

HYDROLOGICAL, GEOMORPHOLOGICAL AND GEOCHEMICAL PROCESSES IN THE OKAVANGO DELTA: WATER RESOURCE MANAGEMENT IMPLICATIONS

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ABSTRACT

The Okavango Delta is an alluvial fan that has been built up by sedimentation into a graben structure connected to the East African Rift Valley. It is supplied with water from the Okavango River, the catchment of which is situated in highlands of Central Angola. The Delta wetland contrasts sharply from its surroundings where rainfall is low, evaporation rates are high and surface water is lacking for most of the year. The river channels are mainly oligotrophic habitats, yet the Okavango Delta is full of plant and animal life. Evapotranspiration leads to concentration of salts under islands, leaving the surface water fresh. This paper discusses the hydrological, geochemical and geomorphological processes of the Okavango Delta in relation to water resource management.

KEY WORDS

Okavango Delta, Hydrology, Geomorphology, Geochemistry, Water Resource Management

1. Introduction

In the past, wetlands were viewed as sinister, forbidding and of little economic value, resulting in their drainage and destruction for agricultural, commercial or residential development [1]. Recently, wetlands have been recognised as important ecosystems that are wildlife habitats and provide a wide range of benefits to human communities [1-2]. The Okavango Delta, in particular, is important for tourism in Botswana.

The Okavango Delta is an alluvial fan that has been built up by sedimentation into a graben structure connected to the East African Rift Valley [3-4]. It is located in Botswana within the Kalahari Basin, and is subject to an annual flood taking the form of a single pulse. In the upper part of the Delta (the Panhandle, see Figure 1) water flows through a well-defined river valley with a gradient of 1:5500 [5]. Here, the flood wave propagates by both channel and floodplain flow. At the end of the Panhandle, the water enters a conical alluvial fan which has a gradient of 1:3400 [5]. The width of the

swamp/floodplain section widens to approximately 80 km, and further increases in the downstream direction. Here, the system is composed of distributaries and channels which are fed by seepage or overland flow across the swamp.

The Okavango Delta receives 15900 Mm³/year of water, of this volume; about 70% is from the Okavango River catchment and the remainder from local rainfall. Less than 2% of this water flows out of the Delta through distal rivers, the rest being lost by evapotranspiration as the net recharge is negligible. The alluvial fan has the area of approximately 22,000 km² with a maximum water surface area of 13,000 km² [6]. The total annual bedload influx is of the order 140 000-170 000 tonnes, 95% of which is deposited in the panhandle. [6].

The Delta contrasts sharply from its surrounding Kalahari where rainfall is low, evaporation rates are high and surface water is lacking for most of the year [7, 8]. The water entering the Delta is oligotrophic [9], yet the Okavango Delta is full of plant and animal life. The species diversity of the Okavango Delta has been reported recently [10]. Hydrological, geochemical, sedimentological, geomorphological and biological processes shape the Delta over different spatial and temporal scales [11-14]. This paper discusses the hydrological, geochemical and geomorphological processes of the Okavango Delta in relation to water resources management.

2. Materials and Methods

This paper presents both new data and relevant literature data. For the new data, water electrical conductivity was determined on site using Hanna HI 9035 meter and pH was determined using a Hanna HI 991001 meter. Surface water quality was determined on between 15th and 28th September 2008, while the groundwater quality was determined on 25th May 2006. Groundwater samples were collected from piezometers located on an island on the Okavango Delta. The island and piezometers have been described elsewhere (Camp Island in [15]).

3. Hydrological processes

3.1 Water flow mechanisms

Once the flood pulse reaches the Okavango Delta, it causes expansion of the inundated area from the annual minimum of 3000-6000 km² to the annual maximum of 6000-13000 km² [16]. The annual minimum inundation extent is achieved around February, and the maximum in August-September. Variability in flood areas between the years is caused by the variation in hydrological inputs (local rainfall and inflow from the Okavango River catchment). At the scale of the entire Delta, the flood does not move as a classic flood wave, with water level/discharge swell slowly propagating through the system. Instead, the flood pulse of the Okavango River is discharged entirely into the central swamp, and the flood spreads slowly from there, with marked decline in water levels occurring rather uniformly throughout the system at the end of the flood season, which coincides with the hot season and thus high evaporation rates [17]. Along most parts of the channel system, it is difficult to distinguish between in-bank and over-bank flows in a classical sense, as, firstly, the channel bottom is often elevated above the surrounding swamp [7] and secondly, water levels are usually high enough (even during low stages) to maintain the hydraulic connection between channel and surrounding floodplains/swamp, so that considerable parts of swamp are inundated throughout the year, with no discernible in-bank phase. In the mid-section of the Delta, channels are shown to carry only 5-50% of water necessary to induce the observed downstream inundation [18].

3.2 Surface water-groundwater interactions

The parent material of the Okavango Delta is mostly well-sorted, medium sand, and suspended sediment load is low. As a consequence, the substratum of the floodplains is well permeable, not sealed by alluvial clays, and infiltration is high. Water balance calculations and measurements reveal that it can reach 400 mm/day [19]. At the scale of the entire system, 24 % of flood water infiltrates and recharges shallow groundwater aquifer [18]. This water flows underground within the local groundwater flow systems towards islands or dry lands, where it is uptaken by dry land vegetation to satisfy their evapotranspiration needs. On the annual basis, evapotranspirative uptake is comparable in magnitude with flood-induced recharge. In a situation of lack of flooding - evapotranspiration can lead to depletion of groundwater resources [20]. The relatively high local groundwater table gradients (1:100) as compared to low regional groundwater table gradients (1:4000) results in a limited role of regional drainage [7] and thus localization of presence of fresh, actively recharged groundwater.

4. Geomorphology

4.1 The Okavango Delta within the Makgadikgadi-Okavango-Zambezi (MOZ) rift depression

Fluvio-lacustrine deposition in northern Botswana has mainly taken place within a large structural depression considered as a south-westerly propagating extension of the East African Rift System (EARS). This rift depression was drained and filled by south-easterly flowing rivers on a number of occasions during the Tertiary and Pleistocene as the area was faulted and half grabens developed [14, 21]. The Makgadikgadi-Okavango-Zambezi (MOZ) depression is controlled by a series of NE-SW normal faults related to rifting which reactivated Proterozoic and Karoo structures (Figure 1) [14, 22]. Tectonic activity along the same trend resulted in uplift along the Zimbabwe-Kalahari axis possibly during the late Pliocene [23] causing the impoundment of proto Okavango, Kwando and upper Zambezi drainage and the development of the Makgadikgadi, Ngami and Mababe sub basins [24].

The nascent Okavango Delta alluvial fan is located within the Kalahari Basin, which is a shallow intracontinental basin. Aeromagnetic and seismic refraction studies suggest that the maximum thickness of sediment, in excess of 300 m, occurs in northern Namibia and in the Okavango graben in Botswana [14]. The major part of the catchment area is covered by unconsolidated to loosely consolidated, chiefly reworked Aeolian sand of the presently active Kalahari Basin. The Okavango Delta sediments represent the youngest (Quaternary) stratigraphic unit of the Kalahari sedimentary basin. Potential sources of the Okavango Delta sediments are mainly Proterozoic granitoids, gabbros and related

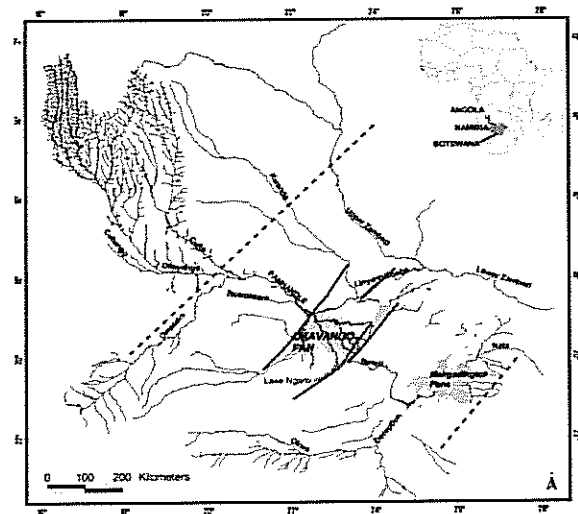


Figure 1. The Okavango Delta within the Makgadikgadi-Okavango-Zambezi depression. Extent of rift depression is shown by the dashed lines.

Volcanic and orthometamorphic rocks exposed in the catchment area in Angola, northern Namibia and northern Botswana.

Alluvial fans preceding the present Okavango fan systems have evolved throughout the Pleistocene. Imagery interpretation of MOZ basin sediments shows a series of older fans in relation to the present Okavango fan Delta. The well-formed alluvial (Okavango) fan is superimposed over the degraded dunes some of which form the present day islands. The fans mainly comprise sandy sediments which lie in flat though down faulted terrain within a south-western extension of the East African rift (EAR) [14]. Subsidence was re-activated approximately 2.4-5.0 Ma along NE-SW [25]. Gecomorphological features within the down warped area also comprise washed longitudinal dunes, present day and relict alluvial fan deposits and salt pans [26] which overlie up to 300 m thickness of Kalahari sands. Periods of dune formation have been tentatively dated using Optically Stimulated Luminescence (OSL) [27]. The past and present alluvial fans are embedded within the over-washed dunes which have not been dated accurately and therefore the date of the first fan system along with its islands and floodplains has not been established.

4.2 Okavango Delta islands

The forms and shapes of islands have been the subject of research undertaken by Gumbrecht et al. [12] who classify islands into four main types based on their shape and assumed origin. A major characteristic of island enlargement concerns the accumulation of calcareous and siliceous deposits under some of the islands, which may be the result of selective salt accumulation resulting from periodic desiccation or riparian tree root uptake or both [28, 29]. Recent work on island sands [28] indicated that they are composed of unsorted quartz grains with an evident matrix which causes loose aggregation. The island sand matrix is made up of two different matrix types; firstly a Si-Al rich clay enhanced amorphous silica (CEAS) and secondly a Ca-rich variant. A CEAS matrix may consist of SiO₂ (68.4 wt %), Al₂O₃ (18 wt %) and Fe₂O₃ (8 wt %) The high silica content suggests that the island CEAS matrix is related to quartz grain and biogenic fragment dissolution with small quantities of clay being identified likely as smectite. The nature of the CEAS matrix invokes high volume porewater origins similar to that suggested elsewhere for floodplain samples [28]. The Ca-rich matrix which is unique in island sands, is composed of SiO₂ (12.8 wt %), Al₂O₃ (3.8 wt %), Fe₂O₃ (1.4 wt %) and CaO (76.4 wt %) being mostly calcitic with relatively little silica and sepiolite clay [28].

The island sands of the Okavango Delta are not subject to surface water flooding but floodwaters discharge under the islands as groundwater at depths of 3-4 m [7]. As the islands lie only a few meters above the floodplains it is possible that higher flooding events in the past contributed to accelerated CEAS matrix formation in the islands, at the same time as this occurred on the

floodplains. The presence of a second Ca-rich matrix type containing sepiolite suggests that the Mg-rich clay formed in a carbonate-rich (high pH) porewater environment [28]. The island sands also contain disseminated calcretes such that sepiolite prevalence may reflect a sustained drying environment. The juxtaposition of apparently earlier CEAS (smectite dominant) matrix formation with later calcitic (sepiolite dominant) matrix formation may be interpreted as reflecting a change in porewater geochemistry from earlier relatively high volume slightly acidic/low EC conditions to later lower volume, more alkaline/higher EC conditions. Assuming that the initial CEAS is a weathering product formed in slightly acidic/low EC porewater similar to that invoked for the floodplains, then the later inclusion of Ca²⁺ (probably as calcite) would require a change in porewater conditions (to around > pH 8) [31], while the increase in salts may also be interpreted as being due to the pumping of sub-island groundwater by riparian trees [13, 32]. Calcite precipitation (and calcrete formation) has elsewhere been suggested as implying a transition to drier environmental condition, relative to earlier flood phases [33]. The juxtaposition of normal CEAS with the Ca-rich matrix might suggest wetter followed by drier events as reflected in different porewater conditions. More work is required to define more definitively the pumping role of riparian trees and their relationship to possible weathering sequences (c.f. [34]) in order to better separate out present day island matrix formation from that occurring in the past.

5. Geochemistry

It is remarkable that although 2% of the water entering the Okavango Delta leaves through the distal rivers Thamalakane, Kunyere and Khwai, the rest being removed from the system by evapotranspiration, the Delta has fresh surface water with low salt content. A review of the water chemistry and water quality of the Okavango Delta has been carried out [35] and highlights the low dissolved solids of the surface water of the Okavango Delta.

5.1 Surface water pH

The values for pH in waters of wetlands are generally circumneutral (6-8) although in ombrotrophic bogs, the exchange of metal ions for hydrogen ions by plants, coupled with the decomposition of organic matter can lead to low pH [36]. High pH values may also be observed due to the presence of algae, especially in eutrophic waters.

For the Okavango Delta, the main channel surface water has near neutral pH, with most studies showing a range in pH of between 5.9 and 7.6 (e.g. [9], [37]). The results for surface water pH from Mohembo (point A) to the flood front at the time of sampling are given in Figure 2. The pH within the Panhandle (sites A to C) and the

Okavango Delta proper (sites D to I) varied only from 6.17 to 7.28. However, along the Boteti river (sites J to L), pH values as high as 8.60 were determined, probably as a result of accumulated bicarbonate and/or carbonate salts in the river sediments of the area.

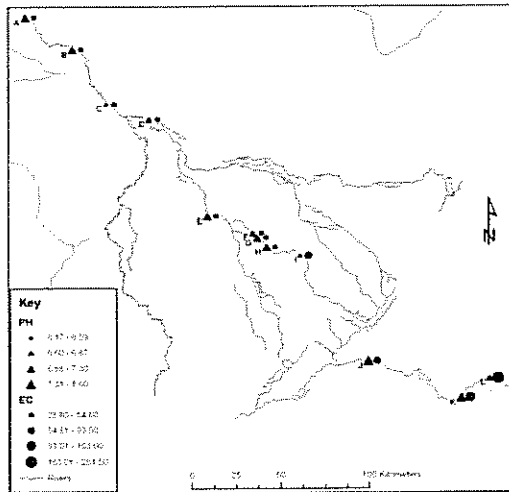


Figure 2. Electric conductivity and pH of surface water of the Okavango Delta.

5.2 Surface water electrical conductivity

The electrical conductivity of the surface water of the Okavango Delta low. The conductivity varied from 29 $\mu\text{S}/\text{cm}$ at Mohembo (point A) to 262 $\mu\text{S}/\text{cm}$ at the flood front in Motopi (point L, Figure 2). The trend in electrical conductivity from Mohembo to the distal edge of the Delta is very clear. At Mohembo (point A), the electrical conductivity is very low indicating water of low total dissolved solids. The conductivity generally increases downwards until the distal parts of the Delta. Evaporative concentration as well as some flushing of salts or water from previous floods is responsible for the increase in conductivity. This trend of progressive increase in electrical conductivity towards the distal parts of the Delta has been reported elsewhere. For example, electrical conductivity values of 25-34 $\mu\text{S}/\text{cm}$ have been reported for Mohembo (Site A on Figure 2) [37] increasing slightly to 30-37 $\mu\text{S}/\text{cm}$ for Shakawe/Drotsky's camp (site B on Figure 3) [37, 38] and increasing further to 64-137 $\mu\text{S}/\text{cm}$ downstream [13, 37]. For surface water there is a change in electrical conductivity by a factor of about 10 over a distance of over 250 km.

5.3 Ground water pH

Several studies have been conducted on the water quality of groundwater under islands of the Okavango Delta [15, 29, 39]. The pH of water is near neutral in the main channel but quickly gets alkaline towards the centre of the

island. pH increased from 5.8 for water from the main channel to a maximum of 8.88 near the centre of the island (Figure 3). It has been shown that the surface water of the Okavango Delta is predominantly bicarbonate in nature, with sodium bicarbonate accumulating in waters under islands, leading to a high pH.

5.4 Ground water electrical conductivity

Conductivity of groundwater of Okavango Delta islands increases from the shores to the centre of the islands. For camp island (Figure 3) the conductivity increases from a minimum of 80 $\mu\text{S}/\text{cm}$ in the surface water to a high of 18,200 $\mu\text{S}/\text{cm}$. This is an increase by a factor of over 200 within a distance of only 220 m, in sharp contrast to the difference in the conductivity of surface water discussed above.

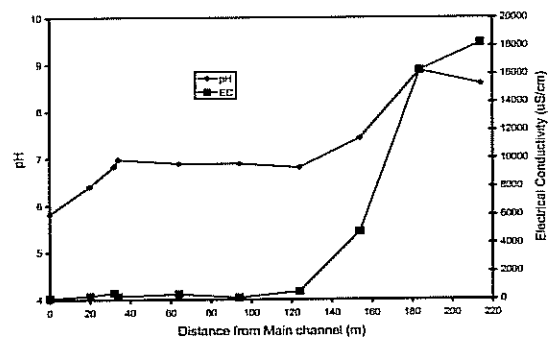


Figure 3. Electrical conductivity ($\mu\text{S}/\text{cm}$) and pH of groundwater under an island of the Okavango Delta. The last point corresponds to the centre of the island.

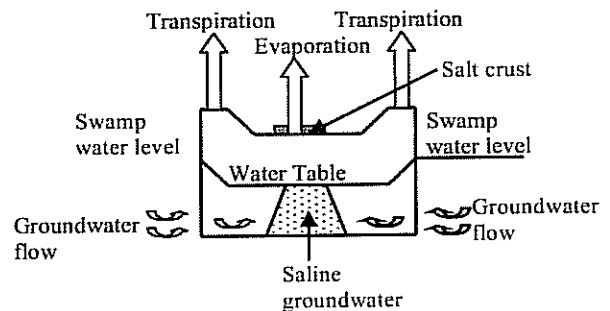


Figure 4. Model of salinisation of groundwater under Okavango Delta islands (after [13]).

The high electrical conductivity and pH at the centre of islands of the Okavango Delta arises as a result of evapotranspiration on the islands [13, 15]. The fringes of the island have continuous flow of water from the swamp to the island due to transpiration of riparian vegetation (Figure 4). This flow is unidirectional and results in salt accumulation under the island, leaving fresh surface water [15]. For this island, the first 120m correspond to a region of fresh water (Figure 3). Solutes in the groundwater undergo evaporative and transpirative enrichment,

forming highly saline salt solutions in the centre of the islands. A maximum electrical conductivity was observed near the centre of the island. This process results in zones of different vegetation at islands of the Okavango Delta. Near the centre, the islands are bare or support only salinity tolerant grasses [15] whereas near the edges, riparian woodlands are supported.

6. Conclusion and Implications of water resources management

Hydrological, geomorphological and geochemical processes shape the Okavango Delta and:

- Occurrence of fresh, actively recharged groundwater is limited to the vicinity of floodplains subject to inundation.
- Rates of recharge from flood water are large, but losses through evapotranspiration are also large. In case of lack of recharge (lower floods or flood shift), depletion of groundwater occurs due to evapotranspiration.
- The channel system has a limited role in distribution of water throughout the system. Decisions about channel maintenance (for navigability and for delivering water downstream) should take this into consideration. Past experience indicates that in the upper Delta there was not a single successful channel maintenance initiative.
- Water level and discharge measurements in the channels reflect very local conditions and may not be representative to downstream hydrology. Hydrological monitoring should, therefore, include mid-scale responses such as distributary inundation patterns from remote sensing.
- Areas of salinisation of groundwater under the Okavango Delta islands have been recommended for soakaways of septic tanks [40], [41] since groundwater at the centre of islands is of high salinity and does not disperse laterally. Until other systems are evaluated, this seems to be an informed option for wastewater disposal in the Okavango Delta.
- Anything that would disrupt the process leading to solute formation under islands would result in increase in the salt concentration of the surface water ultimately ruining the Delta. Such processes could include:
 - Over-harvesting of riparian vegetation e.g. for timber, traditional medicines could reduce transpiration from trees on islands. This could reduce the accumulation of salts under the islands, leading to an increase in salt content of the surface water.
 - Large-scale fires would result in damage of riparian woodlands. Therefore, effects of fires of the Okavango Delta on riparian vegetation need to be determined.
 - There is need to investigate if wild animals reduce the density of the vegetation on the fringes of the islands of the Delta because if they do, the long term effect could be an increase in the salinisation of the Delta.

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