A STUDY OF THE LIKELY CHANGES IN THE HYDROLOGY OF OKAVANGO RIVER DUE TO UPSTREAM DEVELOPMENTS.

STATEMENT OF ORIGINALITY:

Certified that this is the bonafide project work and report (**CEM 702**) of

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Required for the Successful Completion of the MSc in Civil Engineering Degree

Date of Completion of the Report:é é é é é é é é . Student Signature:é é é é é ..

DISCLAIMER:

While utmost care has been taken in the preparation of this research report to provide reliable information, the author shall not be liable for any decision or action taken based on or arising from the use of such information.

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List of Abbreviations

DGS	-	Department of Geological Surveys
DMS	-	Department of Meteorological Services
DSM	-	Department of Surveys and Mapping
DTM	-	Digital Terrain Model
DWA	-	Department of Water Affairs
DWAF	-	Department of Water Affairs and Forestry
EFA	-	Environmental Flow Assessment
EF	-	Efficiency Index
ENWC	-	Eastern National Water Carrier
FAO	-	Food and Agricultural Organization
GIS	-	Geographic Information Systems
GSSHA	-	Gridded Surface/Subsurface Hydrologic Analysis
ICM	-	Integrated Catchment Management
IWR	-	Institute for Water Research
MAR	-	Mean Annual Runoff
MMEWR	-	Ministry of Minerals, Energy and Water Resources
NIGIS	-	National Integrated Geosciences Information Systems
NWMPR	-	National Water Master Plan Review
OBSC	-	Okavango Basin Steering Committee
ODMP	-	Okavango Delta Management Plan
OKASEC	-	Okavango River Basin Secretary
OKACO	-	Okavango River Basin Commission'
ORB	-	Okavango River Basin
RMSE	-	Root Mean Square Error
SADC	-	South African Development Community
SEI	-	Stockholm Environment Institute
SPATSIM	-	Spatial and Time Series Information Modeling
WEAP	-	Water Evaluation and Planning
WERRD	-	Water and Ecosystem Resources in Regional Development
WUC	-	Water Utilities Corporation

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ABSTRACT:

Drinking water supply in Botswana is mainly based on groundwater abstractions which are mostly done in Northern part of the country which includes the Okavango River Catchments. Hydrological modeling of Okavango River Catchment is essential to help in understanding of the hydrology of the watershed and for its water management. The Water Evaluation and Planning (WEAP) model system is used to set up an integrated hydrological model for Okavango River Catchment. This report documents the application of a monthly rainfall-runoff model for the Okavango River Basin. Stream flow is mainly generated in Angola where the Cuito and Cubango rivers arise. They then join and cross the Namibia/Angola border, flowing into the Okavango wetland in Botswana.

The Model gives the results of hydrographs showing how the downstream Region of the Okavango River Basin is likely to behave as the Upstream Region implements its proposed developments. It shows that both the Low and Medium development scenarios can be implemented without any harm to the river and the environment within the river catchment. The low development scenarios is the development implemented in 2015, medium scenario is developments implemented in 2022 whilst High development scenario is implemented in 2032. The High Development Scenario shows that the implementation of the developments may results in very low flows downstream that may even leave some parts of the Okavango Delta with very low flows or even dry when exposed to prolonged low flows. This may also have serious impacts on ecology and tourism in Botswana, and even change the cause of the famous Okavango River. The overall conclusion is that the model, in spite of the limited data access, adequately represents the hydrological response of the basin and that it can be used to assess the impact of future development scenarios.

CHAPTER - 1

INTRODUCTION

This report presents the findings of a hydrological modeling of the Okavango River to predict the downstream impact of water based developments upstream. The study sought to find out the net effect of four possible development regimes on the sustainability of the Okavango Delta in terms of the availability of water to meet its ecological water demand and the replenishment of groundwater in its hinterlands.

The study area is limited to the Okavango River Basin that covers a hydrologically active area of approximately 323 192 km^2 shared by three countries in southern Africa which are Angola, Namibia and Botswana. The river rises in the headwaters of the Cuito and Cubango tributaries in the highland plateau of Angola at an elevation of 1780 metres. It derives its principal flow from 120,000 km^2 of sub-humid and semiarid rangeland in Cuito-Cubango province of Angola before concentrating its flow along the margins of Namibia and Angola and finally spilling into the Okavango Delta at an elevation of 980 metres. (http://www.okacom.org/okavango-river-basin).

The study considered those developments perceived to impact negatively on the sustainability of the Okavango River flow in sustaining the deltaœs water needs. These are the developments that pose increased water demand on the river and its key tributaries like irrigation and urban water demand. The developments that divert or slacken the flow of the river like manmade lakes and dams and those developments that control the actual flow of the river like hydropower plants. The study used the WEAP Model to simulate these developments and their effect on the river flow.

The management of shared resources particularly across national boundaries is an issue that requires constant and systematic consultations to engender a mutual feeling of shared responsibility and equal access to resource benefits. This consultation will only yield sustainable outcomes when they are based on sound scientific analyses. With shared watercourses, the absence of cooperation amongst the states involved is an aspect that will not only breed environmental and socioeconomic degradation for communities and ecologies that are dependent on the watercourse particularly downstream users but may also lead to resource conflict if not properly managed. (Maidment, 1993).

Globally there are treaties and conventions that seek to foster equal access to shared resources and facilitate sustainable development in the watersheds of shared watercourses. In South African Development Community (SADC), the management of shared watercourses is guided by the SADC - Shared Watercourse Protocol. The attainment of the set parameters of these treaties and conventions is achieved through such techniques as Integrated Catchment Management. These techniques are based on the hydrological modeling of shared water courses to guide developments along the shared watershed towards sustainable abstraction.

There are various models used in this process all of which seek to balance the water demands of the various state parties involved with the riparian ecologies sustained by the watercourse and the groundwater flow that depends on the watercourse for replenishment. The models help in studying the effects of changes in the natural environment, both natural and anthropogenic on possible changes in the hydrological system of the shared watercourse. The hydrological modeling of watersheds help the development planners in the watershed to appreciate the short and long term effects of their plans on the sustainability of the watershed ecosystem. The models also help in analysis of present and future hydrological conditions, setting scenarios to answer ñwhat ifò kind of questions. This prepares the development planners on future adversities and also helps them avoid resource depletion by setting sustainable abstraction levels.

1.1 Background and Description to the Problem

The northwest of Botswana including areas around the Okavango Delta depend on groundwater supply for domestic and industrial use water. This groundwater is replenished annually from the flow of the Okavango River and its availability is thus largely dependent on the amount and duration of flow in the Okavango River and Delta. Agricultural activities have also already caused significant impact on groundwater and surface water quality in this area. (National Water Master Plan Review (NWMPR) Volume 8, March 2006).

The upper river reaches of the Okavango River watershed in Angola and Namibia is undergoing urbanization, irrigation and power development based increase in water demand. There are currently planned construction of hydropower plants along the rivers that make up this important watershed including the construction of dams and abstraction points for irrigation and urban water supply in both Angola and Namibia. The reduction in the flow of the Okavango River due to developments upstream will worsen this precarious groundwater supply situation for Ngamiland.

Water resource planning benefits from hydrological models as these models help avoid the development of poor quality water resources. Some of the major problems resulting from poor management of integrated catchments projects are;

- ✓ Dams running dry,
- ✓ Low yields in dams,
- ✓ Floods,
- ✓ Depletion of groundwater due to reduced recharge,
- ✓ Pollution and
- ✓ Low water levels for the downstream ecologies and economies an aspect that may drive resource conflicts.

In order to avoid such problems resulting in poor management of integrated catchment projects, a proper planning is necessary for the catchment. In order to achieve a good plan on the catchment to be able to share the resources sustainably, attention needs to be paid to the following five factors:

- Hydrological data sharing
- National Development Plan sharing
- Joint Commission for the River Catchments decision making.
- Implementation of Common developments that equally contribute to the Riparian states.
- Modeling to enhance planning for the Catchment sustainability

The use of Planning Models such as WEAP is one of the ways through which sustainable Integrated Catchment Management can be achieved.

1.2 Statement of the Problem

The Okavango River is hosting a diverse ecology whose form and pattern follows the spread of the Delta and whose sustainability is based on the flow in the river. This ecology is also sustaining a thriving social economy. The river is also an important source of water for greater Ngamiland and the northwestern part of Botswana for human, livestock and wildlife populations. The river supplies this water both directly and indirectly through direct river abstractions and through the replenishing of the areaǒs groundwater reserves. The flow of the river is largely dependent on the inflow from its drainage basin which stretches from Angola through Namibia. Abstractions in Angola and Namibia thus directly affect the flow of the river into Botswana.

It therefore becomes imperative that development planners along the basin ground their decision on the location and sizing of water harvesting infrastructure and water demand management in sound knowledge of the basin characteristics and its expected response to such human interventions. Failing to analyze and evaluate the hydrological changes of the Okavango River due to developments upstream will lead to the following problems arising;

- ✓ Wrong sizing of upstream developments leading to the depletion of the water resources for downstream users.
- ✓ Failure to anticipate and deal with environmental issues in the catchment
- ✓ Not recognizing the role played by the communities in managing resources
- ✓ Failure to facilitate cooperation amongst the water demand centres.

An international treaty has been established to limit exploitation of the Okavango River and a scientific group of Models to monitor the system.

1.3 Objectives of the Project

To analyze and assess the effects of upstream watershed developments on the hydrology of Okavango River, the following objectives are to be fulfilled;

1. To examine the relationship between the precipitation received by the Okavango River watershed and the level of river flow in the Okavango River over a 30 year period.
2. To assess the impact of increasing water demands at various points along the watershed on the annual flow of the Okavango River.
3. To analyze the effect of the erection of water storage bodies along the watershed on the volume and characteristics of the Okavango River flow.
4. To identify a sustainable development project mix for the upstream areas.

1.3.1 Research Questions

i. To examine the relationship between the precipitation received by the Okavango River watershed and the level of river flow in the Okavango River.
   a. What is the effect of rainfall fluctuations in various segments of the watershed on Okavango River flow?
   b. What is the significance of the contribution of each basin section on the character of the flow of the Okavango River?
   c. What are the current points of water loss in the watershed that affect the flow of the Okavango River?

ii. To assess the impact of increasing water demands at various points along the watershed on the annual flow of the Okavango River.
   a. How will increased water demand at various points along the watershed affect flow in the Okavango River?
   b. How can this increased water demand be managed to reduce effects on the Okavango River flow?
   c. How does the location of water abstraction points upstream affect the flow of the Okavango River?

iii. To analyze the effect of the erection of water storage bodies along the watershed on the volume and characteristics of the Okavango River flow.

   a. How will the sizing of dams built upstream affect downstream hydrology?
   b. How will the location of storage dams upstream affect downstream hydrology?

iv. To identify a sustainable development project mix for the upstream areas.

   c. What level of upstream development will be sustainable for the Okavango River hydrology?
   d. Which types of developments would allow limited negative effects on the Okavango River hydrology?

In this study, the WEAP Model, a lumped model, was used to simulate the hydrology of the Okavango River. The aims of this study are as follows;

1.4 Previous Work

1.4.1 Application of the Pitman Model to the Okavango River basin based on the estimates of undeveloped Catchment runoff.

The hydrology of the data Okavango River Basin (ORB) 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 (Figure 1-1). 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 1930s) 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. A reasonable calibration was achieved, as shown in chapter 5 with good simulation of low flows and errors in peak flows of about 20% (the model more often than not under-estimates peak flows).

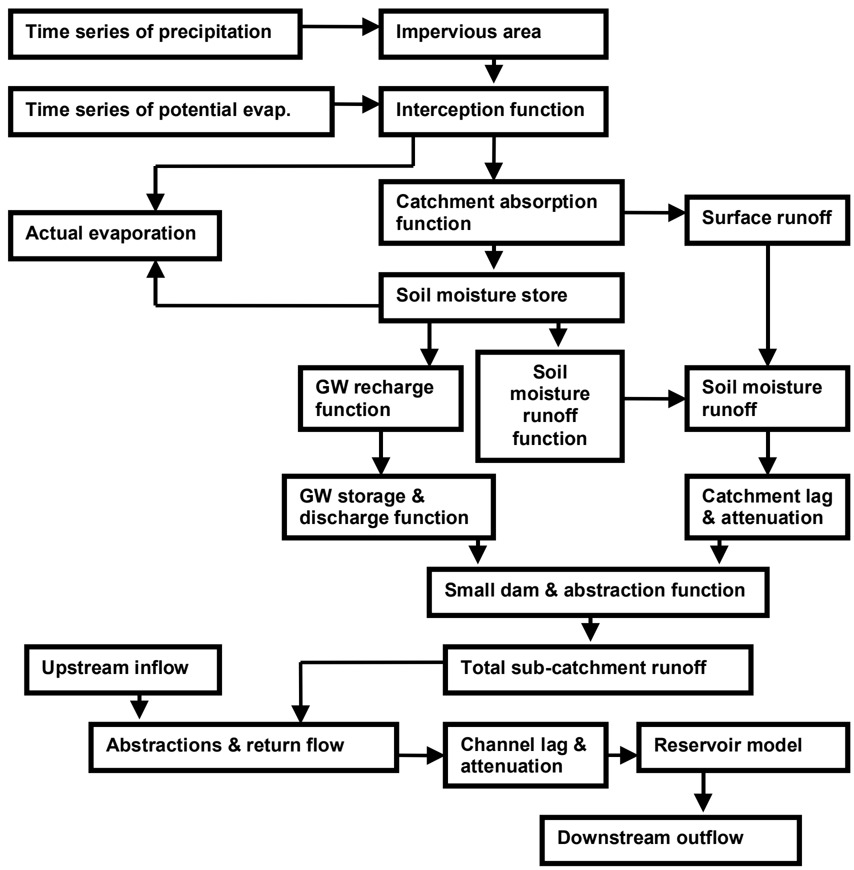
A summary of sub-basin rainfall and naturalised (undeveloped) runoff is shown in Table 1-1 below (Some of the 24 Sub-catchments have been combined and others split to provide rainfall and runoff estimates for each of the main tributaries). (Hughes *et. al.,* 2006).

Table 1-1: Sub basin Run Off.

River / zone	**Area**	**Mean Annual Rainfall**	**Mean Annual Runoff**	**Percentage contribution**
	Km^2	**mm**	**million m^3/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%
Cuatiri	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 the Delta)	**156 250**	**837**	**10 914.7**	**100%**

Source: Hughes *et. al.,* 2006

Figure 1-1: Flow diagram of the main components of the Spartial and Time Series Information Modelling Version of the Pitman Model.



Source: Mendelssohn and El Obeid, 2004.

CHAPTER - 2

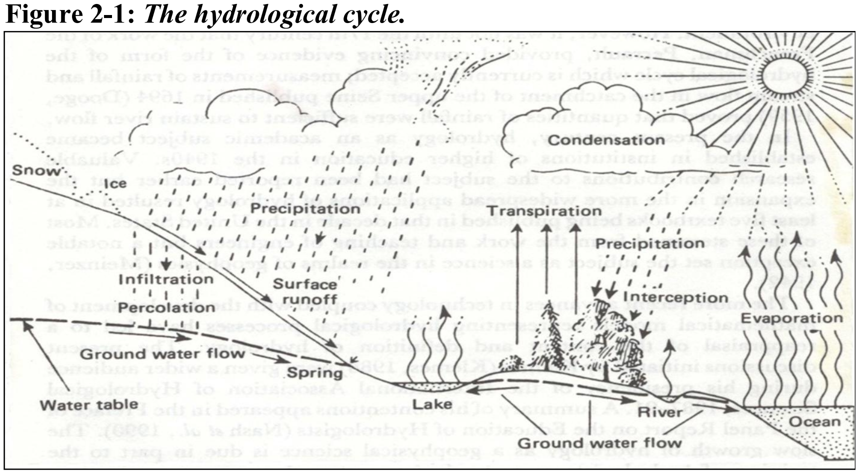
LITERATURE REVIEW

2.1 THEORY

2.1.1 Hydrological Cycle

Most of the Earthôs water is stored on the surface in lakes, rivers and oceans. Direct heating effect of the sunôs radiations on these big reservoirs marks the beginning of the hydrological cycle. Due to the heat energy from the sunôs radiation the surface water is changed from a liquid state into a gaseous state and evaporates into the atmosphere. As the water vapor rises higher and higher it gets cooler again and changes back into the liquid state through a process of condensation, forms clouds and precipitates back into the earthôs surface. The rainfall on reaching the ground may get collected to form surface runoff or penetrates through the ground by infiltration process. The rain water may also be intercepted by vegetation and may evaporate to the air again. When the water has penetrated through the ground, it percolates through the soil layers to reach the water table. As the ground becomes saturated, part of the water is taken up through plant roots then transpired back into the atmosphere, whereas some of the water flows down the gradient by groundwater flow to join the surface runoff into surface streams and rivers flown and may be held temporarily in lakes and finally into oceans.(Figure 2-1). Once the water is back in the oceans and surface water bodies, the whole process starts again, repeating itself again and again forming a hydrological cycle. (Shaw *et al.,* 1999)

Figure 2-1: ***The hydrological cycle.***

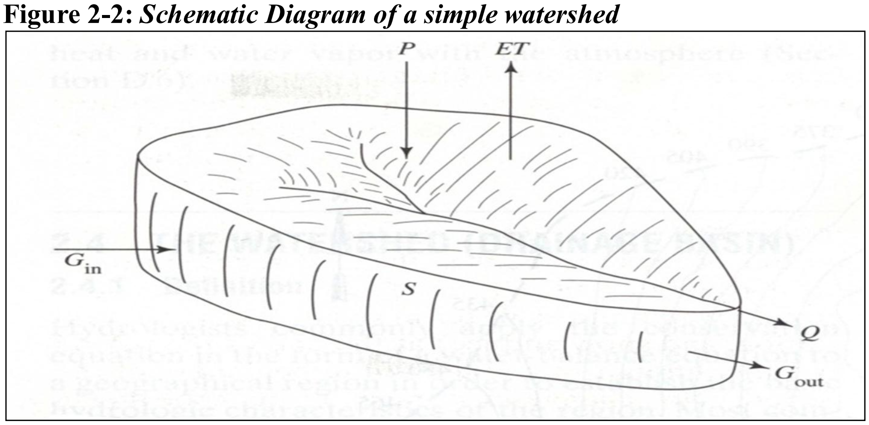


Source: Shaw, 1999

2.1.2 Watershed Hydrology

Water balance is an accounting of inputs and outputs of water in a watershed. A watershed is a land area contributing runoff or draining into a stream at any given point (Chow *et al.,* 1988). The watershed area can be delineated by natural hydrological boundaries such as topography covering a river and its tributaries. (Figure 2-2). Watershed topography, geology and land cover are important in determining the quantity, quality and timing of stream flow at its outlet as well as of groundwater outflow. The hydrology of a watershed can be described by physical laws such as conservation of mass, Newtonǿs laws of motion and the law of thermodynamics (Dingman, 2002).

Figure 2-2: ***Schematic Diagram of a simple watershed***



Source: Dingman, 2002)

The water balance of a watershed is determined by calculating the inputs, outputs and storage change of water in that defined area or volume of land. The water balance of a watershed can be assumed to be the amount of water entering a watershed which is equal to the amount of water leaving the watershed plus the net change in storage in the watershed, that is;

Input ï Output = Net Change in Storage

The major input of water into the land surface is precipitation and the output is evapotranspiration. The water balance equation of a simple watershed shown in the diagram above can be written as shown in equation 2-1 below;

$$\Delta S = P + G_{in} - (Q + ET + G_{out}) \qquad (2\text{-}1)$$

Where P is precipitation, G_{in} is groundwater inflow, Q is the stream outflow, ET is evapotranspiration, G_{out} is groundwater outflow and ΔS is the change in storage. Water balance approach is a good methodology for water resource analysis and it is a good tool for assessment of water needs and utilizations (Dingman, 2002).

2.1.3 Catchment Modeling

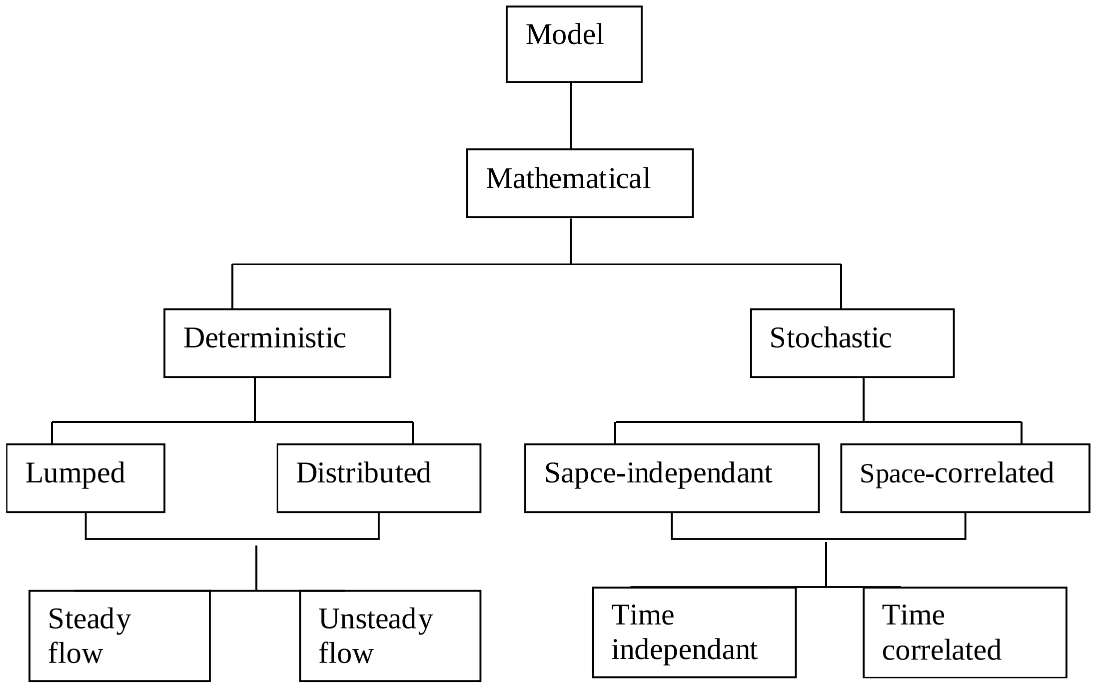
A model is a representation of a portion of the natural or human constructed world. The main characteristic of a simulation model is that it should be able to produce outputs in response to inputs. The three major classes of simulation models are physical, analog and mathematical models. A physical model is a scaled down representation of a real or natural system. In an analog model, the observations of one process are used to simulate another physically analogous natural process. The mathematical model consists of explicit sequential set of equations and numerical and logical steps, which converts numerical inputs into numerical outputs (Dingman, 2002).

A model can be deterministic, where parameters are determined by governing equations, there is no randomness, whilst a stochastic model is partially random, input variables are partially described by deterministic and probability equations. Deterministic and partially deterministic models can be lumped; a system spatially averaged, considered as a single dimensionless point in space, or distributed; hydrological processes considered to be spread over various points in space, and model variable defined as functions of the space dimensions.

Stochastic models can either be space-independent or space-correlated depending on whether variables in space influence each other.

Deterministic hydrological models can be classified as steady flow, whereby flow rate is not changing with time or unsteady flow, and stochastic models can represent a sequence of hydrological events dependent on each other, i.e. time-correlated where the next event in a sequence is partially influenced by the current one or others in a sequence (Figure 2-3). (Chow *et. al*., 1988).

Figure 2-3*: Classification of hydrological models*



Source: Chow *et. al*., 1988).

Rapid advances in computer technology have led to the replacement of physical and analog models by mathematical models which are cheaper and flexible. Hydrological Modeling has become a widely used phenomenon in hydrologic research work. Most of the hydrological research work is nowadays directed towards improving the ability to predict and forecast the impacts and effects of land use and climate change on water balance, groundwater levels and streamflow variability.

The use of hydrologic models has become very important tools in solving practical problems of hydrologic designs, forecasting and planning for development. They are used in formulation of water resources management strategies.

The elements of the modeling process are as follows;

1. *Figuring out the problem and its major concept*
2. *Selection or development of the appropriate model*
3. *Parameter estimation*
4. *Testing and accepting the model*

Some of the examples of the most widely used models of watershed hydrology includes, MIKE SHE, modeling long term water balance and water quality; HBV, predicting non-point source pollution; HSPF and SWMM models and CLEAMS and CREAMS models for predicting runoff from agricultural watershed and WEAP Model used for runoff Planning purposes such as the effects of developments on the downstream of the Okavango River. (Sivapalan, 2002)

2.1.4 Thesis Model Selection

The study also evaluated available hydrological modeling methods and techniques for adequacy and ease of use in the exploration of the goal of this study. The selection process identified and adopted the WEAP Model for the study as it met all the best attributes of a suitable method for the study question. A Table 2-1 below shows the comparison of the three Catchment Management Models that were considered for the application in the research study. The study considered WEAP, MIKE SHE and GSSHA Models;

Table 2-1***: Hydrological Model Selection for the Thesis***

WEAP	MIKE SHE	GSSHA
Water Evaluation And Planning system is a Windows-based decision support system for integrated water resources management and policy analysis.	MIKE SHE is an integrated hydrological modeling system for building and simulating surface water flow and groundwater flow.	Gridded Surface/Subsurface Hydrologic Analysis is a two-dimensional, physically based watershed model
It simulates water demand, supply, runoff, evapotranspiration, infiltration, crop irrigation requirements, instream flow requirements, ecosystem services, groundwater and surface storage, reservoir operations, and pollution generation, treatment, discharge and instream water quality, all under scenarios of varying policy, hydrology, climate, land use, technology and socio-economic factors	It simulate the entire land phase of the hydrologic cycle and allows components to be used independently and customized to local needs	It simulates surface water and groundwater hydrology, erosion and sediment transport.

Used for climate change adaptation studies, and has been applied by researchers and planners in hundreds of organizations worldwide.	Used for the analysis, planning and management of a wide range of water resources and environmental problems related to surface water and groundwater, especially surface-water impact from groundwater withdrawal, conjunctive use of groundwater and surface water, wetland management and restoration, river basin management and planning, impact studies for changes in land use and climate.	Used for hydraulic engineering and research mainly for flood hydrograph estimation. Input is best prepared by the Watershed Modeling System interface, which effectively links the model with geographic information systems (GIS).
WEAP is distributed at no charge to non-profit, academic and governmental organizations based in developing countries.	The license is very expensive to obtain and renew.	The license for installation of the model and GIS services are expensive to obtain and renew.
Easy to input data and run the Model	Due to the complexity of the Model, it is not easy to run it in a short space of time	Takes time to learn and run the Model.

Source: http://www.scribd.com/doc/6914047/Weap20Modelling:

The selection of the appropriate Model to undertake activities has been guided by the following criteria;

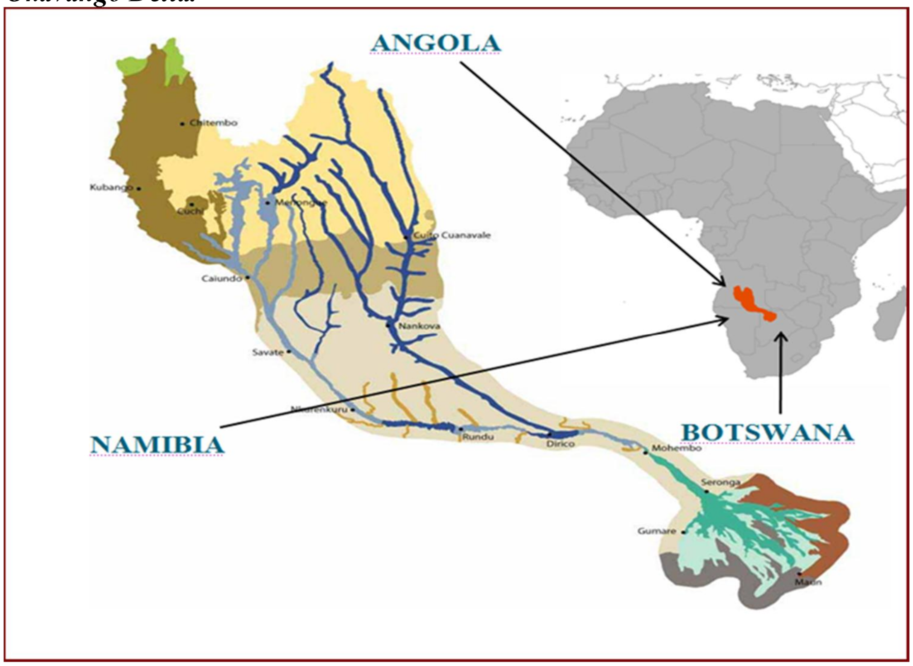
i. The Model needed to take into account all water uses
ii. Adaptable to available data and information gaps as per data obtained from different gauging stations.
iii. Model to be able to handle management options under different scenarios (low, middle and high).

Based on the comparison above, the WEAP model was adopted as the appropriate modeling application because of its policy orientation, flexibility and user friendly interface and because the license is provided for free to public and research institutions in developing countries.

2.1.4.1 Description of Okavango River Basin

The study area is limited to the Okavango River Basin that covers a hydrologically active area of approximately 323 192 km^2 shared by three countries in southern Africa which are Angola, Namibia and Botswana. The Okavango River is the fourth longest river system in southern Africa, running for 1,100 km from central Angola, as the Kubango, through Namibia to the Kalahari in Botswana. (Figure 2-4). The river rises in the headwaters of the Cuito and Cubango tributaries in the highland plateau of Angola at an elevation of 1780 metres. It derives its principal flow from 120,000 km² of sub-humid and semiarid rangeland in Cuito-Cubango province of Angola before concentrating its flow along the margins of Namibia and Angola and finally spilling into the Okavango fan or ódeltaô at an elevation of 980 metres. Several rivers become one as the water moves south and east, branching again when it reaches and ends in the Okavango Delta, one of the largest freshwater inland wetlands on the planet. The river delivers about 10 cubic kilometres of surface flow into the Delta system per annum. (http://www.okacom.org/okavango-river-basin).

Figure 2-4: ***The Map showing the (Study Area) Okavango basins that contribute flow to the Okavango Delta.***



2.1.4.2 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. (Bauer *et. al*., 2002).

2.1.4.3 Selection of development Scenarios

A scenario can be defined as a plausible description of how the future may develop, based on a coherent and internally consistent set of assumptions about key relationships and driving forces. Scenarios are neither predictions nor forecasts. Since it is not possible to predict exactly how the water demands and other factors that affect water resources are going to change in the future it was decided to use scenarios in the current study. A set of scenarios were developed to account for possible changes in the evolution of the water demands, the implementation of the environmental reserve , international agreements water conservation programs and infrastructural development.

For each sector included in the WEAP model (rural, urban, irrigated agriculture, mining and commercial forestry) three scenarios were developed (Figure 2-5). They were called the higher growth (HG), medium growth (MG) and lower growth (LG) scenarios.
All of them were developed based on a mixture of available quantitative and qualitative information and they try to reflect the higher, intermediate and lower ends of the future water demands. There are other factors that can impact future water resources development in the Okavango catchment (e.g., the development of new water infrastructure, application of the environmental reserve, international agreements, water conservation and demand management practices, etc.). Scenarios to account for these other factors were developed separately and then combined with the demand scenarios.

The model shall be used to simulate different development scenarios from low, medium and high developments. The research will be limited to using available hydrological data from Angola, Botswana and Namibia**.**

The present, relatively undeveloped state of the basin provides a known reference point from which extrapolations can be made to assess future development states. This ñPresent Dayò state represents one of the four scenarios that will be assessed as part of the Integrated Flow Assessment.

The four development scenarios were constructed along the following lines:

1. ***The Present Day scenario*** includes all existing water resource developments, notably;

i. About 2 700 ha of irrigation in Namibia (Barnes *et. al.*, 2005).

ii. urban water demands of Menongue and Cuito Cuanavale (Angola), Rundu (Namibia), and Maun (Botswana)

2. ***A low economic growth scenario*** includes;

i. Continuation of historical growth in water demands

ii. Growth rates in Angola reflect recent acceleration associated with resettlement in de-mined areas.

iii. Increased water use mainly due to growth in urban and rural domestic, livestock and irrigation water demands.

iv. Hydropower development in Angola

3. ***A medium growth scenario* which includes;**

i. Increased irrigation in Namibia and Angola

ii. First phase of water transfer from the Kavango to Grootfontein and Windhoek,

iii. One storage based and four run-of-river hydropower stations in Angola

4. ***A high growth scenario which includes***

i. As much as possible of the irrigation potential

ii. Second phase of water transfer from the Kavango to Grootfontein and Windhoek

iii. Construction of all planned hydropower stations

iv. Introduction of a large storage in the upper basin to provide for shortfalls in irrigation water supply and inter-basin transfers.

Figure 2-5: ***Sketch of the three different water demand scenarios considered for each sector.***

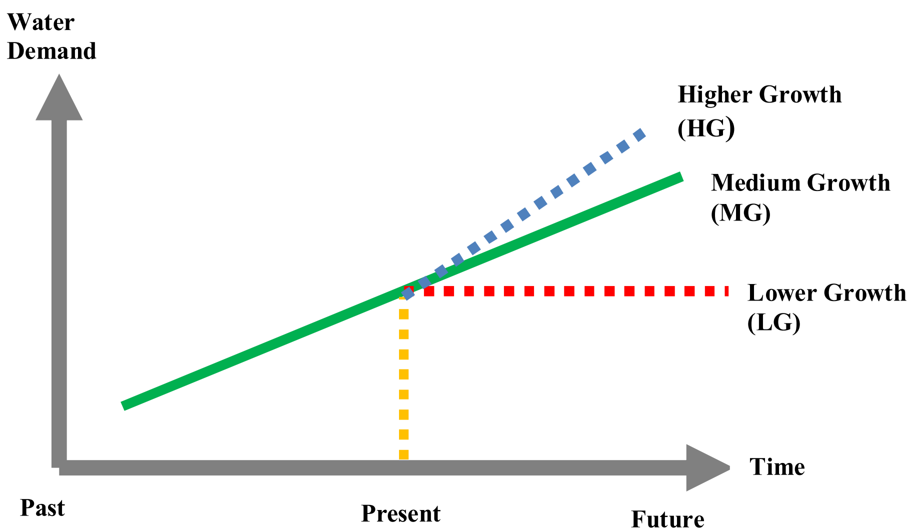
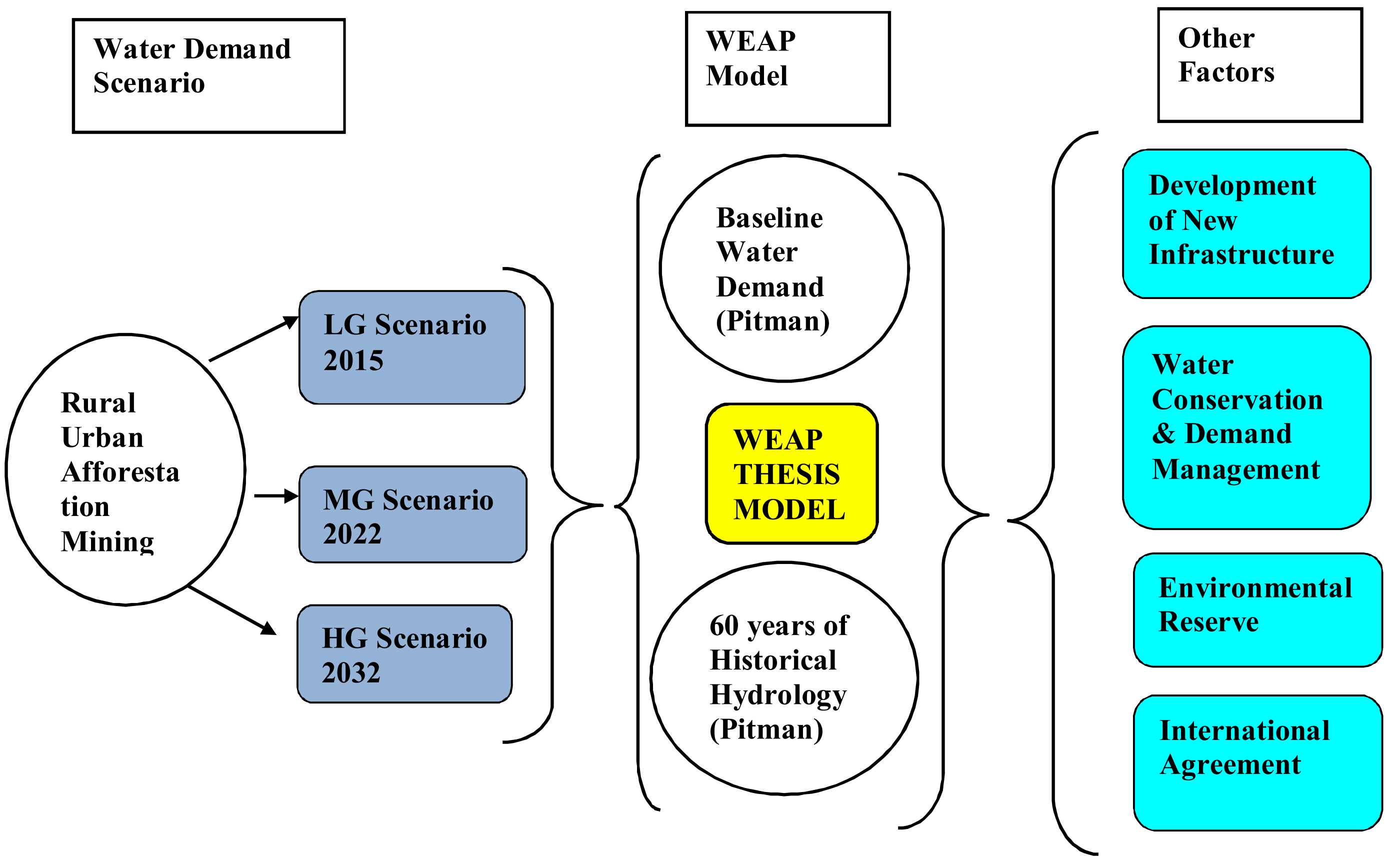


Figure 2-6: *The layout of the scenarios considered, baseline data and the WEAP model.*



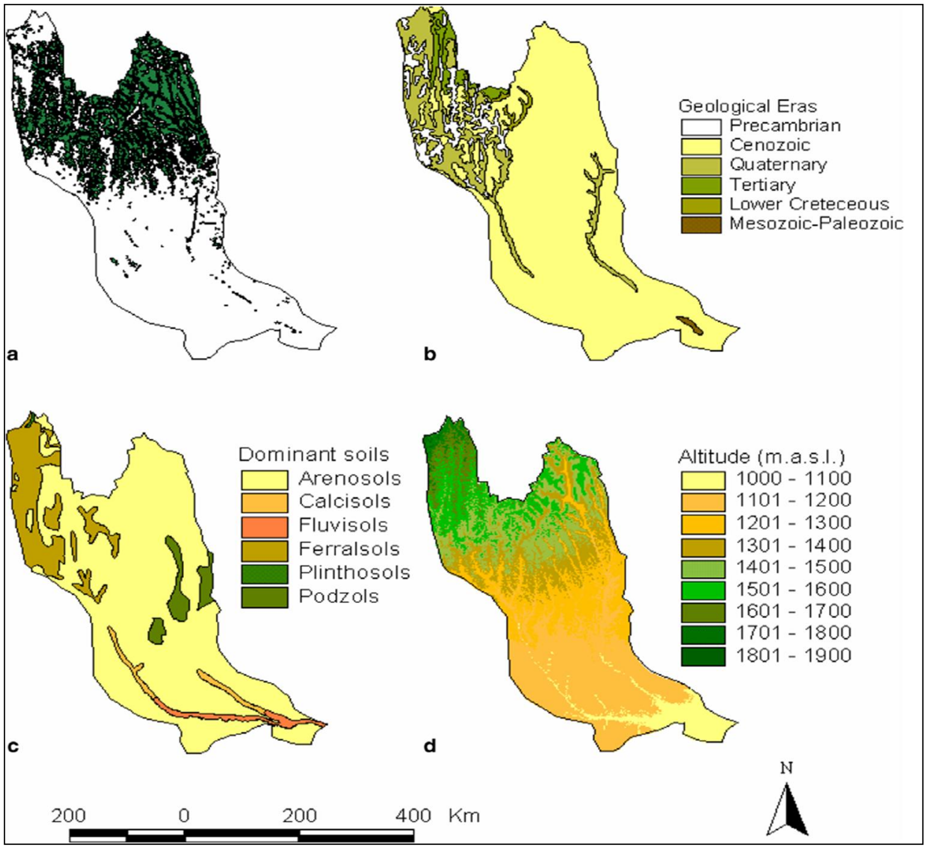
2.2 Input Data

Input data is the hydrological data that was used in this study collected from all the three riparian states i.e. Angola, Botswana and Namibia. Examples of such data are discharge data, rainfall data, evaporation data, irrigation data, urban and rural water demands data.

2.2.1 Hydro-Geological Data

Soil distributions and geology, topography and forest cover are shown in Figure. 2-7 below. Soils information was obtained from Food and Agricultural Organisation (FAO), while the geological information and topography map are from the USGS. Sub-basins in the western upper part of the basin are underlain by rocks of volcanic and metamorphic origin, as well as some Karoo Group sandstone and mudstone, all with a thin mantle of Kalahari Sand. (Mendelssohn and El Obeid, 2004).

Figure 2-7 :*(a) Forest Cover (b) Geology (c) Soils and (d) Altitude of the Okavango River Basin.*



Source: Mendelssohn and El Obeid, 2004

2.2.2 Evaporation Data

2.2.2.1 Angola

Table 2-2 below shows that out of the 7No. of the stations measuring evaporation rate in Angola only one station is operational at Menongue. Other stations are not operational; hence no Angolan evaporation data used was not adequate.

Table 2-2: ***Location of Angolan evaporation measuring stations***

Station name	Number (ID)	Latitude (DMS)	Longitude (DMS)	From	To	Status
Chianga (Huambo)	N/A	12°44ĉ	15°50ĉ	1951	1970	Not operational
Chitembo (Bié)	N/A	13°31ô	16°46ô	1941	1970	Not operational
Cangamba (Moxico)	N/A	N/A	N/A	N/A	N/A	Not operational
Cuvango(ex-		14°28ĉ	16°18ĉ	1951	1967	Not

Arturde Paiva)						operational
Menongue		14°40ô	17°12ô	1953	1967	Operational
Cuito Cuanavale	N/A	N/A	N/A	N/A	N/A	Not operational
Cuangar	N/A	17°35ô	18°39ô	1955	1967	Not operational

Source: Caracterização Sumária das Condições Ambientais de Angola, 1967.

2.2.2.2 Namibia

A Table 2-3 shows the average monthly evaporation data for stations in Namibia for a period of one year. It shows the highest evaporation rate of 218 mm in October, whilst the lowest (127 mm) was experienced in July.

Table 2-3: ***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

Source: Department of Water Affairs and Forestry, Hydrology Division

2.2.3 Population Data

2.2.3.1 Angola

Most of the population which is dominant in the Okavango River Basin in Angola lies in the rural settlements. The highest rural population is experienced in Cuvango (Huila) with the highest projected value of 116 995 in year 2025 and the lowest population of 77 677 in year 2006. The only Urban population stays in Menongue about 356 112 projected in the year 2025 and 235 515 people in 2006 as shown in Table 2-4.

Table 2-4*: *Angola population projection

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	65242	Rural
Cuangar (Kuando Kubango)	Cubango/Okavango	42 428	44 316	46 287	51 608	57 541	64156	Rural
Calai (Kuando Kubango)	Cubango/Okavango	77 250	80 687	84 276	93 964	104765	116808	Rural
Dirico	Cuito / Cubango	8 627	8 976	9 375	10 453	11 655	12 995	Rural

Source: (GEPE - Kuando Kubango 2) FAO / IDA

2.2.3.2 Namibia

The majority of the population shown in Table 2-5 below stay in rural settlements in Namibia along the Caprivi Strip. The data obtained from the National Planning Commission of 2001 shows that a Total of 202 694 people stays along the catchment of Okavango River. Most rural population of about 30 903 occupy Kahenge region whilst 19 173 of the population occupy the Urban region of Rundu.

Table 2-5: ***Population of Kavango Region 2001***

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

Source: National Planning Commission, 2001

2.2.3.3 Botswana

The majority of the population in the Okavango Basin part of Botswana also stay in rural settlements in Ngamiland District. The National Water Master Plan of 2006 shows that in 2005, the population was 133 000 and is projected to be 145 418 in year 2035 and the corresponding water demand are 3 654 and 6 008 m^3/year respectively. (Table 2-6).

Table 2-6: Estimated and projected population growth and Water Demands for the Ngamiland Region

Year	2005	2010	2015	2020	2025	2030	2035
Population Growth	133 000	139 360	141948	143 943	144 765	145204	145418
Water Demand (m^3/year)	3 654.4	4064.66	4 384	4 727.66	5 099.69	5524.37	6 008.8

National Water Master Review of 2006

2.2.4 Irrigation and Urban Water Demands Data

2.2.4.1 Angola Irrigation Demands Data

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.

In the low development water use scenario 3 irrigation schemes were identified downstream of Menongue, namely Missombo, Menongue Agriculture Scheme and Ebitrex, 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 Ebitrex, 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 Okavango River Basin 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:

i. 90 000 hectares in Cuito Cuanavale,
ii. 45 000 hectares in Cuangar/ Calai, and
iii. 35 000 hectares in Calai/Dirico.

2.2.4.2 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;

i. 356 000 inhabitants in the high water use scenario (2032);
ii. 286 000 inhabitants in the medium water use scenario (2022) and
iii. 257 000 inhabitants in the low water use scenario (2015).

The city of Cuito Cuanavale will have the following population;

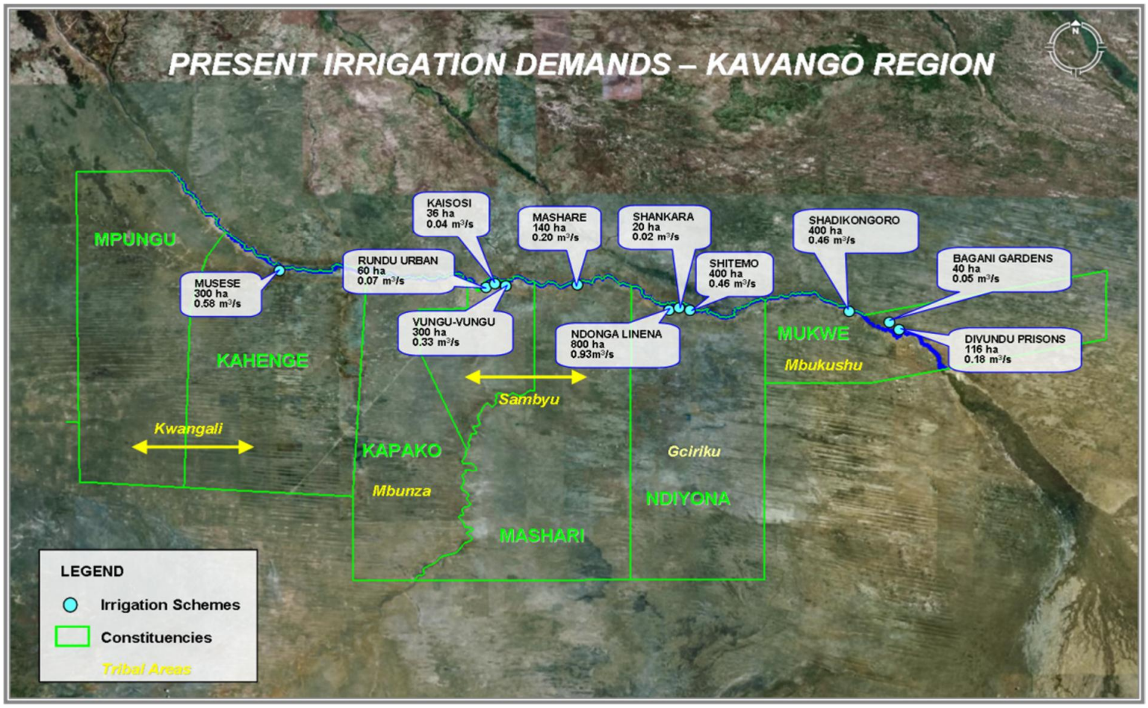
i. 160 000 inhabitants in the high water use scenario;
ii. 128 600 inhabitants in the medium water use scenario and
iii. 115 000 inhabitants in the low water use scenario.

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

2.2.4.3 Namibia Irrigation Water Demands Data

There figure 2-8 below different irrigation schemes practiced in different constituencies in Namibia. The biggest irrigation practised is the 800 Ha of land in Ndonga Linena using 0.93m$^{3/}$s. The irrigation practiced at low scale is the 20 Ha of land in Shankara at 0.02 m^3/s of flow.

Figure 2-8: Existing irrigation developments along the Okavango River.



Source: Beuster, 2007

A Table 2-7 below shows the combined irrigation schemes per constituencies. The highest irrigation demands are experienced at Ndiyona Constituency of about 870 Ha whilst the least is practiced in the Kahenge Region of 300 Ha.

Table 2-7: Combined schemes per Constituency for present and future irrigation

Constituency	Total Irrigable Land (Hectares)			
	2008	**2010**	**2015**	**2025**
Kahenge	300	700	900	900
Rundu Mashari	521	551	551	551
Ndiyona	870	1 270	1 270	1 270
Mukwe	556	556	556	556
Rundu (future)	-	-	1 674	1 674
Mukwe (future)	-	-	4 000	10 518

Source: Barnes *et. al*., 2005

2.2.4.4 Namibia Urban Water Demands Data

Table 2-8 shows Total Water Demand at Rundu for all the schemes from 2008 to a projected year of 2015. It shows that in 2008 there was 2.841 Mm^3/a. This was projected to a total of 4.323 Mm^3/a in year 2025. This data was obtained from a report from Nam Water in 2007.

Table 2-8: ***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

Source: NamWater, 2007

2.2.4.5 The 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 17.280 Mm^3/a (Water Transfer Consultants, 1997) for the Medium Development scenario was used as the demand required from the Okavango River for 2022, while for the High Development scenario (2032), a water demand of 100 Mm^3.

2.2.4.6 Irrigation and Urban Water Demands in Botswana

The surface water abstraction in Botswana shown by the ODMP, 2006 shows that in 2005 Khwai had the least of water abstraction of 148 m^3/day compared to Thamalakane River with 26 571 m^3/day of abstraction. (Table 2-9).

Table 2-9: ***Surface Water Abstractions***

River	Abstractions (m^3/day)	
	2005	**2025**
Okavango	6,285	9,107
Thaoge	1,475	2,140
Boro	1,483	2,710
Muanachira	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**

Source: Okavango Delta Management Plan (ODMP) Analysis of Water Resources Scenarios, 2006

2.2.5 Rural Water Demands Data

2.2.5.1 Angola

Due to the scale at which the basin model was configured, water demands of rural settlements were 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 was then used instead.

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 did not include this demand. The table 2-10 below shows that Sheep, Goats and Pigs are 4% of annual growth whilst cattle are 4%.

Table 2-10: ***Angola Livestock Projections***

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

Source: Provincial Director of Agriculture in Kuando Kubango

2.2.5.2 Namibia

The Table 2-11 below shows that in the year 2008, the rural water demand in Namibia portion of the basin was 2.241 Mm^3/a from human activities, schools and clinics. The human activities was the highest with 1.841 $Mm^3/a)^2$ followed by Schools and clinics. The rural water demands are met mainly by groundwater and were not used as input data into the WEAP model for Namibia.

Table 2-12 shows that in the year 2000, a number of livestock was high with a figure of 272 505 in the Kavango region. In 2005 the total number reduced to 232 225.

Table 2-11: ***Rural water demand projections for Kavango Region (Ministry of Agriculture, Water and Rural Development***

Year	Growth rate (%)	Rural water Demand (Mm^3/a)[2]			Total Domestic (Mm^3/a)
		Human	Schools	Clinics	
2008	1.63	1.841	0.385	0.014	**2.241**
2010	1.50	1.898	0.397	0.015	**2.310**
2015	1.50	2.044	0.428	0.016	**2.488**
2025	1.50	2.373	0.497	0.018	**2.888**

Source: Lund Consulting Engineers, 2003

Table 2-12: ***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**
2005	120 894	1 388	49 519	301	1 699	0	48 169	10 255	**232 225**
2006	125 927	1 472	44 135	524	1 555	1 778	55 116	7 122	**237 629**

Source: Directorate of Veterinary Services

2.2.5.3 Botswana

Table below shows the projected livestock from 2005 to 2036. There were less water requirements in the years of 2011 to 2030 which was around 13000m^3. This is compared to the highest figures observed in the years of 2031 to 2036 which is projected to be 18035m^3.

Table 2-13: ***Projected livestock units (' 000) by livestock category per 5 year Duration range in Maun Region***

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 (m^3)	**15916**	**13222**	**13698**	**13616**	**14355**	**18035**

Source: Table 6-22 to 6-31 page 119/120 NWMPR Volume 8, March 2006.

2.3 DESCRIPTION OF WEAP MODEL

2.3.1 Introduction

The computer-based modeling tool used was the WEAP System Model developed by the Stockholm Environment Institute (SEI) to enable evaluation of planning and management issues associated with water resources development. The WEAP model can be applied to both municipal and agricultural systems. It can address a wide range of issues including sectoral demand analyses, water conservation, water rights and allocation priorities, streamflow simulation, reservoir operation, ecosystem requirements and project cost-benefit analyses (SEI, 2001).

To allow simulation of water allocation, the elements that comprise the water demand-supply system and their spatial relationship are characterized for the catchment under consideration. The system is represented in terms of its various water sources (e.g., surface water, groundwater, desalinization and water reuse elements); withdrawal, transmission, reservoirs, and wastewater treatment facilities, and water demands (i.e., user-defined sectors but typically comprising industry, mines, irrigation, domestic supply, etc.). The data structure and level of detail can be customized (e.g., by combining demand sites) to correspond to the requirements of a particular analysis and constraints imposed by limited data. A graphical interface facilitates visualization of the physical features of the system and their layout within the catchment. (Arranz, 2007).

The WEAP model essentially performs a mass balance of flow sequentially down a river system, making allowance for abstractions and inflows. To simulate the system, the river is divided into reaches. The reach boundaries are determined by points in the river where there is a change in flow as a consequence of the confluence with a tributary, or an abstraction or return flow, or where there is a dam or a flow gauging structure. Typically, the WEAP model is applied by configuring the system to simulate a recent ñbaselineò year, for which the water availability and demands can be confidently determined. The model is then used to simulate alternative scenarios (i.e., plausible futures based on ñwhat ifò propositions) to assess the impact of different development and management options.

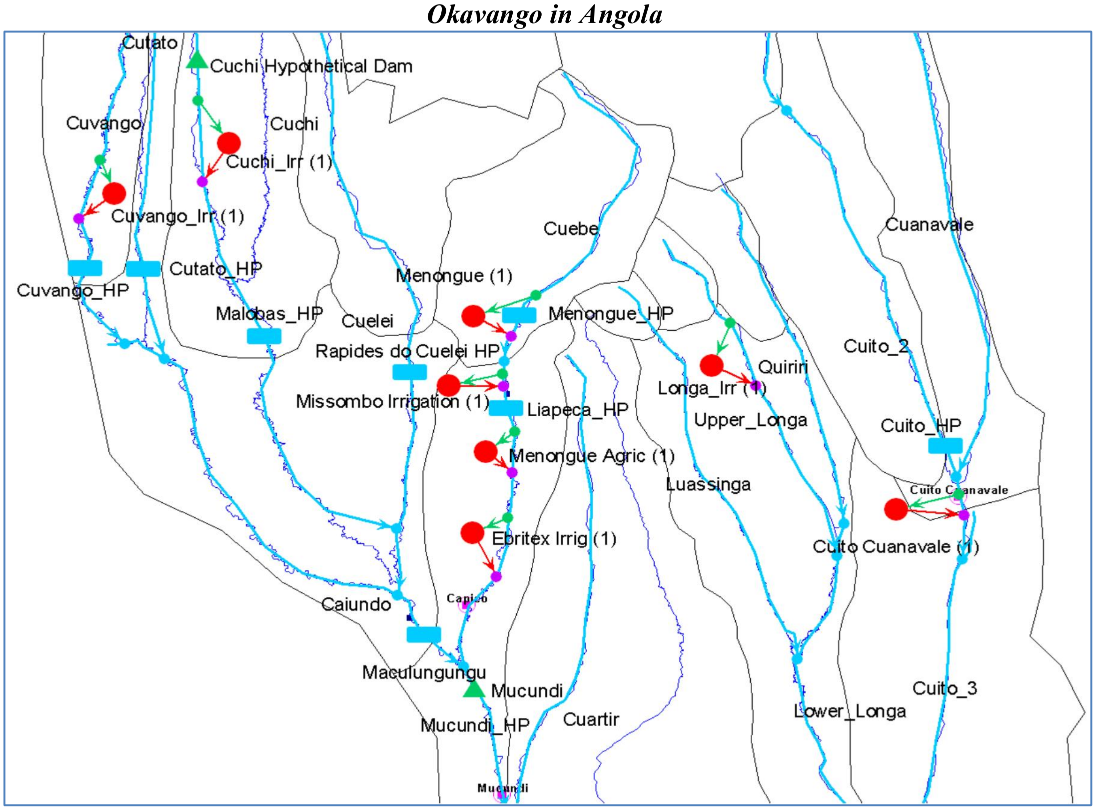
The model optimizes water use in the catchment using an iterative Linear Programming algorithm, whose objective is to maximize the water delivered to demand sites, according to a set of user-defined priorities. All demand sites are assigned a priority between 1 and 99, where 1 is the highest priority and 99 the lowest. When water is limited, the algorithm is formulated to progressively restrict water allocation to those demand sites given the lowest priority. (Sieber *et. al.*, 2004).

The prototype WEAP application of the Okavango River Basin was developed based on information contained in the shared database along with information gathered from other sources in the Basin. Basic categories of data used in developing the prototype model included surface water supply data and estimates of water demand under current conditions and a number of future scenarios. Surface water supply data were derived for a 13 year period (1960-1972) based on simulated stream flows for the Upper Okavango River Basin calculated using the Pitman model developed by the Water and Ecosystem Resources in Regional Development (WERRD) project. These estimates, which were developed for 24 sub-catchments in the Okavango River Basin, were then adjusted so that the average annual accumulated flow past the Mukwe gauge in Namibia was equal to the observed record during the same 13 year period and during the longer 50 year period of record at that gauge. These three distinct surface water supply time series were used to develop a series of hydrologic scenarios. These time series will be introduced into a future version of the Shared Okavango Database.

WEAP operates on the basic principle of water balance accounting, where both the engineered and biophysical components of a water system are represented to facilitate multi-stakeholder water management dialogue on a broad range of topics, including sectoral demand analysis, water conservation, water rights and allocation priorities, reservoir operations, hydropower generation, pollution tracking, ecosystem requirements, and project benefit-cost analysis. WEAP informs management strategies through scenario-driven analyses of possible water futures where the influences of climate, land use management, demand, regulation, and planning objectives can be explored. (Vicuna, 2007).

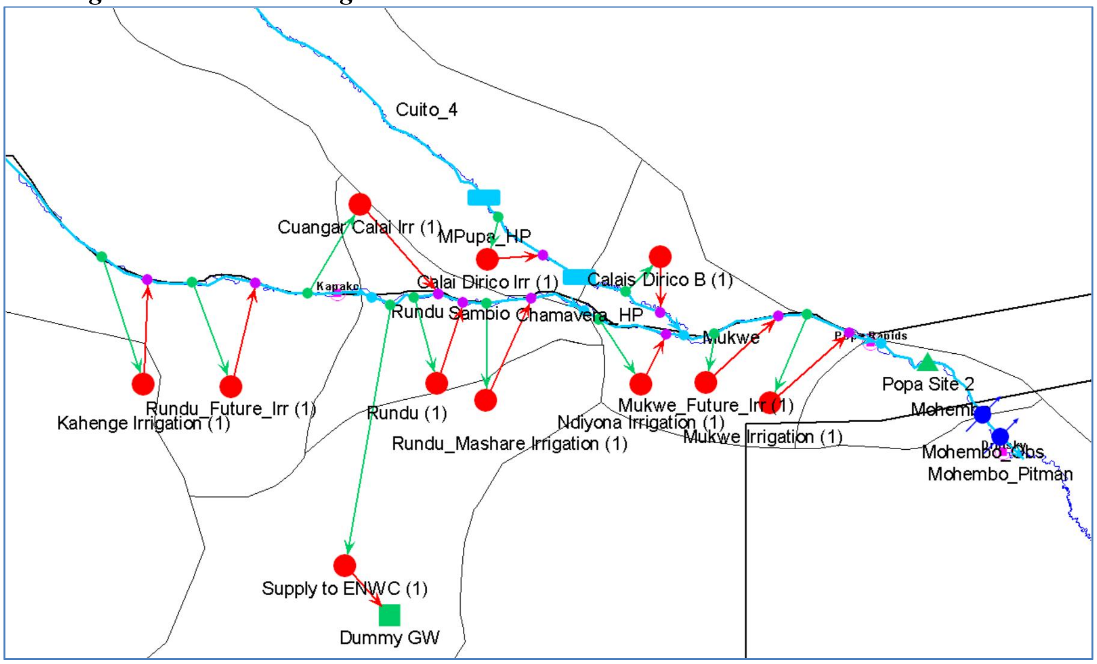
These analyses can be conducted at any number of scales, from municipal water systems and the local catchments to regional, transboundary river systems. Demand (e.g. industrial water use, watershed and agricultural demands through evapotranspiration, and ecosystem requirements) and supply (e.g. precipitation excess, reservoirs, groundwater, desalination plants, etc.) components of a water system are represented in graphical, schematic form with a set of model objects and processes, such as transmission and return flows, wastewater treatment, in-stream chemical degradation or production. Embedded in these objects are a set of transparent allocation, operation, and water quality constraints input by the user. The data structure and level of detail can be easily customized to meet the requirements of a particular analysis.

Figure 2-9: WEAP schematic showing location of proposed developments in the Upper Okavango in Angola



Source: WEAP Study Model, 2014.

Figure 2-10: WEAP schematic showing location of proposed developments in the Lower Okavango shared between Angola and Namibia



Source: WEAP Model, 2014.

The hydrological processes of WEAP water movement are modeled using equations of physical laws; conservation of mass, momentum and energy, or empirical equations obtained from independent experimental research in cases of interception/evapotranspiration and snowmelt. The 1-D and 2-D diffusive wave Saint Venant equations describe channel and overland flow, respectively. The Kristensen and Jensen methods or the Simplified ET for the Two Layer water balance method are used for evapotranspiration, the 1-D Richardsǿs equation or Two Layer water balance method for unsaturated zone flow, and a 3-D Boussinesq equation or the 3-D finite difference method for saturated zone flow. (Hughes, 1997).

2.3.2 Overland flow and Channel flow

When rainfall rate exceeds infiltration rate, it results in surface ponding and eventually surface water flow. Topography, channel shape, flow resistance as well as loses due to evaporation and infiltration are the major parameters used to route surface water as overland and channel flows. WEAPǿs overland flow has options of two methods to calculate water flow on the ground surface. The two methods are; finite difference method which uses the diffusive wave approximation of Saint Venant or the semi-distributed approach base on Mannings equation.

The equation for conservation of mass is given by;

$$\frac{\partial h}{\partial t}+\frac{\partial(uh)}{\partial x}+\frac{\partial(vh)}{\partial y}=i \tag{2-2}$$

where

h is the flow depth above ground surface (m);

u is the velocity (m s^{-1}) in the x-direction,

v is the velocity (m s^{-1}) in the y-direction, and

i is the net input over overland flow (m s^{-1}).

The momentum equations are:

$$S_{fx}=S_{Ox}-\frac{\partial h}{\partial x}-\frac{u}{g}\frac{\partial u}{\partial t}-\frac{1}{g}\frac{\partial u}{\partial t}-\frac{qu}{gh} \tag{2-3}$$

$$S_{fy}=S_{Oy}-\frac{\partial h}{\partial y}-\frac{v}{g}\frac{\partial v}{\partial y}-\frac{1}{g}\frac{\partial v}{\partial y}-\frac{qv}{gh} \tag{2- 4}$$

Diffusive wave approximations of the St Venant equations implemented in WEAP is derived from the fully dynamic St Venant equations, in which the last three terms of the momentum equations are neglected in order to reduce the fully dynamic equations' complexity. Then the momentum equations are;

$$\left.\begin{aligned}S_{fx}=S_{Ox}-\frac{\partial h}{\partial x}=-\frac{\partial z_g}{\partial x}-\frac{\partial h}{\partial x}=\frac{\partial(z_g+h)}{\partial x}=-\frac{\partial z}{\partial x}\\ S_{fy}=S_{Oy}-\frac{\partial h}{\partial y}=-\frac{\partial z_g}{\partial y}-\frac{\partial h}{\partial y}=\frac{\partial(z_g+h)}{\partial y}=-\frac{\partial z}{\partial y}\end{aligned}\right\} \tag{2-5}$$

z_g is the ground surface level and $z = z_g + h$

Sf are the friction slopes in the x and y directions, and

So are the slopes of the ground surface in the x and y directions.

The continuity equation (Equation 2-2) and momentum equations (Equation 2-5) allow the simulation of significant variation in overland flow depth between neighboring cells as well as that of backwater conditions. When applying Manning law for each friction slope, then the above equations become;

$$\left.\begin{aligned} S_{fx} &= \frac{u^2}{K_x{}^2 h^{4/3}} \\ S_{fy} &= \frac{v^2}{K_y{}^2 h^{4/3}} \end{aligned}\right\} \qquad (2\text{-}6)$$

Substituting (Equation 2-5) into (Equation 2-6) and then simplifying further and multiplying both sides by *h*;

$$\begin{aligned} uh &= K_x \left(-\frac{\partial z}{\partial x}\right)^{1/2} h^{5/3} \\ vh &= K_y \left(-\frac{\partial z}{\partial y}\right)^{1/2} h^{5/3} \end{aligned} \qquad (2\text{-}7)$$

Where,

uh and *vh* represent discharge per unit length along the cell boundary in *x*- and *y*-directions respectively [$m^2\ s^{-1}$], and

Kx and *K*y are Manning -M coefficient in *x*- and *y*- directions, respectively.

Using (Eq.2-5) the flow across any boundary between grids can be estimated as shown in equation 2-8 below;

$$Q = \frac{K\Delta x}{\Delta x^{1/2}} \left(Z_U - Z_D\right)^{1/2} h_u^{5/3} \qquad (2\text{-}8)$$

where ;

*h*u is the depth of water that can freely flow into the next cell (actual water depth minus detention storage, mm), and

*Z*u and Z_D are the maximum and minimum water levels, respectively (mm).

Water is added or removed by infiltration, recharge or evaporation in and out of the ponded water in the model grid at the beginning of every overland flow time step. During iteration, since the flow equations are explicitly defined, overland flows are reduced in some situations to avoid internal water balance errors and divergence of the solution scheme. Therefore, outflow as shown (Equation 2-9), should be;

$$\sum |Q_{out}| \leq \frac{\sum Q_{in} + I + \Delta x^2 h(t)}{\Delta t} \qquad (2\text{-}9)$$

where

$\sum Q_{in}$ is the sum of inflows rates ($m^3\ s^{-1}$), and

$I = i\Phi x^2$ is the net input into overland flow in each grid ($m^3\ s^{-1}$).

CHAPTER - 3

METHODOLOGY

3.1 Selection of the Environmental Flow Assessment (EFA) Sites

In all the three countries Angola, Namibia and Botswana EFA sites were selected based on their close proximity to river flow measurement stations. This was motivated by the availability of rating curves and discharge records for use in the assessments. The eight sites selected were used to provide input discharge data for the WEAP Model used in the study.

Table 3-1: ***Environmental Flow Assessment Sites.***

EFA Sites	Country	River	Latitude DMS	Longitude DMS	Location
1	Angola	Cuebe	15°33ĉ	17°34ĉ	Capico
2	Angola	Cubango	16°13ô	17°41ô	Mucundi
3	Angola	Cuito	15°10ô	19°12ô	Cuito Cuanavale
4	Namibia	Okavango	17° 54ô30.81ò	19° 45ô46.46ò	Kapako
5	Namibia	Okavango	18° 02ô09.19ò	21° 25ô39.37ò	Popa Falls
6	Botswana	Okavango	18° 9' 50.5434"	21° 28' 16.8018"	Mohembo
7	Botswana	Khwai	19° 6' 18.8634"	23° 14' 35.3394"	Xakanaka
8	Botswana	Boteti	20° 3' 50.652"	23° 18' 46.947"	Samedupi

3.2 Site Visit

This actually involved visiting some of the hydrometric stations around the Okavango River at Mohembo for the chosen sites for hydrometric data to familiarize the researcher with the hydrology of the river at specific sites and such were also used for data collection.

3.2.1 Baseline Scenario Results from Pitman Model

The results from the Pitman Model (Hughes *et. al.,* 2006) were used as an input data in the baseline scenario for this WEAP Model. The WEAP is used as a planning tool for proposed Water Resources developments. The model is a modified version of the Pitman Model, including more explicit ground and surface water interactions.

However, significant limitations in access to climatological data, and lack of sufficiently long records of observed flow for the eastern sub-basins represented greater challenges to model calibration.

3.2.2 *Model Set Up*

The Okavango basin above Mohembo was divided into 24 sub-basins (Appendix 1) of which 18 had gauging stations at their outlets (Appendix). Of these, 10 are located on the Cubango River (Chinhama to Rundu in Appendix 3). A further five are situated in relatively small headwater tributaries of the upper Cuito River (Cuito to Quiriri in Appendix 3) and have short records with a significant amount of missing data. There are two stations situated close to the inflow to the delta panhandle (Mukwe and Mohembo in Appendix 3). The former has the longest and most complete record. The Omatako River is the largest Namibian tributary but there is no record of this ephemeral river system ever having contributed flow to the Okavango River. (Crerar, 1988).

3.2.3 *Calibration Process*

The calibration was achieved through seasonal flow variation. (Figure 3-1). Sub-basins with similar known (or assumed) characteristics were given similar parameter values and only modified where necessary to achieve satisfactory correspondence between observed and simulated sub-basin outflows. Calibrated parameters (Appendix 2) included surface runoff (ZMIN, ZAVE, ZMAX), the soil moisture storage and runoff function (ST, POW, FT), the ground water recharge (GPOW, GW), and the soil-moisture evaporation (R) parameters.

The correspondence between observed and simulated flow was evaluated using three main objective functions, each calculated on the basis of both un-transformed and natural log-transformed data:

1. Coefficient of determination (R^2).

The measure of the ability to simulate the variation in the discharge hydrographs for a particular river gauging station, R^2.

$$R^2 = \frac{\sum_i (Q_{o,i} - \overline{Q_o})^2 - \sum_i (Q_{s,i} - Q_{o,i})^2}{\sum_i (Q_{o,i} - \overline{Q_o})^2} \qquad (3\text{-}1)$$

Where; $Q_{o,i}$ is the observed daily discharge for day I, $Q_{s,i}$ is the simulated discharge for day I and $\overline{Q_o}$ is the average discharge for the test period.

The maximum value of R^2 is 1 and this expresses a perfect model fit. Previous studies of Danish and international rivers suggest that R^2 value ranges mostly between 0.50 and 0.95 (Henriksen *et. al.,* 2003).

2. Efficiency Index (Ef)

Recognizing the limitations of the correlation coefficient, Nash and Sutcliffe (1971) proposed an alternative goodness-of-fit index, which is often referred to as the Efficiency Index (Ef) as follows;

$$Ef = 1 - \frac{\sum^{n} \left(\lambda - \beta \right)^2}{\sum \left(\alpha - \eta \right)^2} \qquad (3\text{-}2)$$

Where; λ and β are predicted and measured values of the criterion (dependent) variable α, respectively; η is the mean of the measure values of α; and n is the sample size.

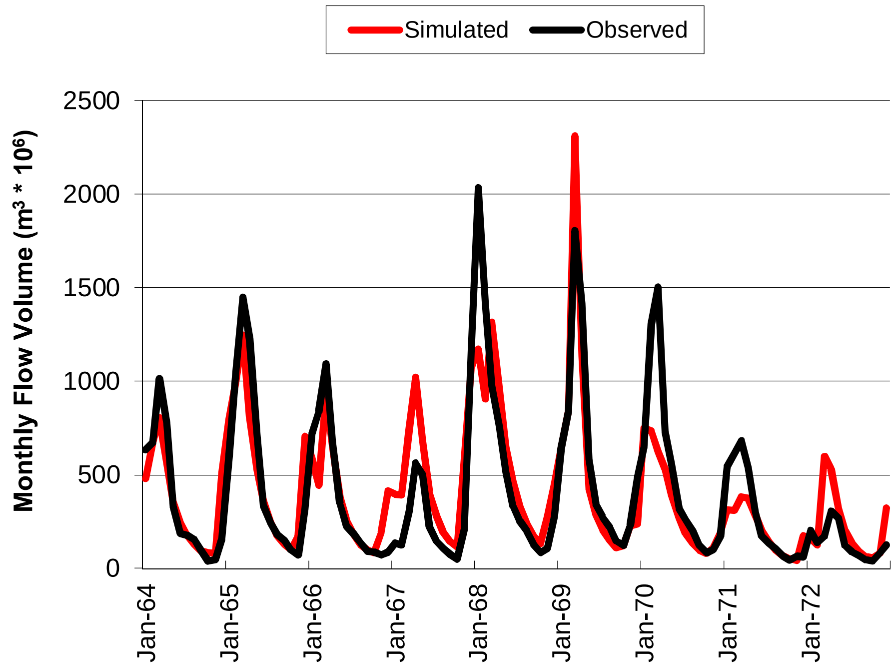
3. Mean monthly percentage error of the simulated flows relative to observed.

The objective of the manual calibration was to limit both untransformed and log-transformed mean monthly percentage errors to within ±5 % and to maximise the R^2 and CE values, while visually ensuring a satisfactory correspondence between observed and simulated flow patterns. This approach ensures that the calibration process does not favour any component e.g. high or low flow of the hydrograph. (Wallingford, 2003).

3.2.4 Calibration Results

3.2.4.1 The Upper Okavango River Basin

Figure 3-1: ***Simulated and observed discharge hydrograph at the gauge situated at the outlet of Caiundo Sub basin in the Cubango River after calibration.***



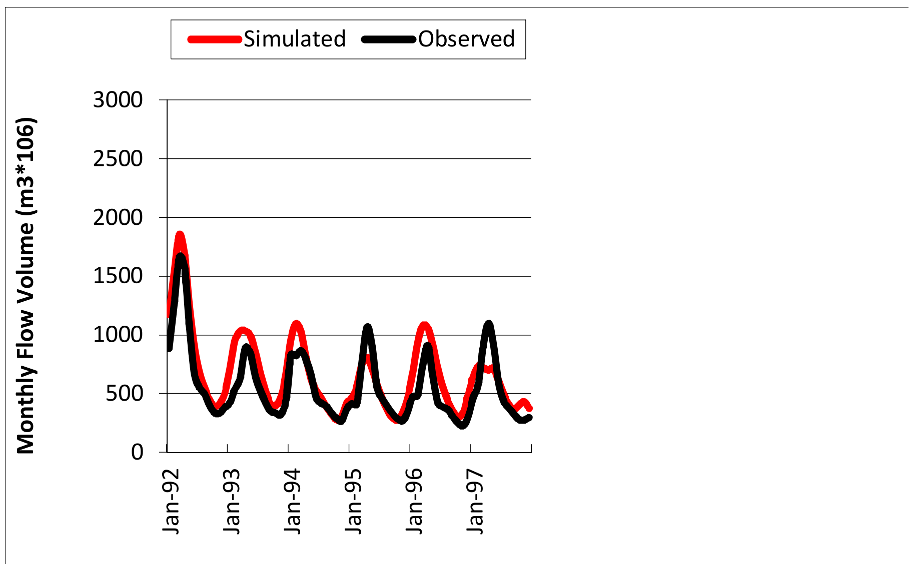
Sources: Hughes et. *al*., 2006

The western tributaries of the upper basin show substantial seasonal flow variation (Figure 3-1) and required a parameterisation with higher drainage densities, and lower transmissivities and storativities, compared to the eastern area, for successful calibration. The Menongue sub-basin (No. 7 in Appendix 1 and Appendix 3) appeared to represent a transitional zone between the harder rock in the western parts and the Kalahari sands of the eastern region (Figure 2-7). Parameters obtained after calibration are shown in Appendix 4. The maximum absorption rate (ZMAX) was highest for the eastern parts of the region, corresponding to higher absorption rates in areas with lower slopes and more permeable soils, i.e. with higher proportions of Kalahari sand. ZMIN shows a similar, but inverse pattern, where decreasing values in an easterly direction may reflect the influence of surface sealing in sub-basins with sandier soils. The soil moisture storage capacity (ST) parameter also increased in an easterly direction, reflecting the greater storage capacities in the Kalahari sand dominated areas. The power of the moisture storage-runoff equation (POW) was lowest in the west, possibly reflecting heterogeneous wetness conditions due to spatially variable soil distributions and significant topographic differences within a sub-basin. (Hughes, *et. al*., 2003)

The correspondence between monitored and modelled river flow was generally acceptable and results were relatively consistent across all sub-basins. It is possible that channel losses start to play a role in Mucundi, which is the lowest sub-basin of the western headwater sub-basins. For the gauging station at the outlet of Mucundi (No 8 in Appendix 1 and Appendix 3), a coefficient of efficiency of 0.745 and a mean monthly error of +0.8 % was achieved (Appendix 5).

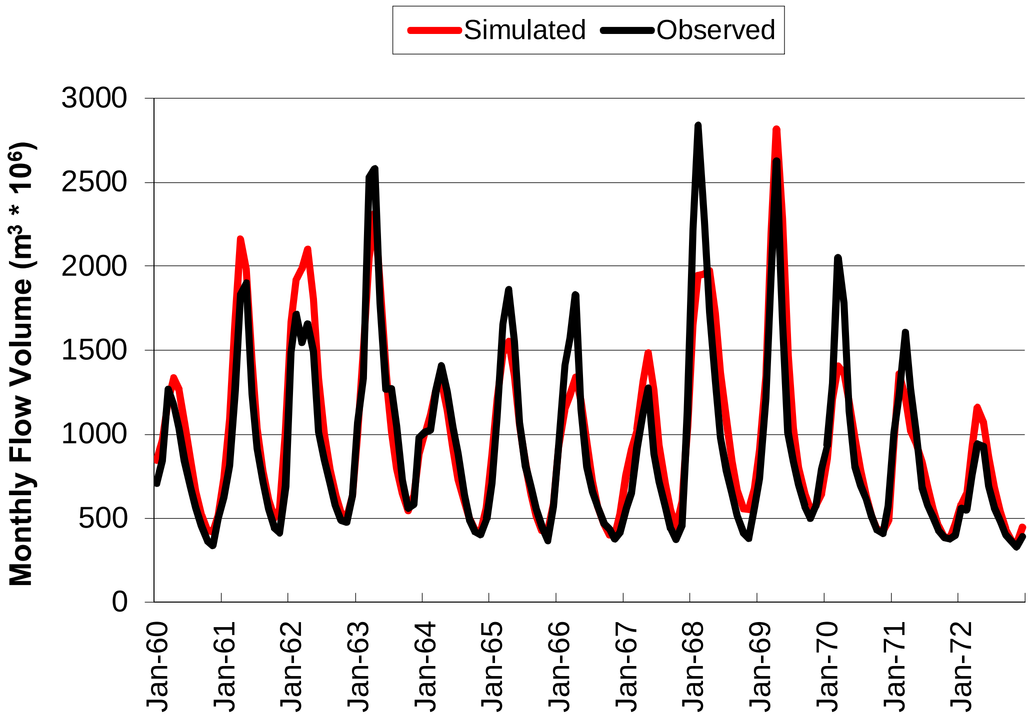
3.2.4.2 The Lower Okavango River Basin

Figure 3-2*: Lower Basin Simulated and Observed Monthly Flow Volume*



Sources: Hughes *et. al*., 2006

Figure 3-3***: Simulated monthly flow at outlet of Mukwe at the Lower part of the Okavango River Basin.***



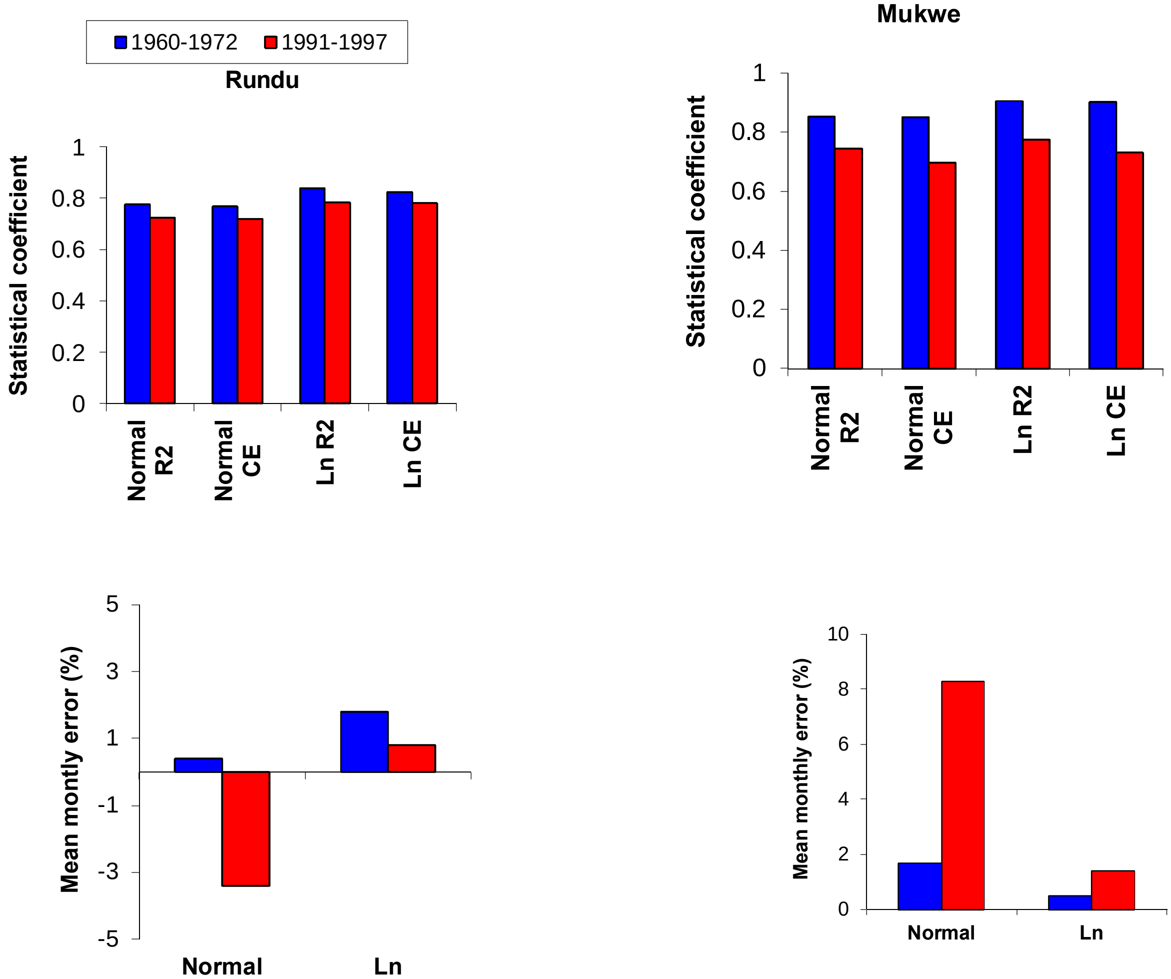
Sources: Hughes et. *al*., 2006

The majority of the downstream sub-basins are also underlain by thick deposits of Kalahari sand (Figure 2-7) and contribute little flow, even during wet years. Downstream decreases in flow, except during wet season events, indicate that channel transmission loss is an important process. Simulation of the integrated flow from the whole basin to the downstream station Mukwe (No. 16 in Appendix 1 and Appendix 3) is shown in Figure 3-3. The calibrated parameters (Appendix 7) reflect this limited contribution and that attenuation of the flow through the channel routing parameter CL is an important process. The volumes and surface areas of the ñdummyò reservoirs, which were used to simulate channel and riparian losses, were quantified on the basis of channel lengths and assumed widths of moist riparian zones. ñDummyò reservoir volumes of 90 and 26 $m^3 \times 10^6$ were used for Rundu (Sub-basin upstream of station 10 in Appendix. 1) and Mukwe (sub-basin upstream of station 16 in Appendix 1), respectively.

Calibrated model parameters reflect the fact that the Omatako River did not contribute to flow in the Okavango during the calibration period. When the model generates a limited amount of streamflow in the Omatako sub-basin during the wet season, the ñdummyò reservoir representing channel losses reduced this to zero flow at the outlet. For the outlet of the Mukwe sub-basin, a coefficient of efficiency of 0.851 and a mean monthly error of +1.7% was achieved (Appendix 5 and Figures 3-3 and 3-4).

3.2.5 Validation Results

Figure 3-4*: Comparison of correspondence statistics at Mukwe.*



Sources: Hughes *et. al*., 2006

In the absence of gauged rainfall data, the validation was based on the revised satellite rainfall data. Comparisons of monitored and measured river discharge were only possible for the two downstream stations for which gauged flow data were available for both the 1960-1972 and 1991-1997 periods. The comparison (Figure 3-3 and Figure 3-4) showed that the results for the validation period were marginally poorer compared to the calibration period, for both Rundu and Mukwe, but still within acceptable ranges.

CHAPTER - 4

DISCUSSION OF RESULTS

4.1 Irrigated Agriculture

The development of irrigated agriculture poses the greatest challenges for the management of the Okavango, largely because of the scale of proposed development in the upper and middle reaches of the river in Angola and Namibia. This would significantly change the flows in the river, both by reducing the overall MAR and by 93-97% in present Day, 69-85% for Medium Development and 69-79% High Development.

4.2 Hydropower Generation

Hydropower generation is technically the most feasible option for the development of large-scale, non-fossil based electricity generation capacity. With the countries energy policies of becoming less reliant on fossil based energy, the development of hydropower generation capacity in the Okavango is potentially at odds with other development objectives e.g. eco-tourism that rely on a high degree of ecosystem integrity. Finding the balance between these seemingly contradicting policy objectives is one of the key challenges when determining the future development pathway of the basin.

4.3 The diversion of water out of the basin

The diversion of water out of the basin as considered earlier by Namibia ï the Eastern National Water Carrier (ENWC) envisaged to be linked with the Okavango River using the Grootfontein-Omatako Canal to supply 100 Mm^3/a of water to the Central Area in the High Scenario is another clear area of concern for the hydrology and ecosystem health of the river. Although less significant quantities of water are involved in comparison to the quantities required for irrigated agriculture, the fact that water is being lost to the river system, may be hydrologically important.

4.4 The simulated inflows to the Okavango Delta at Mohembo

The simulated inflows to the Okavango Delta at Mohembo for all the three development scenarios. (Figure 4-1), shows that very low flows of about $10Mm^3$/s of high

Developments, Medium developments scenario of 200Mm^3/s, low Development Scenario of 300Mm^3/s. The discharge data was used is from year 1959 to year 2001.

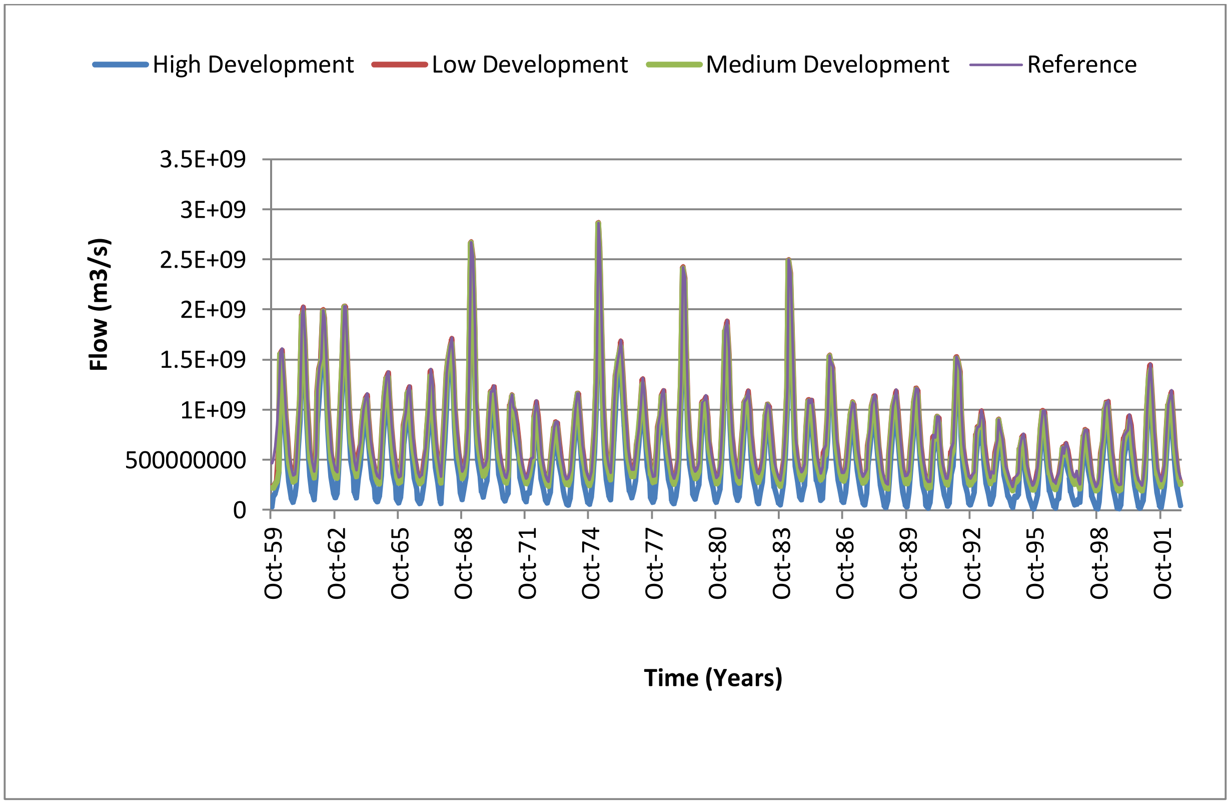
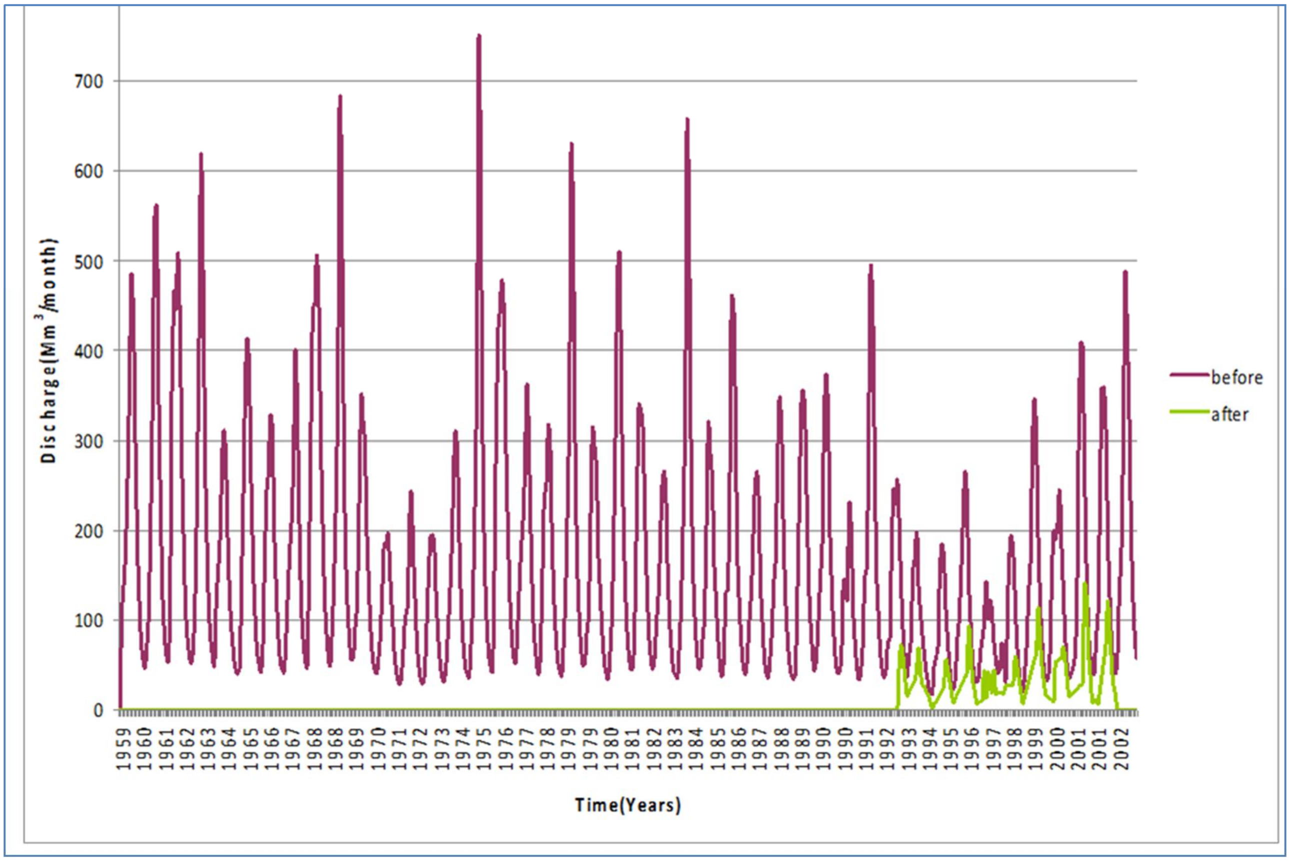


Figure 4-1: ***Simulated inflows to the Okavango Delta–in Mm^3/s, (Reference, low, medium and High development Scenarios)***

4.5 Behavior of Rundu Station before and after high developments

Rundu Station is also located upstream of the Okavango river in Namibia. It shows that before developments (Pitman Model) there were high peak flows of 750Mm^3 /month experienced, but after some developments the WEAP Model shows very low peak flows of almost 20Mm^3/month at Rundu which is situated upstream of Mohembo River. However, it can be also observed that the data in this station was not adequate as the only data generated by the model is from 1993 to 2002 after high proposed developments.

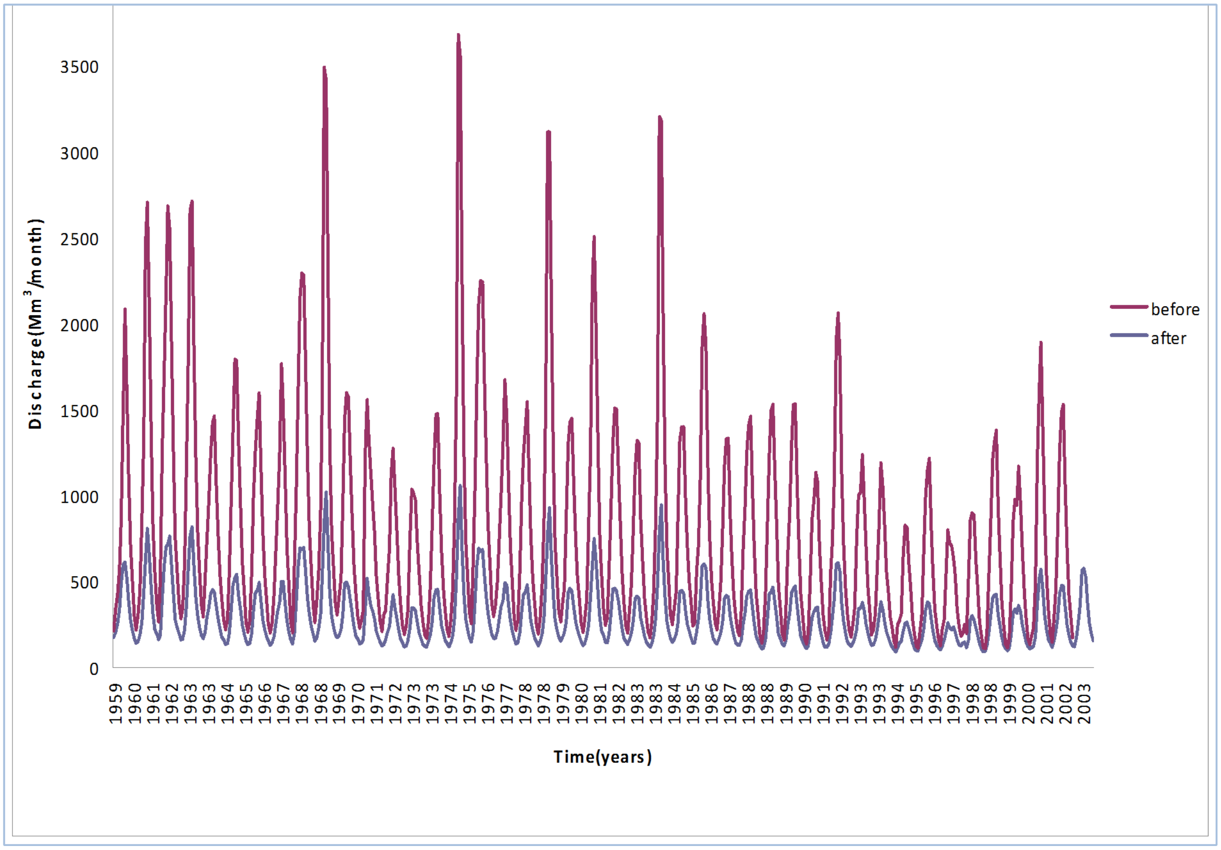
Figure 4-2: ***Flows at Rundu Station before and after developments in the high developments***



4.6 Behavior of Mohembo Station before and after Medium developments

Mohembo station is located downstream of Rundu, in Botswana. WEAP Model shows a very good trend on the flows experienced before the developments with high peak flows of 2500Mm^3/month. The model shows low average flows of 600Mm^3/month experienced after the development. Because the site is located at the downstream end of the entire river basin, it is showing signs of experiencing the harshest impact with very low flows.

Figure 4-3: ***Flows at Mohembo Station before and after developments in the Medium Development***



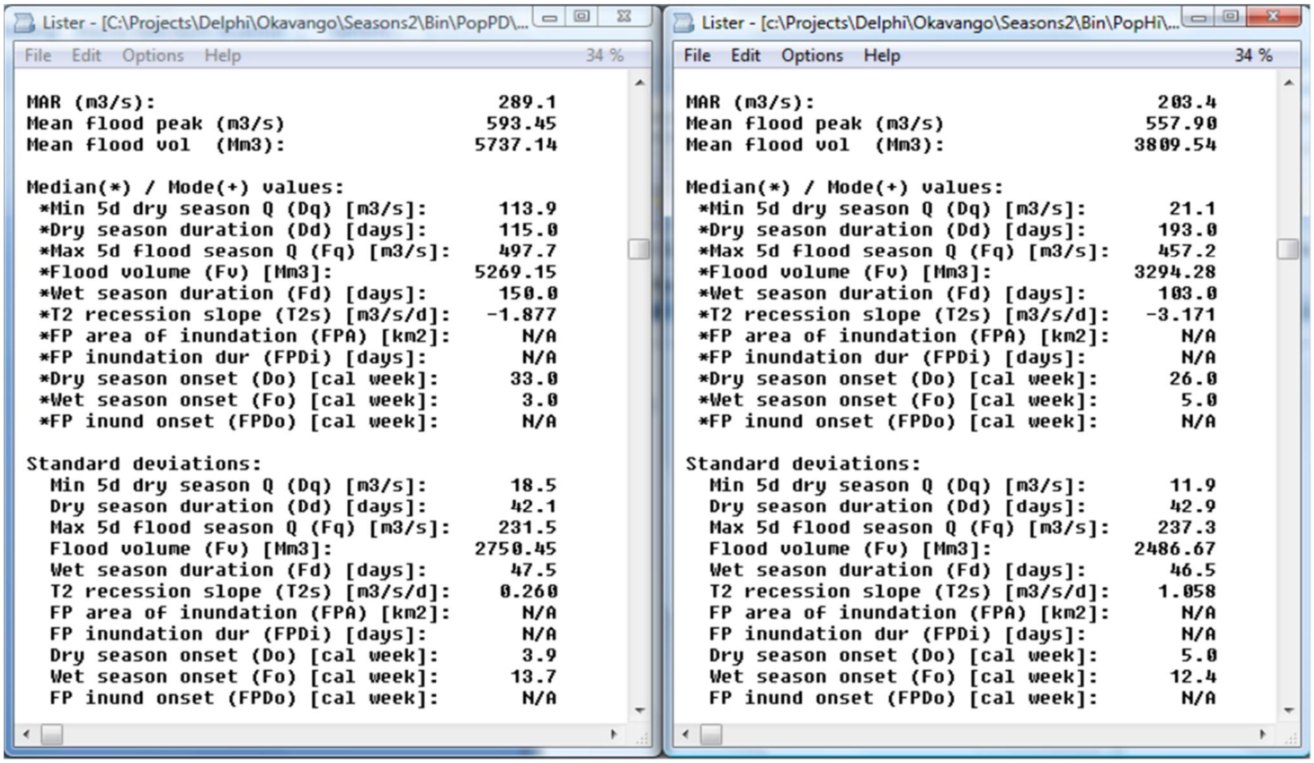
4.7 The impact of the Water Use Scenarios on Key Flow Characteristics

A comparison of the Present Day and High Development scenarios (Figure 4-4) indicates;

a. A reduction of mean annual Delta inflows from about 289 m^3/s (9,100 Mm^3/year), to about 203 m^3/s (6,400 Mm^3/year).

b. An 8% (40 m^3/s) reduction in the median flood season peak flow and an 81% reduction (93 m^3/s) in the median dry season minimum flow. The large decrease in dry season flows, and the relatively small decrease in flood flows is due to the predominance of run-of-river abstraction schemes as opposed to storage (dam) based water supply schemes.

Figure 4-4: ***Hydrological Indicators - Delta Inflows (Left: Current Development Scenario Day and Right: High Development Scenarios)***



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```
MAR (m3/s):                                 289.1
Mean flood peak (m3/s)                      593.45
Mean flood vol  (Mm3):                     5737.14

Median(*) / Mode(+) values:
 *Min 5d dry season Q (Dq) [m3/s]:          113.9
 *Dry season duration (Dd) [days]:          115.0
 *Max 5d flood season Q (Fq) [m3/s]:        497.7
 *Flood volume (Fv) [Mm3]:                 5269.15
 *Wet season duration (Fd) [days]:          150.0
 *T2 recession slope (T2s) [m3/s/d]:       -1.877
 *FP area of inundation (FPA) [km2]:          N/A
 *FP inundation dur (FPDi) [days]:            N/A
 *Dry season onset (Do) [cal week]:          33.0
 *Wet season onset (Fo) [cal week]:           3.0
 *FP inund onset (FPDo) [cal week]:           N/A

Standard deviations:
  Min 5d dry season Q (Dq) [m3/s]:           18.5
  Dry season duration (Dd) [days]:           42.1
  Max 5d flood season Q (Fq) [m3/s]:        231.5
  Flood volume (Fv) [Mm3]:                 2750.45
  Wet season duration (Fd) [days]:           47.5
  T2 recession slope (T2s) [m3/s/d]:        0.260
  FP area of inundation (FPA) [km2]:          N/A
  FP inundation dur (FPDi) [days]:            N/A
  Dry season onset (Do) [cal week]:           3.9
  Wet season onset (Fo) [cal week]:          13.7
  FP inund onset (FPDo) [cal week]:           N/A
```

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```
MAR (m3/s):                                 203.4
Mean flood peak (m3/s)                      557.90
Mean flood vol  (Mm3):                     3809.54

Median(*) / Mode(+) values:
 *Min 5d dry season Q (Dq) [m3/s]:           21.1
 *Dry season duration (Dd) [days]:          193.0
 *Max 5d flood season Q (Fq) [m3/s]:        457.2
 *Flood volume (Fv) [Mm3]:                 3294.28
 *Wet season duration (Fd) [days]:          103.0
 *T2 recession slope (T2s) [m3/s/d]:       -3.171
 *FP area of inundation (FPA) [km2]:          N/A
 *FP inundation dur (FPDi) [days]:            N/A
 *Dry season onset (Do) [cal week]:          26.0
 *Wet season onset (Fo) [cal week]:           5.0
 *FP inund onset (FPDo) [cal week]:           N/A

Standard deviations:
  Min 5d dry season Q (Dq) [m3/s]:           11.9
  Dry season duration (Dd) [days]:           42.9
  Max 5d flood season Q (Fq) [m3/s]:        237.3
  Flood volume (Fv) [Mm3]:                 2486.67
  Wet season duration (Fd) [days]:           46.5
  T2 recession slope (T2s) [m3/s/d]:        1.058
  FP area of inundation (FPA) [km2]:          N/A
  FP inundation dur (FPDi) [days]:            N/A
  Dry season onset (Do) [cal week]:           5.0
  Wet season onset (Fo) [cal week]:          12.4
  FP inund onset (FPDo) [cal week]:           N/A
```

Source: WEAP Study Model, 2014.

4.8 Predicted percentage changes in the flow regime at Popa Falls and the Panhandle.

The WEAP Model Predicted percentage changes in the flow regime at Popa falls and the Panhandle are observed on the Figure 4-5 as;

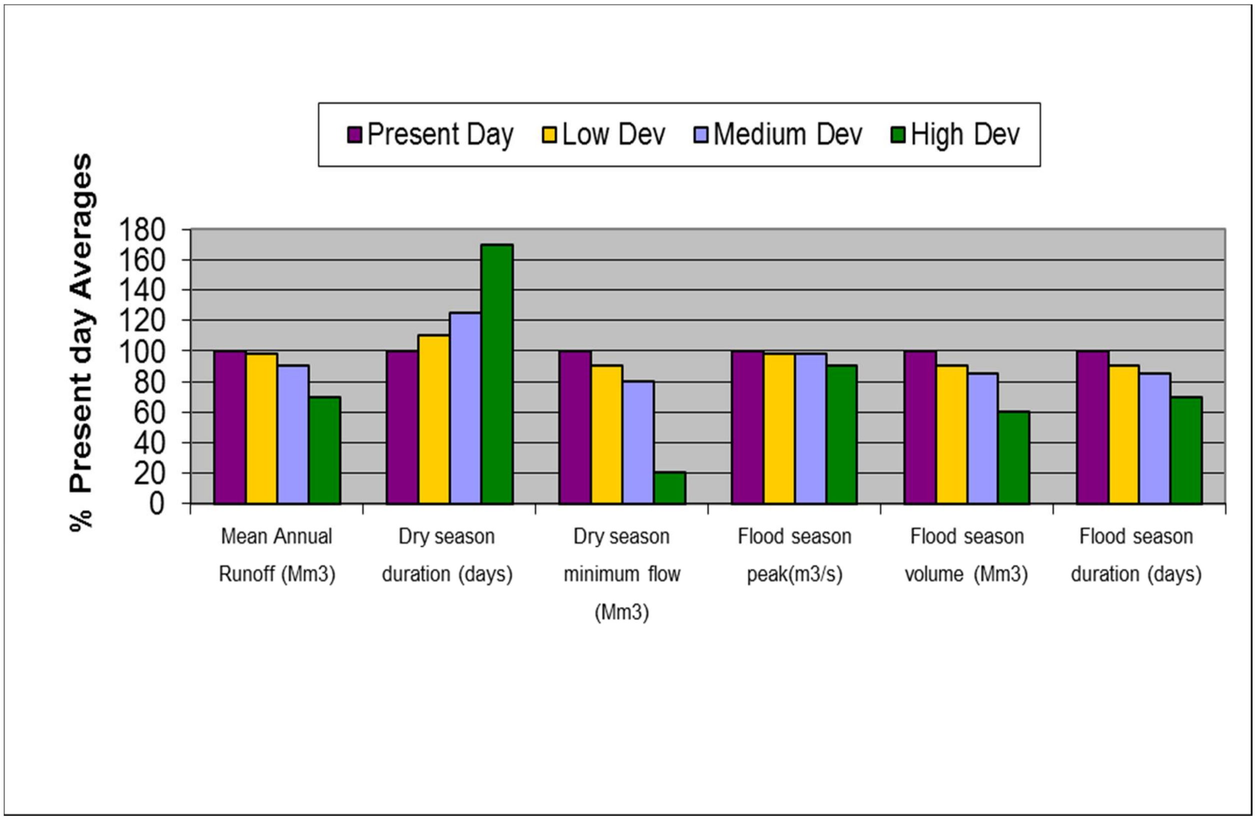
i. The Mean Annual Runoff (MAR) in Mm^3 for present day is 100%, Low Development is 98%, Medium Development is 85% and High Development is very low at 65%.

ii. The Dry Season Minimum flows in Mm^3 shows that for Present Day Scenario it is 100%, Low Scenario is 90% Medium Scenario is 80% and High Scenario very low at 20%.

iii. The Flood Season Volume of flows in Mm^3 similarly shows Present Scenario Development is 100%, Low Development Scenario is 90%, Medium Development Scenario is 85% and High Development Scenario as low as 60%.

iv. The Dry Season Duration of flows in Days shows present Scenario Development is 100%, Low Development Scenario is 110%, Medium Development Scenario is 125% and High Development Scenario as high as 170%.

Figure 4-5: ***Predicted percentage changes in the flow regime at Popa Falls and the Panhandle, compared to Present Day under different scenarios***



CHAPTER - 5

ANALYSIS OF RESULTS

5.1 Irrigated Agriculture

If irrigation schemes are developed without reference to the overall basin, and without coordination of abstractions, the health and integrity of parts of the river and the Delta will be threatened. It is apparent from the findings of the this study that there is limited room for manoeuvre and particular schemes should be assessed through a thorough Strategic Environmental Assessment and Environmental Impact Assessment process with modeling of the hydrological impacts.

The Thesis findings indicate that there is potential for the development of irrigated agriculture on the Cubango River, whilst leaving the Cuito River relatively undeveloped to act as a buffer and reliable source of the flows in the river. The floodplains of the Cuito absorb and even out the flows through the year to some extent and are a critical part of the ecosystem that should be maintained. The Cuito catchment is also more prone to soil erosion, and the development of agriculture there should be undertaken more circumspectly.

5.2 Hydropower Generation

Hydropower development on the Okavango in Angola is being actively reconsidered. There would appear to be less impact on the flows in the river associated with run-of-river schemes, which have relatively low head and minimal storage capacity. There is one storage dam currently under consideration and more careful planning and hydrological modeling will be required including assessment of the transboundary impacts.

It is not known how the proposed dams will be operating, but daily variations in flow as the turbines are brought on stream and off again to meet peak demands, can cause serious changes in the ecosystem and impacts for water users. The design and operation of hydropower schemes should be subject to consideration as part of the overall management of the basin, rather than left solely at the discretion of the developer. Hydropower does not use up water, the river is permitted to flow downstream but the flow pattern is changed by the reservoir. There is also evaporation loss from reservoir surface.

5.3 Diversion of Water Out of the Basin

If the water diversion schemes were to be considered in the future such as the ENWC in Namibia, the hydrological implications for the river as a whole should be carefully considered and local and transboundary impacts assessed by the OKACOM Secretary through OKACOM. Large water diversion schemes should be discussed between the three countries when impact assessments have been completed.

5.4 The simulated inflows to the Okavango Delta at Mohembo

This Study has shown that long-term water resource development plans would lead to major impacts on the Okavango System, but through careful management, choice of efficient water use technologies and appropriate siting of developments. It will be possible to address many of the potential impacts. This study considers that maintaining present day (Current Scenario) ecological conditions in the Cuito sub-basin will be vital for the future integrity and adaptation of the Okavango System. The present development plans in Angola have focused on the Cubango, and the resulting changes in the flow regime can be managed, provided that the buffer of the Cuito sub-basin remains.

5.5 Predicted percentage changes in the flow regime at Popa Falls and the Panhandle.

The following Predicted percentage changes in the flow regime at Popa falls and the Panhandle are observed on the Figure 4-5 above as;

5.5.1 The changes in dry-season flows are by far the most noticeable of the flow impacts. At Capico on the Cuebe, the dry season flows are heavily impacted; the dry season starts about 11 weeks earlier, lasting up to 18 weeks longer and with a minimum flow that drops drastically to about 3% of the current dry season flow. There is a reduction of median dry season minimum flows in the Cuebe River from about 12 m^3/s (Present Day) to about 0.3 m^3/s (High Development). The impacts of these developments are also felt at Mucundi on the Cubango, but much less so.

5.5.2 The impact on the dry season in the river between Kapako and the Panhandle is the end result of the series of water uses along the whole system, with Popa Falls and the Panhandle showing the biggest flow changes. There is little change in the onset of the dry season at Kapako, but at Popa and the Panhandle it starts 1 week earlier under the Low Scenario increasing to 7 weeks earlier under the High Scenario. The changes in duration of the dry season are again most obvious at Popa and the Panhandle, and under the High Scenario the dry season lasts 11 weeks longer.

5.5.3 The dry-season minimum flows show a mixed pattern, with flow levels declining under the Low and Medium Scenario at Mucundi and Kapako, but increasing slightly under the High Scenario due to additional dams storing flood waters and releasing them in the dry season. These sites, both on the Cubango/Okavango upstream of the confluence with the Cuito, fall by 50% compared to the current flows under the Medium Scenario but increase slightly with the High Scenario. At Popa Falls and the Panhandle, downstream of the confluence, there is a different pattern, with flows remaining quite high until the High Scenario, when they fall to 18% of Present Day.

5.5.4 The overall trend is for run-off-river abstractions to reduce flows throughout the year, with the effect being particularly noticeable in the dry season. Dry-season flows tend to be lower, start earlier and last longer than the Present Day, with the effect greatest at Capico, Popa Falls and in the Panhandle.

CHAPTER - 6

CONCLUSIONS

6.1 The relationship between the received precipitation and the level of the Okavango River flow in the basin

The study concludes that the relationship between the precipitation received by the Okavango River watershed and the level of river flow in the Okavango River over a 30 year period are directly proportional. This means the more rainfall in the Basin, the higher the level of the water that flows within the river channel. This happens because the river is perennial and as a result there is less water that infiltrates into the banks and bottom of the river. The Okavango River banks are always saturated with water hence more water built up quickly to fill the river channel immediately when it rains and starts to flow downstream although some water will be lost due to evaporation. It is this precipitation that keeps the life of the river throughout the year.

As a recommendation to this study is that, the rainfall-runoff model be re-calibrated by other future Researchers with a view to improve peak flow simulation. As part of the same exercise, the model also should be extended to cover the hydrological years from 2003 to as recently as possible.

6.2 The impact of increasing water demands at various points along the watershed on the annual flow of the Okavango River.

The study shows that low to medium development scenarios can be implemented so as to manage and control the water demand increase in the Okavango River Basin. However, high development scenarios cannot be implemented because the more high water developments are implemented within the basin, the lesser the annual flow of the river. Low flows within the river may significantly affect the life of the river as some parts of the Delta downstream of Okavango River may run dry.

Examples of increasing water demands scenarios that may affect the flow regime of the river are identified as follows;

i. About 15 000 Ha of irrigation in Namibia.
ii. About 338 000 Ha of irrigation at various locations in Angola.

It is recommended that specific agricultural irrigation schemes should be subject to an Environmental Impact Assessment, with assessments of cumulative and trans boundary impacts set in context by the Socio Economic Assessment. Research and development efforts should be focused on the application of irrigation schemes that are most efficient in their use of water, appropriate to local conditions.

6.3 The effect of the erection of water storage bodies along the Okavango River.

Too many construction water storage bodies along the Okavango River may significantly affect it life downstream. This can only achieved through implementation of small scale to medium scale dams for domestic purposes not agro commercial usage such as irrigation of large farms. Only small pipelines can also be constructed not the construction of the Eastern National Water Carrier in Namibia (ENWC) in Namibia which has a total capacity 100 Mm^3/a. This project can significantly reduce the annual flow of the river and hence affect the flora and fauna life of the river downstream.

Therefore, it is recommended that the individual high scenario developments should be subject to Environmental and Social Impact Assessment with assessment of cumulative and transboundary impacts. It is also recommended that hydropower stations can be implemented up to medium scenario development within the basin, since the structure allows for water flow downstream the river.

6.4 Sustaining development project mix for the upstream areas in the Okavango River Basin.

The project mix in Angola and Namibia comprises of Rural and Urban water demands such as construction of large factories and construction of dams for agro commercial irrigation schemes that uses a lot of water from the river channel. Other examples of projects mix is the large number of population that resides along the river and uses water for all kinds of domestic purposes. The study shows that all these can only be achievable if the low to medium development scenario is implemented. High development scenario can affect the annual run off of the river system. The riparian member states can only sustain the life of Okavango River through,

a) Coordination in planning and implementation of projects between sectors in each country and between the three countries that needs to be strengthened.

b) Through Environmental Impact Assessment and Socio Economic Assessment. Making recommendations for the minimum sizes and siting of water use developments to be considered and approved by the three countries, taking into account cumulative and transboundary impacts.

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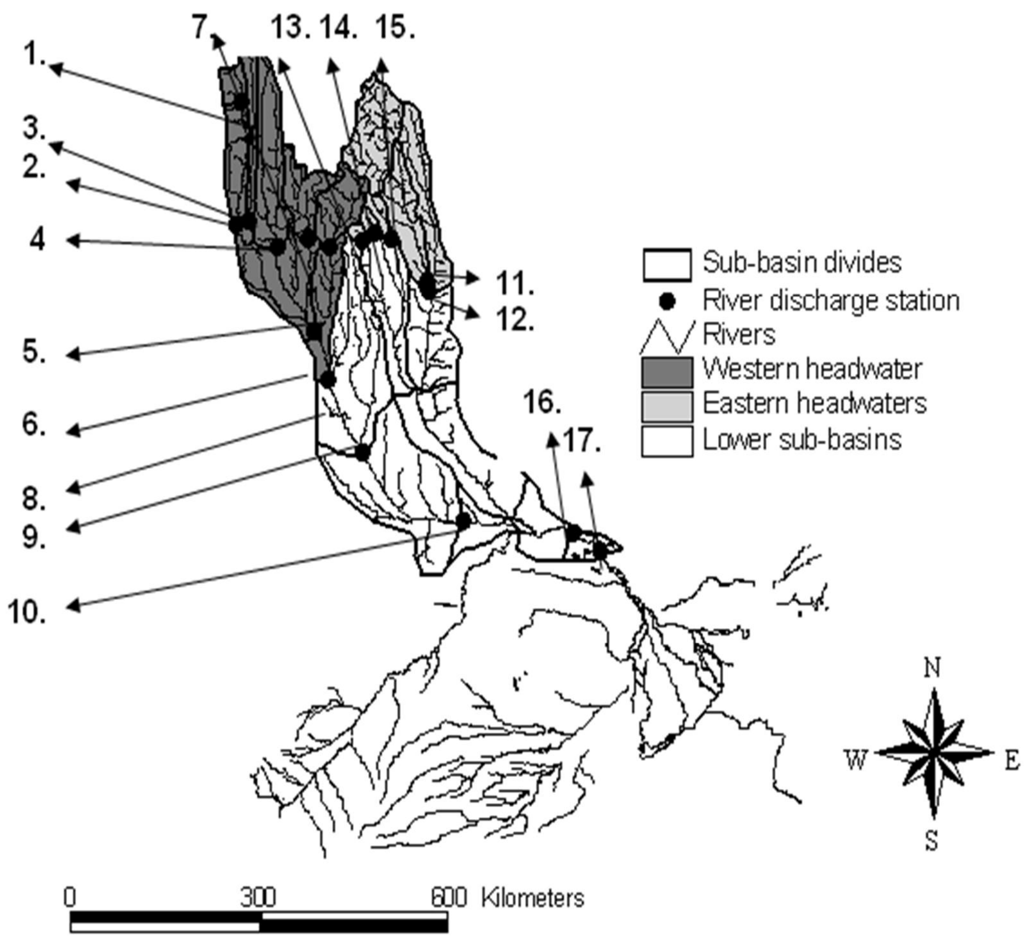
<u>**APPENDICES:**</u>

Appendix A-1:

Okavango River Basin -The basin that contributes flow to the Okavango Delta. Information about the 17 gauged sub-basins.



Source: Hughes *et. al*., 2006.

Appendix: A-2:

Pitman and reservoir model parameters.

Parameter	Units	Pitman model parameter description
RDF		Rainfall distribution factor. Controls the distribution of total monthly rainfall over four model iterations.
AI	Fract.	Impervious fraction of sub-basin.
PI1 and PI2	Mm	Interception storage for two vegetation types.
AFOR	%	% area of sub-basin under vegetation type 2.
FF		Ratio of potential evaporation rate for Veg2 relative to Veg1.
PEVAP	Mm	Annual sub-basin evaporation
ZMIN	mm $month^{-1}$	Minimum sub-basin absorption rate.
ZAVE	mm $month^{-1}$	Mean sub-basin absorption rate.
ZMAX	mm $month^{-1}$	Maximum sub-basin absorption rate.
ST	Mm	Maximum moisture storage capacity.
SL	mm	Minimum moisture storage below which no GW recharge occurs.
POW		Power of the moisture storage-runoff equation.
FT	mm $month^{-1}$	Runoff from moisture storage at full capacity (ST).
GPOW		Power of the moisture storage-GW recharge equation.
GW	mm $month^{-1}$	Maximum ground water recharge at full capacity (ST).
R		Evaporation-moisture storage relationship parameter.
TL	Months	Lag of surface and soil moisture runoff.
CL	Months	Channel routing coefficient
D.Dens		Drainage density.
T	m^2 d^{-1}	Ground water transmissivity
S		Ground water storativity
AIRR	km^2	Irrigation area.
IWR	Fract.	Irrigation water return flow fraction.
EFFECT	Fract.	Effective rainfall fraction.
RUSE	Ml yr^{-1}	Non-irrigation demand from the river.
MDAM	Ml	Small dam storage capacity.
DAREA	%	Percentage of sub-basin above dams.
A, B		Parameters in non-linear dam area-volume relationship
IRRIG	km^2	Irrigation area from small dams
Parameter	Units	Reservoir model parameter description
CAP	Mm^3	Reservoir capacity.
DEAD	%	Dead storage.
INIT	%	Initial storage.
A, B		Parameters in non-linear dam area-volume relationship.
RES1 to 5	%	Reserve supply levels (percentage of full capacity).

Source: Hughes *et. al.*, 2006.

Appendix A-3:

Gauged sub-basins in the parts of the Okavango Basin that contribute to inflow to the Delta.

			Data Record (used)				Mean annual runoff	
No.	**Basin name**	**Upstream catchment area (km^2)**	*Start Date*	*End Date*	*Length (months)*	*Missing data (months)*	m^3*10^6	*mm*
1	Chinhama	1822	10/1963	09/1974	132	2	608.0	334
2	Kubango*	7133	10/1963	09/1974	132	0	1530.3	214
3	Cutato	3621	10/1963	09/1974	132	6	739.6	204
4	Cuchi	10594	10/1963	09/1974	132	6	1345.3	127
5	Cuelei	5466	06/1966	09/1973	100	3	644.3	118
6	Caiundo	38420	10/1957	09/1974	204	52	4758.5	124
7	Menongue*	5623	03/1962	09/1974	151	0	640.8	114
8	Mucundi	50701	05/1962	09/1974	149	7	5197.7	103
9	Catambué*	71260	10/1965	09/1971	72	0	6343.5	89
10	Rundu	95642	10/1945	09/1999	648	0	5204.8	54
11	Cuito	15857	10/1965	09/1974	72	26	3435.6	217
12	Cuanavale	23347	10/1966	09/1967	12	0	3344.6	143
13	Luassinga	540	02/1965	09/1967	32	0	69.4	128
14	Cuiriri	742	10/1964	09/1967	36	0	125.2	169
15	Upper Cuiriri	1395	02/1965	09/1974	116	26	245.1	176
16	Mukwe	226236	10/1949	09/1998	588	0	9584.3	42
17	Mohembo	228778	01/1975	09/2000	312	58	8465.1	37

Source: Hughes *et. al*., 2006.

Appendix A-4:

Catchment characteristics and calibrated Pitman model parameter values for the western upper sub-basins. Parameters not referred to were equal for all sub basins.

	Sub-basin							
Characteristics and parameter values	***Chinhama***	***Kubango***	***Cutato***	***Cuchi***	***Cuelei***	***Menongue***	***Caiundo***	***Mucundi***
Area hard rock (%)	14	33	9	22	28	10	23	5.5
Mean slope (degrees)	1.3	1.3	1.4	1.4	1.4	1.4	1.3	1.4
Forested area (%) AFOR	18.3	40.0	44.0	60.0	66.1	68.4	34.6	36.7
Annual Pan Evap. (mm) PEVAP	1897	1980	1980	1980	2021	2021	2501	2900
Summer min.abs.rate (mm month^{-1}) ZMINs	80	100	100	100	50	10	50	80
Winter min.abs.rate (mm month^{-1}) ZMINw	80	100	100	100	50	10	50	80
Mean abs.rate (mm month^{-1}) ZAVE	400	500	500	400	400	700	600	600
Maximum abs.rate (mm month^{-1}) ZMAX	600	700	700	700	700	1000	1000	1000
Maximum storage capacity ST	400	500	500	620	550	900	1000	1000
Power : storage-runoff curve POW	2.5	2.7	2.6	2.7	3.0	3.0	3.4	3.4
Runoff rate at ST (mm month^{-1}) FT	38	18	35	25	22	15	5	2
Power: storage-recharge curve GPOW	2.0	2.5	2.2	2.5	2.4	2.1	2.5	2.5
Max. GW recharge (mm month^{-1}) GW	20	16	16	16	18	20	6	4
Evaporation-storage coefficient R	0.2	0.2	0.2	0.1	0.0	0.3	0.1	0.0
Surface runoff time lag (months) TL	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Channel Routing Coeff. (months) CL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.02
Drainage Density	0.8	0.7	0.7	0.7	0.6	0.3	0.7	0.7
Transmissivity	10	10	10	15	20	20	15	12
Storativity	0.005	0.007	0.006	0.008	0.008	0.010	0.010	0.010
Initial Groundwater Slope	0.030	0.030	0.030	0.030	0.030	0.012	0.005	0.005

Source: Hughes *et. al.*, 2006.

Appendix A-5:

Correspondence between modelled and simulated flow based on untransformed (normal) and natural log (ln) transformed flow. R2 = Coefficient of determination, CE = Coefficient of efficiency (Nash and Sutcliffe, 1970).

Sub-basin	Location	Months included in calibration	Normal		Ln Values		Mean monthly error (%)	
			R^2	CE	R^2	CE	Normal	Ln
Chinhama	Western headwaters	109	0.843	0.841	0.880	0.879	-4.4	0.4
Kubango	Western headwaters	111	0.780	0.779	0.828	0.788	-2.2	3.5
Cutato	Western headwaters	105	0.814	0.813	0.775	0.752	-0.6	3.3
Cuchi	Western headwaters	105	0.612	0.610	0.697	0.649	-0.7	4.6
Cuelei	Western headwaters	76	0.494	0.494	0.715	0.676	1.5	2.3
Caiundo	Western headwaters	120	0.755	0.751	0.803	0.767	-0.1	2.9
Menongue	Western headwaters	130	0.633	0.608	0.709	0.691	-2.2	-0.4
Mucundi	Western headwaters	121	0.749	0.745	0.809	0.790	0.8	1.9
Catambué	Lower basins	72	0.737	0.736	0.795	0.781	0.2	1.6
Rundu	Lower basin	156	0.775	0.770	0.839	0.823	0.4	1.8
Cuito	Eastern headwaters	67	0.745	0.726	0.758	0.757	-1.1	0.1
Cuanavale	Eastern headwaters	12	0.714	0.693	0.689	0.676	-0.4	0.1
Luassinga	Eastern headwaters	32	0.295	-1.155	0.294	-1.334	-2.4	-1.8
Curiri River	Eastern headwaters	36	0.544	0.518	0.579	0.563	-3.4	-1.1
Upper Cuiriri	Eastern headwaters	69	0.557	0.526	0.554	0.495	2.1	0.8
Mukwe	Lower basin	156	0.852	0.851	0.905	0.901	1.7	0.5
Mohembo	Lower basin	0	-	-	-	-	-	-

Source: Hughes *et. al*., 2006.

Appendix A-6:

Catchment characteristics and calibrated Pitman model parameter values for the eastern upper sub-basins. See Appendix 6 for the values of parameters not referred to.

	Sub-basin				
Array Parameter	*Luassinga*	*Longa*	*Upper Curiri*	*Cuito & North East*	*Cuanavale*
Area with hard rocks (%)	0	0	0	0	0
Mean slope	1.2	1.3	1.5	1.4/1.2	1.4
Forested area (%) AFOR	69.9	77.5	70.0	75.2	71.8
Annual Pan Evaporation (mm) PEVAP	2046	2046	2046	2137	2137
Summer min.abs.rate (mm $month^{-1}$) ZMINs	100	30	50	30	20
Winter min.abs.rate (mm $month^{-1}$) ZMINw	100	30	50	30	20
Mean abs.rate (mm $month^{-1}$) ZAVE	800	500	600	600	600
Maximum abs.rate (mm $month^{-1}$) ZMAX	1200	1000	1000	1200	1200
Maximum storage capacity ST	900	900	900	1000	1000
Power : storage-runoff curve POW	3.4	4.0	4.0	3.2	3.1
Runoff rate at ST (mm $month^{-1}$) FT	12	12	20	12	10
Power: storage-recharge curve GPOW	1.6	1.6	1.6	1.6	1.6
Max. GW recharge (mm month-^{1}) GW	25	30	30	35	16
Evaporation-storage coefficient R	0.5	0.6	0.6	0.6	0.6
Surface runoff time lag (months) TL	0.25	0.25	0.25	0.25	0.25
Channel routing coeff. (months) CL	0.0	0.0	0.0	0.0	0.0
Drainage Density	0.3	0.4	0.3	0.4	0.4
Transmissivity	20	20	20	20	20
Storativity	0.01	0.01	0.01	0.01	0.01
Initial Groundwater Slope	0.025	0.025	0.025	0.025	0.025

Source: Hughes *et. al*., 2006.

Appendix A-7:

Catchment characteristics and calibrated Pitman model parameter values for the lower sub-basins. See Appendix 7 for the values of parameters not referred to.

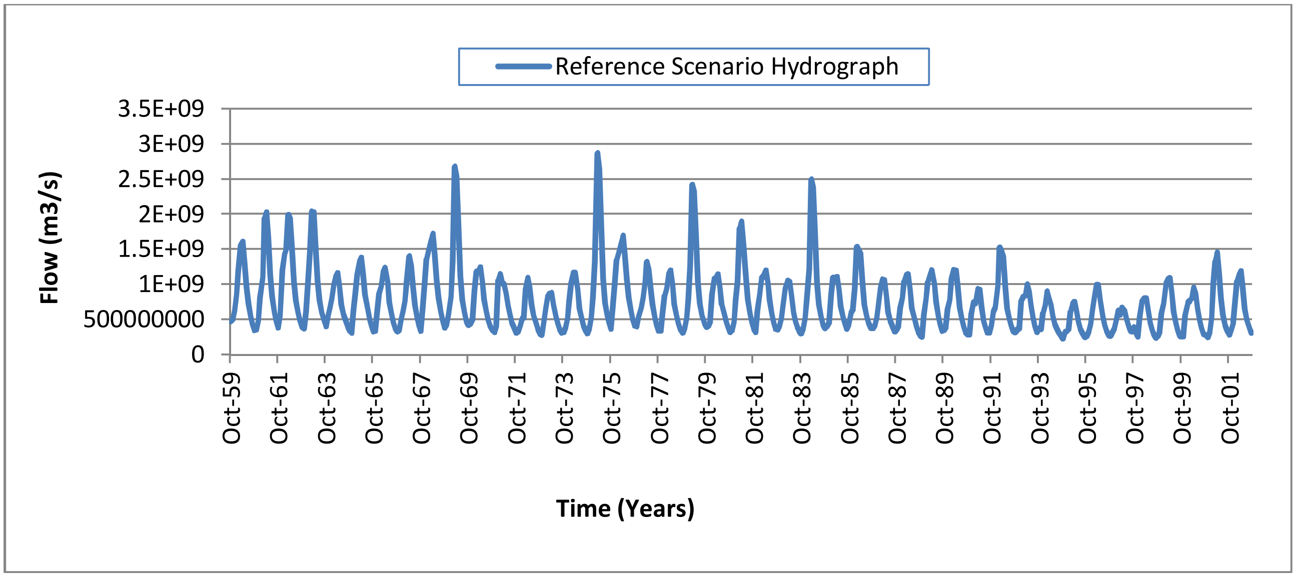
	Sub-basin					
Array Parameter	*Catambué*	*Rundu, Sambio*	*Dirico, Curiri River, P Passagem*	*Omatako*	*Mukwe*	*Mohembo*
Area with hard rocks (%)	0	0	0	0	0	0
Mean slope	0.8	0.3/ 0.3	0.3/ 1.1/ 0.7	0.4	0.3	0.3
Forested area (%) AFOR	11.0	0.0	2.5	0.0	0.1	1.1
Annual Pan Evaporation (mm) PEVAP	2137	2500	2137	2137	2137	2137
Summer min.abs.rate (mm month^{-1}) ZMINs	80	100	100	150	150	150
Winter min.abs.rate (mm month^{-1}) ZMINw	80	100	100	150	150	150
Mean abs.rate (mm month^{-1}) ZAVE	600	600	600	1000	800	800
Maximum abs.rate (mm month^{-1}) ZMAX	1000	1000	1000	1400	1000	1000
Maximum storage capacity ST	1000	1000	1000	1100	1000	1000
Power: storage-runoff curve POW	3.4	3.4	3.4	3.4	3.4	3.4
Runoff rate at ST (mm month^{-1}) FT	1	1	1	0	1	1
Power: storage-recharge curve GPOW	2.5	2.5	2.5	2.5	2.5	2.5
Max. GW recharge (mm month^{-1}) GW	4	2	4	4	4	5
Evaporation-storage coefficient R	0.0	0.0	0.0	0.0	0.0	0.0
Surface runoff time lag (months) TL	0.25	0.25	0.25	0.25	0.25	0.25
Channel routing coeff. (months) CL	0.08	0.15	0.15	0.15	0.00	0.00
Drainage Density	0.7	0.6	0.4	0.2	0.3	0.3
Transmissivity	15	15	15	20	15	15
Storativity	0.01	0.01	0.01	0.01	0.01	0.01
Initial Groundwater Slope	0.003	0.001	0.001	0.001	0.001	0.001

Source: Hughes *et. al*., 2006.

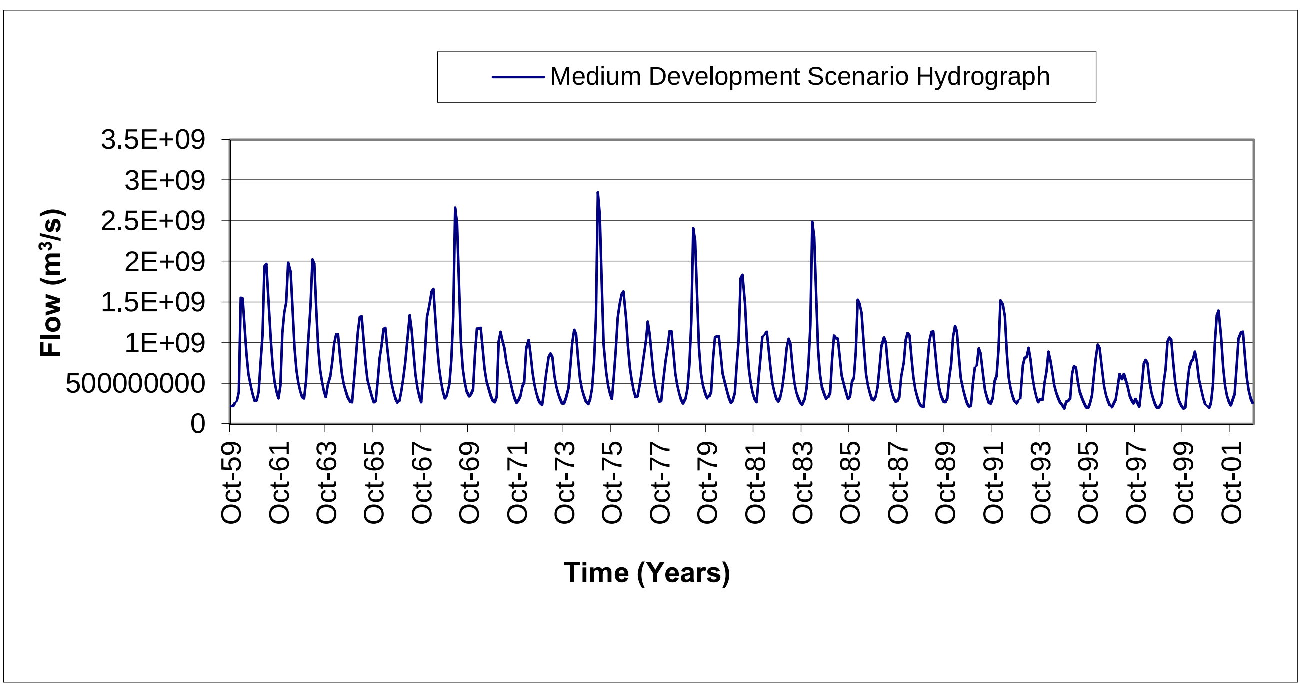
Appendix A-8:

HYDROGRAPHS FOR DIFFERENT DEVELOPMENT SCENARIOS:

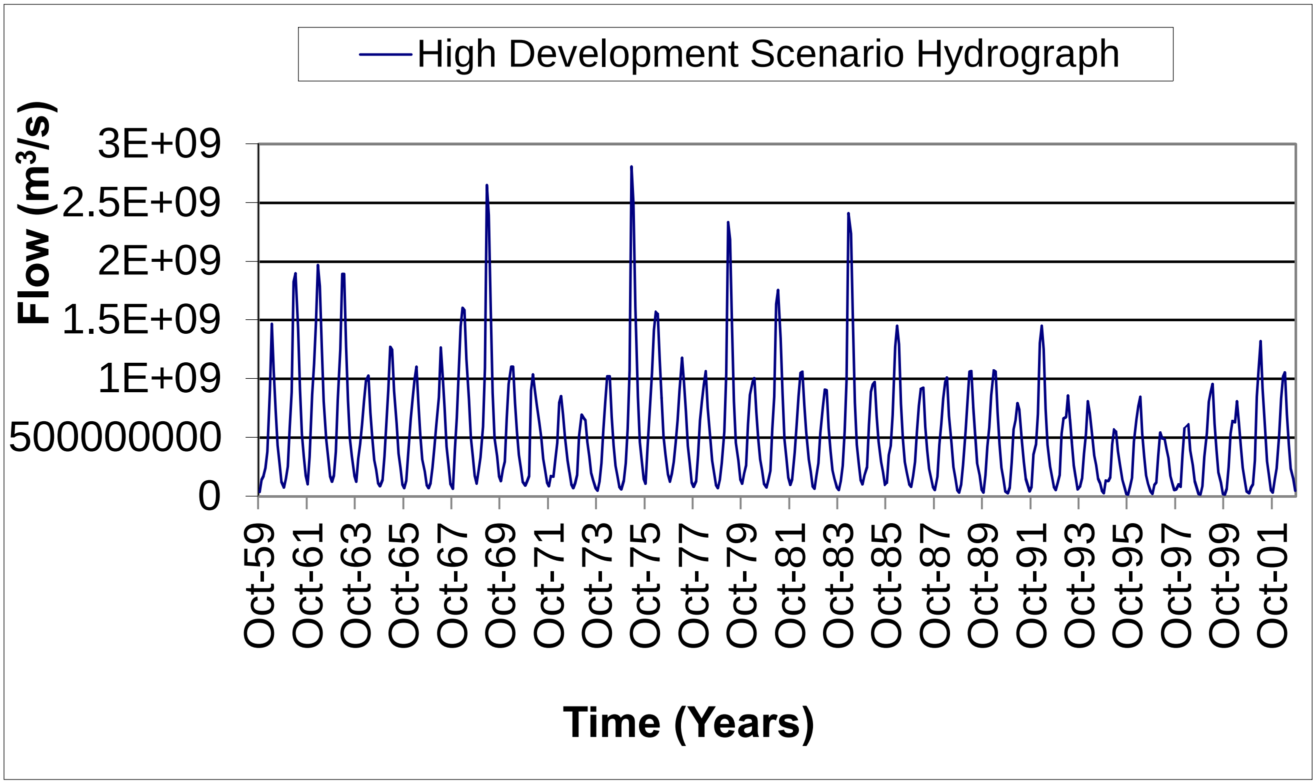
Appendix A8-1: A Current Development Scenario Hydrograph.



Appendix A8-2: A Medium Development Scenario Hydrograph.



Appendix A8-3: A High Development Scenario Hydrograph.



RAINFALL DATA
Appendix A-9:

A9-1: Location of Angolan Rainfall Stations

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

Source: Department of Water Affairs (Angola), 2008.

A9-2: 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	Not-Operational
Andara	11607833	18°04'	21°28'	06-1914	09-1995	
Mpungu	12057660	17°46'	18°26'	12-1962	12-1980	Not-Operational
Kuring Kuru	12061871	17°37'	18°37'	01-1924	05-2007	
Tondoro	12064961	17°46'	18°47'	10-1931	08-2004	
Rupara	12071418	17°51'	19°05'	06-1958	05-1997	Not-Operational
Bunja	12076214	17°51'	19°21'	01-1953	04-2004	
Rundu	12084758	17°55'	19°46'	01-1940	10-2007	
Sambiu	12090545	17°54'	20°02'	09-1935	02-1981	Not-Operational
Mashare	12092649	17°54'	20°09'	01-1969	12-2003	

Source: Namibia Meteorological Services.

A9-3: Location of Botswana Rainfall Stations

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

Source: Botswana NWMPR, 2006.

Appendix A-10:

DATA FOR HYDROGRAPHS OF DIFFERENT DEVELOPMENT SCENARIOS:

Current/Reference Development Scenario, Low Development Scenario, Medium Development Scenario and High Development Scenario.