Water flow dynamics in the Okavango River Basin and Delta—a prerequisite for the ecosystems of the Delta

Lotta Andersson [a,*], Thomas Gumbricht [a], Denis Hughes [b], Dominic Kniveton [c], Susan Ringrose [d], Hubert Savenije [e], Martin Todd [f], Julie Wilk [a], Piotr Wolski [d]

[a] *Department of Water and Environmental Studies, Linköping University, S-58183 Linköping, Sweden*
[b] *Institute for Water Research, Rhodes University, P.O. Box 94, Grahamstown, 6140 South Africa*
[c] *School of Chemistry Physics and Environmental Science, University of Sussex, Falmer, Brighton, UK*
[d] *HOORC University of Botswana, P/Bag 285, Maun, Botswana*
[e] *IHE, P.O. BOX 3015 Westvest 7, 2601 DA Delft, The Netherlands*
[f] *University College of London, 26 Bedford Way, WC1N0AP, London, UK*

1. Introduction

As part of the EU-funded project "*Water and Ecosystem Resources in Regional Development—Balancing Societal Needs and Wants and Natural Resources Systems Sustainability in International River Basin Systems*" (WERRD) (www.okavangochallenge.com), work is carried out aiming to improve and develop scientific methods that will facilitate the understanding of fluctuations of hydrological and ecosystem variables and likely human-induced trends concerning key characteristics of the Okavango River Basin in Southern Africa.

1.1. The Okavango River Basin

The Okavango River Basin, with a total basin area of 530,000 km^2, has about 95% of the water flow in the river contributed by 135,000 km^2 of the catchment, situated within Angola. Increased water take-off is anticipated in the Angolan and Namibian head streams in response to water shortages and increased agricultural demand. With regard to Angola, it is expected that more than one million people in refugee camps gradually will return to areas close to the river. There are also old plans for hydroelectric power generation in Cuito and Cubango that may be taken up again. Also in the Namibian part of the river basin, increased irrigation demand may be expected, in addition to a planned pipeline for water withdrawal.

1.2. The Okavango Delta

The Okavango Delta is a large (22,000 km^2) alluvial fan, tectonically forced, subject to annual flooding. It is composed of a mosaic of floodplains and islands. Due to the large distance from the source area of the feeding Okavango River, the annual flood wave arrives at the Delta apex two months later then the rainy season in Angola. The flood wave undergoes further attenuation during its spreading in the Delta proper, so that the most downstream areas are flooded only in August—i.e. approximately 6 months after the rainfall that generated the flow. The extent of flooding varies seasonally from low in December (3000–5000 km^2, depending on year) to high in August (6000–12,000 km^2). Surface inflow amounts to 10,000 Mm^3 year^{-1} while rainfall supplies approximately 5000 Mm^3 year^{-1}. Out of this, approximately 200 Mm^3 year^{-1} leaves the Delta in the form of surface runoff, and it is estimated that another 200 Mm^3 year^{-1} flows out through the groundwater pathways. This indicates that approximately 97% of the total input is ultimately evaporated. The low topographic gradient of the Delta (1:3470) causes low flow velocities; flow takes place partly through channels, but also through sometimes densely vegetated floodplains. The propagation of the flood front is associated with a rising groundwater table, both within floodplains as well as under the islands. Continuous flow of groundwater between floodplains and islands is responsible for removal of solutes from the system and their immobilisation in the islands groundwater and soils.

Of particular significance in the Okavango ecological systems are impacts which may occur as a result of external factors in the Okavango River Basin upstream of Botswana with possibly detrimental hydrological and ecological effects. Responses to drying of former floodplains may include localised species extinctions leading to changes in community functions (cf. Thibodeau and Nickerson, 1985; Fonseca and Ganade, 2001) and bush encroachment (e.g. Ringrose et al., 1997).

1.3. Aims of the hydrological and ecosystem studies within WERRD

Below, the deliverables from WERRD, related to hydrology and ecosystem analyses are presented, with contact persons in brackets. The project runs between 2002 and 2004.

- Implementation and verification of the Pitman model to assess river flow in the river basin and its subcatchments using historical hydrological and climatological records (L. Andersson).
- Construct a rainfall dataset over the Okavango River Basin using the Tropical rainfall Measuring Mission (TRMM) and Special Sensor Microwave Imager (SSM/I) satellites and instruments (D. Kniveton).
- Dissemination of models and results from the water and land-use resource scenarios for the river basin (L. Andersson).
- Real time modelling of water flow in the river basin, with the Pitman model driven by rainfall datasets obtained from SSM/I and TRMM satellites and instruments (L. Andersson).
- To come up with a quantitative hydrological model of the Delta that would be capable to predict the effects of water abstractions from the system and which could ideally be linked to ecological responses (P. Wolski).
- Definition and mapping of key ecosystem elements (S. Ringrose).
- Adaptation of dynamic landscape models of ecosystem structure and function in response to drying gradients and changes through time (S. Ringrose).
- Determine ecosystem responses under scenarios simulated by the hydrological models of the river basin and the Delta (S. Ringrose).

2. Rainfall over the basin

The precipitation data set used to create the interpolated areal coverage consists of daily and monthly average values from 262 stations (Fig. 1). The number of stations was greatest between 1960 and 1972 and after the onset of the Angola civil war the number of recording stations was drastically reduced. The data collected was taken from the Nicholson African rainfall database available from the National Center for Atmospheric Research (NCAR) Data Support Section (monthly rainfall totals 1901–1975) found on the Miombo CD (a production of the Land Cover Change (www.icc.es), International Project Office and the Miombo Network (www.miombo.gecp.virginia.edu), Servicio Meteorologico de Angola at the National Meteorological Library, UK and the Botswana Meteorological Office.

Fig. 1. Sub-division of the Okavango catchment showing all available raingauges.

The precipitation records were interpolated using the Spine and Inverse Distance Weighted (IDW) interpolation methods within the program ArcView 3.2. These interpolations created an areal precipitation map for each month with a pixel size that represents an area of 8 × 8 km. The areal precipitation for each sub-basin was then obtained by taking an average of the pixel values within each area. The Spline interpolator fits a minimum curvature surface through the input points by fitting a mathematical function to a specified number of points, while passing through the sample points. It works best for gently varying surfaces such as elevation, water table heights or pollution concentrations (Ragnarsson, 2002). The IDW interpolator assumes that the influence of each input point diminishes with distance. Points closer to the processing cell are thus weighted heavier than those farther away. Either a specified number of points or all points within a specified radius can be used to determine the value of the processing cell. A study comparing IDW, spline and kriging for the above data set found that IDW made the best estimations (the error estimated through cross-correlations was lowest) except from 1974 onwards when none of the methods was satisfying (Ragnarsson, 2002).

The precipitation data will be tested against a number of physiographic factors including, topography, soils, land cover and distance from the coast, to determine if these are highly correlated with precipitation amounts. If they are, this information will be used to estimate more representative areal precipitation for use in the model.

Evaporation records were taken from the draft of the Okavango River Basin Preparatory Assessment Study. The potential evaporation data was not interpolated but an average was taken for each sub-basin based on the closest climatic stations.

2.1. Satellite data

Historical satellite based rainfall products for the region have been constructed, using data from Tropical Rainfall Measuring Mission (TRMM), Special Sensor Microwave Imager (SSM/I) and METEOSAT. These sensors have different spectral properties and varying spatial and temporal resolutions, coverages and overpass times. As a tropical orbiter TRMM samples the diurnal cycle of rainfall, whereas SSM/I is restricted to morning and afternoon overpasses due to the satellites' polar orbiting sun-synchronous orbit. However SSM/I does have the advantage of data stretching back to 1988 compared to 1997 with TRMM. METEOSAT has the best spatial and temporal resolution, longest time coverage but unlike its microwave counterparts, measures electromagnetic radiation at wavelengths that are not directly related to rainfall and thus relies on indirect and 'physics poor' transfer functions to estimate rainfall. Todd et al. (2001) has been involved in the development of synergistic methods to provide satellite based rainfall products using histogram matching and neural networks (Bellerby et al., 2000). While these 'proof of concept' studies have provided potential methodologies for combining satellite datasets they have made no attempt to quantify the uncertainty in these predictions other than elementary 'validation' statistics. Such estimates are important for the quantification of uncertainty in hydrological output to be used in policy framing. In the work carried out so far TMI data has been sub-sampled at SSM/I times and compared to PR and all the TMI data to calculate a diurnal correction factor for SSM/I data. The variation in this function has been calculated temporally and spatially. The diurnally corrected SSM/I data (Fig. 2) is then going to be combined with METEOSAT data to produce daily 5 km rainfall data. Results from the study show that there is a strong diurnal component to the rainfall, where the form of the diurnal cycle varies spatially over southern Africa. SSM/I underestimates rainfall in the morning and overestimates in the evening. However, for the Okavango region, correcting factors can be found for SSM/I and errors can be estimated.

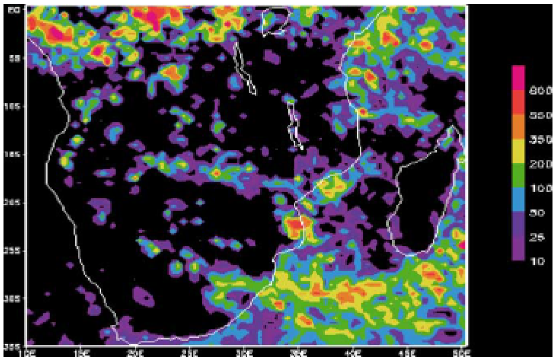

Fig. 2. Rainfall for March 2001(in mm month^{-1})—diurnally corrected SSM/I.

2.2. River discharge in the basin

Initial calibrations of monthly river discharge in the Okavango river basin have been made, using the Pitman model (Pitman, 1973), which is one of the most widely used monthly time-step rainfall-runoff models within Southern Africa. The version that is used here is based upon modifications added during the application of the model for the first phase of the Southern African FRIEND programme (Hughes, 1997). This version has now been incorporated, together with a reservoir water balance model, into the SPATSIM package developed at the Institute for Water Research, Rhodes University.

The Okavango basin above Mohembo weir has been sub-divided into 23 sub-catchments (Fig. 1), of which 17 have gauging stations at their outlet. Of these, 10 are located in the north-west on sub-catchments of the Cubango River. A further 5 are located in relatively small headwater tributaries of the Cuito River and have very short records with a great deal of missing data. The remaining two are close to the inflow to the Delta at Mukwe and Mohembo. The former has the longest and most complete record, while the latter only starts in 1975.

An examination of the observed flow records suggests a different type of runoff response to rainfall from the western tributaries compared to the eastern tributaries. The western tributaries show a great deal more seasonal variation in flow, while the eastern tributaries have high baseflows and relatively small seasonal variations. These observations are consistent with the geological differences between the two areas. The western parts of the upper basin are underlain by sandstones and mudstones, while the eastern parts are underlain by Kalahari sands. These differences and the lack of sufficiently long and representative observed flow data for the eastern sub-catchments suggests that the regional calibration exercise will not be straightforward.

The available rainfall data constrained the standard modelling period to January 1960 to December 1972, a total of 12 years. As this period is short it has been difficult to follow standard modelling procedures of using part of the period for calibration and part for validation.

2.3. *Western upper sub-catchments*

Fig. 3 illustrates the type of rainfall-runoff response of the western upper sub-catchments. They are all quite similar, suggesting that similar parameter value sets may be appropriate.

Overall simulations were successful and the results are relatively consistent across all the sub-catchments. In general terms the calibrated parameter values demonstrate a high degree of consistency with what could have been expected from knowledge of the model conceptualisation and the variations in physiographic characteristics of the sub-catchments. It is possible that channel "losses" are starting to play a role in the lowest of the sub-catchments, which may account for the somewhat higher positive percentage error in the mean flows based on normal values. The parameter values reflect higher infiltration rates in the areas closer to the Kalahari sands region and the flatter slopes of the southern sub-catchments. The calibrated values of groundwater parameters suggest that the runoff from these catchments is subject to relatively long residence times.

2.4. *Eastern upper sub-catchments*

The eastern upper sub-catchments have records of very few months and only two sub-catchments have even close to enough observed data for calibration purposes. As expected, the calibration results are also very poor, except for Cuito (see Fig. 4), which is fortunately one of the larger contributions to downstream flow. The parameter values for Cuito are similar to those used for the Serpa Pinto sub-catchment, which appears to be transitional between the harder rock western areas and the Kalahari sands of the eastern region. The parameter indicates that most of the flow is generated as slowly responding groundwater.

2.5. *Lower sub-catchments*

For all the lower sub-catchments, groundwater reservoirs were included at their outlets to represent infiltration losses from river banks. These reservoirs are assumed to be drained trough transpiration. The volumes and surface areas of these reservoirs were quantified on the basis of the channel length and assumed channel plus riparian zone widths (for example Rundu and Mukwe have reservoirs with full supply volumes of 53 and 22 Mm^3, respectively. In general terms the calibrations have been successful, although the % errors in the mean monthly flows are quite high and positive. It is therefore assumed that channel losses have been under simulated as the amounts of incremental runoff generated in these sub-catchments is quite low. The parameter values are consistent with relatively flat and arid catchments, the main contributions to flow only occurring during exceptionally high rainfall months (Fig. 5).

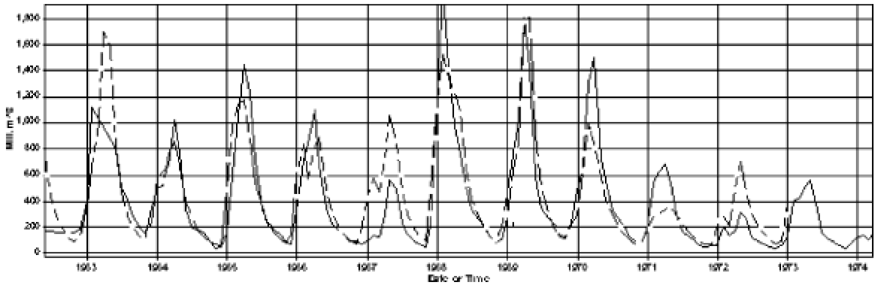

Fig. 3. Observed (—) and simulated (- - -) monthly flows for the Caiundo sub-catchment. For location of the basin, see Fig. 1.

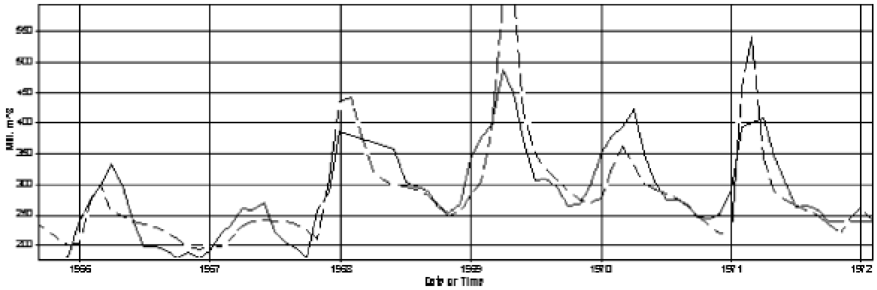

Fig. 4. Observed (—) and simulated (- - -) monthly flows for the Cuito sub-catchment. For location of the catchment, see Fig. 1.

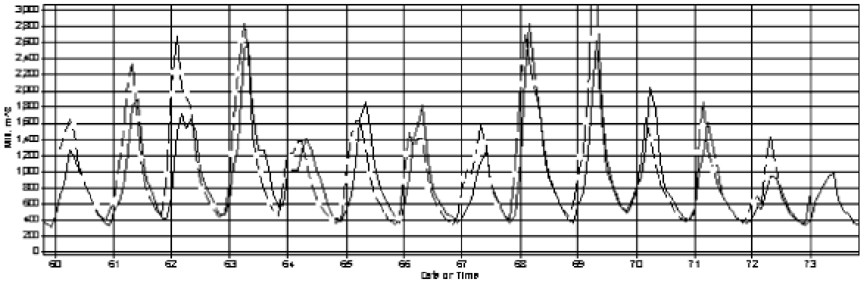

Fig. 5. Observed (—) and simulated (- - -) monthly flows for the Mukwe sub-catchment. For location of the catchment, see Fig. 1.

3. Hydrology of the Delta

Since the size and accessibility of the Okavango prevents extensive fieldwork, it was decided to develop a relatively simple, semi-conceptual, semi-distributed model, based on updating of existing models.

3.1. The review of existing models—what needs to be updated?

A large number of models have been applied for the Delta including Dincer et al. (1987), SWECO (1976), SMEC (1990), IUCN (1993), Gieske (1997) and Manley (1997). The models used differ in coverage, but were all calibrated against the observed outflow from the Delta. The best simulation of the outflow from the Delta was obtained by Gieske (1997). This success was probably attributed to incorporation of a set of empirical, but physically justifiable factors in order to account for antecedent "wetness" conditions (both short-term, i.e. 12 months and long-term i.e. 10 years), and increased outflow due to extreme events (either rainfall, or inflow or both).

Comparison of the results from Gieske (1997) with others indicates that the major model improvement effort should be directed towards a more realistic representation of infiltration and factors influencing its short and long-term variation. It is believed that this can be achieved by explicitly modelling groundwater storage with evaporative abstraction and lateral flows. Incorporation of such elements in the model adds the necessary link to ecological responses—as those are mostly related to availability of shallow groundwater. Other elements that can be improved are as follows:

- Transparent segmentation of the system into physically meaningful (internally uniform in terms of water balance) zones that are represented by model cells.
- Use of recently available topographic information into volume–water level relationship.
- Use of time series of flooding extent available from satellite data in the process of calibration/verification of the model.
- Establishment of a link between model cells and RS-derived flood maps for the purpose of model downscaling.

3.2. Surface water-groundwater interactions

A monitoring network of the groundwater table was established within an associated project, and currently comprises 53 piezometers at 15 locations, with observation time ranging from several months to 5 years. This gives valuable information on groundwater behaviour (Fig. 6). Data is currently analysed in order to regionalize information from the sites. Also, the water balance data from a small catchment gauged by HOORC is analysed. The preliminary results indicate that the contribution of lateral groundwater flow between floodplains and islands can be considerable, and that island evaporation and groundwater storage effects should be included in the model, and are most probable responsible for the system's long term "memory".

3.3. Segmentation of the system into physically meaningful units

The seasonally inundated region was subdivided into seven sub-regions (Fig. 7). For that purpose an automatic routine which seeks minimum openness to adjacent areas (Gyllenhammar and Gumbricht, in preparation) was used. Further segmentation is being worked out on the basis of an indicator which will express the internal uniformity of the water balance and produce units of a size suitable to be represented by a single unit in a model using monthly time step.

3.4. Topographic information

A high resolution DEM of the Okavango Delta is now available (Gumbricht et al., 2001), as well as several detailed GPS surveys. These data are being processed now in order to determine the volume–area relationship.

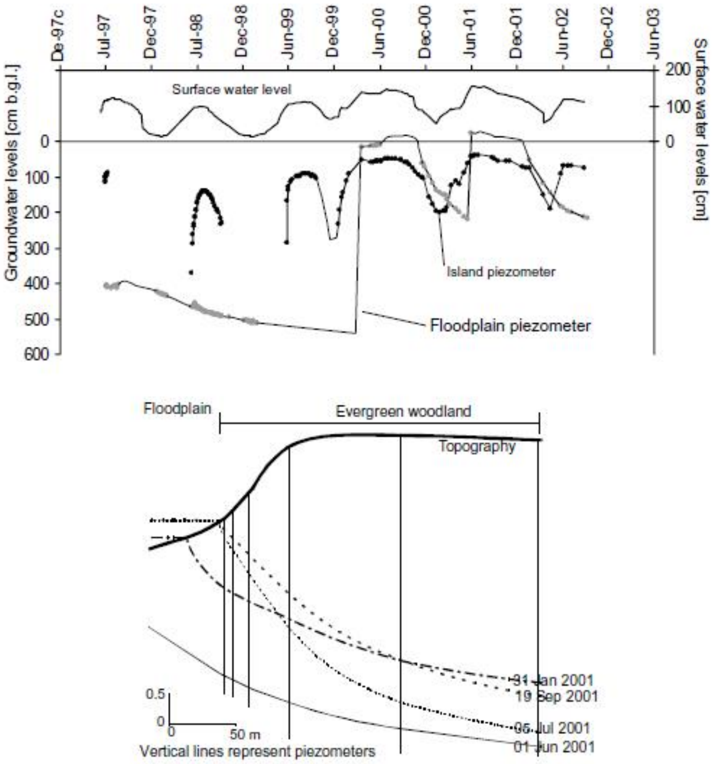

Fig. 6. Above: groundwater fluctuations under a floodplain and an island. Below: island groundwater table profiles for low and high flood season.

3.5. *Time series of flood extent from satellite data*

The spatial extent and area of inundation from 1985 to 2000 has been extracted from daily NOAA satellite data by using unsupervised classification of geometrically and radiometrically corrected images. The best cloud-free image for each consecutive 10-day period was selected and the area of inundation manually verified. The areas inundated in the images for each month were aggregated in order to obtain a representative water distribution image for that month. For a few dates prior to 1985, Landsat TM and MSS data were used. The flood images will be used during calibration of the final model. However, this information has been used already in the analysis of changes in flood distribution and in development of a regression model that simulates the year-to-year variation in maximum flood extent (Gumbricht et al., submitted for publication).

Analysis of the time series of satellite images reveals that there is only minor variation in spatial distribution of floods between years. The most pronounced changes are observed in the distant parts of Boro and Xudum systems. Those can be caused by water diversion due to tectonic activity in the region where the systems separate, or by the influence of dense aquatic vegetation in the upper Boro region, which may have different effect on flood wave propagation dependent on the inundation level. Which is true is uncertain at this stage. If the

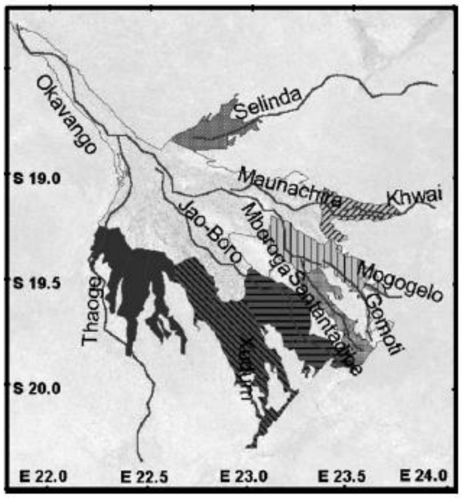

Fig. 7. Segmentation of the Okavango Delta into units representing flow systems, based on minimum interconnectivity.

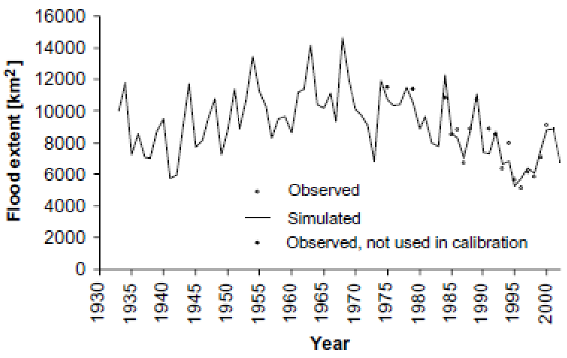

Fig. 8. Maximum annual flood extent from 1932 to 2002 reconstructed using the regression model.

second explanation is found to be realistic, it will be implemented in the reservoir model, making replications of observations possible.

In the regression model, the maximum flooded area is a dependent variable, while the annual rainfall, annual inflow, previous year flood and annual potential evaporation are input variables. The model explains 90% of the observed variation in the maximum flood extent (Fig. 8).

4. Ecosystem distribution of the Delta

Work has been undertaken to determine the value of remotely sensed imagery in the determination of ecological changes which may occur as a result of drying within in the Okavango catchment (Ringrose et al., submitted for publication). Little previous work has been undertaken on characterising the drying gradients of wetlands using remote sensing techniques. Ringrose et al. (1997) have used ETM imagery to help characterise changes in former floodplains and islands as a result of sequential drying along the west side of the Okavango Delta. Initially supervised classification analysis resulted in the identification of key landforms and associated vegetation cover in three areas representative of increasing drying from recent times to the geological past. As a result of the classification, a number of features were identified including former floodplains and islands. Evidence suggested that through time the former island riparian woodland vegetation was colonising the former floodplains and developing into locally encircling protected areas, which in turn became more densely treed, relative to the adjacent, non-protected floodplain. Hence island extensions and infills were identified both on the images and ancillary aerial photography. Use of aerial photography resulted in a classification accuracy (for two of the three areas) between 65% and 70%. Independent results from soil analysis indicated that long-term exposure and drying (along with human impacts) appear to reduce the humic content of the former floodplain soils to zero. Fewer trends were evident from former island soils. In particular soil moisture and pH values remained relatively constant along the island-drying gradient. However an initial marked decline in EC suggested a possible slowing down of salinisation processes, as former islands increasingly became fossil features. This is matched by a decrease in surface litter, which might also infer a decrease in nutrient cycling. However the theory of island agglomeration as suggested by the imagery results was independently confirmed by soil data and patch analysis on the classified image as the number of larger patches increased along the gradient.

5. Discussion and concluding remarks

5.1. Modelling of river flow and rainfall over the River Basin

The results of the initial simulation of the hydrological model for the Okavango river basin are as good as could have been expected given the quality of the input data, the generally low degree to which the rainfall data are likely to represent actual spatial variations in rainfall and the absence of detailed physiographic data. To determine whether improved simulations can be obtained, future attention needs to be given to the following issues:

- The real extent of the different geological zones in the upper catchment areas, as well as the surface soil characteristics of these areas.
- The character and location of the transitional area between the western and eastern sub-catchments.
- The vegetation cover characteristics of all sub-catchments (to refine the parameter values for the interception and evaporation components of the model).
- The sizes of the channel and riparian areas and the way in which channel losses are allowed for in the model.
- Further refinement of parameter values.

As the primary forcing of the hydrological system of the Okavango, an accurate estimate of rainfall is of key importance to modelling river discharge. To this end, satellite data provides us with an opportunity to provide gridded, error-quantified and thus probabilistic as well as deterministic rainfall estimates for the whole catchment at a variety of temporal and spatial scales. A timely event for the project has been the launch of Meteosat Second Generation (MSG) in September 2003. This will provide multi-spectral 4 km spatial resolution satellite data centred over Africa of particular use for satellite based rainfall estimation. Use of this new satellite-data, together with already available satellite-data, will enable a better understanding of geographical distribution of rainfall over the basin, and for periods after the early 1970's, it is the only source of rainfall from Angola, where the main part of the stream flow is generated.

5.2. Links between hydrology of the Delta and ecosystem behaviour

The hydrological Delta model will enable the prediction of the maximum flood extension, three months in advance, and the determination of the floodplain reduction due to abstractions upstream. It has also been confirmed that flood extent is subject to the same controls as the outflow, that antecedent flood conditions are extremely important in the hydrology of the Okavango Delta and that simulation of flood extent in conjunction with outflow is possible.

The work by Ringrose et al. (submitted for publication) has shown the value of remotely sensed imagery in the determination of ecological changes, which may occur as a result of drying within in the Okavango catchment. Since the Delta gets approximately 75% of its water input in the form of inflow from the Okavango river, and only 25% from rainfall on the Delta, scenarios of possible fluctuations and trends in the inflow will be an important input to the hydrological model of the Delta.

By linking scenarios of human impact on the hydrology of the River Basin and the Delta with RS studies of ecosystem response to drying, it will be made possible to determine the ecosystem response to natural fluctuations and human-induced trends of water flow.

References

Bellerby, T.J., Todd, M.C., Kniveton, D.R., Kidd, C., 2000. Rainfall estimation from a combination of TRMM precipitation radar and GOES multi-spectral imagery through the use of an artificial neural network. Journal of Applied Meteorology 39 (12), 2115–2128.

Dincer, T., Child, S., Khupe, B., 1987. A simple mathematical model of a complex hydrologic system. Journal of Hydrology 93, 41–65.

Fonseca, G.R., Ganade, G., 2001. Species functional redundancy, random extinctions and the stability of ecosystems. Journal of Ecology 89, 118–125.

Gieske, A., 1997. Modelling outflow from the Jao/Boro River system in the Okavango Delta, Botswana. Journal of Hydrology 193, 214–239.

Gumbricht, T., McCarthy, T.S., Merry, C.L., 2001. The topography of the Okavango Delta, Botswana, and its tectonic and sedimentological implications. South African Journal of Geology 104, 243–264.

Gumbricht, T., Wolski, P., Frost, P., McCarthy, T.S., submitted for publication. Forecasting the spatial extent of the annual flood of the Okavango Delta, Botswana, Journal of Hydrology.

Hughes, D.A., 1997. Southern Africa FRIEND—the application of rainfall-runoff models in the SADC region. Report to the Water Research Commission by the Institute of Water Research, Rhodes Universtiy. WRC Report No. 235/1.

IUCN, 1993. The IUCN review of the Southern Okavango Integrated Water Development Project, IUCN, Switzerland.

Manley, R.E., 1997. Hydrological modelling of the Okavango Delta system in Botswana, specialist report in: Feasibility study on the Okavango River ro Grootfontein ling of the Eastern National Water Carrier, vol. 4, Department of Water Affairs, Republic of Namibia.

Pitman, W.V., 1973. A mathematical model for generating monthly river flows from meteorological data in South Africa. Report no. 2, Hydrological Research Unit, University of Witwatersrand, South Africa.

Ragnarsson, H., 2002. Precipitation estimation from ground based data in arid climate. MSc Thesis. Aquatic and Environmental Engineering, Uppsala University.

Ringrose, S., Vanderpost, C., Matheson, W., 1997. Use of image processing and GIS techniques to determine the extent and possible causes of land management/fenceline induced degradation problems in the Okavango area, northern Botswana. International Journal of Remote Sensing 18 (11), 2337–2364.

Ringrose, S., Jellema, A., Huntsman-Mapila, P., Baker, L., Brubaker, K., submitted for publication. Use of remotely sensed data to assess the significance of drying gradients in the Okavango Delta, Botswana. (Manuscript for submission to International Journal of Remote Sensing).

SMEC, 1990. Southern Okavango Integrated Water Development. Technical study, Department of Water Affairs, Gaborone, Botswana.

SWECO, 1976. Study of the use, extraction and transfer of Okavango water for development of the Okavango Corridor, final report, Department of Water Affairs, Botswana.

Thibodeau, F.R., Nickerson, N.H., 1985. Changes in a wetland plant association induced by impoundment and draining. Biological Conservation 33, 269–279.

Todd, M.C., Kidd, C., Kniveton, D.R., Bellerby, T.J., 2001. A combined satellite infrared and passive microwave technique for estimation of small scale rainfall. Journal of Atmospheric and Oceanic Technology 18 (5), 742–755.