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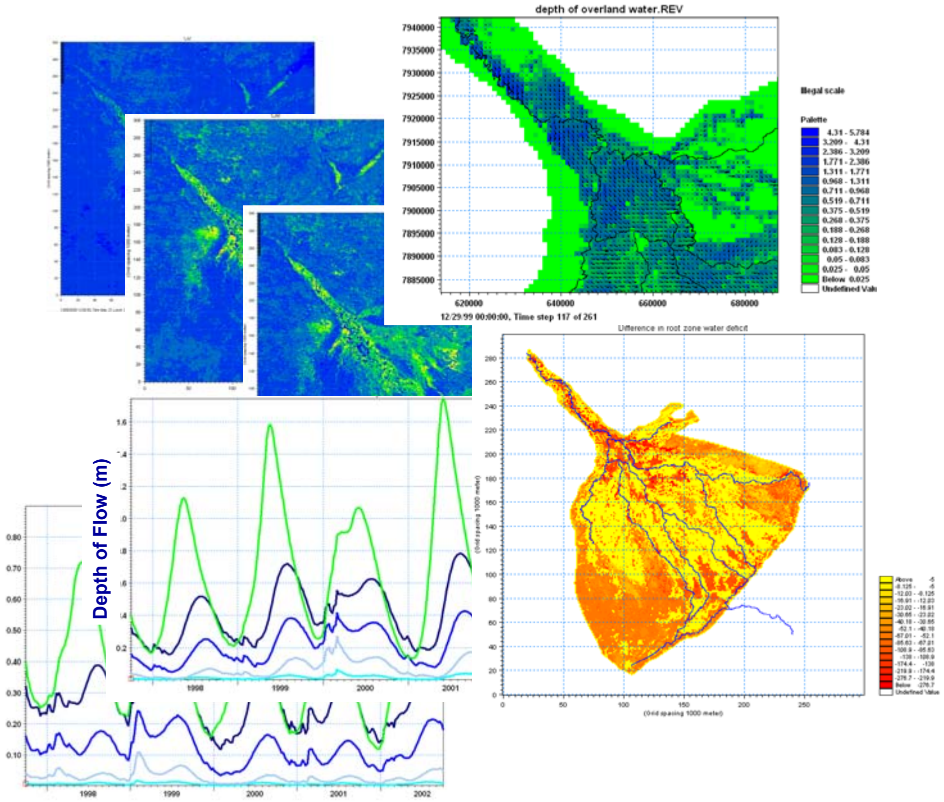
Department of Environmental Affairs
Department of Water Affairs
Harry Oppenheimer Okavango Research Centre

# Okavango Delta Management Plan

## Hydrology and Water Resources



## Analysis of Water Resources Scenarios

December 2005

**Scanagri Denmark A/S**
DHI Water and Environment
Hedeselskabet
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# Okavango Delta Management Plan

## Hydrology and Water Resources

## Analysis of Water Resources Scenarios

## December 2005

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# 1. INTRODUCTION

## 1.1 Background

Hydrology and Water Resources is one of the twelve components comprising the Okavango Delta Management Plan project. The project and the component commenced in May 2003.

The development objective of the Okavango Delta Management Plan is integrated resource management for the Okavango Delta that will ensure its long term conservation, and that will provide benefits for the present and future well-being of the people, through sustainable use of its natural resources.

In line with this development objective, the immediate objectives for the Hydrology and Water Resources component are improved water resources planning, and monitoring and evaluation in the Okavango Delta, based on an enhanced capacity of the Department of Water Affairs. Corresponding to these objectives, the outputs of the component are:

(1) A comprehensive quality controlled database comprising existing climatic, hydrologic, surface water, ground water and sediment data for the Okavango Delta.

(2) Recommendations on the improvement and expansion of the Okavango Delta monitoring network.

(3) A digital Topographic Model of the delta.

(4) An Integrated Hydrologic Model for the delta.

(5) The analyses of the impacts of water resources scenarios for the Okavango Delta Management Plan.

(6) Capability within DWA to maintain and operate the Integrated Hydrologic Model for the establishment and implementation of the ODMP.

This draft Scenario Analysis report focuses on outputs (4) and (5), the Integrated Hydrologic Model and its application to the analysis of the impacts of water resources developments in the delta and the basin upstream. A preliminary analysis of the water resources scenarios was distributed in April 2005. A draft Technical Report on the model was distributed in March, and the final report has been distributed in December 2005. This draft Scenario Analysis report will be followed by a final report for the management plan later in 2006.

## 1.2 Liaison with Stakeholders

This report is intended primarily for the ODMP management planners and those in other component departments who may use the results in their analysis of the impact of the hydrology on their respective sectors (wildlife, vegetation, fisheries, livestock, tourism, etc). While the technical hydrologic discussion is kept to a minimum, and emphasis placed on visual presentations, all readers will profit from a basic understanding of hydrology in general, and the delta hydrology in particular, which can be gained from various ODMP and earlier reports.

The preliminary scenario analysis was presented to the ODMP stakeholders in a Workshop in Maun on 11th February 2005, with the intention of informing the partner institutions and community about the role of the hydrologic model in the management plan, and giving them the opportunity to comment on the analysis and presentation of the results. The Workshop took on a technical slant, which was not the original intention, and neither the representatives nor the DWA staff achieved a proper exchange of information and comment.

Following distribution of the preliminary report, in order to target the stakeholders more effectively, DWA held bilateral meetings with the individual stakeholders to present and discuss the hydrologic analysis, and receive their particular comments and suggestions on how it can meet their individual needs. A representative from the HOORC Data Management component was present, to explain how the hydrologic information can be related with information from the stakeholders' own sectors through the Okavango Delta Information System (ODIS).

A further round of bilateral meetings is planned following distribution of this draft report, with comments incorporated into the final report for the management plan.

## 1.3 Report Structure

A comprehensive technical report on the Integrated Hydrologic Model was distributed in March 2005. The following section 2 provides a simplified description of the model, aimed at providing stakeholders with an understanding of the complex hydrologic processes at work in the delta, and the representation of these processes in the analytical model.

Section 3 sets out the approach to the analysis of a range of scenarios for the Okavango Delta Management Plan, and the preliminary results of the analysis, as animations (videos), maps showing the surface and subsurface waters, time series of water depths and summary tabulated results. Finally section 4 concludes with a summary of the analysis, and possible further applications.

# 2. INTEGRATED HYDROLOGIC MODEL

## 2.1 Introduction

A computer model has two parts, software and data. The software comprises mathematical relationships expressing the movement of water in the atmosphere, on the surface of the earth and below the surface; and algorithms which steer the computations according to the current system state, eg channel wet or dry, soil saturated or unsaturated, etc. The software may be applied to any hydrologic system in the world.

The data describe the topography of the delta and channels, upstream inflows and numerous climatic parameters. The data define the model for the Okavango Delta.

The model outputs numerous parameters describing the hydrologic behaviour within the delta, and how it varies from day to day, month to month and year to year. The parameters include evaporation from open water and the soil, and transpiration from vegetation, water levels and flows over the surface, the level of moisture in the soil, and the level and movement of ground water.

The model is integrated in that it analyses the complex links among the atmospheric, surface and ground waters of the delta with a detailed physical description of the processes. This implies that it is based on the fundamental laws of physics. As these laws are valid in all circumstances, the model may be applied to analyse the impact of possible water resources developments in the delta, and in the basin upstream.

Alternative models which have been developed earlier have been conceptual models based on idealised representations simplifying the processes, which break down if the concept or ideal becomes invalid; and statistical representations which break down if the historical records are invalidated by changes in the system, such as land use changes and structural interventions.

## 2.2 Methodology

### 2.2.1 Key Hydrologic Processes

The key processes governing the hydrologic behaviour of the delta are illustrated in figure 2.1, and may be summarised as:

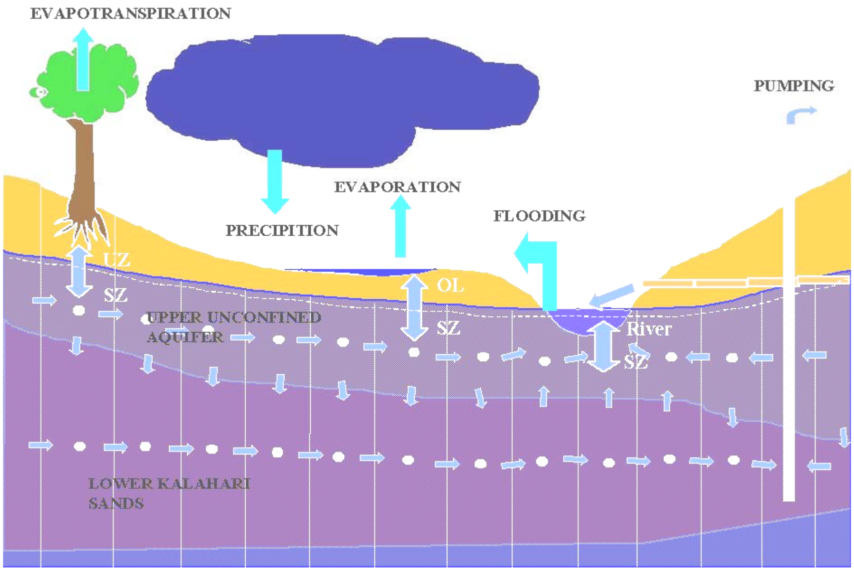

*Figure 2.1: Flow Processes in Delta*

- Seasonal flow pattern through channels, and flood plains and swamps
- Numerous bifurcations in the channels forming the delta
- Extensive spills from the channels to the flood plains and swamps
- Evaporation from open water and transpiration from vegetation
- Infiltration from surface to ground water, and exfiltration from ground to surface water
- Combined role of sediment transport and vegetation
- Salt balance and precipitation on islands

Figure 2.2 illustrates the structure of the hydrologic model, with integrated layers representing the atmospheric waters, surface waters (channels and flood plains), and ground waters (unsaturated and saturated). The individual layers are briefly described in the following sections.

Of the above processes, the hydrologic model will neither simulate the vegetation dynamics nor the salt balance. While the modelling system can describe the movement of salt in the surface and ground waters, this application is beyond the present scope. Vegetation dynamics are not sufficiently well understood to be described in mathematical terms.

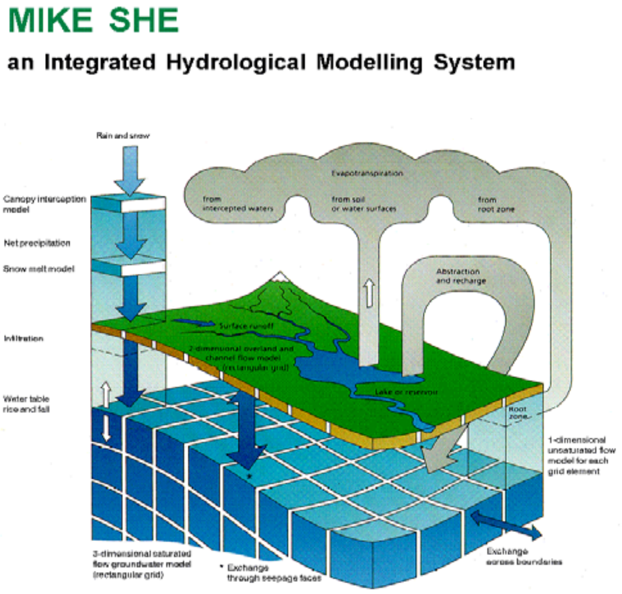

*Figure 2.2: Structure of Hydrologic Model*

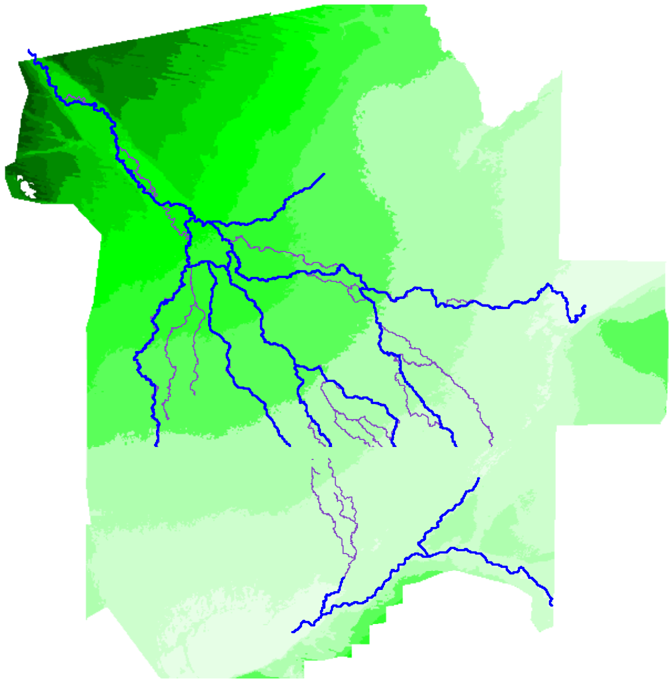

*Figure 2.3: Channel Network*

### 2.2.2 Surface Water

The surface water flows are dependent on the topography of the delta and the channel cross sections. The topography is described by a digital elevation model of the Ramsar area with a 30m resolution, based on aerial radar altimetry and remote sensing. A limited number of cross sections, available at gauging stations and surveyed by researchers, describes the flow through the river and channels. The channel network is derived from recent aerial photographs from DMS, and local knowledge of flow patterns (see figure 2.3).

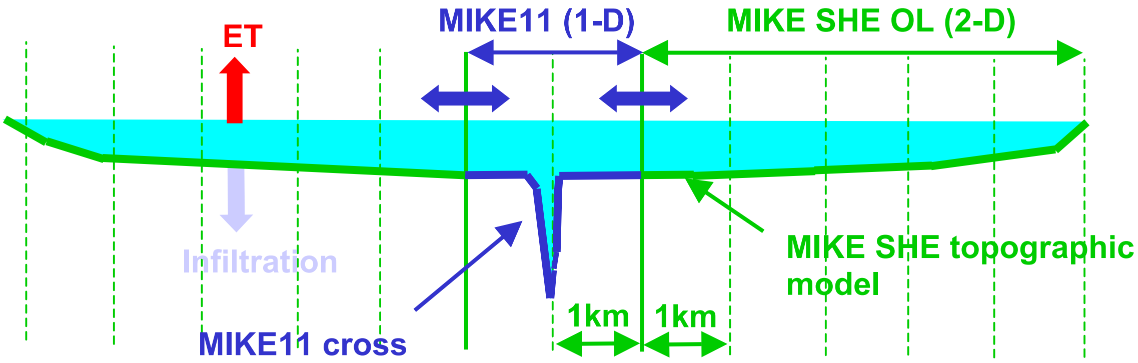

*Figure 2.4: Channel and Flood Plain Coupling*

The surface waters of the delta are described by a full hydrodynamic representation of the flows in the main rivers and channels, and by a distributed kinematic representation of the flows over the flood plains and through the swamps. The descriptions are fully coupled (figure 2.4), and enable the representation of the essentially one dimensional flows through the channels giving definition to the flow, and the spreading and distributed storage over the flood plain (figure 2.5).

### 2.2.3 Subsurface Water

Infiltration rates are significant on the predominantly sandy soils in the early stages of the flood season. The infiltration raises the ground water levels, up to the flood water level. This increases the water available to plants, which in turn increases transpiration from the leaf surfaces to the atmosphere (figure 2.6).

An essential component is the inclusion of the critical unsaturated root zone, the zone from which plants draw water and transpire to the atmosphere. Together with evaporation from open water, this represents the main loss of water in the delta. The soil type distribution and profile definition is shown in figure 2.7.

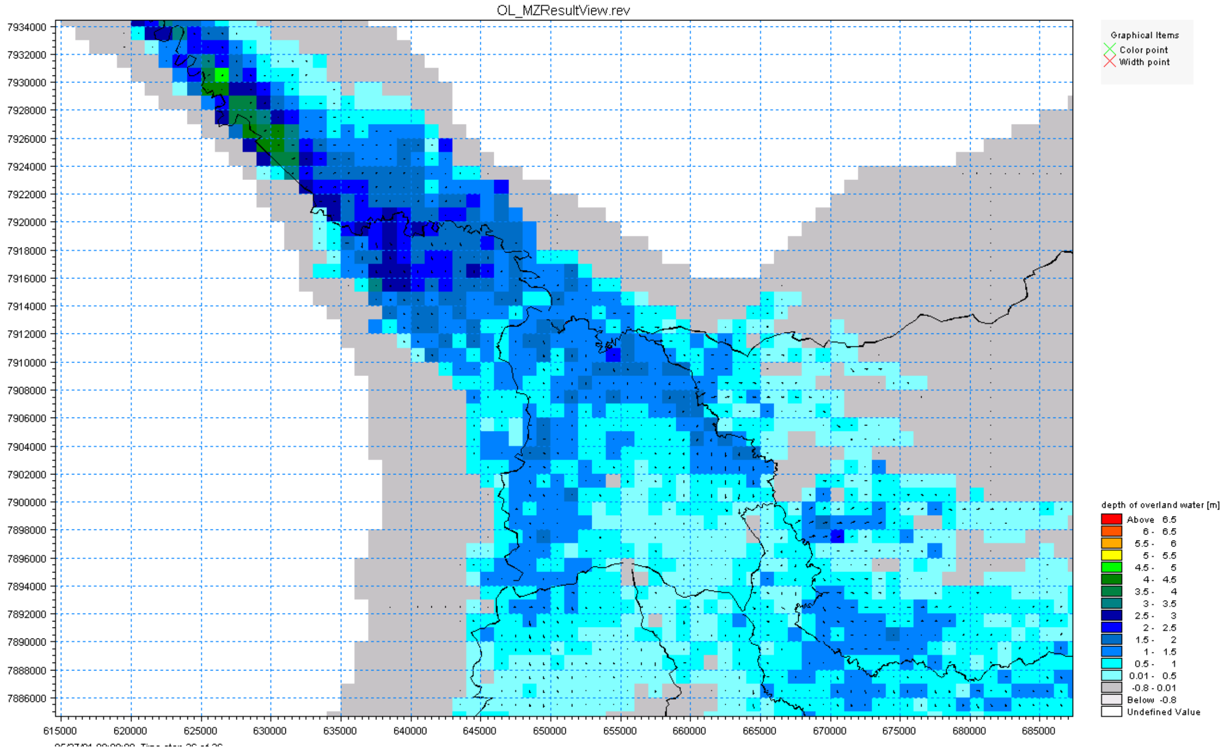

*Figure 2.5: Channel and Flood Plain Flows*

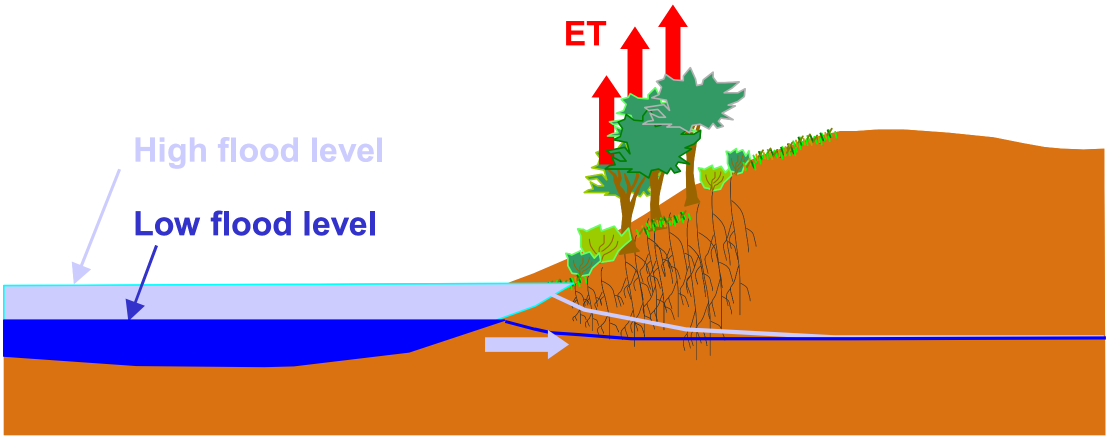

***Figure 2.6: Infiltration and Evapotranspiration Dynamics***

The ground water component is important to account for the local effects of ground water on the water balance, ie recharge and discharge, and evapotranspiration losses. Only the surficial ground water aquifer is represented. Figure 2.8 shows an example of the simulated ground water levels in the delta.

Detailed ground water studies show infiltration and recharge of fresh water lenses embedded in older saline ground water. Given the low topographical relief, limited ground water flow is directed towards local depressions (figure 2.9). Model water balance tests indicate that there is no significant ground water flow from the delta, nor are there data to support such flow hypotheses. Consequently, there is no flow across the subsurface model boundary.

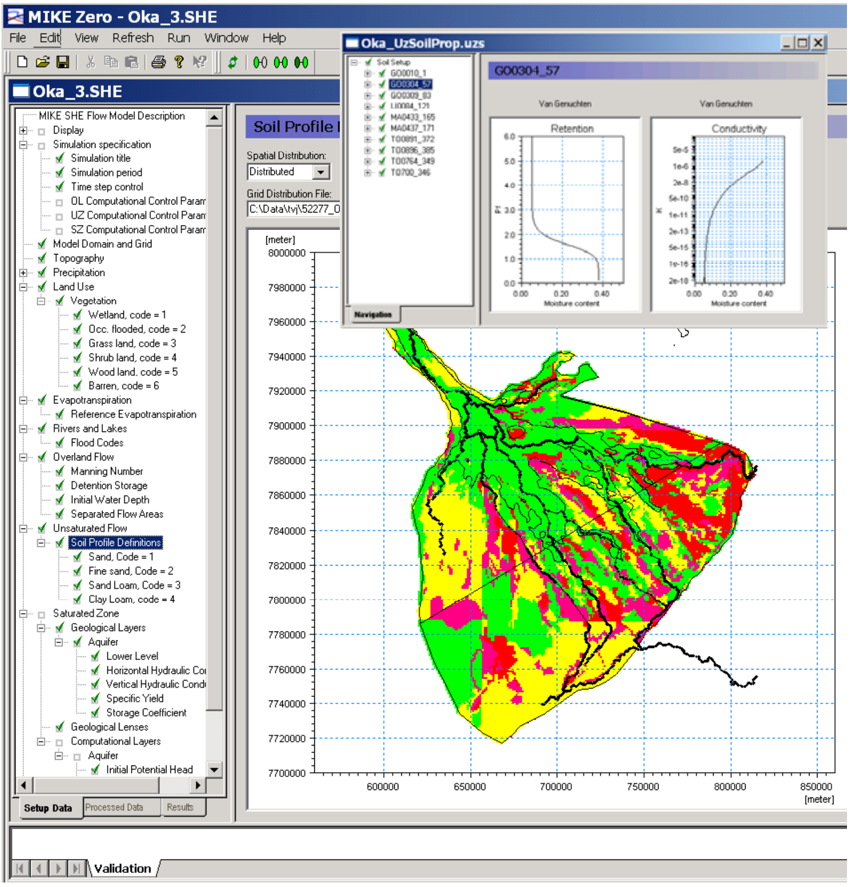
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***Figure 2.7: Soil Type Distribution and Properties***

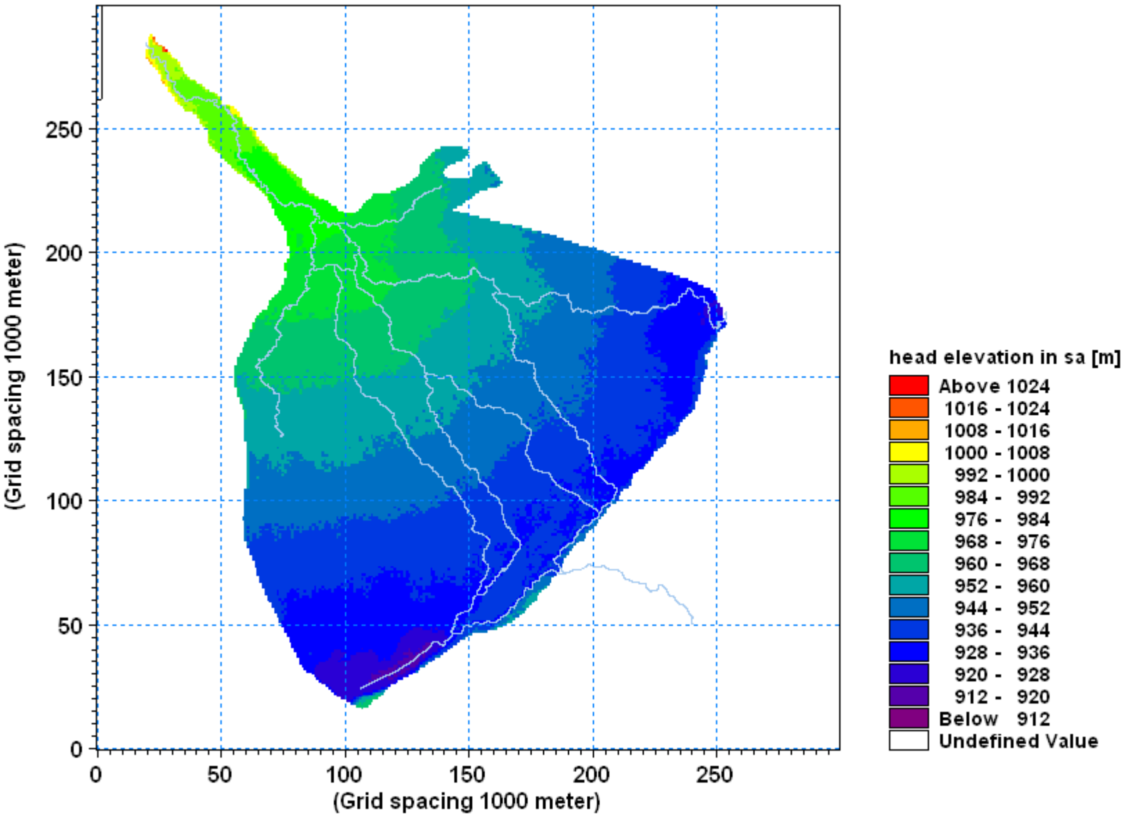


*Figure 2.8: Ground Water Levels*

### 2.2.4 Evapotranspiration

Evapotranspiration from the open water and vegetation in the delta is the key to describing the water balance. Of the main inflows to the delta, river flows from the basin upstream and rainfall over the delta, upwards of 95% is lost to evapotranspiration, the remainder infiltrating to ground water and downstream surface water outflows.

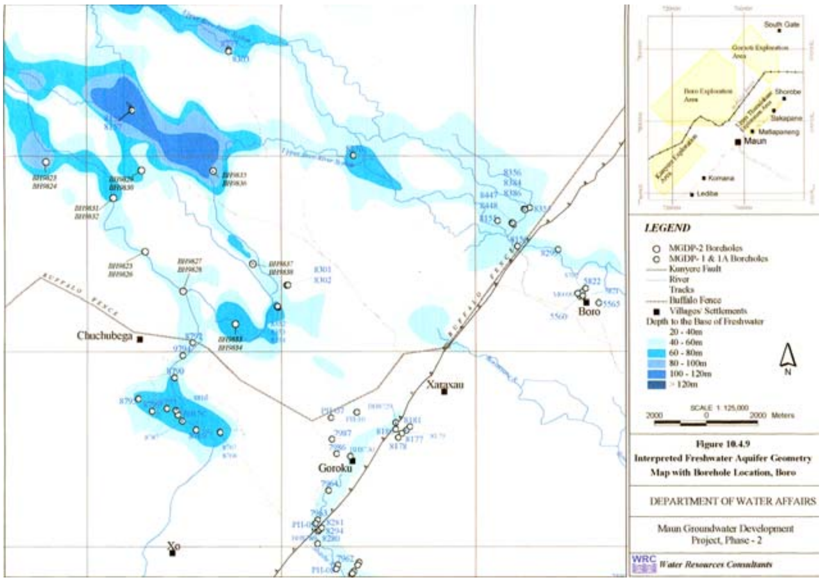


*Figure 2.9: Fresh Ground Water Lenses (Maun GWDP)*

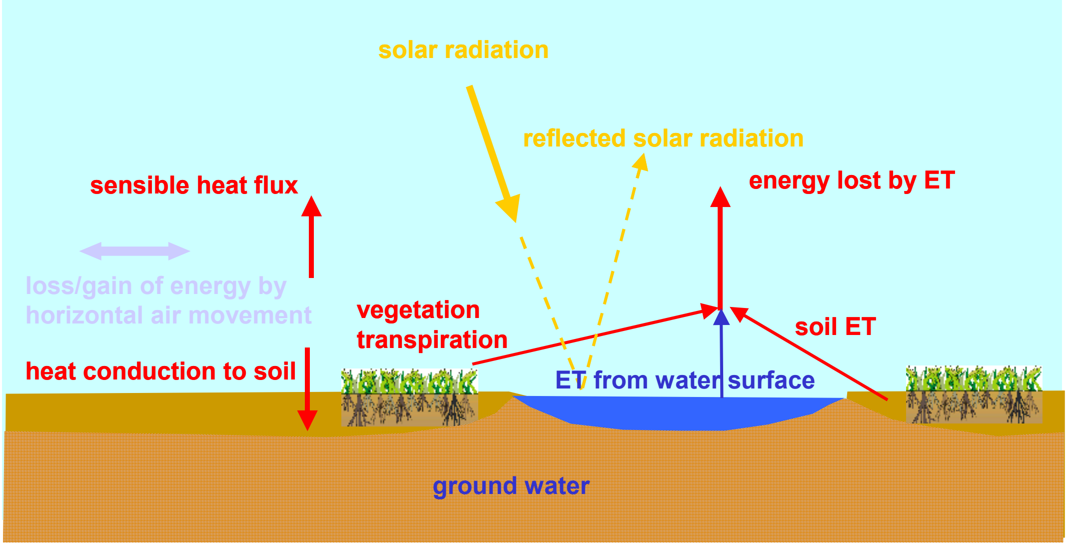


***Figure 2.10: Evapotranspiration and Energy Balance***

The greater the inflows and the corresponding extent of flooding in any one year, the greater the losses to the atmosphere. The rate of evapotranspiration is crucial to the water balance and the extent of flooding. The model uses a soil-vegetation-atmosphere transfer (SVAT) mechanism to describe the process. The evapotranspiration component simulates both the hydrologic and vegetation dynamics (figure 2.10).

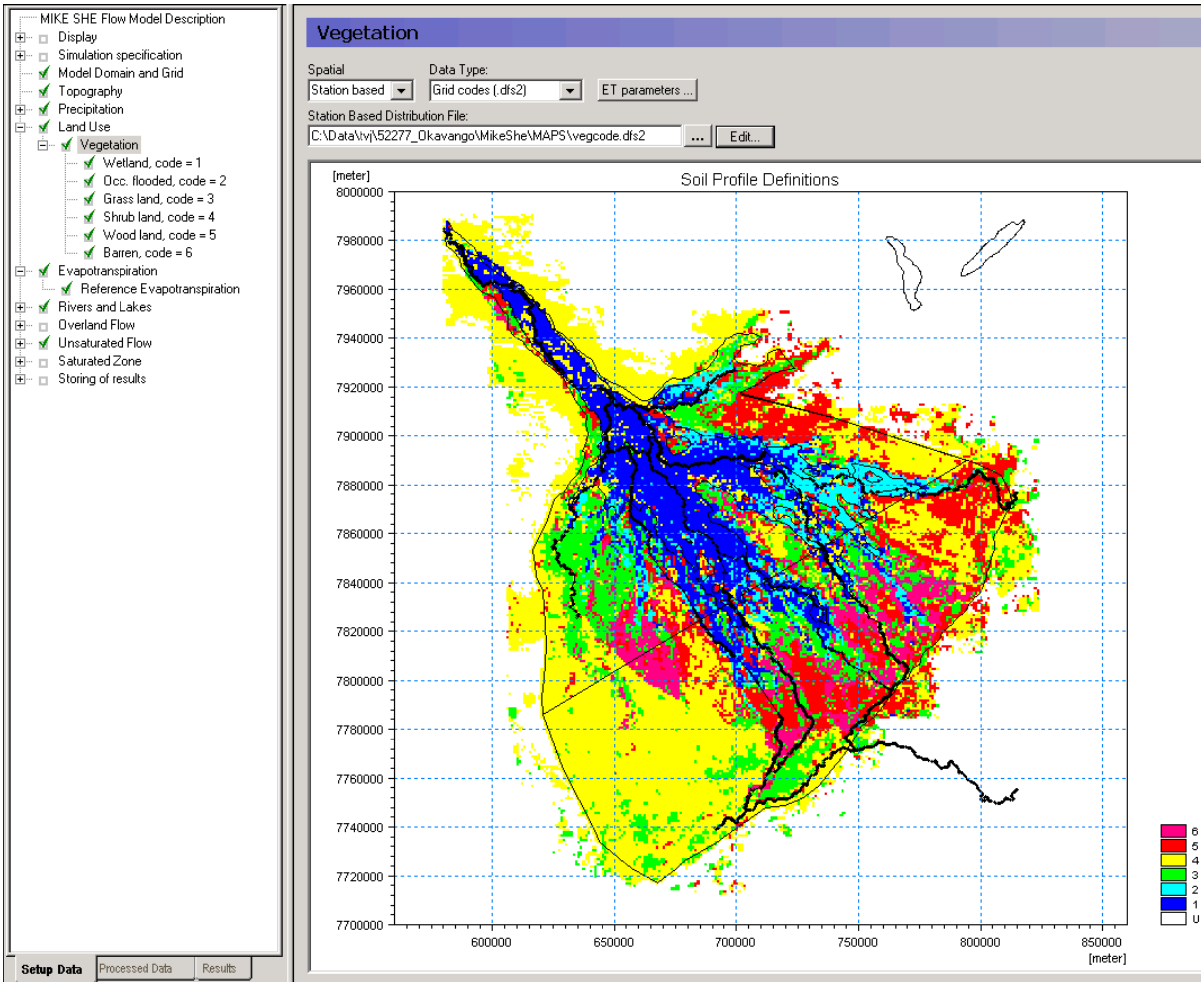
The SVAT component comprises a two layer soil-canopy system linked by a network of resistances. This enables representation of the latent and sensible heat flux between the soil, the canopy and the atmosphere based on humidity and temperature gradients controlled by aerodynamic and stomata resistances, and atmospheric conditions.

The model distinguishes losses from open water, the soil and the vegetation, and thus has a dynamic coupling with the surface and subsurface waters (figure 2.10). The vegetation dynamics are based on remotely sensed data with limited ground verification (see figures 2.11 and 2.12). The relationship between the extent of surface water and the rate of evapotranspiration is shown for the normally and seasonally flooded areas in figure 2.13.

While the SVAT module gives a truly comprehensive representation of the complex evapotranspiration processes, in its application to management planning run times proved excessive. The simpler Kristensen and Jensen method taking the actual evapotranspiration as a proportion of the potential, based on actual soil moisture, vegetation density and flood conditions, was applied instead. The SVAT module is now used to establish the potential evapotranspiration as a one off application, in place of the traditional Penman method, which requires climate data from the inner delta (not available), and which is not applicable to the range of vegetation types found in the delta.

## 2.3 Calibration

The Integrated Hydrologic Model includes a large number of parameters describing hydrological characteristics distributed across the delta. In order to obtain model results that reflect actual field observations, the model parameters are subject to adjustments as part of the calibration process. The parameter ranges in the calibrated model must be physically reasonable, within pre-specified ranges, to support the application of the model to impact assessment.



Vegetation

Spatial: Station based

Data Type: Grid codes (.dfs2)

Station Based Distribution File: C:\Data\tvj\52277_Okavango\MikeShe\MAPS\vegcode.dfs2

*Figure 2.11: Vegetation Distribution (aggregated from HOORC)*

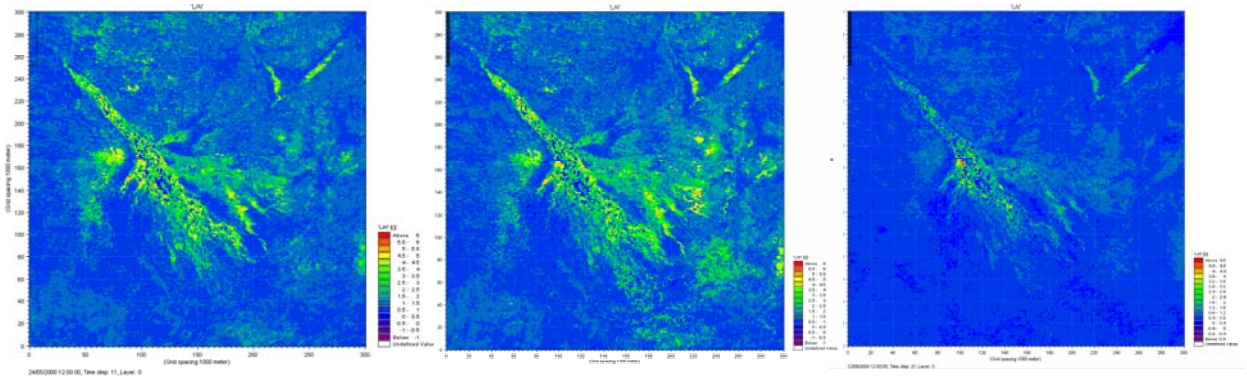


*Figure 2.12: Sequence of Satellite Data showing Vegetation Density*

The complexity of the delta compared to the limited available field data for calibration makes accurate calibration of individual areas or river sub-systems difficult. There is limited basis for assigning local parameter values and no observation data to verify the model performance. Consequently, the model performance is evaluated partly by quantitative and partly by qualitative assessments, looking at the larger scale model outputs.

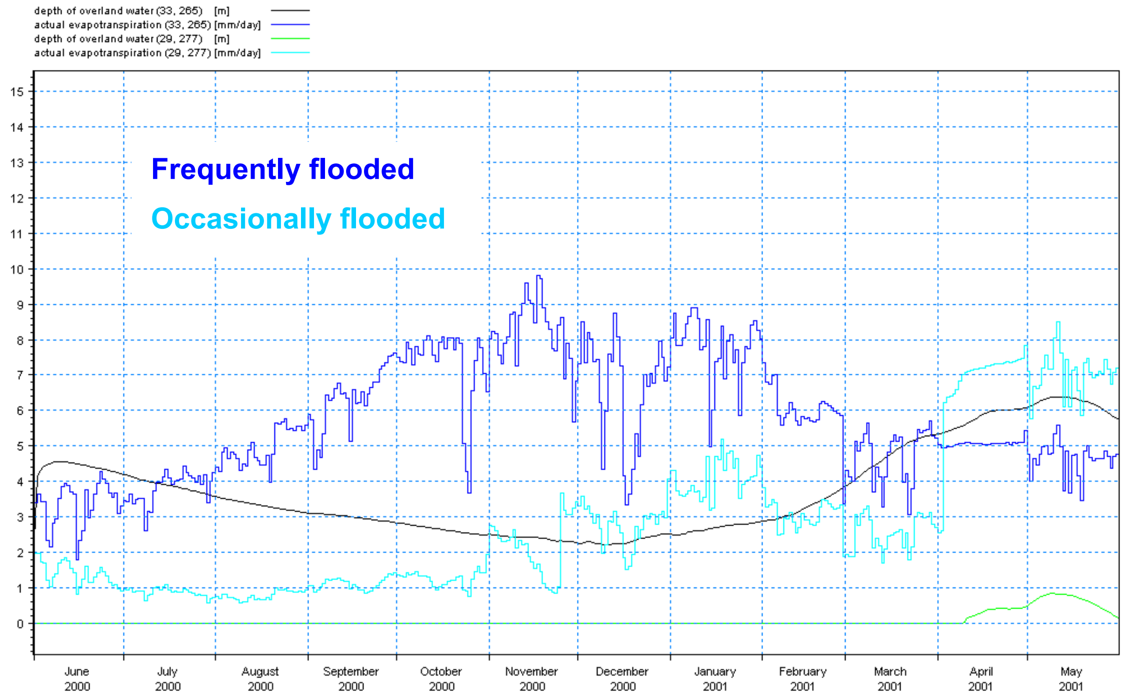


*Figure 2.13: Evapotranspiration and Surface Water Depth*

Model calibration has been targeted towards specific outputs of relevance to the subsequent model applications, as set out in table 2.1.

*Table 2.1: Model Calibration Priorities*

| MODEL RESULT | REQUIREMENT | CALIBRATION REFERENCE | PRIORITY |
|---|---|---|---|
| **Flood extent** | Simulate extent of permanently and temporarily flooded areas in the delta | Comparison with flood extent derived from satellite images | 1 |
| **Water balance** | Simulate total water balance including distributed time-varying ET rates, losses to the subsurface, storage changes and discharges | Gauged continuous discharges downstream | 2 |
| **Water levels** | Simulate mean water levels and water level changes | Gauged datum referenced water levels | 3 |

Selection of calibration period is restricted by two remote sensing data sets. The LAI data based on MODIS data are only available for 2000 to 2004. The flood extents derived from satellite imagery cover the period 1985 to 2000, recently extended by HOORC to 2005. Consequently the period January 2000 to March 2004 was selected for calibration. The period covers a range of climatic conditions over the basin, though not the full range of historical extreme floods and droughts.

The comparison of flood probability based on observed and simulated flood extent is shown in figures 2.14 and 2.15. The model simulates the flood dynamics well, with no systematic bias in the overall trend. The calibration against maximum and minimum flood extents shows a slight tendency to overestimate maxima (+4%), and underestimate minima (-7%). There is also a minor spatial bias towards flooding in the Crescent-Thaoge system (+9%) at the expense of the Panhandle (-7%).

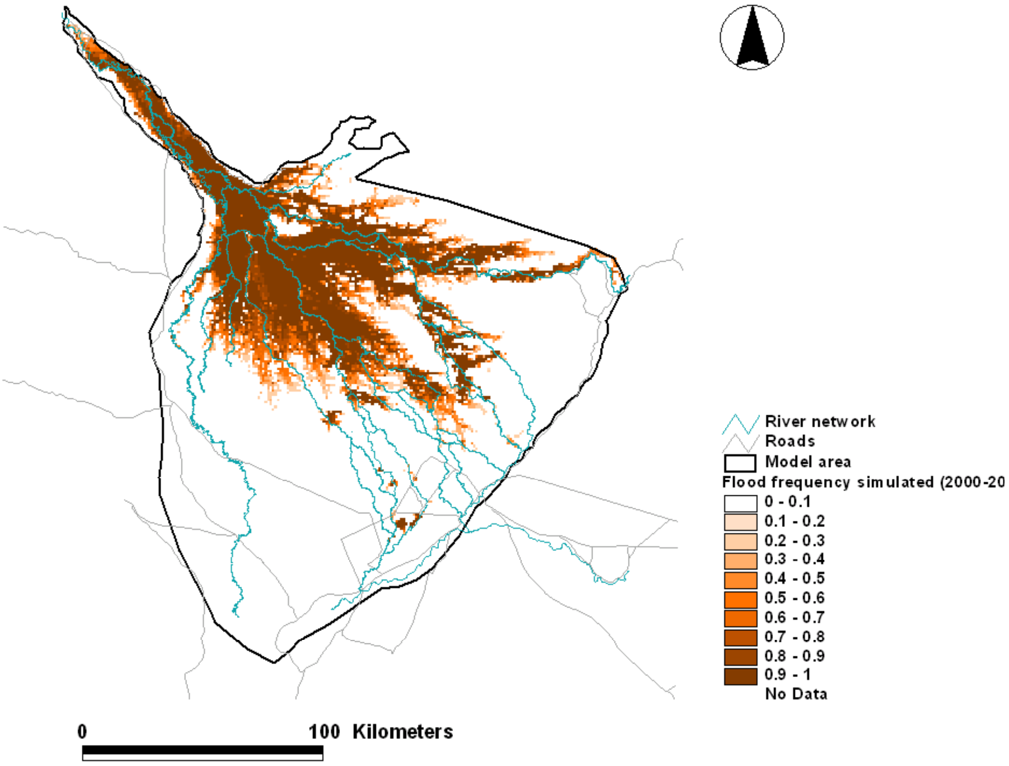


***Figure 2.14: Simulated Flood Frequency for Calibration Period (2000-2004)***

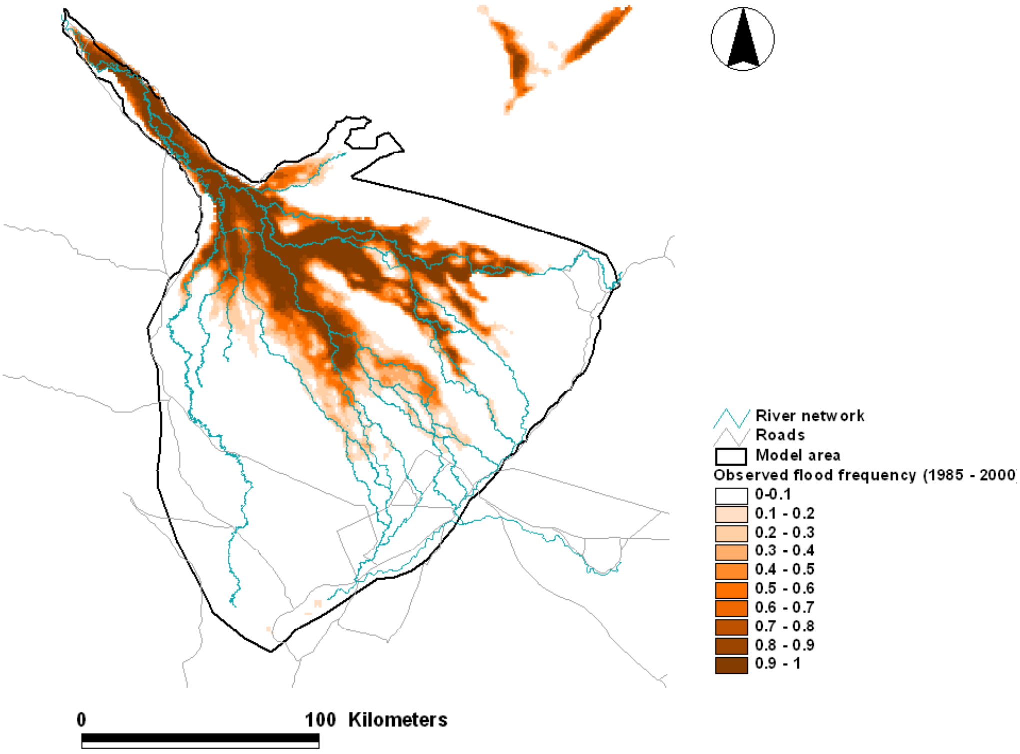


***Figure 2.15: Flood Frequency Derived from Satellite Images (1985-2000)***

Comparison of observed and simulated discharges addresses the water balance in the delta, expressed by the simple relationship:

River inflow + rainfall + evapotranspiration + river outflow +
surface storage change + subsurface storage change = zero

While evapotranspiration is the largest component of the water balance, it cannot be measured. Neither can surface and subsurface storage changes be measured. The model simulation can be assessed looking at the dynamics of the evapotranspiration for different delta zones, figure 2.13. In permanently flooded areas the range is from 2 to 8mm/day, corresponding to the rainy and dry seasons respectively. For the seasonally flooded areas, the range is from 1 to 8mm/day, corresponding to the flood dynamics. For dry areas, the range is from 0 to 5mm/day, corresponding to the vegetation dynamics of the dry and rainy seasons respectively.

The simulated water balance for the calibration period is shown in table 2.2.

***Table 2.2: Simulated Total Water Balance for Calibration Period***

| Water Balance Component | Volume ($Mm^3$) |
|---|---|
| Inflow | 1,301 |
| Rainfall | 1,794 |
| Evapotranspiration | -3,013 |
| Outflow | -7 |
| Surface water storage change | -42 |
| Subsurface storage changes | -32 |
| Water balance error | 1 |

Further details of the model calibration in respect of the water balance may be found in the technical report.

## 2.4 Limitations

The development of the Integrated Hydrologic Model represents a major advance in hydrologic modelling, in particular with the topographic model, the full integration of surface and ground waters, and detailed representation of the complex evapotranspiration processes. It does nonetheless have certain practical limitations, and it is important that these are recognised by the stakeholders and management planners.

### Channel Switching

While the model can predict the impact of cutting and dredging a new channel through the delta, and the impact of closing an existing channel through the encroachment of vegetation, it is not able to predict the occurrence of the formation of new channels, and the realignment of existing channels, which may be initiated by the movement patterns of large mammals and vegetation growth.

Certain trends in sedimentation and channel development and decay may be predicted by the application of sediment transport to the model. Work on this area will be reported shortly. Detailed analyses of selected reaches and areas of the delta may be carried out through the application of two dimensional morphological models. This is beyond the scope of the present component activities.

### Level of Detail and Accuracy

While the technology exists to simulate the hydrologic behaviour of the delta at a high level of detail (applications have been made at the level of individual cultivated fields), this is constrained by:

- The resources available to the component do not permit the development of submodels which could enable the study of a particular area of the delta below the present one square kilometre resolution
- The available data do not justify high expectations on the level of accuracy with respect to absolute water levels and quantities. Recommendations have been made for improved data collection and management which when available could justify further model development.

The key issue at this stage is that the Integrated Hydrologic Model represents the essential hydrologic phenomena in an integrated manner, such that it may be applied with confidence to the assessment of the impacts of future water resources developments on the delta hydrology for the purposes of the management plan.

### Physical Phenomena

The model simulates physical hydrologic phenomena only. Studies have revealed in particular the importance of the interdependency of physical and biological phenomena, for example the movement of large mammals opening new flow paths through the vegetation, sedimentation and vegetation in closing existing channels. The accumulation of salt and the formation of islands in the delta is also not simulated by the model.

### Hydrologic Output

The hydrologic model is integrated in the sense that it integrates atmospheric, surface and ground waters. It does not integrate the various sectors of the management plan.

The output of the model describes the dynamics of the waters of the delta, under present conditions and under future water resources development scenarios. It does not describe the impact on wildlife, vegetation, livestock, fisheries, tourism, etc. Impacts on and management criteria for these sectors have to be assessed by their respective plan components, based on the outputs of the levels and flow patterns presented by the Hydrology and Water Resources component.

# 3. SCENARIOS

## 3.1 Introduction

The ODMP Integrated Hydrologic Model has been run to simulate natural undeveloped conditions in the basin and delta, present development conditions, and development conditions as they may be given a range of water resources development scenarios in the delta and the basin upstream:

- Upstream water resources developments: dams and irrigation schemes in Angola and Namibia
- Deforestation in Angola and Namibia
- Surface and ground water abstractions from the delta
- Clearing major blocked channels in the delta
- Regional climate changes
- Combinations of the above scenarios

These scenarios represent possible conditions in the basin, notionally in the year 2025. Each scenario is compared against the present conditions which serve as a baseline.

The development states are considered static. It would be possible to represent a dynamic basin condition, as populations and corresponding abstractions increase and water resources developments are implemented year on year. This is not considered as it would introduce complications regarding the coincidence of development with hydrologic events, and the impacts would be more difficult to assess. For example, the completion of a dam before a sequence of dry years would have a very different impact if a wet period followed completion.

## 3.2 Hydrologic Inputs

While the existing conditions and the scenario conditions may represent static development states in the basin, the basin is hydrologically dynamic, with variations in the rainfall and other climatic parameters, surface inflows and outflows, and storage changes both seasonally within one year, and over several annual cycles.

In order to analyse the impact of the scenarios, representative hydrologic input data have to be selected. Criteria for selection are set out as follows:

- Real data should be used as opposed to synthetic data – in processing synthetic data, information is lost and false information may be introduced
- The data should reflect critical ie dry conditions in the delta, and also wet conditions
- Sequences of critical years are more important than a single critical dry or wet year
- The data should be recent to represent the existing conditions for baseline comparison
- The data should reflect how the delta may recover in a period of normal inflows after a dry period

The long term inflow in terms of volume per annum from 1933 to date is shown in figure 3.1 for both Mukwe in Namibia and Mohembo in Botswana. Whereas at

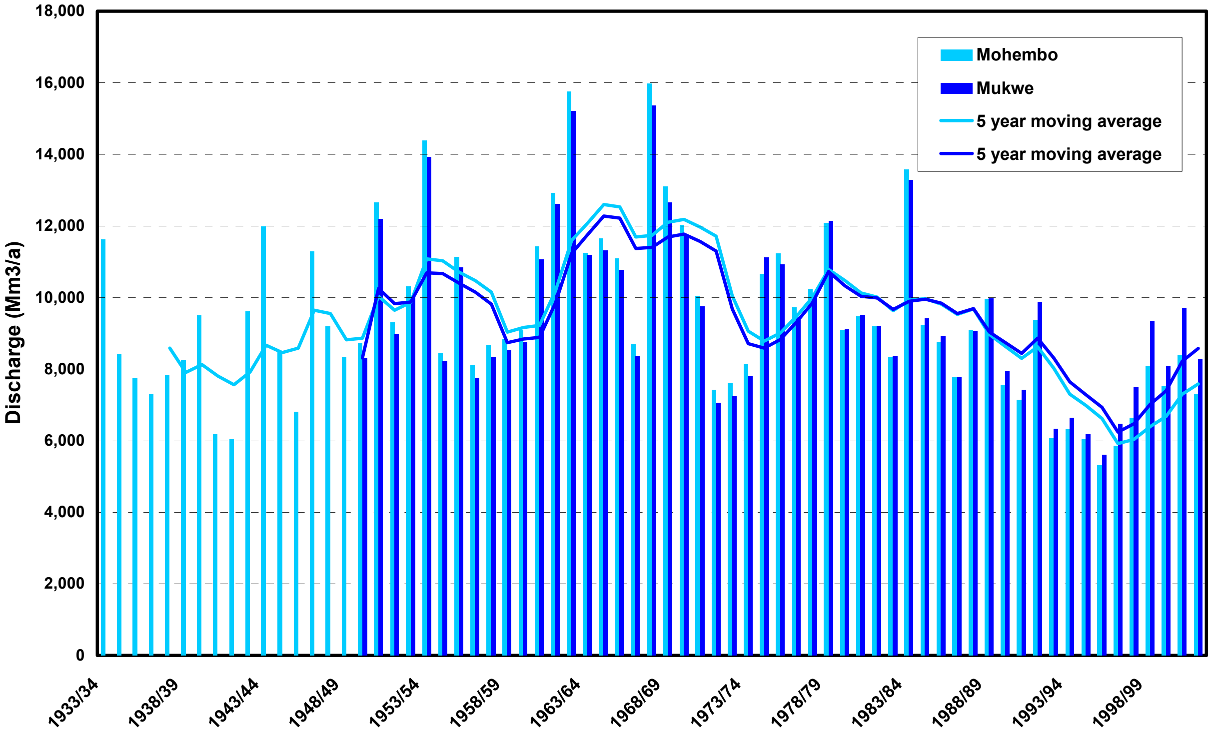


*Figure 3.1: Long Term Inflows at Mukwe and Mohembo*

Mukwe the river is more or less confined to the gauged channel, at Mohembo the river has broadened out with a wide flood plain. It is not possible to gauge the flows over the flood plain, and Mohembo will not represent the total discharge. This is most clearly evinced in the high flow years 1998/99 and 2000/01.

An anomaly appears in the data from around 1950 to 1980, where the total inflow at Mohembo appears higher than Mukwe. As there is no significant inflow to the river between the two gauges, this can only be explained by gauging errors. The series after 1980 is more consistent, with Mukwe showing a higher inflow than Mohembo.

The period from 1992 to 1997 represents the sequence of the five lowest inflow years, and is therefore chosen to provide the input data to analyse the impacts under critical conditions, for both the existing state and possible future states with water resources developments. The following five year period, from 1997 to 2002, represents relatively normal hydrologic conditions in the delta, and has been used to assess how the delta may recover after a sequence of dry years. A high inflow period has also been selected, 1987 to 1992, to assess the impacts under high inflow conditions, as high flood levels of longer duration may also result in ecosystem changes (figure 3.2).

Appropriate time series of inputs (inflows, precipitation, etc) have been prepared and applied to the existing state of the delta. The model results are used as a baseline against which future developments are assessed for their impacts. The inputs are modified to represent conditions which may prevail under future conditions.

To summarise, while the inflows to the delta will be dynamic, ranging over three five year periods representing moderately high floods, critical dry and normal average hydrologic conditions, the existing and future states will be static. This implies that for the duration of the five year model run period, the population for instance will not be increasing, no new dams or irrigation schemes are built, etc.

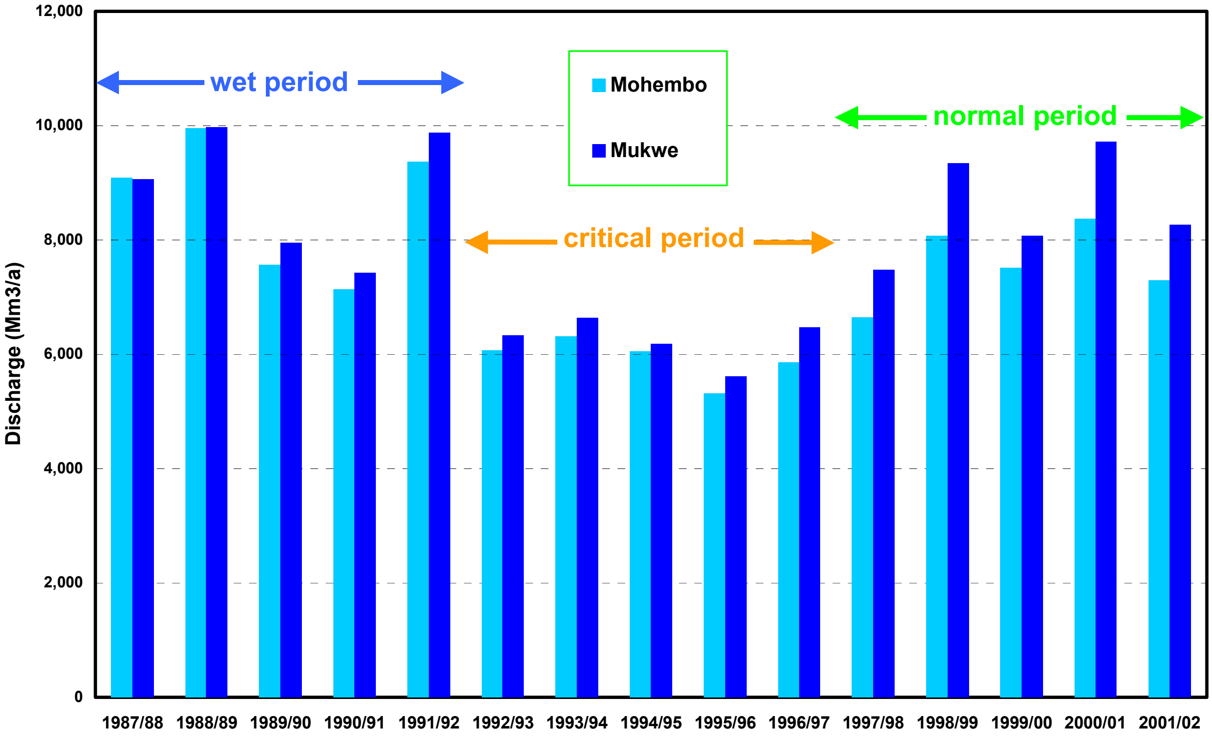


***Figure 3.2: Selected Inflow Periods at Mukwe and Mohembo***

## 3.3 Presentation of Results

In order to assist the stakeholders assess the outputs and their implications for their particular sectors, a common format for the presentation is adopted. The resolution of the model in space is one kilometre, and in time four hours. In order to limit the size of the output files, the results are output with a temporal resolution of one week for surface flows and the unsaturated zone, while the slower responding ground water results are output every two months of the five year period.

For the purpose of presenting summary data, the delta is divided into five zones according to the probability of flooding, as assessed from 15 years of satellite images (source J McCarthy, Stockholm University), with the Panhandle treated as a fifth separate zone (figure 3.3). The probability, delta area and a zone description are given in table 3.1.

***Table 3.1: Delta Zones***

| Model Area (km$^2$) | 28,782 | Description |
|---|---|---|
| Zone 1 - 0.1>FP>0 | 19,322 | rarely flooded |
| Zone 2 - 0.5>FP>0.1 | 3,534 | occasionally flooded |
| Zone 3 - 0.9>FP>0.5 | 2,328 | seasonally flooded |
| Zone 4 - 1>FP>0.9 | 2,152 | normally flooded |
| Zone 5 - Panhandle | 1,446 | Panhandle |

The selected outputs and formats are:

(1) Animated sequence of flooding in the delta showing the monthly variation in flooded area and depth.

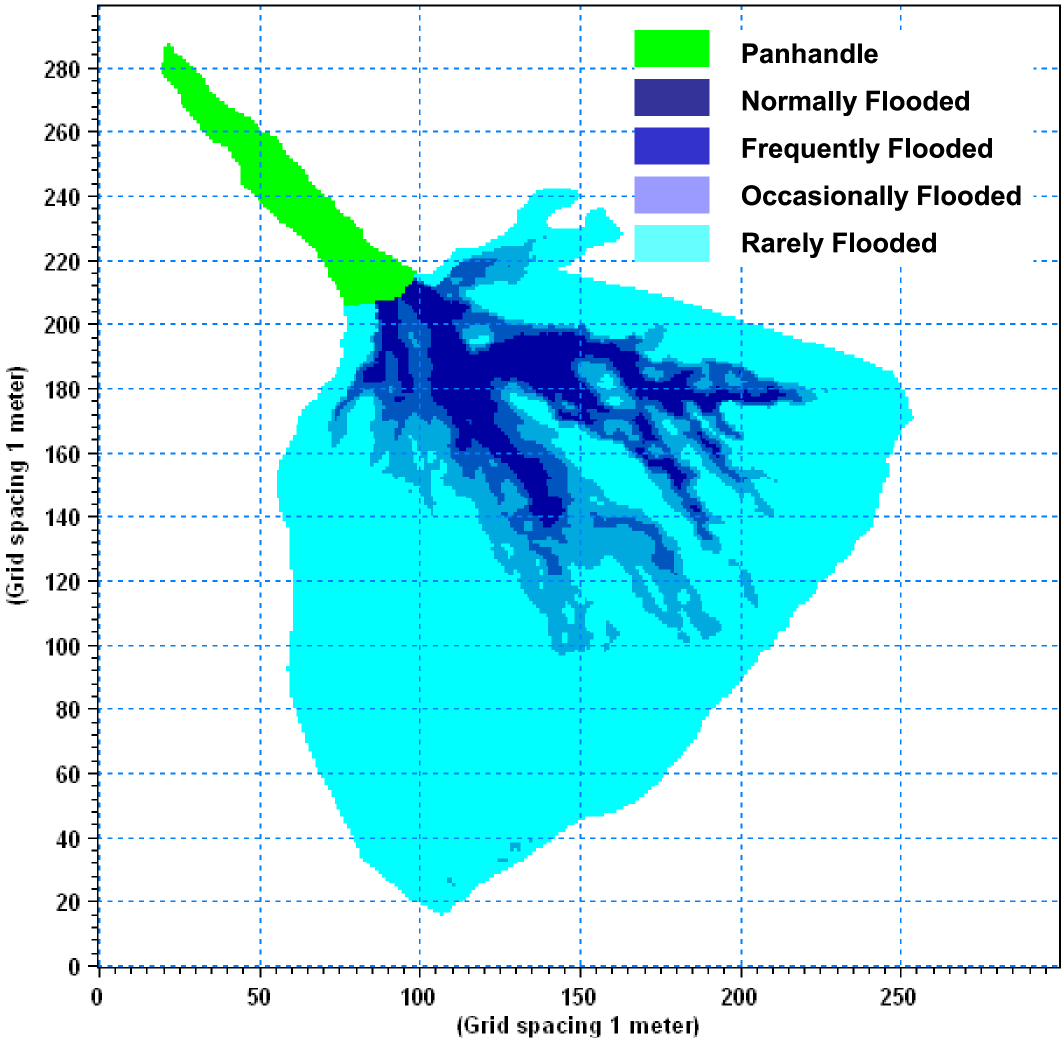


***Figure 3.3: Delta Zones***

(2) Map based on the one kilometre grid showing the minimum depth of water in the delta for the five dry years.

(3) Time series showing the variation in the depth of flooding over the five year period. The depth is averaged for each of five zones (see table 3.1).

(4) Map based on the one kilometre grid showing the minimum level of soil moisture in the root zone (the zone from which plants draw water) in the delta over the five dry years.

(5) Map based on the one kilometre grid showing the maximum depth to ground water in the delta over the five dry years.

(6) Summary tables are prepared showing the following:

- Water balance showing inflows, outflows and storage changes
- Baseline conditions and impacts for the surface water, soil moisture and ground water, for the entire delta and for each of the five zones

A wide range of outputs of all hydrologic parameters in various formats is possible, and can be tailored to the needs of the individual stakeholders. It is possible also to select different zones to calculate average time series and summary results. The above selection has been made by the component as examples of what is useful and meaningful to the stakeholders, and to generate further discussion.

Discussions are underway with HOORC as to which of the above results should be stored in the Okavango Delta Information System, and available directly to stakeholders.

## 3.4 Natural

The natural state of the basin implies no interference in the natural hydrologic processes in the form of land use changes in the catchments, structural interventions in the river system and abstractions from the surface or ground water. The basin at present is close to its natural state, with only minor abstractions for domestic use, livestock and small scale irrigation along the river banks. The present abstractions from the basin upstream and from the delta have been removed from the Baseline case, and the results presented as a Natural scenario along with the other scenarios in tables 3.2 to 3.4.

The difference in the various parameters between the Natural and Baseline states is barely significant. The additional inflow to the delta is equivalent to 28Mm$^3$ per annum or 0.36% of the total. The impact of present abstractions on the Natural basin and delta state is discussed in the context of the Baseline scenario in the following section.

## 3.5 Baseline

### 3.5.1 Introduction

The Baseline scenarios describe the current state of the delta with respect to topography and channel configuration, and the upstream and delta surface and ground water abstractions (see section 3.8.1 for details). This state remains constant over the three five year periods for which the model is run, October 1987 to September 1992, October 1992 to September 1997, and October 1997 to September 2002.

### 3.5.2 Surface Water

The animated depth of flow sequence (figure 3.4) shows the monthly expansion and contraction of the flooded area and depth as the sequence of flood waves for each of the five wet years (1987 to 1992). The wave propagates through the Panhandle and spreads out through the delta. As the graduated scale on the right indicates, dark blue represents the deepest flooding (up to 5.8m), while bright green represents dry land (flooded depth less than 0.02m).

The flood wave pulse can be seen entering the upstream Panhandle, travelling downstream through the Panhandle to the upper delta, and spreading out over the flood plains and swamps. Occasional instantaneous shallow flooding over a wide area is caused by rainstorms. Most of the flood waters evaporate to the atmosphere, while a small proportion infiltrates to ground water and drains downstream.

Figure 3.5 shows the detail for the lower envelope of flooding for the upper delta, ie the area which has never dried in the course of the five dry years (1992 to 1997). As for all grid output, each square is one square kilometre. The squares with a blue tint remain flooded throughout the five year period.

Time series of the depth of surface water are shown for each of the five zones in figures 3.6 and 3.7, for the wet and dry five year periods respectively. The Panhandle is the first area affected by the flood wave from upstream and, being relatively confined within a flood plain around 20km wide, has the maximum range from the seasonal wet to dry periods, around 0.6m in a dry year, and 1.5m in a wet year.

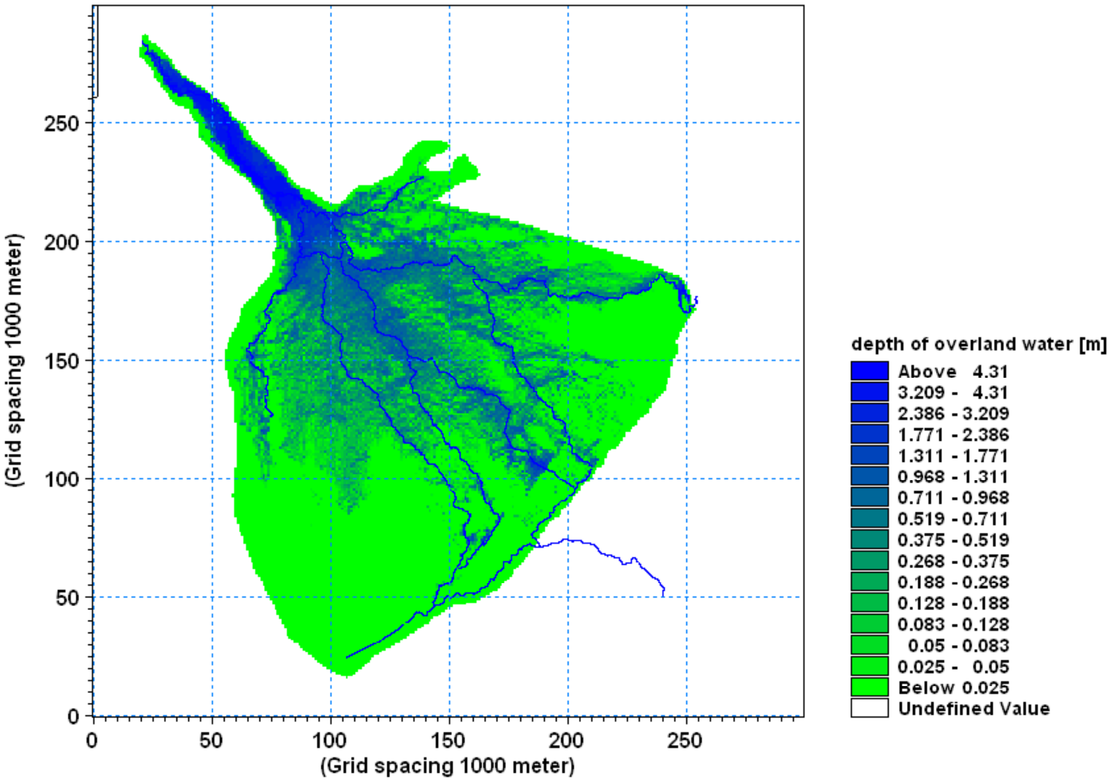


***Figure 3.4: Animated Sequence of Depth of Flow (click image to run)***

As the flood wave propagates through the delta, the range in water levels declines. The accumulated impact of the drought years (figure 3.7) is also felt more as there is a general decline in the flood depth, while there is a gradual recovery through the five wet years (figure 3.6). The impact of rainstorms can be seen during the summer months, especially in the less frequently flooded zones, as blips in the hydrograph.

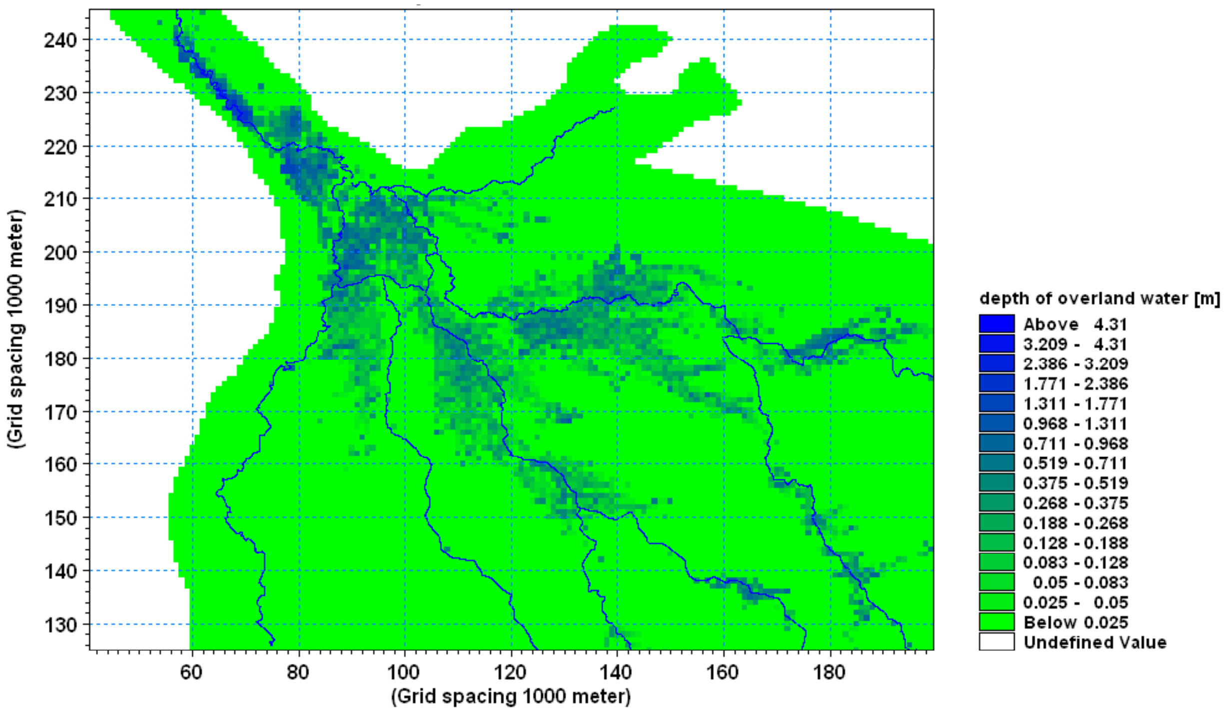
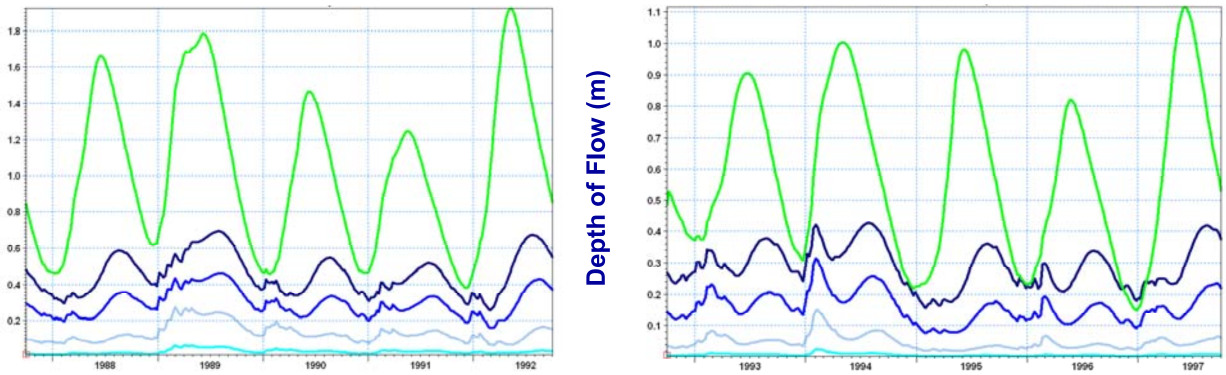


***Figure 3.5: Lower Envelope of Flooding***



***Figures 3.6 and 3.7: Average Depth of Surface Water in Each Zone***

As the summary tables 3.2 to 3.4 show, over the three five year periods the area flooded ranges from 2,770km$^2$ to 14,424km$^2$, while the depth ranges from zero to over 5m. The average depth in the normally flooded area ranges from 0.15m to 0.76m. There is no significant change relative to the Natural basin state.

### 3.5.3 Subsurface Water

The distribution of the soil moisture content is shown as a deficit below saturated level. This indicates the level of stress of drought on the vegetation, and also wildlife and livestock. The lower envelope (maximum deficit in each grid) for the five dry years is shown in figure 3.8. The average deficit ranges from 0.62m in the rarely flooded area, to 0.05m in the normally flooded area.

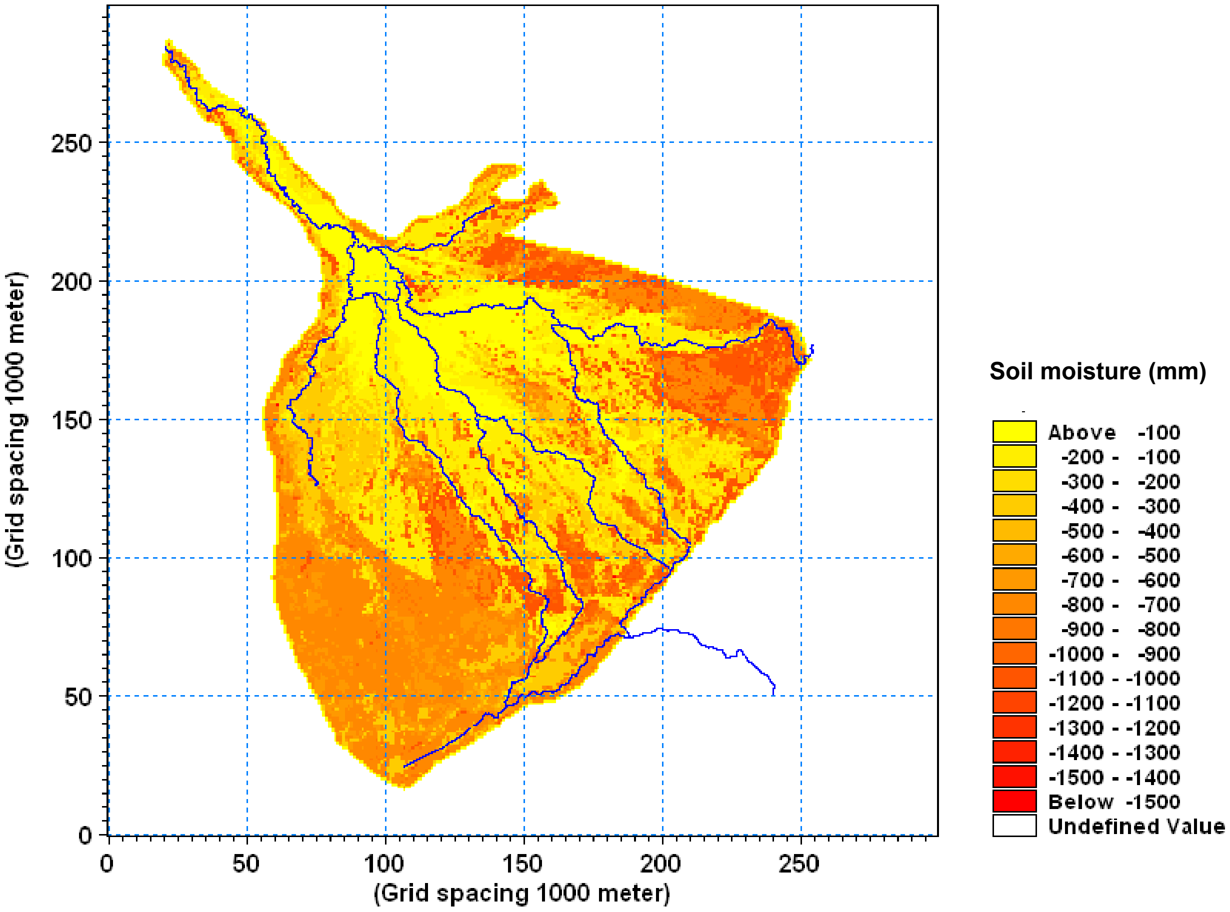


***Figure 3.8: Lower Envelope of Soil Moisture Relative to Saturation***

## *Table 3.2: Summary Results for 1987 to 1992*

| WATER BALANCE (mm/annum) | Natural | Baseline | Angola Dams | U/S Irrigation | De-Forestation | Delta Abstraction | Climate Change | Blockages | AB+AD+IR | AB+AD +IR+CC |
|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation | -487 | -487 | -487 | -487 | -487 | -487 | -384 | -487 | -487 | -384 |
| Evapotranspiration | 781 | 784 | 774 | 732 | 790 | 779 | 582 | 757 | 753 | 519 |
| Inflow | -309 | -308 | -304 | -280 | -327 | -308 | -176 | -308 | -277 | -143 |
| Outflow | 9 | 8 | 8 | 6 | 9 | 8 | 3 | 33 | 7 | 2 |
| Surface Storage Change | 8 | 7 | 8 | 16 | 15 | 9 | -14 | 8 | 5 | 3 |
| Subsurface Storage Change | 16 | 15 | 15 | 22 | 17 | 15 | -5 | 15 | 14 | 5 |
| TOTAL | 17 | 19 | 14 | 8 | 17 | 16 | 5 | 18 | 15 | 3 |

| IMPACTS | Natural | Baseline | Angola Dams | U/S Irrigation | De-Forestation | Delta Abstraction | Climate Change | Blockages | AB+AD+IR | AB+AD +IR+CC |
|---|---|---|---|---|---|---|---|---|---|---|
| **Max Overland flow depth (m)** | **0.30** | **0.30** | **-0.03** | **-0.03** | **0.01** | **0.00** | **-0.15** | **0.00** | **-0.05** | **-0.22** |
| zone 1 (Rarely Flooded) | 0.09 | 0.09 | 0.00 | -0.03 | 0.00 | 0.00 | -0.07 | 0.11 | -0.02 | -0.08 |
| zone 2 (Occasionally Flooded) | 0.32 | 0.32 | 0.00 | -0.05 | 0.01 | 0.00 | -0.20 | -0.12 | -0.03 | -0.27 |
| zone 3 (Seasonally Flooded) | 0.52 | 0.52 | -0.03 | -0.04 | 0.02 | 0.00 | -0.20 | -0.15 | -0.06 | -0.34 |
| zone 4 (Normally Flooded) | 0.74 | 0.73 | -0.08 | -0.03 | 0.04 | 0.00 | -0.24 | -0.17 | -0.12 | -0.44 |
| zone 5 (Panhandle) | 2.02 | 2.02 | -0.41 | -0.03 | 0.06 | 0.00 | -0.90 | 0.01 | -0.49 | -1.47 |
| **Min Overland flow depth (m)** | **0.05** | **0.06** | **0.00** | **-0.03** | **0.00** | **0.00** | **-0.04** | **-0.05** | **-0.02** | **-0.05** |
| zone 1 (Rarely Flooded) | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.07 | 0.00 | -0.01 |
| zone 2 (Occasionally Flooded) | 0.04 | 0.04 | 0.00 | -0.02 | 0.00 | 0.00 | -0.03 | 0.00 | -0.02 | -0.04 |
| zone 3 (Seasonally Flooded) | 0.14 | 0.14 | 0.00 | -0.06 | 0.00 | 0.00 | -0.11 | 0.01 | -0.05 | -0.13 |
| zone 4 (Normally Flooded) | 0.24 | 0.24 | 0.00 | -0.07 | 0.00 | 0.00 | -0.16 | -0.01 | -0.07 | -0.23 |
| zone 5 (Panhandle) | 0.33 | 0.33 | -0.02 | -0.20 | 0.02 | 0.00 | -0.29 | 0.03 | -0.21 | -0.32 |
| **Max Root Zone Water Deficit (m)** | **0.44** | **0.44** | **0.01** | **0.05** | **0.00** | **0.01** | **0.06** | **0.00** | **0.02** | **0.09** |
| zone 1 (Rarely Flooded) | 0.58 | 0.58 | 0.01 | 0.04 | 0.00 | 0.01 | 0.05 | -0.06 | 0.02 | 0.06 |
| zone 2 (Occasionally Flooded) | 0.23 | 0.23 | 0.01 | 0.08 | 0.00 | 0.00 | 0.10 | 0.06 | 0.03 | 0.14 |
| zone 3 (Seasonally Flooded) | 0.11 | 0.11 | 0.00 | 0.06 | 0.00 | 0.00 | 0.12 | 0.10 | 0.03 | 0.18 |
| zone 4 (Normally Flooded) | 0.05 | 0.05 | 0.00 | 0.03 | 0.00 | 0.00 | 0.08 | 0.07 | 0.02 | 0.15 |
| zone 5 (Panhandle) | 0.18 | 0.18 | 0.01 | 0.05 | -0.01 | 0.00 | 0.11 | -0.01 | 0.04 | 0.15 |
| **Max Ground Water Depth (m)** | **1.21** | **1.21** | **0.02** | **0.14** | **0.01** | **0.04** | **0.19** | **-0.02** | **0.08** | **0.27** |
| zone 1 (Rarely Flooded) | 1.68 | 1.67 | 0.03 | 0.09 | 0.01 | 0.06 | 0.09 | -0.24 | 0.05 | 0.13 |
| zone 2 (Occasionally Flooded) | 0.64 | 0.64 | 0.02 | 0.22 | 0.01 | 0.01 | 0.30 | 0.17 | 0.10 | 0.38 |
| zone 3 (Seasonally Flooded) | 0.17 | 0.18 | 0.01 | 0.23 | 0.01 | 0.00 | 0.46 | 0.29 | 0.13 | 0.63 |
| zone 4 (Normally Flooded) | -0.14 | -0.14 | 0.00 | 0.17 | 0.02 | 0.00 | 0.38 | 0.24 | 0.10 | 0.68 |
| zone 5 (Panhandle) | 0.13 | 0.13 | 0.03 | 0.34 | -0.05 | 0.00 | 0.60 | -0.06 | 0.30 | 0.73 |
| **Minimum Flooded Area (km2)** | **4,711** | **4,776** | **-188** | **-1,609** | **72** | **-113** | **-3,201** | **-401** | **-1,328** | **-4,430** |
| zone 1 (Rarely Flooded) | 363 | 444 | -122 | -294 | -57 | -87 | -348 | 269 | -239 | -392 |
| zone 2 (Occasionally Flooded) | 772 | 765 | -22 | -399 | 36 | -6 | -626 | -105 | -305 | -723 |
| zone 3 (Seasonally Flooded) | 1,257 | 1,256 | -20 | -389 | 26 | -16 | -934 | -196 | -286 | -1,173 |
| zone 4 (Normally Flooded) | 1,670 | 1,668 | -4 | -250 | 16 | -7 | -786 | -237 | -216 | -1,548 |
| zone 5 (Panhandle) | 649 | 643 | -20 | -277 | 51 | 3 | -507 | -269 | -282 | -594 |
| **Maximum Flooded Area (km2)** | **14,332** | **14,424** | **-264** | **-1,811** | **137** | **-208** | **-6,458** | **-762** | **-943** | **-8,850** |
| zone 1 (Rarely Flooded) | 6,079 | 6,177 | -226 | -1,598 | 98 | -190 | -4,558 | -59 | -770 | -5,535 |
| zone 2 (Occasionally Flooded) | 2,991 | 2,997 | -3 | -166 | 24 | -17 | -1,284 | -233 | -99 | -2,050 |
| zone 3 (Seasonally Flooded) | 2,156 | 2,155 | -7 | -40 | 10 | -1 | -364 | -199 | -21 | -744 |
| zone 4 (Normally Flooded) | 2,083 | 2,083 | -1 | -9 | 3 | 0 | -144 | -130 | -8 | -282 |
| zone 5 (Panhandle) | 1,013 | 1,012 | -27 | 2 | 2 | 0 | -108 | -621 | -45 | -239 |

Notes:
(1) Water Balance, and Natural and Baseline impact data are presented as absolute values.

(2) Scenario impact data are presented relative to the Baseline.

(3) The first row in each section of the table is the average for the entire delta, the next five rows are the averages for the individual zones.

(4) For the Blockages, the zonal impacts 1 to 4 are for the Nqoga-Maunachira-Khwai-Santantadibe system only; zone 5 is the average impact on the system.

### *Table 3.3: Summary Results for 1992 to 1997*

| WATER BALANCE (mm/annum) | Natural | Baseline | Angola Dams | U/S Irrigation | De-Forestation | Delta Abstraction | Climate Change | Blockages | AB+AD+IR | AB+AD +IR+CC |
|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation | -432 | -432 | -432 | -432 | -432 | -432 | -360 | -432 | -432 | -360 |
| Evapotranspiration | 655 | 655 | 657 | 590 | 668 | 655 | 512 | 641 | 652 | 475 |
| Inflow | -218 | -217 | -220 | -190 | -232 | -217 | -123 | -217 | -191 | -97 |
| Outflow | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 15 | 3 | 2 |
| Surface Storage Change | 2 | 4 | 4 | -4 | 5 | 4 | -10 | 6 | -14 | -11 |
| Subsurface Storage Change | -7 | -7 | -7 | -13 | -6 | -7 | -18 | -7 | -14 | -6 |
| TOTAL | 4 | 6 | 6 | -45 | 7 | 6 | 4 | 6 | 6 | 3 |
| IMPACTS | Natural | Baseline | Angola Dams | U/S Irrigation | De-Forestation | Delta Abstraction | Climate Change | Blockages | AB+AD+IR | AB+AD +IR+CC |
| **Max Overland flow depth (m)** | **0.18** | **0.17** | **0.00** | **0.00** | **0.02** | **0.00** | **-0.07** | **0.01** | **0.00** | **-0.08** |
| zone 1 (Rarely Flooded) | 0.04 | 0.03 | 0.00 | 0.01 | 0.00 | 0.00 | -0.01 | 0.06 | 0.00 | -0.02 |
| zone 2 (Occasionally Flooded) | 0.18 | 0.17 | 0.01 | 0.01 | 0.02 | 0.00 | -0.08 | -0.04 | 0.00 | -0.10 |
| zone 3 (Seasonally Flooded) | 0.35 | 0.34 | 0.01 | -0.02 | 0.03 | 0.00 | -0.14 | -0.06 | -0.02 | -0.15 |
| zone 4 (Normally Flooded) | 0.51 | 0.50 | 0.01 | -0.03 | 0.04 | 0.00 | -0.18 | -0.06 | -0.02 | -0.18 |
| zone 5 (Panhandle) | 1.26 | 1.25 | -0.01 | -0.03 | 0.12 | 0.00 | -0.61 | 0.01 | 0.00 | -0.62 |
| **Min Overland flow depth (m)** | **0.03** | **0.03** | **0.00** | **-0.01** | **0.00** | **0.00** | **-0.02** | **0.00** | **-0.02** | **-0.02** |
| zone 1 (Rarely Flooded) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| zone 2 (Occasionally Flooded) | 0.02 | 0.02 | 0.00 | -0.01 | 0.00 | 0.00 | -0.01 | -0.02 | -0.01 | -0.01 |
| zone 3 (Seasonally Flooded) | 0.06 | 0.06 | 0.00 | -0.03 | 0.01 | 0.00 | -0.05 | -0.04 | -0.05 | -0.06 |
| zone 4 (Normally Flooded) | 0.15 | 0.15 | -0.01 | -0.06 | 0.02 | 0.00 | -0.10 | -0.06 | -0.10 | -0.15 |
| zone 5 (Panhandle) | 0.13 | 0.13 | 0.00 | -0.10 | 0.03 | 0.00 | -0.11 | -0.01 | -0.11 | -0.12 |
| **Max Root Zone Water Deficit (m)** | **0.47** | **0.47** | **0.00** | **0.02** | **-0.01** | **0.00** | **0.03** | **0.00** | **0.02** | **0.06** |
| zone 1 (Rarely Flooded) | 0.59 | 0.59 | 0.00 | 0.02 | 0.00 | 0.00 | 0.01 | -0.01 | 0.02 | 0.04 |
| zone 2 (Occasionally Flooded) | 0.31 | 0.32 | 0.00 | 0.02 | -0.01 | 0.00 | 0.05 | 0.03 | 0.02 | 0.06 |
| zone 3 (Seasonally Flooded) | 0.19 | 0.20 | 0.00 | 0.03 | -0.01 | 0.00 | 0.09 | 0.06 | 0.04 | 0.12 |
| zone 4 (Normally Flooded) | 0.09 | 0.08 | 0.00 | 0.03 | -0.01 | 0.00 | 0.08 | 0.06 | 0.04 | 0.15 |
| zone 5 (Panhandle) | 0.24 | 0.24 | 0.00 | 0.04 | -0.01 | 0.00 | 0.08 | 0.01 | 0.04 | 0.11 |
| **Max Ground Water Depth (m)** | **1.33** | **1.35** | **-0.01** | **0.05** | **-0.03** | **0.01** | **0.08** | **0.02** | **0.06** | **0.14** |
| zone 1 (Rarely Flooded) | 1.72 | 1.74 | -0.02 | 0.02 | -0.03 | 0.01 | 0.00 | -0.02 | 0.02 | 0.05 |
| zone 2 (Occasionally Flooded) | 0.88 | 0.89 | 0.00 | 0.04 | -0.03 | 0.00 | 0.11 | 0.12 | 0.05 | 0.14 |
| zone 3 (Seasonally Flooded) | 0.49 | 0.50 | 0.00 | 0.12 | -0.05 | -0.01 | 0.29 | 0.22 | 0.13 | 0.36 |
| zone 4 (Normally Flooded) | 0.08 | 0.08 | 0.01 | 0.14 | -0.03 | 0.00 | 0.33 | 0.23 | 0.16 | 0.56 |
| zone 5 (Panhandle) | 0.49 | 0.51 | 0.00 | 0.22 | -0.08 | 0.00 | 0.34 | 0.06 | 0.24 | 0.42 |
| **Minimum Flooded Area (km2)** | **2,753** | **2,770** | **-83** | **-1,096** | **263** | **-2** | **-1,870** | **-510** | **-1,185** | **-2,625** |
| zone 1 (Rarely Flooded) | 128 | 129 | -8 | -35 | 10 | 0 | -83 | -2 | -40 | -95 |
| zone 2 (Occasionally Flooded) | 262 | 263 | -14 | -106 | 50 | 0 | -216 | -87 | -114 | -248 |
| zone 3 (Seasonally Flooded) | 692 | 701 | -23 | -317 | 78 | -1 | -567 | -147 | -354 | -660 |
| zone 4 (Normally Flooded) | 1,317 | 1,320 | -33 | -409 | 66 | -1 | -710 | -251 | -436 | -1,276 |
| zone 5 (Panhandle) | 354 | 357 | -5 | -229 | 59 | 0 | -294 | -487 | -241 | -346 |
| **Maximum Flooded Area (km2)** | **10,639** | **10,400** | **230** | **488** | **479** | **-6** | **-994** | **-149** | **728** | **-1,337** |
| zone 1 (Rarely Flooded) | 3,173 | 3,119 | 161 | 639 | 321 | -8 | -580 | 67 | 637 | -784 |
| zone 2 (Occasionally Flooded) | 2,330 | 2,319 | 44 | 60 | 104 | 0 | -259 | -121 | 95 | -349 |
| zone 3 (Seasonally Flooded) | 2,004 | 1,997 | 21 | -25 | 33 | 0 | -69 | -104 | -11 | -103 |
| zone 4 (Normally Flooded) | 2,041 | 2,039 | 8 | -6 | 7 | 2 | -21 | -55 | -1 | -31 |
| zone 5 (Panhandle) | 927 | 926 | -4 | 0 | 14 | 0 | -65 | -213 | 8 | -70 |

Notes: (1) Water Balance, and Natural and Baseline impact data are presented as absolute values.

(2) Scenario impact data are presented relative to the Baseline.

(3) The first row in each section of the table is the average for the entire delta, the next five rows are the averages for the individual zones.

(4) For the Blockages, the zonal impacts 1 to 4 are for the Nqoga-Maunachira-Khwai-Santantadibe system only; zone 5 is the average impact on the system.

## *Table 3.4: Summary Results for 1997 to 2002*

| WATER BALANCE (mm/annum) | Natural | Baseline | Angola Dams | U/S Irrigation | De-forestation | Delta Abstraction | Climate Change | Blockages | AB+AD+IR | AB+AD +IR+CC |
|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation | -421 | -421 | -421 | -421 | -421 | -421 | -367 | -421 | -421 | -367 |
| Evapotranspiration | 719 | 713 | 701 | 671 | 735 | 719 | 527 | 694 | 680 | 492 |
| Inflow | -299 | -298 | -284 | -270 | -317 | -298 | -158 | -298 | -268 | -128 |
| Outflow | 5 | 5 | 4 | 4 | 4 | 4 | 3 | 25 | 4 | 2 |
| Surface Storage Change | 10 | 10 | 9 | 8 | 11 | 10 | 5 | 10 | 13 | 8 |
| Subsurface Storage Change | 1 | 0 | -2 | 0 | 2 | 1 | -5 | 0 | -1 | -4 |
| TOTAL | 15 | 9 | 8 | -8 | 14 | 16 | 4 | 10 | 7 | 3 |
| **IMPACTS** | **Natural** | **Baseline** | **Angola Dams** | **U/S Irrigation** | **De-forestation** | **Delta Abstraction** | **Climate Change** | **Blockages** | **AB+AD+IR** | **AB+AD +IR+CC** |
| **Max Overland flow depth (m)** | **0.29** | **0.28** | **-0.02** | **-0.02** | **0.02** | **0.00** | **-0.17** | **0.00** | **-0.04** | **-0.20** |
| zone 1 (Rarely Flooded) | 0.06 | 0.06 | -0.01 | -0.01 | 0.01 | 0.00 | -0.05 | 0.09 | -0.01 | -0.06 |
| zone 2 (Occasionally Flooded) | 0.30 | 0.30 | -0.02 | -0.03 | 0.02 | 0.00 | -0.24 | -0.10 | -0.04 | -0.26 |
| zone 3 (Seasonally Flooded) | 0.51 | 0.51 | -0.03 | -0.03 | 0.04 | 0.00 | -0.31 | -0.14 | -0.06 | -0.38 |
| zone 4 (Normally Flooded) | 0.76 | 0.76 | -0.07 | -0.03 | 0.06 | 0.00 | -0.39 | -0.16 | -0.12 | -0.48 |
| zone 5 (Panhandle) | 2.16 | 2.16 | -0.13 | -0.02 | 0.06 | 0.00 | -1.02 | 0.00 | -0.31 | -1.37 |
| **Min Overland flow depth (m)** | **0.03** | **0.03** | **0.00** | **-0.01** | **0.00** | **0.00** | **-0.02** | **0.01** | **-0.01** | **-0.03** |
| zone 1 (Rarely Flooded) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.00 | 0.00 |
| zone 2 (Occasionally Flooded) | 0.02 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | -0.01 | -0.02 | -0.01 | -0.02 |
| zone 3 (Seasonally Flooded) | 0.07 | 0.07 | 0.00 | -0.02 | 0.01 | 0.00 | -0.05 | -0.03 | -0.03 | -0.07 |
| zone 4 (Normally Flooded) | 0.16 | 0.16 | 0.00 | -0.03 | 0.02 | 0.00 | -0.11 | -0.06 | -0.05 | -0.16 |
| zone 5 (Panhandle) | 0.16 | 0.16 | 0.00 | -0.08 | 0.04 | 0.00 | -0.14 | 0.02 | -0.11 | -0.16 |
| **Max Root Zone Water Deficit (m)** | **0.48** | **0.49** | **0.00** | **0.01** | **-0.01** | **0.00** | **0.04** | **-0.01** | **0.01** | **0.05** |
| zone 1 (Rarely Flooded) | 0.62 | 0.62 | 0.00 | 0.00 | -0.01 | 0.00 | 0.02 | -0.05 | 0.01 | 0.02 |
| zone 2 (Occasionally Flooded) | 0.31 | 0.31 | 0.00 | 0.02 | -0.01 | 0.00 | 0.06 | 0.04 | 0.02 | 0.07 |
| zone 3 (Seasonally Flooded) | 0.18 | 0.18 | 0.00 | 0.03 | -0.02 | 0.00 | 0.09 | 0.08 | 0.04 | 0.13 |
| zone 4 (Normally Flooded) | 0.08 | 0.08 | 0.00 | 0.02 | 0.00 | 0.00 | 0.07 | 0.07 | 0.03 | 0.15 |
| zone 5 (Panhandle) | 0.22 | 0.22 | 0.00 | 0.03 | -0.01 | 0.00 | 0.09 | -0.01 | 0.04 | 0.11 |
| **Max Ground Water Depth (m)** | **1.34** | **1.36** | **-0.02** | **0.03** | **-0.04** | **0.00** | **0.08** | **0.00** | **0.04** | **0.13** |
| zone 1 (Rarely Flooded) | 1.74 | 1.77 | -0.03 | 0.00 | -0.04 | 0.00 | 0.00 | -0.18 | 0.00 | 0.02 |
| zone 2 (Occasionally Flooded) | 0.86 | 0.88 | 0.00 | 0.05 | -0.05 | 0.00 | 0.13 | 0.11 | 0.05 | 0.16 |
| zone 3 (Seasonally Flooded) | 0.44 | 0.46 | 0.00 | 0.09 | -0.06 | -0.01 | 0.29 | 0.23 | 0.12 | 0.39 |
| zone 4 (Normally Flooded) | 0.05 | 0.05 | 0.01 | 0.07 | -0.03 | 0.00 | 0.30 | 0.24 | 0.12 | 0.58 |
| zone 5 (Panhandle) | 0.42 | 0.44 | 0.00 | 0.17 | -0.09 | 0.00 | 0.38 | -0.04 | 0.22 | 0.47 |
| **Minimum Flooded Area (km2)** | **2,953** | **2,944** | **-58** | **-606** | **296** | **-1** | **-1,849** | **-225** | **-915** | **-2,786** |
| zone 1 (Rarely Flooded) | 151 | 152 | -4 | -35 | 24 | -1 | -96 | 186 | -45 | -115 |
| zone 2 (Occasionally Flooded) | 290 | 291 | -11 | -82 | 52 | 1 | -207 | -79 | -109 | -271 |
| zone 3 (Seasonally Flooded) | 752 | 746 | -22 | -173 | 98 | -2 | -552 | -156 | -264 | -706 |
| zone 4 (Normally Flooded) | 1,359 | 1,359 | -19 | -166 | 63 | 1 | -676 | -260 | -278 | -1,316 |
| zone 5 (Panhandle) | 401 | 396 | -2 | -150 | 59 | 0 | -318 | -309 | -219 | -378 |
| **Maximum Flooded Area (km2)** | **12,879** | **12,825** | **-364** | **-656** | **717** | **-18** | **-7,118** | **-422** | **-855** | **-8,130** |
| zone 1 (Rarely Flooded) | 4,749 | 4,710 | -281 | -517 | 631 | -17 | -4,109 | 63 | -667 | -4,285 |
| zone 2 (Occasionally Flooded) | 2,885 | 2,874 | -56 | -102 | 57 | 1 | -1,951 | -204 | -125 | -2,325 |
| zone 3 (Seasonally Flooded) | 2,140 | 2,138 | -20 | -33 | 18 | -1 | -690 | -180 | -42 | -970 |
| zone 4 (Normally Flooded) | 2,085 | 2,085 | -5 | -4 | 5 | -1 | -255 | -113 | -10 | -372 |
| zone 5 (Panhandle) | 1,018 | 1,018 | -2 | 0 | 6 | 0 | -113 | -434 | -11 | -178 |

Notes: (1) Water Balance, and Natural and Baseline impact data are presented as absolute values.

(2) Scenario impact data are presented relative to the Baseline.

(3) The first row in each section of the table is the average for the entire delta, the next five rows are the averages for the individual zones.

(5) For the Blockages, the zonal impacts 1 to 4 are for the Nqoga-Maunachira-Khwai-Santantadibe system only; zone 5 is the average impact on the system.

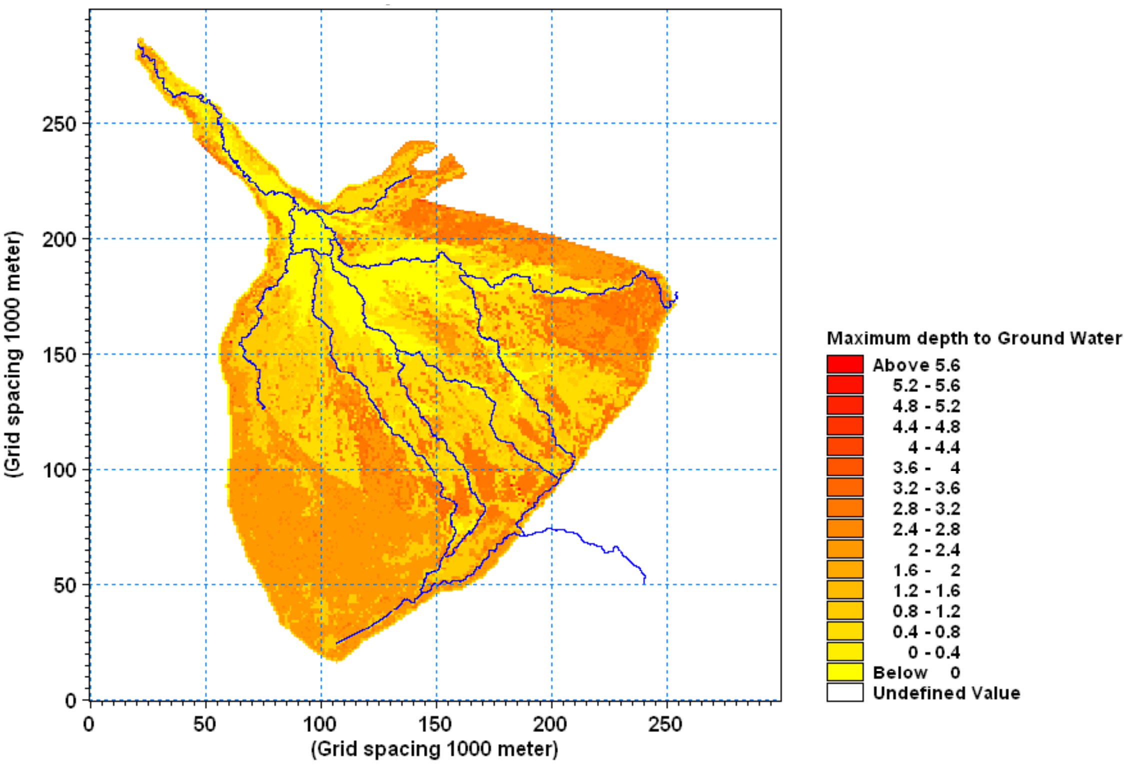


***Figure 3.9: Lower Envelope of Ground Water Depth***

The depth to ground water over the delta area is shown for the lower envelope (maximum depth) over the five dry years in figure 3.9. The model does not include salinity. The Baseline conditions include present day abstraction. The depth ranges from an average of 1.77m in the rarely flooded area to –0.14m (surface flooding) in the normally flooded area. As it is assumed that there is no ground water flow across the model boundary. In periods without surface flooding or rainfall, the water table is drawn down to the depth of the deepest plant roots, a maximum of 3m.

Relative to the Natural conditions in the basin, present upstream and delta abstractions lower the ground water table by an average of 0.02m over the delta in the drier years (tables 3.3 and 3.4). There is little impact in the wet years, table 3.2.

### 3.5.4 Water Balance

The overall water balance for the Baseline and Scenarios is shown in table 3.2 for the wet period 1987 to 1992, table 3.3 for the dry period 1992 to 1997, and in table 3.4 for the normal period 1997 to 2002. Negative values indicate an inflow to the delta (precipitation and river inflow), while positive values indicate an outflow (evapotranspiration and river outflows). Surface and subsurface storage increases are also positive. Abstractions from the delta are not shown in the water balance as they are less than 1mm/annum. The Total should be zero: the small value indicates a minor continuity error (which some investigation is required to reduce). Positive surface and subsurface storage changes indicate an increase in storage in these levels, negative values a decline. The water balance is also shown as a bar chart in figure 3.10, for the wet, dry and normal periods respectively.

In the five dry years, evapotranspiration takes 101% of the total of the inflow from the river upstream and rainfall over the delta, leading to a corresponding decline in the subsurface storage. In the five wet years, evaporation takes 98.6% of the total inflow, with a higher outflow and an increase in the subsurface storage. The water stored in the delta declines through the dry years, and increases through the normal and wet years.

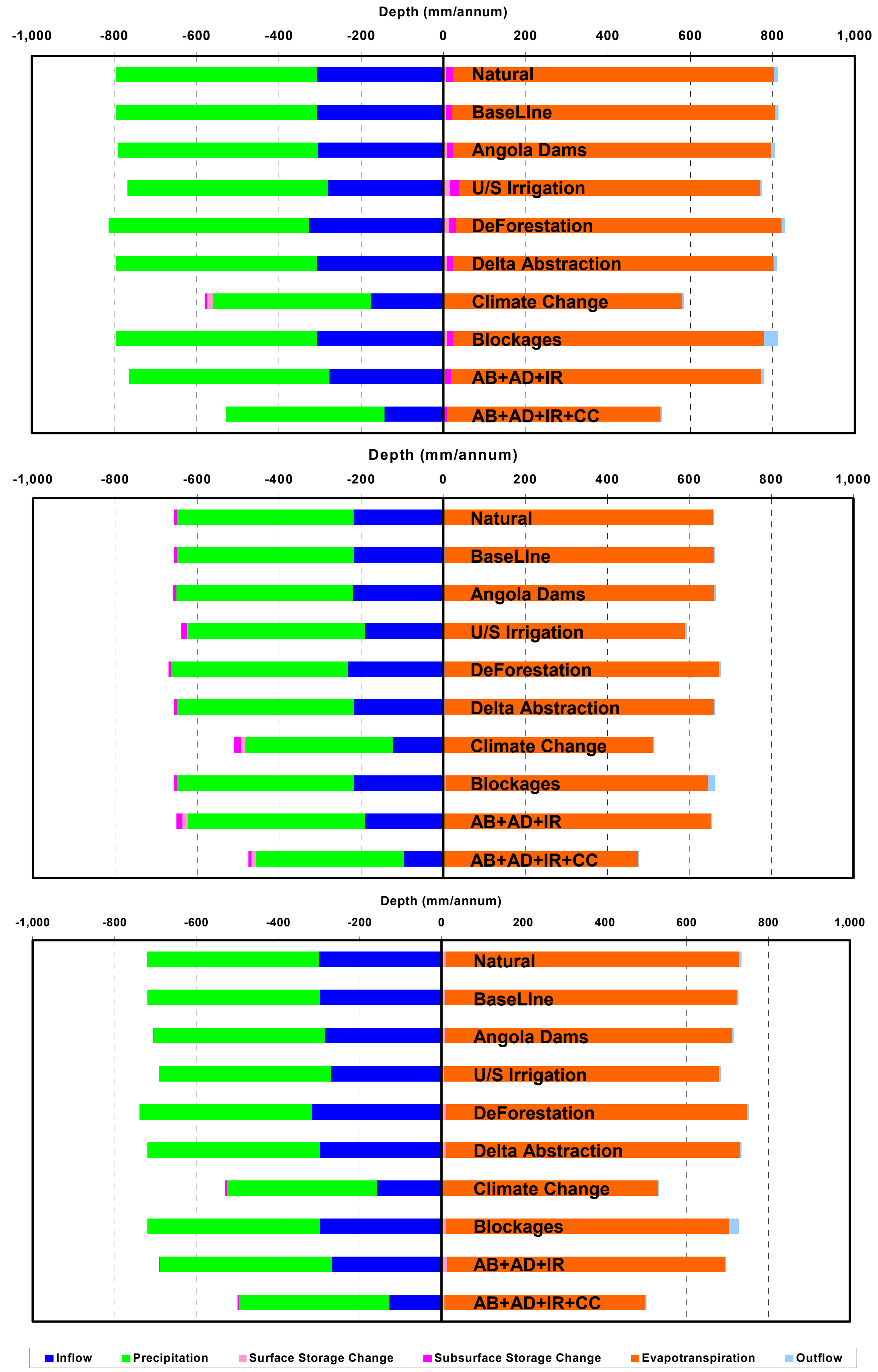


***Figure 3.10: Water Balances for Wet, Dry and Normal Periods (top to bottom)***

## 3.6 Upstream Water Resources Developments

### 3.6.1 Introduction

To date, no significant water resources developments have taken place upstream in Angola and Namibia. In the past, plans have been made for the construction of dams for irrigation and hydropower, but owing to civil strife never implemented. Anticipating that these plans may be revived, the Water and Ecosystem Resources in Regional Development (WERRD) project ran a number of scenarios using a rainfall-runoff model of the basin modified for water resources assessment (Pitman model, Rhodes University), including a scenario for all planned dams.

Under the TwinBas project, the upstream basin model has been refined, additional scenarios simulated and the run period extended concurrent with the ODMP period of analysis, from 1987 to 2002.

A number of sources describes potential irrigation in the upstream basin, in Angola and Namibia. These have been reviewed, and a potential scenario compiled for ODMP.

The corresponding runoff from the upstream basin has been applied under two scenarios: hydropower Dams in Angola and Irrigation, as inflow to the delta upstream. The two potential developments are kept separate for the purpose of initial appraisal, in order that the impact from each can be identified. This will assist in minimising the adverse impacts from these developments.

### 3.6.2 Hydropower

**Introduction**

Investigations carried out in the 1960s led to a proposal to construct ten dams for hydropower in the Okavango Basin in Angola. Of these, three would be run-of-river schemes, with no significant storage or impact on the river flows. Of the remaining dams, six would have a total storage of 6,049Mm$^3$, the seventh is unknown. The dams would be operated to store water during the rainy season, and release water during the dry season. There would be no nett consumption of water. Owing to civil strife in Angola, the plans have not been implemented, but nonetheless represent potential water resources developments.

The Pitman model has been run from October 1959 to September 2002. The model time step and corresponding output is monthly. To prepare the input data for the Integrated Hydrologic Model, daily inflows are required. Monthly factors have been derived, relating the Dams scenario to the present basin state (table 3.5). These factors have been applied to the daily inflow measurements from Mukwe. The hydrographs for the present basin state and the state with the dams in Angola are shown in figure 3.11 for the three five year periods, from 1987 to 2002.

**Surface Water**

The impact of the dams in Angola in the dry years (1992 to 1997) is minimal, with changes in the surface and ground water levels no greater than 0.01m (table 3.2). During the wet years (1987 to 1992), the impact on the maximum depth of overland flow averages a drop of 0.03m over the entire delta, with the impact greatest in the Panhandle with a decrease of 0.41m (table 3.3). The impact on minimum overland flow depths is insignificant. The overall reduction in the upper envelope of flooded area is 264km$^2$ (ie the area which may be flooded at some time during the five wet years), and in the lower envelope 188km$^2$ (ie the area remaining flooded throughout the five years).

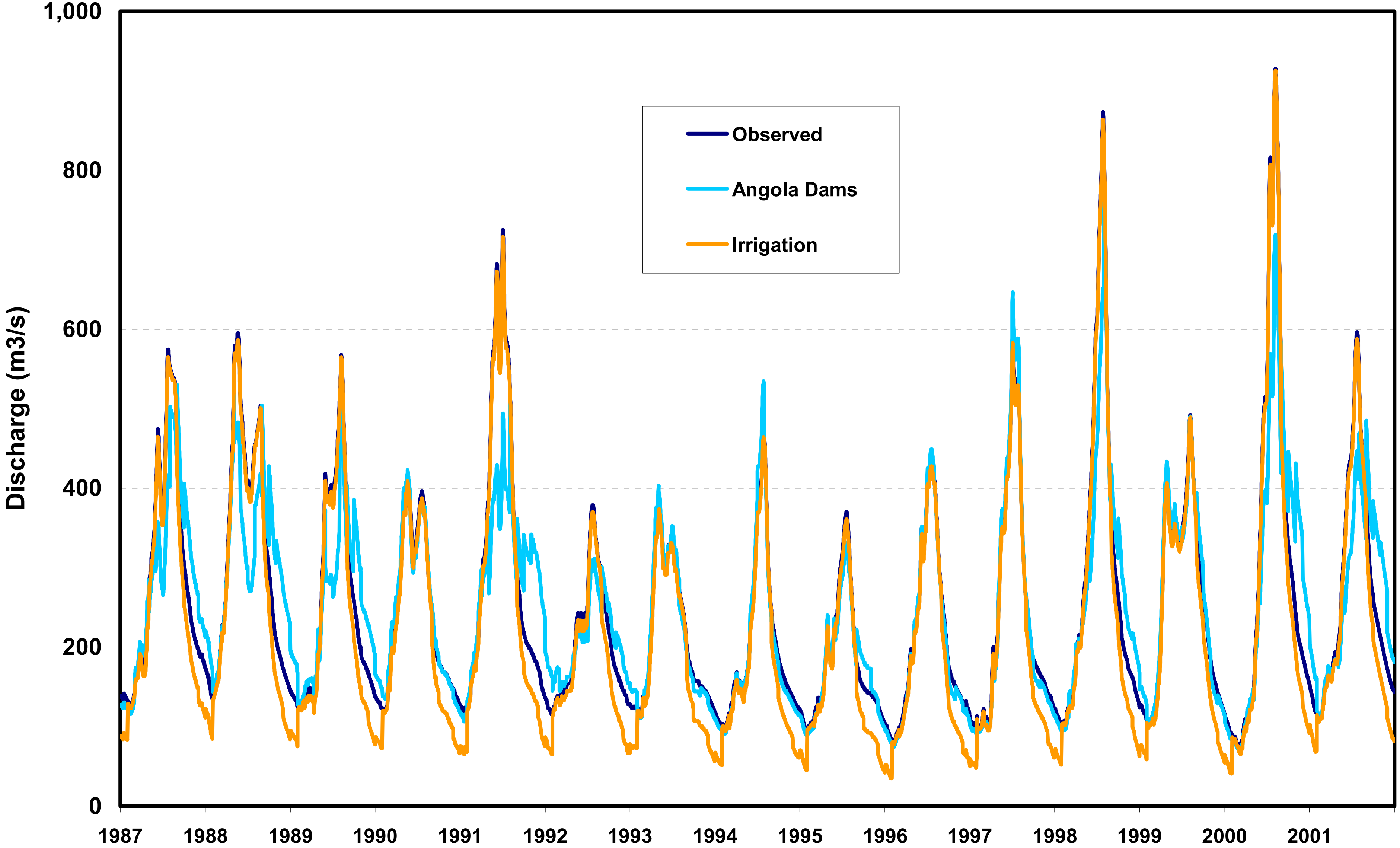


***Figure 3.11: Inflow Hydrographs: Observed at Mukwe, and for Angola Dams and Upstream Irrigation Scenarios***

### Table 3.5: Monthly Inflow Factors for Angolan Dams

| SC9/SC1 | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | TOTAL (Mm3) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1987/88 | 0.920 | 0.922 | 1.032 | 1.098 | 0.908 | 0.753 | 0.725 | 0.909 | 1.150 | 1.336 | 1.344 | 1.230 | **1.027** |
| 1988/89 | 1.276 | 1.056 | 0.994 | 0.951 | 0.811 | 0.738 | 0.689 | 0.831 | 1.095 | 1.445 | 1.602 | 1.564 | **1.088** |
| 1989/90 | 1.344 | 1.039 | 1.081 | 1.109 | 0.892 | 0.721 | 0.685 | 0.879 | 1.130 | 1.493 | 1.362 | 1.371 | **1.092** |
| 1990/91 | 1.209 | 1.125 | 1.114 | 1.058 | 1.013 | 0.950 | 0.971 | 1.019 | 1.042 | 0.994 | 0.992 | 0.929 | **1.035** |
| 1991/92 | 0.927 | 1.081 | 1.061 | 0.928 | 0.675 | 0.629 | 0.681 | 0.947 | 1.237 | 1.562 | 1.753 | 1.736 | **1.101** |
| average | **1.135** | **1.045** | **1.056** | **1.029** | **0.860** | **0.758** | **0.750** | **0.917** | **1.131** | **1.366** | **1.411** | **1.366** | **1.069** |
| 1992/93 | 1.420 | 1.259 | 1.059 | 1.060 | 0.928 | 0.898 | 0.817 | 0.873 | 1.101 | 1.154 | 1.290 | 1.207 | **1.089** |
| 1993/94 | 1.170 | 0.964 | 1.070 | 1.078 | 1.028 | 0.999 | 1.048 | 0.935 | 0.958 | 0.919 | 0.983 | 0.927 | **1.007** |
| 1994/95 | 0.938 | 0.941 | 0.952 | 0.993 | 0.995 | 1.056 | 1.129 | 0.962 | 0.956 | 0.913 | 0.939 | 0.937 | **0.976** |
| 1995/96 | 0.941 | 0.916 | 0.937 | 1.018 | 1.017 | 0.910 | 0.895 | 0.964 | 1.226 | 1.219 | 1.051 | 0.937 | **1.003** |
| 1996/97 | 0.940 | 0.929 | 0.933 | 0.970 | 1.018 | 1.002 | 1.027 | 0.986 | 0.975 | 0.890 | 0.989 | 0.929 | **0.966** |
| average | **1.082** | **1.002** | **0.990** | **1.024** | **0.997** | **0.973** | **0.983** | **0.944** | **1.043** | **1.019** | **1.050** | **0.987** | **1.008** |
| 1997/98 | 0.930 | 0.941 | 0.947 | 0.928 | 1.037 | 1.035 | 1.093 | 1.009 | 1.004 | 0.900 | 0.950 | 0.933 | **0.976** |
| 1998/99 | 0.934 | 0.917 | 1.071 | 0.982 | 0.892 | 0.740 | 0.746 | 0.979 | 1.181 | 1.381 | 1.294 | 1.354 | **1.039** |
| 1999/00 | 1.184 | 1.036 | 1.081 | 1.043 | 1.043 | 1.020 | 0.956 | 0.997 | 1.111 | 1.027 | 0.898 | 0.982 | **1.032** |
| 2000/01 | 0.927 | 0.939 | 0.942 | 1.027 | 0.904 | 0.772 | 0.697 | 0.774 | 1.115 | 1.355 | 1.778 | 1.536 | **1.064** |
| 2001/02 | 1.348 | 1.027 | 1.013 | 0.956 | 0.844 | 0.730 | 0.749 | 0.875 | 1.273 | 1.474 | 1.565 | 1.266 | **1.093** |
| average | **1.065** | **0.972** | **1.011** | **0.987** | **0.944** | **0.859** | **0.848** | **0.927** | **1.137** | **1.227** | **1.297** | **1.214** | **1.041** |
| AVERAGE | **1.094** | **1.006** | **1.019** | **1.013** | **0.934** | **0.863** | **0.861** | **0.929** | **1.104** | **1.204** | **1.253** | **1.189** | **1.039** |

The inflow hydrograph (figure 3.11) shows that during medium to high flood years there is a significant reduction in the peak flow, around 20% in March and April, as the dams fill with the onset of the rains, and downstream releases are limited. Following the rains, there is a corresponding increase in the downstream flows as the stored water is released to generate hydropower. In years with low peak flows, eg 1995, there is little storage as the flows are released downstream to minimise the impact on the delta. With low wet season inflows little water is stored, around 2%, and there is consequently little additional water released in the dry season, and limited overall impact on the outflow from the upstream basin. (The TwinBas project report is awaited for a more detailed explanation of the operating conditions.)

The depth of overland flow for the year 2000 flood wave, the largest in the series analysed, is shown as an animated sequence for the lower Panhandle and upstream delta in figure 3.12. The flow vectors are also shown, showing the changing magnitude and direction of the overland flows.

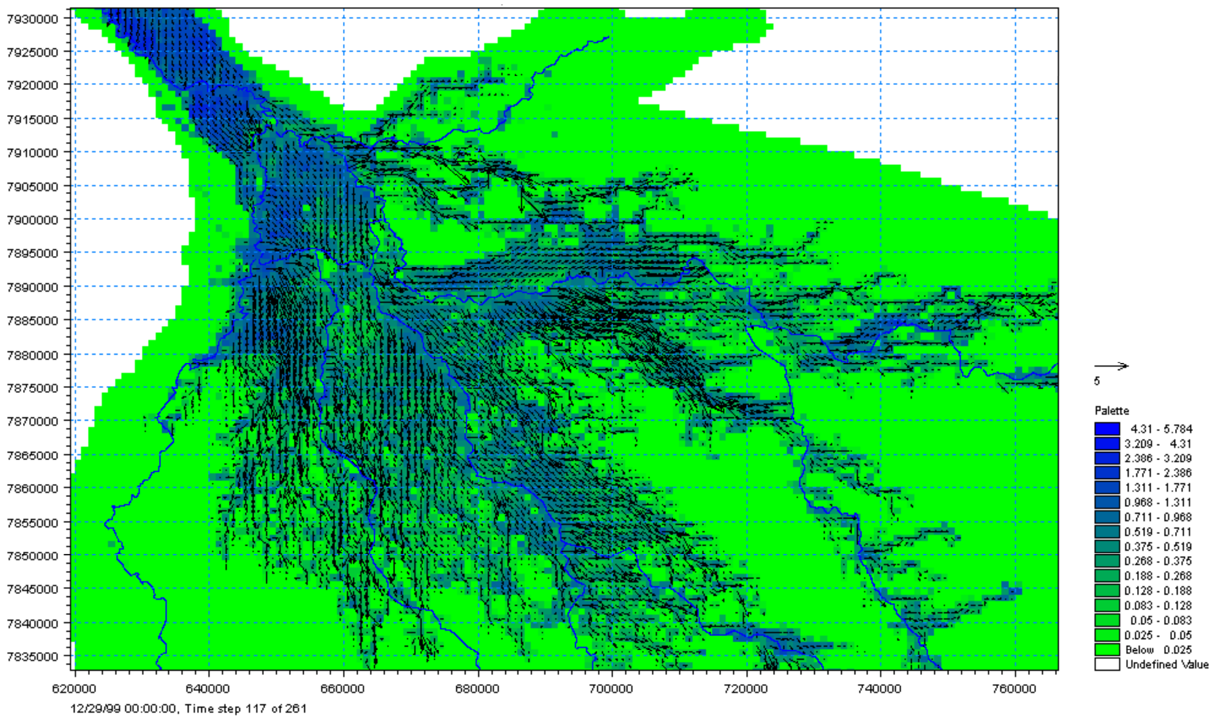


Figure 3.12: Animated Flow and Depth of Flow Sequence (AngolaDams 2000)

### Subsurface Water

Similar to the surface waters, the impact on the subsurface waters is minimal in the dry years, and shows an average increase in the maximum ground water depth of 0.02m across the delta in the wet flow period (table 3.2), corresponding to the greater reduction in inflow as water is stored in the upstream reservoirs.

### Water Balance

There is little impact on the overall water balance for the delta from the dams in Angola (figure 3.10, and tables 3.2 to 3.4), reflecting the fact that the dams do not result in any significant water loss, and there is only a minor redistribution of the annual flows from the flood peak to the flood recession.

## 3.6.3 Irrigation

### Introduction

A number of sources describes potential irrigation in the upstream basin, in Angola and Namibia. These have been reviewed, and a potential scenario compiled based on:

- Irrigation demand based on 15,000m$^3$/ha/a with a 25% return flow
- Irrigated area in Angola: 54,500ha; in Namibia: 7,500ha
- Angola grows vegetables in winter (June to October); Namibia grows maize in summer (December to April)

Based on the above, the monthly irrigation demand is shown in figure 3.13. The impact on the inflow hydrograph upstream of the delta at Mukwe is shown in figure 3.11, for the period 1987 to 2002. The hydrographs show the dry winter inflows are reduced to around 50% of the present inflows.

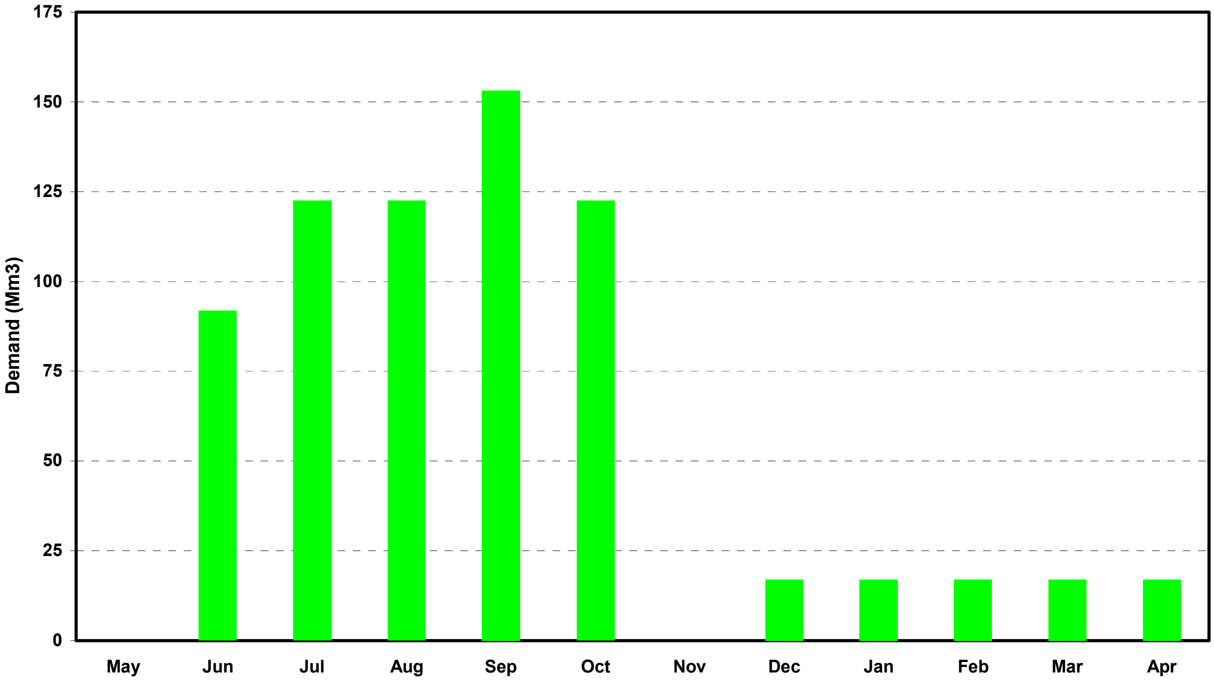


*Figure 3.13: Upstream Irrigation Demand*

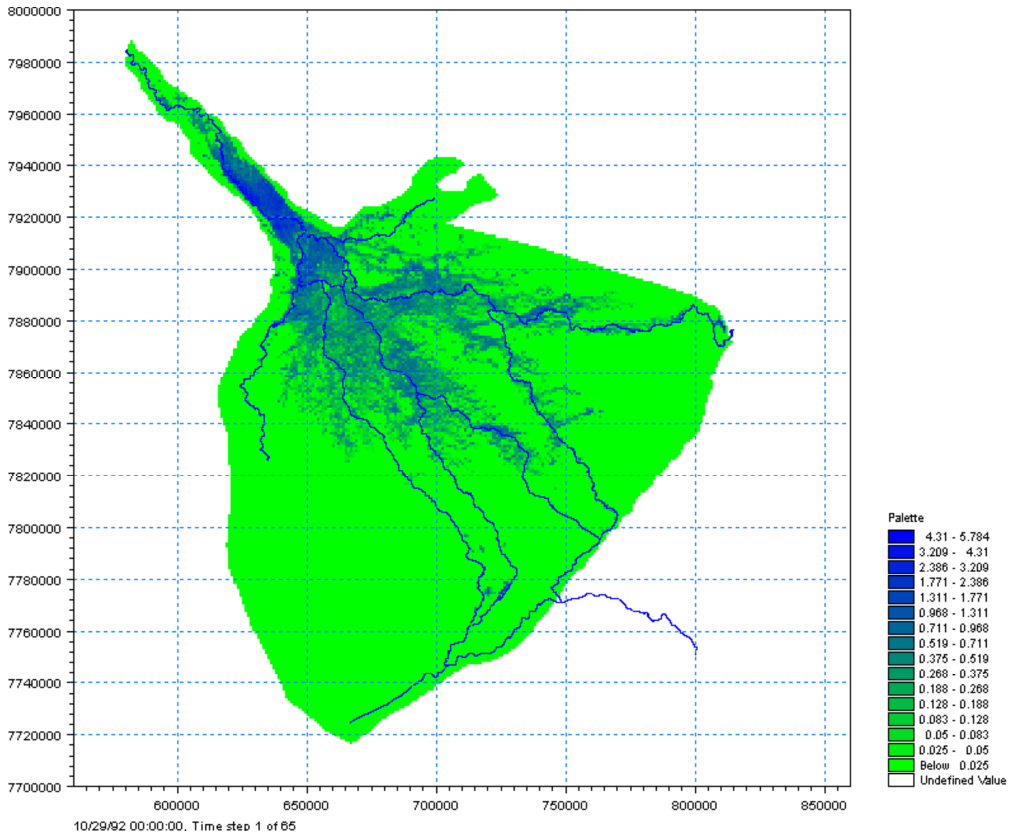


***Figure 3.14: Animated Depth of Flow Sequence (Irrigation 1992 to 1997)***

### Surface Water

The animated depth of flow sequence, figure 3.14, shows the expansion and contraction of the flooded area over the five years of low flows, 1992 to 1997, with a monthly time interval. The maximum depth of flooding is 5.3m, in the Panhandle near Sepupa.

The impact on the lower envelope of flooding, ie the area which never dries, over the five dry years in shown in figure 3.15. The maximum impact on minimum water levels is felt in the Panhandle, with a decrease of up to 1.25m. The average decrease in the Panhandle is 0.10m, and in the normally flooded area 0.06m (table 3.3). Time series showing the impact on the average depth of flooding for each of the five zones of the delta are shown in figures 3.16 and 3.17.

The Panhandle is the first area to receive and store the upstream flood wave, and is as a result the area suffering the greatest impact, with a decline in average surface water levels up to 0.22m at the end of October. The impact in terms of water levels decreases and is delayed as the flood waters spread to the normally flooded areas and on to the rarely flooded areas.

The upper envelope of flooding in the five dry years shows an increase in the flooded area. As for other scenarios, this is the result of heavy rainfall in January 1994 (60mm recorded in one day at Maun) and a shift in the phase of the flood wave, noticeable in figure 3.14, and not indicative of the overall pattern.

### Subsurface Water

The impact of the upstream dams on the moisture content in the root zone is expressed as a deficit relative to saturation. The impact is relatively low, with an average increased deficit in the Panhandle of 0.04m (tables 3.2 to 3.4).

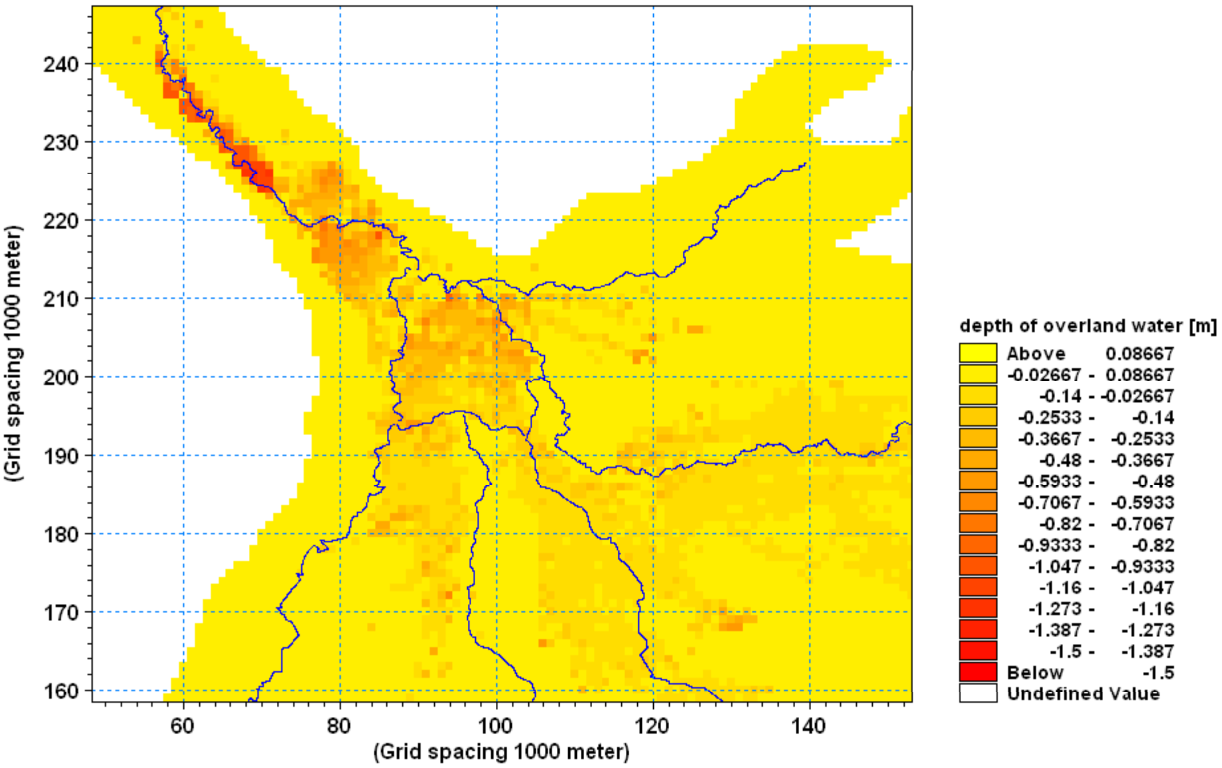
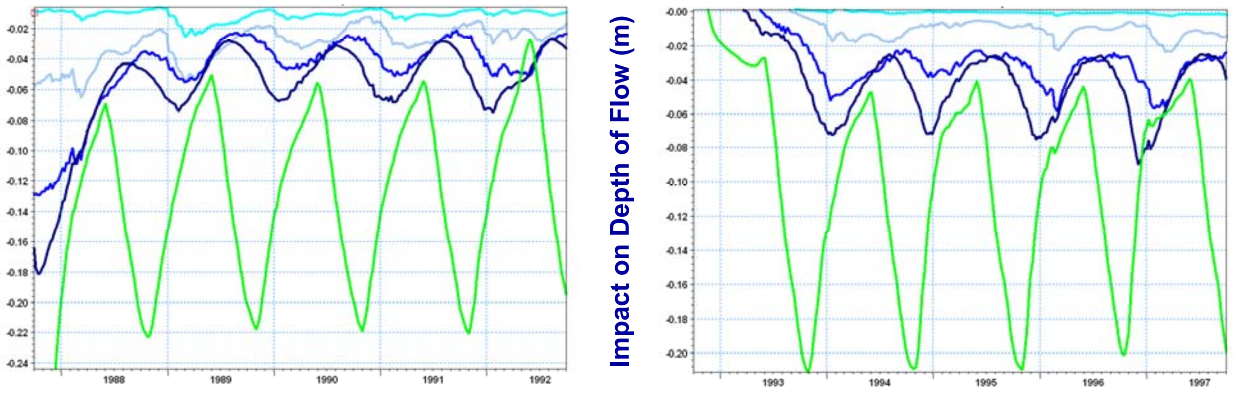


***Figure 3.15: Impact on Lower Envelope of Flooding (Irrigation 1992 to 1997)***

The impact on the depth to ground water is greatest in the Panhandle and the normally flooded areas. Figure 3.18 shows the distribution of the deficit as the lower envelope (maximum depth in each grid) in terms of levels for the five dry years. The average increased depth with upstream irrigation is 0.22m and 0.14m in the two areas respectively.

**Water Balance**

The water balance shows a decline in the inflow to the delta in the dry years from 217 to 190mm/annum, and in the wet years from 308 to 280mm/annum (figure 3.10, tables 3.2 and 3.3). The decrease in inflow is balanced mostly by a decrease in the evapotranspiration, and also by a decrease in the outflow and in the water stored in the delta at the end of each year, both in surface and subsurface waters.



***Figures 3.16 and 3.17: Impact on Average Depth of Surface Water (Irrigation)***

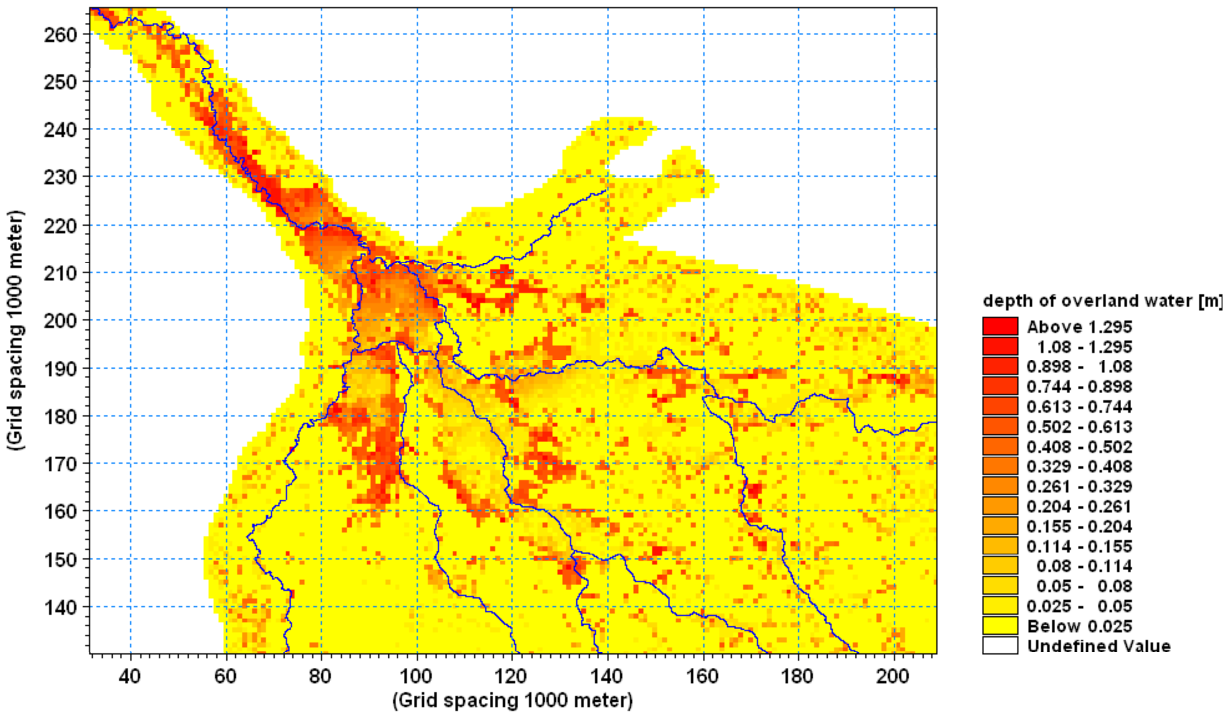


***Figure 3.18: Impact on Lower Envelope of Ground Water Depth (Irrigation 1997 to 2002)***

## 3.7 Deforestation

### 3.7.1 Introduction

The TwinBas project has run the Pitman model of the upstream basin with a deforestation scenario. This assumes that, given increased population pressure along the river banks, a 2km band is deforested. There is less storage of rain water in the vegetation and the root zone, with the result more rapid and increased runoff to the rivers the year round. This is illustrated by the inflow hydrograph at Mukwe in figure 3.19, and in table 3.6, showing the monthly factors applied to the observed Mukwe hydrograph.

***Table 3.6: Monthly Inflow Factors for Deforestation***

| SC11/SC1 | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | TOTAL (Mm3) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1987/88** | 1.074 | 1.076 | 1.067 | 1.062 | 1.056 | 1.057 | 1.058 | 1.052 | 1.060 | 1.073 | 1.068 | 1.073 | **1.065** |
| **1988/89** | 1.074 | 1.074 | 1.079 | 1.067 | 1.060 | 1.062 | 1.054 | 1.048 | 1.054 | 1.066 | 1.065 | 1.073 | **1.065** |
| **1989/90** | 1.075 | 1.080 | 1.069 | 1.060 | 1.052 | 1.070 | 1.055 | 1.040 | 1.053 | 1.070 | 1.067 | 1.073 | **1.064** |
| **1990/91** | 1.076 | 1.078 | 1.069 | 1.062 | 1.060 | 1.051 | 1.053 | 1.082 | 1.021 | 1.110 | 1.067 | 1.075 | **1.067** |
| **1991/92** | 1.079 | 1.084 | 1.067 | 1.058 | 1.059 | 1.060 | 1.052 | 1.054 | 1.056 | 1.057 | 1.070 | 1.071 | **1.064** |
| **average** | **1.076** | **1.078** | **1.070** | **1.062** | **1.057** | **1.060** | **1.054** | **1.055** | **1.049** | **1.075** | **1.067** | **1.073** | 1.065 |
| **1992/93** | 1.071 | 1.074 | 1.073 | 1.067 | 1.023 | 1.049 | 1.057 | 1.055 | 1.060 | 1.067 | 1.072 | 1.076 | **1.062** |
| **1993/94** | 1.075 | 1.076 | 1.070 | 1.057 | 1.046 | 1.058 | 1.067 | 1.065 | 1.068 | 1.070 | 1.079 | 1.081 | **1.068** |
| **1994/95** | 1.081 | 1.081 | 1.081 | 1.083 | 1.058 | 1.069 | 1.146 | 0.995 | 1.074 | 1.078 | 1.084 | 1.082 | **1.076** |
| **1995/96** | 1.083 | 1.084 | 1.086 | 1.075 | 1.052 | 1.062 | 1.063 | 1.061 | 1.070 | 1.071 | 1.075 | 1.078 | **1.072** |
| **1996/97** | 1.079 | 1.080 | 1.075 | 1.065 | 1.064 | 1.066 | 1.072 | 1.065 | 1.069 | 1.073 | 1.078 | 1.080 | **1.072** |
| **average** | **1.078** | **1.079** | **1.077** | **1.069** | **1.048** | **1.061** | **1.081** | **1.048** | **1.068** | **1.072** | **1.078** | **1.079** | 1.070 |
| **1997/98** | 1.082 | 1.084 | 1.086 | 1.076 | 1.072 | 1.065 | 1.065 | 1.067 | 1.071 | 1.073 | 1.080 | 1.083 | **1.075** |
| **1998/99** | 1.082 | 1.080 | 1.077 | 1.050 | 1.059 | 1.063 | 1.063 | 1.039 | 1.064 | 1.068 | 1.111 | 1.081 | **1.070** |
| **1999/00** | 1.080 | 1.081 | 1.071 | 1.043 | 1.040 | 1.060 | 1.086 | 1.059 | 1.069 | 1.069 | 1.073 | 1.082 | **1.068** |
| **2000/01** | 1.083 | 1.081 | 1.079 | 1.085 | 1.057 | 1.055 | 1.061 | 1.064 | 1.040 | 1.065 | 1.068 | 1.072 | **1.067** |
| **2001/02** | 1.079 | 1.077 | 1.074 | 1.055 | 1.067 | 1.065 | 1.052 | 1.057 | 1.055 | 1.066 | 1.083 | 1.072 | **1.067** |
| **average** | **1.081** | **1.081** | **1.077** | **1.062** | **1.059** | **1.062** | **1.065** | **1.057** | **1.059** | **1.068** | **1.083** | **1.078** | 1.069 |
| **AVERAGE** | **1.078** | **1.079** | **1.075** | **1.064** | **1.055** | **1.061** | **1.067** | **1.054** | **1.059** | **1.072** | **1.076** | **1.077** | 1.068 |

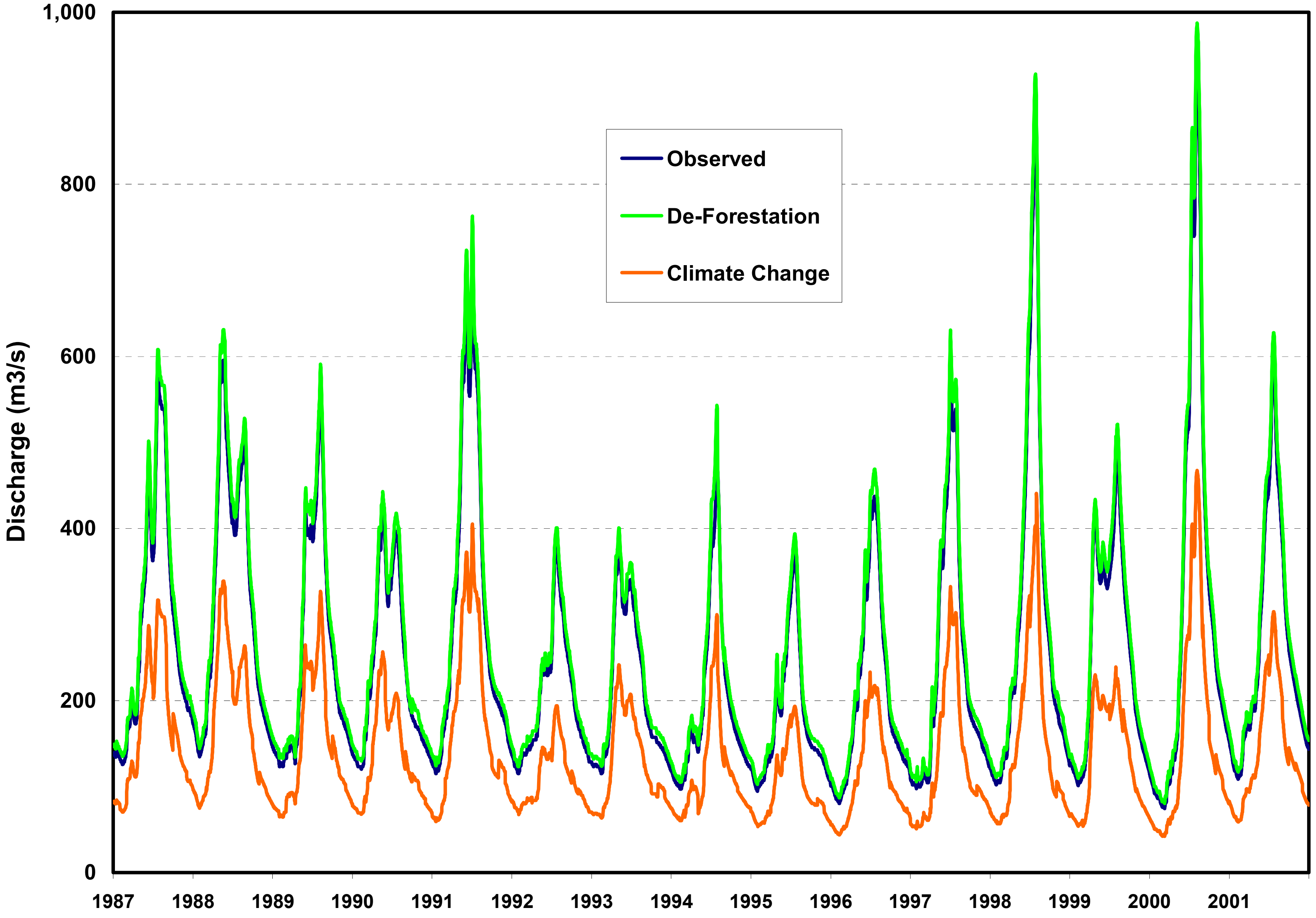


***Figure 3.19: Inflows Hydrographs: Observed at Mukwe, and for Deforestation and Climate Change Scenario***

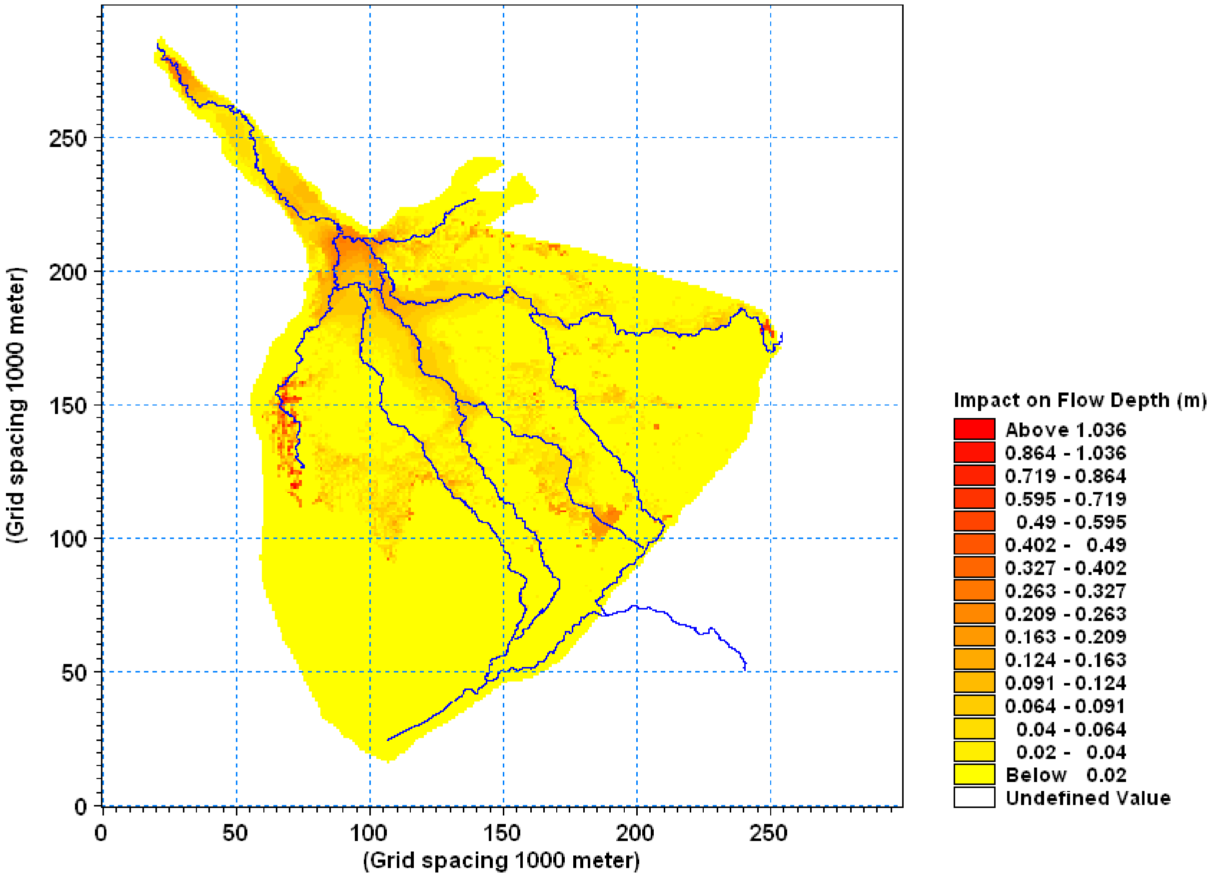


***Figure 3.20: Impact on Upper Envelope of Flooding (Deforestation)***

### 3.7.2 Surface Water

The inflow to the delta increases by around 7%. The corresponding increase in the maximum overland flow depth is greatest in the five normal years, at 0.02m over the entire delta, and in the flooded area 717km$^2$ (figure 3.20). The increase in the minimum flow depth and flooded area is less significant.

### 3.7.3 Subsurface Water

The increased inflows resulting from upstream deforestation also increases the subsurface water, with a decrease of 0.01m in the average soil moisture deficit and of 0.03m in the ground water depth over the delta.

### 3.7.4 Water Balance

As tables 3.2 to 3.4 show, the inflow to the delta increases by around 18mm/annum. This is partly balanced by increased evapotranspiration from the greater flooded area, and by an increase in the surface and subsurface storage, relative to the Baseline. The outflow from the delta is minimally affected.

## 3.8 Abstractions from Delta

### 3.8.1 Introduction

**Surface Water**

Abstractions are taken from the surface waters of the delta for purposes including domestic water supply, livestock, game, small scale irrigation and construction. Permits for abstractions of specified quantities are issued by the Department of Water Affairs, to date a total of 342 permits. Based on the information in the permits, the location and quantity of each abstraction has been assessed, and applied as a constant in time to the Integrated Hydrologic Model.

The abstractions are summarised in table 3.7. The total presently permitted abstraction from the delta is 46,540m$^3$/day, or 17Mm$^3$ per annum. This is 0.22% of the average inflow from 1987 to 2002. The future projected abstraction based on increasing population and rates of consumption is 25Mm$^3$, or 0.32% of the average inflow.

***Table 3.7: Surface Water Abstractions***

| RIVER | ABSTRACTION (m$^3$/day) | |
|---|---|---|
| | 2005 | 2025 |
| Okavango | 6,285 | 9,107 |
| Thaoge | 1,475 | 2,140 |
| Boro | 1,483 | 2,710 |
| Maunachira | 275 | 399 |
| Khwai | 148 | 215 |
| Thamalakane | 26,571 | 38,553 |
| Nhabe | 5,100 | 7,400 |
| Boteti | 5,203 | 7,549 |
| **TOTAL** | **46,540** | **68,074** |

**Ground Water**

Ground water is abstracted from boreholes around the delta, mainly to supply Maun and settlements along the western margin. The location of the present well fields, including Gomoti which is coming on stream, are shown in figure 3.21, and the amount abstracted in table 3.8. The major wellfields supplying Maun are shown bold.

The total amounts to 6Mm$^3$ per annum, 0.08% of the average inflow. The abstractions, from the Maun Ground Water Development Project, are taken as constant, and drawn from the ground water at the level of the filter screen. The projection for 2025, around 14Mm$^3$ or 0.17% of the inflow, retires the Shashe wellfield, and introduces the new Matsebe and Kunyere wellfields (figure 3.22).

### 3.8.2 Surface Water

The impact of the combined abstractions on the surface and ground waters of the delta is negligible. In the five wet years (1987 to 1992), the upper and lower flood envelopes (the maximum and minimum in each grid) are reduced by 208km$^2$ and 113km$^2$ respectively (table 3.2).

### 3.8.3 Subsurface Water

The impact of the abstractions on the soil moisture and ground water levels over the delta is negligible. The impact in the immediate vicinity of the wells is large. Figures 3.23 to 3.25 show examples of the local drawdown or cone of depression for the dry

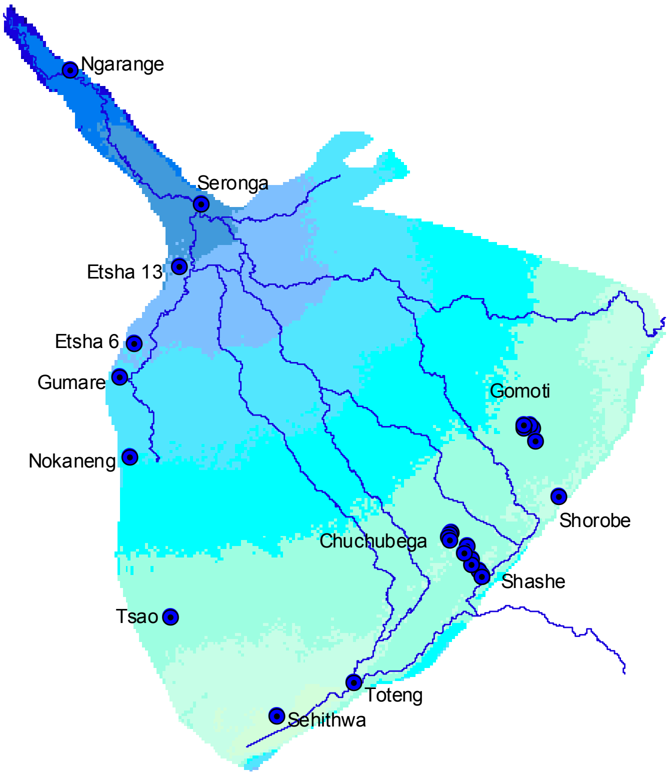


***Figure 3.21: Location of Present Ground Water Abstractions***

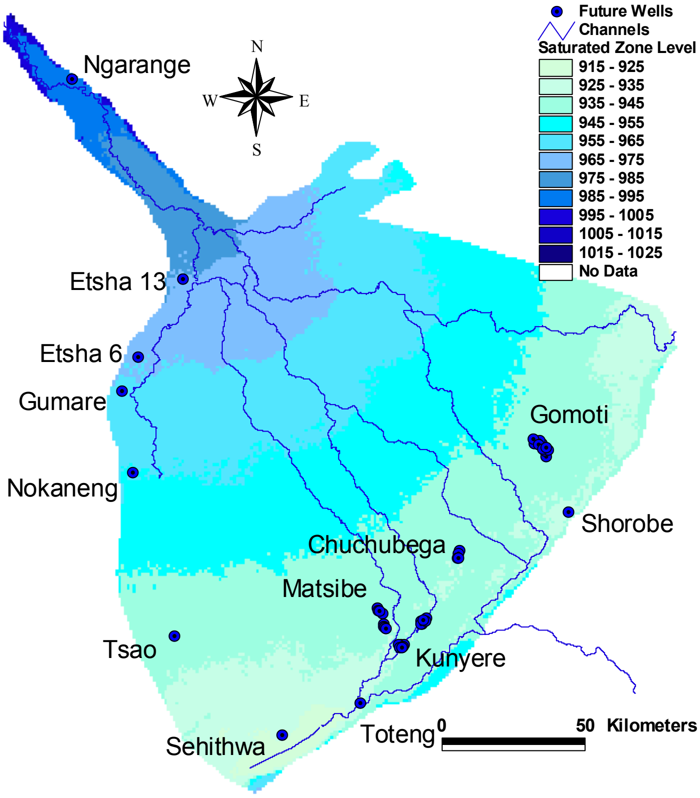


***Figure 3.22: Location of Future Ground Water Abstractions***

years (1992 to 1997). The plots show the drawdown at the well and at a distance of 1km from the well(field) for the Baseline (2005), and the drawdown for the future Abstractions (2025).

At Seronga in the Panhandle (figure 3.23), the influence of the annual flood wave predominates, with an additional trough around 0.5m appearing in the later years and full recovery in the flood period. At Gumare on the western margin of the delta (figure 3.24), the drawdown is progressive, around 0.9m each year, showing little recovery in the flood periods. For future abstractions, the annual drawdown rate is 1.2m. One kilometre from the wellfield, the drawdown is only around 0.1m each year.

Downstream, taking as an example the Chuchubega wellfield (figure 3.25), the annual drawdown is around 1.2m for present abstraction rates. One kilometre from the wellfield, the drawdown is around 0.2m each year. For future abstractions, the annual drawdown at the well is around 1.5m.

***Table 3.8: Ground Water Abstractions***

| **LOCATION** | **ABSTRACTION ($m^3$/day)** | |
|---|---|---|
| | **2005** | **2025** |
| Seronga | 210 | 287 |
| Ngarange | 137 | 185 |
| Etsha 6 | 387 | 522 |
| Etsha 13 | 136 | 184 |
| Nokaneng | 212 | 286 |
| Gumare | 515 | 696 |
| Sehitwa | 230 | 310 |
| Tsao | 191 | 257 |
| Toteng | 234 | 316 |
| Shorobe | 230 | 310 |
| **Chuchubega** | **1,643** | **4,026** |
| **Shashe** | **4,654** | **-** |
| **Gomoti** | **7,666** | **10,066** |
| **Kunyere** | **-** | **12,079** |
| **Matsibe** | **-** | **8,053** |
| **TOTAL** | **16,445** | **37,577** |

The ground water simulations cover the entire delta, with a one kilometre grid and one layer. The model is intended to represent the ground water patterns for the delta as a whole, and is not a substitute for the detailed multi-layer ground water modelling incorporating salinity of the individual well fields. While the results demonstrate the impact on the delta as a whole, in the localities of the wellfields they should be treated as indicative only.

## 3.9 Climate Change

### 3.9.1 Introduction

Potential climate change will have an impact on the delta in respect of inflows from the basin upstream, and the climate over the delta. The WERRD project has run a global climate model HadCM3[1] to predict the changed precipitation and temperature over the basin. For the upstream basin, the Pitman rainfall-runoff model has been applied under TwinBas to predict the modified inflows upstream of the delta (figure 3.11). The modified precipitation and temperature over the delta have been used as direct inputs to the Integrated Hydrologic Model.

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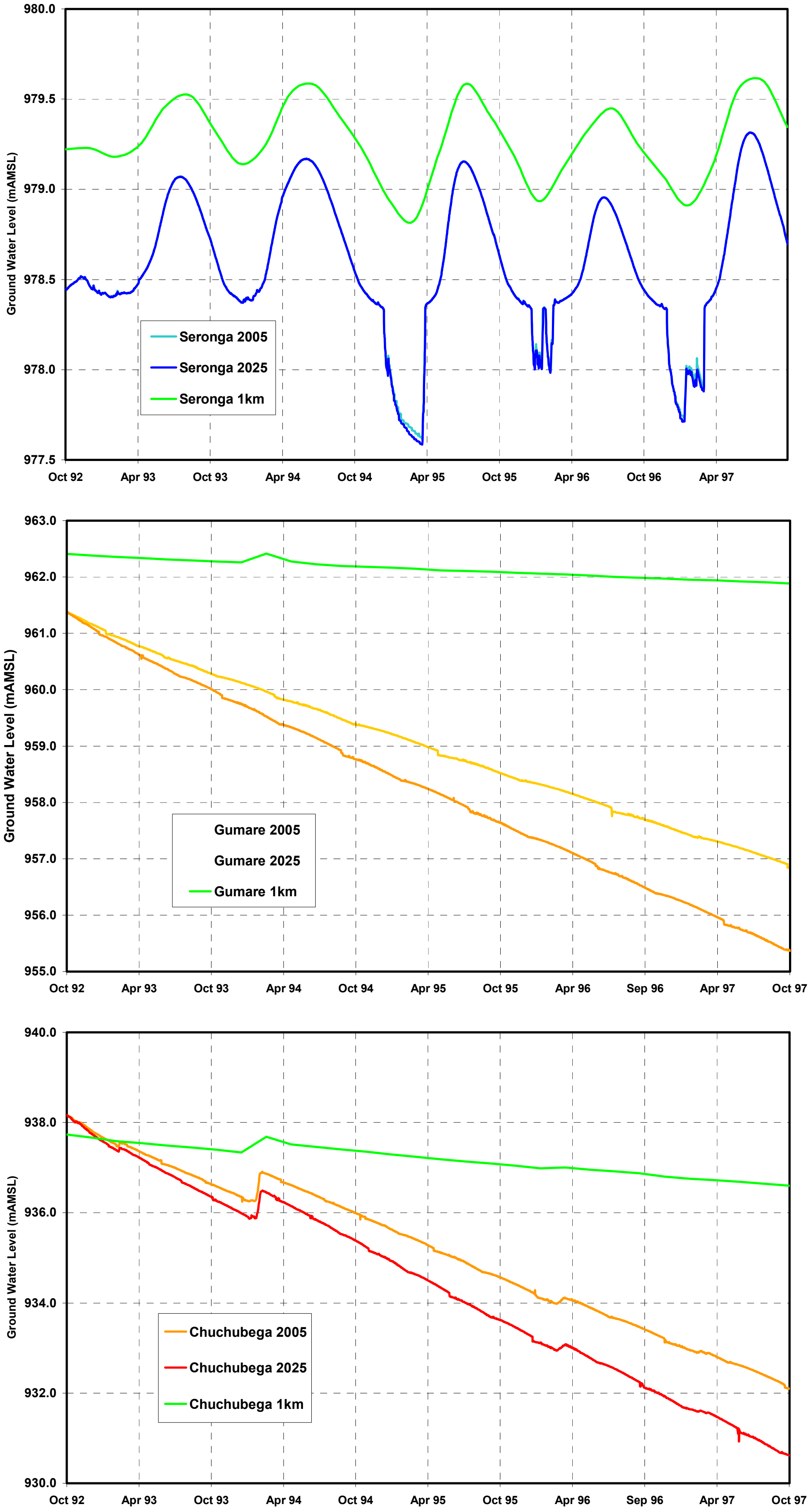
[1] http://www.met-office.gov.uk/research/hadleycentre/models/HadCM3.html



***Figures 3.23, 3.24 and 3.25: Abstraction Drawdown of Ground Water at Seronga, Gumare and Chuchubega (top to bottom)***

## *Table 3.9: Monthly Inflow Factors for Climate Change*

| CL2/SC1 | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | TOTAL (Mm3) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1987/88** | 0.595 | 0.560 | 0.644 | 0.643 | 0.633 | 0.606 | 0.551 | 0.551 | 0.466 | 0.608 | 0.591 | 0.561 | **0.584** |
| **1988/89** | 0.556 | 0.565 | 0.514 | 0.590 | 0.569 | 0.571 | 0.499 | 0.523 | 0.518 | 0.487 | 0.557 | 0.540 | **0.541** |
| **1989/90** | 0.536 | 0.524 | 0.628 | 0.631 | 0.632 | 0.607 | 0.552 | 0.575 | 0.507 | 0.613 | 0.605 | 0.573 | **0.582** |
| **1990/91** | 0.565 | 0.564 | 0.529 | 0.621 | 0.614 | 0.536 | 0.525 | 0.486 | 0.578 | 0.631 | 0.579 | 0.545 | **0.565** |
| **1991/92** | 0.515 | 0.504 | 0.611 | 0.600 | 0.554 | 0.546 | 0.558 | 0.596 | 0.613 | 0.562 | 0.670 | 0.599 | **0.577** |
| **average** | **0.553** | **0.543** | **0.585** | **0.617** | **0.600** | **0.573** | **0.537** | **0.546** | **0.537** | **0.580** | **0.601** | **0.564** | **0.570** |
| **1992/93** | 0.612 | 0.585 | 0.588 | 0.544 | 0.598 | 0.573 | 0.512 | 0.509 | 0.467 | 0.530 | 0.570 | 0.548 | **0.553** |
| **1993/94** | 0.549 | 0.552 | 0.587 | 0.619 | 0.630 | 0.609 | 0.585 | 0.599 | 0.624 | 0.582 | 0.681 | 0.630 | **0.604** |
| **1994/95** | 0.632 | 0.620 | 0.601 | 0.636 | 0.486 | 0.564 | 0.633 | 0.499 | 0.600 | 0.635 | 0.610 | 0.612 | **0.594** |
| **1995/96** | 0.589 | 0.548 | 0.521 | 0.580 | 0.620 | 0.573 | 0.523 | 0.542 | 0.556 | 0.551 | 0.605 | 0.554 | **0.563** |
| **1996/97** | 0.548 | 0.542 | 0.523 | 0.539 | 0.540 | 0.568 | 0.497 | 0.523 | 0.552 | 0.596 | 0.578 | 0.563 | **0.547** |
| **average** | **0.586** | **0.570** | **0.564** | **0.583** | **0.575** | **0.577** | **0.550** | **0.534** | **0.560** | **0.579** | **0.609** | **0.581** | **0.572** |
| **1997/98** | 0.520 | 0.534 | 0.582 | 0.516 | 0.515 | 0.565 | 0.561 | 0.537 | 0.564 | 0.540 | 0.608 | 0.606 | **0.554** |
| **1998/99** | 0.576 | 0.543 | 0.501 | 0.584 | 0.582 | 0.525 | 0.462 | 0.527 | 0.503 | 0.461 | 0.560 | 0.526 | **0.529** |
| **1999/00** | 0.536 | 0.534 | 0.481 | 0.553 | 0.563 | 0.568 | 0.512 | 0.458 | 0.533 | 0.509 | 0.535 | 0.545 | **0.527** |
| **2000/01** | 0.550 | 0.557 | 0.564 | 0.542 | 0.506 | 0.535 | 0.496 | 0.504 | 0.551 | 0.467 | 0.565 | 0.519 | **0.530** |
| **2001/02** | 0.543 | 0.540 | 0.560 | 0.585 | 0.573 | 0.564 | 0.508 | 0.524 | 0.473 | 0.558 | 0.598 | 0.549 | **0.548** |
| **average** | **0.545** | **0.542** | **0.538** | **0.556** | **0.548** | **0.552** | **0.508** | **0.510** | **0.525** | **0.507** | **0.573** | **0.549** | **0.538** |
| **AVERAGE** | **0.561** | **0.552** | **0.562** | **0.586** | **0.574** | **0.567** | **0.532** | **0.530** | **0.540** | **0.555** | **0.594** | **0.565** | **0.560** |

The impact of the climate change scenario is highly significant, in both the flood and dry seasons. River inflows to the delta are reduced by 38% (monthly inflow factors at Mukwe are shown in table 3.9, and precipitation over the delta by 9%. Temperature increases by 2.2ºC (figure 3.26.).

### 3.9.2 Surface Water

Climate Change is the most severe scenario in terms of the reduction of inflows to and precipitation over the delta. The animated sequence of flooding for the five dry years (1992 to 1997) is shown in figure 3.27. The average maximum depth of flow over the entire delta area is reduced by 0.07m, and in the normally flooded areas by 0.18m (table 3.3). Figures 3.28 and 3.29 show the time series of the impacts for each zone, for the wet and dry years respectively.

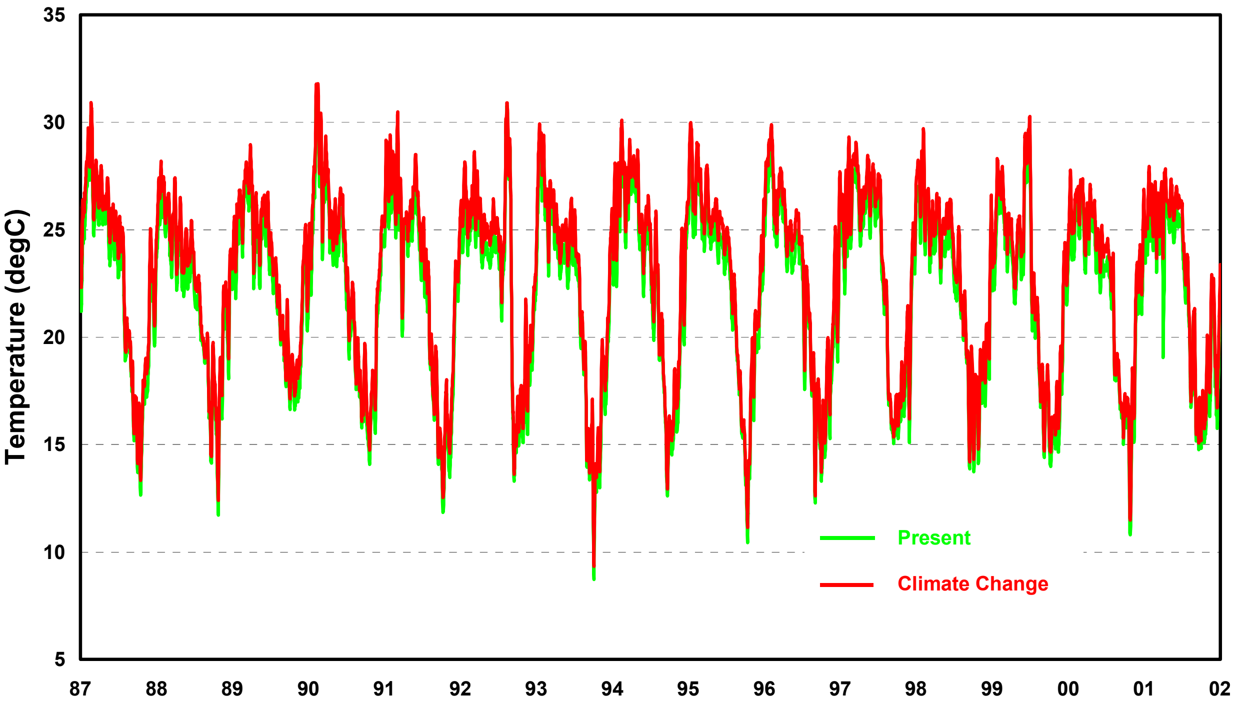


*Figure 3.26: Temperature Increase for Climate Change*

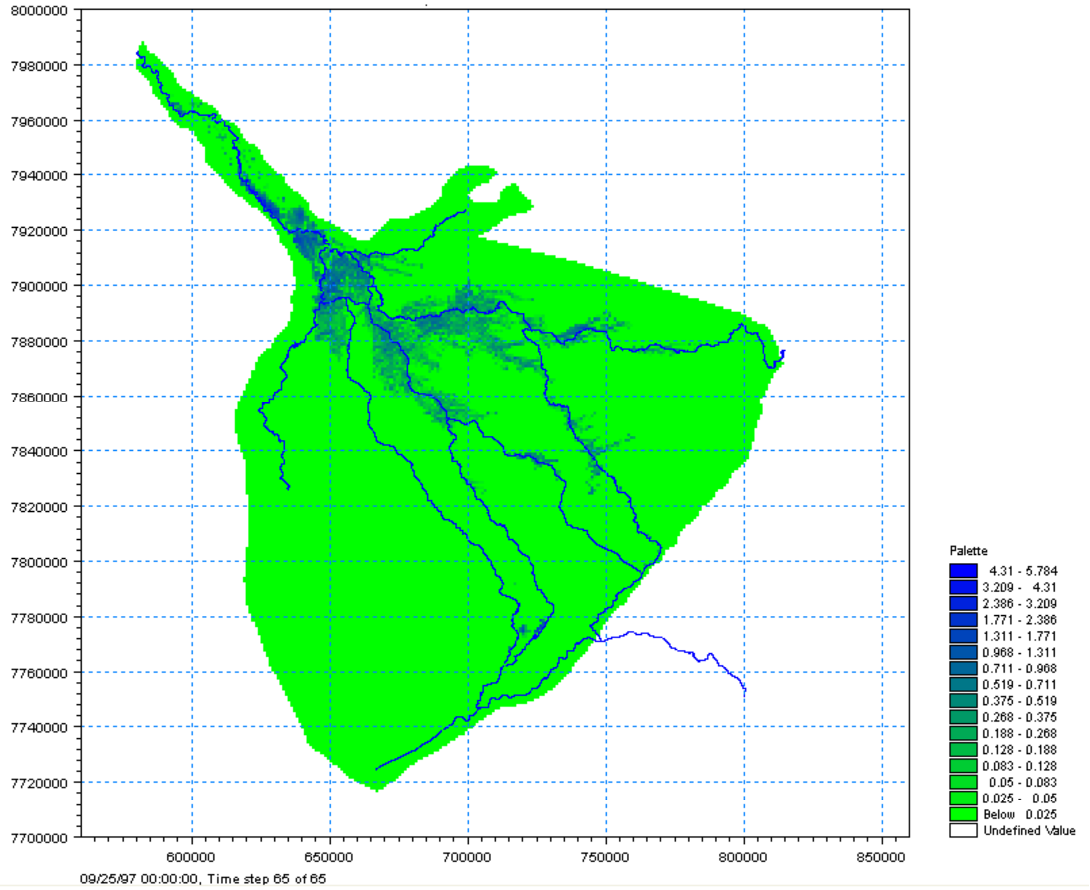
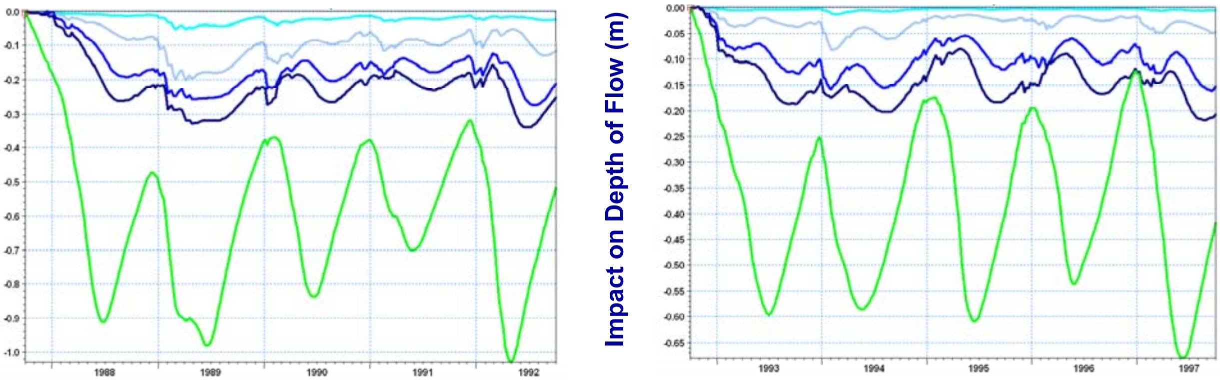


***Figure 3.27: Animated Sequence of Depth of Overland Flow for Climate Change (1992 to 1997)***

The lower envelope for the flooded area over the five normal years is reduced from 1,780km$^2$ for the Baseline conditions to 711km$^2$, a reduction of 60%. The corresponding reduction in the upper envelope is 4,754km$^2$, or 38% (table 3.3). The impact on the lower envelope for surface water flow depth is shown in figure 3.30.

### 3.9.3 Subsurface Water

The subsurface waters of the delta are also severely affected by the climate change scenario, with both the root zone soil moisture deficit and the depth to ground water increasing by an average of 0.04m and 0.07m over the entire delta respectively. Figure 3.31 shows the distributed impact on the soil moisture for the five wet years.



***Figures 3.28 and 3.29:Average Impact on Surface Water for Each Zone***

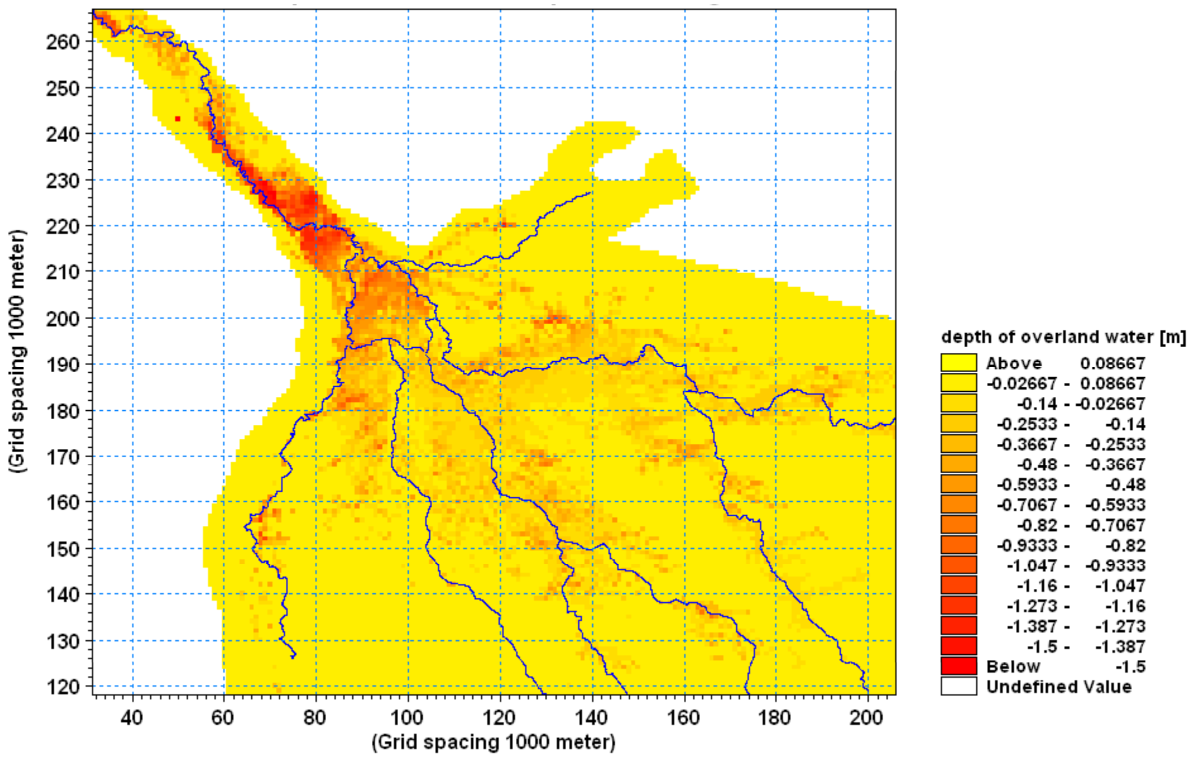


*Figure 3.30: Impact on Lower Envelope of Flooding (Climate Change (1992 to 1997))*

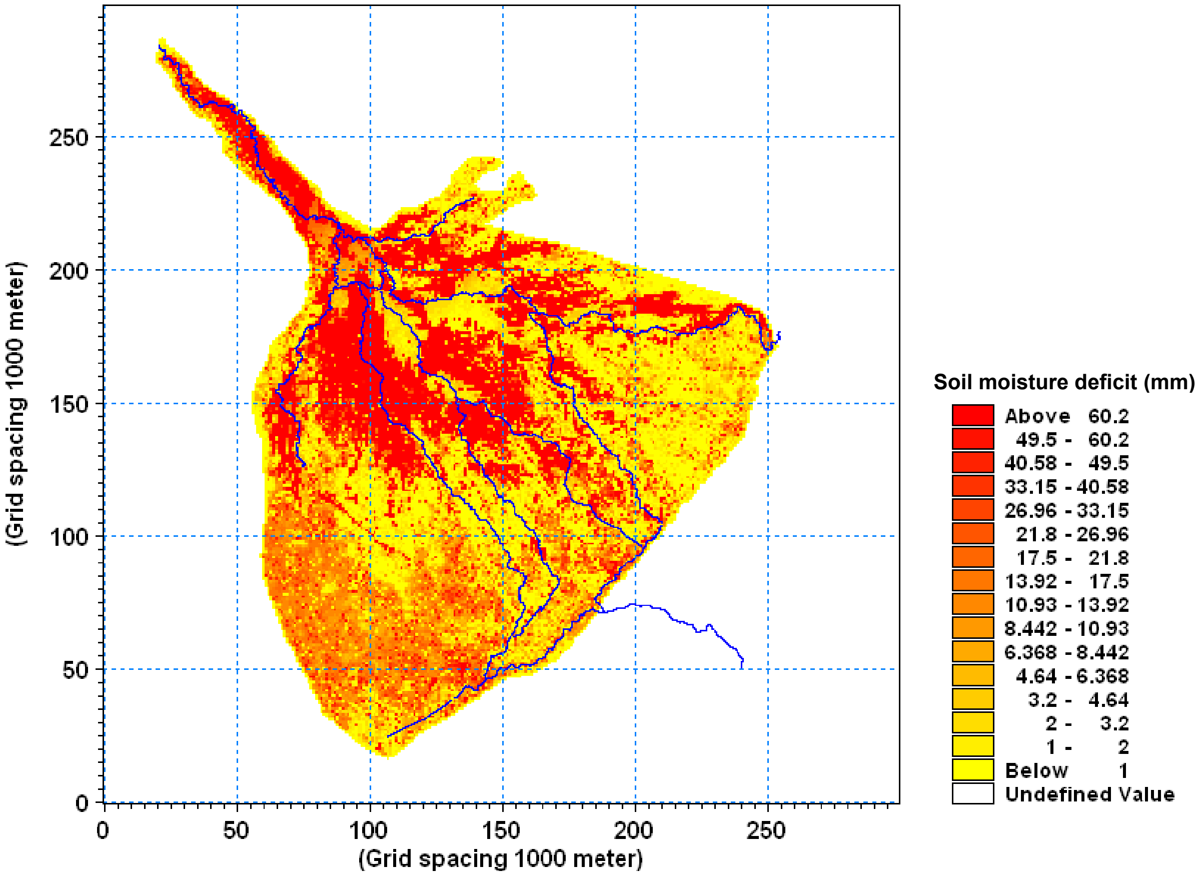


*Figure 3.31: Impact on Lower Envelope of Soil Moisture (Climate Change 1987 to 1992)*

### 3.9.4 Water Balance

The water balance summary for the five dry years (table 3.3), shows that climate change reduces the combined river inflow and precipitation by 166mm/annum, a reduction of 26%. Given a reduced flooded area and soil moisture, the evapotranspiration is reduced by 143mm/annum, the remaining balance appearing in a progressive reduction in the surface and subsurface storages, totalling 25mm/annum, relative to the Baseline. (A difference in the continuity error accounts for the discrepancy of 2mm.)

## 3.10 Channel Blockages

### 3.10.1 Introduction

Changes to the conveyance capacity of the channels can occur naturally through sediment erosion and deposition, and encroaching vegetation; and artificially through cutting reeds and dredging. A set of scenarios has been run removing blockages along the Maunachira and the middle reach of the Santantadibe. This has been effected in the hydrologic model by removing the high channel resistances in the Maunachira and Santantadibe which represent the blockages in the Baseline and all other scenarios.

### 3.10.2 Surface Water

The main impact of clearing blockages is to increase the flow through the channels, thus reducing the water level in the channel and surrounding swamp area upstream, and increasing the water level downstream. The impact on the delta as a whole is insignificant, as can be seen for tables 3.2 to 3.4. The zonal impacts in the Blockages columns are for the Nqoga-Maunachira-Khwai-Santantadibe system only (Zones 1 to 4). The impact on the whole subsystem is give in the row for Zone 5. The areas of the zones within the subsystem are shown in table 3.10.

***Table 3.10: Maunachira Subsystem Zones***

| **Subsystem Area (km$^2$)** | **8,369** | **Description** |
|---|---|---|
| Zone 1 - 0.1>FP>0 | 5,249 | rarely flooded |
| Zone 2 - 0.5>FP>0.1 | 1,013 | occasionally flooded |
| Zone 3 - 0.9>FP>0.5 | 970 | seasonally flooded |
| Zone 4 - 1>FP>0.9 | 1,137 | normally flooded |

Figure 3.32 shows the impact on the maximum overland flow for the wet period, 1987 to 1992. The water levels upstream in the Normally Flooded zone of the subsystem are reduced by an average of 0.17m, while the downstream water levels in the Rarely Flooded zone are increased by 0.11m. Figures 3.33 and 3.34 show the impact of clearing the blockages on the average flow depth in each subsystem zone.

The model is a hydrologic model, and does not simulate encroaching vegetation. Based on previous research, encroaching vegetation may be inferred from sedimentation patterns.

### 3.10.3 Subsurface Water

As shown in tables 3.2 to 3.4, the impact of clearing blockages on the surface waters is reflected in the subsurface waters. The maximum soil moisture deficit upstream

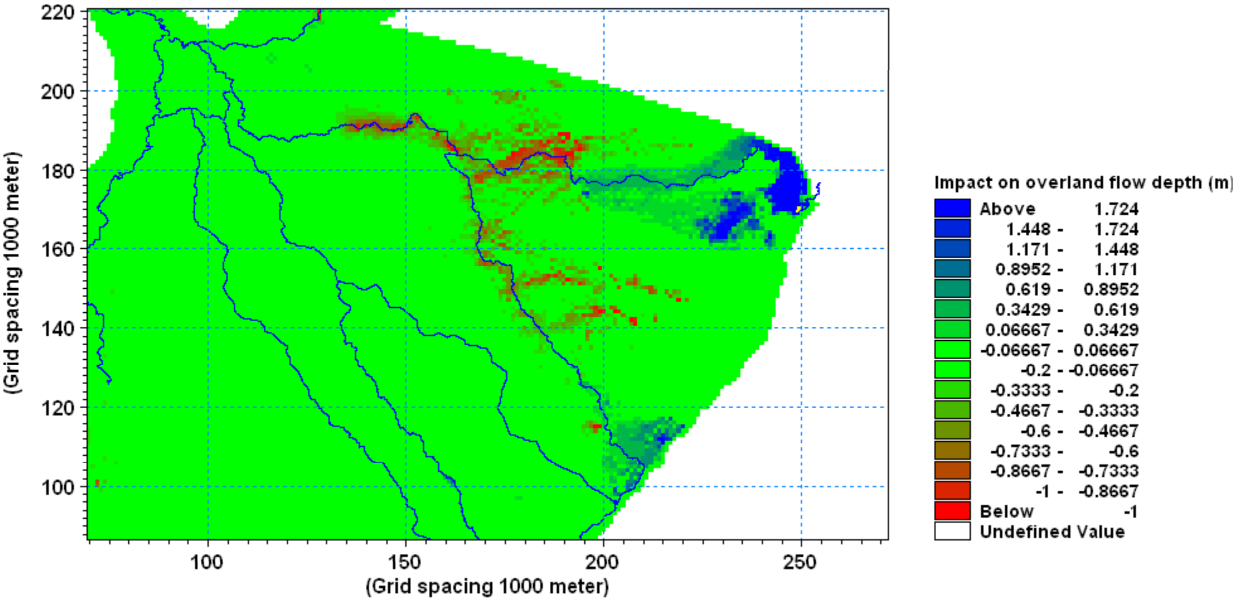


***Figure 3.32: Impact on Upper Envelope of Flooding of Clearing Blockages***

increases by up to 0.07m, while downstream it is reduced by up to 0.06m. The maximum depth to the ground water increases by up to 0.24m upstream (in the normally flooded area), while that downstream is reduced by up to 0.24m (in the rarely flooded area). This is illustrated in figure 3.35.

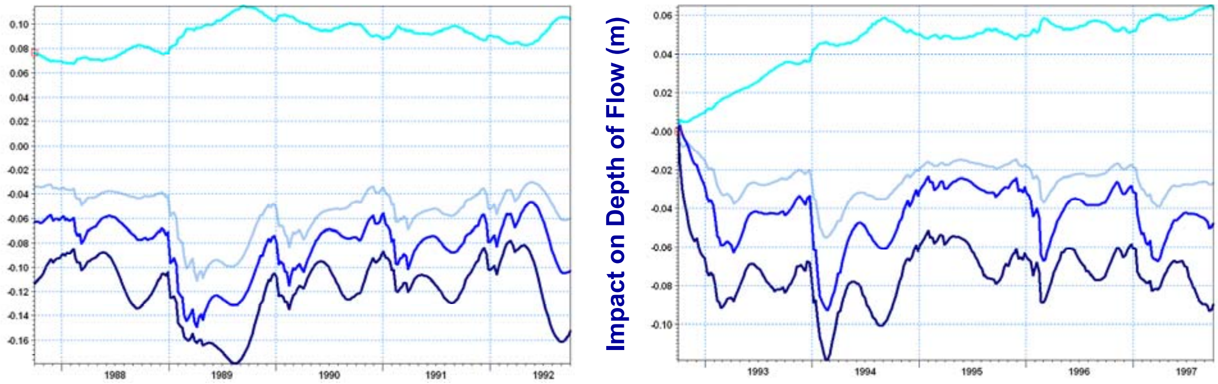
### 3.10.4 Water Balance

The most pronounced impact of clearing blockages in the Nqoga-Maunachira-Khwai-Santantadibe subsystem on the water balance is the increased outflows from the delta. Over the simulated period, the outflow increases from 70Mm$^3$/annum under Baseline conditions, to 150Mm$^3$/annum with the blockages cleared. The main outflows are from the Khwai (to the Mababe Depression) and the Boteti Rivers.

## 3.11 Combined Scenarios

### 3.11.1 Introduction

Excluding the Natural scenario, the six individual scenarios plus the Baseline have been simulated for three five year periods, representing wet, dry and normal conditions in the basin, from 1987 to 2002. The total number of possible combinations of these scenarios is 63. In simulating the six individual scenarios, a



***Figures 3.33 and 3.34: Average Impact of on Surface Water for Each Subsystem Zone (Clearing Blockages)***

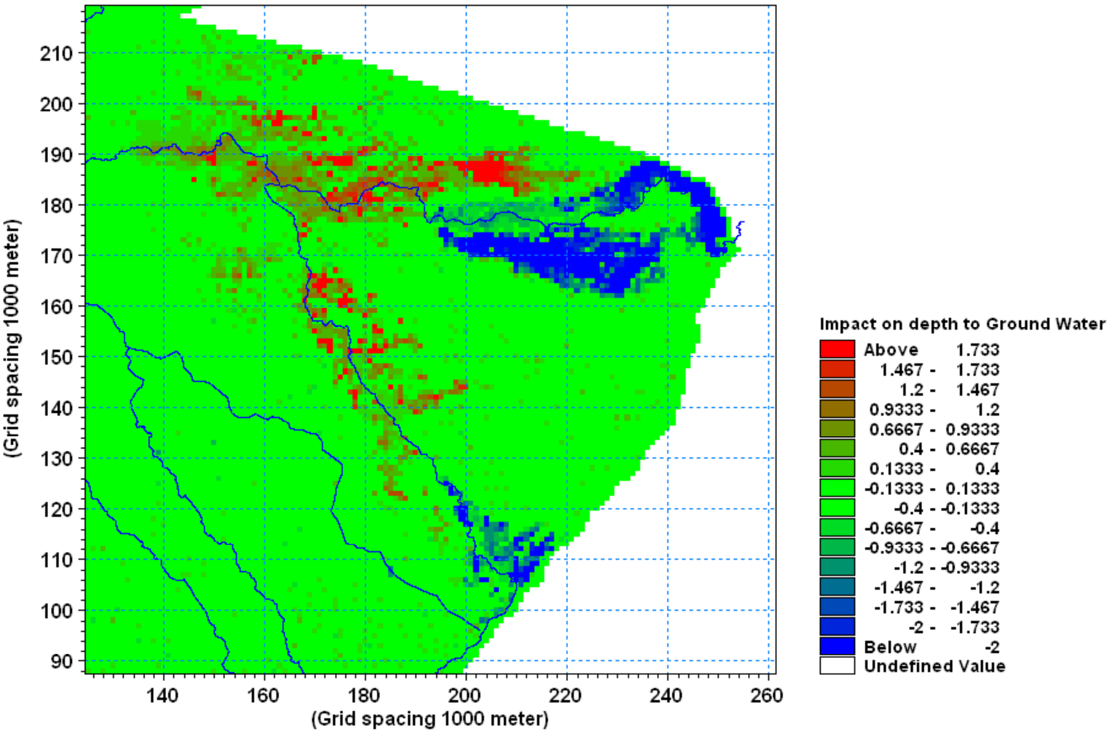


***Figure 3.35: Impact on Lower Envelope of Ground Water of Clearing Blockages***

large amount of data has been produced. The number of combinations has to be limited to a manageable number.

Two combinations have been analysed, representing a high developed state of the basin, ie Angola Dams and Irrigation in the upstream basin, and surface and ground water abstraction to meet local needs in the delta. One combined scenario is without Climate Change (AB+AD+IR), and the second with Climate Change (AB+AD+IR+CC). The impacts are discussed in the following sections.

### 3.11.2 Abstraction, Angola Dams and Irrigation

#### Surface Water

The impacts of the combined scenarios are complex, as impacts from an individual scenarios may accumulate, or cancel each other out. The impacts may accumulate for one period, and cancel for another period. The spatial distribution of the impact is also variable.

This is illustrated by the impact on the upper envelope of overland flow depth (maximum) in the wet period (1987 to 1992), where both the dams and irrigation reduce the inflow, and the average maximum depth across the delta by 0.05m, table 3.2. In the dry years (1992 to 1997), the dams release water and largely compensate for that removed by irrigation (table 3.3).

For the lower envelope of flooding (the area that remains flooded throughout), the impact of the irrigation withdrawals predominates, except in the wet years when significant flood storage in the dams reduces the impact.

#### Subsurface Water

The impact of the combined development scenario without climate change on the subsurface waters of the delta is also to some extent ameliorated by the combination of dams and irrigation. The impacts vary in space and in time among the three simulation periods, wet, dry and normal.

### 3.11.3 Abstraction, Angola Dams and Irrigation, with Climate Change

The combined scenario coupling water resources development in the upstream basin and in the delta with Climate Change produces the most severe impact on the delta. While the impacts of the water resources development combination is accumulative at certain times in certain zones of the delta, in some circumstance the impacts of the individual scenarios when combined cancel each other out. With Climate Change, the water resources developments have uniformly adverse impacts on the delta, ie the combination reduces the waters of the delta further than Climate Change without developments.

#### Surface Water

The impact of the combined scenario on the overland flow depth is most severe in the wet period (1987 to 1992), with a reduction in the upper envelope of 0.22m, and in the lower envelope of 0.05m across the delta. The corresponding impact on the flooded area is to reduce the upper envelope from 14,424km$^2$ to 5,574km$^2$, and the lower envelope, ie the area that remains flooded throughout, from 4,776km$^2$ to 346km$^2$. In the dry period (1992 to 1997), the lower envelope of flooding is 145km$^2$.

The animated sequence of overland flow depth is shown in figure 3.36 for the dry years, and time series of the average depth in each of the five zones in figures 3.37 and 3.38. The impact on the Panhandle is a reduction of 1.7m in April/May 1992, and 0.5m in the normally flooded areas in July 1992.

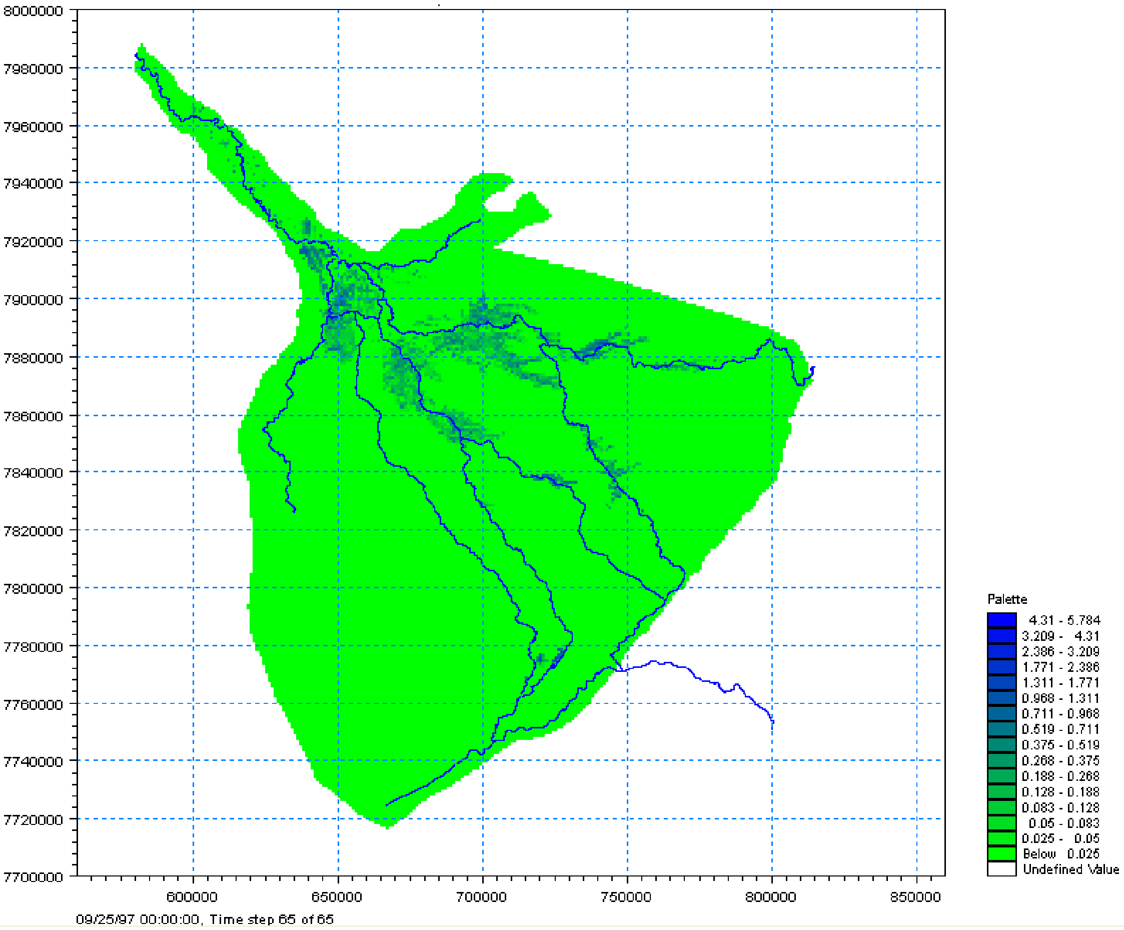
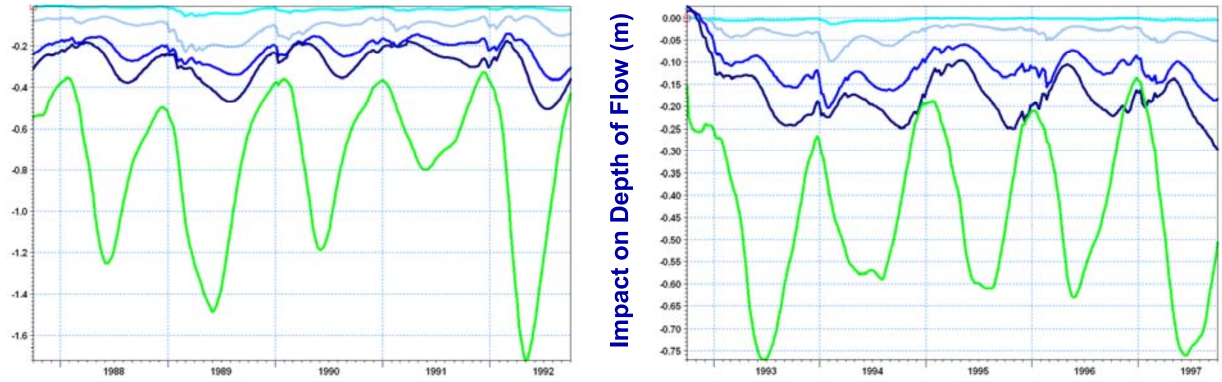


***Figure 3.36: Animated Sequence of Overland Flow Depth for Combined Scenario with Climate Change (1992 to 1997)***



***Figures 3.37 and 3.38: Average Impact on Surface Water for Each Subsystem Zone (Combined Scenarios with Climate Change)***

### Subsurface Water

The impact of the development scenario with Climate Change on the soil moisture averages an increased deficit of 0.07m over the delta (tables 3.2 to 3.4), with the maximum impact in the seasonally and normally flooded areas. The ground water depth increases by an average of 0.18m, with the impact also greatest in the seasonally and normally flooded areas (figure 3.39).

### Water Balance

Under the scenario, the upstream inflows to the delta are greatly reduced, by an average of 55% each year. The rainfall over the delta is reduced by 17%. While the

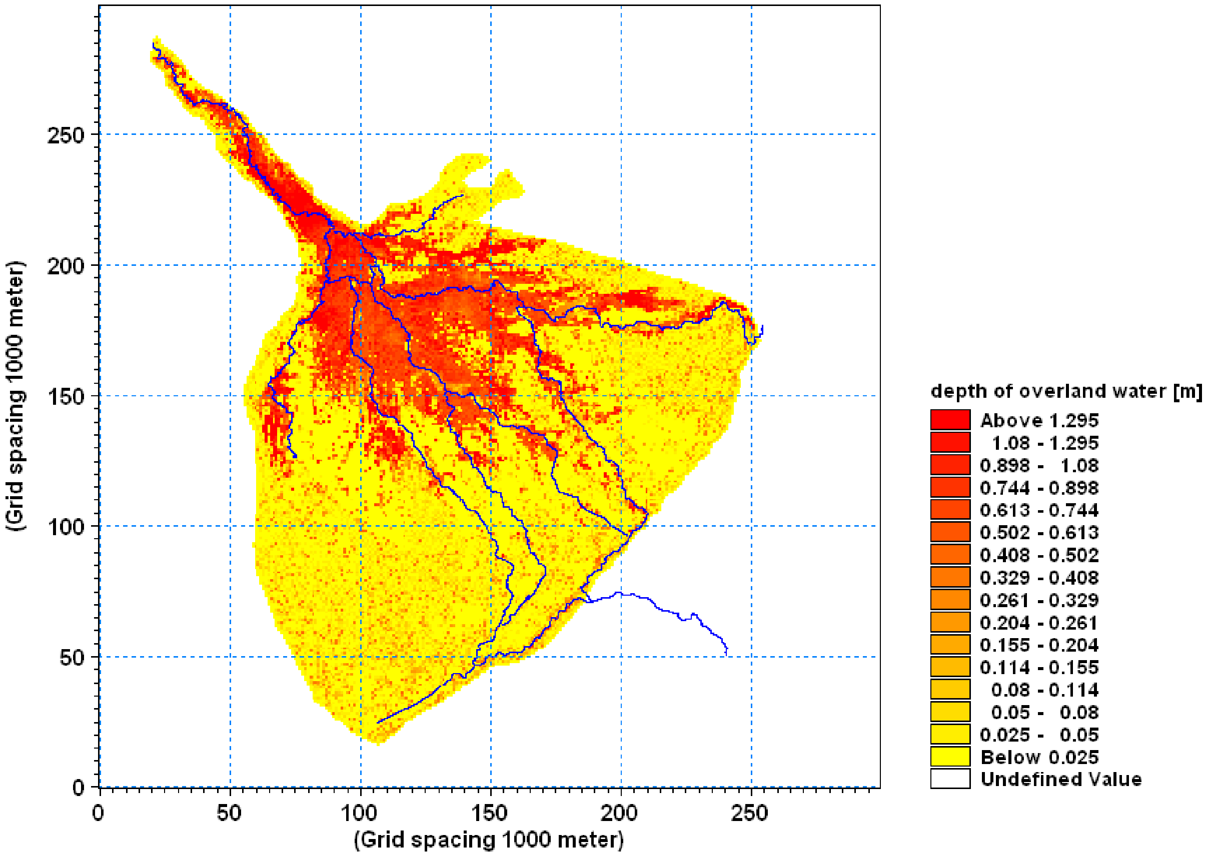


***Figure 3.39: Impact on Lower Envelope of Ground Water of Combined Scenario with Climate Change (1987 to 1992)***

temperature is increased by 2.2ºC, the flooded area suffers a large reduction, and the evapotranspiration declines by 31%.

The outflow from the delta decreases from 150Mm$^3$ per annum to 65Mm$^3$, a reduction of 57%. The nett storage change in the delta drops from an average increase of 1.8mm/annum to an average decrease of 0.3mm/annum.

# 4. CONCLUSIONS

## 4.1 Summary

This report presents the second round of analysis of the hydrology and water resources of the Okavango Delta, as the delta and the source basin upstream exist today, and as it may be twenty years hence. There are no firm published water resources development plans for the basin upstream, though the bases of such developments, mainly irrigation and hydropower, has been laid and discussed.

The Hydrology and Water Resources component of ODMP has reviewed the available information, and derived simplified scenarios to test their potential impact on the hydrology of the delta, using the Integrated Hydrologic Model. The impacts are expressed in terms of:

- the overall water balance among rainfall, evapotranspiration, upstream inflow, downstream outflow, and surface and subsurface storage changes from one year to the next
- the minimum and maximum depth of flooding
- the soil moisture and the ground water depth
- the minimum and maximum area flooded

The flooded area is the most sensitive parameter to water resources developments, showing the impact of declining inflows, revealing delays in the timing of the upstream flood wave and individual rainstorms.

Presentation formats are one kilometre grid based maps showing the spatial distribution of the parameters, animated sequences showing the dynamic spatial variation, time series showing the variation in each of five zones within the delta, and as summary tables. It is possible to express the impacts employing a wider range of parameters and different formats, such as splitting evapotranspiration among evaporation from open water, vegetation and soil, and transpiration from vegetation, infiltration from surface to ground water, ground water flows, etc.

Discussions held with stakeholders suggest that the presentation of results meets their needs. The results will be incorporated in the Okavango Delta Information System, for ready direct access by all stakeholders. Further discussions will be held with stakeholders to confirm the suitability of the presentation, and the possibility of presenting further data and in different formats.

## 4.2 Conclusions from Analyses

The impacts arising from the eight scenarios are briefly summarised as follows.

(1) The basin and delta are presently in a near natural state. To date, land use changes and abstractions from the basin upstream and the delta have a minimal impact on the delta as whole, though local impacts may be significant.

(2) Based on water flows, the potential dams in Angola with a combined storage approximately equal to the annual delta inflow do not have a major impact on the delta. There is no nett water consumption, and little water is stored in dry years, with correspondingly small releases in the dry period. If the old proposals are brought forward, operating conditions need to be verified. The sediment transport implications could be significant, and have not been analysed.

(3) Upstream irrigation in Namibia and especially Angola has a significant impact. The lower envelope of flooding, ie the area that remains flooded throughout, is reduced by 40% in dry years.

(4) Present and future surface and ground water abstractions from the delta are minimally significant, amounting to 0.3% and 0.5% of the inflow respectively. Under future conditions, the upper envelope of flooding, ie the area that may be flooded at some time, is decreased by around 70km$^2$, or 0.6%.

(5) Projected climate change has the most severe impact, reducing both inflows from upstream and rainfall over the delta, and increasing temperature and the rate of evapotranspiration. The lower envelope of flooding is reduced by 68%, from 2,770km$^2$ to 900km$^2$.

(6) The impact of the combined development scenario without climate change is generally similar to that of the most severe component, Upstream Irrigation, though some impacts of the Angola Dams cancel those of the irrigation.

(7) The combined water resources developments with climate change have the most severe impact on the delta. In years with normal inflows, the range of flooded area declines from a maximum of 12,825km$^2$ to 4,695km$^2$, and from a minimum of 2,944km$^2$ to 158km$^2$.

## 4.3 Further Applications

### 4.3.1 introduction

The following are potential further applications:

- As discussed in section 2.4, sediment transport is being introduced to the model – this will enable predictions of the pattern of erosion and deposition in the main channels of the delta, and possible channel shifts
- A smaller grid size, reducing the present 1km$^2$ to say 10,000m$^2$, through the application of local "nested" models covering a small area of the delta
- the introduction of water quality, showing the transport and decay of pollutants throughout the delta

These are discussed in the following sections.

### 4.3.2 Sediment Transport

Sediment transport is being introduced to the model. This will enable general predictions of patterns of erosion and deposition in the main channels of the delta, for the Baseline and Scenario conditions.

Sediment transport is highly dependent on the channel flow velocity. Major sedimentation will occur during high floods. No extreme floods occur within the three five year periods analysed to date. Simulations will be made for a major flood event, eg 1983, whose peak daily flow exceeded the estimated 50 year return period flow of 900m$^3$/s.

### 4.3.3 Nested Models

The Integrated Hydrologic Model of the Okavango Delta covers an area of 29,000km$^2$ with a one kilometre square grid. Available data on the topography and hydrology of the delta do not justify a finer resolution, and computer run times would increase dramatically.

A more appropriate approach to a finer resolution of the grid is to set up a model of an area of particular interest within the delta. The present delta model would provide the boundary conditions at the perimeter of the "nested" model. Detailed topographic and hydrologic data should be obtained for the area of interest.

### 4.3.4 Water Quality

The MIKE SHE modelling system applied to the Okavango Delta includes modules for extensive water quality analysis, including the complex processes of advection and dispersion, decay and eutrophication. To implement this, a major effort would be required to obtain more accurate and detailed topographic and hydrologic data, and systematic water quality measurements which do not exist at present.

## 4.4 Refinement of Scenarios

It is recommended that for the present phase of the delta management plan, the scenarios are kept conceptually simple. The impacts on the delta can be more readily understood and grasped, by concerned parties from local communities through government organisations to OKACOM representatives. With a sound understanding, measures to mitigate adverse impacts can be discussed and agreed among all parties.

There is scope to devise endless scenarios based on combinations and permutations of the six basic scenarios tested to date, and analyse the impact using the hydrologic model. The two combinations carried out to date, ie combined water resources development with and without climate change, show that the impacts of separate developments can accumulate and can cancel each other out, and it can be difficult to comprehend the nett impact. Such combined scenarios should be limited in number to actual proposed plans, as the increased volume of results output will complicate the entire planning process.