Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **30**, 27–39 (2005)
Published online 20 December 2004 in Wiley InterScience (www.interscience.wiley.com). **DOI:** 10.1002/esp.1124

The micro-topography of the wetlands of the Okavango Delta, Botswana

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Received 20 February 2003;
Revised 29 March 2004;
Accepted 25 May 2004

Abstract

The surface of the 40 000 km² Okavango alluvial fan is remarkably smooth, and almost everywhere lies within two to three metres of a perfectly smooth theoretical surface. Deviations from this perfect surface give rise to islands in the Okavango wetlands. This micro-topography was mapped by assigning empirical elevations to remotely sensed vegetation community classes, based on the observation that vegetation is very sensitive to small, local differences in elevation. Even though empirical, the method produces fairly accurate results. The technique allows estimation of depths of inundation and therefore will be applicable even when high resolution radar altimetry becomes available. The micro-topography has arisen as a result of clastic sedimentation in distributary channels, which produces local relief of less than two metres, and more importantly as a result of chemical precipitation in island soils, which produces similar local relief. The micro-topography is, therefore, an expression of the non-random sedimentation taking place on the fan. Volume calculations of islands extracted from the micro-topography, combined with estimates of current sediment influx, suggest that the land surface of the wetland may only be a few tens of thousands of years old. Constant switching of water distribution, driven by local aggradation, has distributed sediment widely. Mass balance calculations suggest that over a period of *c.* 150 000 years all of the fan would at one time or other have been inundated, and thus subject to sedimentation. Coalescing of islands over time results in net aggradation of the fan surface. The amount of vertical aggradation on islands and in channels is restricted by the water depth. Restricted vertical relief, in turn, maximizes the distribution of water, limiting its average depth. Aggradation in the permanent swamps occurs predominantly by clastic sedimentation. Rates of aggradation here are very similar to those in the seasonal swamps, maintaining the overall gradient, possibly because of the operation of a feedback loop between the two. The limited amount of local aggradation arising from both clastic and chemical sedimentation, combined with constant changes in water distribution, has resulted in a near-perfect conical surface over the fan. In addition to providing information on sedimentary processes, the micro-topography has several useful hydrological applications. Copyright © 2004 John Wiley & Sons, Ltd.

Keywords: topographic relief; land cover; alluvial fans; Okavango

Introduction

The surface of the 40 000 km² Okavango 'Delta' alluvial fan of northern Botswana is remarkably smooth, and the land surface almost everywhere lies within two to three metres of a theoretical, perfect conical surface of radial slope 1:3550 (Gumbricht *et al*., 2001). Nevertheless, the local micro-topographic relief on a horizontal scale of tens to hundreds of metres is extremely important, as it governs water flow and sediment transport (McCarthy and Ellery, 1998; McCarthy *et al*., 2002). The micro-topography is also an indicator of the processes that have shaped the landscape (McCarthy and Ellery, 1995; Gumbricht *et al*., 2000). Therefore micro-topography is a potentially powerful source of information on both the functioning and evolution of the Okavango system.

A variety of methods are available for acquiring micro-topographic information, the most appropriate method in any particular case being dependent on the size of the area, data availability and desired accuracy. Topographic data at the resolution of tens of metres can be obtained from stereo pairs of aerial photographs or from satellite images (e.g. SPOT or TERRA) using photogrammetric methods, from radar altimetry using SAR data and image processing, or from laser altimeter data. These require considerable investment in time and money. For remote areas with poor traditional data coverage such as the Okavango region, the Shuttle Radar Topographic Mission (SRTM) holds promise for a new generation of topographic maps. Other SAR radar data sources (e.g. Radarsat or the ERS programmes of satellites) are also frequently used for producing high-resolution topographic maps over inaccessible regions. Unfortunately, these data are not as yet available for the Okavango region. Herein we present an alternative approach for generating micro-topography for the wetlands of the Okavango Delta. The region is characterized by extremely low local relief, with a maximum relief of no more than 2 to 3 m (e.g. McCarthy *et al.*, 1993a; Gumbricht *et al.*, 2001). The average relief is much lower, and in kilometre-long transects, the standard deviation on elevation is typically around 50 cm. Notwithstanding this low relief, the wetland vegetation is extremely sensitive to small topographic variations (Ellery *et al.*, 1993) and therefore provides a window into the micro-topography. Here we use knowledge of the relation between local relief and vegetation in order to generate a micro-topographic map of the wetlands of the Okavango Delta.

Sedimentation on the fan occurs by a combination of clastic and chemical deposition, and we believe that surface features on the fan may provide insight into the mechanisms involved as well as past distribution of sediment. In addition, knowledge of the local micro-topography has several useful practical applications.

Study Area

The Okavango is a large alluvial fan (40 000 km^2) situated in a fault-bounded depression in northern Botswana (Figure 1; Gumbricht *et al.*, 2001). The fan receives water and sediment from the highlands of central Angola. Some

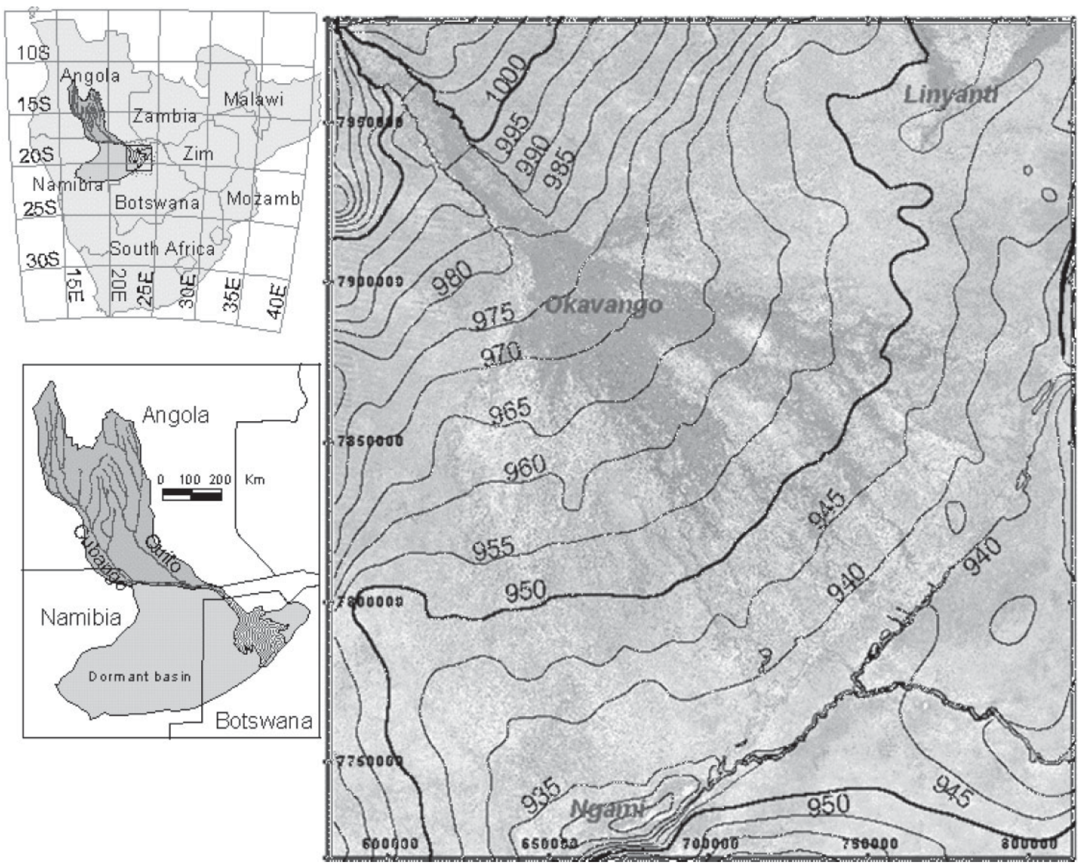

Figure 1. A topographic map of the Okavango Delta, Botswana, superimposed on a composition of Landsat TM scenes. The large map is projected to S. UTM 34, Cape Datum, False Easting 500 000, False Northing 1 000 000, map distance units in kilometres.

9 km^3 of water debouches onto the fan annually, augmented by 6 km^3 of rainfall (McCarthy and Ellery, 1998), which sustains up to 14 000 km^2 of wetland in the upper to mid-reaches of the fan. This wetland has a 'bird's foot' appearance, and is referred to as the Okavango Delta. About 98 per cent of the rainfall and inflow is lost annually by evapotranspiration in the semi-arid climate. The delta is conveniently divided into four physiographic regions: the Panhandle entry valley and its associated swamps; the permanent swamp of the delta proper; the seasonal swamp which is annually flooded; and the occasional swamp which is infrequently flooded. Each physiographic region contains islands, flood plains and wetlands, albeit with different distributions and durations of flooding, reflecting the local micro-topography (Gumbricht *et al*., 2004a). These regions are flanked on their distal side by vast savannah plains of the remainder of the fan, which receive no seasonal flood water.

The annual inflow of sediment into the Delta amounts to approximately 590 000 tons (McCarthy *et al*., 2002). The sediment mix, based on the estimates of annual sediment influx (McCarthy and Ellery, 1998), consists of about 35 per cent sand carried as bedload and 8 per cent of fines carried in suspension (kaolinite and phytoliths; McCarthy *et al*., 1989), together with 27 per cent calcite and 30 per cent amorphous silica carried in solution. Therefore, almost two-thirds of introduced sediment consists of dissolved chemical matter, while one-third is clastic and consists mainly of reworked aeolian sand carried as bedload. The minor suspended load is fairly widely distributed during sedimentation and is not considered further. To the sediment inflow is added another 250 000 tons of aerosols that are annually deposited over the delta (Garstang *et al*., 1998). Clastic sediment deposition gives rise to local relief and forms island nuclei by two mechanisms, namely deposition on the beds of vegetatively confined channels and deposition on point and scroll bars (McCarthy and Ellery, 1998; Gumbricht *et al*., 2004a). After channel abandonment and the desiccation and burning of the surrounding peat, these form 'inverted channel islands' and 'point bar islands' respectively. In addition, island nuclei are created as randomly distributed points on the flood plains by termite colonies ('anthill islands'; McCarthy *et al*., 1998). Once an island nucleus has thus formed, it grows by chemical precipitation, a process driven by the high evapotranspiration by trees on island fringes. The growth of islands is believed to occur by expansion in the soil within the vegetated fringes as a result of the precipitation of calcium carbonate and silica from the groundwater as the salinity of the water rises due to evapotranspirational loss of groundwater (McCarthy *et al*., 1993a). Evapotranspiration of groundwater also leads to a build-up of the more soluble salts and ultimately the formation of salt crusts (trona) on the islands. The position of the trona reveals the groundwater flow direction, with the trona forming in down-flow areas (Gumbricht and McCarthy, 2003). These two forms of sediment deposition on the fan have produced a remarkably smooth cone of fairly uniform gradient, with a gently undulating micro-topography.

Methods

Generating a regional elevation framework

In order to generate a smooth surface on which the high resolution micro-topography could be superimposed, the coarser resolution digital elevation model (DEM) over the Okavango region (Figure 1) described by Gumbricht *et al*. (2001) was resampled. This DEM has a resolution of 500 m with an estimated standard error (over the wetland surface) everywhere less than 1 m. From the original 500 m DEM, slope (steepness) and aspect (direction of slope) were calculated and the data set was resampled at 28·5 m resolution. Each cell in the resampled DEM was assigned an elevation in relation to slope and aspect of the original (500 m) pixel, and an average (smoothing) filter with a kernel size of 7×7 cells was applied, thus creating a more fine-grained version of the original, coarser scale DEM. The derived map was used for representing regional elevations at 28·5 m resolution.

Generating local topography

Vegetation is extremely sensitive to local relief in the Okavango wetland, and therefore a vegetation community map can provide small-scale topographic information. Such a map has been produced for the Okavango wetland by J. McCarthy *et al*. (in press) at a resolution of 28·5 m. In this map, eleven vegetation communities are recognized, in addition to open water. These different communities primarily reflect different flooding frequencies or water depths, and hence are proxies for local topography (Table I; Figure 2). In addition, Gumbricht *et al*. (2004a) have generated a map identifying and categorizing islands within the wetland. This map was used in conjunction with the vegetation community map to distinguish between two community types, namely flood plain grasslands and grasslands which occur in the interior of islands, which typically lie at slightly different elevations.

Data from eleven previously published and two unpublished elevation and vegetation transects from different regions of the seasonal swamps as well as numerous transects across channels and a long transect in the permanent

Table I. Relative elevations assigned to different vegetation communities and islands

Vegetation communities	Relative elevations (m)
Wetland communities	
Major channels in the Panhandle	−2·5
Open water, permanent swamp community in the Panhandle, all major channels on the Delta proper	−2·0
Permanent swamp community on the Delta proper	−1·6
Primary floodplain	−1·3
Secondary floodplain	−0·8
Island communities	
Grassland (island rims)	−0·3
Island salt pan (island centre)	−0·2
Grassland (island centre)	0
Riparian forests, riparian forest islands, anthill islands	1·2
Savannah communities	
Savannah saltpans	−0·2
Savannah grassland	0
Savannah woodland	0·3

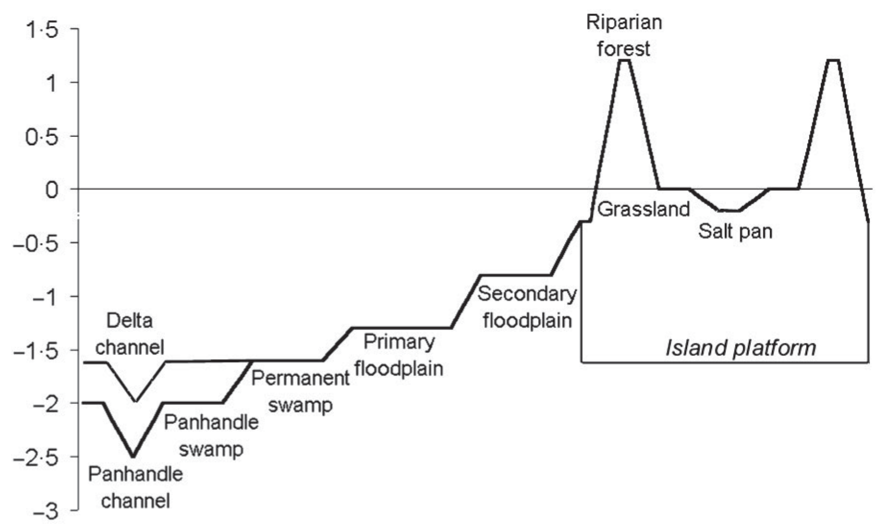

Figure 2. Schematic diagram illustrating the relationship between local topography and vegetation classes, and the elevations (in metres) assigned to each.

swamp (McCarthy and Metcalfe, 1990; McCarthy *et al*., 1991, 1993a, 1998; McCarthy and Ellery, 1994, 1995; UNDP, 1976) were used to assign initial relative elevations to different vegetation communities (Table I). The transects are representative of all vegetation communities as well as the four physiographic regions of the Okavango wetland (Figure 3). All transects have a local datum, and record only the relative elevation. The amplitude of the available transects varies from 0·5 m (transect representing flood plain to grassland) to 2·8 m (relict point bar island with transect from flood plain to dense riparian forest, and transect from channel to grassland island). Permanent swamps in proximity to channels typically have water depths (or, more accurately, water-saturated peat depths) of around 1·5 m, but long transects indicate average depth in the permanent swamp to be of the order of 0·8 m (UNDP, 1976). The maximum local relief in the delta itself can hence be estimated to vary up to a maximum of 3·5 m, with slightly greater relief in the Panhandle.

Ten of the available transects which were sufficiently well geo-referenced (Figure 3) were individually fitted to the vegetation community and island maps. The islands across which transects had been measured, although small, were all identifiable in the vegetation community map, and also the general vegetation communities identified during

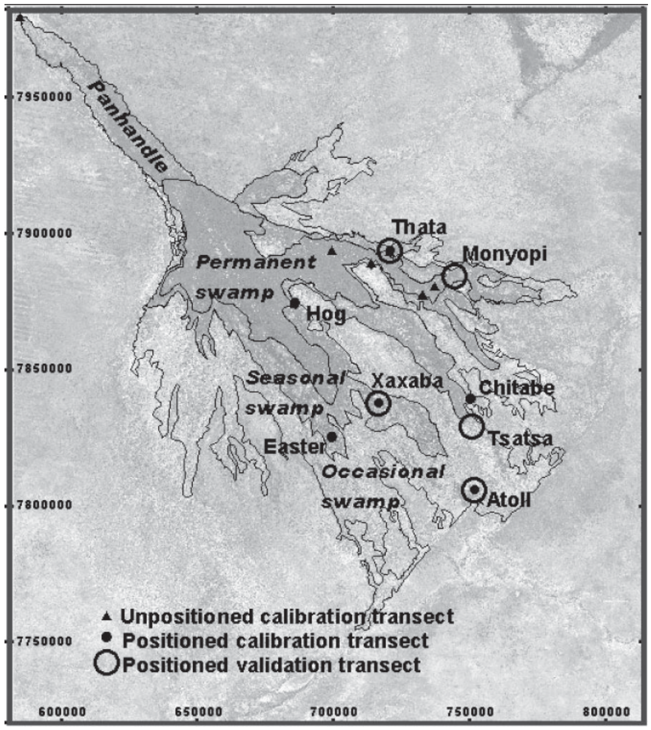

Figure 3. The physiographic regions of the Okavango Delta, and the locations of measured elevation transects (large circles). Not shown are the locations of some 40 long cross-channel transects in the permanent swamps from McCarthy *et al.* (1991, 1992, 1993) and McCarthy and Ellery (1997).

transect measurement corresponded to classes in the vegetation community map, verifying the essential correctness of the satellite-derived maps.

Generalizations, positional errors and classification errors in the vegetation community map prevented a satisfactory statistical evaluation of the relation between relative elevations and vegetation community classes extracted from the map (most classification errors are between flood plain and grassland types, which are ambiguous to classify even in the field). To overcome some of these problems only pixels representing 'core' areas of a particular vegetation community (i.e. pixels surrounded by similar classes) were extracted. Although the statistical relationship improved, misclassification and a low number of pixels prevented automated use of the derived relative elevations. Hence, the final assignment of relative topographic elevation was done manually by combining results of the statistical analysis with knowledge of field conditions and the vegetation community map for the available transects (Table I). The relative elevations were set using the elevation of the grasslands in island interiors and the surrounding savannah grasslands as local datum (zero-level).

The relative elevations of different vegetation communities were assigned to the 28·5 m resolution vegetation community map. The derived map was then smoothed by applying a mean filter with a 3×3 kernel, weighting the central pixel equal to the surrounding eight neighbours. This created a smoother transition zone between classes. This smoothing also created topographic variation within a single vegetation community. For example, riparian forests do not reach their assigned relative topographic elevation unless more than 100 m wide, which corresponds well with the transect data. Similarly, the depth of permanent swamp decreases away from channels towards flood plains and islands.

The above procedure produced a *relative micro-topographic map* showing only local, relative elevation. By superimposing this map on the regional DEM with 28·5 m grain size, an *actual micro-topographic map* was generated.

Accuracy evaluation

The accuracy of the generated actual micro-topographic map (i.e. that superimposed on the DEM) was evaluated in three ways. The first evaluation was done by a direct comparison between five major transects used for calibration and the derived actual micro-topographic map. In the second evaluation, the variances of the transect and modelled data were compared. In the third, derived micro-topography was compared with five transects not used in the calibration. In all cases, datum of the transect was forced to an average fit with the elevations extracted from the actual micro-topographic map.

Results and Discussion

Accuracy of the micro-topographic maps

The full relative micro-topographic map is shown in Figure 4 (in this illustration, the regional slope of the fan has been removed in order to illustrate low-order topographic relief, which tends to be masked if true elevation is used). The statistical correlation (R^2) between the five geo-referenced calibration transects and the modelled micro-topography range from 0·10 to 0·57 (Table II). The correlation coefficients are fairly low, but nevertheless graphical comparison of independent transects (Figure 5) indicates that the model and the actual elevations compare favourably. The low correlation is influenced by minor positional errors between the transect and the map, a few misclassifications of vegetation community in the vegetation community map and by the presence of termite mounds. The general accuracy of the generated micro-topographic map is shown by comparison of the standard deviations and ranges of mapped and measured topography (Table II).

The generally good agreement between the modelled and the actual micro-topography (Figure 5) indicates that the methodology produces essentially correct micro-topography at 28·5 m resolution. However, the map only provides information for those areas in which the vegetation reflects flooding duration. The vegetation contrast between islands and flood plains weakens if areas have not experienced flooding for some time (perhaps 50 years or so), due to the encroachment of shrubs and trees onto abandoned flood plains, and the ability to use vegetation as an indicator of micro-topography is lost. These areas are indicated by the zero level in Figure 4. The area of applicability of the method is larger than that inundated by the annual seasonal flood, because of the effect of rainfall, which, in wet years, tends to create standing water in the areas surrounding the usual maximum seasonally flooded area. The accuracy in the case of the permanent swamp is possibly lower, as measured transects reveal undulations in the water depth that are often not reflected in vegetation. Moreover, vegetation gradients which do exist in the permanent swamp usually reflect nutrient availability rather than water depth. Therefore, in this study, all permanent swamp communities were

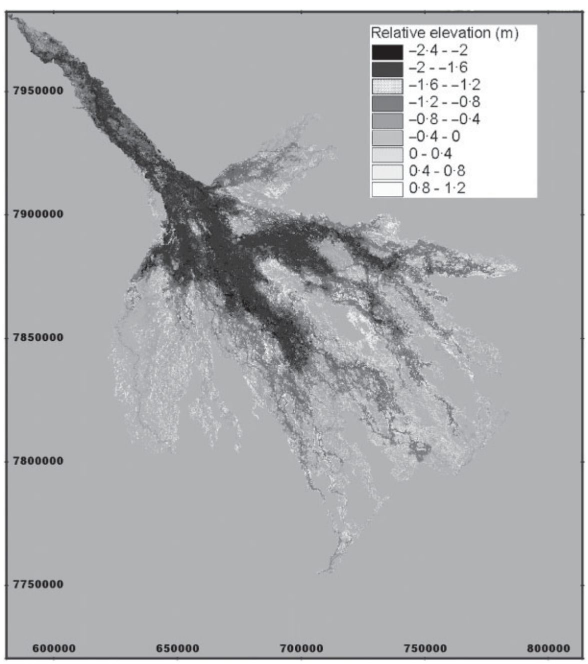

Figure 4. Map showing the relative micro-topography of the Delta.

Table II. Statistical evaluation of the relation between surveyed transects and modelled micro-topography for five geolocated calibration transects and five independent geolocated validation transects. As all surveyed transects only have a local datum, they were fitted to the general level of the model by setting the average difference between the data sets to zero. Range is the maximum span in each transect; standard deviation is the internal standard deviation of each transect; correlation is the statistical correlation coefficient between the surveyed transect and the model

	Range		Standard dev. (m)		
Site	**Transect**	**Model**	**Transect**	**Model**	**Correlation (R^2)**
Calibration					
Atoll	3·8	2·8	0·7	0·64	0·36
Chitabe	2·8	2·5	0·76	0·83	0·57
Easter	2·5	1·7	0·65	0·33	0·55
Hog	2·3	2·2	0·37	0·64	0·1
Xaxaba	1·5	2	0·34	0·54	0·53
Validation					
Atoll	4·2	1·8	0·922	0·51	0·3
Monyopi	2·5	2·8	0·69	0·82	0·66
Thata	2·5	2·7	0·48	0·59	0·48
Tsatsa	4·1	2·7	0·89	0·67	0·14
Xaxaba	2·9	2·1	0·63	0·58	0·49

grouped together as a single class. However, variations in depth with distances from channels, islands and seasonal flood plains are taken into account to model observed variations in depth in the permanent swamp.

While other methods (such as SRTM) might generate more accurate maps of the micro-topography, our methodology carries the advantage that it fits perfectly with other maps generated from the same satellite-based data set, including a vegetation map (J. McCarthy *et al*., in press) and an island map (Gumbricht *et al*., 2004a). More importantly, the method can be used to estimate the surface elevation underlying both dense terrestrial vegetation and vegetated water surfaces, which would not be possible with other methods, including SRTM. The maps thus generated allow for better representation of sediment accumulation and especially analysis of water routing. These permit exploration of the genesis and growth of islands and associated vegetation, both at the regional and especially the local scale, which, due to positional error problems at pixel scale, would not have been possible with a micro-topographic map generated by other means. The micro-topographic maps are also useful in analysing area–volume relationships of both water and land areas, in identifying bottle-necks in flood water distribution, and in providing the basis for distributed hydrological models. As far as we are aware, no other remote sensing technique exists for estimating water depths in vegetated swamps and therefore even when high resolution radar altimetry becomes available, proxy methods as employed here will continue to be used.

The smoothness of the Delta and the origin of micro-topography

Gumbricht *et al*. (2001) have shown that the alluvial fan surface is remarkably smooth, approaching a near-perfect conical shape. Such near-perfect conical surfaces are well documented in the case of fluvially dominated alluvial fans (e.g. Blair and McPherson, 1994), where deposition and erosion maintain the slope. However, sedimentation in the Okavango is dominated not by fluvial processes but by chemical sedimentation, in the form of silcrete and calcrete (some two-thirds of the incoming sediment is carried as solute load). Here we wish to explore how the shape of the fan is maintained under these different sedimentological conditions, as well as the significance of the micro-topography.

Figure 4 shows that there is an increase in the number of islands with increasing distance from the apex of the fan. Most of the islands occur in the seasonal swamps, where there is very little clastic sedimentation taking place. Here, the volume and distribution of islands reflects the spatial distribution of precipitates, and especially calcium carbonate and amorphous silica, as the precipitation of these solutes causes island growth (McCarthy *et al*., 1993a). The micro-topographic model was used to estimate the quantity of calcium carbonate beneath islands. Unpublished data of the authors reveal that calcium carbonate accounts for about 30 per cent of the volume of a typical island (precipitated silica accounts for a further 30 per cent, with possibly wind-deposited accumulations forming the remainder), and

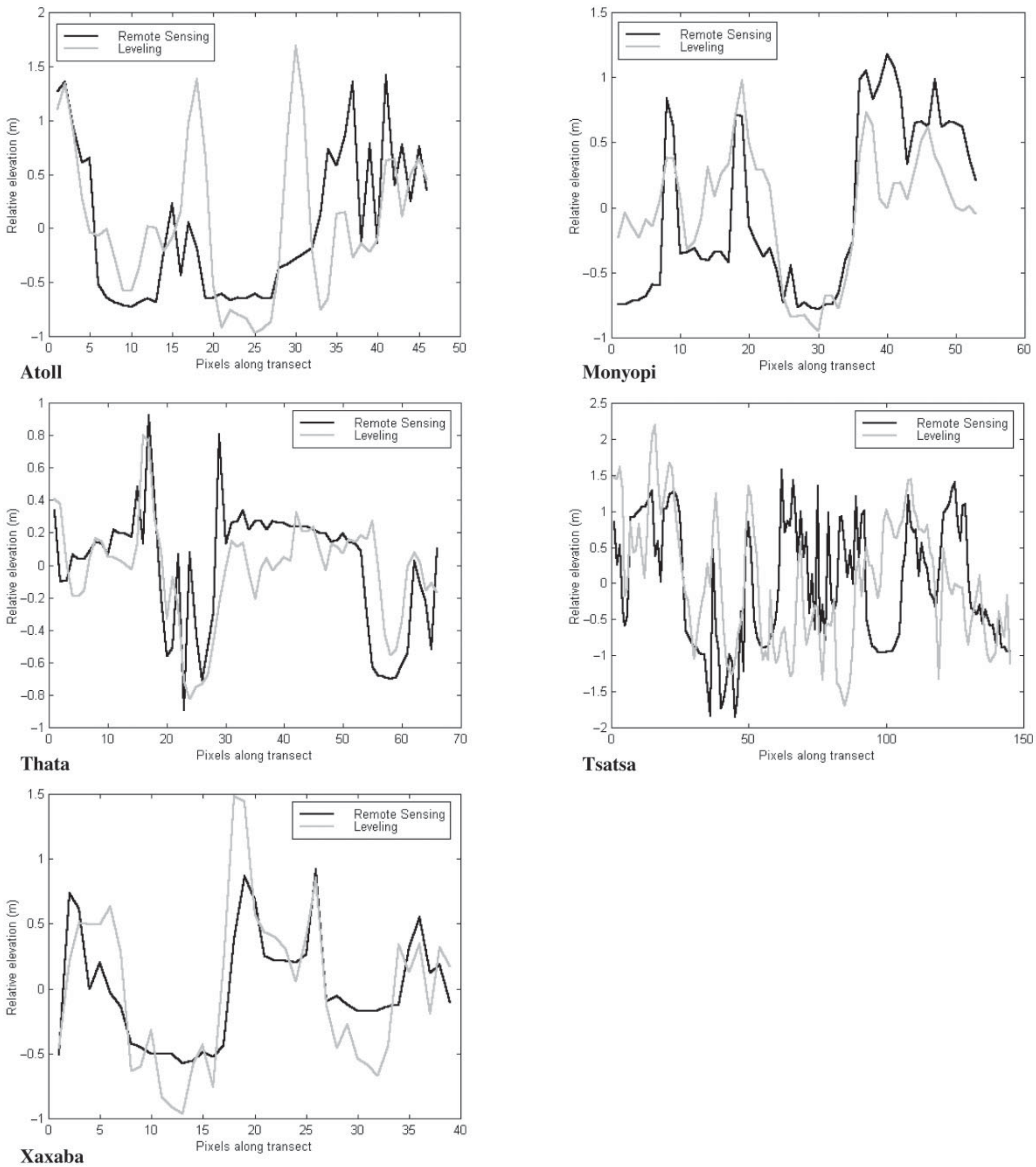

Figure 5. Diagrams comparing the measured topography with that extracted from the micro-topographic map in five regions of the wetland (see Figure 3 for locations of transects).

extends to a maximum depth of 2·8 m below surfaces covered by riverine forest (equivalent to a depth of 1·6 m below grassland in island interiors). In effect, the calcium carbonate forms platforms within and beneath the islands (Figure 2). Recent investigations suggest that the thickness of calcium carbonate precipitates may be somewhat greater on larger islands such as Chief's Island, but in the absence of reliable data this will not be considered in our estimates.

Using the micro-topographic map, the volume of the islands as well as their underlying platforms was calculated (see Figure 2) to be 9×10^9 m^3. Assuming that calcium carbonate accounts for 30 per cent of this volume and has a density of 2 g cm^{-3} (the calcrete is fairly porous), the total amount of near-surface calcite is about 6×10^9 tonnes.

Under current hydrological conditions, $1{\cdot}15 \times 10^5$ tonnes of calcium carbonate are supplied to the wetland each year (McCarthy and Ellery, 1998). At this supply rate, all of the near-surface calcrete could have accumulated in approximately 50 000 years. This estimated accumulation time is relatively robust: for example, excluding all islands larger than 50 km^2 (some of the larger islands may be tectonic in origin) only reduces it by 20 000 years, while including the approximately 100 000 anthill islands (Gumbricht *et al*., 2004a) has negligible influence. This is a remarkably short accumulation period, and indicates that the topography of the wetland could be of relatively recent origin, amounting to no more than a few tens of thousands of years.

McCarthy *et al*. (2002) estimated that about 570 000 tonnes of material is deposited in the wetland each year from Okavango River water (wind-borne deposition is uniformly spread at a delta-wide scale, and consequently we disregard it). This deposition is confined to the wetland itself, which currently amounts to an area of about 14 000 km^2. Assuming uniform deposition, this represents an annual sedimentation rate of 2×10^{-5} m per year. Although this appears slow, in a period of 50 000 years the average aggradation would be 1 m. The average relative elevation of islands is 1·7 m above the level of permanent flooding. Aggradation is not uniformly spread within the wetland, however, but occurs in channels and in peat deposits (clastic sedimentation), and in islands (chemical sedimentation). Focusing the sedimentation would result in greater local aggradation. The total area of islands amounts to $4{\cdot}6 \times 10^9$ m^2 (Gumbricht *et al*., 2004a), about 30 per cent of the total wetland area. If the implied aggradation was focused in this smaller wetland area, aggradation would be in the region of 3 m.

Although these calculations are essentially order-of-magnitude estimates, there is an internal consistency, which indicates that although aggradation is slow, it nevertheless can account for the observed micro-topography of the wetland. Moreover, the calculations indicate that the wetland surface may be relatively young, and that sedimentation provides a mechanism for changing water distribution across the fan surface.

Geomorphological analysis has indicated that the Okavango has been both wetter and drier in the past 50 000 years and, moreover, the distribution of water and hence sediment across the fan surface has changed over time (Shaw, 1988; McCarthy and Ellery, 1998). There is no indication at present what the average sediment influx has been over the last 50 000 years, but the current hydrological conditions, which produce relatively small channels compared to the former large channels discernible in the land forms on the fan surface (McCarthy *et al*., 1993b), may well be below long-term average conditions. In this event, the wetland surface could be younger that the estimated 50 000 years.

These calculations, based on the present distribution of the wetland and its islands on the fan surface, indicate that if the water distribution remained static for a period of 50 000 years, the inundated area would become elevated relative to the surrounding fan surface by 1 m on average. In reality, aggradation is more localized, and is locally greater than the average. Nevertheless, inundated regions would become relatively elevated, which in turn would induce shifts in the distribution of water on the fan surface.

Under present conditions, channels, which transport and eventually deposit bedload, are confined to the Panhandle and permanent swamp of the upper Delta. However, historical records indicate that channels may reach the most distal portions of the Delta, such as the Thaoge channel, which up until 1880 formed a direct link from the Okavango River to Lake Ngami. This provided a direct conduit for the transfer of bedload from the apex to the most distal portion of the fan. In addition to these so-called 'primary channels', McCarthy and Ellery (1997) have identified 'secondary channels', which arise in the upper to mid-fan region from water leaked from primary channels. These are erosive in their upper reaches, but aggradational in their lower reaches and serve to transfer bedload (sand) down the fan surface. Bedload usually accumulates in bars and on the beds of both primary and secondary channels and their distributaries, and channel abandonment results in topographic inversion of the channel as the flanking peat burns off (McCarthy *et al*., 1988). Under present hydrological conditions, these inverted channels typically rise about a metre above the surrounding area (McCarthy *et al*., 1988; Stanistreet *et al*., 1993), but larger channels which were operative in the past produced more elevated tracts, up to 2 m high. The relative elevation of inverted channels indicates that channels fail after only a limited amount of in-channel aggradation has occurred, which is determined by the regional water level. Gumbricht and McCarthy (2003) have shown that elongated islands, many of which represent former channel beds, form a radial distribution on the fan surface, reflecting past primary and secondary channel positions, many of which extend to the very distal parts of the Delta. Under present hydrological conditions, channel systems have a limited life, and form and abandon over a period of about 100 years (Ellery and McCarthy, 1994), resulting in a constant shift in water and sediment distribution across the fan. The cumulative effect of these channels has been to transfer bedload down the fan surface, but the amount of local aggradation that they produce is limited to between 1 and 2 m, over widths of between 10 and 200 m and lengths of between about 5 and 50 km.

A more important function of channels is the distribution of water with its contained solute load. Channels leak because they are vegetatively confined (McCarthy *et al*., 1992), resulting in wide distribution of water in the areas around distributary channels. Raised tracts such as inverted channels or anthills form islands in these swamps, and these accumulate precipitates from the water due to transpiration by trees on the islands (McCarthy *et al*., 1993a).

Precipitation of calcite and amorphous silica in the soils of these islands causes them to grow both vertically and laterally. It seems that lateral growth dominates over vertical growth, as vertical growth will be limited by the level of the surrounding water surface. In addition, the accumulation of soluble toxic salts in the island centres forces tree growth and hence calcite and silica precipitation to the island fringes, thus promoting lateral growth. This precipitation and consequent island growth is responsible for most of the micro-topography of the wetland, while inverted channels contribute a lesser proportion of the raised terrain. In effect, the micro-topography is simply an expression of the localized aggradation taking place on the fan surface. Continued lateral growth of islands, coupled with shifts in water distribution, eventually results in coalescence of islands to create a broad, raised platform, which would constitute an increment of sedimentation on the fan surface.

Channel beds can aggrade by between 1 and 2 m before abandonment, while islands appear to grow vertically to about the same amount, both being limited by water levels in the swamps surrounding the channels. Once abandoned, inverted channels will form local barriers to water flow, and will divert water on the fan surface, while aggraded islands will similarly divert flow. This suggests a feedback mechanism may be operating on a long time scale, which constantly alters water distribution across the fan surface, while at all times maintaining the local relief to generally less than 2 m. In this way, we believe the fan maintains its smooth surface, and sustains its constantly changing micro-topography.

An important corollary of the limited local relief is that the depth of water in the swamps always remains shallow (<2 m), as has been found by measuring water depth along long transects (UNDP, 1976). This implies that a second feedback mechanism is operative: the amount of aggradation is restricted by water depth to around 2 m, producing limited local relief. The limited local relief, in turn, will tend to maximize the area of inundation and restrict water depth.

The permanent swamp is the site of clastic sedimentation and peat formation, and virtually all clastic material is deposited there. Bedload accumulates in channels, whilst suspended load is filtered out by, and accumulates in, surrounding peat. The peat has a low preservation potential and is periodically destroyed by peat fires. Ash accumulation results in net aggradation (McCarthy *et al*., 1988). The area of the permanent swamp (less islands) is 2400 km^2, whilst the area of islands in the seasonal and occasional swamps (where solutes mainly accumulate) is 4300 km^2 (Gumbricht *et al*., 2004a). The permanent swamp therefore accumulates 11·5 kg km^{-2} a^{-1} of clastic material, whilst the islands in the seasonal and the occasional swamp accumulate 12·5 kg km^{-2} a^{-1} of precipitates. Thus clastic and chemical sedimentation are essentially in balance, and aggradation rates in the proximal and distal regions of the Okavango are the same.

The similar aggradation rates of permanent and seasonal swamps suggest that a feedback loop is operating between them which may work in the following way: if aggradation in the seasonal swamps exceeds that in the permanent swamps, the area and depth of permanent swamp will increase, while the reverse will apply if the permanent swamp aggrades faster than the seasonal swamp.

The micro-topography is well defined in the active wetland and its fringes, but the method used here is not applicable to those areas of the fan which do not receive seasonal flood water. However, the coarser resolution DEM developed by Gumbricht *et al.* (2001) provides some indication of the topography in these areas. Although the spatial resolution of this DEM is 500 m, the elevations extracted from long transects indicate that the fan surface beyond the active wetland lies within 2 m of a theoretical smooth surface. This distal surface is presently inactive, but localized aggradation in the present wetland will in the future cause water to shift to these presently dry areas. The calculations above suggest that over a period of 150 000 years (assuming present climatic conditions), all regions of the fan will have experienced active sedimentation.

Permanent swamp areas are periodically abandoned and become dry land. Termites invade these areas and create island nuclei. These eventually enlarge by the mechanisms described above. In time, such areas may revert to permanent swamp as water distribution switches. Islands then become drowned. For this reason, we believe that the undulating topography of the fan is not only a feature of the seasonal swamps, but also exists beneath the permanent swamps. The widespread undulation of the fan surface explains why islands appear to become more common down-fan. In the permanent swamps, many are submerged, but start to emerge in the distal reaches. They are most visible in the seasonal swamps where water is restricted to lowest-lying ground. Towards the fringes of the seasonal swamps, islands start to become less visible, because they are less distinct due to shrub encroachment on flood plains. Beyond the seasonal swamps, the vegetation contrast is completely lost and the local topographic highs that would constitute islands are no longer visible. Thus, the apparent distribution of islands is probably simply an artifact of varying water depth and distribution across the fan surface.

Applications of knowledge of the local micro-topography

The micro-topography mapped in this study has provided insight into the sedimentation processes operating on the Delta. However, it also has several practical applications. Although in-depth discussion of these is beyond the scope of this paper, we mention them here in order to draw attention to them, and thereby to promote further investigation.

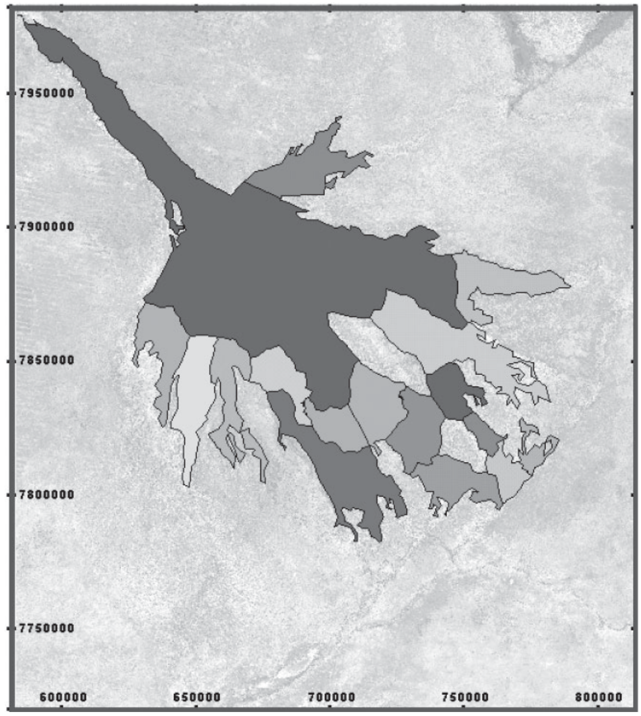

Figure 6. Map showing the sub-regions of the Okavango Delta, derived from analysis of the micro-topography.

1. *Delineation of sub-basins for hydrological modelling.* The micro-topography suggests that the wetland surface is not a single entity, but local micro-topographic barriers permit the division into a number of sub-regions. Sub-regions can be delineated by seeking the minimum openness between local troughs and adjacent troughs (Gyllenhammar and Gumbricht, in press). These sub-regions may be a product of differences in cumulative flooding frequency, the presence of radially arranged, long, sinuous inverted channels which form barriers to lateral flow, as well as tectonic effects. The major sub-regions identified are indicated in Figure 6. These results have been used to explore secular changes in flood water distribution over the last 15 years (Gumbricht *et al*., 2004b), derived from historic satellite imagery, and indicate that a gradual shift of seasonal flood water from the Boro to the Xudum channel is taking place.

2. *Area–volume calculations.* The micro-topography permits the calculation of area–volume relationships of both water (flood plains) and land (islands) at a variety of scales. Previous hydrological models have used data from a single site where micro-topography was mapped in detail (UNDP, 1976; Gieske, 1997), or have made generalizations (Ashton and Manley, 1999). The model developed here allows the variability of island density and distribution to be taken into account in calculating area–volume relationships across the wetland. Such calculations will be of immense value in constructing detailed hydrological models of the wetland (Bauer *et al*., in press).

3. *Hydrological routing*. The micro-topography can also be used to model hydrological routing through the wetland and in principle could be used to create a distributed hydrological model for the entire wetland. Current application of the derived map for sub-pixel parameterization of a hydrological model indicates that model performance has improved significantly compared to modelling with this parameter set to a constant (Bauer *et al*., in press).

4. *Local-scale flood prediction.* Gumbricht *et al.* (2004b) have developed a statistical model for distributed flood prediction, calibrated using inflow and rainfall records, with the resulting flooded area being estimated using coarse resolution (1 km^2) NOAA AVHRR satellite images extending back over 15 years. The model can predict the likely area of flooding three months in advance of the seasonal maximum with an estimated accuracy of better than 90 per cent at that scale. The site specificity of this model is, however, poor, because of its 1 km^2 resolution. The micro-topographic map, when used in conjunction with the flood prediction model and local calibration in the field, could improve the spatial resolution of predicted flood distribution, and in particular could be used to predict which local areas within each 1 km^2 pixel are likely to be flooded for any predicted regional-scale flood.

Conclusions

Wetland vegetation is extremely sensitive to small differences in elevation. Hence the micro-topography of the Okavango wetland could be captured by assigning empirical elevations to remotely sensed vegetation community classes. Even though the method is relatively simple, and somewhat empirical, it produces fairly accurate results, and moreover allows low relief bathymetric data to be obtained, as well as estimates of ground elevation beneath thick forest cover, which would not be possible by other remote means. This micro-topography has several applications related to hydrology and sedimentology.

The analysis of the micro-topography of the wetland has provided insight into the origin of the remarkable smoothness of the fan surface. Sedimentation occurs by precipitation of calcite and amorphous silica in island soils, and by accumulation of bedload sand on channel beds and point bars. The former mechanism accounts for about two-thirds of the total sedimentation on the fan. The resultant vertical aggradation of both is limited by local water depth. Accumulation of bedload in channels results in maximum local aggradation of about 2 m, as channels fail and avulse at or before this degree of aggradation is attained. Aggradation by precipitation of calcite and silica beneath islands is also limited by local water depth, and precipitation is confined largely to island fringes. Islands grow laterally and eventually merge, producing an elevated platform. Island growth is augmented by accumulation of dust and sand blown off the flood plains by the prevailing winds. Preferential aggradation on one part of the fan will cause water to shift elsewhere on the fan surface, thereby moving the site of active sedimentation. In this way, sediment is evenly spread over the fan surface. Water depth limits the maximum local aggradation to around 2 m creating a very smooth surface with restricted local relief. The smoothness of the surface creates a feedback loop by ensuring widespread distribution of water, which limits water depth. The micro-topography is simply an expression of localized sedimentation taking place on the fan. Constant switching of water distribution, driven by local aggradation, has distributed sediment widely over the fan.

The volume of islands, including their underlying carbonate platforms, calculated from the micro-topography, combined with estimates of current sediment influx rates suggest that the land surface of the wetland is probably only a few tens of thousands of years old. Mass balance calculations indicate that over a period of about 150 000 years under current climatic conditions, most of the fan surface would at one time or other have been inundated, and thus subject to sedimentation.

The micro-topographic maps developed in this study have several potential practical applications, especially in hydrological modelling. These include the delineation of sub-regions on the delta surface, area–volume relationships, hydrological routing and flood prediction.

Acknowledgements

This study was made possible by grants from the Swedish Royal Academy of Sciences, the Swedish International Development Agency (SIDA), ETH Zurich, the National Research Foundation and the University of the Witwatersrand. Anglo American Corporation is thanked for providing satellite imagery, and an anonymous referee is thanked for constructive comments.

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