Okavango River Basin Transboundary Diagnostic Analysis Technical Report

OKACOM

The Permanent Okavango River Basin Water Commission

EPSMO-BIOKAVANGO
Okavango River Basin
Environmental Flow Assessment
Hydrology Report:
Data and Models
Report No: 05/2009

H. Beuster, et al.

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Environmental protection and sustainable management of the Okavango River Basin

EPSMO

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Report 03/2009:	Guidelines for data collection, analysis and scenario creation
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- Mr. Francisco Manuel Mateus, Provincial Director of Agriculture and Rural Development in Kuando Kubango;
- National Coordination Unit (EPSMO);
- Project Management Unit (EPSMO)

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- It would have been difficult to in progress of this study had it not been work done during the ODMP exercise.
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- The Ministry of Agriculture, Water and Forestry, Department of Water Affairs and Forestry, Directorate of Rural Water Supply
- The Ministry of Agriculture, Water and Forestry, Department of Water Affairs and Forestry, Directorate of Agricultural Research and Training
- The Ministry of Agriculture, Water and Forestry, Division of Agricultural Engineering
- The Ministry of Agriculture, Water and Forestry, Directorate of Veterinary Services
- The Ministry of Works and Transport, Namibia Meteorological Services
- Namibia OKACOM Basin Steering Committee member, Laura Namene
- Mr. Basil Dax from Nampower
- Informal discussions with Mr. Piet Heyns on Central Area water demands from the Okavango River
- Namibia Water Corporation Ltd
- Collin Christiaan and Hans Beuster for the photographs

Executive Summary

Introduction

Flow scenarios form the basis of the environmental flow assessments that are being undertaken for the Okavango River Basin. A hydrological working group consisting of hydrologists from the three co-basin states of the Okavango River basin was established to develop and populate the hydrological and hydraulic models for the river basin and the delta and to develop flow scenarios.

This report (Volume 5) is the first of two reports produced by the Ecological Flow Assessment (EFA) hydrological working group. The report provides an overview of the current water resource situation and describes the models, hydrological data and development information that form the basis for the simulation of flow regimes at different points along the Okavango River system, including the Delta. The report should be read in conjunction with the Hydrological Scenario Modelling Report (Volume 6), which describes the outcomes of the hydrological modelling of present and possible future flow regimes.

Study Area

The Okavango River Basin consists of the areas drained by the Cubango, Cutato, Cuchi, Cuelei, Cuebe, and Cuito rivers in Angola, the Okavango River in Namibia and Botswana (in Namibia, the river is called the Kavango), and the Okavango Delta. This basin includes the Omatako River catchment in Namibia which is topographically linked to the Okavango River, but due to the low mean annual rainfall (less than 400 mm/year in the headwaters), the river is ephemeral. Due to the sandy nature of the terrain, no surface runoff reaches the Okavango River. Outflows from the Okavango Delta are drained through the Thamalakane and then Boteti Rivers, the latter eventually joining the Makgadikgadi Pans. The Nata River, which drains the western part of Zimbabwe, also joins the Makgadikgadi Pans. The Selinda spillway is located in a local depression and provides an occasional link to the Zambezi River. In times of high flow the Okavango overtops a local high point in the Selinda and spills toward the Cuando/Chobe/Linyanti system (2009 Satellite images provided the first recorded evidence of overflow from the Kavango Panhandle reaching the Kwando/Linyanti/Chobe/Zambezi system through the Selinda Channel). On the basis of topography, the Okavango River Basin thus includes the Makgadikgadi Pans and Nata River Basin and has an occasional link to the Zambezi Basin. This study, however, focuses on the parts of the basin in Angola and Namibia, and the Panhandle/Delta/Boteti River complex in Botswana. The Makgadikgadi Pans and Nata River are not included.

Availability of Hydrological Data and Information
Hydrological modelling of the Okavango River basin is complicated by the limited availability of measured stream flow and rainfall records. Long stream flow records (starting in the 1940s) are available along the lower reaches of the Kavango and Okavango at Rundu, Mukwe and Mohembo, but stream flow records in Angola are only of the order of 10 years long, covering the early 1960s to mid 1970s. Measured rainfall records in Angola are only available until 1972. These sequences were extended with satellite rainfall by Wilk et al. (2006) to September 2003, which means that a calibrated rainfall-runoff model could be used to generate stream flow sequences for the period spanning hydrological years 1958-2002.

Hydrological and Hydraulic Models of the Basin
A series of hydrological and hydraulic models have in the past been developed to reproduce flow conditions observed in the Okavango Basin and Delta. In order to provide the hydrological information required for the EFA, a suite of existing and new models were used. The models were selected and configured to provide current day (baseline) and scenario flow sequences at the eight EFA sites. The modelling sequence and linkages between the models are shown in Figure E-1 below.

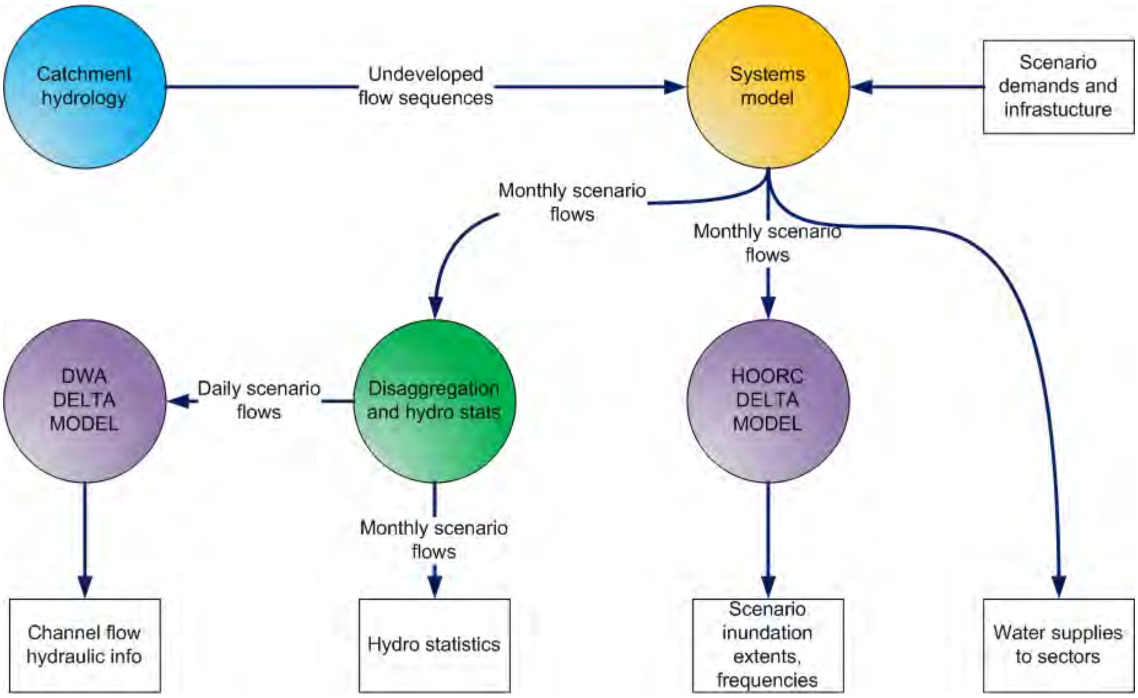

Figure E-1 : Hydrological Modelling Components

The models which were selected for use in the EFA are:

- **Catchment hydrology:** Estimates of naturalised (undeveloped) long-term runoff were obtained from an existing Pitman-based rainfall-runoff model developed as part of the EU funded WERRD project (Hughes *et. al.* 2006). The model was configured to provide runoff sequences at the outlets of 24 distinct sub-catchments upstream of the Delta.
- **Systems Model:** As part of this project, the monthly time-step WEAP systems model was selected and used to configure a reference (Present Day), Low, Medium and High Development scenarios. Inputs to the model include the undeveloped runoff sequences for 24 sub-catchments produced by the Pitman model, irrigation scheme and urban abstractions, in channel

dams for irrigation water supply, inter-basin transfers, run-of-river and storage based hydropower schemes.

- **HOORC Delta Model:** A semi-conceptual model which was previously developed by the Harry Oppenheimer Okavango Research Centre (HOORC) (Wolski et. al. 2006) was used to model inundation frequencies and extents at the Delta EFA sites. The model operates on a monthly time step and includes a dynamic ecotope model that simulates the responses of vegetation assemblages to changes in hydrological conditions. Scenario inflows to the model are provided by the WEAP simulations of basin runoff.
- **DWA Delta Model:** A MIKE-SHE / MIKE 11 hydrodynamic model which was previously configured by Botswana DWA and DHI for the Okavango Delta Management (ODMP) project (IHM Report, 2005) was used to model flow velocities and depths at the Delta EF sites. Scenario flow sequences simulated with WEAP for Mohembo were used as inflow sequences for the Delta model, after disaggregating the monthly flow sequences to a daily time step.
- **Thamalakane/Boteti Model:** Delta outflows simulated by the HOORC model are routed along the Thamalakane/Boteti system with a linear reservoir spreadsheet model (Mazvimavi, 2008) to derive scenario flow sequences at the Boteti EF site. The model was incorporated into the HOORC Delta Model and improved to provide estimates of wetted river length and state changes of the system.
- **Disaggregation and Hydro-Statistics:** A custom utility was developed to disaggregate the simulated monthly WEAP flow sequences to daily flow sequences, to delineate flow seasons (dry, wet and transition) for each year of the 43 year long sequences, and to calculate ecologically relevant flow statistics (“flow categories”).

A summary of sub-basin rainfall and naturalised (undeveloped) runoff is shown in **Error! Reference source not found.**E-1. The estimates are based on a re-arrangement of rainfall-runoff simulations for the 24 sub-catchments in the Pitman model configured by Hughes et. al. (2006).

Table E-1 : Sub-basin Runoff

River / zone	Area	Mean Annual Rainfall	Mean Annual Runoff	Percentage contribution
	km^2	mm	million m3/year	
Cubango	14 400	1 028	1 846.3	17%
Cutato	4 200	1 220	800.1	7%
Cuchi	8 900	1 117	821.2	8%
Cacuchi	4 800	1 207	759.5	7%
Cuelei	7 500	1 114	697.4	6%
Cuebe	11 200	969	678.8	6%
Cuatir	11 600	787	134.3	1%
Cueio	3 700	787	57.0	1%
Cuiriri	12 900	986	565.8	5%
Cuito	24 300	1 051	3 338.7	31%
Cuanavale	7 750	1 073	595.6	5%
Lower Okavango	45 000	608	620.0	6%
Total (upstream of Delta)	**156 250**	**837**	**10 914**	**100%**

Considering the limited availability of measured rainfall and stream flow records, the existing Pitman-based rainfall-runoff model of the basin (Hughes et. al., 2006) performs reasonably well, with good simulation of low flows and errors in peak flows of about 20% (the model more often than not under-estimates peak flows). For traditional water resource assessments the errors in peak flow simulation are not considered to be serious, as it does not significantly affect estimates of run-of-river or storage based yields. In the EFA study it was found that this does pose problems, in that ecologists attach much greater importance to the magnitude of flood peaks and found it difficult to relate simulated peak flows to their knowledge of observed floods and associated ecosystem responses.

A recommendation of this study is that the rainfall-runoff model be re-calibrated with a view to improve peak flow simulation. As part of the same exercise, the model should be extended to cover the hydrological years from 2003 to as recently as possible, as this period includes the recent above-normal flood events of 2009 and 2010. The re-calibration should make use of the stream flow records that are becoming available from rehabilitated flow measuring stations in Angola.

The assembled suite of existing and new models provided adequate information on river flow regimes and inundation patterns at the EFA sites, with some scope for improvement. Major shortcomings include:

- The inability to provide modelled (scenario) information on water quality changes in the system, mainly due to a lack of historical water quality measurements for model calibration
- The absence of a sediment transport model (or models) in the basin upstream of the Delta
- Basic one-dimensional, steady state hydrodynamic models were configured for the floodplain sites in the basin (Cuito Cuanavale and Kapako), but these could be improved substantially by using higher resolution topographical information and the configuration of two-dimensional models.

Water Resource Development Information

The hydrological working group engaged in an intensive exercise to collect information about existing and possible future water resource developments in the Okavango River basin. The information was assembled by means of literature reviews and extensive consultations with water resource planners and managers in the three co-basin states, and formed the basis for formulation of the water resource development scenarios that were evaluated in the EFA.

The water resources of the basin are relatively un-developed at present. Current water use consists mainly of:

- The urban water demands of Menongue and Cuito Cuanavale (Angola), Rundu (Namibia), and Maun (Botswana)
- About 2 700 ha of irrigation in the Namibian portion of the basin
- Rural domestic and subsistence agricultural water demands and water demands of the tourism sector (Namibia and Botswana), all of which are small compared to the irrigation and urban demands

The end of the civil conflict in Angola has provided impetus to plans to develop the dormant agricultural economy in the Angolan portion of the basin and to revive plans for the construction of a number of hydropower schemes. Agricultural development and the rehabilitation of the transport network will see associated growth in the urban water demands of Menongue and Cuito Cuanavale. In Namibia, plans to improve food security could result in substantial growth in irrigation water requirements, although not at the same scale as foreseen for Angola. In Botswana, growth in urban and agricultural water demand could be tempered by the need to conserve natural resources and protect income derived from tourism in the Delta region. Against this backdrop, the following water resource developments that could be associated with a high water demand scenario were identified by the working group:

- About 15 000 ha of irrigation in Namibia
- About 338 000 ha of irrigation at various locations in Angola
- Completion of all planned hydropower stations in Angola, i.e. one storage based and nine run-of-river hydropower stations,
- Extension of Grootfontein-Okavango link of the Eastern National Carrier in Namibia (total capacity 100 Mm^3/a)
- The possible construction of a hydropower station at Popa Falls in Namibia.
- Substantial growth in the urban water demands of Menongue, Cuito Cuanavale, Rundu, and (to a lesser extent), Maun.
- Construction of a reservoir in the Boteti to supplement Maun's future water demands.

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Acronyms and abbreviations

DTM	Digital Terrain Model
(MAWRD), MAWF	(Ministry of Agriculture Water and Rural Development), Ministry of Agriculture, Water and Forestry (Namibia)
DWAF	Department of Water Affairs and Forestry in Namibia
ENWC	Eastern National Water Carrier
NamWater	Namibia Water Corporation Ltd
SADC	Southern African Development Community
DNA	National Directorate of Water (Angola)
INAMET	National Institute of Meteorology and Geophysics (Angola)
DPA	Provincial Directorate of Water (Angola)
HYDATA	Hydrological Database
UNDP	United Nations Development Programme
EPSMO	Project on the Environmental Protection and Sustainable Management of the Okavango River Basin
ORB	Okavango River Basin
SNPC	National Service of Civil Protection (Angola)
FAO	United Nations Organization for Food and Agriculture
INOT	National Institute of Territorial Cadastre (Angola)
NWMPR	National Water Master Plan Review
ODMP	Okavango Delta Management Plan
DMS	Department of Meteorological Services (Botswana)
DSM	Department of Surveys and Mapping (Botswana)
DGS	Department of Geological Surveys (Botswana)
WUC	Water Utilities Cooperation (Botswana)
NIGIS	National Integrated Geosciences Information Systems (Botswana)

1 INTRODUCTION

1.1 Background

An Environmental Protection and Sustainable Management of the Okavango River Basin (EPSMO) Project is being implemented under the auspices of the Food and Agriculture Organization of the United Nations (UN-FAO). One of the activities is to complete a transboundary diagnostic assessment (TDA) for the purpose of developing a Strategic Action Plan for the basin. The TDA is an analysis of current and future possible causes of transboundary issues between the three countries of the basin: Angola, Namibia and Botswana. The Okavango Basin Steering Committee (OBSC) of the Okavango River Basin Water Commission (OKACOM) noted during a March 2008 meeting in Windhoek, Namibia, that future transboundary issues within the Okavango River basin are likely to occur due to developments that would modify flow regimes. The OBSC also noted that there was inadequate information about the physico-chemical, ecological and socioeconomic effects of such possible developments. OBSC recommended at this meeting that an Environmental Flow Assessment (EFA) be carried out to predict possible development-driven changes in the flow regime of the Okavango River system, the related ecosystem changes, and the consequent impacts on people using the river's resources.

The EFA is a joint project of EPSMO and the Biokavango Project. The EFA methodology is based on the evaluation of a reference flow regime ("natural" or "present day") and a range of future flow regimes resulting from water resource developments to make predictions of change for a number of ecological indicators; these usually cover channel geomorphology, water quality, riverine vegetation, fish and aquatic macro-invertebrates. For the EFA, modified future flow regimes are produced with hydrological (and hydraulic) models of the river basin and the delta.

This report (Volume 5) is the first of two reports produced by the EFA hydrological working group and describes the models, hydrological data and development information that form the basis for the simulation of flow regimes at different points along the Okavango River system, including the Delta.

The report should be read in conjunction with the Hydrological Scenario Modeling Report (Volume 6), which provides an overview of the hydrological characteristics of the basin and describes the outcomes of the hydrological modeling of present and possible future flow regimes.

1.2 Scope and purpose of hydrological working group

A hydrological working group consisting of hydrologists from the three co-basin states was established to develop and populate the hydrological and hydraulic models for the river basin and the delta and to develop flow scenarios. The work was undertaken during the course of five week-long hands-on workshops in Maun, Gaborone and Windhoek. The workshop activities are detailed in Appendix A. The members of the group are:

Country	Person	Organisation
Angola	Mr Manuel Quintino	FAO / GEF EPSMO
	Dr Gabriel Miguel	University of Agostinho Neto
	Mr Paulo Emilio Mendes	DNA Angola
Botswana	Ms Kobamelo Dikgola	DWA Botswana
	Mr France Tibe	DWA Botswana
	Dr Chandrasekar Kurugundla	DWA Botswana
	Dr Dominic Mazvimavi	HOORC
	Dr Piotr Wolski	HOORC
	Mr Geofry Khwarae	BIOKAVANGO
Namibia	Mr Andre Mostert	NamWater
	Ms Aune Hatutale	NamWater
	Mr Matthews Katjimune	DWA Namibia
	Ms Penehafo Shidute	DWA Namibia
(Coordinator)	Mr Hans Beuster	EPSMO Process Management Team

Mr Guido van Langehove of the Namibian Department of Water Affairs and Forestry provided valuable contributions on flooding and hydrological data exchange in the basin.

1.3 Layout of this report

Chapter 2 provides an overview of the Okavango River basin and its sub-basins, and lists the representative sites which served as the focus of data collection and for which information on hydrological flow regimes were generated.
Chapter 3 describes the existing and new hydrological and hydraulic models that were selected or developed to provide provide current day (baseline) and scenario flow sequences at the eight EFA sites.
Chapter 4 outlines the field data collection activities of the hydrological working group.
Chapter 5 documents the availability and sources of hydrological data and information that were obtained for the EFA study.
Chapter 6 provides a summary of the water resource development information that formed the basis for the water use scenarios that were assessed in the study.
Data and information sharing arrangements within, and between the riparian countries of the Okavango River basin is described in Chapter 7.
Chapter 8 provides conclusions about the availability and quality of hydrological data in the basin, the modelling process and recommendations on how these could be improved.

2 STUDY AREA

2.1 Description of the Okavango Basin

A brief description of the extent of the Okavango River Basin and its sub-basins is provided in the remainder of this section. The hydrological characteristics of the basin is described in more detail in EPSMO/Biokavango Report Number 6; *Scenario Report: Hydrology*.

The Okavango River Basin consists of the areas drained by the Cubango, Cutato, Cuchi, Cuelei, Cuebe, and Cuito rivers in Angola, the Okavango River in Namibia and Botswana (in Namibia, the river is called the Kavango), and the Okavango Delta This basin includes the Omatako River catchment in Namibia which is topographically linked to the Okavango River, but due to the low mean annual rainfall (less than 400 mm/year in the headwaters), the river is ephemeral. Due to the sandy nature of the terrain, no surface runoff reaches the Okavango River. Toward the west and south, outflows from the Okavango Delta are drained through Kunyere to Lake Ngami, and through the Boteti River which eventually joins the Makgadikgadi Pans. The Nata River, which drains the western part of Zimbabwe, also joins the Makgadikgadi Pans. The Selinda spillway is located in a local depression and provides an occasional link to the Zambezi River. In times of high flow the Okavango overtops a local high point in the Selinda and spills toward the Cuando/Chobe/Linyanti system (2009 Satellite images provided the first recorded evidence of overflow from the Kavango Panhandle reaching the Kwando/Linyanti/Chobe/Zambezi system through the Selinda Channel). On the basis of topography, the Okavango River Basin thus includes the Makgadikgadi Pans and Nata River Basin and has an occasional link to the Zambezi Basin. This study, however, focuses on the parts of the basin in Angola and Namibia, and the Panhandle/Delta/Boteti River complex in Botswana. The Makgadikgadi Pans and Nata River are not included.

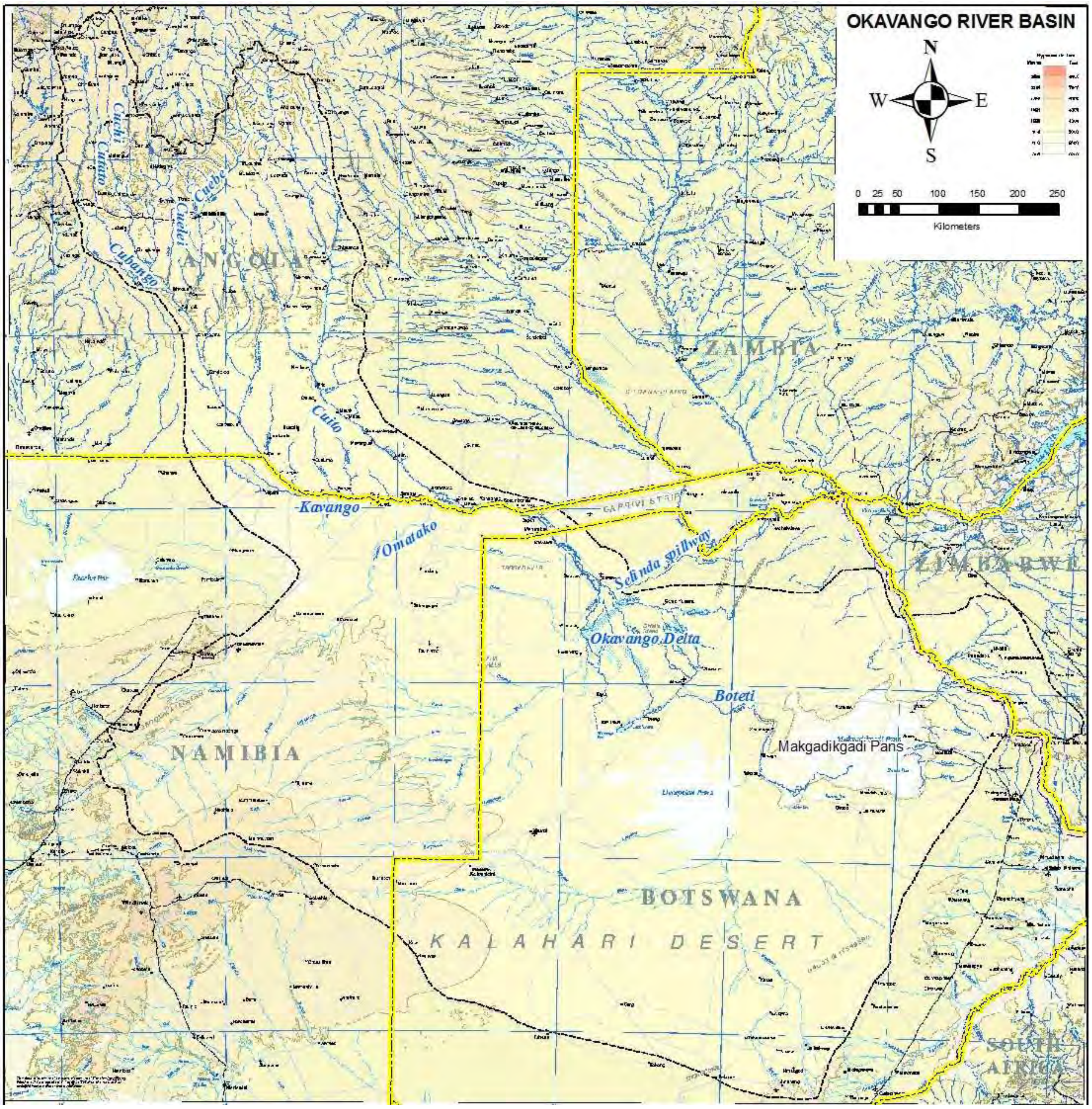


Figure 2-1   The Okavango River Basin

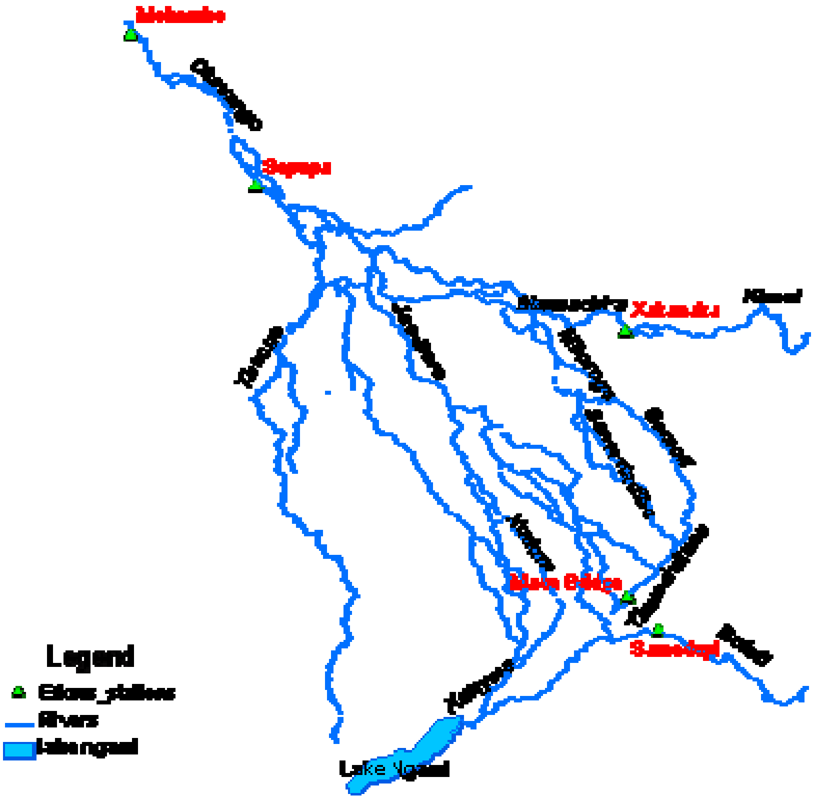


Figure 2-2 The Okavango River Delta, showing drainage into the Thamalakane / Boteti System

2.2 Delineation of the Okavango Basin into Integrated Units of Analysis

Within the Okavango River Basin, representative areas that are reasonably homogeneous in character were delineated and used to represent much wider areas. One or more representative sites were chosen in each area as the focus for data-collection activities. The results from each representative site could then be extrapolated over the respective wider areas. The existing and new hydrological models were selected and configured to provide scenario flow sequences at these sites. The basis for selection of the sites is decribed in EPSMO/Biokavango Report Number 4; *Delineation Report*.

The sites chosen by the national teams are listed in and shown on Figure 2-3.

Table 2-1 Location of the eight EFA sites

EFA Site No	Country	River	Location
1	Angola	Cuebe	Capico
2	Angola	Cubango	Mucundi
3	Angola	Cutio	Cuito Cuanavale
4	Namibia	Okavango	Kapako
5	Namibia	Okavango	Popa Falls
6	Botswana	Okavango	Panhandle at Shakawe
7	Botswana	Khwai	Xakanaka in Delta
8	Botswana	Boteti	Chanoga

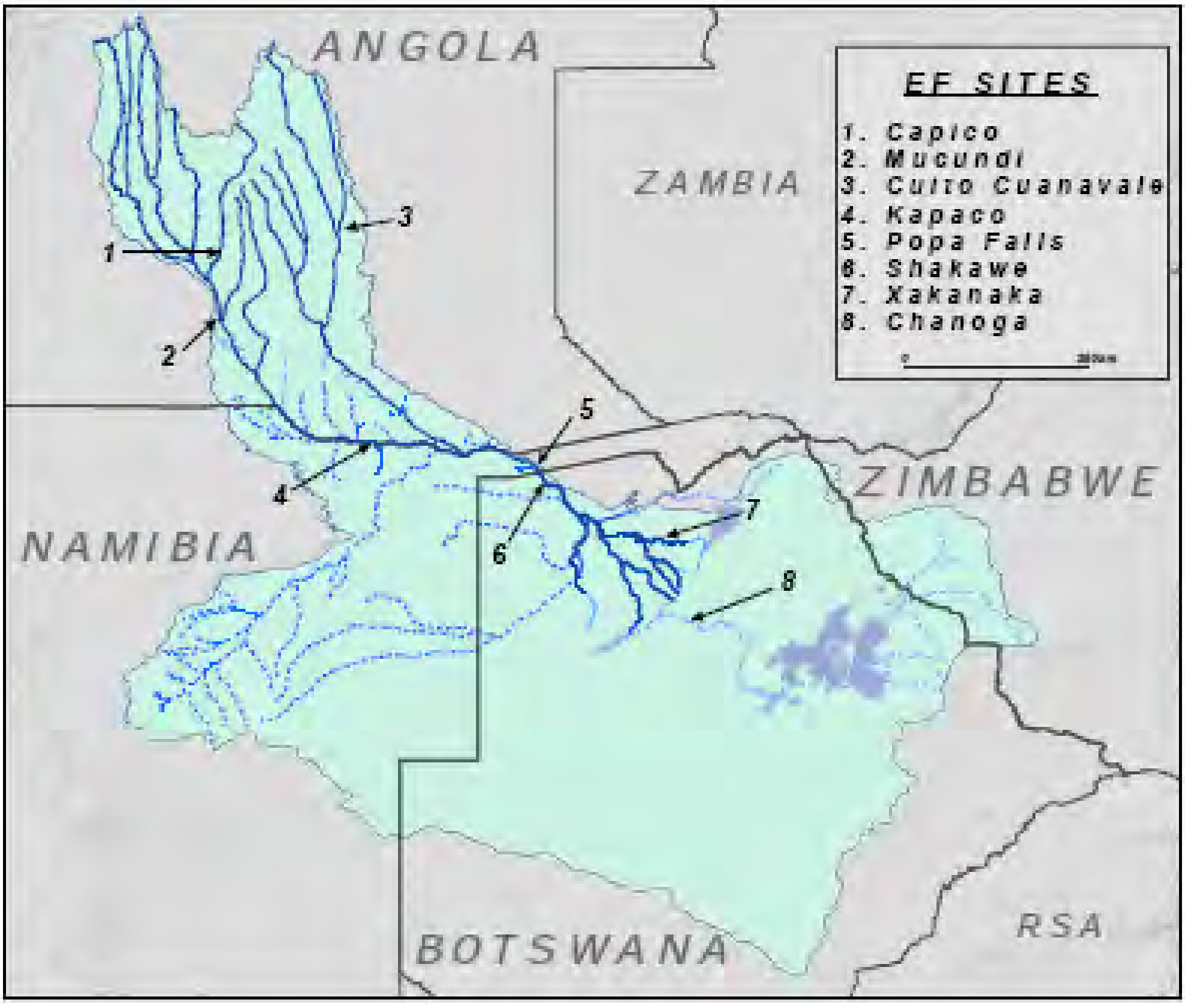


Figure 2-3 Map showing site locations

3 Hydrological and Hydraulic Models

3.1 Overview

A series of hydrological and hydraulic models have in the past been developed to reproduce flow conditions observed in the Okavango Basin and Delta. In order to provide the hydrological information required for the EFA, a suite of existing and new models were used. The models were selected and configured to provide current day (baseline) and scenario flow sequences at the eight EFA sites (

Table 2-1). The modelling sequence and linkages between the models are shown in Figure 3-1.

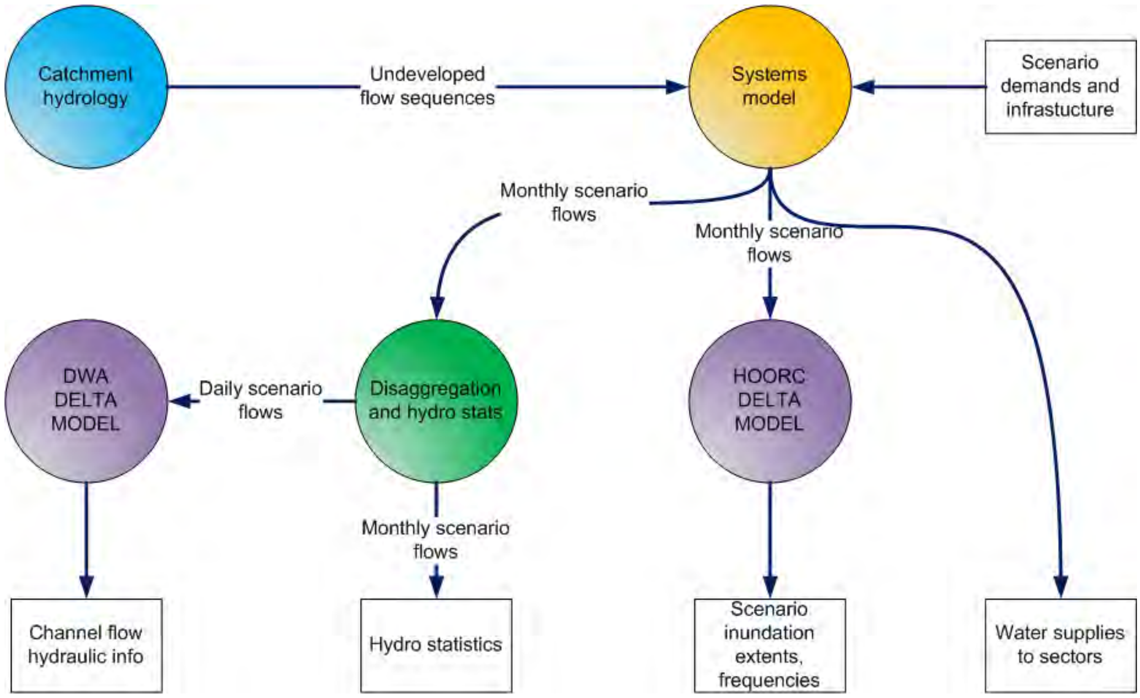


Figure 3-1 : Hydrological Modelling Components

The models which were selected for use in the EFA are listed below. More detailed descriptions of the basin and Delta modelling components are provided in Sections 3.2 and 3.3.

- **Catchment hydrology:** Estimates of naturalised (undeveloped) long-term runoff were obtained from an existing Pitman-based rainfall-runoff model (Pitman 1976) developed as part of the EU funded WERRD project (Hughes *et. al.* 2006). The model was configured to provide runoff sequences at the outlets of 24 distinct sub-catchments upstream of the Delta.
- **Systems Model:** As part of this project, the monthly time-step WEAP systems model was selected and used to configure a reference (Present Day), Low, Medium and High Development scenarios. Inputs to the model include the undeveloped runoff sequences for 24 sub-catchments produced by the Pitman model, irrigation scheme and urban abstractions, in channel dams for irrigation water supply, inter-basin transfers, run-of-river and storage based hydropower schemes.
- **HOORC Delta Model:** A semi-conceptual model which was previously developed by the Harry Oppenheimer Okavango Research Centre (HOORC) (Wolski et. al. 2006) was used to model inundation frequencies and extents at the Delta EF sites. The model operates on a monthly time step and includes a dynamic ecotope model that simulates the responses of vegetation assemblages to changes in hydrological conditions. Scenario inflows to the model are provided by the WEAP simulations of basin runoff.
- **DWA Delta Model:** A MIKE-SHE / MIKE 11 hydrodynamic model which was previously configured by Botswana DWA and DHI for the Okavango Delta Management (ODMP) project (IHM Report, 2005) was used to model flow velocities and depths at the Delta EF sites. Scenario flow sequences simulated with WEAP for Mohembo were used as inflow sequences for the

Delta model, after disaggregating the monthly flow sequences to a daily time step.

- **Thamalakane/Boteti Model:** Delta outflows simulated by the HOORC model are routed along the Thamalakane/Boteti system with a linear reservoir spreadsheet model (Mazvimavi, 2008) to derive scenario flow sequences at the Boteti EF site. The model was incorporated into the HOORC Delta Model and improved to provide estimates of wetted river length and state changes of the system.
- **Disaggregation and Hydro-Statistics:** A custom utility was developed to disaggregate the simulated monthly WEAP flow sequences to daily flow sequences, to delineate flow seasons (dry, wet and transition) for each year of the 43 year long sequences, and to calculate ecologically relevant flow statistics ("flow categories").

3.2 Basin Hydrology

3.2.1 Estimates of naturalised (undeveloped) catchment runoff

The hydrology of the data-poor Okavango River Basin was for the first time modelled at a spatial resolution that would allow for assessments of development impacts at various locations in the basin and on inflows to the Delta by Anderson et. al. (2003). The original model was based on the monthly time step Pitman Model (Pitman, 1973) and consisted of 23 sub-catchments upstream of the Delta. Since then, a modified Pitman model for the Cuito River, which accounts for groundwater recharge and discharge and drainage density was developed (Hughes 2004). The model for the entire basin upstream of the Delta was updated in 2006 (Hughes et. al. 2006) and comprised of 24 distinct sub-basins. Calibration of the model was complicated by the limited availability of measured stream flow and rainfall records. Long stream flow records (starting in the 1940s) are available along the lower reaches of the Kavango and Okavango at Rundu, Mukwe and Mohembo, but stream flow records in Angola are only of the order of 10 years long, covering the early 1960s to mid 1970s. Measured rainfall records in Angola are only available until 1972. These sequences were extended with satellite rainfall by Wilk et al. (2006) to September 2003, which means that the calibrated model could be used to generate stream flow sequences for the period spanning hydrological years 1958-2002. Earlier versions of the model over-predicted low flows and under-predicted wet season peak flows at Rundu and Mukwe. The latest version which was completed in 2006 shows much better predictions of low flows. The under-prediction of peak flows (of up to 20%) is still present, as can be seen from comparisons of observed and simulated flows at Rundu (Figure 3-2 and Figure 3-3).

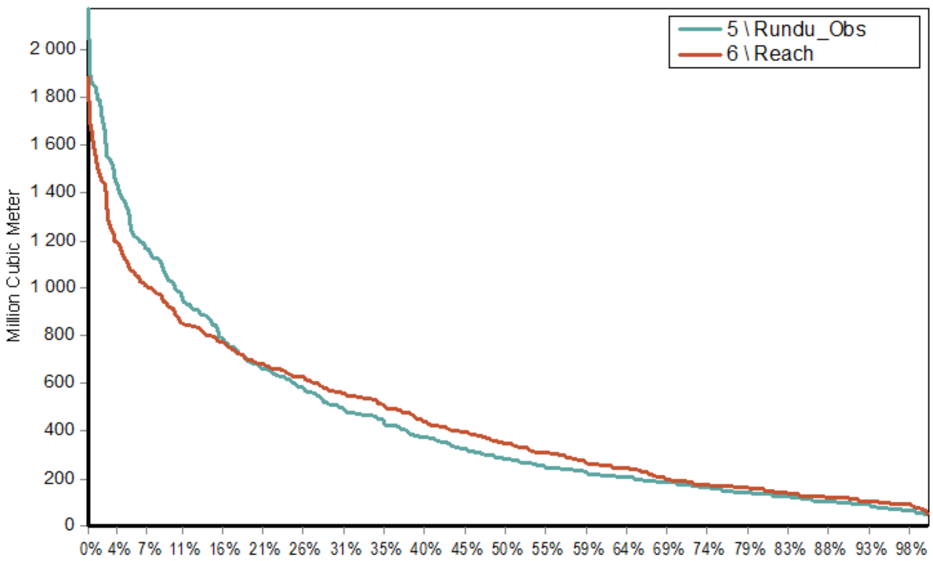


Figure 3-2 : Comparison of observed (blue) and simulated (brown) monthly duration curves at Rundu

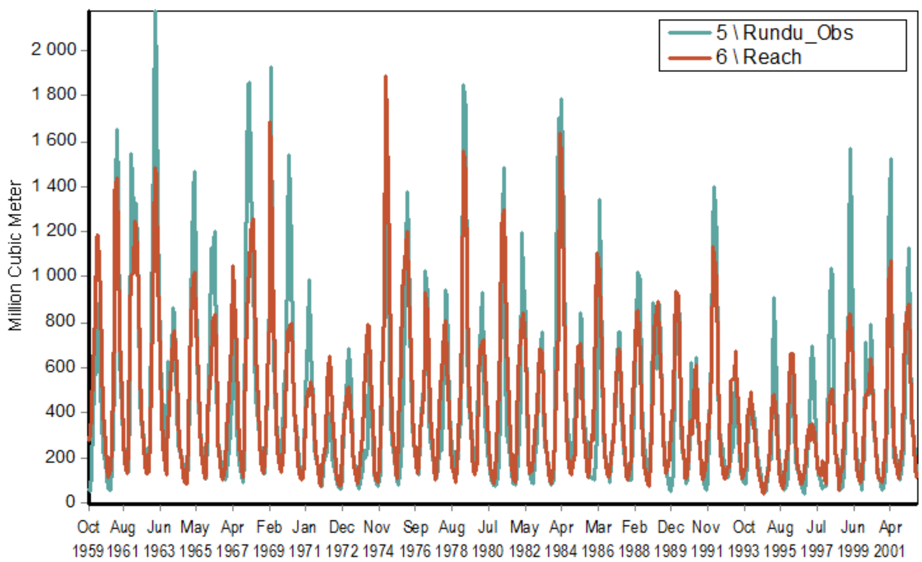


Figure 3-3 : Comparison of observed (blue) and simulated (brown) monthly time series at Rundu

Presently, the Pitman catchment model is the only distributed hydrological model of the basin. While it has improved the understanding of the upstream hydrology, the breakdown of the Angolan gauging stations from the 1970's onwards have put limitations to the validation of the model and the hydrology is still associated with uncertainties. For traditional water resource assessments the errors in peak flow simulation are not considered to be serious, as it does not significantly affect estimates of run-of-river or storage based yields. Of more concern is the fact that the simulation period excludes the recent large flood events of 2009 and 2010, preceded by a devastating drought in 2007. The floods in the Kavango River (and the Zambezi) were the highest on record since 1969[1]. (A discussion of flooding and drought issues is provided in EPSMO/Biokavango Report Number 6; *Scenario Hydrology Report.)* In the EFA study it was found that the under-estimation of flood peaks does pose problems, in that the ecologists attach much greater importance to

[1] G Van Langehove, pers. comm.

the magnitude of flood peaks and found it difficult to relate simulated peak flows to their knowledge of observed floods and associated ecosystem responses.

A recommendation of this study is that the rainfall-runoff model be re-calibrated with a view to improve peak flow simulation. As part of the same exercise, the model should be extended to cover the hydrological years from 2003 to as recently as possible. The re-calibration should make use of the stream flow records that are becoming available from rehabilitated flow measuring stations in Angola. .

3.2.2 Generation of Scenario Flow Sequences

To simulate the effects of future water resource developments on flow sequences at the EF sites, a hydrological systems model was required. The modified Pitman model developed by Hughes et. al. is included in the SPATSIM hydrological modelling system (http://www.ru.ac.za/static/institutes/iwr/software/spatsim.php). The system was used to model the effects of scenario water resource developments on flow regimes in the Okavango as part of the WERRD project. For the EFA Study, the hydrological working group opted to make use of the WEAP modelling system, as it incorporates a simple but powerful scenario creation tool, is capable of simulating run-of-river and storage based hydropower schemes and is especially well suited for the training of hydrologists in systems analysis and scenario planning techniques. The naturalised (undeveloped) runoff sequences of the 24 sub-catchments upstream of the Delta were exported from SPATSIM and used as inflow time series in the WEAP model. Present day (reference) and future water resource developments (irrigation scheme and urban abstractions, in channel dams for irrigation water supply, inter-basin transfers, run-of-river and storage based hydropower schemes) were then configured in the WEAP model for use in the scenario simulations. Flows simulated at Mukwe for the reference scenario were compared with the measured flow record at the Mukwe station to verify that the WEAP model reproduces the original SPATSIM simulation faithfully, and to confirm that the simulation of measured flows is reasonable. The comparison is shown in Figure 3-4.

In order to reflect the current water abstraction practices in the basin, the WEAP model was configured with equal priorities of water supply assigned to all water abstractions. This implies that water supplies to upstream water users are not constrained by downstream demands (such as environmental and cross-border flow requirements). The same approach was followed for the configuration of future water use scenarios, as the intention of the scenario modelling was to illustrate the full impact of increasing upstream water use on downstream water users.

The WEAP model was configured with static development states, i.e. water demands and infrastructure associated with a particular water use scenario were superimposed on the full simulation period. It is possible to model dynamic basin development with growing demands and timed implantation of water resources developments, but for scenario based planning, this introduces unnecessary complexities regarding the coincidence of water resource developments with hydrological events.

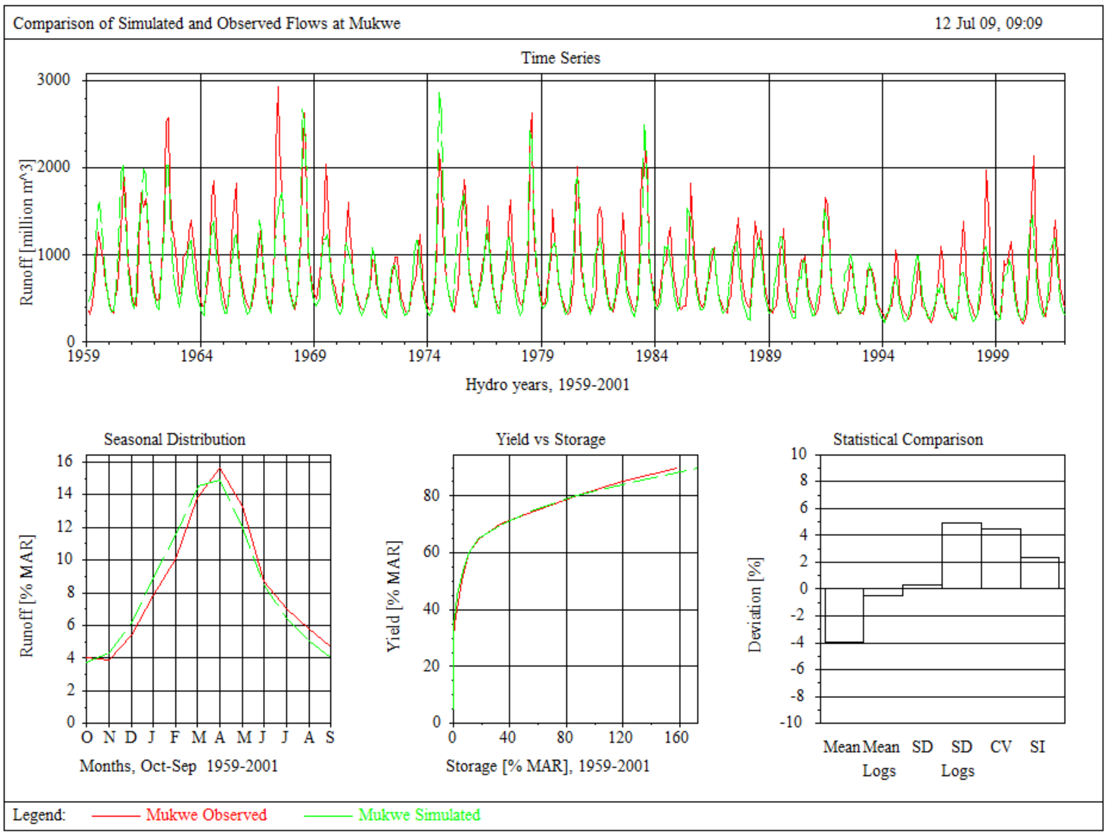


Figure 3-4 : Comparison of WEAP Simulation with Observed Flows at Mukwe

EFA Sites 3 (Cuito Cuanavale) and 4 (Kapako) are situated in river reaches with extensive floodplains. To get an indication of the degree to which the floodplains are inundated under different flow conditions, peak flow - inundated area relationships were developed for the two sites. A first attempt was made by delineating inundated areas from satellite images and correlating these with measured flows at nearby stations. The USGS Glovis Landsat / Modis archive was searched to find images that show a range of inundations for the Kapako and Cuito Cuanavale sites that could be correlated to available streamflow records at Rundu and Cuito Cuanavale, respectively. For Cuito Cuanavale, no images dated before closure of the station were available. For Kapako, there were not enough images showing recognizably different levels of inundation. It was then decided to configure one-dimensional, steady-state hydraulic models for each of the two sites with the US Army Corps of Engineer's freely available HEC-RAS and HEC-GeoRAS modelling systems (http://www.hec.usace.army.mil/software/hec-ras/hec-georas.html). Cross-sections were extracted from the 90m NASA SRTM digital elevation model and improved with main channel cross-sections surveyed during field visits (Section 4). An example of the modelled inundated area associated with a steady flow of 1000 m^3/s at the Kapako site is shown in Figure 3-5.

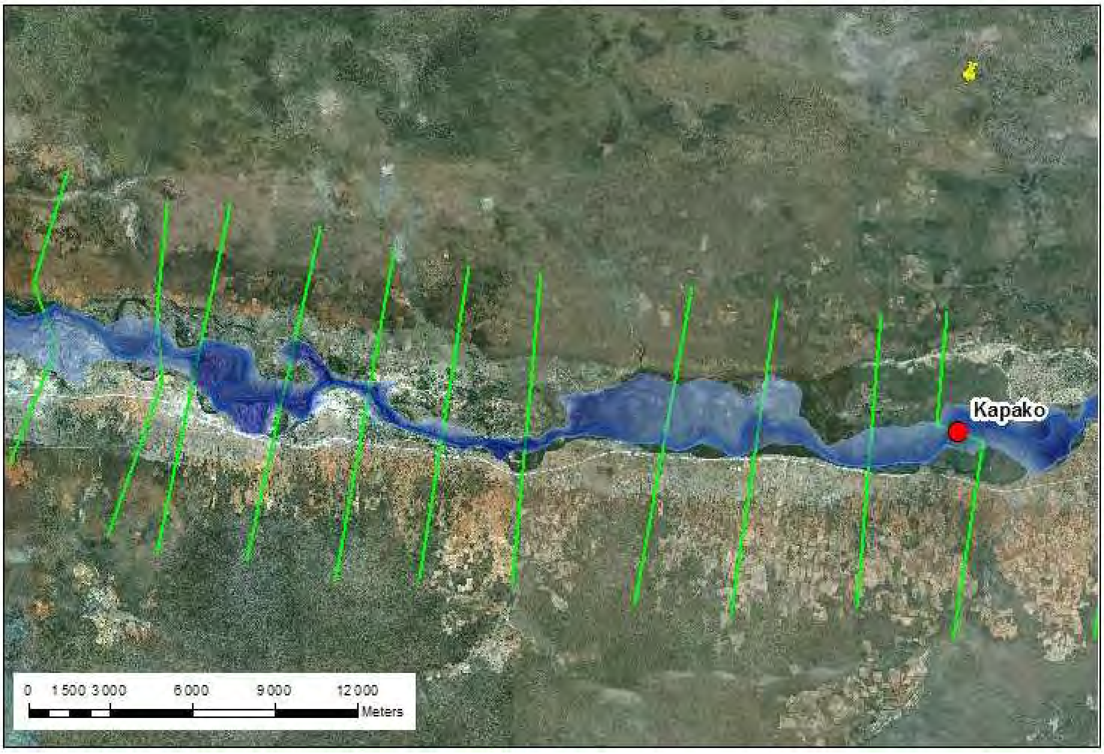


Figure 3-5 : Inundation at the Kapako Site (1000 m^3/s)

3.3 Delta Hydrology

3.3.1 Botswana Department of Water Affairs and Forestry MIKE SHE Model

In March 2004 the development of an Integrated Hydrologic Model (IHM) for the Okavango Delta was initiated under the Okavango Delta Management (ODMP) project, and it was completed in March 2005. The model was transferred to the Department of Water Affairs for use and analysis of scenarios to support the ODMP (IHM Report, 2005). The model was used in this study to estimate the sharing and partitioning of flows amongst the three major river systems of the Delta.

The model was developed using the DHI Water and Environment, MIKE SHE-MIKE 11, 2005 modelling system and was run up to 2004. The model integrates the following four components:

- Soil-vegetation-atmosphere transfer module, describing, in space and time, the loss of water from open water, swamp and terrestrial vegetation to the atmosphere
- MIKE 11 surface water module describing water levels and flows through the main river channels of the delta
- The distributed overland flow module (MIKE SHE) to simulate the two dimensional flow pattern through the swamps and flood plains, with a full automatic coupling with MIKE 11
- MIKE SHE ground water module, based on a three dimensional representation of saturated and unsaturated zones

The calibration of the model against measured flows in the Thamalakane River is not as good as the calibration of the HOORC model at the same point. As simulated outflows into the Thamalakane / Boteti system were required for assessment of impacts at Site 8 (Chanoga), and the fact that the HOORC model is capable of simulating the effect of inundation frequencies and extents on vegetation assemblages, lead to a decision to use the HOORC model for simulation of inundation frequencies and extents and for outflows into the Thamalakane / Boteti system. However, the HOORC model does not simulate flow dynamics in the Delta distributaries whereas the MIKE-SHE model does. As the performance of the MIKE-SHE model in the upper parts of the Delta is acceptable, it could be used to develop flow-depth-velocity relationships at Site 6 (Panhandle at Shakawe) and Site 7 (Delta at Xakanaka) for use in the EF assessments. The relationships are shown in Figures 3-6 to 3-9.

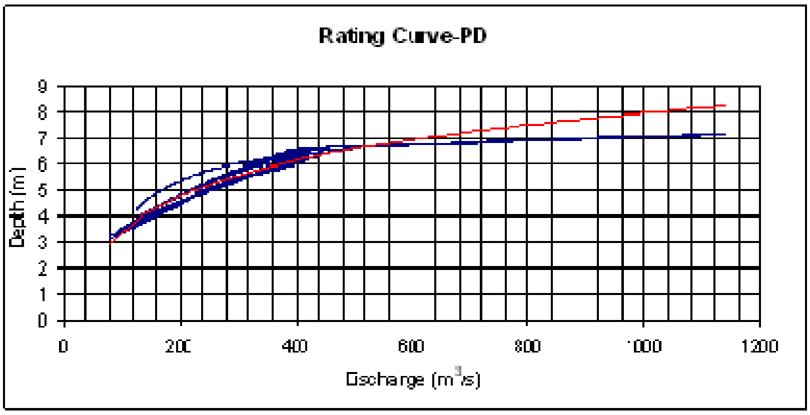


Figure 3-6 : Discharge - Depth Relationship - Shakawe

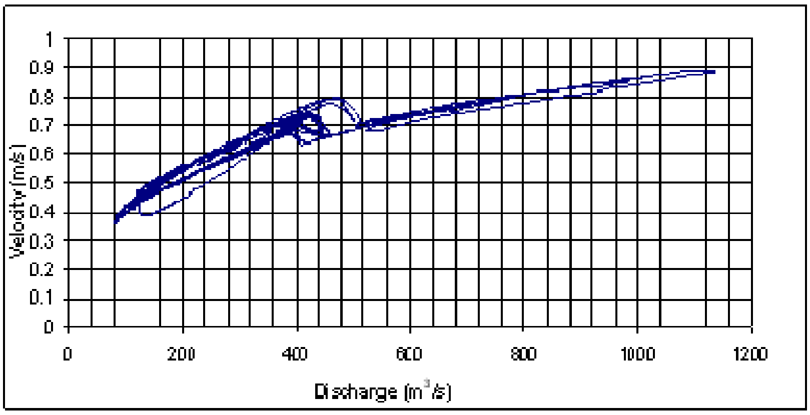


Figure 3-7 : Discharge - Velocity Relationship – Shakawe

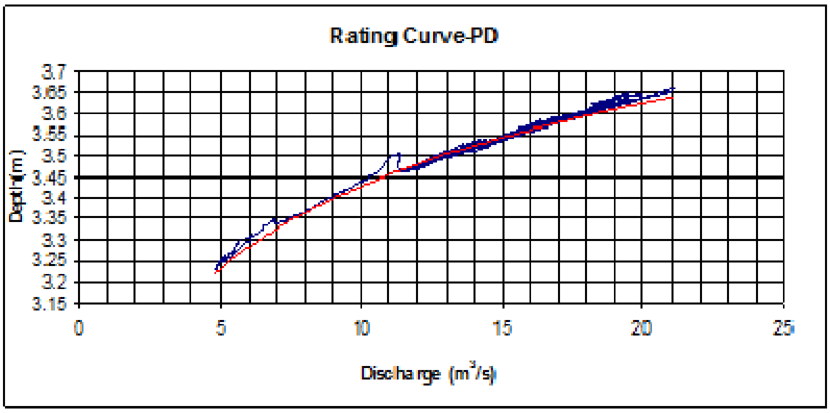


Figure 3-8 : Discharge - Depth Relationship – Xakanaka

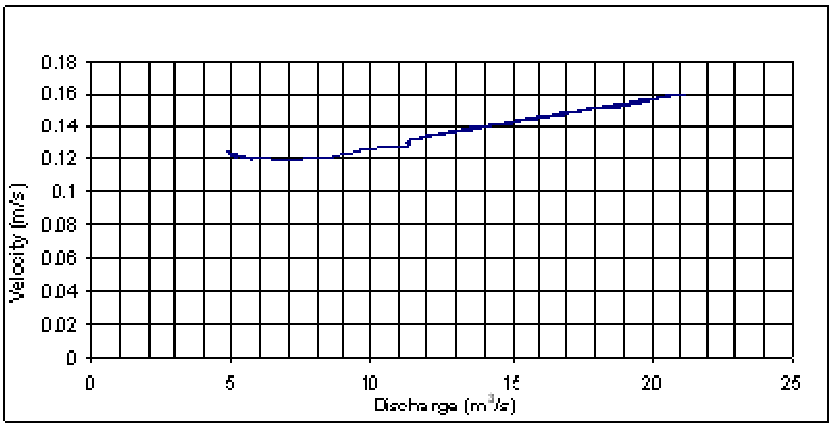


Figure 3-9 : Discharge - Velocity Relationship – Xakanaka

3.3.2 HOORC Conceptual Model of the Delta

A semi-conceptual model which was previously developed by the Harry Oppenheimer Okavango Research Centre (HOORC) (Wolski et. al. 2006) was used to model inundation frequencies and extents at the Delta EF sites.

It is composed of two sub-models. The reservoir sub-model simulates flow of water through the Delta as flow through an array of nine quasi-non-linear reservoirs, each representing a large subdivision of the modelled system. It incorporates a rather complex representation of surface water-groundwater interactions, where floodplains and dryland/island groundwater are simulated separately. The reservoir sub-model maintains closure of surface water and groundwater balances in the system by accounting for all hydrological inputs (inflow, rainfall) and outputs (evaporation and surface water outflows) and internal fluxes (infiltration and groundwater flow). It uses local rainfall and temperatures, and flow at Mohembo as input, and provides water storage, inundated area and outflows through main terminal rivers as output. It runs on a monthly basis, and has been calibrated using observed data for the period of 1968-2002, with calibration targeting agreement between simulated and observed inundated areas in the nine Delta units and outflows through terminal rivers. Second sub-model is a GIS-based model of inundation distribution. In this sub-model the lumped inundated area obtained on a monthly basis from the hydrological sub-model is represented as a map of inundation of 1*1 km resolution. The GIS sub-model is based on the assumption that floods of similar sizes are similarly distributed. In this sub-model, each 1*1 km pixel is characterized by a function describing the probability that it is inundated while inundation area is of a given size. The function was derived based on analysis of inundation maps obtained from NOAA AVHRR images. Monthly inundation maps obtained from this model are further analysed to obtain pixel-scale indices such as inundation duration for each of modeled years and long term frequency of inundation etc.

The dynamic ecotope model was developed in order to classify hydrological conditions obtained from the hydrological/GIS models for the Okavango Delta in terms of hydro-ecological functionality. The model is based on assumption that vegetation assemblages observed at any given site change in response to varying hydrological conditions, which is meant to capture the inherent hydrological and ecological variability in the Okavango Delta. In the original version of the model, hydrological conditions are represented by duration of inundation, while vegetation is captured using four functional classes: aquatics, sedges, grasses and savanna (or permanent swamp vegetation, primary floodplains, secondary floodplains and dry floodplains). The model has a nature of a rule-based expert system, and in its version used in this study, rules were based on experience of authors rather than on rigorous scientific analysis, as the available datasets do no as yet support the latter. The area of additional classes used in the EFA, i.e. channels, lagoons and floodplain pools, was determined as a percentage of the main hydro-ecological classes, based on the analysis of satellite images.

3.3.3 Boteti Hydrology

Flows along the Thamalakane-Boteti River are derived from outflows from the delta, and any rain falling onto the water surface within the channel. There are no tributaries contributing any significant flows along the Thamalakane-Boteti River. The dominant hydrological processes along this river are storage and transmission of outflows from the delta, groundwater recharge, evapo-transpiration, and channel precipitation. A linear reservoir model was selected for modelling flow of water along this river on a monthly time interval. The river was divided into the following sections for modelling purposes:

- from Maun Bridge on Thamalakane River to Samedupi on the Boteti River,
- from Samedupi to Rakops on the Boteti River.

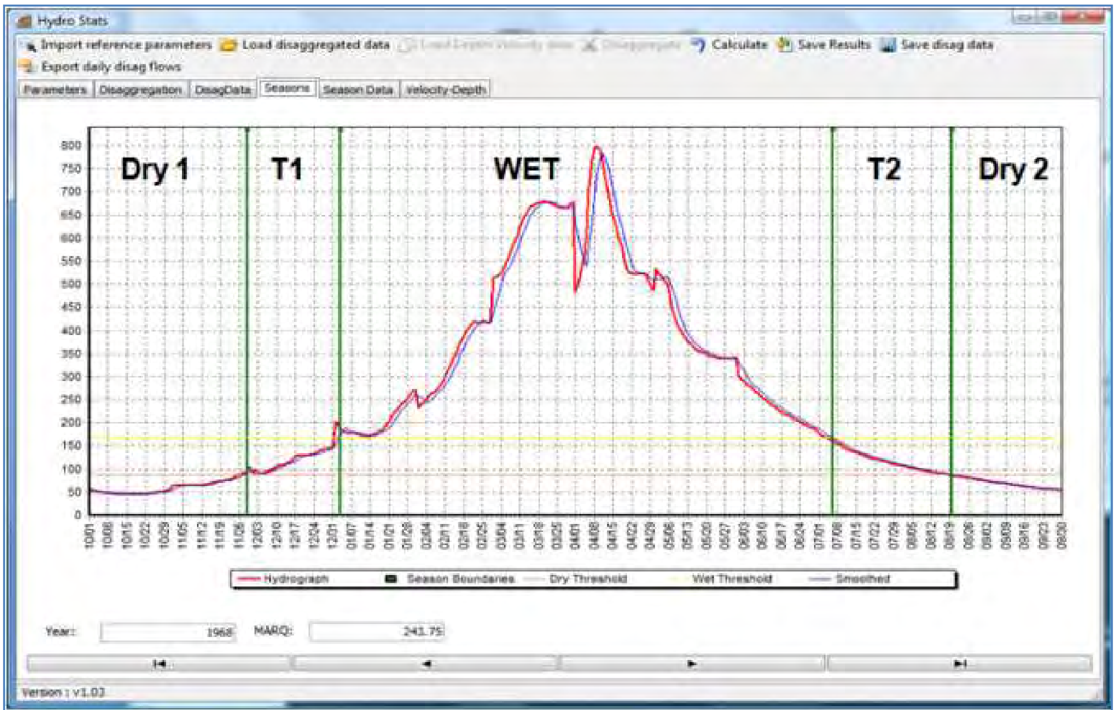
The storage in, and outflow of water from each of these reservoirs was estimated by means of a monthly reservoir balance. The starting and ending points of these reservoirs were selected in order to coincide with the locations of flow gauging stations with data used for model calibration. The contribution of rain falling directly onto the channel was estimated using rainfall measured at Maun and the surface area of each reservoir estimated from the surface area – storage volume relationship derived from a survey (Kraatz, 1976). Evaporation from the reservoirs was estimated from mean monthly evaporation rates measured at Maun. Outflow from each reservoir was a function of the storage volume above a minimum threshold volume. Recharge to groundwater was modelled as a loss which is a function of the volume of water stored in each reservoir.

For the purpose of determination of wetted length of the Boteti river a model has been developed based on the reservoir model of the Okavango Delta. The model strives to account to represent the strong hysteresis in volume-flow relationship observed at hydrometric stations along the Boteti. This hysteresis is conceptually related to the influence of surface water-groundwater interactions on flows in the Boteti, similar to that observed in the floodplains of the Okavango Delta (Ramberg et al. 2006). The model represents the Boteti River between Maun and Mopipi as a single quasi-linear reservoir characterized by a certain volume-area relationship. To capture the interactions between surface water and groundwater, a series of 5 independent groundwater reservoirs each representing groundwater at a reach of the river are used. Each of these is composed of a reservoir representing groundwater storage directly under the river channel, and another one, linked to the first, representing groundwater storage within the riparian/riverine woodland zone. The groundwater reservoirs are recharged from the surface water reservoir, and the recharge occurs only to these reservoirs which represent currently inundated reach of the river. The model works under assumption that the surface water-groundwater flows are one-directional, i.e. there is only infiltration from surface water to channel groundwater reservoir, and that there is only flow from channel groundwater to riverine groundwater. The latter is ultimately removed by riverine woodland evapotranspiration. The model has been calibrated based on the wetted lengths observed between 2000 and 2009, which were derived from field visits and satellite images.

3.3.4 Disaggregation and Hydro-Statistics

A custom utility was developed to disaggregate the simulated monthly WEAP flow sequences to daily flow sequences, to delineate flow seasons (dry, wet and transition) for each year of the 43 year long sequences, and to calculate ecologically relevant flow statistics (“flow categories”). Disaggregation of simulated monthly volumes was done by distributing these monthly volumes according to the relative magnitude of daily flows measured at a nearby station during the corresponding month in the measured flow record. In periods for which no measured flows are available, a proxy month in the measured flow record was selected by finding a month with a measured volume that has a similar exceedence probability as the simulated volume. The disaggregated daily flow sequences were then used to delineate the dry season, a transition season leading into the wet season, a wet season, and a second transition season leading into the next year’s dry season.

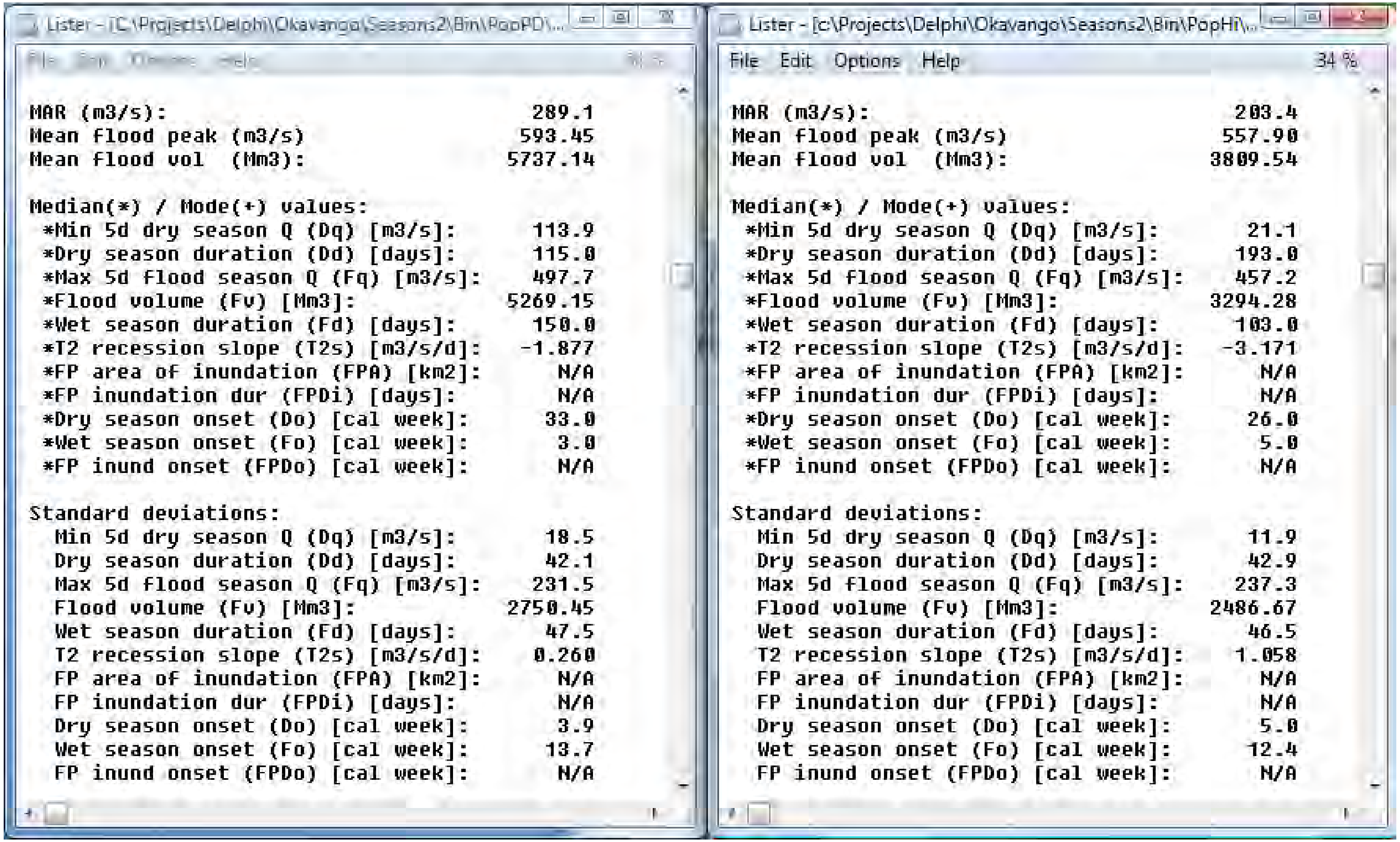
A set of rules were developed to identify the starting dates of the seasons. Rules that were developed for a similar study on the Mekong River were used as a departure point and modified to suit the highly variable (“peaky”) flow regimes that are associated with the Okavango tributaries. The rules were applied to the disaggregated daily flow sequences to calculate flow categories for each year in the record, and for the entire flow sequence. An example of season delineation, and the rules that these are based on, are shown in Figure 3-10. The figure shows a simulated daily flow sequence (red) which was derived by disaggregating a simulated monthly sequence with the daily distribution of a measured flow record. The second line (blue) shows a 5 day moving average of the red line. The moving average sequence was used to calculate flow indicators (5-day minimum dry season flow, 5-day wet season peak flow, etc.). An example of the calculated flow categories is shown in Figure 3-11. A detailed description of the ecological relevance and selection of the flow categories is given in EPSMO/Biokavango Report Number 2; *Process Report*.



All flows averaged over 5 days

End of Dry Season:	Perennial : 2 to 6 x minimum dry-season Q (site specific)
	Ephemeral : 0.4 x mean annual Q
End of Transition 1:	first up-crossing of mean annual Q
End of Flood Season:	last down-crossing of mean annual Q
End of Transition 2:	recession rate over 15 d < 1.0 to 1.2 $m^3/s/d$ (site specific)
	OR down-crossing of Dry / T1 threshold

Figure 3-10 : Season Delineation



	Present Day	High Development
MAR (m3/s):	289.1	203.4
Mean flood peak (m3/s)	593.45	557.90
Mean flood vol (Mm3):	5737.14	3809.54
Median(*) / Mode(+) values:		
*Min 5d dry season Q (Dq) [m3/s]:	113.9	21.1
*Dry season duration (Dd) [days]:	115.0	193.0
*Max 5d flood season Q (Fq) [m3/s]:	497.7	457.2
*Flood volume (Fv) [Mm3]:	5269.15	3294.28
*Wet season duration (Fd) [days]:	150.0	103.0
*T2 recession slope (T2s) [m3/s/d]:	-1.877	-3.171
*FP area of inundation (FPA) [km2]:	N/A	N/A
*FP inundation dur (FPDi) [days]:	N/A	N/A
*Dry season onset (Do) [cal week]:	33.0	26.0
*Wet season onset (Fo) [cal week]:	3.0	5.0
*FP inund onset (FPDo) [cal week]:	N/A	N/A
Standard deviations:		
Min 5d dry season Q (Dq) [m3/s]:	18.5	11.9
Dry season duration (Dd) [days]:	42.1	42.9
Max 5d flood season Q (Fq) [m3/s]:	231.5	237.3
Flood volume (Fv) [Mm3]:	2750.45	2486.67
Wet season duration (Fd) [days]:	47.5	46.5
T2 recession slope (T2s) [m3/s/d]:	0.260	1.058
FP area of inundation (FPA) [km2]:	N/A	N/A
FP inundation dur (FPDi) [days]:	N/A	N/A
Dry season onset (Do) [cal week]:	3.9	5.0
Wet season onset (Fo) [cal week]:	13.7	12.4
FP inund onset (FPDo) [cal week]:	N/A	N/A

Figure 3-11 : Example of Flow Categories - Delta Inflows (Left: Present Day, Right: High Development)

OKACOM

4 Field Data Collection

4.1 Angola

4.1.1 Introduction

The main purpose of the team was to collect relevant data on the Angola portion of the Okavango River Basin (ORB) for the WEAP model. Due to civil war faced by Angola for about 30 years most of accurate data were produced until the end of 1980's. In terms of hydrologic information, due to the obsolescence of data and lack of new data, the team had to resort to the existing historic data. The main data on irrigation potential were collected from the field, through the provincial Director of Agriculture in Kuando Kubango and through the visits made by the National Project Coordinator of EPSMO, to the Okavango River Basin. The National Directorate of Agrarian Hydraulics and Rural Engineering, under the central Ministry of Agriculture provided data on irrigation schemes. It also worth to mention that some relevant data on the Angolan portion of the ORB was provided by the Office of the Vice Minister for Planning.

DNA, *Direcção Nacional de Águas*, provided relevant historic data on Hydrology. Within DNA, the hydrological data were collected from Database (HYDATA) and from existing Yearbooks within DNA.

The data collected from DNA comprised:

- Average daily flows for several old hydrometric stations;
- Monthly flows for several old hydrometric stations;
- Annual flows for several old hydrometric stations;
- Rating curves (for the EFA sites).

The rainfall data were collected from old records of INAMET, the National Institute for Meteorology and Geophysics and from the book "*Caracterização Sumária das Condições Ambientais de Angola*", dated of 1973.
Here is important to mention that INAMET data have too many gaps and the last data were recorded in 2004.

The dispersion of data among various institutions was one of the main constraints.

4.1.2 Site 1: Cuebe River at Capico

Capico site is located in the southern part of Menongue municipality. It falls within the IUA no. 3. Capico is 110 kilometers south of Menongue, the capital city of Kuando Kubango province, driving to the Nambian border. Its geographic coordinates are: latitude - 15°33´ South; longitude - 17°34´ East. The altitude of the zone varies from 1160 to 1250 meters. Most of the people living in Capico belong to the ethnic group Ngangela. There is a small group of resident, which belong to the ethnic group Cocwe (original from Moxico province), who during the civil war displaced from its place of origin and fixed residence in Capico. The existing closed nearby settlements to site are: Massosse and Bitângua on the North and Caïndo on the South.

Cuébe River, one of the tributaries of Cubango (Okavango) River, is the only source of water in the area.

From the lithological point of view the detritic formation, also known as Kalahari formation dominates in the area.

The existing hydrometric station was rehabilitated in December 2005. Nearby the hydrometric station, specifically in zones where the erosion is considerable, were identified ferruginous concrections, typical of lateritic soils.

Observations carried out during the dry season (May – September), indicate that the bottom of Cuebe River is 2,0 meters deep in relation to the surface level of its banks. The natural channel of the river is “U”-shaped. This kind of shape is not observable during the rain season during the peak of the floods, which normally occurs in March of each year.

The main livelihoods of local people are rainfed agriculture (during the rain season from October to April), fishery using the Cuébe River, wild fruits picking and hunting. Handcrafting is also practiced by local people.

Figure 4-1 : Capico hydrometric station, on the Cuebe River, flooded in mid-March 2009

4.1.3 Site 2: Cubango River at Mucundi

Mucundi site is located in the southern part of Menongue municipality, just downstream the settlement of Caïndo. It falls under the IUA no. 2. Mucundi is 192 kilometers south of Menongue, the capital city of Kuando Kubango province, driving to the Namibian border. Its geographic coordinates are: latitude - 16°13´ South; longitude - 17°41´ East. The altitude of the zone varies from 1120 to 1250 meters. People living in Mucundi belong to the ethnic group Ngangela. The existing closed nearby settlements to site are: Chimbueta on the North and Kendelela on the South. The Cubango (Okavango) River, after receiving contributions from Cutato, Cuchi, Cuélei and Cuébe Rivers, is the main source of water in the zone.

The area is dominated by the Kalahari formation, although old granitic formation (Pre-Cambrian), also do exist.

Figure 4-2 : Barrier-Islands on the Cubango River at Mucundi (March, 2009)

In some places it can be observed rapids of small magnitude, originated by the presence of granite in the bottom of the river. On the left bank of the river, the morphology provokes the appearance of a considerable floodplain..

The hydrometric station at Mucundi will be rehabilitated during the second semester of 2009. Approximately 500 meters upstream the hydrometric station, small islands configure the natural channel of the river. In some cases these islands play a role of natural barriers on the sedimentary dynamics of the environment.

The main livelihoods of local people are rainfed agriculture (during the rain season from October to April), fishery using the Cubango (Okavango) River and livestock production. Beekeeping is also practised in the area, but at a small extent.

4.1.4 Site 3: Cuito River at Cuito Cuanavale

Cuito Cuanavale site is located in the eastern side of Kuando Kubango. It falls within the IUA no. 6. The site is located in the municipality of same name. Cuito Cuanavale is 189 kilometers from Menongue, the capital city of Kuando Kubango province, moving easternwards in the direction to Mavinga municipality. Its geographic coordinates are: latitude - 15°10´ South; longitude - 19°12´ East. People living in Cuito Cuanavale belong to the ethnic group Ngangela. The existing closed nearby settlements to the site are: Sacalumbo on the North-West, Chissamba on the North-East, Bocota on the South, Caripa on the South-West and Samungure on the East. The site is located 3 kilometers downstream the junction between rivers Cuito and Cuanavale. The altitude of the zone varies from 1180 to 1250 meters.

The Kalahari sands are the dominant geological formation in the area. There is a geological fault which occurs on the direction NW-SE, which coincides with the main natural channel, the Cuito River. There is also in the area a considerable floodplain crossed by the Cuito River.

Figure 4-3 : Cuito River at Cuito Cuanavale (March, 2009)

The main livelihoods of local are rainfed agriculture (during the rain season from October to April), fishery using the Cuito and Cuanavale Rivers, wild fruit picking and hunting.

4.2 Namibia

4.2.1 Site 4: Okavango River at Kapako

Kapako (GPS: 17° 51' 50.81" S; 19° 34' 47.74" E) is located 20 km west of Rundu where water levels are recorded continuously. The Kapako area is characterised as a well defined river channel with extensive flood plains surrounding the site. To the north of the river is a pool of water that is presently disconnected from the main river.

No water level monitoring equipment is available at the Kapako site. The processed flow record at Rundu was used to disaggregate simulated monthly volumes at Kapako.

Kapako Dry season visit:
The Kapako site was identified from maps as a potential site for this study and was subsequently visited during the period 18 - 24 October 2008. Water was only confined to the river channel and a cross section was run for the wetted area of which the results are presented in **Error! Reference source not found.**. The water level recorded at Rundu on the same day was 3.54 m, equating to a flow rate of about 30 m^3/s.

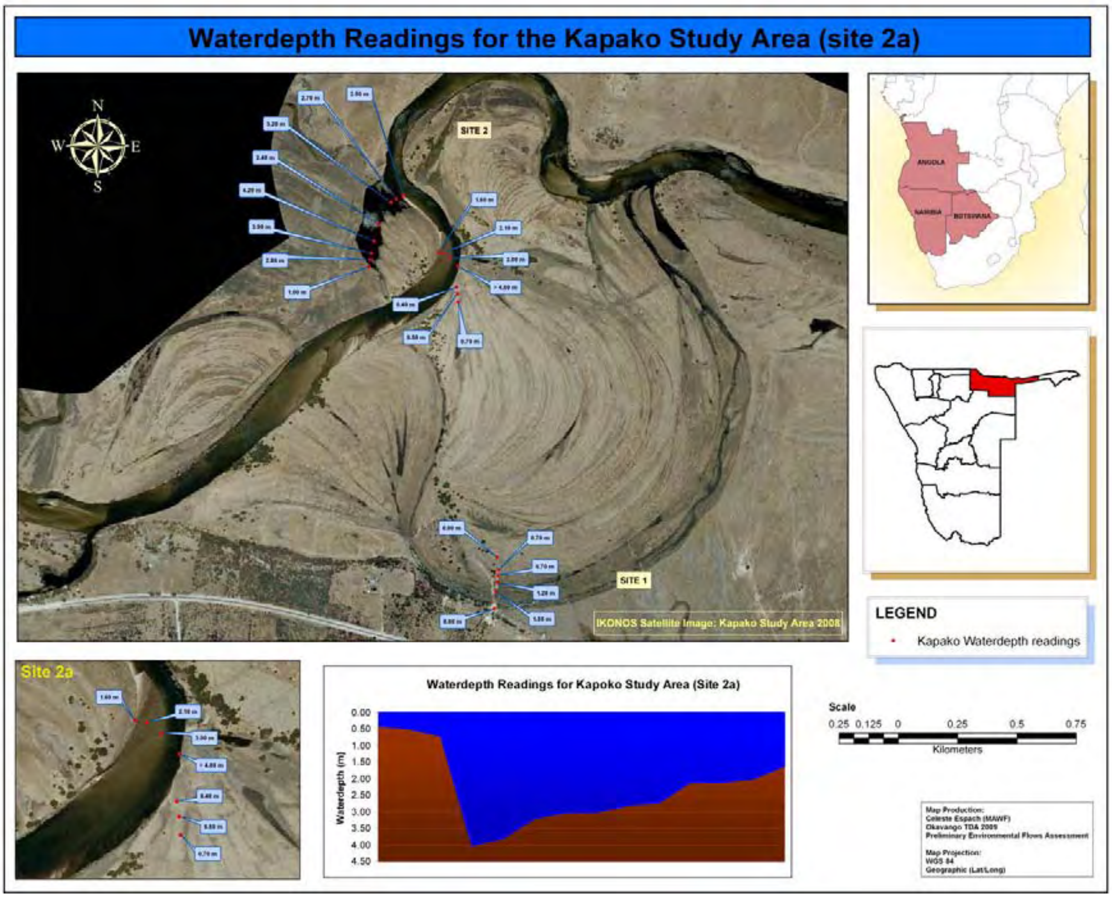


Figure 4-4 : Water depth readings of Kapako during the dry season

Kapako Wet season visit:
The Kapako site was visited during the period 7 - 12 February 2009. The water level recorded at Rundu during this time was 5.26 m, equating to a flow rate of approximately 235 m^3/s. A cross section was run for the same wetted area as during October 2008 and an attempt was made to obtain some depth readings of the flood plain. This proved to be difficult as the area was inundated and due to vegetation was not accessible by boat. Some water depths in the flood plain were logged along the edges of the right river bank and the left flood bank. The collected data is presented in Figure 4-5.

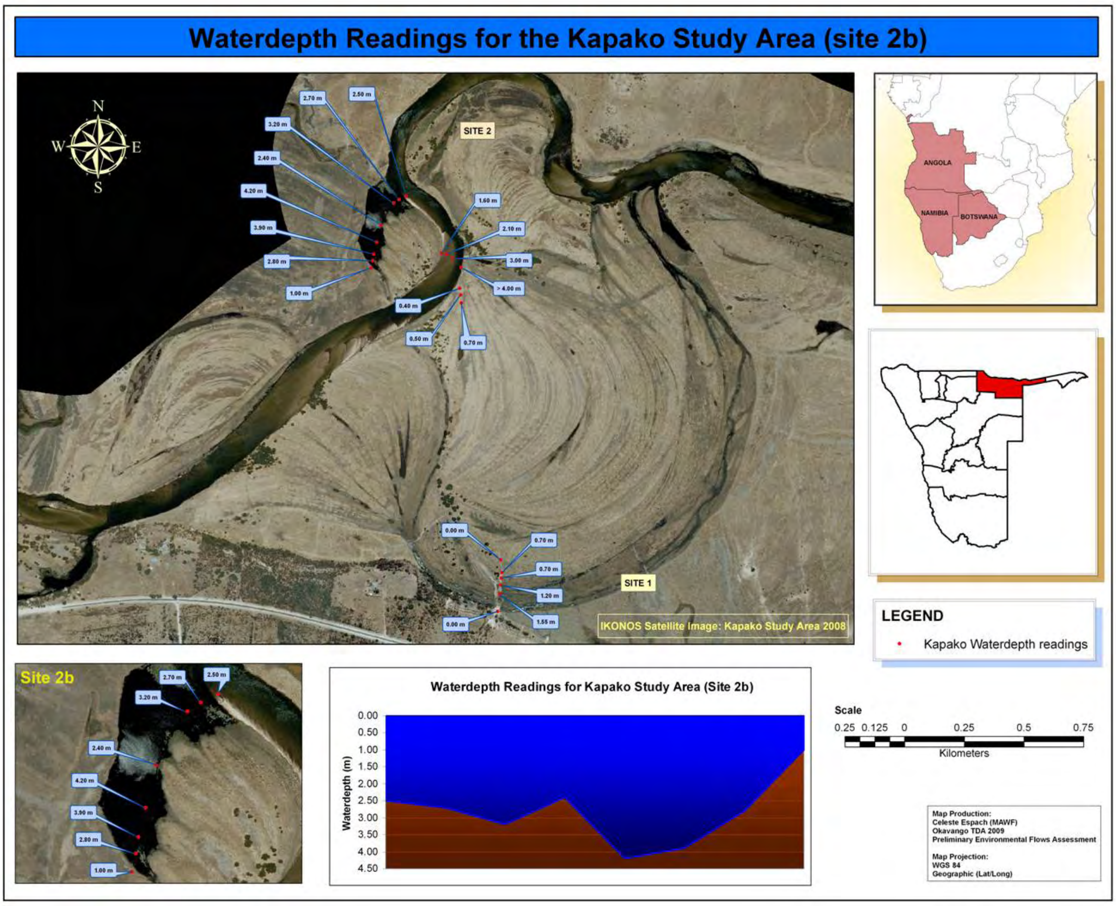


Figure 4-5 : Water depth readings of Kapako during the wet season

For future monitoring it would be required that a correlation between flows in the Kapako flood plain and at Rundu be established. Ideally, a gauge plate along with a water level recording station with a pressure probe should be installed on the flood plain.

4.2.2 Site 5: Okavango River at Popa Falls

Popa Falls (GPS: 18° 06' 58.24" S; 21° 34' 56.06" E) is located 5 km downstream of the Bagani Bridge. The Department of Water Affairs and Forestry of Namibia used to operate a cable way river gauging site just downstream of the Bagani Bridge, however this site has been abandoned. As there is no hydrological data for the Popa site, runoff data from the nearby Mukwe station were used for to estimate flows at Popa Falls.

The area is characterised with a well defined river channel with stable embankments with the main feature being the falls. Refer to Figure 4-6 and

Figure 4-7 for photos of the site. As no water level monitoring equipment was available at the Popa Falls site, it was opted to install a gauge plate at the irrigation pump station..

Figure 4-6 : Aerial view of the Popa Falls site

Figure 4-7 : Left bank of the Popa Falls site

Popa Falls Dry season visit:
The Popa Falls site was visited during the period 18-24 October 2008. Water was confined to the main river channel and a cross section was run for the wetted area. Results are presented in Error! Reference source not found. and Error! Reference source not found.. Approximately 23 km upstream of the Popa Fall site the Department of Water Affairs and Forestry of Namibia records water levels at Mukwe (GPS; 18° 02' 09.19" S; 21° 25' 39.37" E). The water level recorded at Mukwe during this time was 2.49 m which equates to a flow rate of approximately 120 m^3/s. The results are presented in Figure 4-8 and Figure 4-9**.**

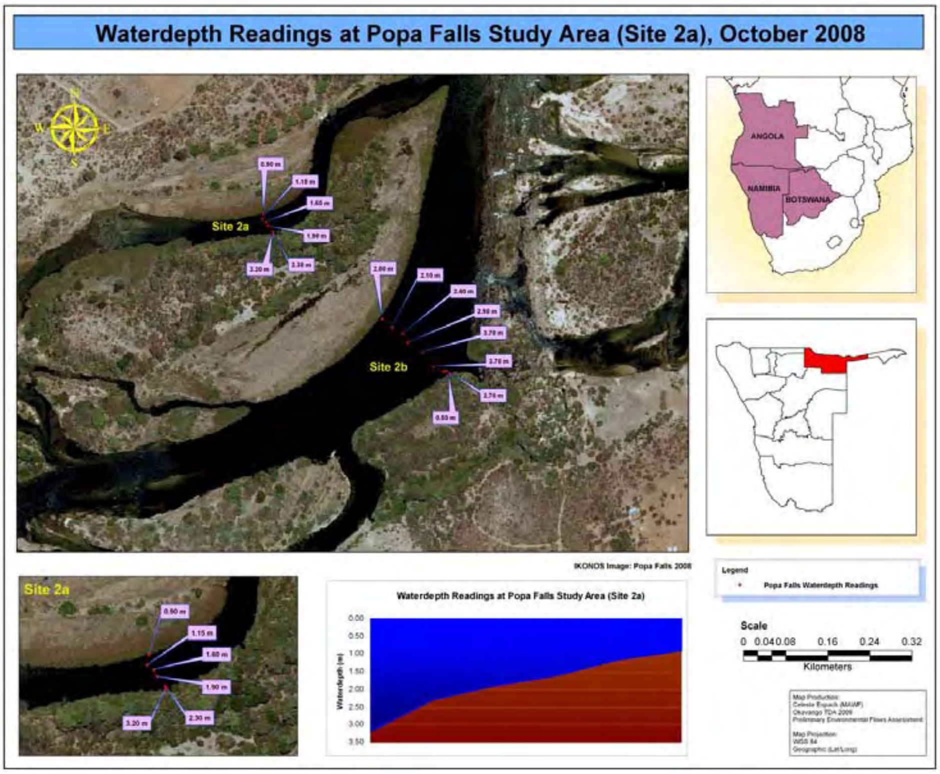


Figure 4-8 : Aerial view and cross section presentation of Popa Falls left channel (dry season)

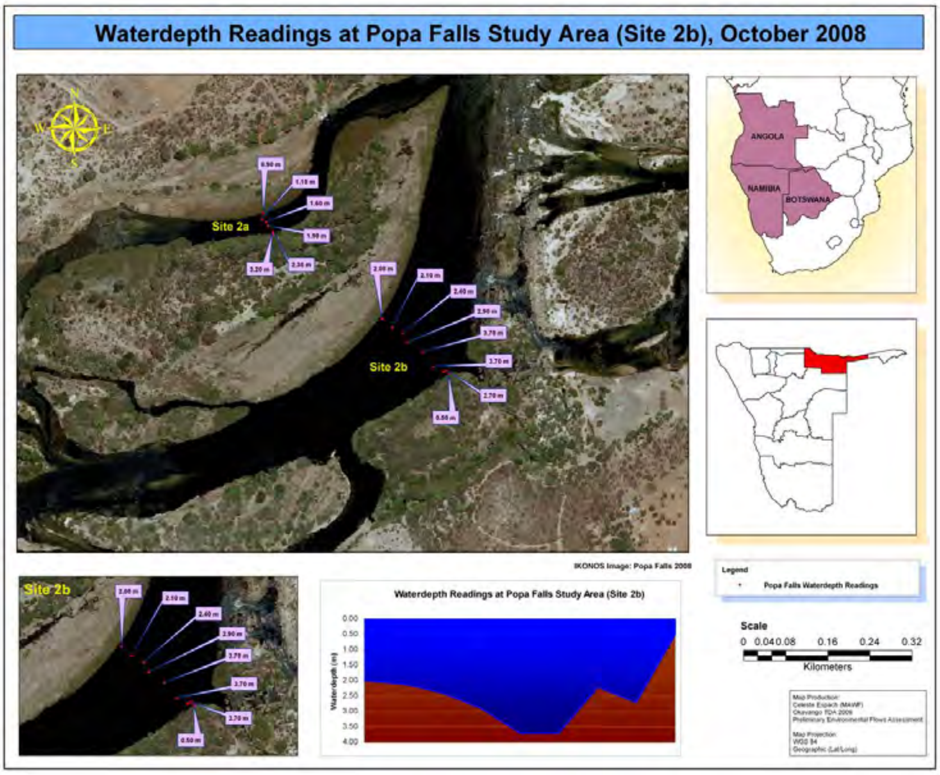


Figure 4-9 : Aerial view and cross section presentation of Popa Falls right channel (dry season)

Popa Falls Wet season visit:

The Popa Falls site was visited during the period 7-12 February 2009. During this visit a gauge plate was installed at the irrigation abstraction point. The water level recorded during this time at Mukwe was 3.25 m which equates to a flow rate of approximately 395 m³/s. A cross section in the right channel was run for the same wetted area as during October 2008 and a second cross section was run at the position of the gauge plate next to the left channel. The results are presented in Figure 4-10 and Figure 4-11.

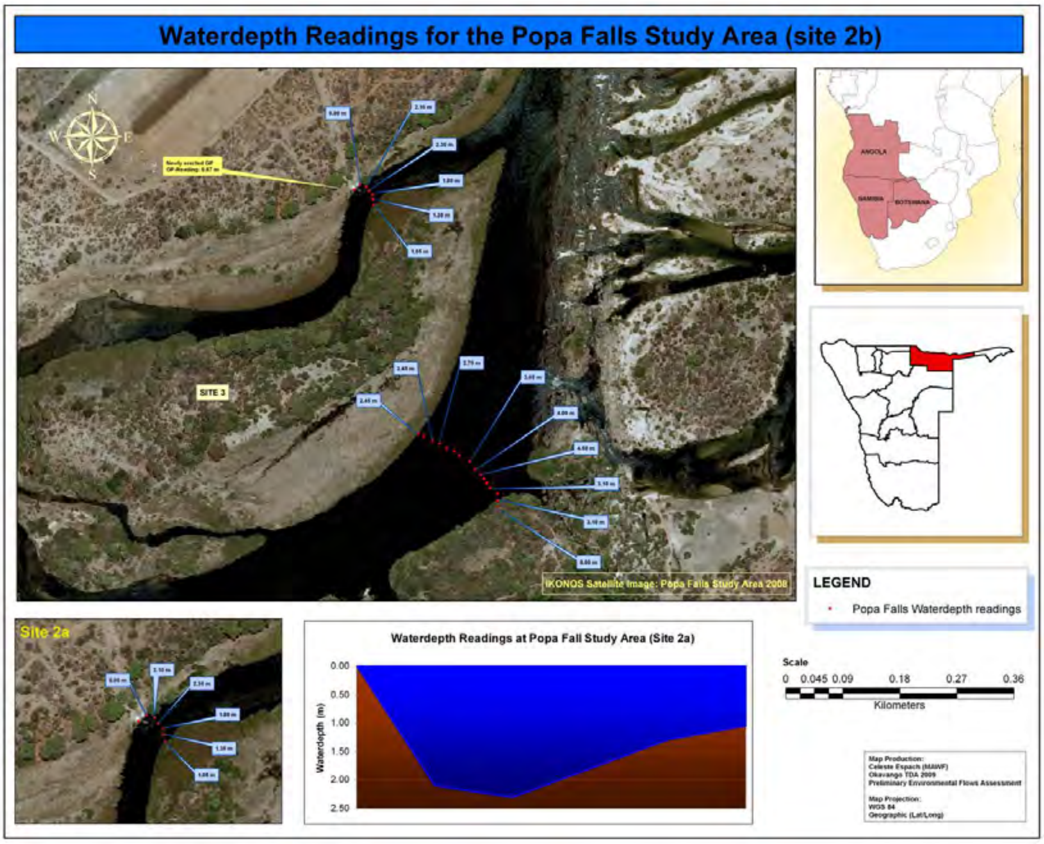


Figure 4-10 : Aerial view and cross section presentation of Popa Falls left channel (wet season)

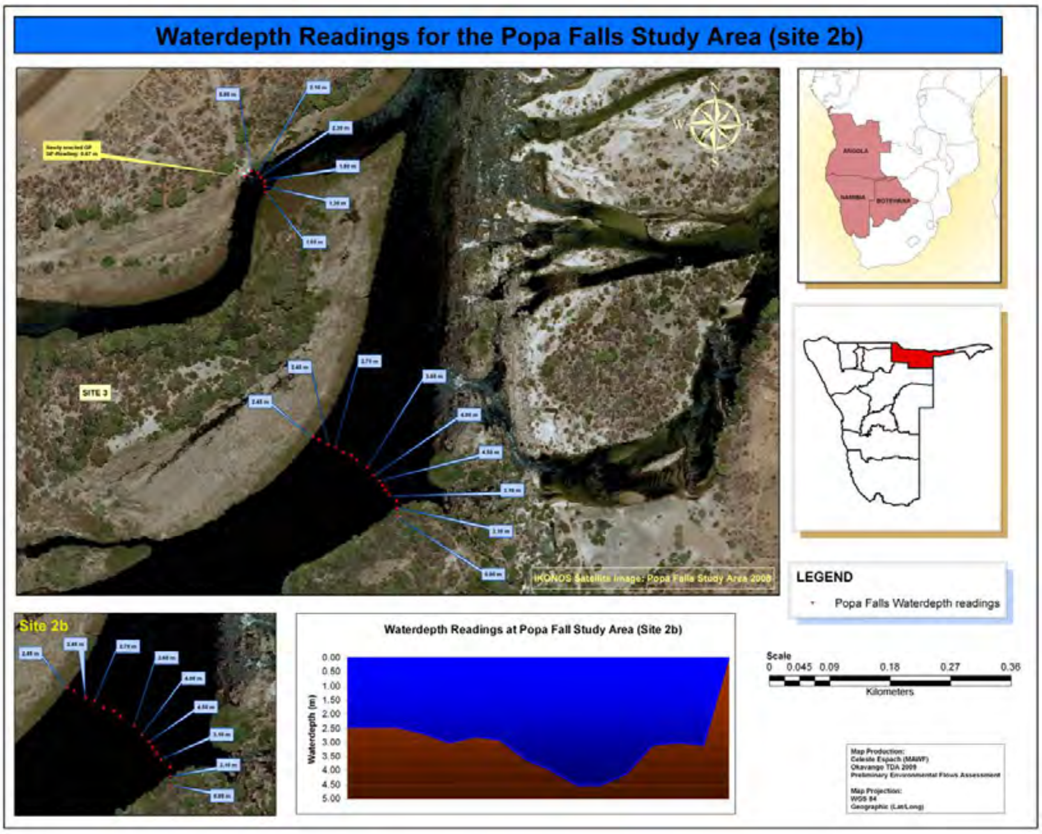


Figure 4-11 : Aerial view and cross section presentation of Popa Falls left channel (wet season)

4.3 Botswana

4.3.1 Site 6: Okavango River in the Panhandle at Shakawe

The Okavango Delta can be classified in terms of flow regime and habitat; permanent swamps, seasonal swamps, occasionally flooded areas, and drylands (McCarthy *et al.* 1988; Murray-Hudson *et al.* 2006). The upper part of the delta, commonly referred to as the Panhandle, consists of a 10-15 km wide and 150 km long valley within which the main channel meanders through. The Okavango River in the Panhandle splits into the western distributary, the Thaoge River, Boro River and Maunachira River. Boro sends out Xudum system in the middle reaches on its west and outflows to Lake Ngame through Kunyere River while Maunachira splits to form Mboroga and Santantadibe Rivers (Figure 4-12). Flow of the Okavango River is therefore partitioned within the delta. Over-spilling of flow from channels onto adjacent floodplains is a common feature within the delta during the high flow period, and in some cases the spilled water joins the same or different channel (Wolski and Murray-Hudson 2006). Of the three main distributaries, the Thaoge River in the west terminates in a series of lagoons and extensive floodplains near its upper end. The Boro upstream flows through lagoons and floodplains and is a single more or less confined channel in the downstream discharging into Thamalakane River and outflows to the Boteti River. Channel banks are very porous as most of them are made of papyrus. The substratum of channels is very permeable resulting in substantial exchange of water between channels, floodplains, and groundwater.

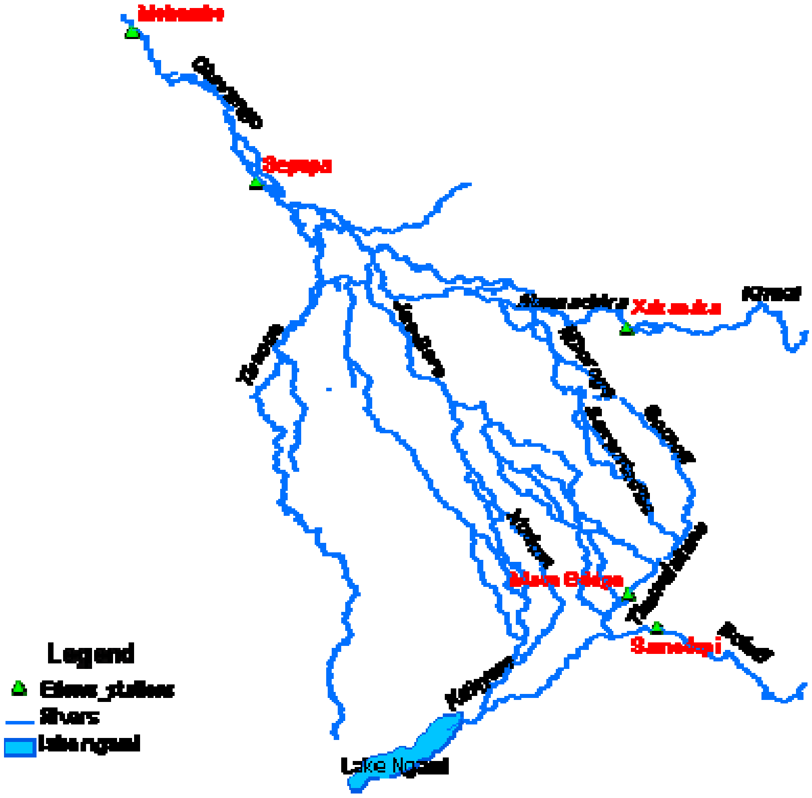


Figure 4-12 : Okavango Delta System

The panhandle of the Okavango River basin in Botswana forms the upper part of the Okavango Delta and its inflow hydro station is at Mohembo (Figure 4-13). The Mohembo station comprises of a hydrometric station where gauging of water levels and discharges are done. The flow rate at Mohembo varies from 120m^3/s in the dry season to 815m^3/s in the peak flood season. The River banks are characterised by savannas and deciduous trees relying on continuous of flow of the river throughout the year..

Figure 4-13 : Gauging Site at Mohembo

The site has a few animals such as Hippos and crocodiles (Figure 4-14) in the river and livestock that graze and feed along the banks. Away from the river banks, the vegetation is completely dry during the dry season. The people who reside along the Panhandle harvest the reeds and practise molapo farming in the floodplain areas.

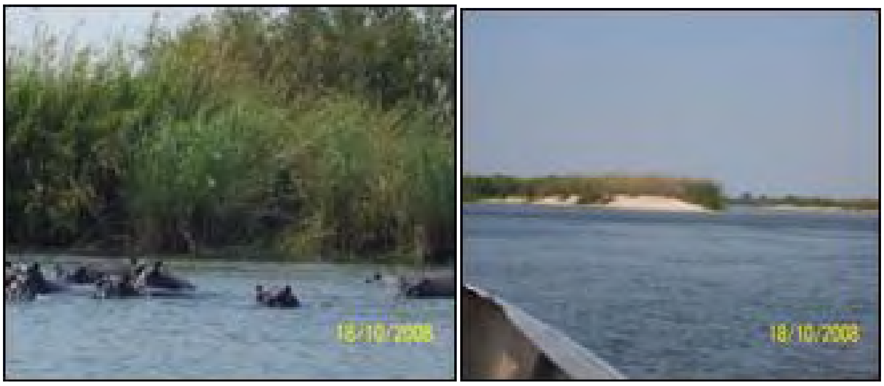


Figure 4-14 : The Panhandle

4.3.2 Site 7: Eastern Okavango Delta around Xakanaka

This site is situated along the Eastern Okavango Delta around Xakanaka on the Maunachira River. It is characterised by very long dry grassland with dry season flows of about 3m^3/s flows of about 8m^3/s in the flood season. The site can be divided into three flood regimes namely permanantly inundated, partially inundated and completely dry. Wildlife that are completely dependant on the water for drinking include elephant, giraffe and kudu (Figure 4-15). The hydrometric station at Xakanaka measures discharges and water levels.

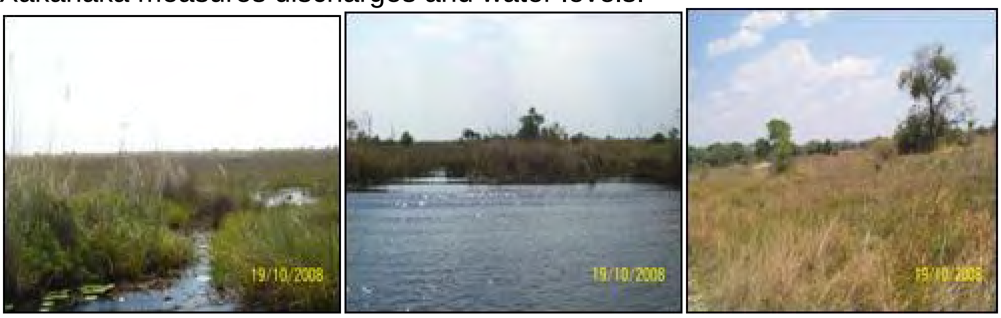


Figure 4-15 : Eastern Delta – Xakanaxa Lagoon

4.3.3 Site 8: Boteti River at Chanoga

This site is located in the downstream of the delta, along the Boteti River. The area has little or very dry grass during the dry season. Various forms of farming are practiced along the river, including stock farming (mainly cattle – see Figure 4-16) and subsistence irrigation of vegetables. The river is also used for fishing and as a supply of drinking water. The hydrometric station at Chanoga is only used for water level measurements.

Figure 4-16 : The Boteti River - Chanoga

5 Hydrological Data and Information

5.1 Measured flow records

5.1.1 Angola

In Angola, EFA sites were positioned close to river flow measurement stations so that rating curves and discharge records were available for use in the assessments. The stations that were selected are shown in Table 5-1.

Table 5-1 : Location of Angolan flow measurement stations

Station name	Number (ID)	Latitude (DMS)	Longitude (DMS)	From	To	Status	Rating curve available?
Cuito Cuanavale	637507	15°10'	19°12'	Feb. 1962	1980	Not operational	Yes
Capico	637501	15°33'	17°34'	Feb. 1962	1980	Operational (*)	Yes
Mucundi	637512	16°13'	17°41'	May 1957	1980	Not operational	Yes

(*) Operational since June 2006, when OKACOM handed over the station to the Provincial Government of Kuando Kubango

5.1.2 Namibia

There are three river flow stations, Rundu, Mukwe and Andara, along the Okavango River that are operated by the Department of Water Affairs and Forestry; Hydrology Division. Table 5-2 summarizes the details of the stations.

Table 5-2 : Location of Namibian flow measurement stations

Station name	Number (ID)	Latitude (DMS)	Longitude (DMS)	From	To	Status	Rating curve available
Rundu	2511M01	17° 54' 30.81"	19° 45' 46.46"	Oct. 1945	Present	Open	Yes
Mukwe	2521M04	18° 02' 09.19"	21° 25' 39.37"	Oct. 1949	Present	Open	Yes
Andara							No

5.1.3 Botswana

The following Botswana flow measuring stations can be associated with the three sites that were selected for analysis in this study.

Table 5-3 : Location of Botswana flow measurement stations

Station Name	Number (ID)	Latitude (DMS)	Longitude (DMS)	From	Status
Mohembo (Okavango)	7112	18° 9' 50.5434"	21° 28' 16.8018"	Oct. 1974	Open
Xakanaxa (Khwai)	7525	19° 6' 18.8634"	23° 14' 35.3394"	Oct. 1971	Open
Maun Bridge (Thamalakane)	7812	20° 0' 6.5514"	23° 15' 11.955"	Oct. 1970	Open
Samedupi (Boteti)	8112	20° 3' 50.652"	23° 18' 46.947"	Oct. 1970	Open

5.2 Rainfall

5.2.1 Angola

Table 5-4 : Location of Angolan rainfall stations

Station name	Number (ID)	Latitude (DMS)	Longitude (DMS)	From	To	Status
Chianga (Huambo)	N/A	12°44'	15°50'	1951	1970	Not operational
Chitembo (Bié)	N/A	13°31'	16°46'	1941	1970	Not operational
Cangamba (Moxico)	N/A	N/A	N/A	N/A	N/A	Not operational
Cuvango (ex-Artur de Paiva)	N/A	14°28'	16°18'	1951	1970	Not operational
Menongue	N/A	14°40'	17°12'	1951	1970	Open
Cuito Cuanavale	N/A	N/A	N/A	N/A	N/A	Not operational
Cuangar	N/A	17°35'	18°39'	1955	1967	Not Operational

5.2.2 Namibia

In the Kavango Region, the Namibia Meteorological Services (NMS) which is responsible for the collection of the country's rainfall data operates rain-gauges and these are summarised in **Table 5-5**.

Table 5-5 : Location of Namibian rainfall stations

Station name	Number (ID)	Latitude (DM)	Longitude (DM)	From	To	Status
Njangana	11592117	18°01'	20°38'	01-1951	12-1963	Closed
Andara	11607833	18°04'	21°28'	06-1914	09-1995	Open
Bagani	1161065					
Mpungu	12057660	17°46'	18°26'	12-1962	12-1980	Closed
Nkuren Kuru	12061871	17°37'	18°37'	01-1924	05-2007	Open
Tondoro	12064961	17°46'	18°47'	10-1931	08-2004	Open
Rupara	12071418	17°51'	19°05'	06-1958	05-1997	Closed
Bunja	12076214	17°51'	19°21'	01-1953	04-2004	Open
Rundu	12084758	17°55'	19°46'	01-1940	10-2007	Open
Sambiu	12090545	17°54'	20°02'	09-1935	02-1981	Closed
Mashare	12092649	17°54'	20°09'	01-1969	12-2003	Open

Rundu is only full-time NMS station with a standing international arrangement that is operated by NMS Staff. The other stations are volunteer-based. Bagani is the only automatic station but was only installed in 2009. Temperature, relative humidity, atmospheric pressure and wind are the other parameters measured by weather stations at Namibia Meteorological Services.

5.2.3 Botswana

Table 5-6 : Location of Botswana rainfall stations

Station Name	Number (ID)	Latitude	Longitude	From	To	Status
Maun	130-MAUN	19° 33' 0"S	26°5'0"S	1-Oct-21	Present	Open
Shakawe	223-SHAK	18° 22' 0"S	21° 50'0"S	1-Feb-32	Present	Open
Nokaneng	169-NOKA	19° 39' 0"S	22° 11' 0"S	1-Jan-55	Present	Open
Sehithwa	211-SEHI	20° 20' 0"S	20° 24' 0"S	1-Sep-58	Present	Open
Gumare	043-GUMA	22° 29' 0"S	28° 42' 0"S	1-May-59	Present	Open

5.3 Evaporation

5.3.1 Angola

Monthly evaporation figures that were used in reservoir simulations and irrigation demand calculations in the WEAP model was based on class A evaporation pan records. The source of information was the book “Caracterização Sumária das Condições Ambientais de Angola, Nova Lisboa, 1972”.

Angolan evaporation records are available for the stations listed in Table 5-7.

Table 5-7 : Location of Angolan evaporation measuring stations

Station name	Number (ID)	Latitude (DMS)	Longitude (DMS)	From	To	Status
Chianga (Huambo)	N/A	12°44’	15°50’	1951	1970	Not operational
Chitembo (Bié)	N/A	13°31’	16°46’	1941	1970	Not operational
Cangamba	N/A	N/A	N/A	N/A	N/A	Not operational

(Moxico)						
Cuvango (ex-Artur de Paiva)		14°28'	16°18'	1951	1967	Not operational
Menongue		14°40'	17°12'	1953	1967	Operational (*)
Cuito Cuanavale	N/A	N/A	N/A	N/A	N/A	Not operational
Cuangar	N/A	17°35'	18°39'	1955	1967	Not operational

(*) INAMET has one climatologic station installed in the premises of Menongue airport. Although the figures provided by "*Caracterização Sumária das Condições Ambientais de Angola*" were recorded only up to 1967, there are data recorded up to 1980s, on a non regular basis.

5.3.2 Namibia

The Namibian Map of Annual Evaporation and Precipitation was used in estimating the gross evaporation for the Okavango River in Namibia. Two evaporation stations that were operated by the Department of Water Affairs and Forestry, Hydrology Division were closed in the 1980's and due to their short records, the data is not provided.

From the evaporation map, an annual gross A-pan evaporation of 2 600 mm was estimated for the Namibian portion of the basin. A pan-to-lake conversion factor of 0.8 was used from January to June, and a factor of 0.7 was used from July to December. The monthly gross evaporation is shown in **Table 5.3**.

Table 5-8 : Monthly gross evaporation for the Okavango River in Namibia

Gross monthly evaporation (mm)											
Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
218	173	151	162	154	173	158	150	129	127	157	184

5.3.3 Botswana

The DWA does not have any evaporation stations in the Okavango Delta proper. The Meteorological Services under the Ministry of Environment Wildlife and Tourism operates a pan evaporation station in Maun and another station at Shakawe about 7km from Mohembo.

5.4 Geohydrological data and information

5.4.1 Angola

Data on groundwater in the Angolan portion of the Okavango River Basin is very poor. The only source of information used by the team was the Hydrological Map of Angola at scale 1:250.000. The map was produced in 1989 by Mac Donald & Partners Limited (UK) and HIPROJECTO, Consultores de Hidráulica e Salubridade S.A under the framework of a SADC project called "Hydrologic Assessment of Sub-Saharan Countries".

The maximum altitude in the Angolan portion of the ORB is approximately 1 780 metres, nearby the surrounding area of Huambo, whereas in the downstream reach, nearby the border with Namibia, the altitude is approximately 1 100 metres. Although the hydraulic gradient for the altitudes mentioned before is about 14%, most of the slope in the basin is gentle (monotonous). This means that the erosive process in the basin occurs more frequently in the upper areas rather than in the downstream areas, where the deposition of sediments of sediments occurs in more considerable manner.

From the geological point of view, the old rocks in the basin are represented by Pre-Cambrian granites. The granites underwent various orogenic processes and simultaneously by the occurrence of various magmatic processes, which originated rocks, such as gneisses, migmatites, etc. The tectonics of the basin are characterized by two directions of geological faults. In the upper basin the geological are predominantly NE-SW, allowing the contact between old granitic formation and the most recent ones (fine sands, silt and clayey schist). In the middle and lower part of the basin, the geological faults are predominantly NW-SE, coinciding with the main natural drain of the area, which is the Cuito River.

The Kalahari sands are found on old granitic rocks and on old igneous complexes. In certain points of the basin, the Kalahari sands have a thickness of more than 10 metres. In the middle section of the basin, the outcrops of granite are met along the bank of Cubango, Cutato, Cuchi, Cuelei and Cuebe Rivers. These granitic outcrops occur due to erosion in the bottom of the rivers before mentioned.
According to the Hydrogeological Map of Angola (scale 1:250.000), the yield of boreholes situated nearby the Cuito River, in the downstream section of the basin, is less than 1 litre per second.

5.4.2 Namibia

a) Introduction

The Namibian- Okavango sub- basins are a huge flat areas located in the north–eastern Namibia covering part of the Omatako- Omuramba subbasin. The only visible surface features are the permanent longitudinal, eastward oriented dunes. This area represents a huge aquifer system with sediments of the Kalahari formation, with most part of the area covered by a thick layer of calcrete covering the underlying bedrock. Groundwater in this part of the country is mainly used for domestic purposes and stock watering. (NGDC. 1991)

Several studies have been carried out in the Basin, these include the Groundwater Investigation in the Kavango and Bushmanland, were various geophysical methods have been employed to locate suitable aquifers in the study area. Methods included the Seismology that was carried out in 1968, the Aeromagnetics survey between 1918 and 1920, Resisitivity and the Ground Magnetic survey, in addition to the GROWAS data base and various Rural Water Supply drilling reports at different settlements in the Basin, Groundwater in Namibia: A*n explanation to the Hydrogeological Map* (G Christelis and W Struckmeier, 2001) that were used in compiling this report.

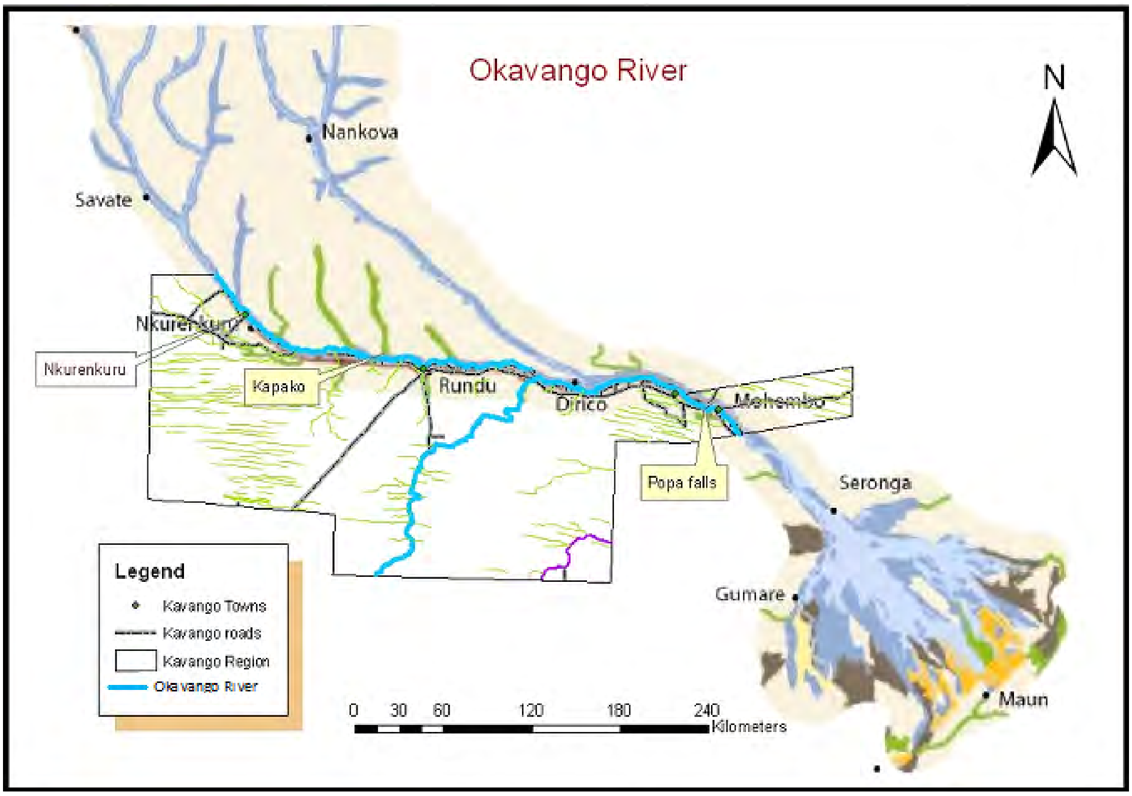


Figure 5-1 : The Namibian portion of the basin, including the two EFA sites: Popa and Kapako

b) Geology and aquifer stratigraphy

The basin is underlain by basal rocks of the Damara Sequence, followed by the Karoo Sequence sediments overlain and intruded by volcanic rocks and covered by the Cretaceous Kalahari Group sediments (NGDC. 1991). The soils in Kavango are made up of light coloured sands, limestone, silicified sandstones and orchreous sands of the Kalahari Sequence that are low in organic matter content. The sandy soils are enriched with silt deposited by the Okavango River in terraces and floodplains (Hydrology Division, 1994).

Two aquifer types are common in the study area, (I) Primary Kalahari aquifers i.e. sand and sand stones that hold water in intergranular pore space and (II) Secondary aquifers *i.e.* fractured aquifers that holds water in the fractures and weathered strata. Some boreholes in the area penetrate the primary aquifer of the Kalahari i.e. the sand and sandstone Kalahari, which extends from the surface to approximately 350 m deep (NGDC. 1991).

c) Water levels and groundwater flow

The water table rises and falls according to the season of the year and the amount of rain that occurs. The typical pattern is that heavy rainfall proportionally increases the groundwater level whilst drought or dry conditions reduce the groundwater level. The groundwater level is the rest water level in the borehole measured with a dip meter the main component used in the monitoring of groundwater as part of standard water resource management in Namibia. Long term monitoring of groundwater levels can determine the status of the aquifer, to indicate whether groundwater levels have dropped significantly and abstraction should be reduced or if the aquifer is coping well and the aquifer could be utilized more efficiently. In areas were the water is intersected in fractures, the water level is normally higher than those in the Kalahari aquifers (Christelis & Struckmeier, 2001).

Groundwater Gradient: determines the flow direction of a groundwater source. The river feeds the aquifers during floods and in areas were the Kalahari aquifers have a shallow groundwater gradient, the Okavango River feeds the aquifers but in most sections of the Okavango River the river gains groundwater. (NGDC.1991).

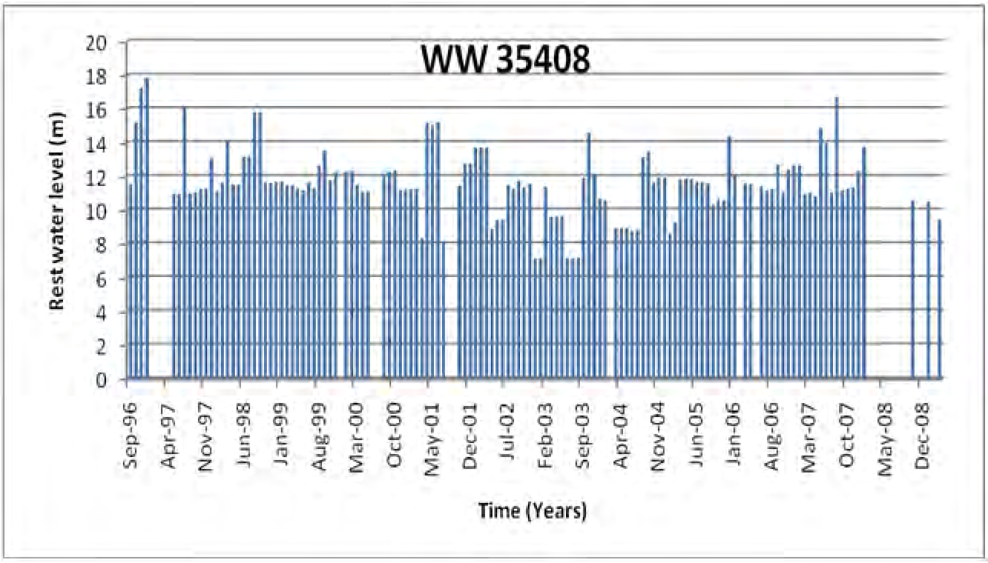


Figure 5-2 : Rest water level for WW35408 over the past 12 years

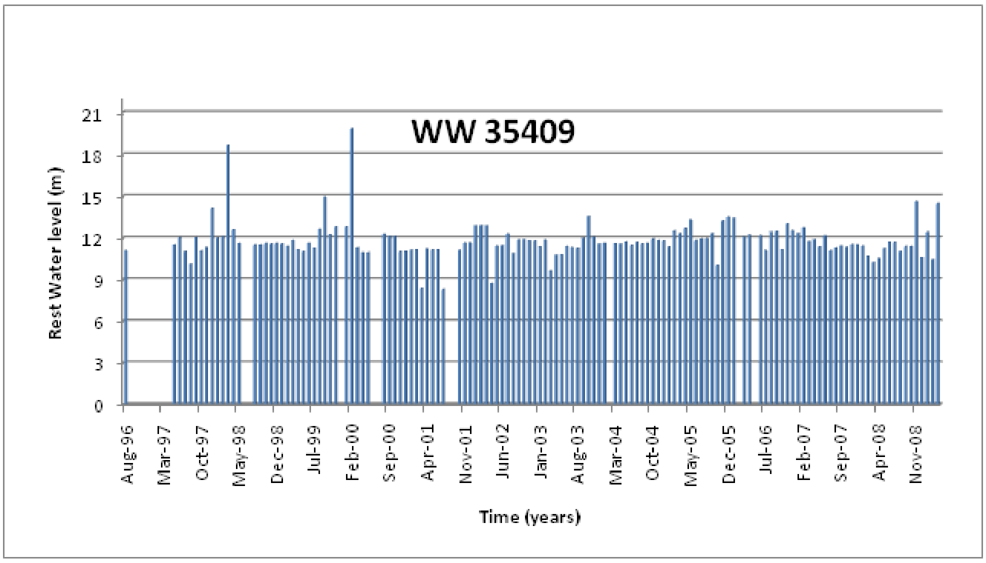


Figure 5-3 : Rest water level for WW 35409 for the past 12 years

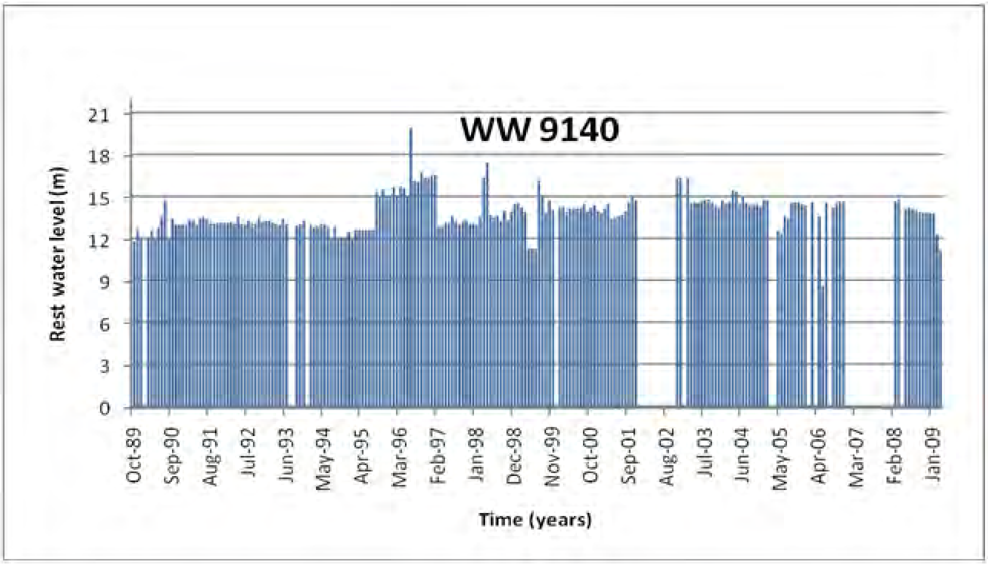


Figure 5-4 : Rest water level for WW 9140 from 1989-2009

Figure 5-2 and Figure 5-3 show rest water levels for boreholes located at Mupini near the Kakapo EFA site which are 200m apart from each other. Rest water level data records are available from 1996-2008. Both WW35408 and WW35409 rest water level are recorded below 12m for most months of the year, with few exceptions of 19.74 m in November 2008, 19.41m in February 1998 and a lowest value of 23, 02m recorded in 2000 for WW 35409. For WW 9140 the average rest water level is above 12m, with the lowest level of 19.94m recorded in June 1996. In comparison the rest water level at WW 9140 is generally a few meters lower than at the two boreholes at Mupini, this could be a result of a deeper aquifer or higher pumping rate or elongated pumping hours.

d) Recharge and Discharge

Groundwater recharge is yet to be understood in the basin, however the Okavango Basin generally receives good rainfall of 400-500mm between the months October and March. Shallow aquifers of less than 20m are recharged directly either by rainfall and ephemeral runoff while deeper aquifers are recharged from the Kalahari basin margins or the underlying fractured aquifers. Studies on water level elevation and hydrochemical evidence suggests significant recharge from the Otavi Group dolomites in the Tsumeb –Grootfontein area. The eastern boundary of the Cuvelai - Etosha Basin seems to be discharging into the Kavango Basin (Christelis & Struckmeier, 2001).Discharges from the aquifer are by means of abstractions, inter-basin flow, and discharge of groundwater to the river where the river is incised into the aquifer.

e) Hydraulic properties

The hydraulic properties of the Kalahari aquifer vary because of its differing amounts of gravel, sand, clay and other rock types. Coarse- grained sediment like sand and gravel have a higher porosity than small-grained sediments like clay and silt, and the pore spaces are better connected and this determines the permeability of the aquifer. Some geological formations allow water to travel through them at a faster or slower rate than others, depending on the porosity and thickness of the medium

(*Transmissivity)* (DWAF-SA, 2006). The better the transmissivity the more water will reach the borehole in a specific time.

Aquifer characteristics can be estimated from data found in borehole reports, such as geologic logs, static water level records, pump test data etc. For instance the pump test is analyzed and interpreted to determine the aquifer potential. Evidence obtained from drilling reports for Rural Water Supply shows that the groundwater yields in the region is relatively good with 90% of boreholes drilled having a possibility of yielding more than 1m^3/h in the Kalahari, or less in areas were fractures are intersected in other parts of the Basin. Boreholes yields along the Okavango river ranges between 0 - 8m^3 /h and with areas that yield up to more than 10m^3 /h that are drilled deeper than 100m into the Kalahari aquifers, (NGDC. 1991). A report for rural water supply compiled by Bitner, 2004 showed a varied range of water yield between 3, 7and 8m^3/h at Makandu, Ngcangcana and Shamahiho respectively (Bitner Water Consult CC, 2006).
A study done on the Andara Water scheme estimated Transimissivity values in the order of 0-15m3/day/m and a Storativity value of about 0.005 in the sandstone aquifers (Hydrology Division, 1994). Data from WW 9140 at Bagani (popa falls) has a yield of 2.5m^3/h while WW 35409 and 35408 all have a yield estimate of 6m^3/h (GROWAS database).

f) Water quality

Groundwater quality is a chemical indicator, which looks at the chemical and bacteriological properties of the groundwater. The groundwater samples in Namibia classified according to the "Guideline for the evaluation of drinking water for human consumption" with reference to the chemical, physical and bacteriological quality of Namibia (The Water ACT, 1956). This groundwater quality classification is used for rural water distribution throughout the country to determine whether water from a certain groundwater source is fit for human consumption or other uses for instance irrigation.

The water quality in the area varies as stripes of saline water and high fluoride concentrations are found in the area. Details of water quality data, lithological logs of boreholes and pumping test results reveal the existence of saline and fresh water groundwater stripes. However there is no consistent system regarding the spatial distribution of fresh and saline and the distribution of the depths and potential yields of the different layers is yet to be known. The type of formation that makes up an aquifer and the travel time determines the type of water an aquifer has, for example pre-Kalahari with calcrete is characterized by saline water and depending on the groundwater gradient the saline water might be discharging into the river.

Groundwater in the Kalahari aquifer along the banks of the river often shows poor quality due to its iron and manganese content, which occasionally exceeds the limits for drinking water. During flood when the river recharges the aquifer, it improves the groundwater quality in those areas. According to NGDC, 1991 good groundwater quality predominates along the river with TDS (Total Dissolved Solids) in some area reaching 1000mg/l and values of more than 3000mg/l have also been recorded and the lowest value recorded of 36mg/l (TDS) at Shakashi. A typical example is the TDS value of 6686mg/l recorded at Mayana borehole in Kavango. Cases of elevated values of iron have also been reported, a typical example is a borehole at Makandu with an iron (Fe) value of 1.62mg/l, however these boreholes are considered critical and can still be utilized for human consumption as they do not exceed the limit for human consumption of 2 mg/l of Fe (NGDC, 1991) .

WW 35408 and 35409 at Mupini are all within 200m from the river. The PH values in these boreholes ranges between 7.7 - 8.2 and the conductivity measured is between 193-330mS/m. A record of 4mg/l of Fe was measured at WW 35408 in 1999 and in WW 35409 the Fe level was never measured above 1mg/l. Thus water from these two boreholes is classified as group C (low risk water) according to the Guideline for the evaluation of drinking water for human consumption in Namibia (GROWAS, 2004).
Two other boreholes at Kakapo (WW 43046 and WW 43045) were classified as group B (good water quality). The groundwater at Bagani (WW 9140) is classified as group D (High health risk-unfit for human consumption) due to high TDS of 3183mg/l and 4mg/l of Fe recorded in 2000 (GROWAS, 2004).

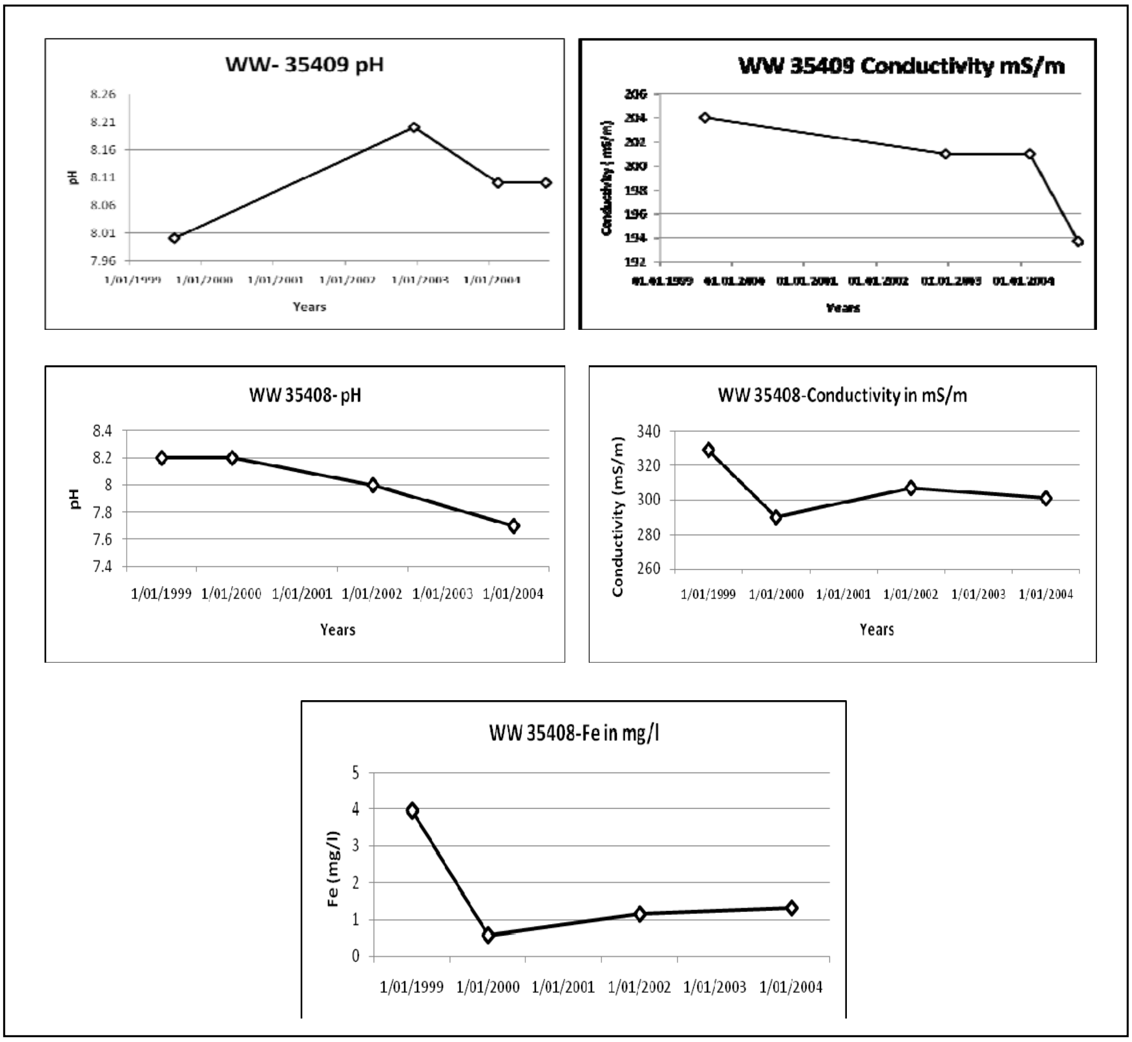


Figure 5-5 : pH, Conductivity for WW 35408 and WW 35409 and Fe for WW 35408 measured over four years

g) Groundwater – Surface water links

The management of water resources in Namibia has focused either on surface water hydrology or groundwater as two separate entities. With the increasing knowledge and development of land and water resources, it is clear that nearly all surface-water features (rivers, lakes etc.) interact with groundwater. The interaction between these two bodies take different forms, mostly, surface water bodies gain water and solutes from groundwater systems and in other situations surface water act as a source of groundwater recharge altering the water quality depending on the source (Jones, 1997).

Consequently the withdrawal of water from the Okavango River can deplete groundwater or alternatively excessive groundwater abstraction can deplete water in river. Throughout this process water constantly moves between the two bodies, sharing contaminants and all solutes. Thus effective IWRM (Integrated Water Resource Management) requires a clear understanding of the linkages between groundwater and surface water as it applies to any given natural resource.

h) Conclusions

- The low number of boreholes at the Kapako and Popa rapids sites are actually not sufficient to get representative values for the groundwater information of these areas and thus monitoring boreholes need to be drilled.
- The water level data for the river was required to compare with the groundwater level, however the database containing these data was not functional and data could not be made available.
- More detailed investigations are yet to be done to determine values of storativity, transimissivity and hydraulic conductivity of the aquifers in Kavango and most of Namibia.

5.4.3 Botswana

a) Soils and Geomorphology

The Okavango delta predominantly has the histosols and arenosols soil types, while islands and ridges have calcium arenosols (ODMP 2008)._The drylands are mostly characterized by white sandy soils with very low inherent fertility and water holding capcity and they are commonly called as Kalahari sandsOther soil types include the gleysols in the lower fringes of the Delta, the luvisols in the lower end and the soil types of the phaeozens found in the surrounds of Nokaneng and Tsau South East.

b) Geology

The Okavango Delta lies within a north-easterly trending half graben, related to the east African Rift System (Hutchins et al 1976). The major boundary structures are the Thamalakane and Kunyere faults with a down throw to the north-west and are still active. The Gumare Fault has a parallel strike to the major faults. The oldest rocks in the district consist of metavolcanic Kgwebe Formation and metasedimentary Ghanzi Group of upper Proterozoic age. Karoo Supergroup rocks unconformably overlie lower proterozoic basement rock outcrop south west of the delta at Lake Ngami on the graben side of the Kunyere Fault. The Kalahari Group sediments occue as Aeolian sands in the grabens of the Panhandle of the Delta.

c) Hydrogeology

Three major aquifers formations exist in the Okavango Delta region. These are the Basement rocks, Karoo and Kalahari Group sediments. Karoo and Basement rocks, where they occur shallow depth, also form locally important aquifers. The Kalahari group sediments comprise the most important known aquifers. Recharge in the Okavango Delta has been estimated in the order of 7 to 10mm/annum (ODMP 2008**).**

6 Water Resource Development Information

To provide information for the construction of three development scenarios for the EFA ((EPSMO/Biokavango Report Number 6; *Hydrological Scenario Modelling Report*), the three country teams collected information on possible and planned water resource developments from national water resource development plans, feasibility studies and regional and sub-regional water resource development plans. The information are summarised in the remainder of Section 6.

6.1 Population

6.1.1 Angola

The last census of population in Angola took place in the 1970s. Most of the current figures on population are obtained through statistical manipulations. For the purpose of the modelling exercise data were collected from the Rapid Assessment Water Resources and Water Uses in Angola, carried out in 2005. Using data from 2005 and using the appropriate formula, projections were made for the various time horizons.

Another valid source of data on population was the information provided by a joint survey made FAO and IDA, the Agrarian Development Institute of the Ministry of Agriculture.

Table 6-1 : Angola population projections(1)

Municipality (Province)	Sub-Basin	2006	2008	2010	2015	2020	2025	Remarks
Catchiungo (Huambo)	Cubango / Okavango	142 688	148 453	155 057	172 881	192 754	214 911	Rural
Chitembo (Bié)	Cuito	117 729	122 486	127 935	142 641	159 038	177 319	Rural
Cangamba (Moxico)	Cuito	11 482	11 946	12 477	13 912	15 512	17 295	Rural
Cuvango (Huíla)	Cubango/Okavango	77 677	80 816	84 411	94 114	104 933	116 995	Rural
Cuito-Cuanavale (Kuando Kubango)	Cuito	105 731	110 435	115 348	128 607	143 390	159 873	Rural
Menongue (Kuando Kubango)	Cubango/Okavango	235 515	245 992	256 935	286 469	319 398	356 112	Urban
Cuchi (Kuando Kubango)	Cubango/Okavango	43 316	45 066	47 071	52 482	58 515	65 242	Rural
Cuangar (Kuando Kubango)	Cubango/Okavango	42 428	44 316	46 287	51 608	57 541	64 156	Rural
Calai (Kuando Kubango)	Cubango/Okavango	77 250	80 687	84 276	93 964	104 765	116 808	Rural
Dirico	Cuito / Cubango	8 627	8 976	9 375	10 453	11 655	12 995	Rural

(1) Sources of Information: 1) GEPE - Kuando Kubango 2) FAO / IDA

6.1.2 Namibia

a) Population Census of 2001 of Kavango Region

The Population and Housing Census was last taken in 2001 and the Kavango Region had a total population of 202 694. The distribution for each constituency is shown in Table 6-2 (National Planning Commission, 2001).

Table 6-2 : Population of Kavango Region 2001

Constituency	**Population**
Kahenge	30 903
Kapako	26 263
Mashare	16 007
Mpunge	18 660
Mukwe	27 250
Ndyona	19 565
Rundu Rural East	18 250
Rundu Rural West	26 623
Rundu Urban	19 173
Total	202 694

b) Projected urban population

In 2007, in the analysis of future water demands for the Kavango Region, the Namibia Water Corporation had used a total population for Rundu urban of 41 342 in 2001 which included two settlements, Sauyemwa and Kaisosi, located on the outskirts of the town (NamWater, 2007). A growth rate of 2.5% per annum was used to project the population. Because of lack of population data for the two settlements, the population of 41 342 and the 2.5% growth rate was adopted to project the urban population until 2025 as shown in Table 6-3.

Table 6-3 : Estimated urban population of Kavango Region

	Estimated population			
	2008	**2010**	**2015**	**2025**
Rundu Urban	49 000	52 000	58 000	75 000

c) Projected rural population

For the rural population in the Kavango Region, the population projections to 2017 are presented in Table 6-4 (Lund Consulting Engineers, 2003). A growth rate of 1.5% as used in the report was adopted to project the rural population to 2025.

Table 6-4 : Estimated rural population of Kavango Region

	Estimated population			
	2008	**2010**	**2015**	**2025**

Kavango Rural	201 743	207 968	224 041	260 009

6.1.3 Botswana

The Okavango Delta region is comprised of mostly settlements with population that does not cause any significant impact on the Okavango Delta resource. The few areas with significant population are Maun, Shakawe/Gumare, Ikoga, Beetsha, Seronga and Sepopa. Estimates and projections of water demands were done during the National Water Master Plan review of 2006. The estimated and projected population growth and Water Demands for the Ngamiland Region as per the National Water Master Review of 2006 is shown below.

Table 6-5 : Estimated and projected population growth and Water Demands for the Ngamiland Region as per the National Water Master Review of 2006

Year	2005	2010	2015	2020	2025	2030	2035
Population Growth	133 000	139 360	141 948	143 943	144 765	145 204	145 418
Water Demand (m^3/year)	3 654.4	4 064.66	4 384	4 727.66	5 099.69	5 524.37	6 008.8

The major gap with regard to water demands and populations is that the village populations in the delta are not reflected. The projections are made based on the region as a whole.

6.2 Irrigation and Urban Water Demands

6.2.1 Angola – Irrigation Water Demands

Data on irrigation were collected from FAO statistics, from the Directorate of Irrigation and Rural Engineering of the Ministry of Agriculture and from the Provincial Director of Agriculture in Kuando Kubango. Additional data on irrigation were collected from field visits by the National Project Coordinator of EPSMO, to the Okavango River Basin.

In the low development water use scenario 3 irrigation schemes were identified downstream of Menongue, namely Missombo, Menongue Agriculture Scheme and EBRITEX, totalling an area of 28 000 hectares. These schemes are intended to abstract water from the Cuebe River, upstream of Capico.

In the medium development water use scenario 6 irrigation schemes totalling 198 000 hectares were identified, namely Missombo, Menongue Agriculture Scheme and EBRITEX, with an area of 28.000 hectares and with water abstraction from the Cuebe River, and Cuvango, on the Cubango River, Cuchi on the Cuchi River and Longa on the Longa River, with a combined area of 170 000 hectares.

The high development water use scenario involves all the irrigation schemes of the medium water use development scenario, plus irrigation schemes in Cuangar/Calai on the Cubango River, Calai/Dirico on the Cuito River. In this scenario, the total area to be irrigated is 338 000 hectares.

It is worth mentioning that due to water limitation in the ORB, a total of 170 000 hectares that are considered to be arable were not taken into consideration when the high development scenario was constructed. These areas are distributed as follows:

- 90 000 hectares in Cuito Cuanavale,
- 45 000 hectares in Cuangar/ Calai, and
- 35 000 hectares in Calai/Dirico.

6.2.2 Angola – Urban Water Demands

Two demand centres were considered for the urban water projections, namely Menongue and Cuito Cuanavale. Water demands of centres such as Tchicala Tcholoanga and Ctchiungo (Huambo province), Cuvango (Huila province), Chitembo (Bié province), Cangamba (Moxico province) and Cuchi, Cuangar, Calai and Dirico (Kuando Kubango province) were not included in the hydrological model of the basin, as they are small compared to the urban and irrigation water demands.

According to the projections the city of Menongue will have the following population:

- 356 000 inhabitants in the high water use scenario (2025);
- 286 000 inhabitants in the medium water use scenario (2015) and
- 257 000 inhabitants in the low water use scenario (2010).

The city of Cuito Cuanavale will have the following population:

- 160 000 inhabitants in the high water use scenario;
- 128 600 inhabitants in the medium water use scenario and
- 115 000 inhabitants in the low water use scenario.

For the purposes of calculation of the volume of water consumed by the population, a per capita useage of 100 litres/person/day was used for the urban areas.

Population projections are shown in the table 6.3.1.1, below:

Table 6-6 - Angolan population projections

Municipality	2008	2010	2015	2020	2025
Catchiungo	148 453	155 057	172 881	192 754	214 911
Chitembo	122 486	127 935	142 641	159 038	177 319
Cagamba	11 946	12 477	13 912	15 512	17 295
Cuvango	80 816	84 411	94 114	104 933	166 995
Cuito Cuanavale	110 435	115 348	128 607	143 390	159 873
Menongue	245 992	256 935	286 469	319 398	356 112
Cuchi	45 066	47 071	52 482	58 515	65 242
Cuangar	44 316	46 287	51 608	57 541	64 156
Calai	80 687	82 276	93 964	104 765	116 808
Dirico	8 976	9 375	10 453	11 655	12 995

At the beginning of the exercise an annual population growth rate of 2.2% was considered. After presentation of the preliminary results to OKACOM-Angola, this figure was changed to 2.7%.

6.2.3 Namibia – Irrigation Water Demands

The Division of Agricultural Engineering in the Ministry of Agriculture, Water and Forestry provided the existing and future irrigation development information along the Okavango River. Refer to Figure 6-1 for a schematic map of the present irrigation schemes.

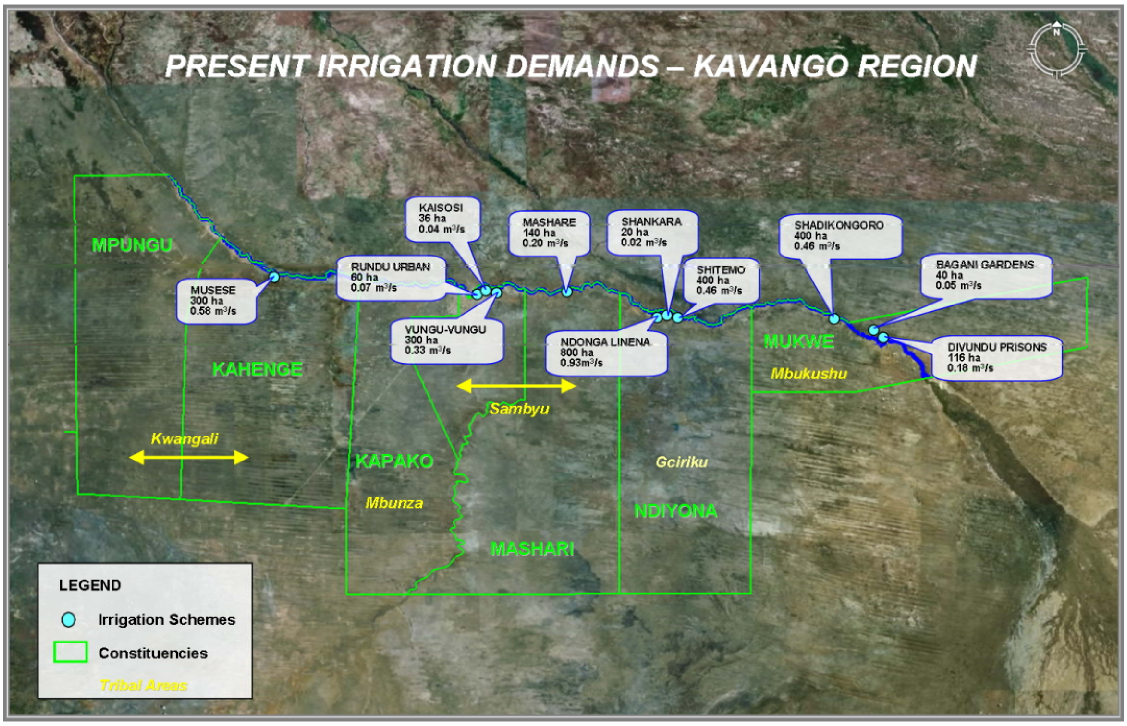


Figure 6-1 : Existing irrigation developments along the Okavango River

The individual irrigation schemes were grouped together for each constituency, and the total present and future hectares anticipated for agriculture presented in Table 6-7**.** The future irrigation areas are based on a development scenario that was developed by the Green Scheme Agency which allowed for the equal and fair distribution of water allocation between the different Tribal Areas. Water allocations were arrived at after providing for environmental flow requirements in the Kavango River. The scenario is described in detail in an irrigation report produced for the TDA (Liebenberg, 2009)

Table 6-7 : Combined schemes per Constituency for present and future irrigation

Constituency	**Total irrigable land (hectares)**			
	2008	**2010**	**2015**	**2025**
Kahenge	300	700	900	900
Rundu - Mashare	521	551	551	551
Ndiyona	870	1 270	1 270	1 270
Mukwe	560	560	560	560
Rundu (future)[1]	-	-	1 674	1 674
Mukwe (future)	-	-	4 000	10 600

[1]574 hectares were inadvertently excluded, and water use result calculations indicate that the amount is negligible

6.2.4 Namibia – Urban Water Demands

a) Rundu

The Namibia Water Corporation supplies bulk water to the town of Rundu, in the Kavango Region. A summary of the projected water demands for Rundu is presented in Table 6-8. Demand projections to 2015 (NamWater, 2007), and a growth rate of 2.5% was used to project the demand to 2025.

Table 6-8 : Water Demand Projections for schemes at Rundu

Year	N'karapamwe Reservoir (m^3/a)	Industrial Tower (m^3/a)	Total (Mm^3/a)
2008	1 836 815	1 004 266	2.841
2010	1 929 804	1 055 107	2.985
2015	2 183 396	1 193 757	3.377
2025	2 794 931	1 528 110	4.323

b) Central Area of Namibia

The Eastern National Water Carrier (ENWC) is envisaged to be linked with the Okavango River using the Grootfontein-Omatako Canal to supply water to the Central Area. A volume of 17 Mm^3/a (Water Transfer Consultants, 1997) for the Medium Development scenario was used as the demand required from the Okavango River for 2015, while for the High Development scenario (2025), a water demand of 100 Mm^3/a (Heyns, personal comment, 2009) was used. The preliminary design of the scheme is based on a premise that the dams in the system will provide balancing storage to meet peak demands. This was done to minimise the cost of the pipeline from the abstraction point. The pipeline was therefore sized to deliver flows at a constant rate equal to the mean annual demand.

6.2.5 Botswana – Irrigation and Urban Water Demands

Permits for abstractions of specified quantities are issued by the Department of Water Affairs. 342 permits of surface water abstractions were used during the ODMP exercise to assess their impacts in the delta. Abstractions are taken from the surface waters of the delta for purposes including domestic water supply, livestock, game, small scale irrigation and construction. The abstractions were summarised as shown in Table 6-9 below. The 2025 projected abstraction was based on increasing population and an additional water demand of 21.5 Mm^3/year, or 0.20% of the average annual inflow.to the Delta

Table 6-9 : Surface Water Abstractions (ODMP Analysis of Water Resources Scenarios 2006)

River	Abstractions (m3/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**	**68,073**

Groundwater abstractions were also included during the ODMP exercise. Ground water is abstracted from boreholes around the Delta, mainly to supply Maun and settlements along the western margin. The groundwater abstraction amounts are shown in table below and the total amounts to 6Mm^3 per annum, 0.08% of the average inflow. The projection for 2025, is around 14Mm^3 or 0.17% of the inflow.

Table 6-10 : Groundwater Abstractions (ODMP Analysis of Water Resources Scenarios 2006)

LOCATION	**Abstractions (m3/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
Tsutsubega	1,643	4,026
Shashe	4,654	-
Gomoti	7,666	10,066
Kunyere	-	12,079
Matsibe	-	8,053
TOTAL	**16,445**	**37,577**

6.3 Rural water demands

6.3.1 Angola

Due to the scale at which the basin model was configured, water demands of rural settlements not considered, as they are very small compared to the irrigation and urban demands. For the purposes of calculation of the volume of water consumed by the rural population, a per capita consumption of 50 litres/person/day can be used.

There is a small number of livestock in the Angolan portion of the Okavango River Basin. Due to the insignificant amount of water consumption associated with livestock, the basin model does not include this demand.

Livestock projections are shown in Table 6-11, below:

Table 6-11 : Angola Livestock Projections

Type of Animal	Year 2008	Year 2015	Year 2020	Year 2025	Remarks
Cattle	101342	124638	144490	167503	Annual gouwth of 3%
Sheep	27372	36020	43824	53319	Annual growth of 4%
Goats	27372	36020	43824	53319	Ditto
Pigs	27372	36020	43824	53319	Ditto

6.3.2 Namibia

Water consumption for the rural areas in the Kavango Region was obtained from the Ministry of Agriculture, Water and Rural Development (Lund Consulting Engineers, 2003). In the report, a growth rate of 1.5% was used to project the water demands from 2010 until 2017. The same growth rate was used to project the water demands until 2025, and collectively, the rural water demands including livestock water requirements are shown in Table 6-12.

Table 6-12 : Rural water demand projections for Kavango Region

Year	Growth rate (%)	Rural water Demand (Mm^3/a)[2]				Total Demand (Mm^3/a)
		Human	Schools	Clinics	Livestock	
2008	1.63	1.841	0.385	0.014	3.478	5.718
2010	1.50	1.898	0.397	0.015	3.585	5.895
2015	1.50	2.044	0.428	0.016	3.862	6.350
2025	1.50	2.373	0.497	0.018	4.482	7.370

[2]The rural water demands are met mainly by groundwater and were not used as input data into the WEAP model.

The last livestock census was taken in 2006. For the Kavango Region, the livestock results since 2001 are summarized in
Table 6-13 as provided by the Directorate of Veterinary Services in the Ministry of Agriculture, Water and Forestry.

Table 6-13 : Livestock census for the Kavango Region

Census Year	Cattle	Sheep	Goats	Horses	Donkeys	Pigs	Poultry	Dogs	Total
2000	127 043	446	61 736	542	1 341	3 007	63 269	15 121	272 505
2001	122 301	1 165	50 812	456	1 665	2 899	59 340	8 209	246 847
2002	122 633	410	50 893	502	1 685	2 580	87 227	7 329	273 259
2003	120 454	470	45 997	460	1 568	3 344	56 145	8 243	236 681
2004	120 496	88	46 411	598	1 600	2 536	62 372	6 284	240 385

2004	120 496	88	46 411	598	1 600	2 536	62 372	6 284	240 385
2005	120 894	1 388	49 519	301	1 699	*N/A	48 169	10 255	232 225
2006	125 927	1 472	44 135	524	1 555	1 778	55 116	7 122	237 629

*Data not available

6.3.3 Botswana

Rural domestic water demands in the Delta region are included in the water demand estimates shown in Table 6-9 and Table 6-10. For the NWMPR- 2006, in order to estimate the livestock water demands, the projected livestock population by region was converted to livestock units. One livestock unit requires 45 litres of water per day; this translates into 16.4 m^3 per head per annum. To obtain water demands, the rate was applied to livestock units.

Table 6-14 : Projected livestock units (' 000) by livestock category per 5 year Duration range in Maun Region Table 6-22 to 6-31 page 119/120 NWMPR Volume 8, March 2006

Category	**2005-2010**	**2011-2015**	**2016-2020**	**2021-2025**	**2026-2030**	**2031-2036**
Cattle	625	526	543	561	588	745
Goats	243	208	221	209	229	289
Sheep	21	17	17	15	16	18
Donkeys	70	54	53	44	41	46
TOTAL LSU	**959**	**805**	**834**	**829**	**874**	**1098**
WATER REQUIRE-MENTS (m3)	**15916**	**13222**	**13698**	**13616**	**14355**	**18035**

6.4 Hydropower

6.4.1 Angola

Data on hydropower potential were obtained from old studies carried out by Technicians from Portugal and from the former Republic of Yugoslavia. Mr. Paulo Emílio Mendes, the Head of the Water Resources Division of DNA, provided some additional data. The hydropower scenarios include the development of 10 run-of-the river schemes (Cuvango, Cutato, Malobas/Cuchi, Cuelei, Lyapeca, Mucundi, Maculungungu, Cuito, Mpupa and Xamavera), and the construction of one storage-based regulation dam at Mucundi.

6.4.2 Namibia

Pre-feasibility studies have been carried out for the development of hydropower scheme at Popa Falls near Divindu in the Kavango Region. At the time it was decided not proceed with feasibility level assessment of the scheme due to the need for extensive environmental impact studies. A possible run-of-river hydropower scheme was modelled for the medium and high development scenarios with the characteristics shown in Table 6-15. This information was provided by Nampower.

Table 6-15 : Possible hydropower scheme at Popa Falls

Parameter	**Estimated amount**
Maximum turbine flow	280 (m^3/s)

Fixed head	9.75 (m)
Generating efficiency	94.5 (%)
Plant factor	100 (%)

6.4.3 Botswana

To date, no hydropower schemes have been planned in the Botswana portion of the basin.

7 Water Resources Management Information

7.1 Data and Information Management

7.1.1 Angola

In Angola, DNA is the government body for hydrological data collection and management. DNA works in a close collaboration with Provincial Directorates of Water (DPA). Data collected in the field are sent to DNA for processing and dissemination. The data collected is stored in the national database, the HYDATA.

Currently the hydrological data management is poor. In the past the national hydrometric network consisted of about 189 stations. Most of the stations were derelict during the civil war, leaving the country with a paucity of hydrological data to support water resources management.

The database, HYDATA, was populated with data collected until the end of 1980s. Currently the HYDATA is not functioning, despite many attempts to repair it. Therefore, most of the data used for the Environmental Flows Assessment are historic.

Due to lack of incentives the Water Sector is understaffed. There are government plans targeting at the rehabilitation of the hydrological network, enabling the sound management of water resources. Multilateral, like the World Bank, have also plans to help the development of the national Water Sector, including the rehabilitation of hydrometric stations.

7.1.2 Namibia

The Directorate of Resource Management in the Department of Water Affairs and Forestry is responsible for water resource management nation wide. Data collection and management of surface water is by the Hydrology Division; groundwater by Geohydrology Division and water quality by Water Environment.

The Namibia Water Corporation (NamWater) collects hydrological data and then forwards it to the Department of Water Affairs and Forestry who are the custodians of the country's data. The collection of data by NamWater is done by their Hydrology and Geohydrology sections under the Planning and Water Resources Division, and by the Water Quality Services Division.

Namibia Meteorological Services in the Ministry of Works and Transport is responsible for the collection of the national rainfall data.

Currently, there are two databases in use to store hydrological and geo-hydrological data. The HYDSYS database is used by the Hydrology Division, DWAF. While the Geohydrology Division, DWAF uses the Ground Water Information System (GROWAS) database. NamWater does not have databases and use Excel in the Division, but database options are being investigated.

Hydrological data collection for the Kavango River is primarily done by means of automatic recorders and/or telemetry. Some supplementary data is received from farmers who read daily rain gauges, and staff at regional offices.

One major constraint is a lack of capacity within Namibia to install new monitoring equipment.

The Namibia Water Corporation Act of 1997 stipulates that upon request from the Department of Water Affairs and Forestry, NamWater is to provide rainfall, river flow, groundwater levels, water abstraction from water resources and water quality data. Also NamWater is to make provision for the dissemination of data to the public.

The Department of Water Affairs and Forestry provides hydrological information to the co-basin countries. The Hydrology Division, DWAF is a participant in the SADC Hydrological Cycle Observation System project (SADC-HYCOS).

DWAF disseminates flood information within Namibia and to neighbouring countries by means of a daily Hydrology Division flood bulletin and daily SMS flood messages.

During the rainy season, Hydrology, NamWater provides weather information (from NMS) and daily water levels of dams via email and press releases to keep the public informed. The NamWater website, www.namwater.com.na does archive a weekly bulletin of dam levels in the country.

7.1.3 Botswana

The Hydrology and Water Resources Division is responsible for the collection of hydrological data on a daily basis at Mohembo and at monthly intervals in the other hydrometric stations in the delta. The data collected by the Maun and Gumare Water Affairs Stations are passed on to the Head Office in Gaborone where the data is processed for use in various projects relating to the Delta. Currently, emphasis is placed on entering the hydrometric data to improve availabity to the stakeholders.

The Harry Oppenheimer Okavango Research Centre (HOORC) in Maun also collects hydrological data for their research purposes at selected sites in the rivers of the Delta. The HOORC has established a hydro monitoring station on the Boro River to conduct research on water quality and flow measurements.

HOORC developed the Okavango Delta Information System during the Okavango Delta Management Plan Project. The available data categories include boundaries, climate, culture, ecology, hydrology, environmental hazards, flora, fauna, land use, geology and other features. Information about the Okavango Delta and other planning processes including hydro models, consultancy reports, documents, journal articles, websites of the institutions, photographs and other databases including the Peter Smith collections are also available in HOORC.

Data sharing agreements among the stakeholders were drawn up by HOORC with the assistance of the Chief Technical Advisor. However, there are several constraints in sharing the data collected by the Hydrology Division. The primary concern for the stakeholders is that the data cannot be obtained by interested parties as the Department of Water Affairs has a policy of charging for data procurement. In addition, there is still confusion in sharing of data between institutions such as Water Affairs and HOORC and the other Government Departments. The other reason is that the databases used by the various institutions are incompatible.

The major institutions responsible for hydrological data collection in Botswana are the Department of Water Affairs (DWA), Department of Meteorological Services (DMS), Department of Surveys and Mapping (DSM), Department of Geological Surveys (DGS) and the Water Utilities Cooperation (WUC). The table below shows a list of data collected in each department;

Department	Data Collected
DWA	Flow, Water Levels, Cross sections, Water Quality Data, Groundwater levels, Pumping data, Rainfall
DMS	Rainfall, Temperature
DSM	DEM's, Maps
DGS	Soil Data, Boreholes information
WUC	Dams information

The DWA's Hydrology and Water Resources Division is responsible for Hydrological services. The division used HYDATA for data archiving. It is anticipated that the division will soon shift to HYDSTRA database under the SADC HYCOS project. DWA and DGS share a common database called NIGIS – National Integrated Geosciences Information Systems, mainly for borehole information storage.

7.2 Data Sharing and Exchange

7.2.1 Introduction

It is often the case in international shared river basin, that the hydrological institutions of the countries have differing views and priorities regarding hydrological information exchange. Downstream countries tend to place a high priority on effective data exchange, either to ensure timely reaction to water disasters, or to monitor water use in catchments upstream of their country and cross-border inflows. The views in this section have been collated from the hydrological institutions in the three riparian countries of the Okavango Basin.

In an international shared river basin, exchange of hydrological (river flow and quality) information should serve particular purposes, most importantly:

- Exchange of water levels in near real-time, in order to pass on information on events ('disasters') that may have negative impacts, in particular flood conditions (or drought situations or pollution accidents).
- Regular sharing of processed water levels and/or flows, in order to inform about hydrological conditions, and to possibly identify and correct discrepancies between data sets at an early stage.
- Passing on of data in case of ad-hoc requests for particular projects.

In none of the above cases, passed on information should be used for setting up parallel databases. The data should be used for the specific purpose for which it was asked and/or passed on. If the same data is needed for another purpose again at a later stage, the newest data should be asked and passed on, or at least the validity of the previous data sets should be confirmed.

Good courtesy in all cases is also to fully acknowledge the source of information in any documents, reports and publications and to send copies thereof to the source organization.

7.2.2 *The existing situation*

Within the framework of OKACOM, the three member countries are negotiating a Protocol on Hydrological Data Sharing. At present there are no formal mechanisms in place, but Namibia and Botswana have been exchanging river flow information from as early as in 1982. Despite political issues then, combined flow gaugings were carried out in the common border area to resolve apparent differences between the Mohembo and Mukwe stations in Botswana and Namibia respectively.

Until recently, there has been virtually no formal exchange of hydrological and water disaster information between Angola and Namibia. The situation has improved somewhat during the course of 2009, when information on flood levels in Angola were communicated to Namibia via email and cell phone.

There are attempts by the Government of Angola (Goa), through the SNPC, *Serviço Nacional de Protecção Civil* (the National Service of Civil Protection) to establish a sound Early Warning System nationwide. The SNPC is working in a close collaboration with UNDP, with the United Nations Organization for Food and Agriculture (FAO), through EPSMO, with DNA, with INAMET and with INOT, I*nstituto de Ordenamento do Território* (the Institute for Territorial Cadastre)

7.2.3 *Disaster Management*

While the implementation of the draft protocol on hydrological data sharing will go some way to alleviate the situation, it does not specifically address water disaster management requirements. It is a recommendation of this study that a set of comprehensive disaster preparedness, implementation and management plans, protocols and decision support systems be developed for the basin to mitigate the possible effects of floods, droughts and major pollution accidents.

Typical components of such a disaster management system include:

- A Disaster Information Management system consisting of:
    - A GIS / Database system to collect, process, manage and control data and critical information to predict upcoming floods, droughts and surface water pollution disasters.
    - Hydrodynamic and hydrological models to predict the extent and severity of flooding, droughts and pollution plume dispersion.

- Emergency Response Plans to define emergency response activities with regard to floods, droughts and pollution. The protocols should consider critical issues related to emergency response to floods, drought and major pollution accidents, including:
    - Early notification and internal communication
    - Early public communication on national and local levels
    - Early response (evacuation, recovery and rescue plans) including transport and logistics
    - Tasks of different organizations in implementing early response measures, lines of command
    - Trans-boundary communication and mutual assistance aspect
    - Other relevant aspects

- Disaster preparedness plans to enhance flood, drought and pollution disaster preparedness, including:

- An information management system as mentioned previously
- Government response information, including flow of information and lines of command and decision structures; and
- A Public information system.

A Mitigation Preparation Plan. Once the emergency responses to the disaster have been delivered, the responsible governments have to deal with rehabilitation, restoration and possibly repatriation. A general framework and guidance for preparation and implementation of rehabilitation, restoration and repatriation activities should be provided. The plans should emphasize logistic, organizational, legal, financial and international aspects and recommendation for organizing rehabilitation and reconstruction works.

8 Conclusions and Recommendations

8.1 General

8.1.1 Hydrological and Hydraulic Models

Considering the limited availability of measured rainfall and stream flow records, the existing Pitman-based rainfall-runoff model of the basin (Hughes et. al., 2006) performs reasonably well, with good simulation of low flows and errors in peak flows of about 20% (the model more often than not under-estimates peak flows). For traditional water resource assessments the errors in peak flow simulation are not considered to be serious, as it does not significantly affect estimates of run-of-river or storage based yields. In the EFA study it was found that this does pose problems, in that the ecologists attach much greater importance to the magnitude of flood peaks and found it difficult to relate simulated peak flows to their knowledge of observed floods and associated ecosystem responses.

A recommendation of this study is that the rainfall-runoff model be re-calibrated with a view to improve peak flow simulation. As part of the same exercise, the model should be extended to cover the hydrological years from 2003 to as recently as possible to include the severe drought of 2007 and the major flood events of 2009 and 2010. The re-calibration should make use of the stream flow records that are becoming available from rehabilitated flow measuring stations in Angola.

The assembled suite of existing and new models provided adequate information on river flow regimes and inundation patterns at the EFA sites, with some scope for improvement. Major shortcomings include:

- The inability to provide modelled (scenario) information on water quality changes in the system, mainly due to a lack of historical water quality measurements for model calibration
- The absence of a sediment transport model (or models) in the basin upstream of the Delta
- Basic one-dimensional, steady state hydrodynamic models were configured for the floodplain sites in the basin (Cuito Cuanavale and Kapako), but these could be improved substantially by using higher resolution topographical information and the configuration of two-dimensional models.

The hydrological working group engaged in an intensive exercise to collect information about existing and possible future water resource developments in the Okavango River basin. The information was assembled by means of literature reviews and extensive consultations with water resource planners and managers in the three co-basin states, and formed the basis for formulation of the water resource development scenarios that were evaluated in the EFA.

The water resources of the basin are relatively un-developed at present. Current water use consists mainly of:

- The urban water demands of Menongue and Cuito Cuanavale (Angola), Rundu (Namibia), and Maun (Botswana)
- About 2 700 ha of irrigation in the Namibian portion of the basin
- Rural domestic and subsistence agricultural water demands and water demands of the tourism sector (Namibia and Botswana), all of which are small compared to the irrigation and urban demands

8.1.2 *Water Resource Development*

The end of the civil conflict in Angola has provided impetus to plans to develop the dormant agricultural economy in the Angolan portion of the basin and to revive plans for the construction of a number of hydropower schemes. Agricultural development and the rehabilitation of the transport network will see associated growth in the urban water demands of Menongue and Cuito Cuanavale. In Namibia, plans to improve food security could result in substantial growth in irrigation water requirements, although not at the same scale as foreseen for Angola. In Botswana, growth in urban and agricultural water demand could be tempered by the need to conserve natural resources and protect income derived from tourism in the Delta region. Against this backdrop, the following water resource developments that could be associated with a high water demand scenario were identified by the working group:

- About 15 000 ha of irrigation in Namibia
- About 338 000 ha of irrigation at various locations in Angola
- Completion of all planned hydropower stations in Angola, i.e. one storage based and nine run-of-river hydropower stations,
- Extension of Grootfontein-Okavango link of the Eastern National Water Carrier in Namibia (total capacity 100 Mm^3/a)
- The possible construction of a hydropower station at Popa Falls in Namibia.
- Substantial growth in the urban water demands of Menongue, Cuito Cuanavale, Rundu, and (to a lesser extent), Maun.

Construction of a reservoir in the Boteti to supplement Maun's future water demands.

8.2 Angola

Recording of hydrological information in Angola stopped in the 1980s, when the civil war increased in intensity. Therefore most of the data and information used by the team are historic. The age of the existing data and information will have an effect on the accuracy of the study results.

The first pre-condition for better water resource planning and management is the rehabilitation of the hydrometric network nationwide. Based on the new data and information to be collected, the Water Authorities need to re-think the management of the Water Sector.

Actions on flood response and the calibration of stations should be prioritised.

The inventory and monitoring of groundwater should also be seen as a priority area for research.

8.3 Namibia

Both the monitoring sites Kapako and Popa Falls sites do not have hydrological monitoring equipment and reference was made to stations upstream and downstream of the investigated sites. Funding will be required to develop and monitor hydrological stations at Kapako and Popa Falls. Present recording of water levels and flow gaugings, as been conducted by the MAWF should continue to be carried out to enable to record comprehensive information of the sensitive sites identified.

The recommendations are broken up into two phases as further data collection and monitoring will depend on future project and funding. It is recommended that for the present situation:

- Satellite images be obtained for Kapako during the dry and wet seasons to monitor the extent of the floodplain inundation.

- Field observations be done and correlated with Rundu water levels to determine when the flood starts inundating the floodplain and when the flood subsides to such an extent that the floodplains are exposed at Kapako.

- Weekly water level readings to be taken at the pump station at Popa Falls.

- Flow gaugings be carried out downstream of Popa Falls to establish a rating curve for Popa Falls.

For phase 2 it recommended that:

- Hydrological water level recording stations be constructed at a representative site for Kapako and Popa Falls, and that funding be sourced for this.

The responsibilities for these actions will have to be agreed internally between Namwater and DWAF Namibia.

8.4 Botswana

There is a disconnection between government departments in terms of data sharing. There is also duplication of responsibilities. The departments are not informed of the needs of sister departments. The Meteorological Services should for example be aware of the Department of Water Affair’s rainfall and climate information requirements.

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The Okavango River Basin Transboundary Diagnostic Analysis Technical Reports

In 1994, the three riparian countries of the Okavango River Basin – Angola, Botswana and Namibia – agreed to plan for collaborative management of the natural resources of the Okavango, forming the Permanent Okavango River Basin Water Commission (OKACOM). In 2003, with funding from the Global Environment Facility, OKACOM launched the Environmental Protection and Sustainable Management of the Okavango River Basin (EPSMO) Project to coordinate development and to anticipate and address threats to the river and the associated communities and environment. Implemented by the United Nations Development Program and executed by the United Nations Food and Agriculture Organization, the project produced the Transboundary Diagnostic Analysis to establish a base of available scientific evidence to guide future decision making. The study, created from inputs from multi-disciplinary teams in each country, with specialists in hydrology, hydraulics, channel form, water quality, vegetation, aquatic invertebrates, fish, birds, river-dependent terrestrial wildlife, resource economics and socio-cultural issues, was coordinated and managed by a group of specialists from the southern African region in 2008 and 2009.

The following specialist technical reports were produced as part of this process and form substantive background content for the Okavango River Basin Transboundary Diagnostic Analysis.

Final Study Reports	**Reports integrating findings from all country and background reports, and covering the entire basin.**		
		Aylward, B.	*Economic Valuation of Basin Resources: Final Report to EPSMO Project of the UN Food & Agriculture Organization as an Input to the Okavango River Basin Transboundary Diagnostic Analysis*
		Barnes, J. et al.	*Okavango River Basin Transboundary Diagnostic Analysis: Socio-Economic Assessment Final Report*
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