HIERARCHICAL PROCESSES AND PATTERNS SUSTAINING THE OKAVANGO : AN INTEGRATED PERSPECTIVE FOR POLICY AND MANAGEMENT

T. Gumbricht[1] and T.S. McCarthy[2]

Abstract

A nested hierarchy of processes and patterns from continental tectonics to anthill islands sustains the Okavango system in Botswana. The stage of climatic and depositional environment set by the African Superswell once gave birth to the Okavango, but also holds it death sentence as waters from the catchment deflect away. The catchment is the key scale for preserving the Okavango – the balance of inflowing water, sediments and nutrients shapes the Okavango Fan, builds the Islands Mosaic and sustains the Wetland and its wildlife. To manage the Okavango linkages across scales and how they feedback must be acknowledged.

INTRODUCTION

The concept of nature organised as a continuous, hierarchal scale stems from early western ideas (Lovejoy, 1936). These ancient ideas pertaining to a static graduated natural order of all beings – the great chain of being, persisted in western thought until the 19th century. The idea of complex systems being organised as hierarchies is much more recent (Koestler, 1967). Hierarchy theory is now adopted in concepts pertaining both to physiology and geophysiology (e.g. Allen and Starr, 1982). Hierarchy theory combined with the theory of self-organising dissipative structures (Prigogine, 1980) presently forms the most comprehensive ideas on the functioning of life. Such dissipative systems are neither small number causative, nor large number stochastic; but rather complex middle-number systems (Weinberg, 1975). Energy and matter processing (i.e. communication) is reciprocal, and determined by the nested hierarchy of interfaces. Wetlands can be seen as typical middle number systems. Using the ancient metaphor of micro- and macro-cosmos, wetlands are often compared with kidneys and have been widely adopted as natural water purifiers (e.g. Mitch and Gosselink, 1986). The life-supporting value of wetlands is very high (Costanza *et al*, 1997).

Studies on wetlands, however, are almost always treating wetlands as small-number causative or large-number statistical systems with an arbitrary scale discretisation. Most wetland studies focus on short timescales (i.e. years), emphasising, for example, saturation levels and detention times for biogeochemical spiralling of nitrogen and phosphorus through the wetland. Geological settings and the importance of slower but constraining processes, or feedback processes over different scales, are seldom considered.

Here we adopt hierarchy theory and landscape ecological perspectives for exploring the processes and

---

[1] World Agroforestry Centre, Entebbe, Uganda. Corresponding author: thomas_gumbricht@hotmail.com
[2] University of the Witwatersrand, South Africa

patterns that sustain the Okavango in northern Botswana. In a holistic European tradition we consider the landscape "the total character of a patch of the Earth" (von Humboldt), where processes and patterns are tightly knit together. The aim of this study is to present a holistic perspective of scale integrated processes and patterns that, in reciprocity, create the viable environment of the Okavango. From this holistic perspective we extract deterministic cause-effect relations across different scales to identify risks and threats to the Okavango stemming from both natural and anthropogenic impacts.

HIERARCHICAL SCALES OF PROCESSES AND PATTERNS FORMING THE OKAVANGO

The Okavango is a mosaic of thousand of islands embedded in a matrix of wetlands fed by ever shifting waterways (see McCarthy and Ellery, 1998 for an overview). Early travellers referred to this bird-foot shaped area as an "inland delta". By definition, however, a delta debouches into a major water body, which the Okavango does not. A technically more correct classification would be alluvial fan, and Stainstreet and McCarthy (1993) suggested that the Okavango should be classified as a "low sinuosity meandering" alluvial fan. The timescale and processes for erecting a fan is, however, slower and different compared to the processes forming the channels, wetlands and islands of a delta. Herein we hence use the concepts of the Okavango as a *Wetland*, an *Island Mosaic* and an *Alluvial Fan* to represent three distinct spatio-temporal scales.

The Okavango *Wetland* is the fastest changing scale with annual flooding and seasonal changes in water levels. The definition of wetland as an "area permanently or regularly flooded with water" excludes the islands, which compose around a quarter of the surface of the present Okavango Delta. The islands are also much more stable features and persist over tens of thousands of years, a scale we refer to as the *Island Mosaic* scale. The *Alluvial Fan* is approximately double the size the present Delta, and is evolving an order of magnitude slower. The *Fan* is situated in a depression formed by tectonically induced surface collapses around 2 million years ago. It is hence constraining both the *Island Mosaic* and the *Wetland*. The *Fan*, in turn, is formed by water and fluvial sediments from the *Catchment* in the Angolan Highlands. The *Catchment* is a consequence of processes related to its position at the southwestern terminus of the East African Rift valley. The East African Rift Valley is ripping the Africa continent in two parts and this process is driven, that is constrained, by magmatic upwelling which rises the entire continent - the *African Superswell*. The *African Superswell* determines regional climate and runoff pattern, as well as their secular changes.

This broad view of the Okavango illustrates the most important aspects of hierarchy theory; the constraint larger scales exercise over smaller scale, the constrained smaller parts being composed of many generically similar features, the agglomeration of smaller scale processes feeding back to larger scales, the strong reciprocity between function and form, and the fact that any compartmentisation of this hierarchical integrative system more or less is arbitrary. Compartments seldom have any ontological significance, but are rather a convenient epistemological approach for creating model units that can be used for conceptualisation. Certain "quanta" of the hierarchical scale, however, act as filters for energy and matter processes, having a set of interfaces with higher information processing capacity (Holling, 1993). Keystone species at different scales are hypothesised to be able to entrain and dominate processes and patterns at various scales (ibid). Dangerfield *et al.* (1998) has suggested papyrus, hippopotamus and termites being keystone species in the Okavango: confining channels, opening up new channel routes and nucleating islands respectively.

THE AFRICAN SUPERSWELL – GEOLOGICAL SETTING AND TECTONIC PROCESSES

The Okavango is situated on the edge of the East African Rift valley, at its southwestern tip (Gumbricht *et al.*, 2001). The active uplift associated with the African Superswell (Lithgrow-Bertelloni and Silver, 1998) is generating the dynamic topography that is necessary for the formation of large alluvial fans. Erosion and matter transport is high and the terminal depression formed by the rift valley accumulates this matter as it deposits. Also the other two large inland wetlands of Africa, the Sudd and the Niger are found in similar settings (McCarthy, 1993).

The African Superswell and associated active faulting also determines the area feeding the wetland, i.e. its catchment. Historical evidence strongly suggests a secular change in general flow route of the rivers emanating from the Angolan Highlands. The continental uplift associated with the Superswell probably initiated headward erosion of the lower Zambezi. Over time the Zambezi River has hence captured more and more of the water from the Angolan Highlands. The Kwando River, now making a distinct 90 degree turn in the Linyanti, is a likely source of water having formed oversized ox-bow lakes that can still be seen on the surface of the Okavango Delta. The Kwando River is also the most likely source of water that once filled the Mkgadikgadi pans downstream of the Okavango. That water filling the Mkgadikgadi came this way is suggested by the underfit Boteti River. ?

Gumbricht *et al.* (2001) found that the steepest route out of the Okavango Alluvial Fan is towards the Linyanti. This indicates that the capturing of water from the Angolan Highlands to the Zambezi is an ongoing process. The next river to be captured by the Zambezi would then be the Okavango, which would ultimately seal the faith of the Okavango.

Geological processes on the scale of the African Superswell influence global circulation patterns and global climate. The geological spatial scale set by the African Superswell is hence complemented by large-scale changes in climate and precipitation. The topographic dynamics and climate changes together constrain the amount of water and sediments that reaches the Okavango. A large part of the Okavango catchment is at present dormant, but sedimentological investigations (Thomas and Shaw, 1991) reveal that other climates with higher precipitations in the past have existed.

It is estimated that the African Superswell is in the order of tens of millions of years in the making (Burke, 1996). The area of the uplift is around ten million km^2, and this anomalous uplift is globally unsurpassed. In our analysis of the hierarchical scales constraining the Okavango we have used the scale of the African Superswell as the largest scale. This is not strictly true, as even larger scales exist that affects the Okavango, but for all practical reasons these scales can be disregarded.

THE OKAVANGO CATCHMENT – WATER AND SEDIMENT INFLOW DYNAMICS

The total catchment of the Okavango is about 380 000 km^2. The land surface of the catchment is probably older than the Superswell, but its topography and function in relation to the Okavango is younger. Of the catchment area about half is actively contributing runoff, whereas the remaining half is dormant. The dormancy is not an artefact that can be related to the catchment scale, but rather to the larger scales constraining the catchment (see above). Given a certain climate, rainfall pattern and topography internal characteristics of the catchment itself will however determine the amount of water and sediments that will reach the downstream Okavango area. Specifically it is the processes and patterns of the soil-vegetation-atmosphere interface that will largely determine this. The processes at this interface as integrated over the catchments also feeds back to influence the regional climate.

The precipitation that falls over the catchment is partitioned between evapotranspiration and runoff (disregarding changes in water storage and water molecule cleavage and reassembling). The partitioning is largely determined by vegetation distribution and cover (Gumbricht, 1996). There is a strong reciprocity between vegetation types, and climate/precipitation; areas with high rainfall are also colonised by vegetation with high growth capacity and hence high evapotranspiration. This tends to dampen the effects of slow changes in climate and precipitation both in time and space. Catastrophic events, and rapid climate changes will however lead to lag times in this adjustment, with subsequent consequences for runoff generation.

Changes in land use/cover also infer changes in soil erodability. With losses in vegetation and associated increases in runoff the unidirectional flow of matter from upper to lower catchment accelerates. This can be induced both by natural changes, but at present is potentially more affected by managerial regimes.

There is a distinct difference in the timescales under which (normal) natural causes and anthropogenic causes operate. Natural changes in land cover are slow, unless released by catastrophic events, whereas anthropogenic driven changes can be fast. The latter can be in the order of decades, whereas the former are relevant on centuries to millennia and longer. Global climate changes (i.e. changes in the constraining scales for the catchment) are anticipated to lead to higher climatic variations, hence less resilient vegetation ecosystems, with potentially more intermittent flow regimes that can also enlarge erosion. Such effects can be seen in other parts of Africa, including the East African Rift Lakes region.

THE OKAVANGO ALLUVIAL FAN – SMOOTHING AND LOCAL SAGGING

The alluvial fan underlying the Okavango is formed by the water borne sediments being deposited over an area of approximately 30 000 km^2. Estimates by Gumbricht and McCarthy (micro-topography, in prep.) on the deposition rate of fluvial sediments indicate that the presently active Delta is rising by approximately 1 metre in 50 000 years. The alluvial fan is about double the size of the active delta, and could hence be estimated to rise 1 meter in 100 000 years. The continuous deposition of matter is a prerequisite for maintaining the extreme smoothness that forms the Alluvial Fan and that allows the harbouring of the Island Mosaic and Wetland on its surface.

At present only small amounts of clastic sediments (bedload) reaches the fan itself; instead most is deposited in the Panhandle entry corridor (McCarthy *et al.*, 1991). Detailed analysis of the slope in the Panhandle reveals that there is a kink in it (Smith *et al.*, 1997), which has been attributed to recent tectonic activity. Bedload inflow to the fan will only commence once the sediment built-up in the Panhandle has rearranged the slope. This shows what a delicate balance there exists between inflow, geomorphology, sediment transport and deposition. It also illustrates the confining effects by tectonic activity on sediment distribution on the scale pertaining to the Alluvial Fan. Another such effect might be the Xo flats, a depression around the Jao channel.

The sediment build-up on the Alluvial Fan causes sagging of the crust, superimposing locally driven tectonic activities over the scale determined by the African Superswell. Gumbricht *et al.* (2001) found that the palaeo lake shores of Mababe and Mkgadikgadi are not horizontally embedded over the surrounding terrain. Mababe is tilted 15 metres towards the south (i.e. the central Okavango Fan) and Makgadikgadi shows a v-shaped notch, with the deepest incision corresponding almost exactly to the centreline of the alluvial fan.

This self-driven sagging is an extremely important process as it mitigates external forces tilting the Alluvial Fan in any direction. Together with the continuous adding of sediments it generates a negative feedback loop of self-control and stabilises the fan shape. This is probably also partly the answer to why there is no regional tilting seen on the fan (Gumbricht *et al.*, 2001).

THE ISLAND MOSAIC - SEDIMENTATION PATTERN

The surface of the active Okavango Delta is around 20 000 km^2. The Delta is characterized by low local relief of no more than 2 to 3 metres (Gumbricht and McCarthy, microtopo in prep.) superimposed over the regional variation on the alluvial fan. In kilometre long transects, the standard deviation of the local relief is typically around 50 cm. The Delta surface is changing substantially faster than the surface of the Alluvial Fan on which it is situated. The first European travellers reaching the area around 1850 found Lake Ngami filled with water from the Thaoge channel. Since then the Thaoge channel has dried out and water flow shifted first to the Nqoga and then the Jao. Gumbricht *et al.* (2002a) found that over the last 15 years there has been a secular change of water flow from the Jao-Boro systems towards the Xudum. These shifts in water distribution are well known and have been attributed to sedimentation (McCarthy *et al.*, 1986), to tectonic effects (Wilson, 1973) or to major floods (UNDP, 1976).

The lack of regional tilting of the Fan surface led Gumbricht *et al.* (2001) to conclude that sedimentation was the active process. The recently documented change in flooding from the Jao-Boro to the Xudum (Gumbricht *et al.*, 2002a), is however unlikely to be driven by sedimentation as no clastic sediments reaches the Jao-Boro system (see above). The most likely candidate for this change is hence tectonic movement; a strong case also because of the Xo flats terminates at what is identified as a fault running across the Jao-Boro.

Even if the channels shifts position on a centennial scale, islands are much more persistent. Of the 600 000 tons of sediments flowing in to the Okavango every year, 90 % is accumulated building the Alluvial Fan and the Island Mosaic. Sedimentation occurs at interfaces where the transport or dissolution capacity of water is lowered. Channel and island margins are the most important interfaces capturing the sediments in a non-random manner typical of deltas. In general islands are born by clastic sedimentation processes and grow by chemical sedimentation processes.

Sand settles in the rivers as water seeps through the flanking vegetation but the sand stays behind. When water seeks a new route, the old channel will stand out as an Inverted Channel island. In the inner curves of the meandering rivers water flow is slower, and the sand settles to form Scroll bar islands. Termites forming small anthills may colonize randomly distributed sand dunes. The number of termite formed anthills in the Okavango is in the order of hundred thousand (Gumbricht *et al.*, 2002b), and hence the termites must be considered a keystone species in the Okavango (Dangerfield *et al.*, 1998).

Once an island has thus nucleated it grows by salt precipitation under the islands. This happens as the island's trees consume so much water that the salt left behind form crystals – hence forcing the island to grow. Gumbricht and McCarthy (microtopo, manuscript) investigated the volume of islands and speculate that islands grow faster than the surrounding fan. Hence islands are the most persistent features of the Delta surface. Islands also grow in an elongated manner that aligns them with the azimuth of the Fan (Gumbricht and McCarthy, 2002, IAS). Salt accumulation is preferentially happening at the downstream side of islands. The shape of islands hence directs water flow to be largely parallel to the azimuth of the Alluvial Fan. More important, islands, together with vegetation (see below) forces channels to stay put despite instable positions on their own raised channel beds. This generates the flip-flop behavior of channel switching seen in the Okavango.

The island cycle of birth and growth as such is also crucial for the salt and water balance of the Delta. The total perimeter of islands determines the amount of water evapotranspirated from islands, and hence the salt accumulation taking place (Bauer *et al.*, 2002). The model results by Bauer *et al.* (2002) also indicate that the islands must reach ages of a fifty to hundred years for the salinity of the groundwater to rise to such levels that density sinking occur.

Island types, sizes and distribution vary throughout the Okavango (Gumbricht *et al.*, islands, in press). In the Panhandle, islands are clustered at the upper portion, and are of the scroll bar type covered with grasslands. Islands cover larger parts of the Panhandle compared to the Permanent swamp in the proximal part of the proper fan, and only a relative low proportion has developed salt crusts. The lack of salt crusts indicate that islands are relatively young; the agglomeration in the upper part is an indication of an anomalous situation, attributed the kink in the Panhandle slope (see above). Island size and relative island spatial coverage increase from the permanent swamp, over the seasonal swamp and to the occasional swamp. This is an artefact of difference in island age, and dominating growth processes. Clastic sediments compose islands nearer the apex of the delta, whereas older islands towards the distal end are largely grown from chemical sediments over a clastic core as "amoeboid islands" (ibid.).

THE OKAVANGO WETLAND – VEGETATION, AND WATER AND SALT BALANCE

The Okavango wetland is partly fed by local summer rains ($6x10^9m^3$ per annum), but is annually flooded when the floodwaters from the Angolan highlands arrive between February and May ($9x10^9$ m^3 per annum). The flood wave takes three to four months to traverse the wetland. Only a few percent of the total inflowing volume is lost to discharge through the Boteti River. Even if as much as 95 % or more of the inflowing water is evapotranspirated, the salinty of the water only increases three fold (McCarthy *et al.*, 1998). The entering water is extremely nutrient poor, and patches of vegetation communities are resilient over decades even if flooding regimes change. The vegetation is in a sense hence a memory of the inundation situation over decades. When channels shift position and the peat surrounding the dying channels burns, large amounts of nutrients are released, creating a boom in terrestrial vegetation.

Nutrient locked
in Okavango veg
x Next

The Okavango Wetland consists of four physiographic regions; the Panhandle, the permanent swamp, the seasonal swamp, and the occasional swamp. The Panhandle is an entry channel to the Okavango alluvial fan, and is permanently flooded. It is dominated by large stands of papyrus and reeds (*Phragmites communis*). The permanent swamp is situated at the apex of the Delta proper. Also the permanent swamp is dominated by papyrus and reed, but with a higher degree of different sedges in its lower parts. The seasonal swamps are dominated by floodplains, where reeds largely give way for sedges (Ellery and Ellery, 1997). Areas that get flooded only during wet years are occupied by grasslands and form the occasional swamp. The area of the permanent swamp is around 4 000 km^2; the seasonal swamp is also around 4000 km^2, with the largest recorded flood over the last 30 years of almost 12 000 km^2 (McCarthy *et al.*, 2002).

The extent of the flooding is mostly dependent on water inflow, both from the upper catchment and as local rainfall, and to a lesser degree on antecedent inundation conditions (Gumbricht *et al.*, 2002a). Evapotranspiration is constant, and does not seem to influence the *variation* in flooding. The spatial constancy of evapotranspiration is also confirmed by satellite imagery (Bauer *et al.*, 2002). The Wetland hence has a slow, or even static influence on the flooding. Floating mats of both dead and living plant debris (sudds), however, can choke a channel and hence divert flow rapidly.

Albeit the low relief of the Okavango, the wetland vegetation is extremely sensitive to small topographic variations. Papyrus cannot stand drying out of the root system, whereas most riparian tree species cannot stand drowning of the roots and lower trunk. Papyrus is a keystone species in the Okavango – it confines the chennel to stay put by its density adjacent to the channel. The nutrient poor water can sustain luxury growth of papyrus in a thin board, but this board is enough to keep the waters in the channel as the channel bed rises due to sedimentation (see above). The channel is hence raised above the surrounding, and water will only find a new route when hippopotamus paths open up a new route through the papyrus. Also hippopotamus must hence be considered a keystone species.

Terrestrial vegetation species also have very different salt tolerance. The slower (constraining) scale of island growth and salt accumulation is confining the distribution of species across islands (Ellery and McCarthy, 1993) but the vegetation is also the driving force accumulating the salt and forcing island growth. As salt accumulate due to evapotranspiration the host island expands along the land-water interface. The old fringe gets salinized, species intolerant to salt succumb and invade outward towards the new island fringe as the island expands. This feedback driven migration pattern of vegetation insures the continued growth of the island.

DISCUSSION – DISTURBANCE REGIMES AND THEIR POTENTIAL EFFECTS

The hierarchical scales of the Okavango are summarised in Figure 1. At each scale the processes and patterns that sustain the Okavango are constrained by larger and slower scales. As in other complex hierarchical systems the agglomeration of the processes and patterns at a smaller and faster scale to a large extent compose the larger scale. Hence there is in general a strong feedback loop between scales.

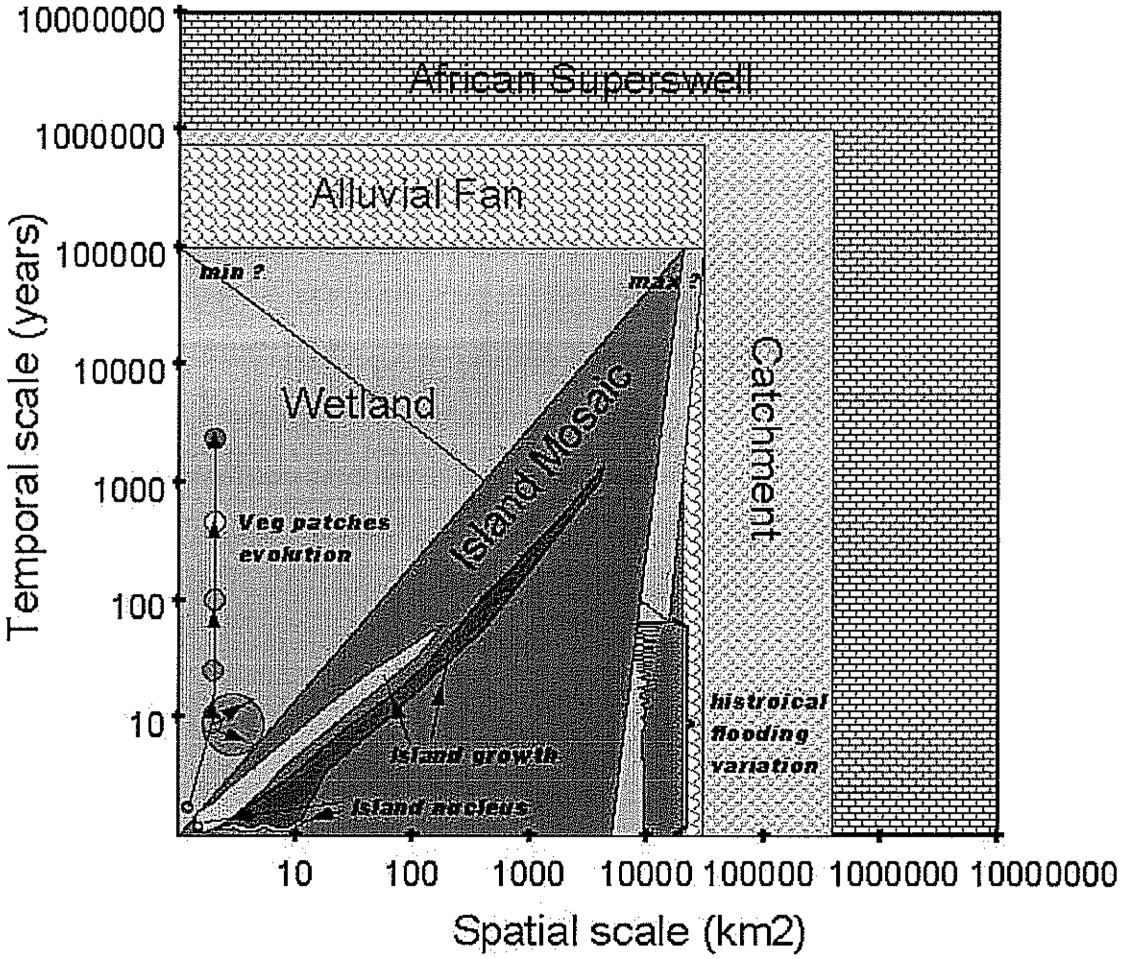

Figure 1. *Hierarchical scales of processes and patterns sustaining the Okavango (see text)*

Tectonic activity has a large influence on the Okavango. Earth movements associated with the African Superswell gave birth to the Okavango, but also hold the ultimate faith of the Okavango. Also the Okavango will once deflect into the Zambezi as has the Kwando already done. That the steepest route over the Fan surface is towards the Linyanti indicates that this could happen at any time. But the tectonic activity associated with the superswell also influences the Okavango more frequently, albeit on smaller scales. Small earth movements have the potential of changing the sediment transport and water routing. The present sediment accumulation in the Panhandle, the Xo flats, and the secular change in water distribution on the fan surface from the Jao-Boro towards the Xudum might well be caused by such movements. However, locally generated tectonic activity, resulting from sagging of the Earth's crust as a result of sediment accumulation on the Alluvial Fan, is also important. Over very long time periods and large scales it is less significant, but the tilting of the palaeo-lakeshores of Mababe and Makgadikgadi reveal that locally the sagging effect might be short-term dominating.

One important implication is that the local sagging effect mitigates the tendency of the Superswell generated tectonics to deflect water towards the Zambezi.

Constructing dams in the catchment preventing sediments from reaching the Okavango would eliminate the feedback mechanism that local sagging has over large-scale tectonic movements. As this feedback mechanism is estimated to work on scales of hundreds of thousands of years, the short-term risk must be considered minimal. Large-scale cultivation and deforestation of the catchment would have the opposite effect – an increase in water and sediment inflow. An increased rate of the build-up of the Alluvial Fan could, however also lead to a deflection of water towards the Zambezi – the lag time in the crustal sagging might be too slow, and the route towards the Linyanti will become increasingly steep until the waters escapes this way. An increased sedimentation rate also means faster cycles of channel shifting, which will affect the tourist industry and the stability in vegetation patches. The risk of increases in sediment load is hence potentially larger, and also a more likely effect of agricultural developments in the upper catchment.

Another effect stemming from changes in the catchment could be increased nutrient export, leading to eutrophication of the Okavango wetland. This would probably lead to large-scale vegetation changes. Encroachment by water hyacinth (*Eichhornia crassipes*) might become a risk with eutrophication.. This will choke the channels and potentially eliminate the Papyrus as a keystone species, with consequences for the entire hydrological and sedimentiological functioning of the Okavango system. At present only the tourist industry can induce eutrophication directly in the Okavango. The small scale of tourism is, however, unlikely to cause major problems, and as shown by McCarthy *et al.* (waste water, in prep.) properly constructed and positioned soak-aways (in island centres) are very effective means for treating the wastewater and preventing the spread of pollution.

Present plans for water abstraction in the upper catchment are restricted to the Namibian national water plan which calls for the abstraction of 120 million m^3 per annum from the Okavango River at Rundu (P.Heyns, pers. comm.to TSM, although reported by Pallett (1997) to be 100 million m^3). This would lead to a loss of wetland area of around 100 km^2, equalling about 2 to 3 % of the permanent swamp. Water abstraction for domestic water supply is hence unlikely to cause major changes to the Okavango in the near future. Development of large-scale irrigation schemes can potentially lead to more devastating effects.

Dredging of channels to allow boat traffic or increase downstream water flow can affect the Okavango both on the Wetland and the Island Mosaic scale. The most obvious, almost direct impact would be a decrease in the flooding area. Dredging would also prevent the channel shifting, which translates to fewer new islands being born. If this would change long-term patterns in island sizes and distribution, the salt-water balance could potentially be affected. The short-term gains by dredging would include the access to present transport systems and infrastructure, including air strips and tourist camps. Dredging over decadal scales would probably only have minor impacts on the abiotic components of the system. Ecological stagnation as a result of losses of creative destructionism (Holling, 1986) could appear in shorter time scales. In the long run dredging cannot withhold the natural channel shifting. Dredging will rather lead to a delay in channel shifting, and then a faster, and potentially more unpredictable, change in channels and distribution of flooding.

CONCLUSIONS – GEOPHYSIOLOGY AND VIABILITY OF THE OKAVANGO

The uniqueness and viability of the Okavango is related to the interplay of processes and patterns nested in hierarchical scales ranging from small anthill islands to the African Superswell, and operating on timescales from the seasonal flooding up to millions of years. The ecological integrity of the Okavango is closely linked to the constant change and communication between the interfaces of these nested scales. The ecological sustainability is perhaps best captured by the cyclic phases identified by Holling (1986): exploitation, conservation, creative destructionism, and renewal.

The Okavango is a good example of a complex middle number geophysiological system, which has many similarities with physiological systems. The Okavango Wetland with its distributary channels is like the bloodstream and lymphatic system, with fast turnover and transporting nutrients and other dissolved substances. The Islands Mosaic is like the internal organs, processing the nutrients and energy, keeping the balance of the "blood". The Fan is the skeleton and the skin, the bodily envelope and backbone keeping the organs in place. What comes in via the Panhandle is like the food intake. The Superswell and the climate it fosters is the general environment. Changes in the environment affect the quality and amount of food available. The food intake is of course most crucial for the organism. The channel blockage is like a blood clot, demanding a bypass; the sediment build-up in the channels is like plaque formation, more slowly forcing a bypass. An increase in sediment input is like obesity, leading to faster plaque formation and general health problems. Increased nutrient load is like increasing the risk of blood clots. Changes in the salt balance will disturb the island kidney functions, but as with physiological kidneys the resilience is rather high. The annual pulse of water is the heartbeat, the pump that drives the viability.

The general environment set by the Superswell, which once gave birth to the Okavango, also holds it ultimate death sentence. Policy and management cannot prevent the tectonic processes to deflect the water towards the Linyanti. But once this happens curative measures that artificially kept the Okavango alive for centuries, even millennia, can be put in place in the form of dams. The ethics of such a curative measure might be questioned by the downstream countries that otherwise would have received the waters. Policy at an international scale is hence a key issue at this scale.

The catchment that determines the water, nutrient and sediment inflow to the Okavango is the key scale for sustaining the Okavango over decades to millenniums. As the basin is shared between Angola, Namibia and Botswana, international policy is required. The most likely effects of changes in the catchment include:

1. decreased water inflow by water abstraction,
2. increased sediment load through land conversion in the upper catchment, and
3. eutrophication by nutrient export and agricultural development in the upper catchment.

The present plans for water abstraction in Namibia (around 100 million m^3 per annum) would decrease the area of flooding with around 100 km^2 (Gumbricht *et al.*, 2002a). The noticeable effect on the ground will be small, overshadowed by the interannual variation in flooding. It is unlikely that water abstraction for domestic water supply will amount to such levels that it severely damages the Okavango. Large-scale irrigation schemes in the upper catchment could potentially lead to larger amounts of water being abstracted and hence to more severe damages. An increase in the load of sediments would have noticeable effects only after decades. The general effect of increased sediment loading would be a faster cycling of channel shifting, island birth and growth and crustal sagging. There might be negative ecological effects, as habitat shifting would be expected, potentially creating less resilience and fewer ecological niches. Also the infrastructure, especially airstrips, access roads and campsites, would be affected, with potential economic threats to the tourist industry. Eutrophication effects carry the largest risk over the next decades. The ecological functioning, and the papyrus (keystone species) regulating the hydrological functioning of the extremely nutrient poor Okavango will most likely be negatively affected by eutrophication. Invasion by opportunistic species like the water hyacinth (*Eichornia crassipies*) could have devastating effects, choking the channels and changing the hydrological functioning, channel shifting and salt-water balance.

The impacts of catchment scale processes and patterns on the Okavango cannot be managed within the Okavango system itself more than for short scales. Using the Panhandle for sewage treatment and as a sedimentation basin ("liver") could mitigate increases in nutrient and sediment loads over decadal scales. But over longer periods this would not be possible. The scale of the catchment prevents curative remedies to be used for sustaining the Okavango; preventive actions are needed. This calls for a combination of national and international policy and management. We feel that a key issue is to determine the upstream-downstream water and water-pollution rights. The economical value of the water for irrigation, industrial and domestic use, tourism, biodiversity and life support functions etc need to be determined. The cost-benefit relations could then be used for putting a financial structure in place that would allow the most efficient use of the water. This could very well mean downstream users paying upstream stakeholders for preserving water quality and water flow, and the international community paying for preservation of biological diversity and life support functions.

Local activity in the Okavango system itself impacting the sustainability includes water abstraction, dredging and eutrophication. These activities will impact the Okavango in a similar manner as would the corresponding activities in the catchment, albeit on a smaller but more direct scale. The sparse population and poor soils surrounding the Okavango means that water abstraction will likely not reach such levels that the system will be severely threatened. Dredging to keep the existing infrastructure in place can have larger effects, inflicting the ecological sustainability by preventing "creative destructionism" and lead to stagnation of the ecological dynamics and loss of biodiversity. The risk for local eutrophication from tourist camps is small. All the potential local impacts are relatively easily manageable given that knowledge about the system and decision support tools is disseminated to managers and decision makers.

REFERENCES

Allen, T.F.H., and T.B. Starr, 1982. *Hierarchy: perspectives for ecological complexity*. University of Chicago Press.

Bauer et al., 2002. *Is density flow balancing the salt budget of the Okavango Delta? Evidence from field and modelling studies*. SWIM. 17th Delft University of Technology in Delft (The Netherlands) May 6 to 10, 2002.

Burke, K. 1996. The African Plate. *South African Journal geology*, 99: 341-409.

Constanza et al. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387 15 May 1997

Dangerfield, J.M., McCarthy, T.S., Ellery, W.N., 1998. The mound-building termite Macrotermes michaelseni as an ecosystem engineer. *Journal of Tropical Ecology*, 14: 507-520.

Ellery, K. and Ellery, W. 1997. *Plants of the Okavango Delta, a field guide*. Tsaro Publishers.

Ellery, W. N., Ellery, K., and McCarthy, T.S., 1993. Plant distribution in islands of the Okavango Delta, Botswana: determinants and feedback interactions. *Africa Journal of Ecology*, 31: 118-134.

Gumbricht, T., 1996. Modelling water and vegetation reciprocity - a landscape synthesis in GIS. Royal Institute of Technology, Division of Land and Water Resources. TRITA-AMI, PhD 1011, Thesis.

Gumbricht, T., T. McCarthy, T. and C. Merry, 2001. The Topography of the Okavango Delta, Botswana, and its sedimentological and tectonic implications. *South African Journal of Geology*, 104: 243-264.

Gumbricht, T., McCarthy, J. and McCarthy, T.S., 2002a. Channels, wetlands and islands in the Okavango Delta, Botswana, and their relation to hydrological and sedimentological processes. Accepted for publication in Earth Surface Processes and Landforms.

Gumbricht, T., Wolski, P., Frost, P. and McCarthy, T.S., 2002b. Forecasting the spatial extent of the annual flood in the Okavango Delta, Botswana. Submitted to Journal of Hydrology.

Gumbricht, T. and McCarthy, T.S. The micro-topography of the wetlands of the Okavango Delta, Botswana. In prep.

Gumbricht, T. and McCarthy, T.S., 2002. Spatial patterns of islands and salt crusts in the Okavango Delta, Botswana. 16th Intl. Sedimentological Congress, Johannesburg, 2002, pp 132-133.

Holling, C.S., 1986. Resilience of ecosystems: local surprise and global change. In: W.C. Clark and R.E. Munn (Eds), *Sustainable development of the biosphere*. Cambridge University Press, pp. 292-317.

Holling, C.S., 1992. Cross-scale morphology, geometry, and dynamics of ecosystems. *Ecol. Monographs*, 62: 447-502.

Koestler, A., 1967. *The ghost in the machine*, Macmillan, New York.

Lithgrow-Bertelloni, C. and P.H. Silver, 1998. Dynamic topography, plate driving forces and the African Superswell. *Nature*, 395: 269-272.

Lovejoy, A., 1936. *The great chain of being*. Harvard University Press.

McCarthy, J., Gumbricht, T., McCarthy, T.S., Frost, P.E., Wessels, K. and Seidel, K., 2002. Flooding patterns of the Okavango wetland in Botswana between 1972 and 2000. Accepted for publication in Ambio.

McCarthy, T.S., 1993. The great inland deltas of Africa. *Journal of African Earth Sciences*, 17: 275-291.

McCarthy, T.S., Ellery, W.N., Rogers, K., Cairncross, B. and Ellery, K., 1986. The roles of sedimentaion and plant growth in changing flow patterns in the Okavango Delta, Botswana. *South African Journal of Science*, 82: 579-584.

McCarthy, T.S., Stainstreet, I.G. and Cairncross, B., 1991. The sedientary dynamics of active fluvial channels on the Okavango fan, Botswana. *Sedimentology*, 38: 471-487.

McCarthy, T.S., Bloem, A and Larkin, P.A., 1998. Observations on the hydrology and geohydrology of the Okavango Delta. *South African Journal of Geology* 01, 101-117.

McCarthy, T.S. and Ellery, W.N., 1998. The Okavango Delta. *Transactions of the Royal Society of South Africa* 53: 157-182.

Pallett, J., 1997. *Sharing Water in Southern Africa.* Desert Research Foundation of Namibia, Windhoek, Namibia. 121pp.

Prigogine, I., 1980. *From being to becoming*. Freeman, New York.

Smith, N.D., McCarthy, T.S., Ellery, W.N., Merry, C.L. and Ruther, H., 1997. Avulsion and anastomosis in the panhandle region of the Okavango Fan, Botswana. *Geomorphology*, 20: 49-65.

Stainstreet, I.G. and McCarthy, T.S., 1993. The Okavango Fan and the classification of subaerial fan systems. *Sedimentary Geology* 8: 115-133.

Thomas, D.S.G. and Shaw, P.A., 1991. *The Kalahari Environment.* Cambrigde University Press.

UNDP, 1976. *Investigation of the Okavango as a primary water resource for Botswana*. Technical Report, United Nations Development.

Weinberg, G.M., 1975. *An introduction to general systems thinking*. John Wiley and Sons, New York.

Wilson, B.H., 1973. Some natural and man-made changes in the channels of the Okavango Delta. *Botswana Notes and Records,* 5: 132-153.