MODELING CONCEPTS AND REMOTE SENSING METHODS FOR SUSTAINABLE WATER MANAGEMENT OF THE OKAVANGO DELTA, BOTSWANA

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ABSTRACT:

The Okavango Delta is one of the world's most fascinating wetland systems. The highly dynamic flooding forms the basis for a multitude of different ecosystems and plant and animal communities. Water scarcity and economical development lead to an increasing pressure on the ecosystem. A hydrological model is being developed to help making management decisions more sustainable by simulating possible impacts. The model can simulate anthropogenic changes such as water abstraction, damming, dredging and climate change. A key input parameter for the hydrological model is the topography, particularly the statistical properties of the topographic variability. These properties can be quantified using aerial remote sensing data.

1. INTRODUCTION

In northern Botswana, Southern Africa, the Okavango River forms a huge wetland system called the Okavango Delta. Sedimentation into a graben structure that is connected to the East African Rift Valley has built up this large alluvial fan. The waters of the Okavango River (mean discharge ~300 m^3/s) originate in the humid tropical highlands of Angola, flow southward into the Kalahari basin, spill into the Okavango Delta and are consumed by evapotranspiration (McCarthy, 1992; McCarthy et al., 1998). The Okavango Delta is an extremely complex and dynamic hydrological system. At the same time, it is the major regional freshwater resource, with Angola, Namibia and Botswana sharing the Okavango River basin, and one of the most beautiful nature reserves in Southern Africa. Growing water demand in all three countries puts the resource under increasing pressure and the intricate management problem of reconciling the needs of man and nature calls for a sound understanding of the system. To this end, a hydrological model of the Okavango Delta is being developed together with Botswana's Department of Water Affairs. The model can be used for a priori analysis of different management strategies, most importantly for the evaluation of different options for the water supply of the villages and towns scattered around the Delta.

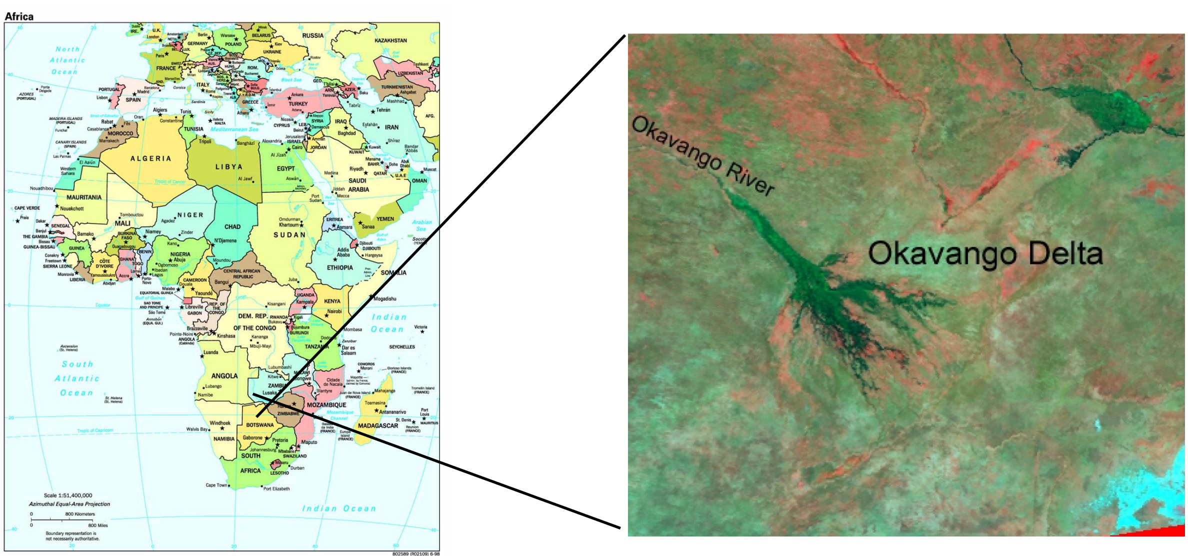


Figure 1. Location of the Okavango Delta

There are four controlling parameters for the dynamics of the Okavango Delta:

1. The inflow into the Delta via the Okavango River, which has a pronounced seasonality but also varies strongly from one year to the other.
2. The rainfall over the area.
3. The evapotranspiration from the wetland and its surroundings.
4. The topography.

In this paper, we focus on the role of topography in controlling the dynamics of the Okavango Delta. Apart from large scale topographic variations that determine the distribution of water into the different parts of the wetland, the topographic variability on the microscale (<1km) is the key factor controlling the effective hydraulic conductivity of the model cells.

The hydrological model of the Okavango Delta is developed within the framework of the finite difference groundwater flow model MODFLOW (McDonald and Harbaugh, 1988) and working under the preprocessing software Processing Modflow V5.0. Modules for evapotranspiration, surface flow and upscaling of the microtopography into the effective hydraulic parameters are added to the program package. Getting high quality spatially distributed input data is a key factor for the success of the modelling study. Therefore, we make use of satellite and airborne image data and advanced remote sensing techniques to quantify input parameters like rainfall, evapotranspiration (ET) and topographic variability.

2. HYDROLOGICAL MODELLING AND REMOTE SENSING

The rationale behind the Okavango Delta modelling effort is to give decision makers in Botswana and the neighbouring countries a simulation tool that can be used to study the effects of different management scenarios. What is the impact of abstracting a small part of the inflowing water to supply the villages along the southern fringe of the Delta? What happens, if new wellfields are established at the lower end of the Delta to satisfy the growing water demand of the town of Maun, the regional population and tourism centre? What is the impact of setting up hydroelectric power stations in the highlands of Angola, strongly modifying the river's seasonality? Because of the complexity of the Okavango Delta, these questions are difficult to answer qualitatively, let alone quantitatively or at least semi-quantitatively from just looking at the problem and using common sense. The need for hydrological modelling was therefore recognized almost two decades ago and several attempts have been made to systematically describe the controlling parameters and their interactions within the framework of a hydrological model (Dincer et al., 1987; SMEC, 1987; Gieske, 1997). The principal drawback of those models was that they used a very coarse, box-like discretization to represent the Okavango Delta hydrological system. The model parameters were therefore difficult to interpret physically and were derived by fitting the model response to the observed hydrograph of the Thamalakane River, which is the principal outflow of the Delta.

The new model is a spatially distributed finite difference model for transient surface and groundwater flow. The basic properties of the different model versions are summarized in Table 1. The model consists of two layers, the upper layer for the surface flow in channels and swamps and the lower one for the groundwater flow in the underlying aquifer, which is hydraulically coupled to the upper layer. The interface between the two layers is the topographic surface.

Figure 2 shows the model area and the spatial discretization in the 1 km resolution case. Spatially distributed inputs like rainfall and ET can have different values at each model cell for each stress period and can be readily imported from GIS software via an ASCII-interface (Figure 3). The input data for the hydrological model is the same for the whole duration of one stress period. The division of the stress periods into a number of time steps is for numerical reasons. The model calculates the hydraulic head in each model cell for each time step. If the hydraulic head is above the topographic surface for a certain horizontal location, the respective model cell in the upper layer is flooded and surface flow takes place. If the hydraulic head is below the topographic surface, the upper layer falls dry and pure groundwater flow results. By comparing the hydraulic head and the topographic elevation, the extent and shape of the flooded surface is easily extracted from the model results. The shape of the flooded surface and its development in time is then compared to satellite imagery (e.g. NOAA-AVHRR), which gives extremely important calibration information. Fitting the model to reproduce the spatial flooding pattern should yield much better calibration results than just using the hydrograph of the outflow for calibration.

Version	Number of Layers	Spatial Resolution	Number of cells per layer	Time discretization (stress period)	Number of time steps per stress period
2.x	2	5 km	80x80	1 month	60
4.x	2	2 km	200x200	1 month	300
5.x	2	1 km	400x400	1 month	1000

Table 1. Properties of the hydrological model

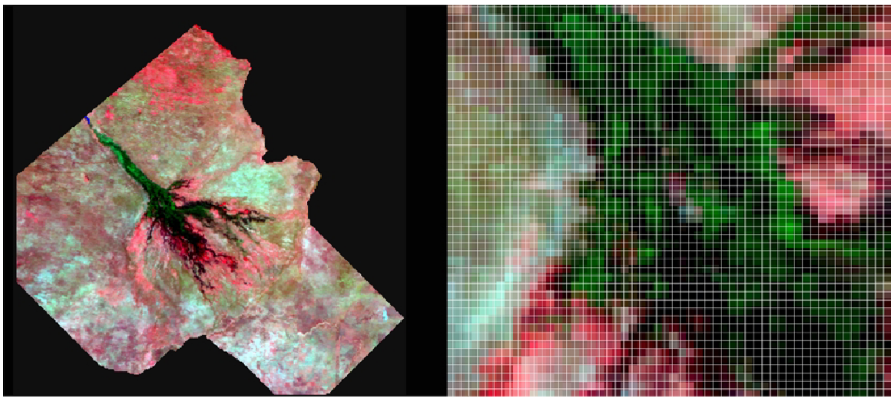


Figure 2. Model area of NOAA image (left) and spatial resolution (1 km, right)

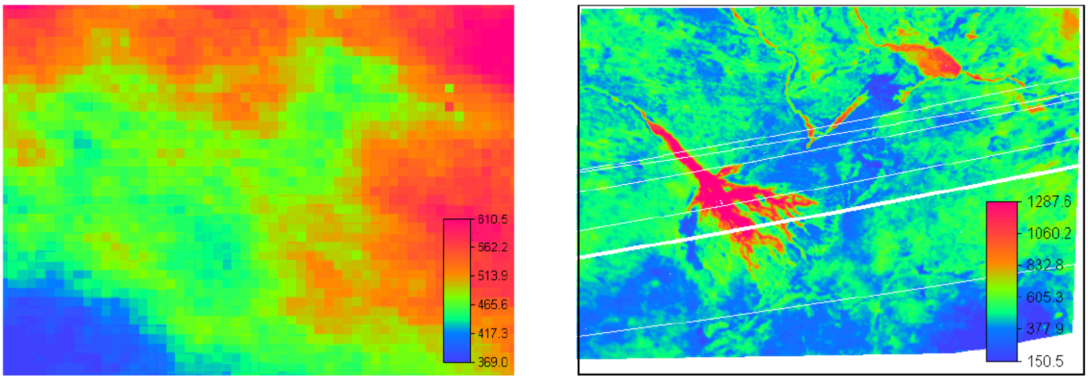


Figure 3. Spatially distributed model input parameters. Left: Rainfall in mm/a, averaged 1995-2000. Right: Average ET in mm/a from 97 NOAA-AVHRR images in the period 1990-2000. White stripes (missing scanlines) are due to transmission errors

Figure 4 shows some model results in 2 km resolution. The principal shape of the Delta is nicely reproduced and in the lower layer, the groundwater mound formed by the wetland can be clearly seen. Forthcoming calibration studies will use time series of flooding maps derived from NOAA-AVHRR images (McCarthy et al., 2002) as well as water level records archived by Botswana's Department of Water Affairs (DWA). Preliminary results suggest that the three parameters to which model results are most sensitive are: (1) the hydraulic conductivity of the swamp, (2) the Strickler coefficient of the major channels in the Delta and (3) the vertical hydraulic conductivity between the two model layers. For all parameters, reasonable initial estimates are available and the calibration information will be used to update the initial estimates using Bayesian parameter estimation techniques.

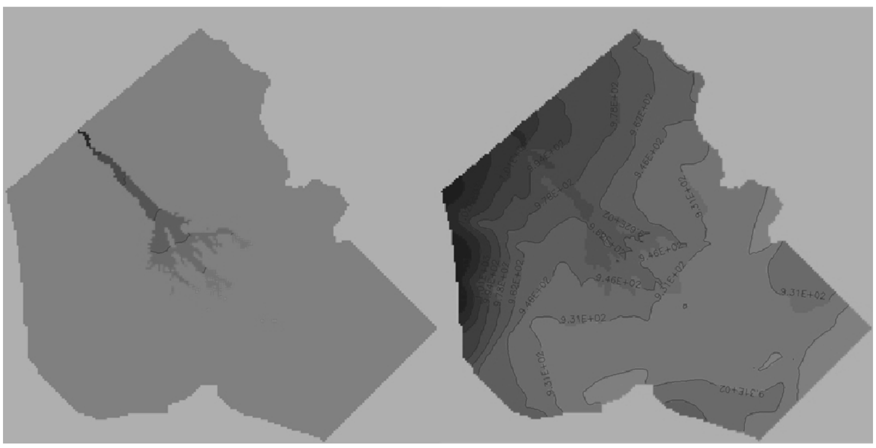


Figure 4. Model results: Water levels in the upper layer (left) and in the lower layer (right)

Obviously, the model requires a lot of spatially distributed input parameters. The most efficient way to get these input parameters is using satellite imagery and remote sensing. In the subsequent sections of this paper, we will focus on the topography as one of the most important input parameters. In the next section, we will briefly describe how topographic variability influences the effective hydraulic parameters, whereas the last section focuses on how to extract the microtopographic variability from available remote sensing data.

3. THE ROLE OF TOPOGRAPHY

When modelling large systems such as the Okavango Delta, a common problem is that the model cell (in our case 1km) is much larger than the characteristic length of the topographic features (islands, small channels etc.). We therefore have to derive effective parameters for the flow model, taking into account the statistical properties of the microscale variability.
Consider steady state low velocity surface water flow over a flat terrain with a roughness, e.g. due to grass or other vegetation, which is large enough to lead to a quasi linear flow law. In that case, the depth integrated specific flux q (m^2/s) can be written as:

$$q = k_f \cdot (h-b) \cdot \nabla h \tag{1}$$

where k_f is the hydraulic conductivity (m/s), h is the elevation of the water table (m) and b is the elevation of the terrain (m). This is the standard equation for the unconfined aquifer. How does the situation change if the terrain is no longer flat but varying in topographic elevation? Let us consider a normally distributed, uncorrelated terrain, where the topographic elevation has the following probability density function:

$$p(b) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{b^2}{2\sigma^2}\right) \tag{2}$$

If the water table is much higher than the mean elevation of the terrain, the geometric mean of the local water depths that are bigger than zero (wet locations), can be taken as the effective depth on the large scale:

$$\overline{(h-b)^{geo}}\Big|_{wet} = \exp\left(\int_{-\infty}^{h} \ln(h-b)\, p(b)\, db\right) \tag{3}$$

However, if the water level decreases, more and more isolated ponds are formed, that are not connected any more to both sides of the cell and therefore do not contribute to large scale flow. This phenomenon can be treated with the aid of percolation theory. Using results from Stauffer and Aharony (1994), we derived an effective thickness relationship that holds for small as well as for big water level elevations:

$$(h-b)_{eff} = \left(\frac{P(h)-p_c}{1-p_c}\right)^{\mu} \cdot \overline{(h-b)^{geo}}\Big|_{wet} \tag{4}$$

where p_c (percolation threshold) and μ are empirical parameters that depend on the exact form of the flow domain. For our case they are 0.5927 and 1.3 respectively. P(h) is the cumulative probability density function of the terrain, expressed as

$$P(h) = \int_{-\infty}^{h} p(b)\, db \tag{5}$$

In principle, once the topographic variability is known, we can therefore derive the effective hydraulic parameter using the above formulae. The effective hydraulic parameter can now be calculated on the one hand using Equation 4 and on the other hand by running a high resolution numerical model, where the terrain variability is resolved. Results are shown in Figure 5. But obviously, this theory can only be a first approximation, because only one statistical parameter of the terrain microtopography (the standard deviation) determines the effective hydraulic parameter, whereas other important statistics like (possibly anisotropic) correlation lengths are neglected. Nevertheless, the reader may have got a feeling for the approach and for how we are going to use the detailed digital elevation data, the derivation of which is discussed in the next section.

4. DEM GENERATION FROM REMOTE SENSING DATA

4.1 Digital Elevation Models (DEMs) and Data Sources

Digital elevation models are becoming an increasingly popular tool in many forms of environmental research including geomorphology, hydrology and environmental modelling. A DEM is an important component of hydrological models where it provides the topographic base information. A DEM can provide spatial information about several terrain features such as elevation, slope, aspect, drainage and other terrain attributes.

Currently, digital elevation data are derived from one of the following alternative sources: ground surveys, photogrammetric data capture from aerial or satellite remote sensing images, digitized cartographic data, interferometric or stereo SAR or the direct measurement of elevation using LIDAR technology. Each of these sources has advantages and disadvantages in generating DEM. Moreover, in all cases, the resolution at which data points are sampled is important in determining the usefulness of the resulting DEM.

4.2 Photogrammetric Data Capture

The photogrammetric technique is a fast, reliable and relatively cost-effective way of generating digital elevation models. In this work, the analytical photogrammetric method is used. To set up the model in the analytical plotter, three phases are performed - the inner, relative and absolute orientations. Note that, the accuracy of any photogrammetric measurement is premised on the use of ground control points. Since there is no ground control points (GCPs) available for the Okavango delta, we created hypothetical coordinates using image parameters (such as scale of the photographs, distance between fiducial marks, camera focal length) to establish control points in the model. The average ground height above sea level of the model area (i.e. 969

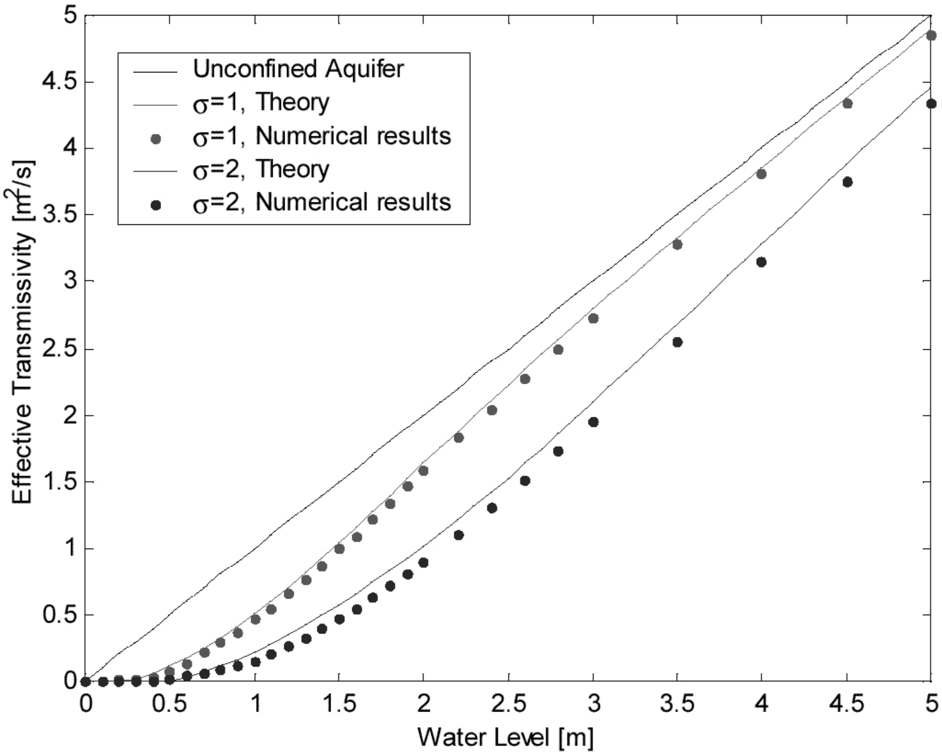


Figure 5. Effective transmissivity relationships (for k_f=1m/s): Theoretical predictions (lines) and numerical results (circles)

m) has been taken as a base to measure elevations. From overlapping areas of two consecutive photographs, 17 well distributed control points are established during the course of exterior orientation for achieving a good (parallex-free) stereomodel. Once these three orientation steps are completed, object points in the analytical stereomodel are measured for DEM generation.

Digital elevation models of portions of the Okavango delta were derived from black and white aerial images (diapositives of 1: 44,000 scale) taken on 29 August 1991, using the above mentioned photogrammetric procedures. The forward overlap was 60%. The focal length of the camera was 152.82 mm and flying height 7666 meters above mean sea level. The WILD AVIOLYT AC3 analytical plotter and AVIOSOFT photogrammetric software (DIO program for creating, editing and output of the control-point and camera calibration files; ORI program for the orientation of pairs of stereophotographs; and DTM program for the data acquisition for digital elevation models) were used.

The method of data capture chosen is dictated by the objective of the research, the nature of the surface morphology and the ways in which the data are going to be analysed and displayed. The Okavango delta is composed of complex topographic features (Figure 6). Broadly interpreted geographic features within this image of the delta are scattered low-altitude islands (mid-grey to bright), salty land surface (brightest), varied width of channels (dark black) and low lying swampy areas (dark-grey to darkish). In this work, DEMs are measured and recorded as a series of parallel profiles spaced 100 meters apart on the ground. One model area of 4.80 km x 8.84 km on the ground comprises 50 profiles. The selection of profile distance is guided by the high quality DEM requirements for hydrological modelling as well as the amount of time needed to measure the DEM. On each profile, a variable number of sample height points (on an average 173 points per profile) are measured based on the complexity of terrain features. Since the Okavango delta is a low-lying wetland, the range of height difference has been found to be 18.58 meter (z-minimum= 957.60 m and z-maximum= 976.18 m) for this model.

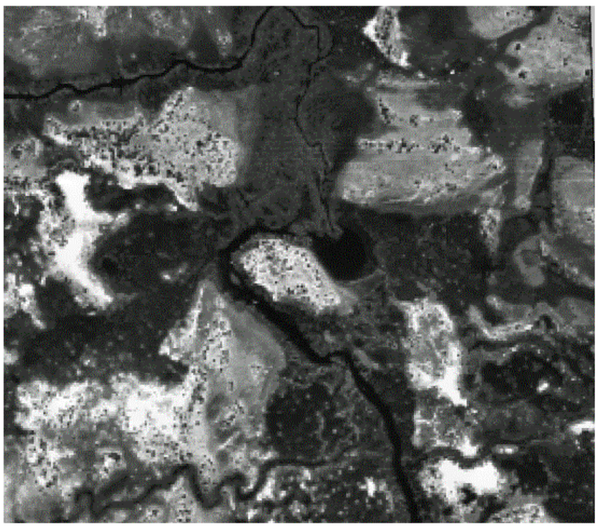


Figure 6. Aerial image of a portion (4.315 km x 3.755 km) of the Okavango delta

4.3 Model Construction

The terrain data captured is usually modeled in one of the following three ways - as a regular grid of heights, as a triangulated network or as contours and flowlines, depending on the source and/or preferred method of analysis. Each of these data structures offers advantages for certain applications. In this study, the triangular-based grid approach is used. The reason for using this approach is that every measured data point is being used and honored directly, since they form the vertices of the triangles used to model the terrain. It also gives better representation of the terrain surface. However, we can also perform interpolation of original sampling measurements to determine heights of additional points.

Figure 7 shows a color-coded 3-D perspective view of the digital elevation model of a portion of the Okavango delta. Since the model area visually looks almost a flat surface due to very low range of height differences, we exaggerated the model by a factor of 10. Although an accuracy assessment has not been performed yet, the visual inspection of the result clearly demonstrates the importance of photogrammetric method in generating high quality digital elevation model. Comparative analysis of variograms (Figure 8), created by two different methods - leveling (ground-based survey) and photogrametry, supports our visual inspection result, even though the variograms are for two different areas of the delta. The variograms have been used as a superior technique to identify unexpected variations in the spatial structure of the elevation model, which may be indicative of systematic or isolated errors (Polidori et al., 1991).

The transects and variograms created from leveling (ground-based) as well as photogrammetric measurements are shown in Figure 8. Although different geographic areas are used in these two methods, the results statistically show a remarkable degree of similarity in their trends. Note that, leveling being a ground survey method it produces very accurate height measurements (Weibel and Heller, 1994). However, photogrammetric methods are more suitable to generate elevation models for large areas than the time consuming ground-based methods.

5. CONCLUSIONS

The topographic variation is one of the most important parameters shaping the Okavango Delta and controlling its dynamics. The scale at which numerical modelling can operate at reasonable computational cost is much larger than the typical scale of the topographic features. Therefore, only the statistical properties of the topographic variation can be taken into account. To extract these statistical properties, a high resolution DEM is needed. Photogrammetric techniques are a fast and cost-effective way of generating digital elevation models from remote sensing data. It has been found that a high spatial resolution of the DEM is required for better representation of terrain features of the delta, since the range of height differences is very small. The present study is limited by the lack of ground control points as well as camera calibration values.

A field campaign, including measurement of GCPs is planned for spring/summer 2002. Since the Okavango delta is very large not all aerial images can be processed. Thus, we plan to process, only some target characteristic regions from aerial imagery and the rest with lower resolution satellite imagery. Although satellite data can not provide the height accuracy required for hydrologic modelling, we will try to use correlations between aerial and spaceborne data in order to propagate the more accurate DEM from aerial imagery and the statistics derived thereof to the areas covered by the spaceborne data.

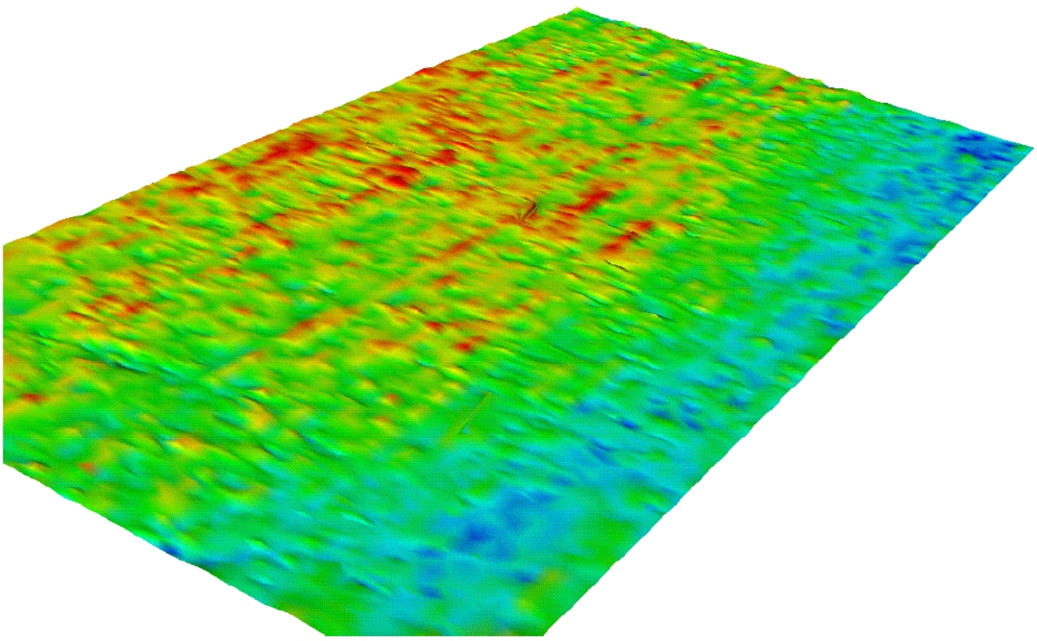
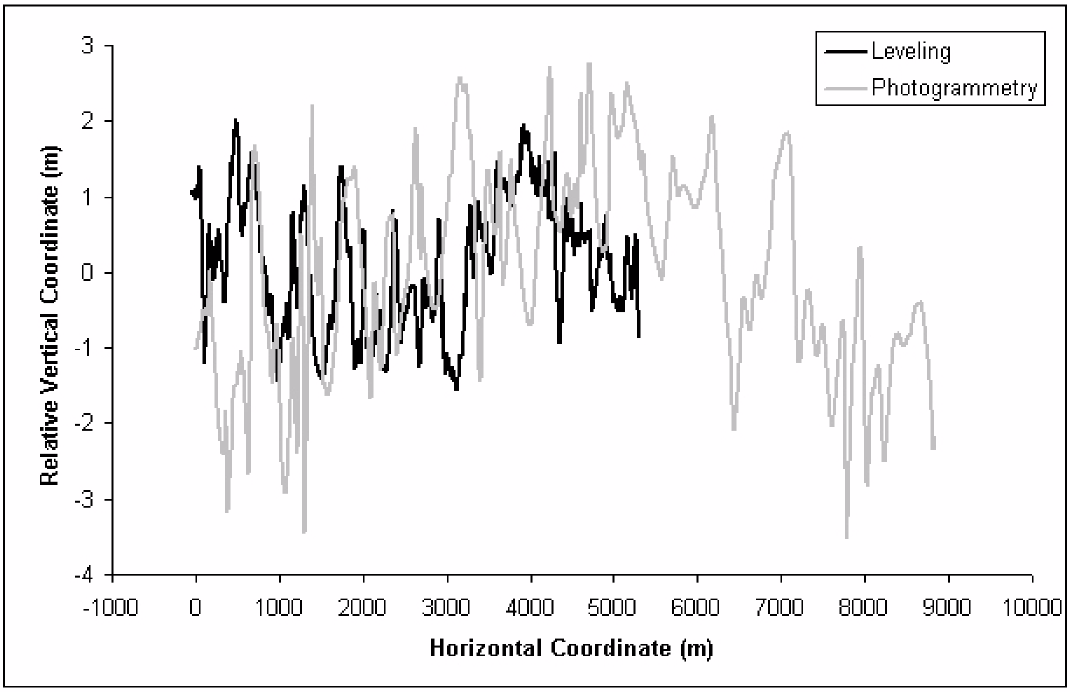


Figure 7. DEM of a portion (8.84 km x 4.81 km) of the Okavango delta. Elevation values ranges from 957.60 m (blue) to 976.18 m (red) above mean sea level



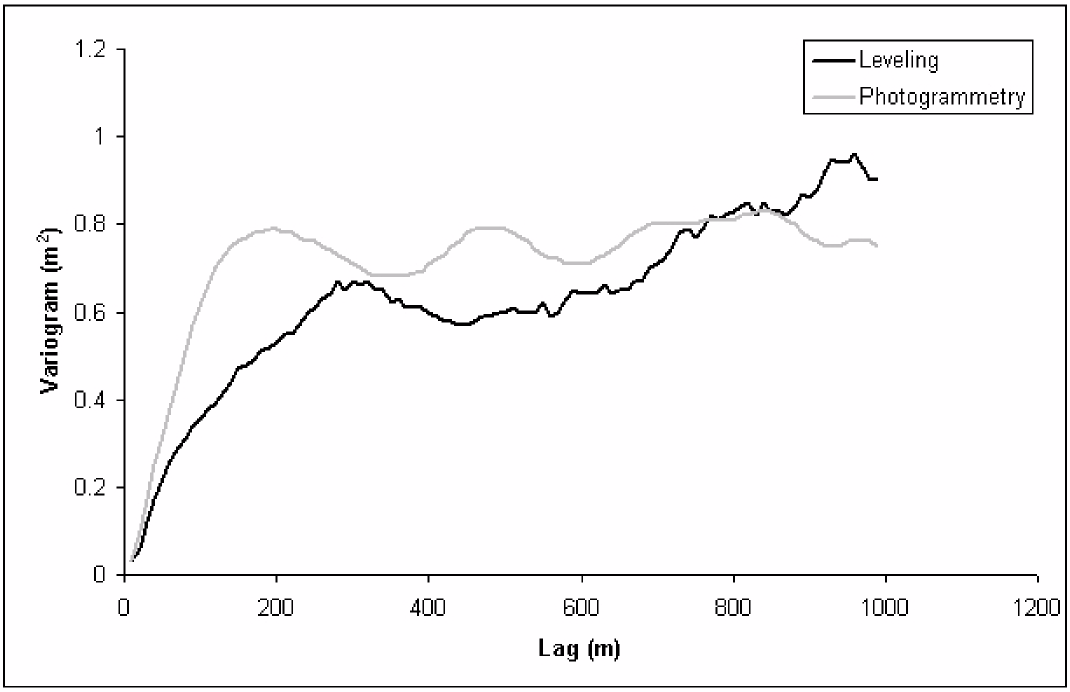


Figure 8. Results from leveling and photogrammetric height measurements: above transects, below variogram result

In addition, we will investigation methods for automating the DEM generation process and delineation of features, like islands,, using scanned aerial imagery.

Thus, remote sensing techniques can help make our hydrological model of the Okavango Delta more reliable. The hydrological model in turn can be used as a tool for assessing impacts and sustainability of different management options.

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