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Channels, wetlands and islands in the Okavango Delta, Botswana, and their relation to hydrological and sedimentological processes

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Abstract

The Okavango wetland in northern Botswana is one of the world's largest inland deltas. The Delta is a dynamic environment with shifting channel routes, causing growth and decay of flanking wetlands, and giving birth to islands. Primary island nuclei are formed by fluvial processes and bioengineering, and subsequently grow into secondary larger islands of irregular shape by clastic and chemical sedimentation, and later by coalescence. This article presents classifications and quantitative estimations of channels, wetlands and islands of the Okavango Delta. Islands were classified dependent on composition, pattern of composition, shape and juxtaposition. 90 % of all islands in the entire wetland were identified, with a classification accuracy of 60 to 85 %. Smaller islands of the nucleus types dominate the upper parts of the Delta, whereas larger secondary islands are more common in the distal part, a reflection of the age of the islands. Islands in the entry valley of the Delta, the Panhandle, are larger in the top end - the primary region of recent clastic sedimentation. The overall size distribution of islands in the Delta, however, shows no clumps, indicating that island growth is a uniform process over time and space. The total area flooded at least every decade is approximately 14 000 km^2, of which 9 000 km^2 is classified as actual wetland. Channel meandering decreases from the Panhandle to the distal part of the Delta, with the abandoned Thaoge channel as an exception. Occurrence of fluvially formed islands in the distal Delta indicates that the water flow and area of inundation must once have been much larger.

Introduction

The Okavango wetland in northern Botswana (Fig. 1) is one of the world's largest inland deltas. The Delta is in fact an alluvial fan covering almost 40 000 km^2. However, the area regularly affected by flooding at present is substantially smaller, and herein the term Okavango wetland is used to denote this smaller area.

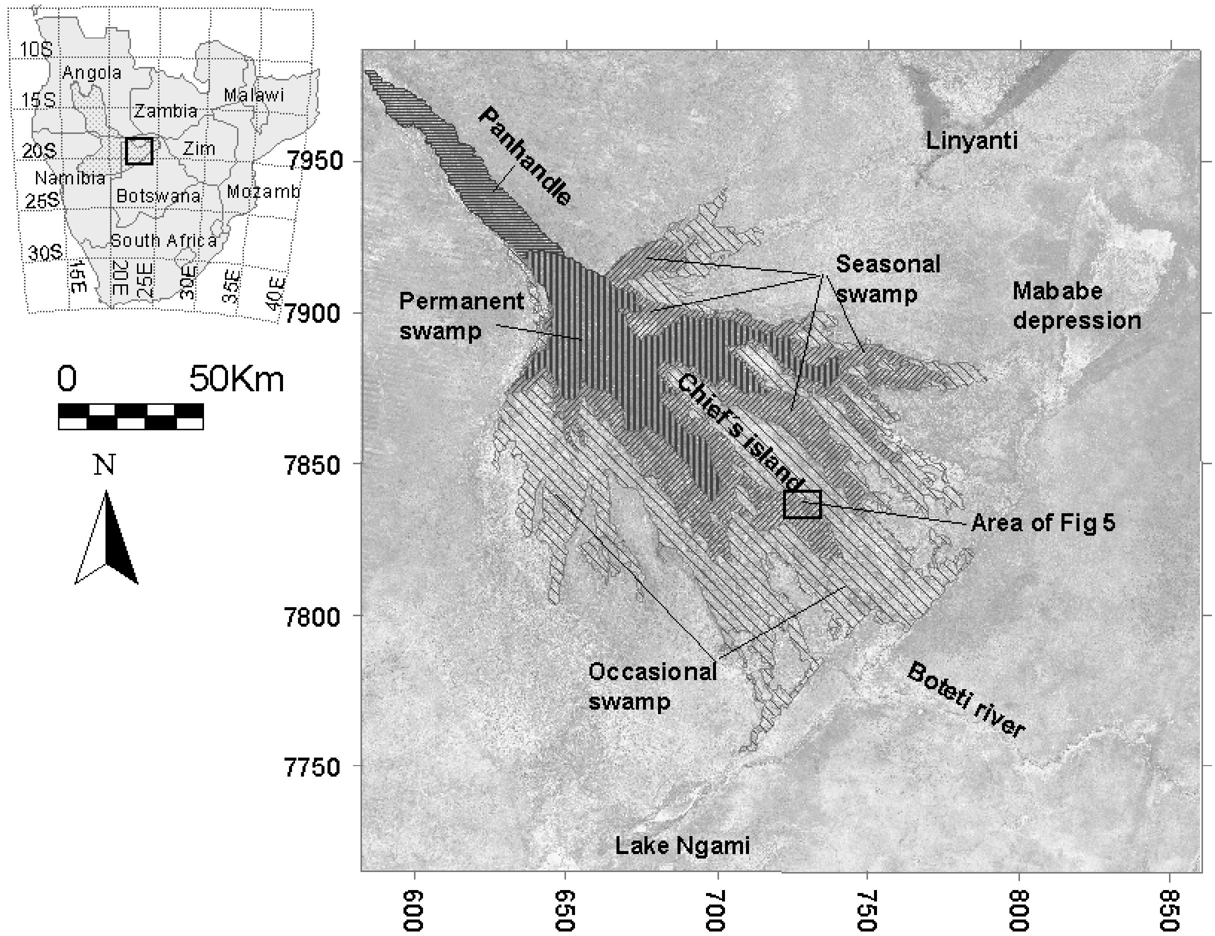

Figure 1. The Okavango Delta, Botswana, and its major physiographic regions (see text). The maps are projected to S UTM 34, using the Cape datum (Central meridian: 21; Scale factor: 0.9996; False Easting: 500 000; False Northing: 10 000 000). The coordinates are given in km in the main map.

The Okavango wetland is partly fed by local summer rains (~$6x10^9 m^3$ 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. Annual and interannual variations in water input are high, and historical evidence suggests that the flow has been both much bigger and also substantially smaller in the past. Over the past two centuries historical records reveal that the channel distribution on the Delta has changed (McCarthy and Ellery, 1998).

McCarthy and Ellery (1998) calculated the annual influx of bedload to the Panhandle to be 170 000 tons, with an additional 39 000 tons of suspended load. The chemically dissolved matter influx is estimated to be about twice this clastic sediment load (McCarthy and Ellery, 1998). Dissolved anions are heavily dominated by carbonate, balanced by cations of calcium, magnesium, sodium and potassium, and by silica. The total annual sediment load hence amounts to more than 500 000 tons, of which less than 5 % leaves with surface outflow as dissolved constituents. Garstang *et al*. (1998) estimated the annual aerosol-borne sedimentation over the Delta to be 250 000 tons. Sedimentation over the Delta surface is controlled by a variety of mechanisms, which all contribute towards continuously remoulding the land surface.

Even though the Delta is surprisingly well covered by maps, there is a lack of both quantitative and qualitative descriptions of its major components; channels, wetlands and islands (Fig. 2). The Delta is a continuum from wet to dry areas, which constantly change over a variety of spatial and temporal scales. Some areas are permanently flooded, some get flooded each year, others are only flooded during particularly wet years.

Figure 2. Major components of the Okavango Delta – channels, wetland and islands. Note how the riparian forest dominated island coalesces into a single landmass during the dry season. The area of the photograph is indicated in Fig. 5.

The aim of this study was to classify the continuum of wet and dry areas into object oriented classes of islands, and wetland regions; to estimate the qualitative and quantitative distributions of these components throughout the Okavango wetland; and to analyse their relation with hydrological and sedimentological processes. The article presents, to the authors' knowledge, the first digital object oriented dataset of islands, wetlands and channels with full spatial coverage of the Okavango Delta.

In this study, most emphasis has been put on the islands of the Delta, as they are considered to be the most sustained features of the landscape, surviving the intermittent existence of channels and related wetlands. As a working hypothesis islands were divided in discrete classes and the occurrence, size and density of island types was analysed in relation to physiographic regions and channels in various stages of development.

Method

Physiographic regions of the Okavango Delta

The Okavango Delta is commonly divided into four major physiographic regions (Fig. 1; Table 1): i) a confined entry channel, the Panhandle, ii) the permanent swamp, iii) the seasonal swamp, and iv) the sand dominated lower parts that are occasionally flooded, herein referred to as the occasional swamp. None of those broad regions is uniform in character, however, and each consists of a mosaic of wetter and drier areas, but with a particular type dominating. The Okavango wetland is surrounded by, and also contains large islands dominated by dry woodland and savannah.

Table 1. Physiographic regions with typical ecoregions of the Okavango Delta.

Physiographic region	Typical wet ecoregions	Typical dry ecoregions
Panhandle	Permanent swamp communities, Primary floodplain	Grassland Riparian forest
Permanent swamp	Permanent swamp communities, Primary floodplain, Secondary floodplain	Grassland Salt crust Riparian forest
Seasonal swamp	Primary floodplain (around channels), Secondary floodplain	Grassland Salt crust Riparian forest
Occasional swamp	Occasionally flooded grassland	Grassland Riparian forest
Dryland	-	Dry woodland/grassland

Herein wetlands are defined as areas that are flooded annually. Islands are defined as areas that rise above the floodplain, dominated by non-aquatic vegetation. Areas with non-aquatic grasslands that are not annually flooded, but have been flooded at least once per decade during the last 30 years are defined as an intermediate class, partly belonging to island, partly to the wetlands, herein termed "occasionally flooded grassland".

McCarthy and Gumbricht (submitted 2001) recently presented an ecoregion / land cover map covering the whole Okavango Delta. In their study high spatial resolution Landsat TM data (28.5 metres) were supplemented with approximately 200 low resolution satellite images for high temporal resolution of the flooding pattern. Combining these data sources with ancillary data they created a simplified ecoregion (or land cover) map in 10 classes based on flooding frequency and vegetation types (Table 2).

Table 2. Ecoregion classification scheme and example of species within each class.

Ecoregions/land cover classes	**Example of species / vegetation types**
River / Madiba / Backswamp lakes	*Nymphaea spp*
Permanent swamp communities	*Cyperus papyrus, Vossia cuspidata, Phragmites communis L., Typha capensis*
Primary floodplain	*Miscanthus junceus, Phragmites communis L., Cyperus articulatus, Schoenoplectus corymbosus*
Secondary floodplain	*Panicum repens, Sorgastrum friesii, Imperata cylindrica*
Dry grassland / Savannah thickets	Different grasses, sparse thickets, *Pechuel-loeschea leubnitziae*
Dry grassland / Savannah thickets occasionally flooded	Different grasses, sparse thickets, *Pechuel-loeschea leubnitziae*
Sparse dry grassland / salt crust	*Sporobolus spicatus, Pechuel-loeschea leubnitziae, Cynodon dactylon*
Sparse dry grassland / salt pan occasionally flooded	*Sporobolus spicatus, Pechuel-loeschea leubnitziae, Cynodon dactylon*
Riparian forest	*Ficus natalensis, F. sycomorus, F. verrucolosa, Diospyros mespiliformis, Phoenix reclinata, Syzygium cordatum, Garcinia livingstonei*
Dry woodland (dominated by *Acacia* spp.)	*Acacia erioloba, A. nigrescens, Combretum spp., Lonchocarpus spp.*
Dry woodland (dominated by mopane)	*Colophospermum mopane*
Dry woodland (dominated by *Combretum* spp)	*Combretum spp*

McCarthy and Gumbricht limited the Panhandle region to where the Okavango River bifurcates and forms the Thaoge and Nqoga channels (Figs.1 and 3). This point corresponds with the centre-point of the fan shaped downstream Delta (Gumbricht *et al*., in press). The permanent and seasonal swamps were delimited from flooding frequency (50%) and occurrence of dominating species (Table 2). Division between seasonal and occasional swamp was set at a flooding frequency of 10 % and the occurrence of key species.

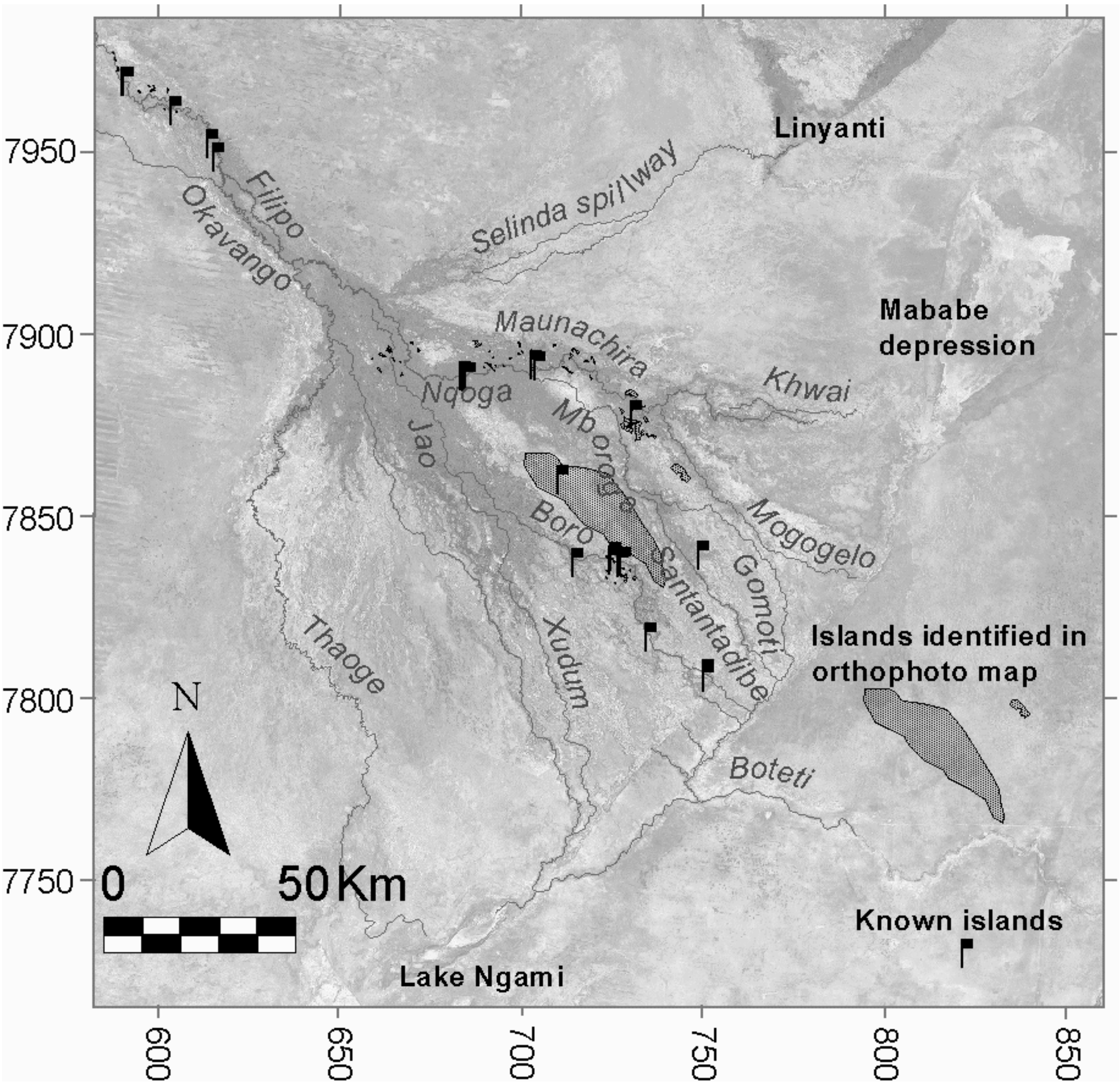

Figure 3. Channels in the Okavango Delta. The flag markers and island polygons indicate island sites used for evaluating the accuracy of the island classification (see text).

Channels of the Okavango Delta

Wilson (1973) identified three types of channels; upper or primary channels which link directly to the inflowing Okavango River, channels acting as distributaries of the upper (permanent) swamps, and outlet channels draining water from the perennial swamp. McCarthy *et al*. (1992) used a twofold classification of channels; either primary, which carry sediments directly from the source, or secondary that carry no externally derived sediment load. In this article the latter classification system is used.

Channel meandering

Channel meandering was analysed by comparing channel length at three scales; straight length from start to end, at 5 kilometre resolution and at 50 metre resolution. The ratio between the derived lengths is a measure of channel sinuosity or fractal dimension. Channels were extracted from the classification by manual on screen digitising. Where channels were vaguely defined, maps in the scale 1:250 000 to 1:350 000 were used as supplementary information.

Wetland distribution

The wetlands form a continuous matrix in the Delta landscape, and it is neither possible nor meaningful to create an objectification of the wetlands as such. The distribution of wetland ecoregions was instead analysed in relation to the identified physiographic regions.

Islands of the Okavango Delta

The Delta literary contains thousands of islands ranging in size from small, irregular islands a few square metres in area to large islands mainly harbouring dry woodlands. The bewildering variety of islands poses a problem for classification. Herein island classification was done based on genetic models for island formation reviewed by McCarthy and Ellery (1998).

The islands of the Delta continuously develop and change in close interaction with physical, chemical and biological processes of the Delta. Islands are hence not randomly distributed; they have logical patterns of juxtaposition, topography, chemistry and vegetation (McCarthy *et al*., 1998a). There appear to be three broad types of processes nucleating primary islands: islands related to meandering channels (point and scrollbar islands); islands formed by raised and abandoned channel beds (inverted channel islands); and irregular islands initiated as “anthills” and grown by termite bioengineering (Dangerfield *et al*., 1998; McCarthy *et al*., 1998a).

All island nuclei have the potential to grow, either by direct aeolian or fluvial sedimentation, or by the volumetrically more important chemical precipitation (see below) (McCarthy and Ellery, 1998).

Channel meandering is a dynamic process where the meandering river continuously erodes the convex side of the channel, with the concave side accumulating sediments forming a point bar. Periods with sustained high flow leave a trace as a raised bow-shaped sand bar on the concave side of the channel and a scroll bar is thus formed. At present over 90 % of the bedload sediment that enters the Okavango wetland settles in the Panhandle (McCarthy *et al*., 1991). Fluvial processes contributing to island initiation and growth are hence at present restricted to the panhandle and upper Nqoga (Fig. 3).

Sedimentation on the beds of the primary channels raises the channel bed to above the surrounding terrain because the sediment stays confined by the dense aquatic vegetation adjacent to it. Water leaks (or filters) from the channel to the backswamp areas and the channel system aggrades. Eventually the lateral hydraulic gradient becomes too large and avulsion occurs; a new channel is born, frequently nucleated on hippo (*Hippopotamus amphibius*) paths (McCarthy *et al*., 1998b). The estimated lifetime for a channel and its flanking wetlands is in the order of centuries (McCarthy *et al*., 1992). The abandoned channel desiccates and the flanking peat burns off turning the former channel bed into an elevated terrestrial ecosystem; a favoured habitat for riparian forests (inverted channel island). The surrounding wetland is replaced by grasslands, or secondary floodplains.

Anthill islands are initiated by termites, especially *Macrotermes michaelseni* which construct large anthills above the level of flooding. They also accumulate nutrients, thus creating a favourable habitat for colonisation by terrestrial vegetation (Dangerfield *et al*., 1998); terrestrial plants become established which attracts browsers and grazers, which subsequently leads to further nutrient enrichment (McCarthy *et al*., 1998a).

Transpiration (mainly by deep rooted trees) causes islands to grow laterally through chemical precipitation of calcite and possibly amorphous silica. Increasing vegetation, notably tree establishment, hence feeds island growth. It has also been suggested that island growth is related to deposition of aerosols, carried in large amounts over the region through the anticyclonic climate system dominating the Kalahari (Garstang *et al*., 1998), and also by local transfer of dust from the flood plains to islands (Krah, pers. comm.). The quantitative importance of regional and local aeolian processes in island development is however unknown. Over the relatively flat Delta surface vegetation distribution will be a key determinant in deposition pattern.

Primary island nuclei are formed by physical or biological processes (anthills, scrollbars and inverted channels) and can grow laterally and vertically by chemical precipitation and dust accumulation, and may evolve into an irregular shape. Herein the term “amoeboid” island is used to denote such secondary islands as a group, even if nucleated as point bars or abandoned channels. The nucleus can often be distinguished even after growth. Dependent on vegetation cover and distribution amoeboid islands are further subdivided (Table 3). If sufficiently elevated, amoeboid islands in both occasionally and regularly flooded areas may be colonised by trees forming “Riparian forest islands”. “Grassland islands” form where regular flooding prevents trees from establishing. “Salt islands” are dominated by a salt crust, or have a central salt crust partly surrounded by riparian forest. The salinity gradient determines species composition from island rim to interior (see Ellery *et al*., 1993), and the salt crust itself is either free of vegetation or dominated by very salt tolerant grasses (e.g. *Sporobolus spicatus)*. Large islands usually dominated by Dry woodland, are of unknown origin and are classified as “Dry woodland islands”. “Mixed islands” represent coalescence of two or more of the other types, and are here divided into those with and those without salt crusts.

Table 3 Scheme of island genesis and types in the Okavango Delta used in this study. Underlined category indicates priority class in the classification.

Island genesis	**Island coverage**	**Island class**	
		Form classification	**Coverage classification**
Primary islands			
Scrollbar	Grassland	Scroll bar	Grassland
	Riparian forest	Scroll bar	Riparian forest
	Mixed grassland / Riparian forest	Scroll bar	Mixed
Inverted channel	Riparian forest	Inverted channel	Riparian forest
Ant hill	Tree / grassland	Anthill	-
Secondary islands			
Amoeboid	Riparian forest	Amoeboid	Riparian forest
(grown from a primary island nucleus)	Central salt crust with rim of riparian forest	Amoeboid	Salt / Mixed with salt
	Central riparian forest with rim of salt	Amoeboid	Mixed with salt / (Riparian forest)
	Grassland	Amoeboid	Grassland
	Mixed grassland / Riparian forest	Amoeboid	Mixed / Grassland / Riparian forest
	Dry woodland	Amoeboid?	Dry woodland

From a recent study of the topography of the Okavango Delta, Gumbricht *et al*. (in press) concluded that tectonics play no significant role in channel or island distribution, or island formation. This suggests that large dry woodland islands of the Delta, including Chief's island (Fig. 1), are areas that have not been influenced by a channel or flooding for a longer (millennial) time. Large islands may be extreme examples of the amoeboid type.

Island delineation

The ecoregion/land cover classification presented by McCarthy and Gumbricht (submitted 2001) used knowledge on island spatial architecture to achieve a reliable classification of land cover in different parts of the Okavango Delta. In this study their land cover classification was used for delineating, classifying and analysing islands throughout the Delta. Islands were defined as contiguous areas surrounded by wetland (Fig. 4). Islands were classified from information on shape, size, land-cover content and distribution as well as juxtaposition in relation to the channel network.

Using the river channel network as seed areas, wetland areas as friction surfaces and non-wet (grasslands, forests and salt crusts) classes as barriers (Fig. 4), a cost-grow function was applied to the whole data set. Isolated areas into which the cost-grow function could not reach were delineated as islands. As islands grow during the dry season and shrink during flooding season two island data sets were constructed. The island-wetland intermediate class ("occasionally flooded grassland") was initially defined as a barrier, i.e. set to belonging to islands, using a threshold of 10 % flooding for the distal wetlands ("occasionally flooded area" in Fig. 1). The resulting image hence represents a sort of island "maximum" during the dry season (Figs. 2 and 4). "Minimum" or "core" island areas were extracted by applying the same method, but regarding the "occasionally flooded grassland" as a wetland, and by allowing growth into non-forested rim (1 cell, or 28.5 m) of the islands (Fig. 4). Also single, outstanding trees were allowed to be flooded (i.e. were regarded as anthills). For both datasets contiguous island areas were grouped and the land cover content of each island patch extracted, for the forest and salt crust class divided into "core" and "rim" area, again using 1 cell (28.5 m) as the width of the rim. In this way islands with interior salt crusts could be distinguished from those with salt crusts on the rim. Note that the wetland classes (water, permanent swamp communities and floodplains) become parts of islands if enclosed by "dry" classes (Fig. 4). These areas indicate the existence of a saltpan, albeit flooded at the time of the satellite image acquisition.

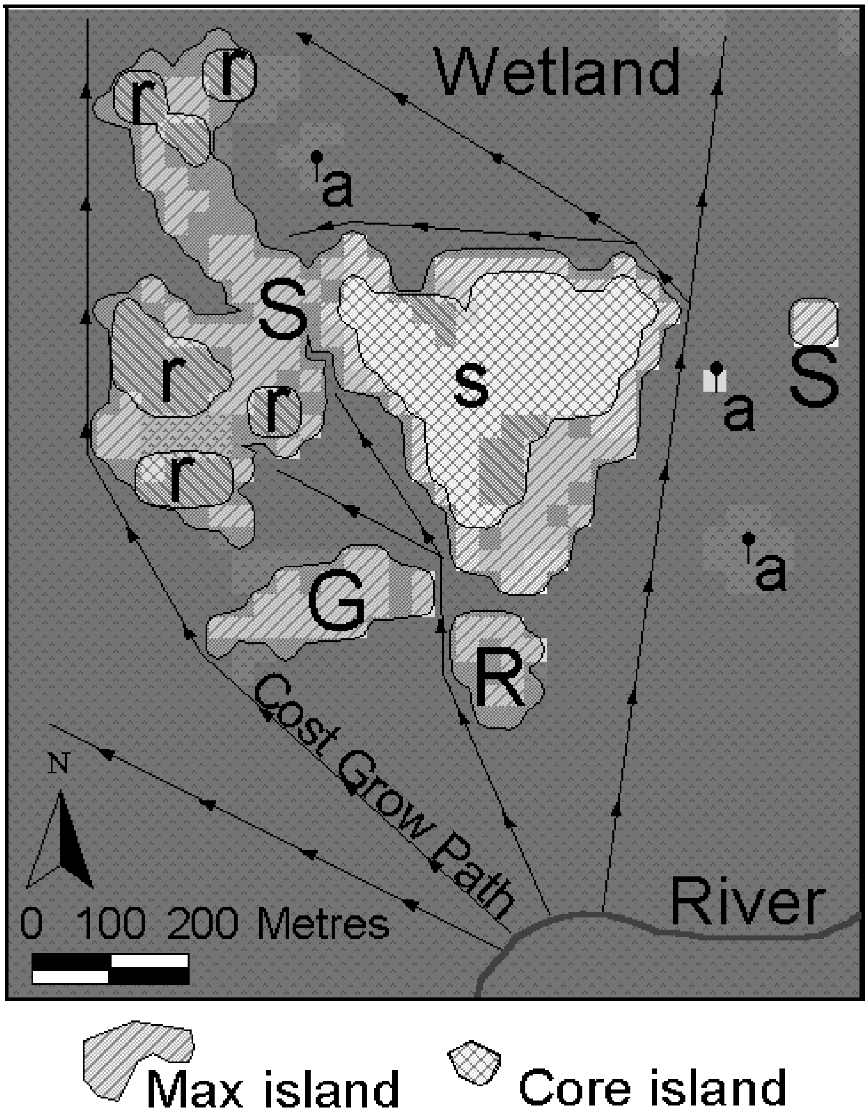

Figure 4. Island classification from the ecoregion map. Island areas were delineated by adopting a cost grow function in two steps (see text), deriving core and maximum extents of islands. Island coverage and coverage distribution, form, juxtaposition and size were used in a second step to classify islands; in this map: a – anthill, g – grassland, r – riparian forest, s – salt, capital letters for maximum islands. Note the small wetland patch *in* the large "S" island, situated between three "r" islands in its south western corner.

Island classification

All islands were classified dependent on composition, pattern of composition, shape and juxtaposition (Table 4, Figs 4 and 5). Hierarchical rules were inferred as given in Table 4, i.e. once identified the classification did not change. The classified islands correspond to various island types as given in Table 3. Islands were primarily classified into classes considering both genesis and coverage, and islands that could not thus be resolved were instead classified according to coverage. This dual classification scheme was kept in order to preserve information. The anthills and inverted channel islands were all considered to be forested. Anthill may be un-forested but only forested anthills could be identified in the background land cover data by McCarthy and Gumbricht (submitted 2001). Inverted channel islands only occur in the lower Delta, and are almost without exception forested. The scrollbar islands, on the other hand, are seldom forested; being situated in the upper, by stage variation affected Delta and Panhandle. Former scrollbar islands with substantial tree cover belong to the amoeboid class, being transformed through physical, chemical and biological processes.

Table 4 Island classification based on composition, pattern of composition, shape and juxtaposition. Classification was done using hierarchical rules, i.e. the first rule that identifies an island sets the category. Island classes 4 to 6 were generalised into single coverage classes. Classes 4 and 5 were joined with the Salt island class, and class 6 was joined with the Riparian forest class. In the evaluation, island categories derived from Rule no. 4, 5 and 8 were classified as Salt islands, and those from Rule no. 6 and 7 as Riparian forest islands.

Island type		**Definition**	**Rule no.**
Island genesis	***Island coverage***		
Anthill island	Riparian forest	< 4 cells and 100 % riparian forest	1
Scroll bar island	Grassland	> 75 % grassland, distance from channel < 1 km, roundness < 0.75	2
Inverted channel island	Riparian forest	> 75 % riparian forest, distance from channel > 1 km, roundness < 0.75	3
Amoeboid	Salt crust with riparian fringe	Salt crust in core, and > 10 % riparian forest in rim	4
Amoeboid	Riparian forest with salt crust	> 50 % riparian forest, and > 25 % salt crust	5
Amoeboid	Riparian forest with grassland	> 50 % riparian forest, and > 25 % grassland, or > 10 % riparian forest in rim and > 50 % grassland	6
Amoeboid	Riparian forest	> 75 % riparian forest	7
Amoeboid	Salt crust	> 50 % salt crust	8
Amoeboid	Grassland	> 50 % grassland	9
Amoeboid	Dry woodland	> 50 % dry woodland forest and dry grassland, larger than 10 km^2	10
Amoeboid	Mixed coverage with salt crust	Remaining islands with salt crust	11
Amoeboid	Mixed coverage	Remaining islands (lacking salt crust)	12

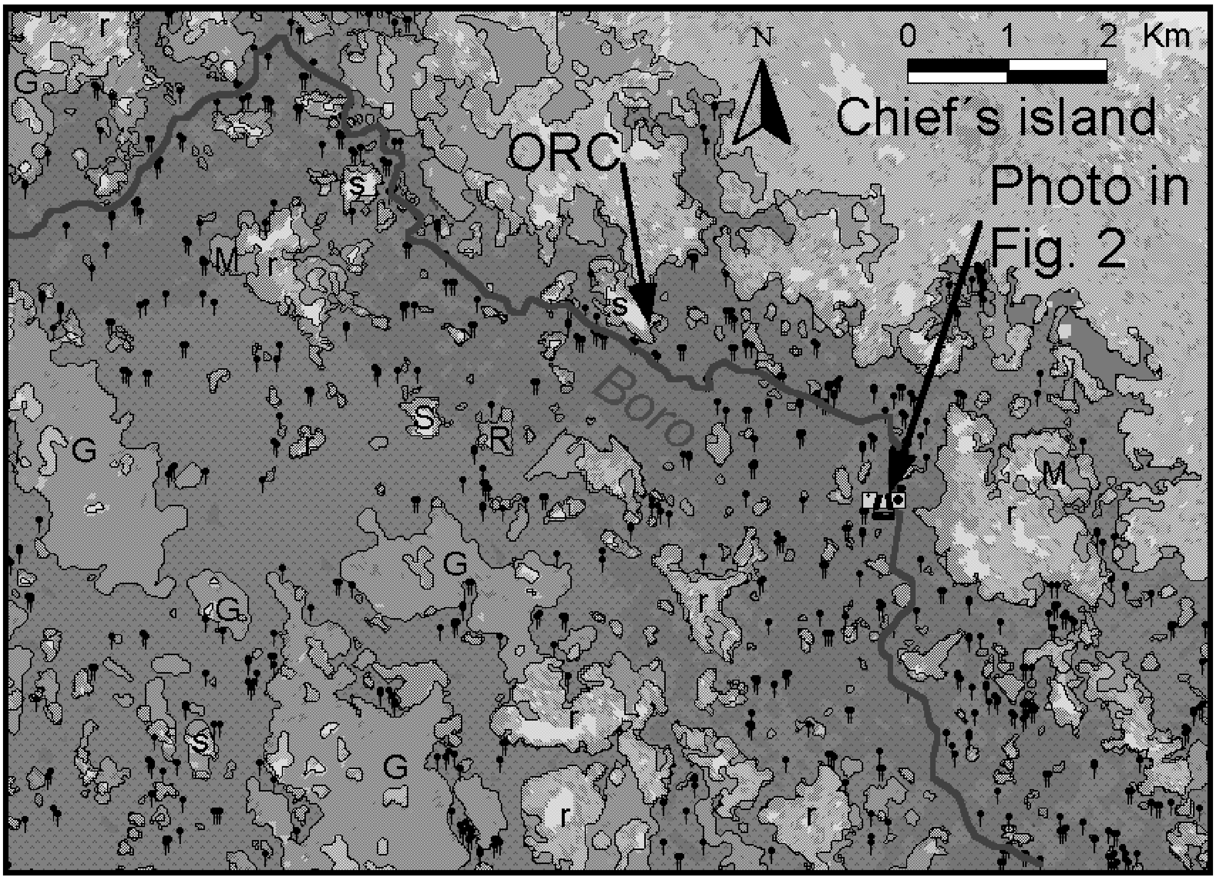

Figure 5. Detail illustrating the island object classification. The classes of a few islands are illustrated, g – grassland, r – riparian forest, s – salt, capital letters for maximum islands. The site marked ORC is the Harry Oppenheimer Okavango Research Centre field station, situated on a core salt island that is part of Chief's island (Dry woodland island). The area of detail is also shown in Fig. 1.

Anthill islands vary 4 orders of magnitude in size: from a few square meters to up to 5000 m^2. At the chosen scale of study (grain size of 28.5 meters) subpixel identification and fuzziness lead to difficulties resolving the size and shape of anthills. Hence, anthill islands were treated as a separate class of island in the analysis.

The accuracy of the derived island classification was tested against two independent data sets for the occurrence of islands as such, and for the island classes: a smaller but accurate dataset of 22 islands known to the authors through field visits or aerial surveys with photo documentation; and one larger but less accurate dataset derived from studying 1:50 000 scale topographic maps overprinted on aerial orthophotos (see Fig. 3). The latter are the largest scale maps available, and islands are indicated on those maps. The dataset was created by randomly selecting 80 islands from orthophoto maps distributed over different physiographic regions.

From detailed studies, and earlier fieldwork it is, however, evident that the topographic map is erroneous in its representation of islands. Geopositional inaccuracies and lack of detailed maps prevented us from identifying true anthills, and also made it impossible to assess any overestimations of islands in the classification.

Analysis of hydrological and sedimentological island relations

The distribution of sizes and types of islands was analysed in relation to the defined physiographic regions (Fig. 1), and in relation to channels in different stages of development (Table 5; Fig. 3). Islands with centres falling in a physiographic region, or being within 2 km from a channel were included in the analysis. Okavango and Filipo were used for representing old and new primary channels in the Panhandle. Filipo is an example of an anastomosed channel; the age of the present Filipo channel is not known. The Nqoga is at present the only primary channel in the Delta proper directly linked to the Okavango River, but aggradation is leading to avulsion into the adjacent secondary channels. Water is filtered through to the lower lying Jao channel, which is increasingly draining a larger portion of the outflow from the Delta. In the seasonal swamp the Santantadibe channel was selected for representing a failing (old) channel, and Boro for representing a fairly new channel.

Table 5 Channels and their environments used for analysing island occurrence and types.

Channel	Physiographic region	Hydrological regime	Sedimentological regime
Okavango	Panhandle	Old, primary meandering channel	Clastic sediments
Filipo	Panhandle	New, primary meandering channel	Clastic sediments
Nqoga	Permanent swamp	Old primary channel dying back	Clastic and chemical sediments
Jao	Permanent swamp	New secondary channel	Chemical sediments
Boro	Seasonal swamp	New secondary channel	Chemical sediments
Santantadibe	Seasonal swamp	Old secondary channel dying back	Chemical sediments
Thaoge	Occasional swamp	Old ephemeral channel, no flooding for past 50 years	Relict sediments

Results

Channel meandering

The Panhandle channels are generally of high sinuosity (1.8 to 1.9), while the channels on the fan are substantially lower (1.2 to1.4). The Thaoge channel is anomalous with a sinuosity of 2.3 (Table 6).

Table 6. Sinuosity of the channels in the Okavango Delta.

	Channel						
	Okavango	**Filipo**	**Nqoga**	**Jao**	**Boro**	**Santantadibe**	**Thaoge**
Length straight (m)	82	26	77	51	104	63	132
Length 5 km interval (m)	90	29	88	54	115	65	159
Length 50 m interval (m)	154	48	143	69	137	75	300
Sinuosity (5 km : straight)	1.1	1.1	1.1	1.1	1.1	1.0	1.2
Sinuosity (50 m : straight)	1.9	1.8	1.9	1.4	1.3	1.2	2.3

Wetland area

The total area of the Okavango wetland (as opposed to the Okavango Delta), including islands is approximately 13 500 km^2 (Table 7). The area affected by flooding at least occasionally during the last 30 years is approximately 9 000 km^2.

Table 7. Area of the Okavango wetland.

	Physiographic region			
Ecoregion	**Panhandle**	**Permanent**	**Seasonal**	**Occasional**
Total area (km^2)	817	2507	3287	7082
Forest and grassland (%)	5	3	17	55
Flooded grassland (%)	12	2	15	37
Secondary floodplain (%)	0	1	41	7
Primary floodplain (%)	37	12	21	1
Permanent swamp (%)	41	75	6	0
Water (%)	5	7	1	0

Island classification

The 22 islands surveyed by the authors were all represented in the island classification. These islands represent all physiographic regions, and all classes except inverted channel islands. Out of the 22 islands, 16 (or 70 %) were correctly classified, with an additional 3 being closely related classes. The extents of most islands were such that the actual size falls between the delineated “core” and “maximum” extent in the classification.

Out of 80 islands identified in orthophoto maps in the scale 1: 50 000, 71 (or 89 %) were delineated (Table 8). In general the mapped islands were again smaller than the maximum island extent in the delineation, but larger than the core areas (cf. Fig. 5). Islands not identified were in general small. All forested islands larger than 5 hectares, and all salt islands larger than 25 hectares were delineated. The largest unidentified island was a grassland island of 50 hectares. The orthophoto derived dataset represented islands ranging in size from 0.5 to 50 000 hectares.

Table 8. Island classification accuracy (columns: orthophoto maps, rows: classification). Dark grey cells show correct form and coverage classification, light grey cells correct coverage.

	Scrollbar	**Inverted**	**Anthill**	**Amoeboid**						
	Grassland	Riparian	Riparian	Riparian	Grassland	Salt	Mixed salt	Mixed	Dry wood	**Sum**
Scrollbar (Grassland)	**2**									**2**
Inverted (Riparian)		**1**		**1**						**2**
Anthill (Riparian)		**1**		**2**		1				**4**
Amoeboid (Riparian)		**3**		**11**				1		**15**
Amoeboid (Grassland)	**1**			3	**10**	2				**16**
Amoeboid (Salt)						**16**				**16**
Amoeboid (Mixed salt)						**3**	**2**			**5**
Amoeboid (Mixed)					2	5	1	**1**		**9**
Amoeboid (Dry wood)									**2**	**2**
None	1	1		3	1	3				**9**
Sum	**4**	**6**	**0**	**20**	**13**	**30**	**3**	**2**	**2**	**80**

45 of the 80 islands (56 %) were correctly classified, the mismatch, however, often being between nearby classes (Table 8). If using a simplified coverage classification scheme with only the island classes forested, grassland and salt crust, between 60 and 68 (dependent on the mixed class) out of 80 islands (75 to 85 %) were correctly classified.

Island classes and distribution

Our classification indicates that there are approximately 150 000 islands in the Okavango wetland, of which about 60% are small anthill islands (Table 9). The density, coverage and type of islands found in the Okavango wetland varies between the physiographic regions (Table 9). Island coverage (maximum islands) in the permanent swamp is only 5 % of the total area, whereas islands cover 50 % of the occasional swamp and 25 % of the seasonal swamp. The large island coverage in the Panhandle (18 %) is attributed to grass dominated islands in the upper part, most of which are regularly flooded when the seasonal flood enters the Panhandle. Stage variation in the Panhandle is up to 2 meters, explaining both the types and sizes of the islands in this region.

Table 9. Island types found in the different physiographic regions of the Okavango wetland.

	Physiographic region			
	Panhandle	**Permanent**	**Seasonal**	**Occasional**
Average island size (km^2)	4.6	2.8	8.0	14
Number of large islands	3139	4198	11043	24733
Scrollbar islands (%)	3	2	0	0
Inverted channel islands (%)	28	25	30	25
Riparian forest islands (%)	20	30	36	30
Grassland islands (%)	47	17	14	2
Salt islands (%)	0	12	5	1
Mixed islands with salt (%)	0	11	11	13
Mixed islands (%)	2	3	4	29
Dry woodland islands (%)	0	0	0	0
Number of Anthill islands	13685	16517	29009	43942
Total number of islands	16824	20715	40052	68675

The size distribution of islands (maximum extent) follows the coverage and density of islands; but the general patterns of size distributions are almost similar in all physiographic regions, and appear to be distributed in a power law (Pareto distribution) (Fig. 6). Grassland islands dominate in the Panhandle and upper part of the Delta, whereas mixed islands dominate the lower part. Islands dominated by riparian forests, including inverted channel islands, appear evenly distributed throughout the wetland. Scroll bar islands are largely confined to the panhandle and permanent swamps.

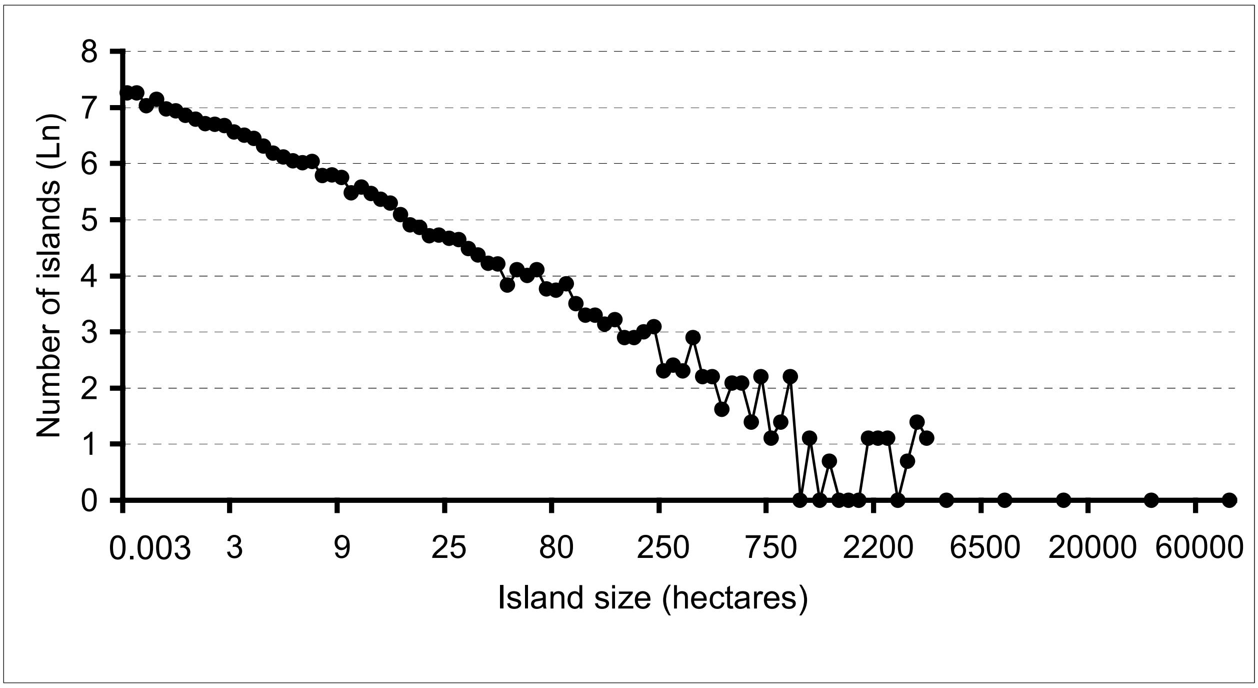

Figure 6. Distribution of island sizes (maximum islands) versus number of islands (Ln-Ln plot) for larger, i.e. non-anthill, islands in the Okavango Delta.

Islands along channels

The density and distribution of islands along different channels of the Okavango Delta reflect the physiographic classification (Table 5) of the river (Table 10). No difference could be found between the "old" Okavango and "new" anastomosed Filipo channels of the Panhandle, neither related to islands (Table 10) nor meandering (Table 6). The two channels in the permanent swamp (Nqoga – old, and Jao - new) show a difference in island distribution, with Nqoga having a larger portion of grassland and inverted channels islands, and much less salt islands compared to the Jao channel. Nqoga is also a more meandering channel compared to Jao (Table 6).

Table 10. Island types around selected channels of the Okavango wetland.

	Channel						
	Okavango	**Filipo**	**Nqoga**	**Jao**	**Boro**	**Santantadibe**	**Thaoge**
Segment length (km)	90	29	88	54	115	65	159
Average large island size (ha)	3.2	2.1	2.1	1.5	7.3	5.3	4.6
Number of large islands	1049	419	721	167	1379	1289	1938
Large islands per km	12	14	8.2	3.1	12	20	12
Scrollbar islands (%)	8	4	3	2	0	0	2
Inverted channel islands (%)	17	20	34	30	30	36	34
Riparian forest islands (%)	32	25	36	22	26	34	29
Grassland islands (%)	41	50	18	10	8	3	10
Salt islands (%)	1	0	2	4	13	14	13
Mixed islands with salt (%)	0	0	3	12	16	11	8
Mixed islands (%)	1	0	2	4	13	14	13
Dry Woodland islands (%)	0	0	0	0	0	0	0
Number of Anthill islands	6036	2726	3612	788	2595	2775	5541
Anthills per km	67	94	41	15	23	43	35

Discussion

Channel meandering decreases from the Panhandle to the distal part of the Delta, with the abandoned Thaoge channel as an exception. Scrollbar islands are common along the Okavango channel, and a few scrollbar islands have been identified in the upper portions of both Nqoga and Jao, on the Maunachira, as well as in the Thaoge. Having studied some of the islands in detail on maps in the scale 1: 50 000 superimposed on aerial photographs, it seems that there exists relict scroll bar islands in both the Maunachira and Thaoge channels. The highly meandering pattern of the Thaoge indicates that more water must have flown through the system in the past. Historical records reveal that the lower Thaoge ceased to flow around 1880 (see McCarthy and Ellery, 1998). At that time clastic sediments must have been carried beyond the apex of the fan, and not as presently being confined to the Panhandle. As speculated by McCarthy *et al*. (1991) the present situation with 90 % of the clastic sediment load being deposited in the Panhandle, must be transient. In the past higher sediment load entering the Thaoge may have induced meandering. The frequent occurrence of inverted channel islands throughout the seasonal, and even the occasional, swamps indicate that changes in flow regime are likely and that the distribution of permanent swamp has extended into what is now occasional swamp.

The present total wetland area of the Okavango Delta is clearly smaller than normally quoted. The flooded areas of the Panhandle and the permanent swamp shrink to 3200 km^2 when the grasslands surrounding the scattered islands dry out. The total area that gets at least flooded every decade is approximately 14 000 km^2, of which 9 000 km^2 is classified as actual wetland.

90 % of the islands in the Okavango Delta were delineated, missing out on small forested and larger un-forested islands. The island type classification generally could identify the correct island coverage class. Island form factors were less accurately identified, hence the classifications of inverted channel islands and scrollbar islands were less successful. In general the primary cores of such islands found were too irregularly distributed to allow an identification of the form.

The distribution in island sizes and coverage increasing from the proximal to the distal end of the Delta is likely to be a reflection of the average age of the islands. The younger islands in the proximal part are smaller and also in general anthill, scrollbar or inverted channel island types. Islands in the distal end are conversely older and more frequently of the secondary amoeboid type, with coalesced islands of the mixed type dominating the occasional swamp. The Panhandle is different, with a greater portion of larger secondary islands of the grassland class. This is probably caused by the recent clastic sedimentation, confined to the Panhandle over at least the last decades, and the large stage variation preventing trees from establishing.

The change in slope in the Panhandle (Smith *et al.*, 1997; Gumbricht *et al.*, in press) coincides with the appearance of anastomosed channels, including the Filipo. Closer scrutiny of the Filipo channel reveals that over long stretches of its course it has reoccupied old channel positions (Smith *et al.*, 1997). This is a probable explanation why there is no difference in island distribution or sinuosity between the Okavango and the Filipo.

Salt crusts are comparatively rare in the Panhandle compared to the other physiographic regions. In the permanent swamp, Nqoga, being directly linked to the Okavango River, has less salt crusts than the more recently formed Jao. The low frequency of salt islands in the Panhandle is puzzling, as it has been shown that salt accumulation is a consequence of transpiration and duration of inundation (McCarthy *et al.*, 1993). The Panhandle area must have experienced longer inundation than any other region of the Delta, yet salt islands are rare. This may, in part, be a consequence of the general paucity of treed islands in the Panhandle, which in turn is a consequence of the higher stage variations. However, even treed islands in the Panhandle lack significant salt accumulation, and the reason for this is unclear. There is a higher proportion of salt islands along the distal channels of the Delta (Boro, Santantadibe) compared to the proximal channels (Nqoga, Jao), which may reflect a general increase in salinity of swamp water down the fan due to evaporation of surface water. In distal areas, therefore, ground water lost by transpiration is recharged by more saline water than in the proximal areas of the Delta, so that salt accumulation is faster.

The channels of the distal swamp (Boro, Santantadibe) have lower sinuosities than the proximal channels (Table 6), and are not meandering. The overall size distribution of islands is fractal (Fig. 6), with no clear size clumps, showing that island growth must be a uniform process. New islands are continually being nucleated by termites and fluvial sedimentation, and these grow in size over time. Small islands grow slower than large islands. Smaller islands will grow primarily by chemical sedimentation, while aeolian processes will become more important on larger islands. Island coalescence will also be a significant process, particularly for intermediate to larger islands. Islands enlarge over time, and by coalescence eventually form an increment of sedimentation on the Delta surface, upon which new swamp systems will form. Sediment budget estimates reveal that clastic input to the Delta (ca. 200 000 t/yr) is far outweighed by aerosol (250 000 t/yr) and solute (ca. 350 000 t/yr) accumulation. Island growth must therefore be the dominant process of sedimentation in the Delta. Clastic sedimentation is confined to the permanent swamp and Panhandle, an area of about 3 300 km^2. Chemical sedimentation occurs mainly in the seasonal and occasional swamp over an area of about 10 000 km^2. Aerosol fallout occurs over both types of terrain. Sedimentation rate over the permanent swamp and Panhandle is thus $85t/km^2/yr$, while the seasonal and occasional swamps receive about $50t/km^2/yr$.

Conclusion

Land cover and its spatial configurations was used to delineate and classify islands in the Okavango wetland in Northern Botswana. 90 % of all islands in the entire wetland were identified, with a classification accuracy of 60 to 70 % for island type. The definition of island types was chosen to relate to the genesis and coverage of islands. Form factors were adopted for classification of scroll bar islands and inverted channel islands. Only considering island coverage in three classes (forest, grassland and salt) classification accuracy was 75 to 85 %. As the processes for initiation and growth of island is not corroborated, the definitions must be seen as preliminary. To the authors´ knowledge the article presents the first estimate of the number, sizes and types of islands in the Okavango Delta.

The upper part of the Panhandle has a comparatively high proportion of islands, all classified as primary scroll bar islands or amoeboid grassland islands, the reason being that the upper location functions as a primary sedimentation basin, with a strongly meandering channel. A large proportion of the islands in the Panhandle and permanent swamp are dominated by grassland, which we attribute to frequent flooding and higher stage variation, preventing trees from being established.

The total area of the Okavango Wetland that is at least occasionally flooded is 14 000 km^2, of which only approximately 9 000 km^2 is actually wetland or (annually) flooded grasslands. The Panhandle and the permanent swamp comprise 3300 km^2. As much as 17 % of the Panhandle area consists of seasonal swamp. In the permanent swamp, scattered islands of smaller size make up only 5 % of the total area. The area of the seasonal swamp equals that of the Panhandle and permanent swamp. These figures are substantially smaller than the areas usually quoted. That the area of the Okavango wetland has been larger in the past is evident from the meandering and associated scroll bar islands in the Thaoge channel.

There is a relation between island sizes, densities and types from the proximal to the distal part of the Delta. The Panhandle and permanent swamp have fewer and smaller islands, being predominantly of the primary (nucleus) types, whereas islands in the seasonal and occasional swamps are larger of the secondary (amoeboid) type. We conclude that this is a reflection of the age of the islands, where islands in the lower parts have had longer time to accumulate sediments and even coalesce. In addition, although permanent swamp does occasional extend into the distal Delta, this region is more often characterized by seasonal swamp, where the majority of islands are nucleated by termite mounds, and these tend to evolve to amoeboid types. The lack of any size clumps among islands indicates that the island forming processes are scale invariant – islands of all sizes have a proportional growth rate. The Pareto distribution of islands and the small sizes of primary (nucleus) islands clearly indicate that islands go through a development from genesis (up to a 1000 m^2) through sediment accumulation (hectare to square kilometre size) where after coalescence seems to dominate the growth processes. Islands larger than km^2 size are hence in general formed by coalescence of several secondary islands (i.e. are of the types "Mixed" or "Dry woodland"), and grow even faster as separating low areas close. We believe that these large islands eventually all will coalesce and that new channels will form over their surfaces in the next cycle of wetland formation. Island formation and growth is the dominant sedimentary process in the Delta, exceeding fluvial sedimentation by a factor of nearly 3. However, fluvial sedimentation occurs over a smaller area, and the rates of fluvial sedimentation and island growth are about the same.

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Channels, wetlands and islands in the Okavango Delta

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