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Mapping hydrological units in the Okavango Delta

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1 Introduction

In the framework of developing a hydrological model of the Okavango Delta there is a need to divide the system to be modelled into hydrological units. This need stems from the following:

- Hydrological processes and physical properties governing those processes within the analysed system are heterogeneous in space.
- The model, to be physically realistic should account for that heterogeneity.
- The heterogeneity can be captured by distinguishing hydrological units within the analysed system. Model computational units should represent the hydrological units.

Fluxes such as evaporation, infiltration and downstream discharge are different at various locations within the system. The differences between those fluxes result from differences in hydrological properties of the environment. Downstream discharge is influenced by hydraulic resistance and local water table slope. Infiltration is determined by infiltration capacity of the soil and relationship between surface and groundwater. Evaporation is influenced by factors determining energy balance partitioning at the surface, such as vegetation cover and water depth. All of these factors vary from location to location. However, in spite of their spatial heterogeneity, similarities occur. For example, a considerable stretch of a floodplain can be characterised by a relatively uniform vegetation cover, substratum properties and topography. The spatial heterogeneity can thus be captured by distinguishing units that are characterized by a certain degree of internal uniformity, but which are different than the other units. Such units can be distinguished at various spatial scales.

It is important to maintain the maximum possible link between model computational units and the physical system represented by the model. In this way, the model units can be independently parametrizated, i.e. model unit paramteres can be based on the physical characteristics of the area they represent rather than on calibration of the hydrological model. The parameterisation is simpler when the computational units represent physical units that account for hydrological heterogeneity.

The objective of the work presented here could thus be defined as follows:

- To define and delineate the extent of the parts of the Delta that are characterized by different suite of properties influencing hydrological processes and which are to be represented by model units.

2 Spatial heterogeneity in hydrology and hydrological units

Properties of media forming hydrological systems display a degree of heterogeneity at various scales. Due to the nested character of hydrological heterogeneity, the schematising of heterogeneous fields is process and scale dependent. A unit that is internally heterogeneous can be treated as a uniform component of a larger scale heterogeneity field, which, in turn, may be considered homogeneous at even larger scales (Fig. 1).

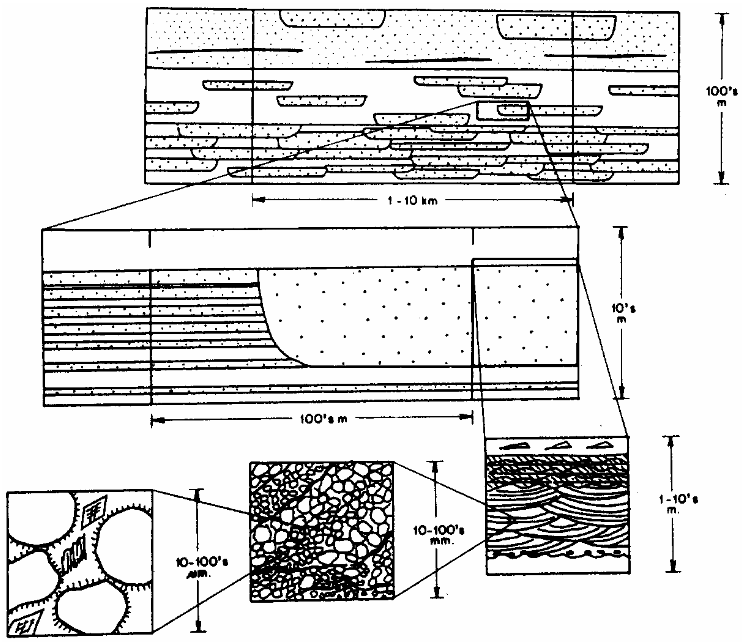

Fig. 1 Nested nature of spatial heterogeneity (after Weber, 1986)

The spatial distribution of hydrological properties (i.e. heterogeneous fields) can be of either continuous or discontinuous in character, and can be characterised by a certain degree of randomness and spatial correlation. Randomness may be the result of the random character of an analysed property, but often stems from incompatibility between the heterogeneity scale of a principally deterministic field, measurement scale and measurement density. Thus, by nature, infiltration rates, soil water potential, permeability and soil moisture contents, which vary at a very small scale and are sampled at a very small scale, are variables with a strong random component. Aquifer hydraulic conductivity, due to the fact that it can be measured for relatively large integration volumes by pumping tests, displays less randomness. But since the scale of such measurements is still considerably smaller than that of most of flow problems, even those are often treated in a stochastic manner.

The determination of spatial distribution of hydrological parameters from a limited number of small-scale measurements can be achieved within either an interpolation or regionalization framework. When the density of point measurements is comparable to the scale of variability, interpolation can be used. Deterministic (e.g. Thiessen polygons or linear interpolation) or a stochastic interpolation (kriging) framework is available, depending on the way the heterogeneity is perceived (Isaaks and Srivastava, 1989). When actual measurements are few, the spatial heterogeneity of hydrological properties can be captured by analysing proxy data (covariables).

Usually, a link exists between environmental factors and hydrological parameters. Units that differ in hydrological properties can thus be delineated by mapping such controlling factors. The environmental factors change in space in an often discontinuous manner, or are represented in this way. Of course, there is heterogeneity of hydraulic properties within the “environmental factor unit”, but the differences between units can often be of more importance for the analysed process than within-unit heterogeneity.

Segmentation of target parameter fields into units is usually carried out by analysis of one or several spatial variables that express the influencing environmental factors. The variables can be either discontinuous nominal classes like lithology, soil or land use, or classified numerical variables such as topographic slope or drainage network density. The units are often called regionalization units or simply hydrological units (Simmers, 1984). In a few systematic regionalization schemes dealing with catchment hydrological processes, names such as hydrologicaly similar units (Schultz, 1994), hydrological response units or hydrotopes (Wolski, 1999) were used.

The link between model units (computational unit) and hydrological units varies, depending on the type of model and application. Some models, such as SHE or MODFLOW use a rigid, grid-based model structure and thus hydrological units are not explicitly represented. If hydrological units are larger than the grid cells, parameters of the hydrological unit are attached to all the grid cells falling within that unit. If hydrological units are smaller than the grid cells, an effective grid cell parameter can be obtained from for instance statistical or stochastic analysis of sub-grid heterogeneity as expressed by the hydrological units.

Some models, however, are constructed to represent hydrological units explicitly. For example, in models based on the finite elements method of solving groundwater flow equations, the boundaries of computational units can be aligned to represent geometry of hydrological units. Catchment hydrology models such as WATBAL (Refsgaard and Knudsen, 1996) explicitly represent water balance units identified from GIS, although the units capture variation in vertical fluxes only (evaporation, infiltration and percolation).

Semi-conceptual lumped or semi-distributed models do not represent well the hydrological heterogeneity of “horizontal” fluxes such as surface runoff. This is so because the representation of hydrological processes is often based on simplified, schematic mathematical descriptions of hydrological response of the unit, rather than processes contributing to that response. As a consequence, parameters used by such models represent aggregated properties of the unit and cannot be directly measured in the field. There are, however, examples of “hybrid” models – i.e. models that have structure of a semi-conceptual model, but use explicit link between measurable catchment properties and model parameters (e.g. Wanakule, 1996, Wolski, 1999, De Vries, 1994). These, however, deal with groundwater runoff dominated systems, and examples of similar applications to surface runoff dominated system are rare.

3 Heterogeneity of hydrological processes and hydrological properties within the Okavango Delta

The Okavango Delta is a large and internally heterogeneous hydrological entity: it is a mosaic of channels, floodplains[1] and islands. Channels vary in depth, width and sinuosity. Floodplains are extremely diverse: apart from various sizes and planar shapes they differ primarily in characteristics of hydroperiod (duration, depth and frequency of flooding). Also, floodplains are characterized by the presence or absence of a surficial peat layer and are different in terms of substratum characteristics. Additionally, they can be covered by a variety of plant communities from aquatic plants such as *Nymphaea* sp to dense *Papyrus Cyperus* stands to *Phragmites Australis* to seasonal grasses such as *Imperata Cylindrica* and *Panicum Repens* (Ellery and Ellery, 1997). Islands vary in size, shape and vegetation cover.

Traditionally, what is known as the Okavango Delta is divided into parts based on two criteria:

- Presence of distributary systems
- Differences in flooding frequency and flood duration

Distributary systems

This is the natural division of the Delta based on the fact that flow in the Delta separates at its apex into basically 4 main systems that split further downstream, giving rise to 11 distributaries in its distal part. Fig. 2 shows the basic segmentation and names of the distributary systems.

[1] For simplicity, we do not differentiate here between papyrus swamp, grassy backswamps and seasonal primary or secondary floodplains. Term “floodplains” is used here in its generic meaning and denotes all areas that are floodable (thus both permanently, seasonally and occasionally).

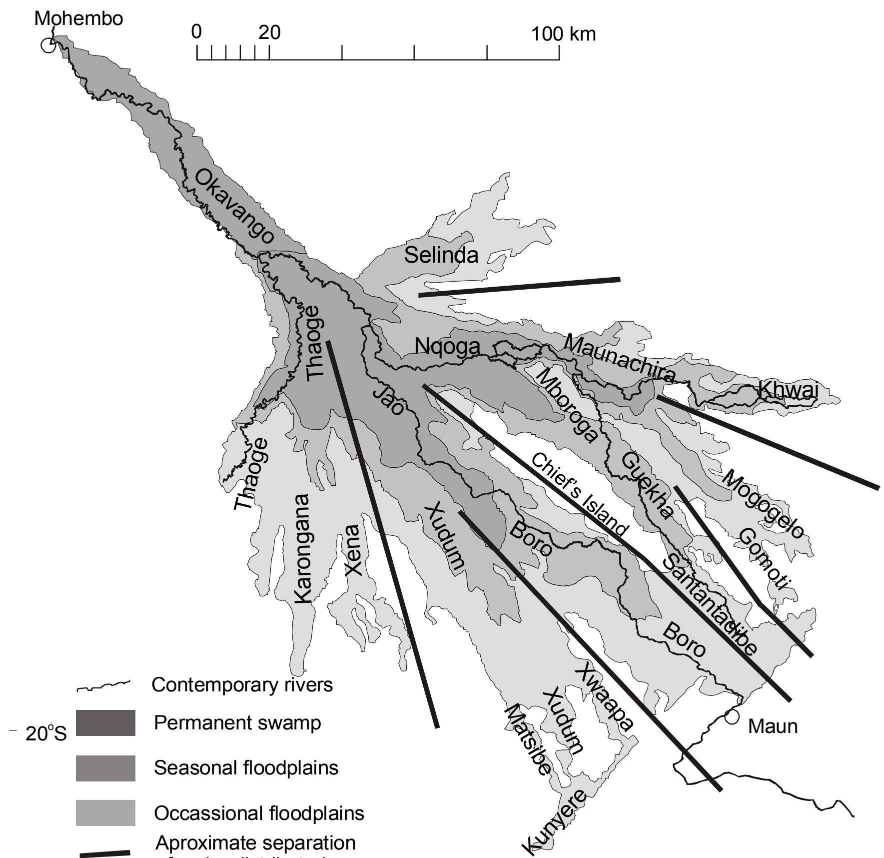

Fig. 2 Distributary systems and flooding zones of the Okavango Delta

The distributary systems represent separate flow paths, and thus form separate hydrological entities (similar to sub-catchments). They can be characterized by different properties, but their segmentation is not in fact based on differences in properties. Some stratification in hydrological properties occurs, however, in the downstream direction in each of the flow systems.

Flood frequency zones

Traditionally, four and sometimes five main zones are distinguished in the Okavango Delta based on flood frequency. Those are: permanent swamp, seasonal floodplains (regularly flooded and irregularly flooded), intermittently or occasionally flooded zone and drylands (SMEC, 1989). Such division reflects variation in hydro-ecological processes. The zones are composite ones: e.g. the intermittently flooded “zone” does not include only floodplains, but also islands within the belt where intermittent flooding occurs. Only the Chiefs Island escapes classification into any flood frequency unit, and is included in the dryland zone. Also, the Panhandle is often treated as a separate unit.

The division into flood frequency zones captures differences in terms of hydrological processes (frequency and duration of inundation), and to a certain extent the differences in properties of the units (SMEC, 1989). This is so because there is a feedback between geomorphology, vegetation and flood frequency. The flood frequency – vegetation link is an obvious one, and has been frequently described in the literature (Ellery and Ellery, 1997, SMEC, 1989). The link between flood frequency and geomorphology results from an inter-dependency between flood regime and the mechanisms of sediment deposition and the development of islands in the Okavango Delta (McCarthy and Ellery, 1995, McCarthy et al., 1993, McCarthy et al., 1986, Dangerfield et al., 1998). In this geomorphological concept, islands are said to originate as termite mounds, inverted channels or remnants of dry climate landforms (dunes). The first of these processes needs at least some time without inundation for the termites to establish themselves and later for trees to colonize the termite mound. The second type needs longer period of dry conditions in the flooding-avulsion-abandonment cycle. The third type needs even longer periods of drier conditions. The likelihood of dry conditions increases downstream with the reduced frequency of inundation. Thus, islands are rare in the permanent swamp zone where inundation is permanent, and their frequency increases downstream. Additionally, chemical precipitation processes that contribute to floodplain substratum texture, are more likely to be important in the intermittently flooded zone. The result of all those processes is that properties such as flow resistance, geometry of the flow domain, properties determining infiltration and evaporation (at larger scales) are in general captured by the flood frequency zoning.

Segmentation of the Okavango Delta into units based of flood frequency poses, however, a significant problem. Namely, the boundaries of such flood frequency units are not clearly defined and vary on a short term and long-term basis. Long-term variations in flood size were observed in the last 80 years (Fig. 3). Analysis of flood frequency for the entire 80 years window is thus meaningless, as there are areas (covered by floods larger than 9000 km^2), which were flooded frequently in the 1960s and were virtually not flooded during the 1990s. Similarly, areas that were constantly inundated in the 1960s were only seasonally inundated during the 1990s. Analysis of flooding frequency for 10-year windows (i.e. separately for the 1960s and 1990s) provides more a uniform frequency distribution, but significant differences occur between such windows. As a consequence, segmentation of the Delta into flood frequency units is ambiguous, and so is any grouping of the hydrological properties that is based on such units.

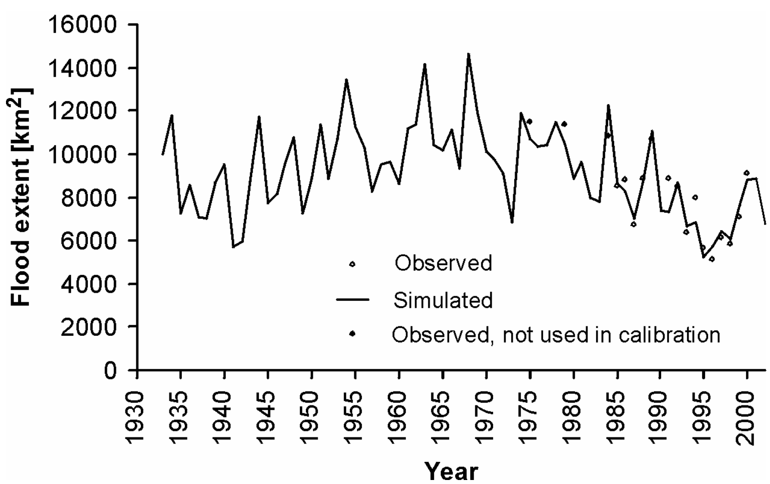

Fig. 3 Long term variation in flood size (after Gumbricht et al., 2003)

4 *Segmentation of the Delta in the previous models*

In the past, several hydrological models were created to represent the Delta hydrology. Some of them had semi-distributed character. This is how the model computational units were linked to the modelled system:

Dincer et al. (1976) model was composed of 13 cells. The authors describe segmentation into units in the following way:
"Even a casual glance at the satellite imagery of the Okavango Swamp shows some distinct features of the swamp which are important in the conception of a mathematical model of the swamp:
1) the most upstream portion of the swamp which is usually called the Panhandle region, is a well-defined floodplain type of swamp where the inflow of the Okavango River flows basically undivided, meandering between the parallel borders of the Panhandle.
    a) At the outlet of the Panhandle there is a central region where the flow is divided into four major primary systems [..].

These rather clear divisions and subdivisions of the Okavango Swamp provide a good guidance in selecting the general layout of the cells of the Okavango Swamp mathematical model. The number of cells in the flow direction is simply determined by the period used for the inputs, such as inflow, precipitation and the evapotranspiration. When monthly inputs are used, the model requires four or five cells along the flow line to simulate the travel of the flow wave in the swamp. According to this, the first cell of the model includes the Panhandle and the apex of the Okavango Delta. The downstream cells are defined by the general configuration of the distributary systems. “

Manley’s (WTC, 1997) model was, similarly to the Dincer’s one, composed of 13 cells. The author thus “…divided the Delta into 13 sub-areas or cells, each of which was related to a defined geographical area. These cells were chosen on the basis of the eco-zoning map and took account of features such as preferred flow paths and islands. “

Gieske’s (1997) model covered only the Okavango-Jao-Boro flow system. It was composed of 4 cells. Segmentation into units was essentially arbitrary. The units did not have specified representation in space and model parameters were calibrated using an automatic optimization routine. None of them were derived directly based on physical characteristics of the roughly defined zones the units were to represent.

Summarizing, the three existing models used explicit segmentation of the Delta into distributaries. Division of the distributaries into series of units was less objective. A link between physical properties of the environment and the parameters of computational units is not apparent in any of the models.

5 Approach

From the analyses presented above, it can be concluded that the units that are to be derived here should account for:

- size of the system and possibility of unit paramterization

  In theory, hydrological units at a plot scale (tens of m) can be distinguished, or mapped, based on environmental factors that influence hydrological processes, namely soils, vegetation and morphology. However, information on factors such as soils is virtually non-existent, floodplain vegetation reacts dynamically to flood conditions, and topography is derived in an indirect way from a land cover map. All these cause that the accuracy of determination and parameterisation of processes (such as evaporation, infiltration and flow) at that scale are questionable, and lead to the adoption of semi-distributed, semi-conceptual large units based hydrological modelling approach. As a consequence, the hydrological units to be used here, are:
  - large: comparable with the scale of the system
  - complex: internally heterogeneous
  - behaving like uniform entities when analysed at the system scale

- presence of flow (distributary) systems

- quantitative differences in hydrological processes

  The key element here is that the units should be independent of flood regime. In other words, what should distinguish the units is not duration and frequency of flooding, but rather factors that influence hydrological processes that are independent on the flood regime. In this way, units can be distinguished that would differ in water balances when subject to the same flood regime.

The following environmental factors (independent on flood regime) determine hydrological processes at the scale of the system:

- Geometry of floodplain/island system

  This factor influences infiltration dynamics, groundwater storage and indirectly surface flows (through determining geometry of flow system).

- Floodplain substratum

  This factor influences infiltration. Since there are no soil maps available, and no simple relationship has been noticed between soil type and surface reflectance as observed in satellite images, an indirect way of accounting for the role of this factor is used here. In the report on surface water-groundwater interactions (Wolski, 2003) it was noted that infiltration was evapotranspiration-driven, and that in the few studied sites floodplain soil played little role in determining infiltration flux. The sites studied were located mainly in the upper and middle reaches of the Delta, where floodplain soils are rather sandy. In the distal part of the Delta the likelihood of occurrence of clayey substratum increases. There, floodplain soils can have limiting effect on infiltration. That, in turn, could result in less development of riparian vegetation. However, the riparian zones there are often well developed (Ringrose et al., 2003), what indicates that even in the distal part floodplain substratum plays little role in determining infiltration flux. We therefore assume that the infiltration can be indirectly assessed by the size of riparian vegetation units.

- Topography

  This factor influences storage and surface flows.

The floodplain vegetation is a very important factor influencing water balance. However, floodplain vegetation is dynamic and changes depending on flooding frequency and flood duration, and thus has not been included above.

In view of the above, to account for the three major factors influencing hydrological processes in the Okavango Delta, i.e. floodplain topography, bifurcation of flow (distributaries) and geometry of floodplain/island system, the following procedure was devised in order to determine the hydrological units of the Okavango Delta. Three independent methods were used for delineation of hydrological units of specific characteristic. Agreement of the units derived with each of the methods was then studied, and unit division/merging or alignment was done when necessary. The following methods and criteria for differentiation are used:

1. Segmentation into distributary systems with the following criteria: independence of flow paths, restriction of flow across the boundaries for at least part of the flooding season.

2. Differentiation of topographical sub-basins of a certain degree of independence and enclosure with the criterion of minimum openness to other systems.

3. Differentiation of units based on the floodplain/island system characteristics with the following criteria: differences in floodplain/island area ratio, length of island perimeter, size of riparian zones.

6 Segmentation of the Okavango Delta into hydrological units

6.1 Distributary systems

The distributary systems form independent hydrological entities. As such they are the most natural units the Delta can be divided into. To delineate the distributary systems the following were analysed:

- flow pattern obtained from time sequence of flood maps
- water distribution from Landsat images
- ground information and archival data

Segmentation (delineation of unit boundaries) was based on the following criteria:

- boundaries were set between areas where flow is to a certain extent independent
- possible minimum exchange of water across the boundaries
- direction of flow across the boundaries is rather well defined
- boundaries form natural barriers to flow – i.e. flow is impeded on them and flood front is held there for some time during flood propagation.

Flood maps obtained from classification of NOAA AVHRR images, covering years of 1984-2000 were stacked sequentially according to increasing flood size. The sequence of filling up of areas as the flood wave propagates through the Delta was observed from the stacked maps and boundaries were drawn according to the above criteria. The basic configuration of island system was additionally studied from Landsat images (April 2000 for high flood coverage and January 1999 for low flood coverage). Those allowed for drawing boundaries of the units so that they followed chains of islands rather than floodplains.

The resulting map of units is shown in Fig. 4. Arrows indicate links between the units.

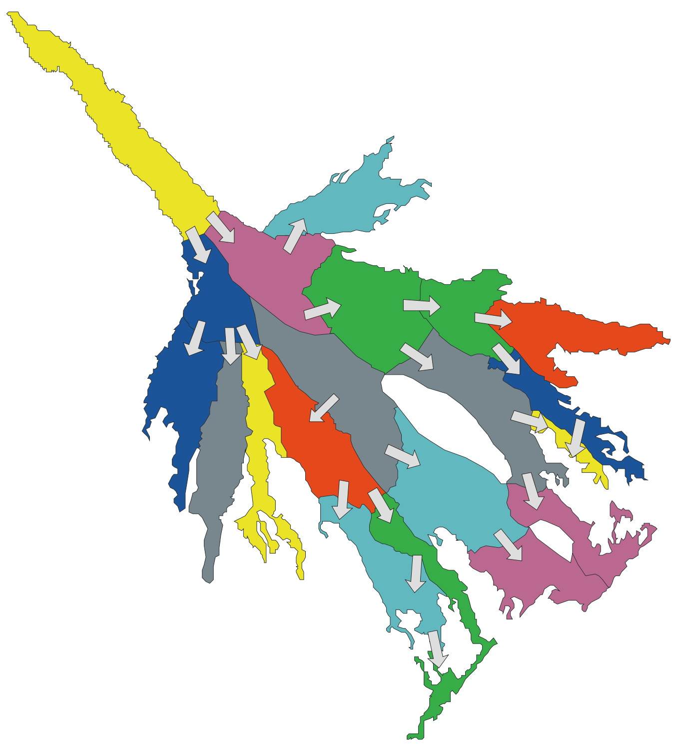

Fig. 4 Segmentation of the Okavango Delta into distributary systems

6.2 Sub-basins

This segmentation is based on the assumption that the Delta is composed of a set of relatively independent basins, which form topographic depressions within the regional topography.

The method used for segmentation of the Delta into sub-basins is based on minimum connectivity between the sub-basins determined from a digital elevation model (DEM). It has been described in detail in Gyllenhamar and Gumbricht (submitted). The DEM used here was prepared on the basis of disaggregation of a coarse scale DEM using the land cover map. The procedure is described in detail in Gumbricht et al. (submitted). The method of differentiation of sub-basins comprises three steps:

1. Identify and fill all depressions in the topographic data set,

2. Select the largest depressions as nuclei areas for sub-basin delineation,

3. Expand nuclei areas by cost distance growth to engulf intermediate areas.

<u>Identification and filling of depressions</u>

This is an iterative process where all the topographical depressions are identified. A depression is a cell, or a set of spatially connected cells for which surrounding cells are topographically higher.

<u>Selection of the largest depressions as nuclei areas</u>

In this step the depressions are vectorised and the area of each is calculated. A user-defined number of depressions to become subbasin nuclei, *n*, are then selected based on size.

<u>Expansion of nuclei areas by cost distance growth to engulf intermediate areas.</u>

The final step involves a growth process where non-nuclei cells are joined with the nucleus area to which each cell has the shortest travel distance over a friction surface derived from topography. For each nucleus area a friction surface is created by applying a cost grow function with travel cost inversely related to elevation. Each cell is assigned to the nuclei with the smallest cost distance to that particular cell. This was intended to represent reduced flow discharge in shallow water.

After the iteration process, the nuclei have assimilated their neighbours with the least cost distance and grown to a sub-basin. All enclosed areas will then be assigned to sub-basins.

The results of the segmentation are presented in Fig. 5. The Panhandle and the permanent swamp zone remain undivided. This partly results from the fact that topographic map used in this exercise is derived from a land cover map. The permanent swamp area is essentially featureless, and as a consequence, there is little data that could support differentiation of sub-basins.

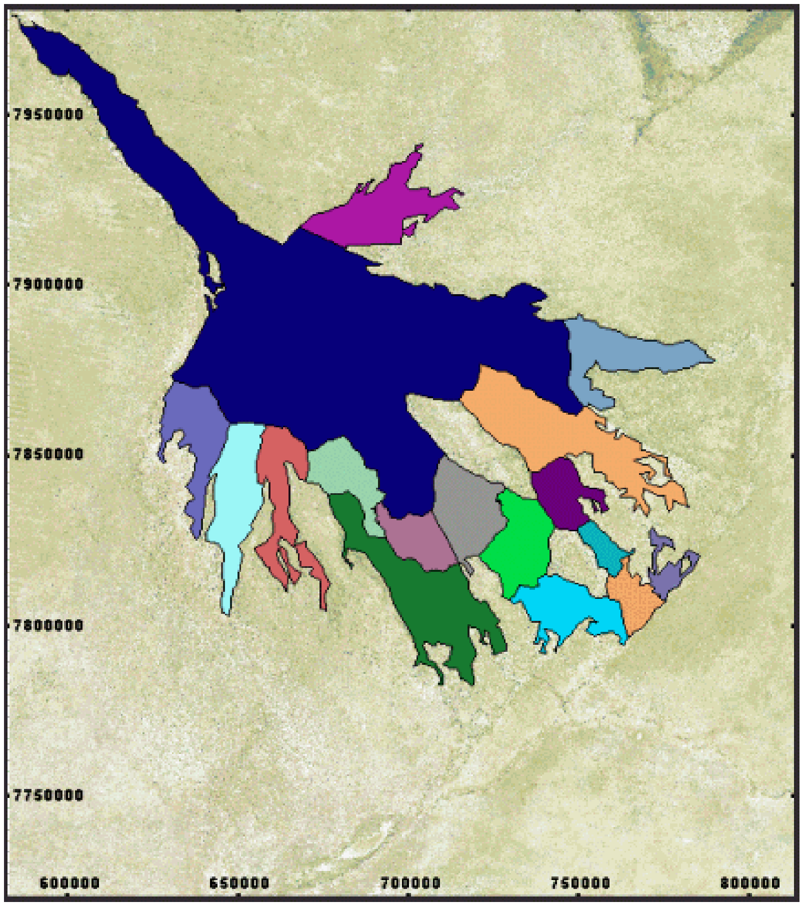

Fig. 5 Segmentation of the Okavango Delta into sub-basins

6.3 Geometry of island/floodplain system

This procedure was intended to map larger scale units that are different in water balance. The method used here is based on the assumption that the unit-scale water balance is determined by the geometry of floodplain/island system and abundance of riparian vegetation.

The method is based on three steps:

1. geometric properties of the floodplain/island system are determined for a set of arbitrary grid cells,

2. the grid cells are classified into classes based on differences/similarities in their properties,

3. spatial groupings of the grid cells belonging to various classes are then delineated. Those are considered composite units retaining some internal uniformity.

<u>Determination of geometric properties of island/floodplain system for a set of grid cells</u>

The selection of the size of the grid cells was based on the assessment of spatial correlation of the floodplain/island system. For that, a semi-variogram was calculated for a map picturing floodplains and islands (Fig. 6). The semi-variogram shows that the floodplain/island features display spatial correlation at distances of less than 1500 m, and for longer distances they are less and less related. It means that heterogeneity of floodplain/island system shows at scales larger than the 1500 m, so a grid size of 2500 m was considered appropriate for the analyses.

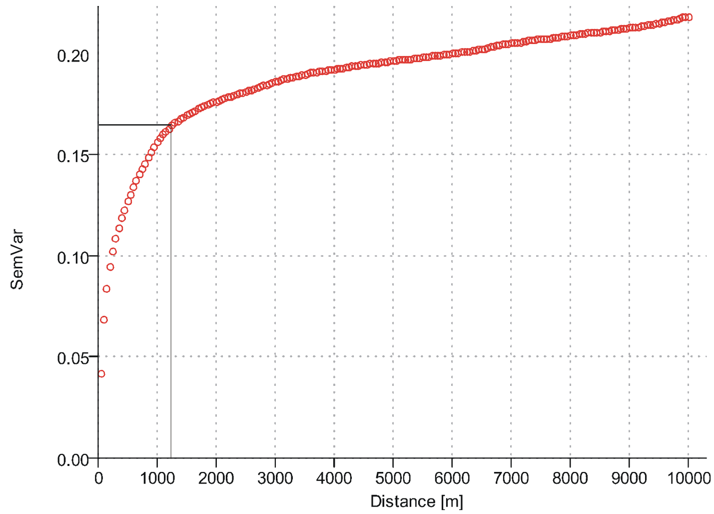

Fig. 6 Semi-variogram of the floodplain/island system map

The following properties describing the floodplain/island system were used to reflect differences in hydrological processes at the scale of a grid cell:

- Island area percentage in each of the grid cells (ISL)
- Length of island perimeter within a grid cell (PERIM)
- Riparian zones area percentage within a grid cell (RIP)

Those properties were parameterized based on land cover map obtained from classification of satellite images (McCarthy, J. and Gumbricht, in press). Maps visualizing the heterogeneity of those properties are presented in Fig. 7, Fig. 8 and Fig. 9.

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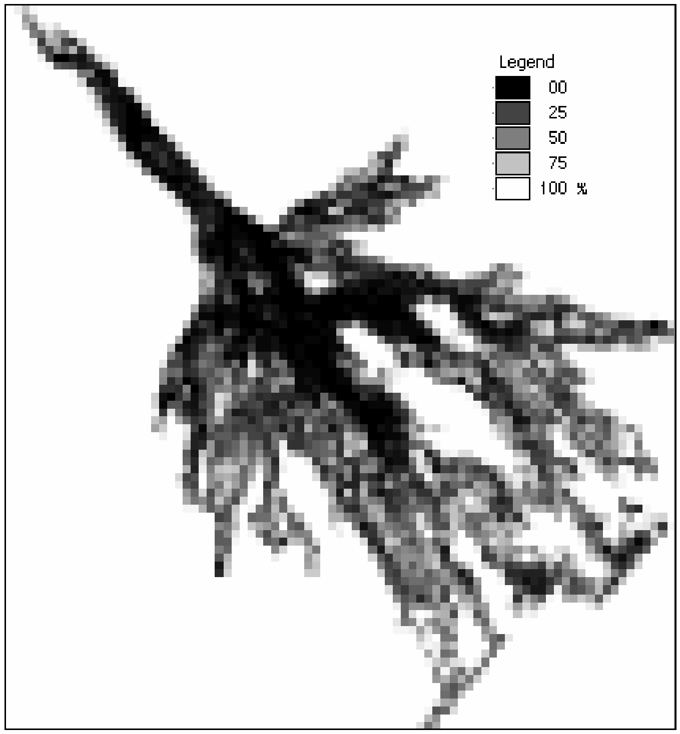


*Fig. 7 Island area percentage in 2500*2500 m grid cells. (ISL)*

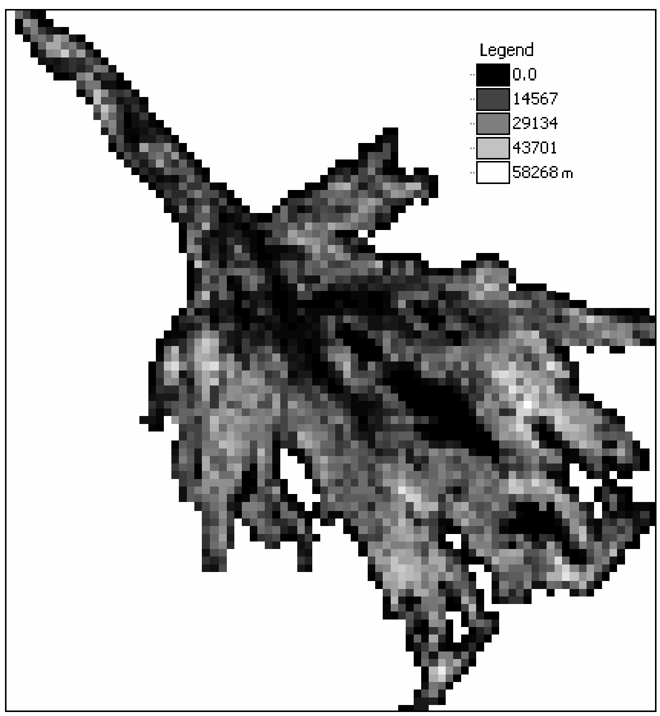


*Fig. 8 Island perimeter length in 2500*2500 m grid cells {PERIM)*

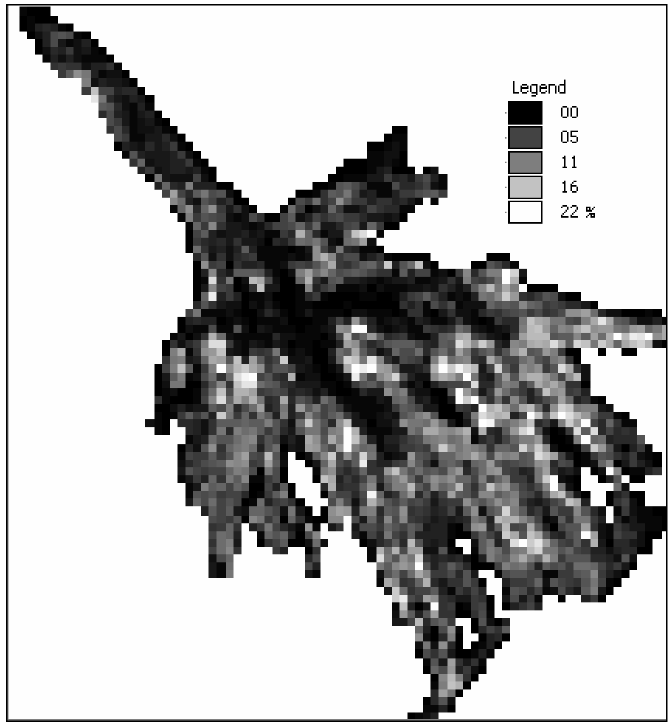
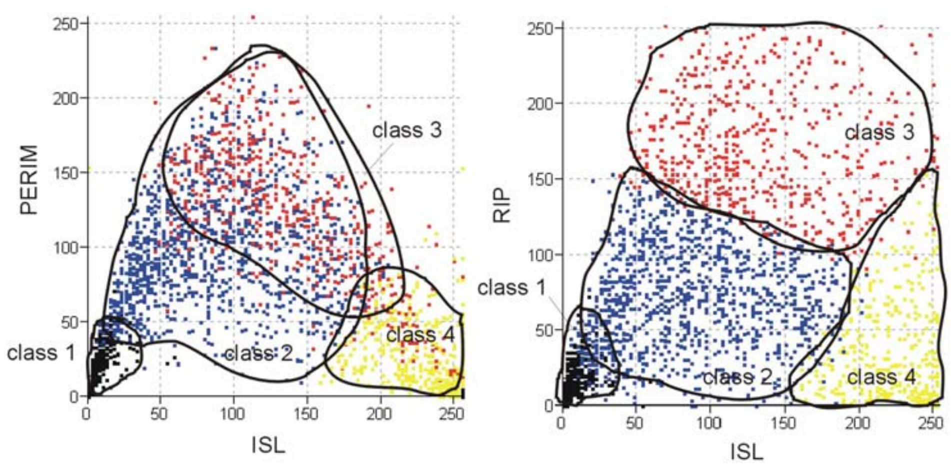


*Fig. 9 Riparian zone area percentage in 2500*2500 m grid cells (RIP)*

Classification of grid cells according to their properties

Fig. 10 shows the relationship between the three parameters (ISL, PERIM and RIP) for the grid cells. This 3-dimentional feature space was divided into groups (clusters) using unsupervised clustering procedures.



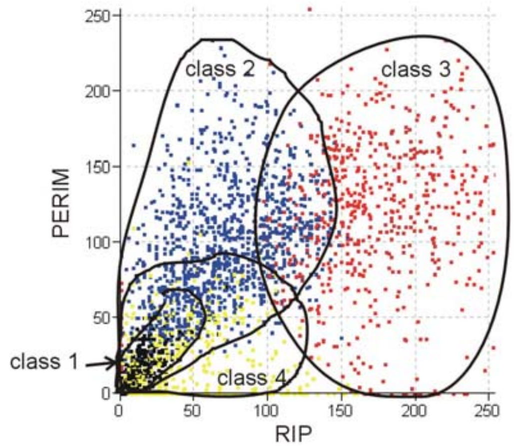


Fig. 10 Feature space of ISL, PERIM and RIP variables

Delineation of spatial groupings of grid cells falling into each of the classes

Grid cells belonging to each of the clusters were visualized as a map, and the grouping into large units was done manually (Fig. 11).

The feature space of the grid-scale parameters does not show any significantly different groups of grid cells. The parameters are rather uniformly distributed over the spectrum of values. The clustering is thus rather arbitrary. Four classes were distinquished, that essentially differ in "wetness" (understood as wetness when flooded). Two extreme cases are Class 1 which represents pure floodplains and Class 4 which represents drylands. In the first one there are no islands and so a low island to floodplain ratio and no riparian vegetation, while in the second one there is some riparian vegetation and high island to floodplain ratio. In between there is a "wetter" Class 2 and "drier" Class 3.

The "wet" Class 1 occupies the central part of the permanent swamp, The "dry" Class 4 coincides with the major islands. The "wetter" Class 2 covers the Panhandle, Maunachira, Selinda, mid-Boro, central Guekha, Xudum, Thaoge, and Xwaapa, Boronyana area and Shorobe floodplains. The "drier" Class 3 covers Khwai, Mogogelo, Gomoti, Santantadibe, Lower Boro. Lower Xudum and Karongana.

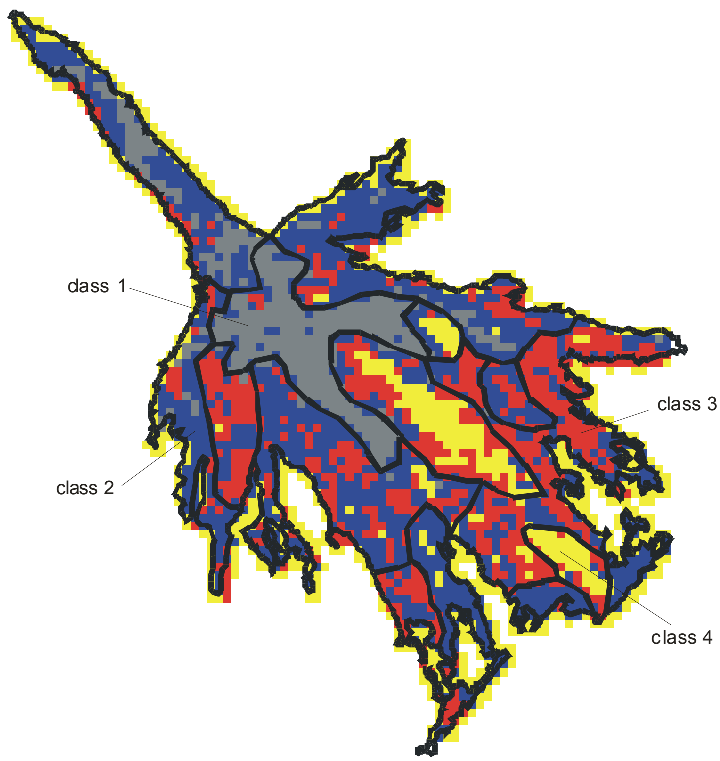


Fig. 11 Segmentation of the Delta based on the environmental factors influencing water balance

7 Final segmentation

Comparison of the results of the three segmentation methods used reveals the following:

- Segmentation into distributary systems is similar to segmentation into topographic sub-basins
- Segmentation into distributary systems allowed for partitioning of the permanent swamp, which in the sub-basins method was represented as a single large unit.
- In the middle and lower Delta the major differences between the segmentation into distributaries and sub-basins are as follows:
  - middle Boro and lower Santantadibe both remained undivided into distributaries, while each of them was split into two separate sub-basins.
  - Xwaapa and Xudum were distinguished as separate distributaries, while they were classified as one topographic sub-basin.
  - Similarly, Mogogelo and Gomoti were distinguished as separate distributaries, while they were classified as one topographic sub-basin

The units obtained from the analyses of island/floodplain system:

- generally substantiate the segmentation of the wider Thaoge into western Thaoge, Karongana and Xene systems, with the central Karongana being the “drier” unit
- support separation of Xwaapa and Xudum/Matsibe

- support separation of Shorobe floodplains from the lower Santantadibe and Gomoti

- support division of middle Boro into two units

The final segmentation has thus been derived as a combination of the three methods, with the following specific solutions:

- The permanent swamp area was divided according to the distributaries method

- The distributaries method results were adopted for segmentation of the Xudum system

- Middle and lower Boro and Santantadibe were sub-divided according to the sub-basins method

- Segmentation of the "wider" Thaoge was based on the sub-basins method, with extension of the three units to the north as obtained from the distributaries method.

- Gomoti and Mogogelo were separated from Guekha as in the distributaries method.

The resulting segmentation is presented in Fig. 12

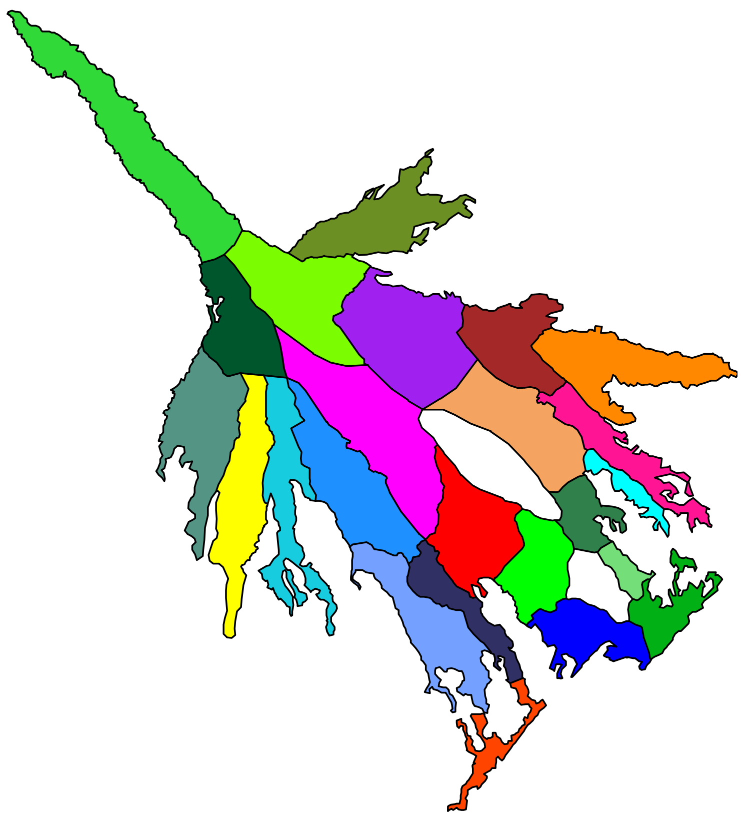


Fig. 12 Segmentation of the Okavango Delta into units to be represented in the hydrological model

8 References

Dangerfield, J., McCarthy, T.S. and Ellery, W., 1998. The Mound-building Termite Macrotermes michaelseni as an Ecosystem Engineer. Journal of Tropical Ecology, 14: 507-520.

De Vries, J.J., 1994. Dynamics of the interface between streams and groundwater systems in lowland areas, with reference to stream net evolution. J. Hydrol, 155: 39-56.

Dinçer, T., Child, S. and Khupe, B., 1987. A simple mathematical model of a complex hydrologic system - Okavango Swamp, Botswana. J. Hydrol., 93(1-2): 41-65.

Ellery, K. and Ellery, W., 1997. Plants of the Okavango Delta. A Field Guide. Tsaro Publishers, Durban, South Africa.

Gumbricht, T., McCarthy, T.S. and Bauer, P., The micro-topography of the wetlands of the Okavango Delta, Botswana. Submitted to Earth Surface Processes and Landforms.

Gumbricht, T., Wolski, P. and McCarthy, T.S., 2003. Forecasting the spatial extent of the annual flood in the Okavango Delta, Botswana. J. Hydrol., in press.

Gyllenhammar, A. and T. Gumbricht. WASUBI: A GIS tool for subbasin identification of topographical complex waterscapes. Submitted to Environmental Software

Isaaks, E.H. and Srivastava, R.M., 1989. An introduction to applied geostatistics. Oxford University Press.

McCarthy, J, and T. Gumbricht. Multisource rule-based contextual classification of ecoregions of the Okavango Delta, Botswana. Accepted for publication in International Journal of Remote Sensing.

McCarthy, T.S. and Ellery, W.N., 1995. Sedimentation on the distal reaches of the Okavango fan, Botswana, and its bearing on calcrete and silcrete (ganister) formation. Journal of Sedimentary Research A: Sedimentary Petrology & Processes, A65(1): 77-90.

McCarthy, T.S., Ellery, W.N. and Ellery, K., 1993. Vegetation-induced, subsurface precipitation of carbonate as an aggradational process in the permanent swamps of the Okavango (delta) fan, Botswana. Chemical Geology, 107(1-2): 111-131.

McCarthy, T.S., Ellery, W.N., Rogers, K.H., Cairncross, B. and Ellery, K., 1986. The roles of sedimentation and plant growth in changing flow patterns in the Okavango Delta, Botswana. South African Journal of Science, 82(10): 579-584.

Refsgaard, J.C. and Knudsen, J., 1996. Operational validation and intercomparison of different types of hydrological models. Water Resour. Res., 32(7): 2189-2202.

Ringrose, S., Vanderpost, C. and Matheson, W., 2003. Mapping ecological conditions in the Okavango delta, Botswana using fine and coarse resolution systems including simulated SPOT vegetation imagery. International Journal of Remote Sensing, 24(5): 1029-1052.

Schultz, G.A., 1994. Meso-scale modelling of runoff and water balances using remote sensing and other GIS data. Hydrol. Sci. J., 39(2): 121-142.

Simmers, I., 1984. A systematic problem-oriented approach to hydrological data regionalization. J. Hydrol, 73: 71-87.

SMEC, 1989. Ecological zoning of the Okavango Delta. Unpublished report, Ministry of Local Government and Lands, Gaborone, Botswana.

Wanakule, N., 1996. A lumped parameter model for the Edwards Aquifer. Technical Report no 163, Texas Water Resources Institute fo Texas A&M University, http://eardc.swt.edu/edwards/model/nlpmodel.html.

Weber, K.J., 1986. How heterogeneity affects oil recovery. In: L. L.W. and C. H.B. (Editors), Reservoir characterization. Academic Press.

Wolski, P., 1999. Application of reservoir modelling to hydrotopes identified by remote sensing. ITC publication 69 Thesis, ITC, Enschede, the Netherlands, 192 pp.

Wolski, P., 2003. Update of conceptual hydrological model of the Delta. Report to EU funded project ICA-4-CT-2001-10040. D2.1, Harry Oppenheimer Okavango Research Centre, Maun, Botswana.

WTC, 1997. Feasibility study on the Okavango River to Grootfontein link of the Eastern National Water Carrier. Unpublished report, Department of Water Affairs, Ministry of Agriculture, Water and Rural Development, Windhoek, Namibia.