy 2006). The propagation of the flood therefore strongly depends on the depth to groundwater, which itself depends on floods of previous years and rainfall events. A high water table allows for less infiltration and causes the flood to proceed further downstream. This leads to a more extensive flooding and a higher outflow from the Delta. Storage of groundwater thus causes a memory effect.

On a large scale, groundwater flows seem to be mainly vertical and the connection of the swamp water to regional groundwater appears to be very limited. Studies on stable isotopes (Dincer et al. 1978; McCarthy et al. 1998a) showed that the outflow from the wetlands to regional groundwater is spatially limited and of a small quantity. Nevertheless, McCarthy (2006) notes that due to faulting, the basement rocks beneath the Delta are highly fractured and that groundwater could possibly leave the area along these discrete pathways. McCarthy (2006) also gives a summary of numerous studies on the near surface and regional groundwater of the Okavango Delta.

If one looks at the water balance of the Okavango Delta, evapotranspiration by far exceeds precipitation in yearly and monthly means. Groundwater recharge in nonflooded areas is therefore quantitatively and temporally limited. Regional groundwater was shown to originate from ephemeral strong rainfall events (Mazor et al. 1977). High tritium concentrations and temporal head variations in the shallow Kalahari Beds aquifer give proof of recharge. An increase of tritium concentrations was observed after the rainy season of 1970. Isotopic compositions of water with respect to oxygen and hydrogen were found to be on the light side of the southern African meteoric water line. This also supports the hypothesis that regional groundwater recharge occurs during strong rainfall events when only a small proportion is lost to evaporation. Surface waters in the channels of the wetlands are isotopically heavier. Groundwater samples from within the wetlands lie on the evaporation line, suggesting recharge from surface water. These results show that to a large extent the swamp system is hydrologically isolated from the regional groundwater. Only at the western margin of the wetlands, does the isotopic composition suggest some mixing with regional groundwater.

Reflecting the low population density, the central part and the eastern margins of the wetlands are poorly equipped with boreholes. McCarthy et al. (1998a) derived a long-term depth to the groundwater map from 167 boreholes in the Okavango region. The boreholes being for the most part situated on the southern fringes of the wetlands, the high information density in this area makes it possible to map reasonably well the gradient of the piezometric surface. The water table is generally close to the surface in the central wetlands and at the margins drops with steep gradients to levels around 40 m below surface. The mound shape of the piezometric surface could be interpreted as leading to regional groundwater recharge which would be in contradiction to the isotopic studies. The likely explanation therefore is that the spreading groundwater lens is consumed through transpiration by deep-rooted vegetation. Direct evaporation is limited to areas of very shallow water tables as the coarse texture of the sandy soils does not allow a strong capillary rise. The overall relation between infiltration, direct evaporation and evapotranspiration on the islands can be studied with simple mass balances using the solute concentrations of different waters.

No continuous and consistent long-term time series of the total dissolved solid (TDS) concentration of the water flowing into the Okavango Delta at Mohembo is available. Occasional measurements and estimates by various authors indicate that the average TDS concentration is around 40 mg/l. Assuming a constant TDS concentration of 40 mg/l and an average inflow of 300 m^3/s at Mohembo, one can calculate the total amount of solutes entering the Okavango Delta through the inflow as $3.8 \cdot 10^9$ kg/year. Typical rainfall TDS in the region is around 5 mg/l (Gieske 1992). The average wetland surface area is about 5,000 km^2 (McCarthy et al. 2003) and average rainfall, as recorded by Botswana Government's Meteorological Services, is about 480 mm/year. The resulting dissolved solute input by rainfall of about $1.2 \cdot 10^7$ kg/year is negligible compared to the solute input by the inflow. If the Boteti River, which conducts small ephemeral outflows over some tens of kilometres before also drying, is included in the salt-balance calculation, the surface outflow of water and solutes from the balance volume is zero.

Dincer et al. (1987) published an analysis of stable isotope and salinity data from different locations in the Okavango Delta. Differences in the degree of accumulation of salinity and heavier stable isotopes were used to infer the relative contributions of transpiration and evaporation to the total water loss. Evaporation accumulates both salinity and heavier stable isotopes (due to the fractionation occurring with the phase change of water), while transpiration accumulates salinity only, with no isotope fractionation occurring in the roots where water is taken up from the source. Dincer et al. (1987) explained their salinity and isotope data with a simple plug flow model and demonstrated high ratios of evaporation to transpiration in winter (vegetation is less active) versus low ratios in summer (transpiration dominates).

Despite the significant salt mass input, surface waters in the Okavango Delta are generally fresh. This indicates that a significant amount of surface water is not removed by evaporation from the water surfaces but by infiltration to the shallow alluvial aquifers and subsequent evapotranspiration. A simple mass-balance box model for the surface water component reads

$$\frac{\Delta}{\Delta t}(Vc) = Q_{\mathrm{in}}c_{\mathrm{in}} - Q_{\mathrm{GW}}c \qquad (1)$$

where V is the volume of the surface water component, c its concentration, Q_{in} the inflow, c_{in} the concentration in the inflow and Q_{GW} the infiltration flow. Assuming steady state in volume and concentration, one gets

$$c_{\mathrm{steady}} = \frac{Q_{\mathrm{in}}c_{\mathrm{in}}}{Q_{\mathrm{GW}}} \qquad (2)$$

where c_{steady} indicates the steady state surface water concentration. Surface water concentrations in the Okavango

Delta are rarely higher than about 100–200 mg/l, and a value of about 100 mg/l is a representative average. This implies that the infiltration flow is approximately 40% of the total inflow. Note that infiltration takes away 40% of the water together with the solute mass contained in it. The concentration of the water remaining in the channels is not affected by the process. All the dissolved solutes removed from the surface water by infiltration are accumulated in the shallow groundwater.

Hydraulic gradients are steepest on the wetland/dryland interface. The infiltration water flux is thus concentrated along the shoreline of the Delta, where a fringe of riverine vegetation and the associated transpirative demand establish large differences in water tables. Inside the permanent wetlands, hydraulic gradients are much smaller and consequently infiltration fluxes are minor. The specific infiltration flux I per unit length of shoreline can be estimated as (Bauer 2004)

$$I = \sqrt{\mathrm{ET}_{\max} d_{\mathrm{ex}} T} \tag{3}$$

where T is the transmissivity of the aquifer, and the depth-to-groundwater dependence of the evapotranspiration is assumed to obey the relationship

$$\mathrm{ET}(h) = \mathrm{ET}_{\max}\left(1 - \frac{S-h}{d_{\mathrm{ex}}}\right). \tag{4}$$

In Eq. 4, ET is the actual phreatic evapotranspiration rate, h is the piezometric head in the aquifer, $\mathrm{ET}_{\max}$ is the potential evapotranspiration rate, S is the elevation of the topographic surface and d_{ex} is the so-called extinction depth of evapotranspiration.

The shoreline length of the Okavango Delta was estimated from an island database derived from satellite imagery (Gumbricht et al. 2004). Depending on the threshold island size, shoreline lengths are on the order of several thousand kilometres (Fig. 8). The specific infiltration flux I (Eq. 3), corresponding to the infiltrating volume per day and per meter of shoreline, is calculated as about 1 m^2/day with typical Okavango parameters of T= 10^{-4} m^2/s, $\mathrm{ET}_{\max}$=5 mm/day and d_{ex}=20 m. The large extinction depth reflects significant transpiration fluxes caused by deep-rooted vegetation. Multiplying this result by 6,900 km of shoreline (island sizes larger or equal to 100 m) results in an estimated total infiltration flux of 110 m^3/s, which is equal to 37% of the inflow and of the same order of magnitude as the result of the box mass balance calculation. In terms of system management, it is thus important to preserve the long shoreline of the Okavango Delta, to ensure high surface water quality.

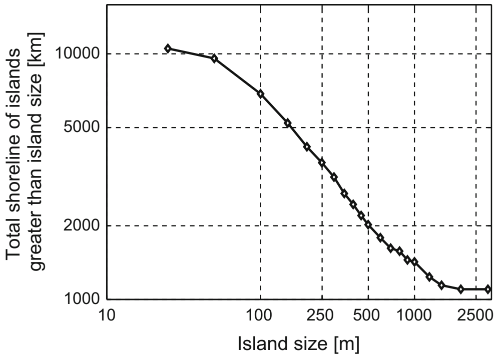

Fig. 8 The shoreline of the Okavango Delta expressed as the total shoreline of permanent and seasonal islands with an equivalent diameter greater than a given size (Gumbricht et al. 2004; Bauer et al. 2006c)

The ratio of infiltration and inflow has also been investigated in more local settings in the seasonally flooded areas where the largest annual variation in depth to groundwater is found. Boreholes which can be used to quantify the infiltrating volume are still limited to a few study sites. As expected, in these sites outside of the permanent swamp, the ratio of infiltration to evaporation is larger than the average value for the Delta as a whole. This ratio further varies considerably during flooding.

A first attempt to quantify the locally infiltrating water is the field study by Dincer et al. (1976). A pool structure of 5.8 km^2 in the seasonal swamps (adjacent to Beacon Island in the Xudum area) was isolated in a way that in- and outflow could be measured. Precipitation and evaporation were recorded on site. The water balance over two consecutive years showed that infiltration to the groundwater amounted to 4–5 times the losses by evaporation. As shown by the stable isotope studies, the overall wetlands do not act as a regional groundwater recharge system. This means that the important flows infiltrating locally in swamps are leaving the system by evapotranspiration from adjacent islands.

A second local study by Ramberg et al. (2006a) focuses on a 0.4 km^2 floodplain (Phelo's floodplain) which is also located in the seasonal swamps but adjacent to the 10 km wide Chief's Island. Its inflow is limited to a 20–30 m wide channel. There is no outflow. Inflow was measured through a constructed flume for the floods of 1997–1999. Calculations of changes in storage were based on a local 10 m resolution digital elevation model. No precipitation occurred during the studied flood seasons and evapotranspiration was calculated using the Penman formula with coefficients adjusted to reflect climatic conditions of Botswana (these coefficients were derived by SMEC 1987). Meteorological data were taken from the station at Maun, some 53 km away. In addition to solving the water balance, point infiltration rates were directly measured in several transects arranged perpendicularly to the shore. Direct evaporation from the water surface was calculated to amount to 9–12% of the annual inflows, leaving approximately 90% of the inflow for infiltration. Extrapolation of the direct infiltration measurements to the entire floodplain yielded an infiltration rate between 40 and 50% of the inflow. Several piezometers installed in the floodplain revealed rises in groundwater levels of 1.5 m/day and higher immediately after the onset of inundation. An important finding was that the groundwater rise diminishes quickly with distance from the flood front. A

DOI 10.1007/s10040-009-0436-0

rise of 3 m was recorded in a piezometer located 20 m away from the maximum inundation perimeter of 1997, whereas in 1998 the flood stopped at a distance of 250 m from the same piezometer, generating a rise of only 0.4 m. Based on their results, Ramberg et al. (2006a) describe the infiltration process in two phases. In the first phase, vertical infiltration occurs through the vadose zone limited only by vertical hydraulic conductivity. The entire soil column is not yet saturated at that point. In the second phase, once the groundwater level has reached the surface, a process which took 1–3 days at the studied site, lateral infiltration towards island areas takes place and is limited by horizontal hydraulic conductivity and gradients towards the island. High infiltration capacities of $4.6 \cdot 10^{-4}$–$1.2 \cdot 10^{-3}$ m/s found by Boring and Björkvald (1999) confirm the very intensive first infiltration phase.

Wolski and Savenije (2006) present the results of further studies on the same (Phelo's) floodplain as well as on a nearby location comprising a regularly flooded area (Boro channel floodplain) and the adjacent island (Camp Island). Two series of piezometers are installed in transects reaching from the floodplains to the dry land side. Evaluation of the time series of piezometric heads reveals that at both locations the gradient is always directing groundwater flow towards the island. Reversal of the local groundwater flow back to the swamp has never been observed either during or after recession of the flood level. This is in agreement with findings from the Okavango Research Group of the University of Witwatersrand, South Africa: McCarthy et al. (1991a) studying an island in the north-eastern part of the wetlands (north of Maunachira Lediba), McCarthy and Ellery (1994) for an island situated in the central wetlands at the limit between permanent and seasonal swamps (island at Xaxaba), and McCarthy and Ellery (1995) for the Camp and Atoll Islands close to a main channel in the seasonal swamps (see Fig. 1 for location of the islands). The constant flow direction plays a key role for solute transport characteristics of the wetlands.

Wolski and Savenije (2006) built simple numerical models of their two study sites. They conceptualised the underground in two zones: highly permeable floodplain deposits and island soils of low permeability. Time dependent constant head boundaries were defined at the floodplain side of the models. The calibrated models succeed in reproducing the observed water levels at the piezometric transects over several years. Evaluation of the model results shows that the highest groundwater flows of 0.55–0.6 m^2/day) occur during flood rise, but even before the flood arrives, flows are also substantial at 0.4–0.5 m^2/day. The gradient towards the island stays high as a result of the sizable evapotranspiration losses from the island throughout the year.

The importance of antecedent conditions on the infiltrating volume is studied by changing the initial hydraulic heads in the model. Initial conditions for 1, 2, 3 and 10 years without flooding were simulated and fed into the models. For the floodplain linked to the smaller island, the effect of antecedent conditions vanished within 1 year, whereas for the larger islands, an effect was observed for the following 5 years. This means that after a prolonged drought, the groundwater levels underneath a small island can be reset to normal in one single flood season, whereas for a large island—where the ratio of perimeter to area is much smaller—several flood seasons are necessary to raise the water levels back to normal. Islands of less than 500 m in width are expected to display no memory effects, whereas long-term effects are expected on larger islands and on the fringes of the wetlands. Island vegetation is not sensitive to a few years of drought as it continues to extract water from the deeper water storage.

On an island, at the limit between the seasonal and the permanent swamp, McCarthy and Ellery (1994) detected diurnal fluctuations of the water table in piezometers located in the densely vegetated fringes of the island. Fluctuations did not exceed 1.5 cm in the island centre and amounted to a maximum of 7 cm towards the island edge. The fluctuations could be ascribed to the daily transpiration cycle. Bauer et al. (2004) measured similar diurnal fluctuations on Thata Island and used these fluctuations to estimate evapotranspiration rates. They interpreted the measurements with a conceptual model of an island, with fixed heads at the shores and time dependent uniform evapotranspiration from the surface, neglecting spatial variation of ET due to non-uniform landcover and salinity gradients. A comparison with the isotope profile method to estimate evaporation showed good agreement for the centre of the island. Because of the very sparse vegetation in the centre of Thata Island, transpiration can be neglected there.

At large scales, surface-water groundwater interactions in the Okavango Delta are mainly characterised by vertical flows. Despite the high infiltration rates, no regional groundwater recharge occurs and the aquifer serves as a buffering reservoir between highly seasonal flooding and more regular evapotranspiration. On a small scale, however, lateral groundwater flow towards islands is one of the main mechanisms regulating the hydrology of the Okavango Delta wetlands. The size and distribution of the multitude of islands covering the wetlands determine, together with antecedent conditions and precipitation, which portion of the annual flood infiltrates to local groundwater. The difference between regional and local flows is underlined by the groundwater level gradients which are on the order of ~1:4000 at the regional scale but as high as 1:200–1:100 at the local scale (Wolski and Savenije 2006). With the strong linkage between floodwater and island groundwater, not only the floodplain vegetation but also the adjacent riparian vegetation is strongly dependent on frequency and length of flooding.

The upstream catchment area

The division between the Okavango catchment and the distributary system of the Okavango Delta is geomorphologically defined by the entrance of the Okavango River into the Panhandle region. In the upstream, the course of the Okavango River is well defined, whereas starting in the Panhandle, extensive floodplains appear, leading to a fast decrease in channel discharge. Hydrological records, starting as early as 1930, are available from the stations of Mukwe (Namibia) and Mohembo (Botswana) which are within 40 km of each other. From there the catchment area of the Okavango extends over 165,000 km^2 upstream with the farthest part roughly at a distance of 800 km. The northern part of the basin is situated in the Angolan highlands. It receives large amounts of precipitation (up to 1,300 mm/year), which contribute practically all the runoff. The southern parts of the basin are semi-arid and the catchment lying within Namibia contributes almost no discharge. Geological differences in the headwater regions are also an important factor. In the western part of the basin, a relatively thin layer of Kalahari sands is underlain by volcanic and metamorphic rocks with low hydraulic conductivity while the eastern headwaters originate from a region with a much thicker layer of Kalahari sands. Consequently the variability in discharge is larger in inflows from the western part and the regime of inflows from the eastern part has a baseflow character (Hughes et al. 2006).

Compared to the Delta, the catchment area in Angola has received very little scientific attention. Due to the civil war and the persisting land mine hazard, data availability is extremely limited. During the war period from 1975 to 2002, only sparse hydrological and meteorological measurements were conducted, making the situation for model development and calibration difficult. In 2003, the first of a series of rainfall-runoff models based on the Pitman model (Pitman 1973) was developed by Andersson et al. (2003). In this first model, 23 sub-catchments upstream of Mohembo were used. Hughes (2004) developed a model for the Cuito River (see Fig. 1), one of the two main tributaries of the Okavango River, in which groundwater recharge and discharge are incorporated as new components and the drainage density of the channel network is taken into account. A second model by Hughes et al. (2006) comprises the entire catchment by considering 24 distinct sub-basins.

General information on the physical characteristics of the catchment is available at a sufficient resolution for modelling purposes as carried out by Anderson, Hughes and co-workers. The geology of the catchment can be extracted from the geological map of Africa by Persits et al. (2002). A digital elevation model with a 90-m resolution is available for large parts of the globe as a result of the Shuttle Radar Topographic Mission (e.g. Farr et al. 2007). The Global Vegetation Modelling Unit has produced a 1-km resolution landcover map of the globe based on 14 months of data from the VEGETATION instrument onboard the SPOT 4 satellite (Bartholomé and Belward 2005). A soil classification map with a resolution of 30 arc-seconds (~1 km) has been produced by the World Food Organisation (FAO 1992), which also provides a resampled version with a 2 arc-minute resolution.

More problematic is the limited availability of time varying meteorological data and discharge data for calibration. Gauged rainfall data are only available until 1972, while accurate satellite based rainfall estimates are only available from more recent years. Wilk et al. (2006) developed a distributed monthly rainfall dataset at a 0.5° resolution for the period 1991–2002 which is incorporated into the modelling work of Hughes et al. (2006). The initial rainfall data set was generated from data of the Special Sensor Microwave Imager (SSM/I) onboard satellites of the Defence Meteorological Satellite Programs (DMSP) which provides data back to 1987. A procedure was developed to remove the bias resulting from discrete satellite sampling times and a diurnal precipitation cycle with a maximum in the local afternoon, making use of data from several satellite-based microwave sensors. The diurnal cycle for the Okavango region was derived from satellite data of the Tropical Rainfall Monitoring Mission (TRMM) which was launched in late 1997 and provides three-hourly data.

For the period from 1969 to 1972, the available gauged precipitation time series were interpolated to a regular grid and subsequently precipitation inputs for the sub-basins were extracted from that grid to generate model inputs. The applied interpolation method was found to be a minor source of inaccuracies compared to the limited number of rain gauges.

Given the limited data availability, the performance of the model by Hughes et al. (2006) is satisfactory. Low flows are well simulated, whereas errors in the simulated peakflows are on the order of 20%. Gauging problems at high flows are possible but these errors are still small compared to the overall uncertainty of the model. The limited accuracy of the model must be taken into account when model results are applied for consecutive studies. For instance, if the model is used to predict outflow from the catchment for the next flooding season as a result of past precipitation events, large errors must be expected, irregular under- and overestimations of the outflow being significant. The model is better suited for long-term statistical analyses. The model manages to reproduce a series of years with smaller or larger outflows within the calibration and validation periods (1960–1972 and 1992–1997 respectively). A general shift towards drier years, as expected in the region as a result of global warming, can therefore also be simulated.

Sources for data characterising the Okavango Delta

The success of hydrological models to reproduce flow conditions observed in the Okavango Delta depends largely on the availability and precision of input data. A large number of datasets related to the Okavango Delta region are nowadays available on the Internet or have been published and are available upon request. For non-commercial scientific studies, most of these datasets can be obtained free of charge. The size and difficult accessibility of the Okavango wetlands make remote sensing data particularly useful as a compliment to ground-based measurements. The advantage of remote sensing methods is that they result in distributed data, but they require complicated calibration procedures and should always be checked against ground truth measurements. Newly emerging techniques like satellite based gravimetry and radar altimetry have to be assessed, and how far hydrological modeling of wetlands can build on them still needs to be determined.

Topography

The Shuttle Radar Topography Mission (SRTM) carried out by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency from the USA, together with the German and Italian Space Agencies in February 2000 (Farr et al. 2007) provide a unique dataset of elevations at a 3 arc-second (~90 m) resolution for all areas situated in-between 60°N and 58°S. Unfortunately, its vertical accuracy of approximately 5 m for most of the African continent (Rodriguez et al. 2005; Farr et al. 2007) is insufficient for hydrologic applications in the Okavango Delta. An additional problem of the SRTM data, which applies also to other remotely sensed elevations, is that the topography of flooded areas cannot be obtained. The SRTM was flown in February when the flood extent was low. Regardless, the bottom elevations of large areas of the permanent swamp could not be recorded as the instrument could only measure water-surface elevations.

A micro-topographic map has been generated by Gumbricht et al. (2005), making use of a vegetation map derived from Landsat Thematic Mapper (TM) scenes (McCarthy et al. 2005) and an island map (Gumbricht et al. 2004). Empirical elevations relative to the water surface were assigned to the vegetation community classes. The island map was used to further differentiate grassland on floodplains from grassland in the centre of islands. The relative elevations were added to a 500-m resolution regional elevation model generated by Gumbricht et al. (2001), which is based on a combination of remote sensing, ground measurements, and interpolation. The elevation model obtained in this way has the resolution of Landsat scenes (28.5 m). It has been compared with elevation measurements on the ground, along five transects. The correlation coefficient (R^2) between the measured transects and the elevation model was found to be poor, ranging from 0.1 to 0.57. However, structurally the elevation model compares well with the measured transects. Relative low and high reaches corresponding to islands and lagoons are captured by the model. Given its underlying classifications, the micro-topographic elevation model can, however, only be applied in areas were flooding is frequent enough to sustain a vegetation community which is well adapted to flooding. A flooding frequency of at least one event every few years is required. Naturally, the area where topography can be modelled is also the area that is the most interesting for hydrological modelling. On the whole it can be stated that topography is the most critical parameter for the reconstruction of flooded areas in a model. Yet, topography in the Okavango Delta region is not known to a sufficient accuracy.

Properties of the Kalahari Beds Aquifer

A major groundwater exploration programme spanning two phases (1995–1997 and 2000–2004) was carried out by the Department of Water Affairs to supply water to the village of Maun and surrounding areas. This programme resulted in a total of over 150 boreholes (both for exploration and production) being drilled in the distal part of the Delta. A suite of geophysical borehole logging methods was carried out at more than 100 sites, resulting in over 7,000 m of logged length. The methods used included natural gamma count, self-potential (SP) resistivity, and resistance techniques. The natural gamma count method is especially suited for distinguishing between sands, clayey sands and clay while resistivity methods give an indication of the water quality in addition to lithologic differentiation if contrasts are sufficient. The self-potential method is also well suited for distinguishing lithological contacts, although it is not as efficient as the natural gamma count method. Figure 9 shows a sample

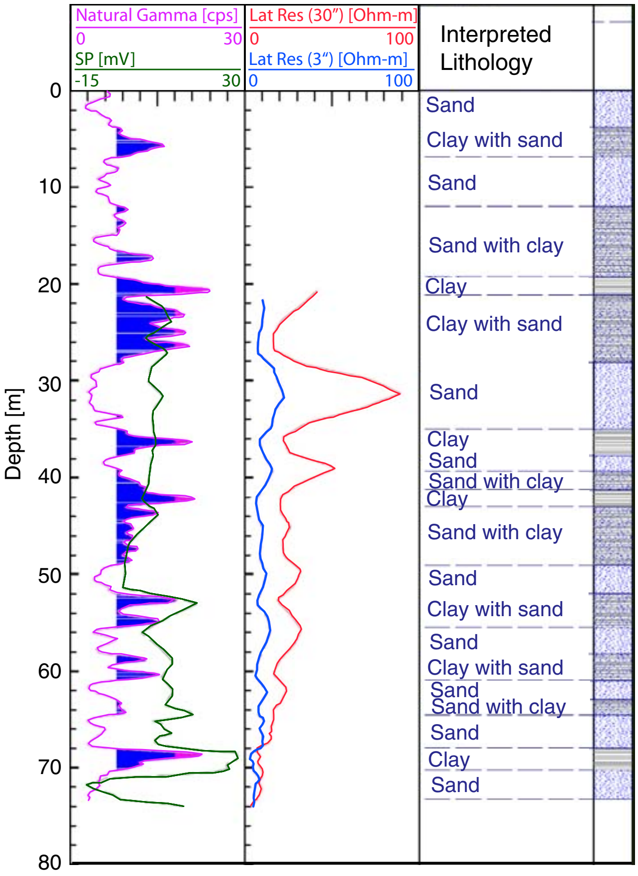

Fig. 9 Typical lithological log interpretation based on borehole geophysics and observed drilling sludge, borehole 10043, Kunyere. *SP* self-potential; *Lat Res* lateral resistivity; *cps* counts per second. Notice how the natural gamma peaks across clay and drops across sand layers. (modified after DWA 2004)

geophysical borehole log and the resulting lithological interpretation.

An integrated interpretation of lithological and geophysical logs resulted in the following observations:

- Clean sands (fresh water layers) are characterised by low gamma counts (<8 counts/second) and higher resistivities—20–200 Ohm-m—while saline clean sand layers are characterised by gamma counts similar to fresh water layers but with distinctly low resistivities (<10 Ohm-m).
- Clays are characterised by high gamma counts (>17 counts/s) and lower resistivity (<10 Ohm-m).
- Interlayered sand and clay beds are characterised by generally moderate gamma counts (8 – 17 counts/s) and resistivities ranging between 10 and 20 Ohm-m.

Geological cross sections were made both paralleling and straddling major faults (Kunyere and Thamalakane) to investigate the role of these faults on the deposition of sediments. The following observations were made:

- Large-scale interlayering of material with high hydraulic conductivity (fine-to-medium-grained sands) and low conductive layers (clay, clayey and silty sands) prevails.
- There is a continuous lateral extent of high and low conductive layers both parallel and perpendicular to the major faults.
- Low conductive layers are mainly clayey in nature towards the faults and become more silty further away from the faults (i.e. towards the Panhandle).
- High conductive layers pinch out while low conductive layers thicken towards the major faults (i.e. in a southeast direction from the Panhandle).

The basic conceptual depositional model derived from the spatial distribution of high and low conductive layers is that of a tectonically active (i.e. syntectonic deposition) basin alternating between fluvial and lacustrine deposition (DWA 2004). The Kunyere and Thamalakane faults acted as barriers to outflow from the Delta. The coupling of these fault barriers with hydrologic/climatic conditions and degrees of tectonic activity resulted in either fluvial or lacustrine dominated deposition in the lower Delta. Wetter periods in the past resulted in relatively extensive standing water bodies, effectively dammed by the Kunyere and Thamalakane faults, covering most of the lower Delta and forming lakes on the downthrown sides of the faults. Bedload sands transported by the upper Delta rivers were deposited at the northwestern margins of the lakes while extensive volumes of suspended materials (clays and silts) were deposited across the submerged areas (DWA 2004). Drier periods led to river dominated flow reaching the fault areas (as in the present period) and hence lead to fluvial deposition of sands. These alternating cycles resulted in the development of a multilayered aquifer system with sands acting as the high conductive layers while clay, clayey- and silty-sands formed low conductive layers. Figure 10 shows schematic depositional cycles and the resulting multi-layered aquifer as seen from one of the cross-sections perpendicular to the Kunyere Fault.

The prevalence of clay material on and near the fault zones causes these faults to effectively act as groundwater

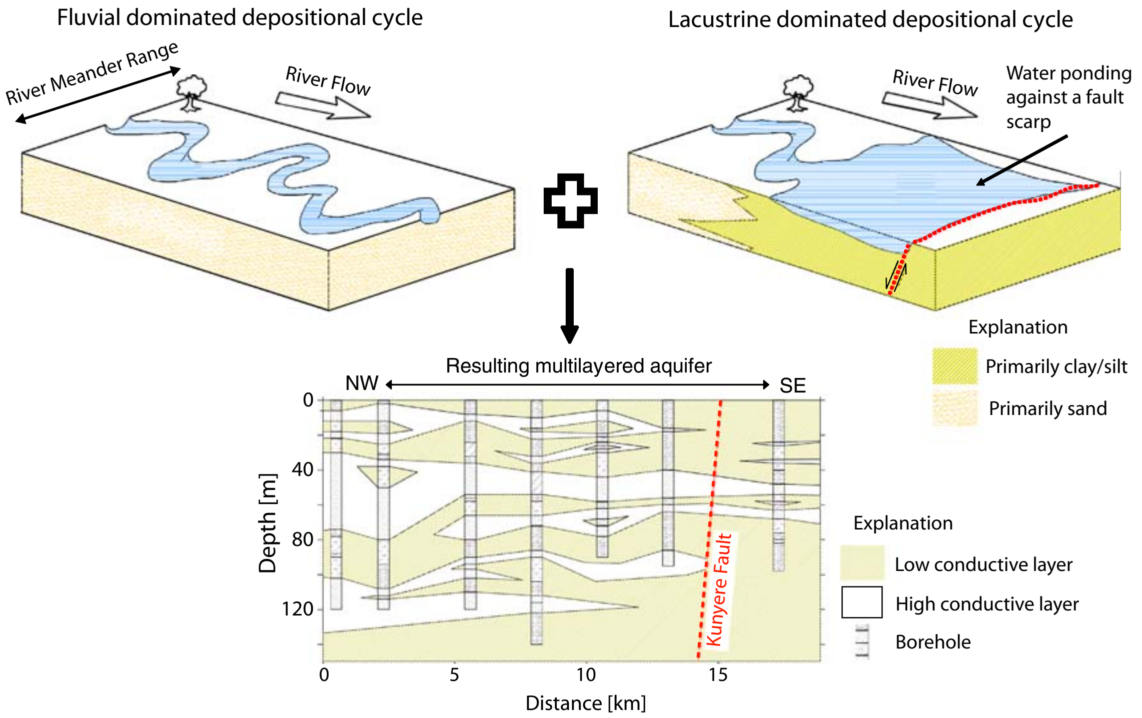

Fig. 10 Alternating fluvial and lacustrine depositional cycles have resulted in a multilayered aquifer system (modified after DWA 2004)

flow barriers as shown by the steep hydraulic gradients across the faults. The change in lithology of the low conductive layers from being clay dominated at or near the faults, grading into silt-dominated material away from them (northwest direction), means that leakage through these layers increases in this direction. This phenomenon manifests itself in a slow response to flooding by boreholes near the faults, as compared to the faster response of boreholes further northwest from the faults (DWA 2004).

Pumping tests were carried out in 78 boreholes by DWA (2004) in the lower part of the Delta to assess hydraulic parameters. The goal of the DWA (2004) project was to drill boreholes only within the depth of fresh layers (on average within the top 60 m) and therefore the general observations made should be understood in that context. The aquifer's response shows that it is predominantly leaky-confined, although in minor cases, both unconfined and confined cases were encountered. The confined cases occurred mostly in deep conductive layers in the range of 70–80 m below ground level. Test pumping analyses at 39 observation boreholes show median values of 35 m^2/day and 0.00143 (dimensionless) of transmissivity and storativity, respectively. A range of 3–165 m^2/day in transmissivities and of $6.0 \cdot 10^{-4}$ to $7.1 \cdot 10^{-2}$ in storativities was observed (Fig. 11). The aquifer's distribution over the lower Delta is practically homogeneous and this situation is expected to prevail over the entire main Delta because of similar depositional conditions. However the situation may slightly change towards the Panhandle area. Stream power in the Panhandle is larger and prevents the deposition of clays and the formation of low conductive layers. Hence, predominantly unconfined conditions are expected in the Panhandle, with increased values of transmissivity and storage.

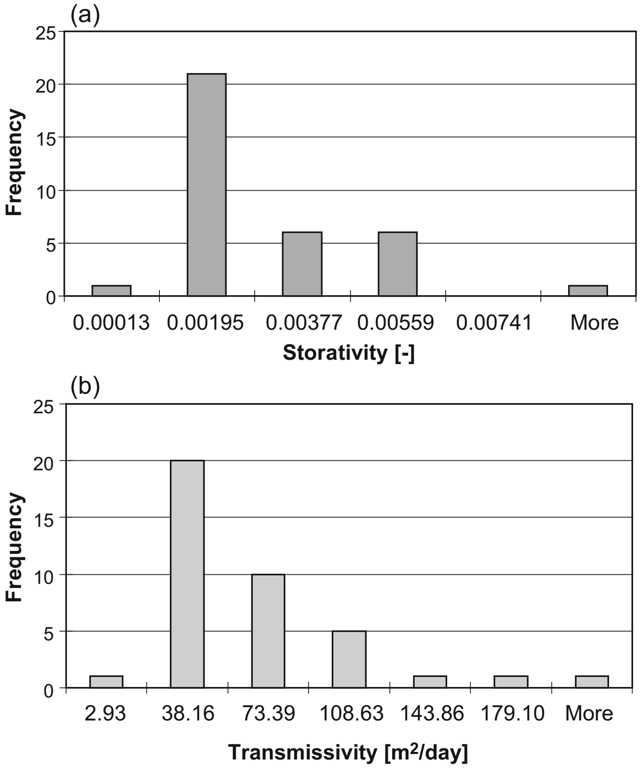

Fig. 11 Histograms showing **a** storativity and **b** transmissivity distributions of the Kalahari Aquifer in the distal lower Delta. Note that the distribution is not symmetric but skewed to the left in both cases and therefore it is better to take the median values and not the mean for both parameters

Soil map

A soil map of Botswana at the scale 1:1,000,000 has been published by FAO (1990). This map is available from the web page of the European Digital Archive of Soil Maps - EuDASM (http://eusoils.jrc.it/esdb_archive/EuDASM/Africa, EuDASM 2005). A digitised and slightly more detailed soil map is available through the Sharing Water Project (RAISON 2004). The Sharing Water Project was founded by the US Agency for International Development and was carried out by partner institutions from several countries including Angola, Namibia and Botswana. The overall purpose of the project was to help in ensuring the sustainable management of the entire Okavango Basin. The project website hosts an extensive database. Some of the datasets which are directly linked to hydrological modelling are referred to in this article.

Vegetation cover

The ecoregion classification by McCarthy et al. (2005) is based in a first step on the statistical classification of Landsat TM 5 scenes acquired in July and August 1994. Supervised and unsupervised maximum likelihood classifications were used in a combined way. A second step involved flooding patterns between 1972 and 2000 at 1-km resolution, as determined by McCarthy et al. (2003). The wetlands were classified into 12 ecoregions ranging from rivers to dry woodland. Contextual information such as the distance of pixels from the river network was also used. A total of 170 sample sites were surveyed, one-quarter of which was used to train the algorithms and three-quarters to validate the methodology. The classification into 12 ecoregions resulted in an accuracy of 46.2%. When classifying into six ecoregions, the accuracy was increased to 74.3%. The main difficulties in classifying the Okavango wetlands were found to be the similar spectral responses of different vegetation types (e.g. *C. papyrus* and various tree species), the high spatial variability of the vegetation cover, and its temporal variability due to fluctuations in water availability.

A second classification by Ringrose et al. (undated report) is available through the Sharing Water Project (RAISON 2004). Its spatial resolution of 30 m is the same as the ecoregion classification. A major difference to the work by McCarthy is the number of classes: based on vegetation types (e.g. grassland, woodland) and dominant species, 47 classes are distinguished. The classification uses supervised classification of Landsat TM scenes, supplemented by the analysis of aerial video imagery.

For an accuracy assessment, the 47 classes are reduced to eight combined classes, resulting in an accuracy of 75%. This accuracy is strongly class dependent; the accuracy of, for instance, the combined island class is only 46%.

Soil moisture

Soil moisture at a 1-km resolution is in principle available for the entire Okavango catchment area from the Advanced Synthetic Aperture Radar (ASAR) sensor onboard the Environmental Satellite Envisat (Bartsch et al. 2006; Wagner et al. 2007). Radar backscatter, however, is also largely influenced by surface roughness and vegetation. Consequently, the spatially and temporally heterogeneous cover of the Okavango Delta results in an ambiguity of the backscattered signal. In areas with forest, the volume backscattering from the canopy is too strong to distinguish changes of backscattering resulting from soil moisture (Sabel et al. 2007). The soil-moisture patterns of most of the central areas of the Okavango wetlands can thus not yet be determined from remote sensing. Soil moisture of the upstream catchment area has been successfully derived from Envisat ASAR imagery. A good correlation between soil moisture in the upper parts of the catchment and discharge at Mohembo with a time lag of three months has been observed (Bartsch et al. 2007).

Precipitation

Long time series of gauged precipitation measurements are only sparsely available for the Okavango catchment. With the onset of the civil war period in Angola in 1975, the number of hydrometeorological measurements dropped significantly (Wilk et al. 2006). The situation is better for the Okavango Delta where the stations Shakawe and Maun, situated at the up- and downstream ends of the Delta, have provided continuous time series of basic meteorological variables since 1973, available for instance through the National Climatic Data Centre of the US Department of Commerce (http://www.ncdc.noaa.gov, NCDC 2008). However, long precipitation records do not exist for the centre of the wetlands, where microclimatologic effects will influence variables such as temperature and wind speed.

For modelling purposes, it is very convenient to use precipitation derived from remote sensing. The Famine Early Warning Systems Network (FEWS NET) provides 10-day sums of precipitation at a resolution of approximately 10 km since 1995 and daily sums since 2002 (Fig. 12). The data are based on infrared images from Meteosat, meteorological ground station records, and microwave satellite observations (Herman et al. 1997). The accuracy of the algorithm was analysed by Xie and Arkin (1997), who determined a root mean squared (RMS) error of around 0.5 mm/day for the Okavango Delta region.

The satellite of the Tropical Rainfall Measurement Mission (TRMM) was launched in November 1997 and has provided data since January 1998. Precipitation amounts are calculated with a 0.5° spatial resolution and are available as three-hourly accumulations. The primary instruments on the satellite providing rain data are a precipitation radar, a passive microwave imager, and a visible and infrared scanner (Adler et al. 2007). The lower horizontal resolution of the TRMM data as compared to the FEWS NET is, depending on the type of application, compensated by information on the vertical structure of the precipitation process. The accuracy of the method depends strongly on the precipitation type, performing best for convective precipitation. Several validation studies of TRMM precipitation are summarised in Huffman et al. (2007).

Evapotranspiration

Actual evapotranspiration rates can be assessed through remote sensing data by means of surface energy balance methods. A wet pixel with evapotranspiration tends to be cooler than a dry pixel, with corresponding differences in the radiative properties recorded by the satellite. Algorithms such as the simplified surface energy balance index, S-SEBI (Roerink et al. 2000), can be used to calculate evapotranspiration on a daily basis. The method is well suited to generate patterns of evapotranspiration, but has a low absolute accuracy. Calibration with ground

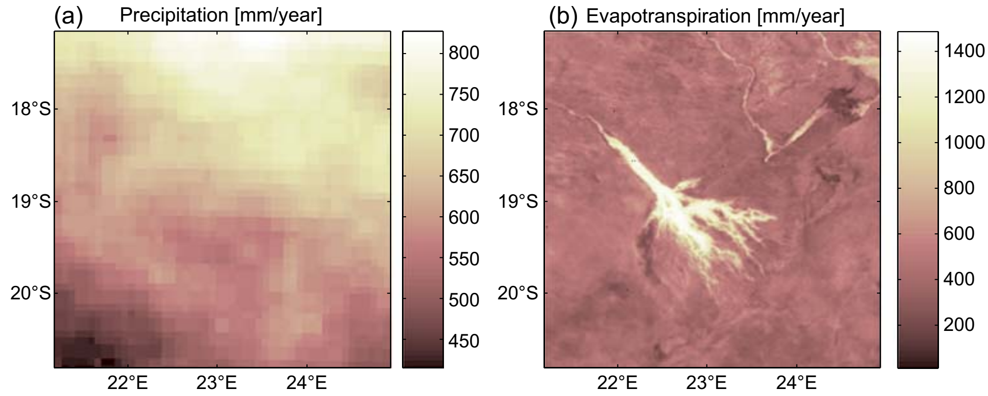

Fig. 12 1990–2000 averages over the Okavango Delta area of **a** precipitation, as available from the Famine Early Warning Systems Network and of **b** actual evapotranspiration (modified after Bauer et al. 2006a)

measurements is therefore necessary. Brunner et al. (2004) have used the chloride method to calibrate potential recharge maps (i.e. precipitation minus evapotranspiration) obtained from remote sensing.

Discharges and water levels

The Department of Water Affairs of Botswana is carrying out intensive monitoring of water levels and discharge rates inside the Okavango Delta which provides valuable data for hydrological modelling. The inflow to the Delta at Mohembo has been measured daily since 1975 and monthly discharges are available since 1933. This is especially valuable, as up to now a hydrological model combining the catchment area in Angola and the Okavango Delta has not yet been developed. Models of the Okavango Delta have been fed with discharge measurements taken at the stations Mohembo (Botswana) or Mukwe (Namibia). The two stations are separated by only about 40 km of incised channel. Still, data differ, especially at high flows when flows may bypass the Mohembo measurement station. Sefe (1996) conducted a detailed study on the Mohembo data and found many points to lie outside the range of possible stage-discharge relationships.

Flooding patterns

Seasonal flooding patterns derived from satellite data can provide valuable information for the calibration of hydrological models. Yet, the usefulness of remotely sensed data needs to be reviewed for each dataset. Vegetation in the Delta, being exposed to seasonal variation of water availability and small-scale variations of topography, changes on a scale of meters. The resulting complex patterns of land cover in the Delta limit the applicability of many remote sensing data products since a relatively high spatial and spectral resolution is needed (Neuenschwander et al. 2005). Most of the studies presented hereafter rely on satellite images in the visible and thermal ranges. In comparison to sensors operating in the microwave range, these ranges have the advantage of providing a higher spectral resolution. However, the major disadvantage of images in the visible and thermal range is that it is not possible to obtain data when the region is covered by clouds. Cloud cover is frequent during the rainy season, which fortunately does not coincide with the flood peak. Regardless, analysis of the seasonal variability of the flooding is strongly hindered by clouds when using passive sensors.

Neuenschwander et al. (2002) investigated the applicability of data acquired by the ALI (Advanced Land Imager) instrument onboard the EO-1 (Earth Observing Mission 1) satellite. Since ALI was developed as a technology demonstration instrument and can therefore not be used as an operational land imager, extensive processing of the data is inevitable.

Seasonal variability not only of the fluctuating flooded area but also of vegetation patterns can be seen on ALI images of the southern part of the Delta. The evolution of a flooding event can be assessed by classifying a series of images into different land cover classes. Land cover classes related to inundation (water, permanent swamp and intermittent marshes) are extracted for spatial analysis. The total areal extent of the respective classes in a series of images shows the effects of flooding, with a maximum flooded area in August (Neuenschwander et al. 2002).

The longest time series of flooding patterns can be obtained by the method presented by McCarthy et al. (2003). Flooding patterns derived from nearly 400 Advanced Very High Resolution Radiometer (AVHRR) images recorded by the US National Oceanic and Atmospheric Administration (NOAA) satellites were compiled for the time from 1972 to 2000. Imagery from the Landsat satellites and the Along-Track Scanning Radiometer (ATSR) onboard the second European Remote Sensing satellite (ERS-2) were used to calibrate and evaluate the classification. The detection of shallow water bodies and wetlands on satellite data is a difficult task since the signal of water, especially when using data with coarse resolution, interferes with other surface types.

In a first step, sufficiently cloud free images were selected and from these images the clouds were masked out. Supervised classification techniques had to be rejected due to inaccuracies of the images' geometry and the use of different sensors. The distinction between flooded and non-flooded pixels was carried out using an unsupervised clustering method. The number of clusters was gradually minimised, and thus the area of each class maximised, until pixels of the largest class within the Delta also occurred outside the Delta area. The inundation of small pools caused by local rainfall was disregarded if it did not last longer than 1 month. Landsat and ATSR data were applied only to check the coherence of the flooding patterns visually (McCarthy et al. 2003).

Later the classification of AVHRR images was evaluated using classified Landsat and ATSR images, where these classifications were regarded as true. The spatial agreement of flooding patterns determined with both methods was found to be between 79 and 89% for images covering the whole area. The flooding extent reaches its maximum between July and September and has a minimum between January and February. The central and eastern regions of the Delta show the largest extent of flooding. Over the entire period of analysis (from 1972 to 2000), the smallest extent of flooding was found in February 1996 and the largest extent in August 2000 (McCarthy et al. 2003).

However, the method presented by McCarthy et al. (2003) has some drawbacks. The high sensitivity to clouds strongly limits the seasonal coverage; during the rainy season only few data are available. The coarse resolution of 1 km inhibits the detection of small-scale features such as channels, lagoons and islands. A pixel only partly consisting of wetland differs strongly enough from a pixel outside the Delta area to be classified as inundated. This effect leads to an overestimation of the total flooded area. Nevertheless, the relative dynamics of flooding are reliably reproduced (Milzow et al. 2008a).

The need for the use of higher resolution images is also pointed out by Wolski and Murray-Hudson (2006a). Landsat images with a resolution of 30 m were classified into different inundation and dry land classes using spectral characteristics. Most of the inundated and dry classes could be separated well, whereas a large overlap in spectral characteristics of densely vegetated, permanently flooded areas and riparian woodlands made the separation difficult. A combined approach of supervised and unsupervised classification as well as the consideration of geometric properties of inundated areas resulted in relatively high accuracies of flood mapping. Disconnected inundated patches were classified as dry land, taking into account that the flooded area is usually continuous. The accuracy was assessed using aerial photographs (Wolski and Murray-Hudson 2006a). It is not discussed in the article whether continuity may exist at a sub-pixel scale in the form of narrow channels linking apparently disconnected inundated patches. Given the high resolution of 30 m, this is however expected to occur only in a few cases.

Active microwave techniques are relatively insensitive to clouds and thus allow a better seasonal coverage. Meier (2006) used Envisat ASAR images available since 2002 with a resolution of 150 m. Zones likely to flood were identified by a high temporal variation of pixel values, which is a consequence of the seasonal change in reflectance of the earth surface. Areas with low temporal variance were masked out and disregarded during further image processing. On radar images, open water surfaces are characterised by low backscattering values due to the high reflectance of water. In contrast, flooded vegetation is characterised by high backscattering values due to the double reflection effects of the water surface and the vegetation. A stepwise approach was chosen for the classification of single pixels. In a first step, pixels with unambiguously low or high values were classified directly. A second class was formed by those pixels having a value within a close range to the values of the first class. As an additional constraint, the temporal variance of that particular pixel had to be above the median value. Finally, the third class was composed of pixels with a medium-low or medium-high value. Besides a stronger criterion for the temporal variance, these pixels were only classified if they belonged to a continuous cluster where at least one pixel was classified in the first or second class (Meier 2006).

The recognition of open water surfaces is possible as the view is quite unobstructed; the classification of flooded vegetation though is difficult due to the superposition of changing backscattering characteristics (Meier 2006). Resulting from the higher resolution of the ASAR data, micro-topographic features can be resolved as well as inundation around channels. Quantitative comparisons of the inundated area show that the areas obtained from NOAA AVHRR images are much larger than those from ASAR images (Fig. 13). Small structures such as channels, small ponds, and lagoons contribute strongly to the total inundation (Milzow et al. 2008b).

To overcome the drawback of coarse resolution, Milzow et al. (2008a) used data from the Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) onboard the Advanced Land Observation Satellite (ALOS) with a 10-m resolution. A cloud-free mosaic was built using seven images within the period from 25–30 August 2006. Open water surfaces were extracted by applying a threshold on the near infrared band (NIR), based on the fact that water absorbs light at this wavelength. The vegetation in shallow floodplains typically appears impervious to visible and infrared radiation. Yet, the difference between flooded vegetation and vegetated dry land was large enough in the visible range to delineate inundated areas using the three visible light bands (Milzow et al. 2008a).

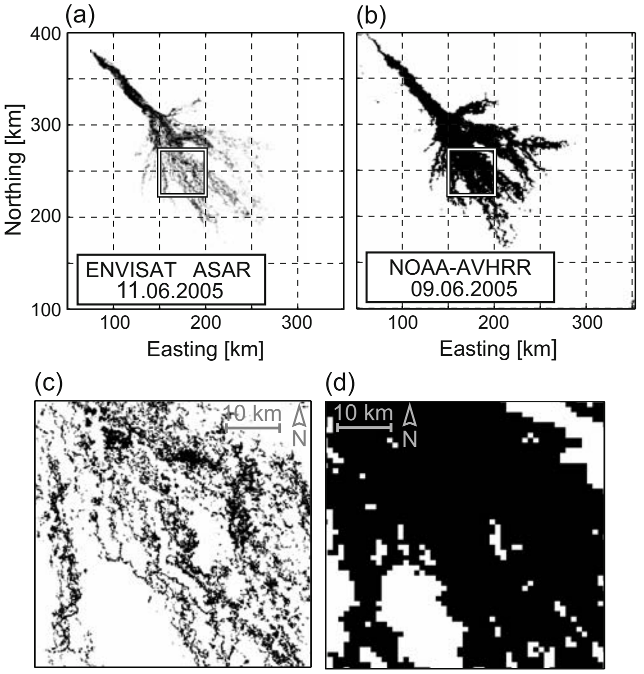

Fig. 13 Flooding patterns derived from Envisat ASAR with a 150-m resolution (**a**) and from NOAA-AVHRR with a 1 km resolution (**b**). **c**–**d** Details of the framed areas in **a** and **b** respectively. *Black areas* were classified as flooded and *white areas* as dry. (Milzow et al. 2008b)

The application of remotely sensed data for the calibration of hydrological models shows promising improvements. A good compromise between long time series of low-resolution data and short temporal coverage of high resolution has to be found.

Modelling the hydrology of the Okavango Delta

The history of hydrological modelling of the Delta

Hydrological modelling of the Okavango Delta has a long history. Model development went from conceptual box models, to multibox models, to highly resolving physically based hydrodynamic models. Together with the increase in complexity of numerical models, additional groundwater components were included by modellers. Overall model realism could be increased considerably by including groundwater components, thus confirming the importance of the groundwater surface-water linkage in the Okavango swamps. The motivation for modelling was always derived from the need to predict the outcome of planned measures both in the upstream and inside the Delta. Changes in the inflow to the Okavango wetlands or alterations inside the wetlands will undoubtedly result in a change of flooding patterns, both spatially and temporally. Ashton and Neal (2003) qualify it as a "matter of urgency" to evaluate the response of the wetlands to decreased or changed inflows. Due to the complexity of the system, numerical models seem today to be the only feasible solution for such an assessment.

The first numerical flow model of the Okavango Delta was compiled within a project of the United Nations Development Program (UNDP) and the Food and Agricultural Organisation (FAO) in the mid-1970s (UNDP 1977). Dincer (1985) further developed this conceptual model in which one cell was used to represent the entire swamp system. The single cell model was later refined into a model with up to 10 cells (Dincer et al. 1987). The flooded area A in m^2 for the cell and the water volume V in m^3 stored in the cell are related by the simple function:

$$V = b \cdot A^{n} \tag{5}$$

where b and n are empirical parameters derived from a single 5-km^2 experimental area at Beacon Island. This exponential relation of volume to area was later challenged by McCarthy et al. (1998a) because it is valid only for small areas that can be approximated by a bowl-shape. In reality, the wetlands consist of a multitude of pools and on a large scale are better approximated by a linear relation between volume and area. Dincer et al. (1987) point out changes over time of the spatial flow distribution (which they call regimes) and see sedimentation as cause for these changes. Their model was therefore calibrated independently for different periods, yielding different model parameter sets to describe different regimes.

Dincer's model was further modified to a 13-cell model by the International Union for Conservation of Nature (IUCN) (Scudder et al. 1993) introducing, e.g. changes in the relation of volume to flooded area. Areas of intermittent A_{int} and perennial A_{p} swamp for each cell were determined from ecological zoning maps and the associated depth range r was defined. The inundated surface A was then derived from the water depth, d as

$$A = A_{\text{P}} + \frac{d \cdot \left(A_{\text{int}} - A_{\text{p}}\right)}{r} \tag{6}$$

A non-linear volume-to-outflow relation based on Manning's formula, and a loss component accounting for water losses as the waterfront reaches dry areas were also introduced into Dincer's model. Details are given in Gieske (1997). Because long-term losses to groundwater represent only a small proportion compared to evapotranspiration, groundwater percolation was not included in the model. However, Scudder et al. (1993) recognised the importance of the soil in storing water during initial flooding. Apparent regime changes, leading to different relations between the inflow at Mohembo, precipitation and outflow of the different subsystems are discussed, but for model calibration, only one regime was considered. Double-mass analyses of precipitation records of gauges in and around the Delta were performed and the time series of the rain gauges at stations Shakawe and Maun (respectively at the inflow and outflow of the Delta), which were used as model inputs were corrected accordingly.

Gieske (1997) suggested that the regime changes are not due to physical changes in the channel network and that the precipitation time series should not be corrected. His explanation invokes the long-term memory effects of the wetland system. Shallow groundwater levels are influenced by climatic conditions of the last decade, to which short-term events (annual precipitation and flow peaks) are then added to result in the yearly outflow of the wetlands. This explanation is later supported by the results of statistical analyses from Wolski and Murray-Hudson (2008) pointing out the differences between hydrological changes which are physically induced (as is the shift in flood distribution from the Thaoge to the Xudum) and transient changes due to the non-linearity of the system (as are these regime changes). Gieske (1997) constructed a four cell hydrological model limited to the Jao/Boro flow system. The parameters that were time invariant in the model by Dincer et al. (1987), and had to be adjusted for every regime period, were replaced by a time variant parameter. This parameter was derived from cumulative rainfall departures (CRD) with a 10-year long-term memory. The relation between the flood distribution in the different subsystems and antecedent rainfall is still empirical, but is based on the important impact of groundwater levels on surface water flow. Without considering regimes or rainfall corrections, Gieskes' model achieved much better simulation results of the outflows at the downstream end of the subsystem than the previous models by Dincer et al. (1987) and Scudder et al. (1993).

Based on the 13-cell IUCN model, Water Transfer Consultants (1997) developed a model to assess to what extent water abstraction in the upstream will have an impact on the outflow and the area flooded. The major change was the inclusion of a memory effect on shallow groundwater. When a cell is wetted, a loss term is subtracted, amounting to 30 mm/month since the cell was last flooded. The flooded areas are, as in the IUCN model, a linear function of the water volume stored in each cell.

The four reservoir models presented above succeed in simulating the outflow at the end of the Boro channel with different degrees of accuracy. However, a major shortcoming of all four models is that channel and floodplain flow are not simulated separately. Models of the Okavango wetlands have always been in demand for their supposed ability to evaluate the impact of water-management policies. One intervention technique is the clearing of channels from encroaching vegetation. The impact of such a clearing cannot be simulated properly if channel and floodplain flow are not simulated separately.

The discharge at the end of the Boro system is undeniably an important variable. The water supply of the township of Maun depends directly on this surface water and on the local groundwater fed by the system. However, the ecological value of the wetlands consists of the multitude of different ecosystems spread over the Delta, and preserved by flooding of different frequencies, lengths and water depths. These hydrological variables, their spatial distribution, and how they are affected by water-management policies definitely require distributed hydrological modelling for meaningful simulations. The main difficulty for distributed modelling is data availability. Topography and vegetation maps are now available at a resolution of 28 m. For meteorological and groundwater records, the data availability is more restricted. Long-term meteorological records are limited to two stations at the edges of the wetlands, whereas it is recognised that microclimatic effects may play a significant role in the heart of the wetlands. There exists good information on surface water levels close to the main channels of the wetlands, but in the dry season, when the channels have dried up, groundwater level records are rare. Another difficulty arises from the different scales at which the hydrological processes occur. Whereas groundwater heads are smoothly distributed over large distances, the channel network and topography of the floodplains are sensitive at a much finer scale.

Recognising the necessity for distributed hydrological modelling, the first spatially distributed model of the Delta was constructed by Bauer (2004) at the Swiss Federal Institute of Technology in Zurich (ETH Zurich). This model is based on MODFLOW software (Harbaugh et al. 2000) of the US Geological Survey (USGS), with special additions. Two model layers represent the surface water with overland and channel flows and the aquifer respectively. A water table rising into the first layer triggers surface water flow. The grid resolution is 1 km x 1 km. The vadose zone is simulated indirectly by a function decoupling groundwater and surface water, with increasing depth to groundwater. Precipitation and potential evapotranspiration are combined and multiplied by a factor decreasing with depth to groundwater. Due to this simplification, a delay between precipitation and groundwater recharge cannot be reproduced. For overland flow, it is argued that, given the low flow velocities and shallow water depths compared to vegetation height, a linear energy loss law relating water level gradients and discharge is reasonable. Stem density is approximately constant for all encountered water depths and vegetation friction dominates over bottom friction. Channels were conceptualised as surface flow cells (of 1-km resolution), with flow computed by Manning's equation and scaled with a factor (channel width/cell width) to account for the size of the channel. Overland flow in channel cells is neglected. The model simulates the water years from 1970 to 2006 with one parameter set. The observed flooding pattern is reasonably reproduced after adjusting four global parameters. It was used successfully for the assessment of water-management measures (Bauer et al. 2006a). This is the first model which is sufficiently physically based to use it in the extrapolation from the present state to a state not formerly seen, and thus, to simulate future scenarios.

At the Harry Oppenheimer Okavango Research Centre (HOORC), Wolski et al. (2006) developed a hybrid reservoir-GIS (geographic information system) model in which flooding maps are simulated by combining yet another reservoir model with a digital elevation model and historical flooding maps derived from satellite data. The reservoir model itself represents an advance over the earlier box models, as for the first time it explicitly considers groundwater reservoirs. The effect of previous years of, e.g., high rainfall or inflow, resulting in higher groundwater levels and reduced infiltration in the following year can be simulated, resulting in a larger simulated flooding extent. Each of the nine surface reservoirs that the model consists of is linked to five underlying floodplain groundwater reservoirs, which are recharged by surface water depending on the flooded area in the surface reservoirs. Each of the floodplain groundwater reservoirs is linked to an island groundwater reservoir. In this way, the lateral groundwater flow away from the floodplains as described in Wolski and Savenije (2006) is conceptualised. Groundwater flow between groundwater reservoirs is not possible. The relation of volume to flooded area is represented by a power law of the same type as in Dincer et al. (1987), but the coefficients are determined for each surface reservoir from the 28 m resolution micro-topography generated by Gumbricht et al. (2005). The reservoir model is well able to simulate outflow in the different subsystems over high and low flow periods with one set of parameters. Unfortunately, groundwater level data are insufficient to verify the simulated volumes stored in the groundwater reservoirs. From these simulated volumes, flooding patterns are now derived. An empirical relationship between flood volume, as modelled for each distributary system, and observed flooding patterns in the same system is considered. Observations of flooding patterns were taken from NOAA-AVHRR satellite images that were classified by McCarthy et al. (2003). The period from 1984 to 2000 was chosen for the calibration of the volume to flooding pattern relationship (P. Wolski, Harry Oppenheimer Okavango Research Centre, personal communication, 2007). Differences in flooding patterns within one distributary system for floods of the same volume cannot be explained by the methodology and are treated as random variation. The simulation period presented in Wolski et al. (2006) ranges from 1990 to 2000 and is therefore not different from the calibration period. Because the model is not physically based, the predictive power of the model for new system states has still to be shown.

DHI (Danish Hydraulic Institute) Water and Environment (Jacobsen et al. 2005) developed a spatially resolving model within the Okavango Delta Management Plan (ODMP) (Government of Botswana 2007) based on the MIKE SHE and MIKE 11 software. The spatial discretisation is also 1 km × 1 km. Channel flow is simulated by solving the Saint-Venant equations for a one-dimensional river network. Flow cross sections are interpolated between 30 measured cross-sections of 2 km width, thus including a floodplain zone. Overland flow over the entire model is calculated with the two-dimensional-Saint-Venant equation. Surface roughness is derived from vegetation maps. Unsaturated flow to the groundwater is described by Richards's equation in one dimension. Evapotranspiration from all surface and groundwater components is simulated by a soil-vegetation-atmosphere transfer model (MIKE SHE SVAT) by calculating heat fluxes. The complex SVAT model requires many distributed vegetation and meteorological inputs, some of which are derived from remotely sensed data; for example, leaf area index and albedo were derived from MODIS imagery available every 10 days.

The calibration of the DHI model was targeted at the correct simulation of flooded areas as observed from NOAA-AVHRR data (McCarthy et al. 2003). Because of the long computational time needed to run the model (11 hours to simulate 1 year on a standard PC), only a manual calibration was performed. The calibrated model performs very well in reproducing the flooded areas of the flood in 2000. However, it must be noted that the calibration and validation period of 1.5 years is very short and does not guarantee model performance in reproducing long-term changes. Also, the flood in 2000 was very large due to heavier than usual local rainfall, a situation occurring only once in many years. While the flooded areas are reproduced by the model, no correlation is achieved between simulated and observed flows.

As an extension to the DHI model, two detailed hydrological models with a 250-m resolution were derived for two branching zones (Scanagri 2006b). Boundary conditions were set as time varying fixed heads extracted from the large-scale model. Simulations were carried out to identify the impacts of channel clearing (by reducing flow resistance) and water abstractions on flow and flooding. The detailed models did not perform much better in simulating discharges than the main model. The results concerning channel clearance scenarios are thus questionable. However, an interesting finding is that the impact on water levels is significant (up to 1 m) only on a very local scale while changes propagating over tens of kilometres are much smaller (on the order of 0.1 m). The simulation of groundwater abstractions from the Delta combined with the effect of possible upstream dams result in a rather homogeneous decline of water levels.

The latest distributed model (Milzow et al. 2008b) is a further development of the ETH Zurich model by Bauer (2004). In this new version, all major channels are included explicitly as one-dimensional objects, in addition to the overland flow governed by the topography. Discharges and water depths are simulated with Manning's equation for rectangular cross sections. Channel discharges at the end of the Boro system are simulated considerably better by this model than by the DHI model. However, at low flows the simulated channel discharges drop to zero, whereas in reality some residual flow is still observed. Owing to the simpler approach, the computational time on a standard PC of 1 h per simulated year is far less than the time required by the DHI model. Longer-term scenarios can therefore be simulated. Some results of the ETH Zurich model are shown in Figs. 14, 15 and 16. As observed from measured water levels, the amplitude of simulated surface water elevations is large in the Panhandle, decreases in the rapid expansion of the Delta, and increases further downstream as water becomes more concentrated in single channel systems. Transects through the simulated water levels show that the infiltrating rivers let the water table rise to the surface, while in-between the channel systems the water table is several meters lower. The model simulates a regional groundwater outflow, conceptualised as drains, of 4.6 m^3/s. This represents 1.2% of the inflowing 300 m^3/s, together with the 80 m^3/s of precipitation on a surface of 5,000 km^2. The remainder of the incoming water is lost to evapotranspiration, with 65% leaving the system via the upper, surface water, layer and 35% leaving via the groundwater layer. The 35% evapotranspiration from the groundwater layer can be interpreted as resulting mainly from transpiration by vegetation. This value is in good agreement with the simple box model estimate presented in the section Groundwater-surface water interactions in the Okavango Delta.

The model is not validated against new distributed flooding patterns. It is, however, remarkable and speaks for the quality of the model that it performs well in

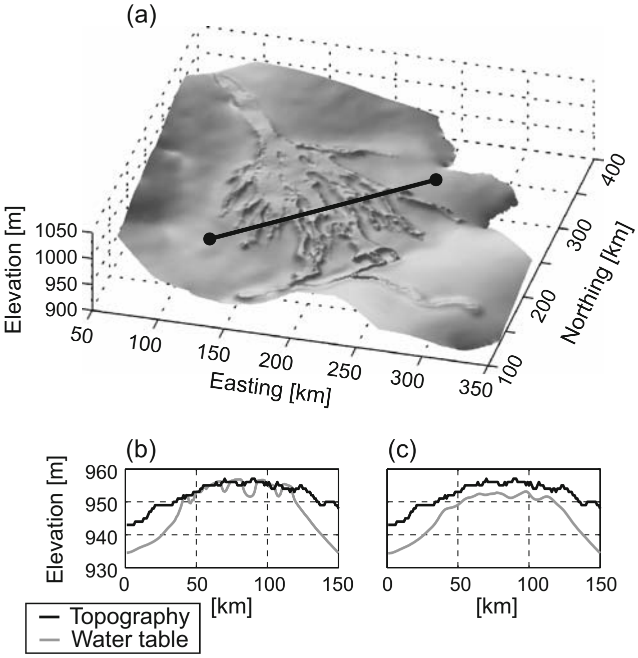

Fig. 14 Results of the Okavango Delta model developed at ETH Zurich. **a** Three-dimensional-plot of the simulated water table during the wet period with *black line* indicating the position of the transects **b** and **c**. The transects show the water table together with the topography during the wet season (**a**) and during the dry period (**b**) (modified after Milzow et al. 2008b)

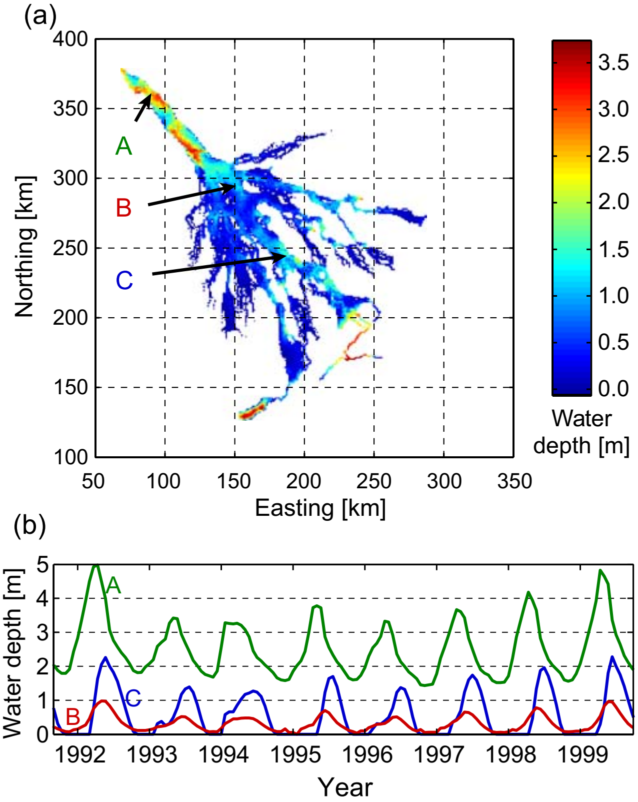

Fig. 15 Results of the Okavango Delta model developed at ETH Zurich. **a** Simulated flooding pattern and surface water depths in m for one time step during the wet period. **b** Time series of water depths at three selected locations: the highest amplitude of the water level occurs in the Panhandle at *A*, it decreases in the central floodplains (low amplitude at *B*), and increases again further downstream (intermediate amplitude in *C*) (modified after Milzow et al. 2008b)

simulating the flooding of Lake Ngami, a lake at the southwestern end of the wetlands which is flooded irregularly, only every few years. The flooding state of Lake Ngami was simulated correctly in 22 out of the 27 years from 1981 to 2007.

Modelling an area as large as the Okavango wetlands requires, evidently, a number of assumptions and simplifications. The three latest models, developed respectively at HOORC, DHI, and ETH, follow different strategies for that purpose. As a result, the models perform best for different applications and are complementary.

The HOORC model, which links water volumes to observed flooding patterns, is the most precise model in simulating flooding patterns given small changes in meteorology and inflow. Also, it is the best suited model to investigate small-scale spatial changes as for instance the flooding of specific small lagoons. It is however limited to states which have previously occurred and cannot simulate the impact of changes in the topography, vegetation or channel characteristics. The DHI model is simulating processes of the vadose zone the most realistically. This detailed simulation of the soil-atmosphere linkage requires a fine discretisation and leads to long computational times. Flow routing is also handled in great detail with a large number of cross-sections reproducing the shape of the channels and adjacent floodplains as far as they are known. Only short time periods can be simulated given the detailed level of modelling and therefore problems arise in the calibration of the model. The strategy is certainly promising for models of sub-areas of the Okavango wetlands. The ETH model, like the DHI model, simulates flooding patterns on a purely physical basis. It can therefore be used to simulate new system states as, for instance, conditions drier or wetter than ever observed, a changed topography or changed channel characteristics. The required computation times are considerably shorter than those for the DHI model owing mainly to simplifications in the evapotranspiration modelling and in the flow routing through channels. Long time series can thus be simulated, the price being less precision at the local scale. The model has been developed with a focus on the overall water distribution over the wetland rather than on changes in, for instance, a specific lagoon.

Simulating the impact of changes in water management, climate, and land use

The three most recent distributed hydrological models have all been used to study anthropogenic impacts on the extent and distribution of flooding in the Okavango Delta. Induced changes can be summarised into four main categories: (1) reduction of inflow to the Delta by upstream water abstractions for irrigation, industrial and household water supply, (2) redistribution of flows inside the Delta area by channel dredging and clearing, (3) changes in inflow to the Delta with respect to quantity and

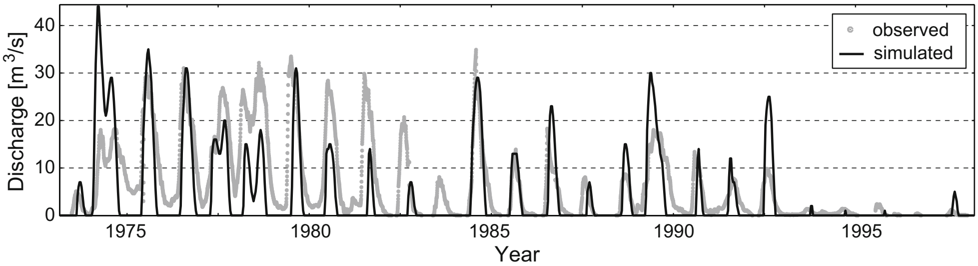

Fig. 16 Results of the Okavango Delta model developed at ETH Zurich. Simulated and observed channel discharge for the Boro Junction gauging station at the downstream end of the wetland system, located approximately 10 km northeast of Maun

quality by land-use changes in the Angolan catchment area, and (4) hydrological changes due to global warming. The first two induced changes differ from the other two as they do not involve direct modifications of the catchment area. In order to evaluate their impact, it is therefore sufficient to simulate the hydrology of the Okavango Delta with altered inflows. The two other induced changes necessitate a model of the whole catchment because of the altered relation between precipitation and runoff and the changes in precipitation and temperature respectively.

Impacts of scenarios which can be simulated locally without a basin model, of the categories 1 and 2 defined above, were already analyzed by means of the ETH Zurich model (Bauer 2004; Bauer et al. 2006a). Diverse scenarios of surface water and groundwater abstractions were simulated and it was found that the influence of domestic abstractions is negligible even when considering water needs for the entire basin and population growth as projected for 2025. Estimated possible abstractions of 5 million m^3/day for irrigated agriculture are by one order of magnitude larger than domestic water needs. Abstractions of this magnitude are found to have a significant impact on the flooded area, especially in peripheral areas. A decrease in the inflow leads to an even larger decrease in the flooded area. In the simulated 20-year time series, the main impact was on the frequency of occurrence of flood events with small flooded areas. The flooded areas of less than 3,000 km^2 increased eight-fold. This means an increase of areas which are flooded less frequently and thus prone to a shift of vegetation from pure grassland to bushland. For a dam proposed for the site of Popa Falls, but never built, with a reservoir volume of 10^7 m^3, virtually no influence on the flooding of the Delta was found. However, larger hypothetical dams in Angola led to a damping of the strongly seasonal inflow and spatial changes of the flooded area. Upstream seasonal swamps were decreased in size, whereas downstream seasonal swamps were increased. This occurred because the lower inflow peaks led to less flooding in the upper Delta, and the higher baseflow caused by dam releases led to larger transfers of water to the lower Delta. Still, the impact of dams is less than the impact of projected agricultural abstractions. Dredging of a specific channel—the Nqoga—is found to impact not only downstream regions of that channel, but through backwater effects it also influences the water distribution at the scale of the entire Delta.

In 2003, a hydrological model for the catchment, the adapted Pitman precipitation-runoff model as presented in the section The upstream catchment area was developed. The outflow of the catchment at Mohembo simulated with this model under various climate change and land-use scenarios has been used as input to all three distributed models of the wetlands. The approaches chosen for the three models are similar. Model outputs under present conditions are compared to model outputs under changed but stationary conditions derived from local, regional or global development scenarios (e.g. dredging, water abstractions, or climate change respectively). The impacts of the different induced changes are simulated separately in order to assess the individual impacts. Of course the simulation of combined effects is equally feasible and is carried out to a certain extent but is less instructive given model and scenario uncertainties.

The ODMP Integrated Hydrologic Model developed by DHI has been applied for scenarios corresponding to hypothetical conditions for 2025 (Scanagri 2006a), based on climate change and development predictions. Modified input time series are created according to the scenarios and starting with past sequences of relatively wet years and of relatively dry years separately. As in Bauer (2004), possible future dams in Angola were not found to have a major impact on hydrologic conditions in the Delta. The impact of projected irrigation (a yearly abstraction of about 700 million m^3 with most abstractions between June and October, corresponding to about 7% of the yearly river flow) was found to be significant and has the potential to decrease the area of the permanent swamp by 40% for dry years and by 20% for average years. Similar values have been proposed by Bauer et al. (2006a) with a 20% decrease of the permanent swamp for the same decrease in inflow, but homogenously spread over the year. Similar to earlier work, the model shows that local abstractions of surface water and groundwater in the Delta region have only minimal consequences. The impact of climate change was found to be by far the most significant. Projected scenarios assume a warming of 2.2°C, a 9% decrease of precipitation, and a 38% reduction of inflow. Assuming these climate changes, the model predicted a decrease of the permanent swamp area by 68%. The clearing of blockages in the Maunachira and Santantadibe channels (see Fig. 1) was simulated by decreasing the flow resistance parameters for the associated model reaches. The observed impact was a local shift of flooded areas towards the downstream direction, as well as a doubling of the outflow from the wetlands. Deforestation in the catchment is the only induced change which increases the water availability in the Okavango Delta. Its impact on the permanent swamp area can be an increase of around 10% in dry as well as normal years. Besides the impact on minimum and maximum areas, the impact on classes with intermediate flooding frequency is also shown. This is important because many of the ecosystem types of the wetlands rely on a certain frequency of flooding.

The hybrid reservoir-GIS model by Wolski et al. (2006) was applied by Murray-Hudson et al. (2006) to study the impact of climate change and development scenarios in the catchment area. The strategy is similar to the one adopted for the DHI model. Seven functional classes ranging from permanent floodplain to dryland were defined based on inundation frequency and related to vegetation communities. Development scenarios consisting of different degrees of water abstractions, damming and deforestation in the catchment were considered. The impact of climate change was evaluated in more detail with data from three general circulation models (HadCM3, CCC and GLFD) for two greenhouse gas emission scenarios (A2 and B2) and for the periods from 2020 to

DOI 10.1007/s10040-009-0436-0

2050 and from 2050 to 2080. Also, the differences in climate change for the catchment area and the Delta area were considered separately for each of the scenarios because they differed in tendency and amount. Baseline time series of wet and dry sequences of years were used to generate the modified inputs. From the model outputs, the size and distribution of the functional classes were extracted and compared to the baseline model run. The impact of water abstractions was found to be significant for high abstraction rates only. This is consistent with the results of the ETH Zurich and DHI models. The lower water availability resulted in a shifting of the functional classes. The permanent floodplain diminished in size, the dryland area increased, whereas intermediate classes were barely affected. Deforestation led to the opposite effect: a shifting of classes by an increase of the permanent swamp. The damped flow resulting from damming was also found to impact the flooding of the wetlands: the permanent swamp area increased in the dry period and diminished in the wet period. The natural variability is thus reduced by dams and strong repercussions on ecosystems are to be expected. The wide range of projected conditions in the climate change scenarios led to possible changes ranging from drier to wetter conditions in the Delta. Hardly any firm conclusion was possible given the discrepancy of projected climate conditions. Climatic uncertainty leads to a range of possible impacts which is much broader than the magnitude of the impact of development in the catchment.

The third model used to estimate climate impacts on flooding patterns is the MODFLOW 2000 based model by Milzow et al. (2008b). Burg (2007) used this model in combination with results from five general circulation models (CSIRO, HadCM3, CCC, GFDL and CCSR) and a combined development scenario for the period 2050–2080 and 2070–2100. The baseline period chosen was from 1960 to 1990. Unlike in the study by Murray-Hudson et al. (2006), for each scenario, the changes in climate over the Delta region were assumed identical to those over the catchment area. Of the five circulation models, the CSIRO model was the only one to project wetter conditions, the four others models predicting drier conditions. In order to establish the connection between simulated hydrology and status of the ecosystems, the correlation between model output of the unchanged baseline period and vegetation classifications was analysed. A surprisingly good correlation was found between the simulated depth to groundwater and the classification into 12 ecoregions by McCarthy et al. (2005), while the flooding frequency was not well correlated to the ecoregions. Ecoregions were then linked in a probabilistic approach to depths to groundwater. Similarly to the results from Murray-Hudson et al. (2006), drier future conditions resulted in a decrease of the permanent swamp area with a shifting of the other ecoregions. The change in ecoregions due to development in the upstream basin was found to be about 75% less than the change due to climate change.

A common and somewhat disillusioning finding of the three distributed model applications is that the impact of climate change is larger than the impact of probable water abstractions. This puts the options of Okavango water management in the conservation effort around the Okavango Delta into perspective. A challenge also lies in the projected increase of inflow to the wetlands resulting from deforestation. The sensitivity of the basin outflow to deforestation has been shown to be quite strong in the catchment model. However, given the simplified nature of the model, quantitative evaluations must be taken with care. Finally, as demonstrated by the studies of Murray-Hudson et al. (2006) and Burg (2007), the expected effect of climate change in the Okavango region remain uncertain. Murray-Hudson et al. (2006) state clearly that “It is beyond the scope of [their] paper to assess which of the climate models and scenarios for greenhouse gases concentrations are most realistic”. Besides the improvements that can be made in hydrological models, further progress in general circulation models is a prerequisite for successful prediction of the future hydrology of the Okavango Delta.

Salt transport and deposition

The Okavango Delta is the terminal sink of a large river system. Huge quantities of water are consumed by evapotranspiration (Bauer et al. 2006a; Gieske 1997; McCarthy and Ellery 1998). Evapotranspiration has two components: evaporation and transpiration by plants. Evaporation is a fully accumulating process, i.e. all the dissolved solids remain in the residual water. Transpiration partly takes the dissolved solids away with the water uptake and partly leaves them behind, but in the long term, vegetation does not remove salt, it simply stores the salt. For low concentrations, transpiration can also be treated as a fully accumulating process. For a quantitative understanding of freshwater/saltwater dynamics in the Okavango Delta, these eco-hydrological feedback mechanisms are essential (Bauer-Gottwein et al. 2007b; Trapp et al. 2007). However, the surface water salinity is low throughout the system. Highly saline waters only occur in isolated pans and in the shallow alluvial aquifers that surround the Delta. Several studies have focused on the overall system salt balance and on solute transport and deposition mechanisms in the Okavango Delta (Bauer-Gottwein et al. 2007a; Bauer et al. 2004, 2006b; Ellery et al. 1993a; Gieske 1996; Gumbricht et al. 2004; McCarthy and Ellery 1994; McCarthy et al. 1986b, 1991a, 1993a, 1998a).

The available data indicate that the vast majority of solutes entering the Delta are deposited in shallow alluvial aquifers along the fringes of the wetlands. The combined action of evaporation and transpiration by plants seems to be the main driving force of the infiltration process. Phytotoxicity of salt and plant salt uptake are important eco-hydrological feedback mechanisms driving water flow and solute transport in the shallow groundwater. Mineral precipitation removes solutes from the groundwater and accounts for a significant part of the system’s salt balance. In places where evaporative water loss from the shallow groundwater is significant, density-driven vertical flow is locally important. Early studies identified extremely strong local salinity gradients in the Okavango Delta (e.g. McCarthy et al. 1986b, 1991; McCarthy and Metcalfe 1990), based on ground surveys with geoelectrical methods and borehole logging. With the advent of airborne geophysical exploration techniques, regional-scale mapping of the freshwater/saltwater distribution in the system has become feasible and provides fascinating new insights into salt transport and deposition processes at the larger scales (Campbell et al. 2006).

Salinity and water quality have important implications for water resources management in the region (Linn et al. 2003). Exploitable freshwater resources are embedded in a saline environment and pumping strategies need to take the potential mobilisation of saline water into account. Moreover, some components of the salinity are toxic and may prohibit human water use. For instance, Huntsman-Mapila et al. (2006) report elevated arsenic concentrations in many parts of the Okavango shallow groundwater system.

Salt transport and deposition processes on islands

One prototypical freshwater/saltwater system in the Okavango Delta is the island system. Islands occur in the permanent and seasonal parts of the wetlands and form a superficial high salinity anomaly in a generally fresh environment. Okavango islands have been the focus of a number of studies which addressed water flow and salinity transport, mineral deposition, geomorphologic processes, and vegetation dynamics.

A general conceptual model of the Okavango islands is shown in Fig. 17 and is primarily based on the work of T. S. McCarthy and A. Gieske (e.g. McCarthy and Ellery 1994; Gieske 1996). Water flows from the swamp surrounding the island to its centre, thus establishing a concentric flow pattern. Because both evaporation and transpiration leave behind a major part of the dissolved solids in the residual water, the shallow groundwater salinity increases steadily from the island's fringe towards its centre. The vegetation cover reflects the groundwater salinity pattern. Woody species that require a permanent fresh water supply are restricted to the fringes of the island, while more salt tolerant species grow further inland. The island's centre is heavily salinised and therefore plant cover is sparse or absent (Ellery et al. 1993a; McCarthy and Ellery 1994). The solubility limits of various minerals (most importantly carbonates and silica) are exceeded due to consecutive evaporative salt enrichment. In the peripheral zone, mineral precipitation leads to the swelling of soils and to slightly elevated areas. In the island's centre, soils are heavily cemented and hydraulic conductivities are reduced because of mineral precipitation (McCarthy et al. 1991a, 1993a; McCarthy and Metcalfe 1990). It has been shown that Okavango swamp water contains significant amounts of humic acids and other dissolved organic matter (Mladenov et al. 2005, 2007). Humic acids may form complexes with metal ions and enhance their solubility (Bauer-Gottwein et al. 2007a).

In the central parts of the island, groundwater salinities rise to values of 20 g/l or more. Since these highly concentrated brines have a greater density than the underlying freshwater, fingering instabilities may transport

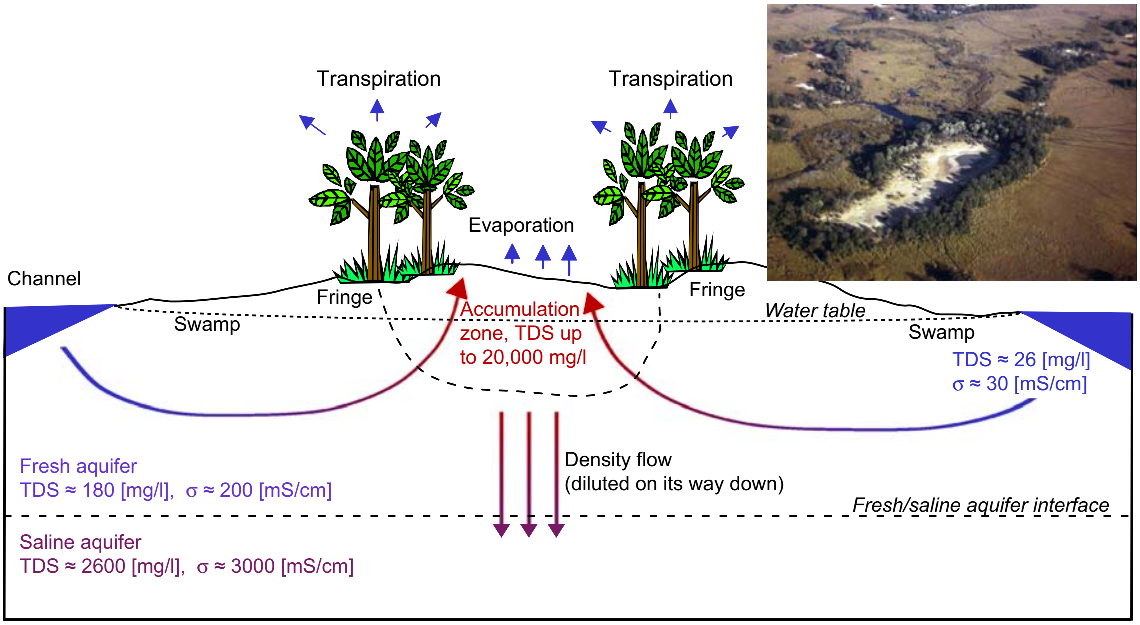

Fig. 17 Conceptual model of a salt accumulating island and photo of such an island in the Delta. The *arrows* indicate movement of water and water vapour, where *blue colour* indicates freshwater and red saline water. σ is the electrical conductivity, and TDS is the concentration of total dissolved solids (modified after Bauer et al. 2006c)

the superficial brines into deeper aquifer units against the vertically upward flow driven by evapotranspiration (Gieske 1996; Zimmermann et al. 2006). Density driven flow phenomena have been directly observed on one island using non-invasive geophysical imaging techniques (Bauer et al. 2006b). Upcoming airborne electromagnetic mapping campaigns will show whether this phenomenon is observable on other islands, and will elucidate its importance for the regional-scale system salt balance.

Peripheral freshwater lenses

In the periphery of the Okavango Delta, the environment is generally saline as confirmed by both sparse groundwater samples taken from boreholes and regional airborne electromagnetic data (Campbell et al. 2006; McCarthy et al. 1998a). The regional airborne electromagnetic (AEM) data show that freshwater anomalies in this generally saline region perfectly correlate with ephemeral streams and rivers being recharged by the wetlands of the Okavango Delta. The freshwater lenses around the streams are important for water supply (Linn et al. 2003; Thangarajan et al. 2000) and the hydrology is driven by the feedback mechanisms between plant transpiration and salt accumulation.

Infiltration from the ephemeral rivers into the shallow aquifers is driven by head differences and lateral hydraulic gradients. Lateral hydraulic gradients are primarily established by evapotranspiration. The locations of the freshwater lenses mapped by AEM methods coincide well with the occurrence of dense riparian woodlands as mapped with remote sensing methods (Ringrose 2003). However, phreatic transpiration by riparian woodlands (which is the dominant process in these systems due to relatively large depths to groundwater) is limited by deteriorating water quality, and decreases to zero in the highly saline "interfluve" areas. Simulation and quantitative analysis of these systems thus requires a coupled simulation approach to water flow and salinity transport (Bauer et al. 2006b). Model simulations show that freshwater infiltrates into the shallow aquifer and is successively depleted as it flows from the river towards the interfluve areas. Residual salinity is deposited where the transpiration flux decreases to zero, producing sharp interfaces between the saline and the fresh part of the domain. This is in good agreement with the freshwate/saltwater patterns observed in the AEM data (Fig. 18).

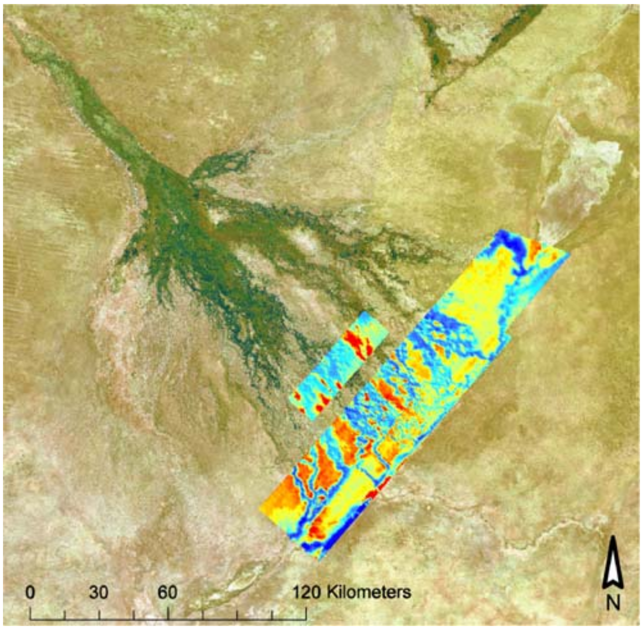

Fig. 18 Airborne electromagnetic (AEM) map superimposed on Landsat view of the Okavango Delta. *Red and yellow tones* correspond to high electrical conductivity and therefore high salinity, while *blue and green tones* represent the low electric conductivity of fresh water. AEM data by Campbell et al. (2006)

Water quality

At present, there are no significant water-quality problems in the Okavango Delta. Nutrient concentrations in the inflow are at near-natural levels and anthropogenic contamination is practically absent. However, with continued economic development in the Delta's catchment, the quality of the inflowing water is likely to be impaired. Eutrophication and contamination with wastewaters (e.g. from mining operations) are among the most significant threats to the Delta's ecological integrity. The existing spatially distributed hydrological models can be extended to simulate the transport and fate of various contaminants and chemical species. Standard packages for advective-dispersive reactive transport simulation are available (e.g. MT3DMS, Zheng and Wang 1999) and can be coupled to the available flow models of the Okavango Delta. Such tools would allow for a detailed analysis of the impacts of water pollution, both in the inflow and locally in the Delta. Moreover, coupled flow and transport simulators could be used to model the freshwater/saltwater distribution in the Delta at a regional scale. Results of recent and upcoming airborne electromagnetic mapping campaigns (Campbell et al. 2006) provide a unique opportunity to calibrate and verify such models.

Policy design and decision support

The Okavango River and the Okavango Delta constitute the only reliable permanent freshwater resource in the region of north-western Botswana and north-eastern Namibia. The river and the Delta have therefore been repeatedly targeted as sources of water for various development projects. Over the last century, the perception of the Okavango Delta has changed from a potential source of freshwater in a water scarce region (see McCarthy et al. 1998a for an overview of the various proposed schemes) to an ecosystem that provides valuable goods and services. Several studies have attempted to quantify the different use and non-use values derived from the Okavango Delta wetlands (Mbaiwa 2003, 2005a, b; Mmopelwa 2006; Mmopelwa and Blignaut 2006).

One issue that is still awaiting systematic research is the existence values associated with the Okavango Delta. Being one of the last true wildernesses in southern Africa, the Okavango Delta is expected to have significant existence values for people far beyond the national boundaries of Botswana and even beyond the international tourist community. A recent review of wetland valuation literature found an average total economic value of wetlands of about US$ 100 (in 1995) per hectare per year (Brander et al. 2006). The value of individual wetlands showed a huge variation from less than 10 to more than US$ 10,000 per hectare per year. Assuming a total size of the Okavango Delta of 30,000 km^2, and using the average economic value, the total value of ecosystem goods and services would be US$ 300 million (in 1995) per year, which is equivalent to about 4% of Botswana's gross domestic product (GDP). Monetarising the significant existence values associated with the Okavango Delta will be a key task for managers and decision makers in the region. Studies in other parts of the world have demonstrated that people are willing to pay for global ecosystem and biodiversity preservation (e.g. Kramer and Mercer 1997). Payment schemes will have to be devised in order to monetarise the global willingness to pay for the sustainable use and preservation of the Okavango Delta.

The key task for hydrological models of the system, which emerges in this context, is to help transform modifications in the flow regime into modifications of ecosystem goods and services. Ultimately, decision makers will want to know what effect the construction of an upstream reservoir or an irrigation district is going to have on the wildlife in the Okavango Delta, on the fishing activities, and on the tourism industry. Hydrological models will therefore have to be coupled with ecosystem models and economic models. For example the work by Burg (2007), linking simulated depths to groundwater with vegetation classes, attempts to address both hydrological and ecological issues. An interdisciplinary effort is required to find out how ecosystem state variables depend on hydrological state variables. Decision makers and managers of other wetland systems face similar challenges and early research into the "eco-hydrology" of wetlands has been reported in the literature (e.g. Loucks 2006).

Obviously, hydrological models will have to be set up and operated over a range of scales in order to address the various practical questions arising in the day-to-day management of the system. Optimisation of freshwater extraction from local freshwater lenses for the water supply of Maun will require detailed three-dimensional coupled flow and salinity transport models, whereas questions of climate change and large-scale water abstraction require a catchment-scale water balance modelling approach. The Okavango Delta Management Plan (ODMP) project was the first systematic attempt to collect all relevant scientific knowledge and data and to set up procedures for the long-term management of the Okavango Delta. The purpose of the ODMP is to "integrate resource management for the Okavango Delta that will ensure its long-term conservation and that will provide benefits for the present and future well being of the people, through sustainable use of its natural resources" (Government of Botswana 2007).

However, the most crucial issue for the sustainable management of the Okavango River system and the Okavango Delta is the trans-boundary nature of the water-resources system. The ODMP recognises this problem, but in the absence of significant stakeholder involvement from Namibia and Angola, no concrete actions have been proposed. There is no doubt that increased development activities in upstream Angola will have significant impacts on the flow regime and water quality in the Okavango River. In a way, the almost pristine state of the Okavango River system is a direct consequence of decades of civil war in the Angolan parts of the catchment, which were under the control of the UNITA (União Nacional para a Independência Total de Angola) rebels. After the death of Jonas Savimbi in 2002 and the subsequent disarmament of the UNITA, development prospects in this part of Angola have significantly improved.

Benefits derived from ecosystem goods and services in the Okavango Delta should be equitably shared between Botswana, Namibia and Angola. In the absence of such a benefit-sharing agreement, Namibia and Angola will have no incentive to contribute to the preservation of a next-to-natural flow regime and water quality in the Okavango River. The sharing of benefits is made difficult by the fact that the opportunity cost for the upstream seems larger than the direct use value of the downstream. According to L. Petersen, ETH Zurich (unpublished data, 2007) Botswana has an estimated income of US$ 176 million per year from tourism to the Delta. The value of a previously planned water abstraction for Windhoek, Namibia amounts to about US$ 37 million per year in water fees. Agricultural water abstractions in Angola may lead to foreign exchange savings by maize production of as much as US$ 49 million. Further, only US$ 90 million of the US$ 176 M revenue from tourism in Botswana go into the fiscal resources of Botswana, while almost half leaves the country as revenue to foreign investors. A possible solution requires funds from the outside world and/or embedding of the water issue into other tripartite issues which would as a package lead to a satisfactory solution with regard to the conservation of the Delta. Funds from the outside for the service of saving the Okavango wetlands would not be illogical, as the conservation of biodiversity is a benefit for and service to the global community.

The challenge for sustainable water resources management in the Okavango River Basin is still huge. The worst outcome for the Delta regarding water quantity would be if the most probably negative impact by climate change coincides with maximum abstractions for agriculture. Water quality changes associated with agriculture and other development would increase the pressure on water resources. The contribution hydrological models could

DOI 10.1007/s10040-009-0436-0

make towards better solutions to the water allocation problem is to provide transparent trade-off information and scenario simulations.

Acknowledgements This research has been supported financially by the Swiss National Science Foundation under project no. 200021-105384. The authors are thankful to P. Brunner, T. S. McCarthy, D. Molnar, and T. Siegfried for their thorough review of the manuscript as well as to E. Holzbecher, J. Wilk, P. Renard, and an anonymous editor for their reviewing work.

References

Adler R, Braun S, Stocker E, Marius J (2007) Tropical Rainfall Measuring Mission, TRMM, Senior Review Proposal. Laboratory for Atmospheres, NASA Goddard Space Flight Centre, Greenbelt, MD, USA

Andersson L, Gumbricht T, Hughe D, Kniveton D, Ringrose S, Savenije H, Todd M, Wilk J, Wolski P (2003) Water flow dynamics in the Okavango River Basin and Delta: a prerequisite for the ecosystems of the Delta. Phys Chem Earth 28:1165–1172

Andersson L, Wilk J, Todd MC, Hughes DA, Earle A, Kniveton D, Layberry R, Savenije HHG (2006) Impact of climate change and development scenarios on flow patterns in the Okavango River. J Hydrol 331:43–57

Ashton P, Neal M (2003) An overview of key strategic issues in the Okavango Basin. In: Turton A, Ashton P, Cloete E (eds) Transboundary rivers, sovereignty and development: hydropolitical drivers in the Okavango River Basin. African Water Issues Research Unit and Green Cross International, Pretoria, South Africa

Atekwana AB, Hogan JP, Kampunzu AB, Modise MP (2003) Early structural evolution of the nascent Okavango Rift Zone, N.W. Botswana. East African Rift System Conference, Addis Ababa, Ethopia, June 2004

Bartholomé E, Belward AS (2005) GLC2000: a new approach to global land cover mapping from Earth observation data. Int J Rem Sens 26(9):1959–1977

Bartsch A, Scipal K, Wolski P, Pathe C, Sabel D, Wagner W (2006) Microwave remote sensing of hydrology in southern Africa. The 2nd Göttingen GIS and Remote Sensing Days: Global Change Issues in Developing and Emerging Countries, Göttingen, Germany, 4–6 October 2006

Bartsch A, Pegram G, Sinclair S, Vishel T, Pathe C, Sabel D, Doubkova M, Bartalis Z, Scheffler C, Wagner W, Scipal K (2007) SHARE: validation, evaluation and evolution document. Contract No. 19420/05/I-EC, ESRIN, Frascati, Italy

Bauer P (2004) Flooding and salt transport in the Okavango Delta: key issues for sustainable wetland management. Diss. No. 15436, ETH Zürich, Switzerland

Bauer P, Thabeng G, Stauffer F, Kinzelbach W (2004) Estimation of the evapotranspiration rate from diurnal groundwater level fluctuations in the Okavango Delta, Botswana. J Hydrol 288:344–355

Bauer P, Gumbricht T, Kinzelbach W (2006a) A regional coupled surface water/groundwater model of the Okavango Delta, Botswana. Water Resour Res 42, W04403. doi:10.1029/2005WR004234

Bauer P, Held R, Zimmermann S, Linn F, Kinzelbach W (2006b) Coupled flow and salinity transport modelling in semi-arid environments: the Shashe River Valley, Botswana. J Hydrol 316 (1–4):163–183

Bauer P, Supper R, Zimmermann S, Kinzelbach W (2006c) Geoelectrical imaging of groundwater salinization in the Okavango Delta, Botswana. J Appl Geophys 60:126–141

Bauer-Gottwein P, Langer T, Prommer H, Wolski P, Kinzelbach W (2007a) Okavango Delta Islands: interaction between density-driven flow and geochemical reactions under evapo-concentration. J Hydrol 335:389–405

Bauer-Gottwein P, Rasmussen NF, Feificova D, Trapp S (2007b) Phytotoxicity of salt and plant salt uptake: modeling ecohydrological feedback mechanisms. Water Resour Res 44, W04418. doi:10.1029/2007WR006067

Boring M, Björkvald L (1999) A minor field study of the infiltration rate on a floodplain in the Okavango Delta, Botswana. Research report. Göteborg University, Sweden and Harry Oppenheimer Okavango Research Centre, University of Botswana, Gaborone, Botswana

Brander LM, Florax R, Vermaat JE (2006) The empirics of wetland valuation: a comprehensive summary and a meta-analysis of the literature. Environ Resour Econ 33:223–250

Brunner P, Bauer P, Eugster M, Kinzelbach W (2004) Using remote sensing to regionalize local precipitation recharge rates obtained from the Chloride Method. J Hydrol 294:241–250

Brunner P, Hendricks Franssen HJ, Kgotlhang L, Bauer-Gottwein P, Kinzelbach W (2007) How can remote sensing contribute to groundwater modelling? Hydrogeol J 15(1):5–18

Burg V (2007) Climate change affecting the Okavango Delta. MSc Thesis,ETH, Eidgenössische Technische Hochschule Zürich, Switzerland. http://e-collection.ethbib.ethz.ch/show?type=dipl&nr=338. Cited 27 November 2007

Campbell G, Johnson S, Bakaya T, Kumar H, Nsatsi J (2006) Airborne geophysical mapping of aquifer water quality and structural controls in the Lower Okavango Delta, Botswana. S Afr J Geol 109:475–494

Dangerfield JM, McCarthy TS, Ellery WN (1998) The mound-building termite *Macrotermes michaelseni* as an ecosystem engineer. J Trop Ecol 14:507–520

Department of Water Affairs (2004) Maun Groundwater Development Project: phase 2, resources ssesment and aellfield xevelopment. TB 10/3/5/2000–2001. Final report volume 1, main report. Ministry of Minerals Energy and Water Resources, Gaborone, Botswana

Dincer T (1985) The development of a mathematical model of the Okavango Delta: phase 2 report. Department of Water Affairs, Gaborone, Botswana

Dincer T, Heemmsra HH, Kraatz DB (1976) The study of hydrological conditions in an experimental area in the seasonal swamp. Tech. note No. 20, UNDP FAO, BOT/71/506, FAO, Rome

Dincer T, Hutton LG, Kupee BBJ (1978) Study, using stable isotopes, of flow distribution, surface-groundwater relations and evapotranspiration in the Okavango Swamp, Botswana. STI/PUB/493, IAEA Symposium on Isotope Hydrology, IAEA, Neuherberg, Germany, pp 3–26

Dincer T, Child S, Khupe B (1987) A simple mathematical model of a complex hydrological system: Okavango Swamp, Botswana. J Hydrol 93:41–65

Diniz AC, Aguiar FP (1973) Recursos em terras com aptidão para o regadio da bacia do Cubango [Land evaluation to assess the irrigation suitability in the Cubango Basin region], Série Técnica, no. 33, Instituto de Investigação Agronómica de Angola, Nova Lisboa, Angola, 1973, 27 pp

Ellery WN, McCarthy TS (1998) Environmental change over two decades since dredging and excavation of the lower Boro River, Okavango Delta, Botswana. J Biogeogr 25:361–378

Ellery WN, Ellery K, McCarthy TS, Cairncross B, Oelofse R (1989) A peat fire in the Okavango Delta, Botswana, and its importance as an ecosystem process. Afr J Ecol 27:7–21

Ellery WN, Ellery K, McCarthy TS (1993a) Plant-distribution in islands of the Okavango Delta, Botswana: determinants and feedback interactions. Afr J Ecol 31:118–134

Ellery WN, Ellery K, Rogers KH, McCarthy TS, Walker BH (1993b) Vegetation, hydrology and sedimentation processes as determinants of channel form and dynamics in the northeastern Okavango Delta, Botswana. Afr J Ecol 31:10–25

EuDASM (2005) The soil maps of Africa. European Digital Archive of Soil Maps. http://eusoils.jrc.it/esdb_archive/EuDASM/Africa. Cited 29 October 2008

FAO (1990) A soil map of the Republic of Botswana. Soil Mapping and Advisory Services Project, AG:DP/BOT/85/011 FAO, UNDP, Ministry of Agriculture, Gaborone, Botswana

FAO (1992) The digitized soil map of the world: notes, world soil resources report 67(2–7), Release 1.1, FAO, Rome, 32 pp

Farr TG et al (2007) The shuttle radar topography mission. Rev Geophys 45:RG2004. http://www2.jpl.nasa.gov/srtm/. Cited 27 November 2007. doi:10.1029/2005RG000183

Garstang M, Ellery WN, McCarthy TS, Scholes MC, Scholes RJ, Swap RJ, Tyson PD (1998) The contribution of aerosol- and water-borne nutrients to the functioning of the Okavango Delta ecosystem, Botswana. S Afr J Sci 94:223–229

Gieske A (1992) Dynamics of groundwater recharge: a case study in semi-arid eastern Botswana. PhD Thesis, Free University of Amsterdam, The Netherlands

Gieske A (1996) Vegetation driven groundwater recharge below the Okavango Delta (Botswana) as a solute sink mechanism: an indicative model. Botsw J Earth Sci 3:33–37

Gieske A (1997) Modelling outflow from the Jao/Boro river system in the Okavango delta, Botswana. J Hydrol 193:214–239

Government of Botswana (2007) Okavango Delta Management Plan Project: Draft final Okavango Delta Management Plan, Department of Environmental Affairs, Gaborone, Botswana

Gumbricht T, McCarthy TS, Merry CL (2001) The topography of the Okavango Delta, Botswana and its tectonic and sedimentological implications. S Afr J Geol 104:243–263

Gumbricht T, McCarthy J, McCarthy TS (2004) Channels, wetlands and islands in the Okavango Delta, Botswana, and their relation to hydrological and sedimentological processes. Earth Surf Process Landf 29:15–29

Gumbricht T, McCarthy TS, Bauer P (2005) The micro-topography of the wetlands of the Okavango Delta, Botswana. Earth Surf Process Landf 30:27–39

Harbaugh AW, Banta ER, Hill MC, McDonald MG (2000) MODFLOW-2000, the US Geological Survey modular ground-water model: user guide to modularization concepts and the ground-water flow process. US Geol Surv Open-File Rep 00–92, 121 pp

Heinl M, Neuenschwander A, Sliva J, Vanderpost C (2006) Interactions between fire and flooding in a southern African floodplain system (Okavango Delta, Botswana). Lands Ecol 21:699–709

Herman A, Kumar VB, Arkin PA, Kousky JV (1997) Objectively determined 10-day African rainfall estimates created for famine early warning systems. Int J Rem Sens 18:2147–2159

Huffman GJ, Adler RF, Bolvin DT, Gu GJ, Nelkin EJ, Bowman KP, Hong Y, Stocker EF, Wolff DB (2007) The TRMM multi-satellite precipitation analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. J Hydrometeorol 8:38–55

Hughes DA (2004) Incorporating groundwater recharge and discharge functions into an existing monthly rainfall-runoff model. Hydrol Sci J 49:297–311

Hughes DA, Andersson L, Wilk J, Savenije HHG (2006) Regional calibration of the Pitman model for the Okavango River. J Hydrol 331:30–42

Huntsman-Mapila P, Mapila T, Letshwenyo M, Wolski P, Hemond C (2006) Characterization of arsenic occurrence in the water and sediments of the Okavango Delta, NW Botswana. Appl Geochem 21:1376–1391

Hutchins DG, Hutton SM, Jones CR, Loernhert EP (1976) A summary of the geology, seismicity, geomorphology and hydrogeology of the Okavango Delta, Department of Geological Surveys, Gaborone, Botswana

Jacobsen T, Macdonald A, Enggrob H (2005) Okavango Delta Management Plan, Hydrology and Water Resources, Integrated Hydrologic Model, Technical report, DHI Water and Environment, Hørsholm, Denmark

JVC (1993) Central Area water master plan: phase 1, vol 3: water demand. Report No. DIR/1/93/3, Department of Water Affairs, Windhoek, Nambia, 121 pp

Kampunzu AB, Akanyang P, Mapeo RBM, Modie BN, Wendorff M (1998) Geochemistry and tectonic significance of the Mesoproterozoic Kgwebe metavolcanic rocks in the northwest Botswana: implications for the evolution of the Kibaran Namaqua-Natal Belt. Geol Mag 135(5):669–683

Krah M, McCarthy TS, Annegarn H, Ramberg L (2004) Airborne dust deposition in the Okavango Delta, Botswana, and its impact on landforms. Earth Surf Process Landf 29:565–577

Kramer RA, Mercer DE (1997) Valuing a global environmental good: US residents' willingness to pay to protect tropical rain forests. Land Econ 73:196–210

Lancaster IN (1979) Evidence for a widespread late Pleistocene humid period in the Kalahari. Nat 279:145–146

Linn F, Masie M, Rana A (2003) The impacts on groundwater development on shallow aquifers in the lower Okavango Delta, northwestern Botswana. Environ Geol 44:112–118

Loucks DP (2006) Modeling and managing the interactions between hydrology, ecology and economics. J Hydrol 328:408–416

Mazor E, Verhagen BT, Sellschop JPF, Jones MT, Robins NE, Hutton L, Jennings CMH (1977) Northern Kalahari groundwaters: hydrologic, istopic and chemical studies at Orapa, Botswana. J Hydrol 34:203–234

Mazvimavi D, Wolski P (2006) Long-term variations of annual flows of the Okavango and Zambezi rivers. Phys Chem Earth 31:944–951

Mbaiwa JE (2003) The socio-economic and environmental impacts of tourism development on the Okavango Delta, north-western Botswana. J Arid Environ 54:447–467

Mbaiwa JE (2005a) Enclave tourism and its socio-economic impacts in the Okavango Delta, Botswana. Tour Manage 26:157–172

Mbaiwa JE (2005b) Wildlife resource utilisation at Moremi Game Reserve and Khwai community area in the Okavango Delta, Botswana. J Environ Manage 77:144–156

McCarthy TS (1992) Physical and biological processes controlling the Okavango Delta: a review of recent research. Botsw Notes Rec 24:57–86

McCarthy TS (2006) Groundwater in the wetlands of the Okavango Delta and its contribution to the structure and function of the ecosystem. J Hydrol 320:264–282

McCarthy TS, Ellery WN (1994) The effect of vegetation on soil and ground water chemistry and hydrology of islands in the seasonal swamps of the Okavango Fan, Botswana. J Hydrol 154:169–193

McCarthy TS, Ellery WN (1995) Sedimentation on the distal reaches of the Okavango Fan, Botswana, and its bearing on calcrete and silcrete (ganister) formation. J Sediment Res A65:77–90

McCarthy TS, Ellery WN (1998) The Okavango Delta. Trans R Soc S Afr 53:157–182

McCarthy TS, Metcalfe J (1990) Chemical sedimentation in the semi-arid environment of the Okavango Delta, Botswana. Chem Geol 89:157–178

McCarthy TS, Ellery WN, Rogers KH, Cairnscross B, Ellery K (1986a) The roles of sedimentation and plant growth in changing flow patterns in the Okavango Delta, Botswana. S Afr J Sci 82:579–584

McCarthy TS, McIver JR, Cairncross B (1986b) Carbonate Accumulation on Islands in the Okavango Delta, Botswana. S Afr J Sci 82:588–591

McCarthy TS, Stanistreet IG, Cairncross B, Ellery WN, Ellery K, Oelofse R, Grobicki TS (1988) Incremental aggradation of the Okavango Delta. Geomorphology 1:267–278

McCarthy TS, McIver JR, Verhagen BT (1991a) Groundwater evolution, chemical sedimentation and carbonate brine formation on an island in the Okavango Delta swamp, Botswana. Appl Geochem 6:577–595

McCarthy TS, Stanistreet IG, Cairncross B (1991b) The sedimentary dynamics of active fluvial channels on the Okavango fan, Botswana. Sedimentology 38:471–187

McCarthy TS, Ellery WN, Stanistreet IG (1992) Avulsion mechanisms on the Okavango fan, Botswana: the control of a fluvial system by vegetation. Sedimentology 39:779–795

McCarthy TS, Ellery WN, Ellery K (1993a) Vegetation-induced, subsurface precipitation of carbonate as an aggradational process in the permanent swamps of the Okavango Delta. Chem Geol 107:111–131

McCarthy TS, Green RW, Franey NJ (1993b) The influence of neo-tectonics on water dispersal in the northeastern regions of the Okavango Swamps, Botswana. J Afr Earth Sci 17:23–32

McCarthy TS, Barry M, Bloem A, Ellery WN, Heister H, Merry CL, Ruther H, Sternberg H (1997) The gradient of the Okavango Fan, Botswana, and its sedimentologic and tectonic implications. J Afr Earth Sci 24(1/2):65–78

McCarthy TS, Bloem A, Larkin PA (1998a) Observations on the hydrology and geohydrology of the Okavango Delta. S Afr J Geol 101(2):101–117

McCarthy TS, Ellery WN, Bloem A (1998b) Some observations on the geomorphological impact of hippopotamus (*Hippopotamus amphibius* L.) in the Okavango Delta, Botswana. Afr J Ecol 36:44–56

McCarthy TS, Ellery WN, Dangerfield JM (1998c) The role of biota in the initiation and growth of islands on the floodplain of the Okavango alluvial fan, Botswana. Earth Surf Process Landf 23:291–316

McCarthy TS, Cooper GRJ, Tyson PD, Ellery WN (2000) Seasonal flooding in the Okavango Delta, Botswana: recent history and future prospects. S Afr J Sci 96:25–33

McCarthy JM, Gumbricht T, McCarthy T, Frost P, Wessels K, Seidel F (2003) Flooding patterns of the Okavango wetland in Botswana between 1972 and 2000. Ambio 32(7):453–457

McCarthy J, Gumbricht T, McCarthy TS (2005) Ecoregion classification in the Okavango Delta, Botswana from multi-temporal remote sensing. Int J Rem Sens 26:4339–4357

McConnell RB (1959) Notes on the geology and geomorphology of the Bechuanaland Protectorate. XX Cong. Geol. Int., 1956. Assoc. Serv. Geol. Afr., Nairobi, Kenya, pp 175-186

Meier P (2006) Identifizierung der Überflutungsmuster im Okavango-Delta mittels ASAR-Satellitenbildern [Identification of flooding patterns of the Okavango Delta using ASAR satellite imagery]. MSc Thesis, ETH Zürich, Institute of Environmental Engineering, http://e-collection.ethbib.ethz.ch/show?type=dipl&nr=274. Cited 28 January 2009

Milzow C, Kgotlhang L, Burg V, Kinzelbach W (2008a) Setup and calibration of a distributed hydrological model of the Okavango Delta using remote sensing data. Proceedings of the Model-CARE 2007 Conference, Denmark, IAHS Publ. 320, IAHS, Wallingford, UK, pp 169–175

Milzow C, Kgotlhang L, Kinzelbach W, Meier P, Bauer-Gottwein P (2008b) The role of remote sensing in hydrological modelling of the Okavango Delta, Botswana. J Environ Manage. doi: 10.1016/j.jenvman.2007.06.032

Mladenov N, McKnight DM, Wolski P, Ramberg L (2005) Effects of annual flooding on dissolved organic carbon dynamics within a pristine wetland, the Okavango Delta, Botswana. Wetlands 25 (3):622–638

Mladenov N, McKnight DM, Wolski P, Murray-Hudson M (2007) Simulation of DOM fluxes in a seasonal floodplain of the Okavango Delta, Botswana. Ecolog Model 205:181–195

Mmopelwa G (2006) Economic and financial analysis of harvesting and utilization of river reed in the Okavango Delta, Botswana. J Environ Manage 79:329–335

Mmopelwa G, Blignaut JN (2006) The Okavango Delta: the value of tourism. S Afr J Econ Manage Sci 9:113–127

Modisi MP, Atekwana EA, Kampunzu AB, Ngwisanyi TH (2000) Rift kinematics during the incipient stages of continental extension: evidence from the nascent Okavango rift basin, northwest Botswana. Geol 28:939–942

Murray-Hudson M, Wolski P, Ringrose S (2006) Scenarios of the impact of local and upstream changes in climate and water use on hydro-ecology in the Okavango Delta, Botswana. J Hydrol 331:73–84

NamPower (2003) Pre-feasibility Study for the Popa Falls Hydro Power Project, preliminary environmental assessment. Executive summary. http://www.nampower.com.na/docs/Executive%20Summary1.pdf. Cited 28 January 2009

NCDC (2008) National Climatic Climate Centre of the U.S. Department of Commerce. http://www.ncdc.noaa.gov. Cited 01 September 2008

Neuenschwander AL, Crawford MM, Ringrose S (2002) Monitoring of seasonal flooding in the Okavango Delta using EO-1 Data. Proceedings of the 2002 International Geoscience and Remote Sensing Symposium, Toronto, June 2002

Neuenschwander AL, Crawford MM, Ringrose S (2005) Results of the earth observing-1 Advanced Land Imager (ALI) data to assess vegetational response to flooding in the Okavango Delta, Botswana. Int J Rem Sens 26(19):4321–4337

Obakeng OT, Gieske ASM (1997) Hydraulic conductivity and transmissivity of a water-table aquifer in the Boro River system, Okavango Delta. Lobatse, Botswana Geological Survey Department, Botswana Geological Survey Department bulletin series 46, Botswana Geological Survey Department, Gaborone, 69 pp

Pallett J (1997) Sharing water in southern Africa. Desert Research Foundation Namibia, Windhoek, Nambia, 121 pp

Passchier CW, Trouw RAJ, Ribeiro A, Paciullo FVP (2002) Tectonic evolution of the southern Kaoko belt, Namibia. J Afr Earth Sci 35:61–75

Persits F, Ahlbrandt T, Tuttle M, Charpentier R, Brownfield M, Takahashi K (2002) Map showing geology, oil and gas fields, and geological provinces of Africa, Ver. 2.0. US Geol Surv Open-File Rep 97–470A. http://pubs.usgs.gov/of/1997/ofr-97-470/OF97-470A/. Cited 27 November 2007

Pike JG (1970) Iterim tecnical notes on the hydrology and water resourses of the Okavango River system. Surveys and training for the developmentof water resources and agricultural production, Botswana. Technical note no. 5, UNDP, FAO, Government of Botswana, Gaborone

Pinheiro I, Gabaake G, Heyns P (2003) Cooperation in the Okavango River basin: the OKACOM perspective. In: Turton A, Ashton P, Cloete E (eds) Transboundary rivers, sovereignty and development: hydropolitical drivers in the Okavango River Basin. African Water Issues Research Unit & Green Cross International, Pretoria, South Africa

Pitman WV (1973) A mathematical model for monthly river flows from meteorological data in South Africa. Report No. 2/73, Department of Civil Engineering, Hydrological Research Unit, Report No. 2/73, University of the Witwatersrand, Johannesburg

RAISON, Research and Information Services of Namibia (2004) Sharing water: towards a transboundary consensus on the management of the Okavango/Cubango River Basin. Natural Heritage Institute, San Francisco. Data previously available at http://www.sharingwater.net (site currently unavailable). Data availability in future will be identical and/or via http://www.orc.ub.bw and/or via http://www.okacom.org (C. VanderPost, Harry Oppenheimer Okavango Research Centre, personal communication, 2008)

Ramberg L, Wolski P, Krah M (2006a) Water balance and infiltration in a seasonal floodplain in the Okavango Delta, Botswana. Wetlands 26(3):677–690

Ramberg L, Hancock P, Lindholm M, Meyer T, Ringrose S, Sliva J, Van As J, VanderPost C (2006b) Species diversity of the Okavango Delta, Botswana. Aquat Sci 68:310–337

Reeves CV (1972) Rifting in the Kalahari? Nat 237:95–96

Reeves CV (1978) The gravity survey of Ngamiland, 1970–1971, Bulletin 11, Geological Survey of Botswana, Gaborone

Ringrose S (2003) Characterisation of riparian woodlands and their potential water loss in the distal Okavango Delta, Botswana. Appl Geogr 23:281–302

Ringrose S et al (undated report) Results and struggles of the elephant habitat mapping project. Internal report, Harry Oppenheimer Okavango Research Centre, University of Botswana, Maun, Botswana

Rodriguez E, Morris CS, Belz JE, Chapin EC, Martin JM, Daffer W, Hensley S (2005) An assessment of the SRTM topographic products. JPL Publ, D31639, Jet Propulsion Laboratory, Pasadena, CA, 143 pp

Roerink GJ, Su Z, Menenti M (2000) S-SEBI: a simple remote sensing algorithm to estimate the surface energy balance. Phys Chem Earth (B) 25:147–157

Sabel D, Pathe C, Wagner W, Hasenauer S, Bartsch A, Kuenzer C, Scipal K (2007) Using ENVISAT ScanSAR data for characterising scaling properties of scatterometer derived soil moisture information over Southern Africa. ENVISAT & ERS Symposium, Montreux, Switzerland, 23–27 April 2007

Scanagri (2006a) Okavango Delta Management Plan, Hydrology and Water Resources, Analysis of Water Resources Scenarios, Scanagri, Allerød,Denmark

Scanagri (2006b) Okavango Delta Management Plan, Hydrology and Water Resources, Detailed Integrated Hydrologic Model, Scanagri, Allerød,Denmark

Scholtz CH, Koczynski TA, Hutchins DG (1976) Evidence of incipient rifting in southern Africa. Geophys J R Astronom Soc 44:135–144

Scudder T et al (1993) The IUCN review of the southern Okavango integrated water development project. IUCN, Gland, Switzerland, 544 pp

Sefe FTK (1996) A study of the stage-discharge relationship of the Okavango River at Mohembo, Botswana. Hydrol Sci J 41:97–116

Shaw P (1985) Late quaternary landforms and environmental change in Northwest Botswana: the evidence of Lake Ngami and the Mababe depression. Trans Inst Br Geogr, New Series 10:333–346

Shaw P, Nash DJ (1998) Dual mechanisms for the formation of fluvial silcretes in the distal reaches of the Okavango Delta Fan, Botswana. Earth Surf Process Landf 23:705–714

SMEC (1987) Study of open water evaporation in Botswana. Snowy Mountains Engineering Corporation, Ministry of Local Government and Lands, Gaborone, Botswana

Smith ND, McCarthy TS, Ellery WN, Merry CL, Rüther H (1997) Avulsion and Anastomosis in the panhandle region of the Okavango Fan, Botswana. Geomorphology 20:49–65

Swap RJ (1996) Transport and impact of southern African aerosols. PhD Thesis, University of Virginia, USA

Thangarajan M, Masie M, Rana T, Uhl V, Bakaya T, Gabaake GG (2000) Simulation of arid multi-layer aquifer system to evolve optimal management schemes: a case study in Shashe River Valley, Okavango Delta, Botswana. J Geol Soc India 55:623–648

Thomas DSG, Shaw PA (1988) Late Cainozoic drainage evolution in the Zamezi Basin: geomorphological evidence from the Kalahari rim. J Afri Earth Sci 7: 611-618

Thomas DSG, Shaw PA (1991) The Kalahari environment. Cambridge University Press, Cambridge, 284 pp

Tooth S, McCarthy TS (2004) Controls on the transition from meandering to straight channels in the wetlands of the Okavango Delta, Botswana. Earth Surf Process Landf 29:1627–1649

Trapp S, Feificova D, Rasmussen NF, Bauer-Gottwein P (2007) Plant uptake of NaCl in relation to enzyme kinetics and toxic effects. Environ Exp Bot. doi:10.1016/j.envexpbot.2008.05.001

Tyson PD, Garstang M, Swap R (1996) Large-scale recirculation of air over southern Africa. J Appl Met 35:2218–2236

UNDP/FAO (1977) Investigation of the Okavango Delta as a Primary Water Resource for Botswana. UNDP/FAO, DP/BOT/71/506, Government of Botswana, Gaborone

UNESCO (1971) Convention on Wetlands of International Importance Especially as Waterfowl Habitat. Ramsar, Iran, 2 February 1971, UN Treaty Series No. 14583. As amended by the Paris Protocol, 3 December 1982, and Regina Amendments, 28 May 1987

Wagner W, Pathe C, Sabel D, Bartsch A, Kuenzer C, Scipal K (2007) Experimental 1km soil moisture products from ENVISAT ASAR for Southern Africa. ENVISAT & ERS Symposium, Montreux, Switzerland, 23–27 April 2007

Water Resources Consultants (1997) Maun Groundwater Development Project, phase 1: exploration and resource assessment. Department of Water Affairs, Botswana, Gaborone

Water Transfer Consultants (1997) Feasibility study on the Okavango River to Grootfontein link of the Eastern National Water Carrier. Department of Water Affairs, Ministry of Agriculture, Water and Rural Development, Windhoek, Namibia

Wilcox RE, Harding TP, Seeley DR (1973) Basic wrench tectonics. Bull Am Assoc Petrol Geol 57:74–96

Wilk J, Kniveton D, Andersson L, Layberry R, Todd MC, Hughes D, Ringrose S, Vanderpost C (2006) Estimating rainfall and water balance over the Okavango River Basin for hydrological applications. J Hydrol 331:18–29

Wolski P, Murray-Hudson M (2006a) Reconstruction 1989–2005 inundation history in the Okavango Delta from archival Landsat TM imagery. Proceedings of the GlobWetland symposium, Frascati, Italy, 19–20 October 2006

Wolski P, Murray-Hudson M (2006b) Flooding dynamics in a large low-gradient alluvial fan, the Okavango Delta, Botswana, from analysis and interpretation of a 30-year hydrometric record. Hydrol Earth Syst Sci 10:127–137

Wolski P, Murray-Hudson M (2008) An investigation of permanent and transient changes in the flood distribution and outflows in the Okavango Delta, Botswana. Phys Chem Earth 33:157–164

Wolski P, Savenije HHG (2006) Dynamics of floodplain-island groundwater flow in the Okavango Delta, Botswana. J Hydrol 320:283–301

Wolski P, Savenije HHG, Murray-Hudson M, Gumbricht T (2006) Modelling of the flooding in the Okavango Delta, Botswana, using a hybrid reservoir-GIS model. J Hydrol 331:58–72

Xie PP, Arkin PA (1997) Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. Bull Am Meteorol Soc 78:2539–2558

Zheng C, Wang PP (1999) MT3DMS: a modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems. Documentation and user's guide. US Army Corps of Engineers, Washington, DC

Zimmermann S, Bauer P, Held R, Walther J, Kinzelbach W (2006) Salt transport on islands in the Okavango Delta: numerical investigations. Adv Water Resour 29:11–29