DECLARATION

I, the undersigned, hereby declare that this dissertation entitled, “Conception of a simplified model for the monitoring of flood wave (Case study of the Limpopo River Basin)”, is my own work, and that all the sources I have used or quoted have been indicated or acknowleged by means of completed references.

Florence, 21 June 2011

(Gisela Marília Armindo Mabote)

DEDICATION

Where would I be without my family? My parents deserve special mention for their inseparable support and prayers. My Father, Armindo Mabote, in the first place is the person who put the fundament my learning character, showing me the joy of intellectual pursuit ever since I was a child. My Mother, Lídia Mabote, is the one who sincerely raised me with her caring and gently love.

To my brothers Dário, Vanise and in particular to my cousin Júnior, this is a challenge for you to reach greater heights, knowing you can do better.

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Last but not the least, my family and the one above all of us, the omnipresent God, for answering my prayers for giving me the strength to plod on despite my constitution wanting to give up and throw in the towel, thank you so much Dear Lord.

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List of Abbreviations

ARA- Sul	South Regional Water Administration
DEM	Digital Elevation Model
DNA	National Directorate of Water
INE	National Institute of Statistics
RMSE	Root Mean Square Error
GIS	Geographic Information Systems

ABSTRACT

Livelihoods in the Limpopo River Basin remain under the perpetual threat of floods whose frequency and adverse impacts have become more pronounced with the occurrence of each event. The capacity of current measures to mitigate the adverse impacts of floods on the basin's environmental and socio-economic systems has been significantly exacerbated by limitations in flood monitoring and forecasting as well as predicting the areas that are likely to be inundated.

In this study, we developed a methodology associated with Geographic Information Systems, in order to improve the flood forecasting and thus making decisions on options for flood management. To this end, it was a "routing" tributaries flow through connections of cells in Microsoft Excel and from the resulting equations of flows observed, we calculated the heights provided in Combomune and Chokwe, and then made to optimize the their impact, ie, took up their best result of impacts.

From the calculations maded can be documented that the travel time of two days is the period expected to lead to flooding after Chokwe leaving to Massingir dam, and flows above 1000 m^3/s and lower to 1500 m^3/s, wave takes on average three full days trip from Beit Bridge to Combomune with a speed of 1.08 m / s, the coefficient of determination is $R^2 = 0.9623$.

1. INTRODUCTION

1.1. Context

The following study entitled "Conception of a simplified model for the monitoring of flood wave (case study on the Limpopo River Basin), " appears in the fulfillment of the requirements for obtaining Professional Master's degree in Irrigation Problems in Developing Countries in Univesita degli Studi di Firenze in order to devise methods to monitor the flood wave. Floods are natural phenomena that are part of so many others that cause natural disasters in the world. The area of the Limpopo river basin has been shown to have characteristics prone to the occurrence of this phenomenon. He cites the example of the floods of 2000, considered the most severe that the country already crossed with damage estimated at about 800 lives lost and more than seven hundred fifty million dollars in material damage (DNA, 1998, and ARA-Sul, 2000). The impact of the floods in Mozambique is exacerbated by the weak development of methods for monitoring and lack of specialized staff for this purpose. For mitigation of impacts, it becomes necessary to identify early areas of flood risk for different levels of flooding and the continuous prediction of the flow using GIS techniques, Sensing and Hydrological Models Reassemble. The application of these flow modeling, forecasting and coordination of flood management can help reduce the human and economic losses in the region, specifically, on the Mozambican side, which is located downstream, thus providing information needed to guide improvements in the prediction of the same.

If this knowledge is available, the monitoring system of flood wave will have a tool to alert with advance the population in risk areas to take precautions and minimize the effects of extreme floods. It is within this context that this project was created, whose sole purpose is to devise a simplified model for monitoring wave of floods in the Limpopo river basin through the matrix of observed flows.

1.2. Problem

Absence of a simplified model for monitoring wave of floods in the Limpopo basin taking into account that current models used are complex and do not offer conditions to be operated by local materials and lack of qualified personnel for this purpose.

1.3. Justification

The latest events (accident in Massingir dam) showed the need for rapid responses in calculating optimal balancing the impacts of discharges downstream of the dam by "routing" of the flow.

1.4. Hypotheses

- **True:** by analyzing the observed data is possible to devise a simplified model and minimize the impacts of flooding downstream in Combomune and Massingir;
- **False:** through analysis of observed data is not possible to devise a simplified model and minimize the impacts of flooding downstream in Massingir and Combomune.

2. OBJECTIVES

2.1. General Objective

- Develop a simplified model in MS-Excel for monitoring wave of floods in the Limpopo river basin in order to handle natural disasters.

2.2. Specific objectives

- Calculate the ratio between the tributaries flow gauging stations in the South african Beit Bridge and Mozambican Combomune;

- Calculate the height provided of Macarretane dam, Chockwe and Xai-xai resulting from contributions of Massingir dam and flows related to Combomune;

- Quantify the impacts of flooding downstream of Combomune and Massingir.

3. MATERIALS AND METHODS

3.1. Materials

3.1.1. Softwares

- Ms-Excel
- Arc View 3.2ª

3.2. Methods

To achieve the predertermined goals, was followed the following methodological approach:

3.2.1. Data Collection

For the design of the model were collected data from the Massisngir dam discharges and flow of Beit Bridge (A7H008), Combomune (E-33) and Chokwe (E-35).

3.2.2. Principle of Model

The simplified model for monitoring of flood wave of the Limpopo river basin was based on study of correlations between the flows and their heights where they derived several equations used to simulate flow, propagation time (comparison charts) and through curves flow exists in the offices of ARA-SUL, used to calibrate the results. The figure below illustrates the layout of hydrological network of study area, represented in Ms-Excel.

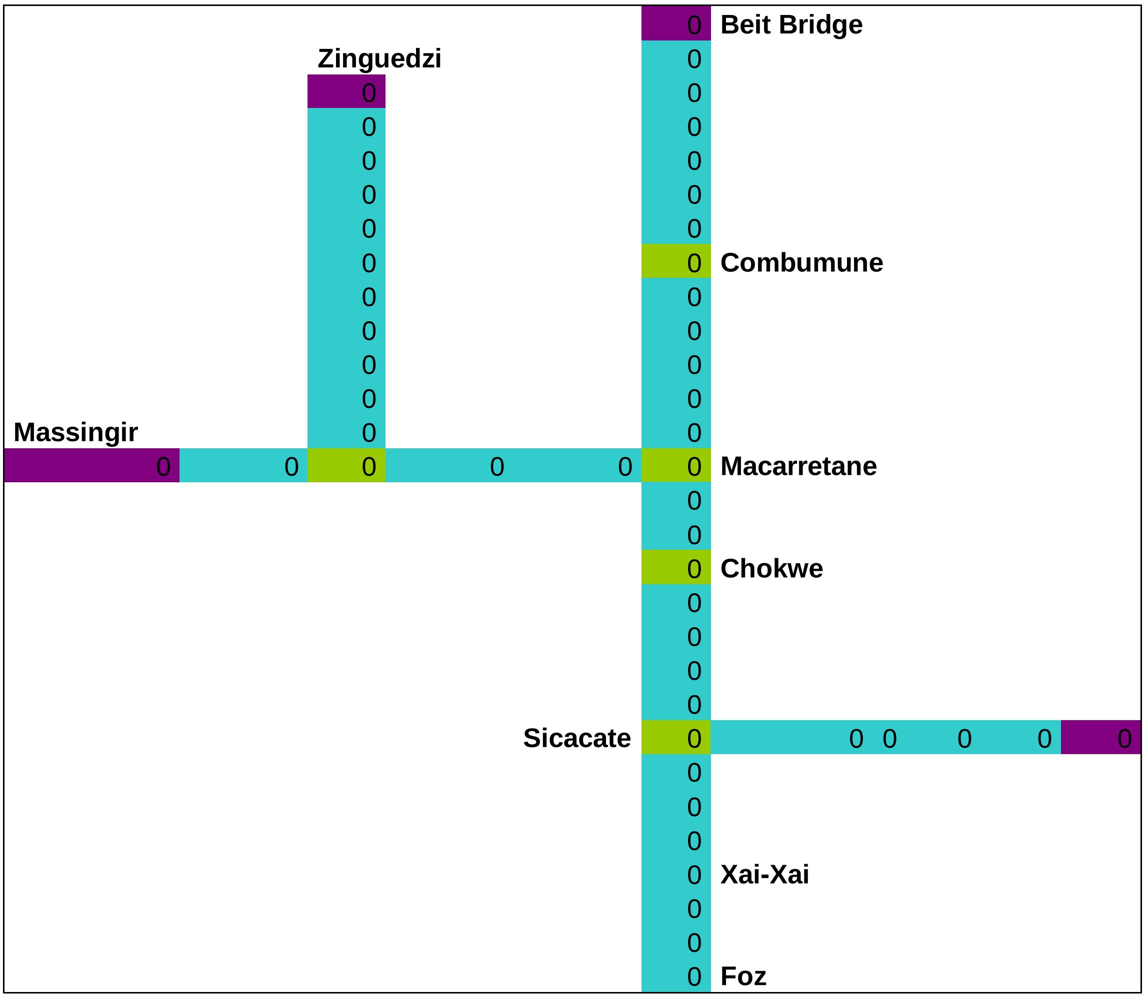


Figure 3.1: Scheme of the hydrological network of the lower Limpopo

The model consists of routing flow through connections that link cells in MS-Excel and equations resulting from correlations of observed flows. We caalculate the heights provided in Combomune and Chokwe and tributaries flow through the Beit Bridge.

3.2.3. Relation Belt Bridge and Combomune

This analysis was done in order to assess the relationship between the tributaries flow hydrometric station in South Africa's Beit Bridge (A7H008) and the Mozambican Combomune (E-33). Equation 3.1 is a result of this relationship.

$$Q_{comb} = 0.7649Q_{bb} + 106.81 \quad \text{[Equation 3.1]}$$

Where:

Q_{comb} – Flow of Combomune

Q_{bb} – Flow of Beit Bridge

To calculate the average speed we used the following equation:

$$v = \frac{e}{t} \qquad \text{[Equation 3.2]}$$

Where:

V – Velocity

e- Espace

t – Time

The distance was calculated using GIS (ArcView 3.2) and the time calculated on the basis of hydrographs.

3.2.4. Relation Massingir, Combomune and Chokwe

This analysis was done in order to assess the relationship between the flows of rivers in the hydrometric station Chokwe (E-35) as a result of the contributions coming from Massingir dam and the hydrometric station of Combomune (E-33). Equation 3.3 is a result of this correlation with a coefficient of determination R2 = 0946.

$$H_{ch} = 0.5834Q_{m+c}^{0.3101} \qquad \text{[Equation 3.3]}$$

Where:

H_{ch} – Height in Chokwe

Q_{m+c} – Flow in Massingir and Combomune

3.2.5. Relation Massingir, Combomune and quota Macarretane

Following the methodological approach mentioned above, it was possible to establish a mathematical analysis of the flow of water from the Massingir and Combomune regarding quotas of Macarretane dam. Equation 3.4 is a result of this correlation with a coefficient of determination R2 = 0.8605.

$C_{mac} = 0.0007Q_{m+c} + 97.118$ [Equation 3.4]

Where:

C_{mac} – Quota Macarretane

Q_{m+c} – Flow ofl Massingir and Combomune

3.3. Model calibration and verification

a) Calibration

As had already been referred to this model the losses are accounted for by the coefficients and does not take into consideration the inputs (precipitation) that occasionally can only check points downstream of the initial conditions. This problem makes the model extremely difficult to gauge. In other words, the calibration of this model will be or is based on adjustment of salary through a quest for better trend regression. For this study he used a linear regression trends and some cases it was kind of regression testing the Power.

b) Verification

First verification was done by comparing the information produced by the model with the observed. Second by comparing the results produced by the same equations using the correlations and results produced by the flow equations currently in use in the ARA-SUL. The Root-Mean-Square Error (RMSE) was used to verify the model errors is given by the equation 3.5. in Walford (1994).

$$RMSE_m = \sqrt{\frac{1}{N}\sum_{i=0}^{N}\left[F_m(Z_i) - f_m(Z_i)\right]^2}$$ [Equation 3.5]

Where:

N – Number of observations

F_m – Field data

fm – Data provided

In addition to the formulations described above were used the following flow equations for the calibration and verification of the model:

b.1. Combomune

$Q_c = 6.988*(h_c - 1.4)^{2.8585}$ [Equation 3.6]

Where:

Q_c - Flow of Combomune

h_c – Height observed in Combomune

b.2. Chokwe

To: h < 7, 10; $Q_{ch} = 63.096*(h_{ch} - 1.40)^{2.8585}$ [Equation 3.7]

To: h>7, 10; $Q_{ch} = 2796.68 + 2250*(h_{ch} - 6.9)^2$ [Equation 3.8]

Where:

Q_c - Flow of Chokwe

h_c – Height observed in Chokwe

3.4. Predicted impacts of flooding

a) Flood area mapping

The methodology recommended by Verdin et al (2004), *United States of Geological Survey* (2001) was used to map the flood zone and to quantify the likely impacts of flooding. *The FEWS Stream Flow Model* interface contains a function *Flooded Area Map*, which creates a map showing the areas to be inundated by the floods. The function uses the predicted flow depths and corrected by the DEM Digital Elevation Model data to identify areas where flooding may occur. Equation 3.9 is governing this process is the energy equation:

$$H = z + y + \frac{v^2}{2g} \qquad \text{[Equation 3.9]}$$

Where:

z– is the elevation of the river bed above datum (m)

y – is the depth of flow or pressure head (m)

v – is the flow velocity at the river cross- section (m/s)

g – the gravitational force

The sum of the pressure head (y) and elevation above datum (z) constitutes the river stage while the third term $\frac{v^2}{2g}$ is the velocity head. For this study, the flood area mapping was implemented combined with both GIS ArcView 3.2a and Spatial Analyst 3.2 nd 1.1 because these systems allow geographers to collect and analyze information much more quickly than was possible with traditional research techniques.

Flood impact assessment

The sub-basin of Xai-Xai was selected to quantify the impacts of flooding downstream. To this were superimposed in the villages and public infrastructure (schools and hospitals) as maps of flood risk. Three levels of flooding were selected as defining the maximum level of inundation of the flood of 2000 in Xai-Xai, which was 10.5 m. Equation 3.10 exists in the offices of ARA-

Sul was used to select the map of inundation areas, and areas that can be flooded with the initial reference level of flood alert in Xai-Xai, which was set in the range of 4,5m.

Based on research conducted in Australian offices and Mozambican Meteorology flood levels for this study were classified as:

1. Flooding level 1: which corresponding the fresh flooding up to moderate flood;
2. Flooding level 2: which is corresponding the major flooding and;
3. Flooding level 3: which corresponding the extreme flooding.

The next step was to determine the inundated area related to the alert level in Xai-Xai, the following equation was applied:

$\Delta x = 10.5 - x$ [Equation 3.10]

$N1 = 10.5 - \Delta x$

$N2 = N1 + \Delta x$

$N3 = N2 + \Delta x$

where:

Δx – is a constante; x – is initial flood level; N1 – level 1; N2 – level 2; N3 – level 3;

The equations 4.5 and 4.6; and initial level at Xai-Xai which is 4.5 m, where used to define the three levels of flood namely:

(i) Flood level 1 (4.5 m- 6.5 m);

(ii) Flood level 2 (6.5 m-8.5 m) and

(iii) Flood level 3 (8.5 m- 10.5 m).

b) Prediction of flows, travel time and mapping of safe areas

To define alternative measures for reducing the impact of flood from Olifants was done by one assumption and three calculations:

(i) Assumption: The rest of Limpopo contributes up to water level of (3 m) at Xai-Xai.

(ii) Calculation 1: What is the water level at Xai-Xai using Massingir monthly water balance model if:

1. Water level is (95m-105m),

2. Water level is between (105m-115m) and,

3. Water level is between (115m-125m).

To convert the daily discharges to water levels we used the equation of the flow curve which is illustrated below:

$h=2.1093*Ln(Q)-11.491$ [Equation 3.11.]

Where:

h- Is the water level

Ln- Natural Logarithm

Q – Is the discharge

(iii) Calculation 2: Calculation of interval flood peak travel time using hydrographs by comparing sequential hydrographs time series using GeoSFM.

(iv) Calculation 3: Identification and mapping of safe areas using GIS ArcView 3.2a.

4. LITERATURE REVIEW

4.1. Introduction

The study started with a review of existing literature on related studies, which had been undertaken under Limpopo River Basin and globally. The data collection, the model selection and calculations were supported by literature reviewed.

Definition of flood

Republic of Mozambique and United Nations Development Programme (2000) define flood as an unusually high stage of a river at which the river channel becomes filled and above which it overflows its banks. Floods are the most destructive events related to meteorological processes and poor understanding of flood forecasting contributes to loss of life and cause of damage to infrastructure, and on the other hand can lead to costly over design of infrastructure located on floodplains (Asante, 2001; United States of Geological Survey, 2001). Flow events follow a pattern that shows a distribution behaviour, which makes it to be described using statistics. Maidment (2002) grouped the flows distribution into three categories low flows, medium flows and high flows (Figure 2.1) which shows the physical definition of flood. Low flows range between 0m^3/s and 250 m^3/s and may be a serious threat to lives as a result of water shortage; Medium flows range between 250 m^3/s and 2500 m^3/s pose no danger to their surrounding environment. In contrast, floods occur when the flow is above 2500 m^3/s; normally cause disasters and vast damages to their surroundings.

Causes of floods

National Institute of Meteorology (2002) identifies a number of factors that can contribute to that imbalance, which can be meteorological or non meteorological causes, including:

- Heavy, intense rainfall;
- Over-saturated soil, when the ground can't hold anymore water;
- High river, stream or reservoir levels caused by unusually large amounts of rain;
- Urbanization or lots of buildings and parking lots etc.

Impacts of floods

Republic of Mozambique and United Nations Development Programme (2000) classify the impacts of flood in two stages, namely impacts during and after flooding. The impacts during the flood are the first stage of flood damages and also classified as negative impact (Jinch, 2005; Asian Development Bank, 2003) depending on the level of flood (Figure 2.2a) and access to the affected area can be difficult often through boats (Figure 2.2b) or air transport.

(a) (b)

Figure 4.1. Some of flooding impacts (a) and acess to flooded area using boat (b) (Source: Republic of Mozambique and United Nations Development Programme (2000))

Other negative impacts of floods include loss of human and animal life's, spread of diseases (malaria, cholera, etc) migration (Jinch, 2005; Asian Development Bank, 2003) and economic impact for example in 1999 the Mozambique GDP was 10% and after 2000 flood was decreased to 5% (Brito, 2000) in Waternet, 2003.

Other positives impacts of floods are: increase of agricultural production example of China with the production of cotton increased in 15% after flood in 1999 (Jinch, 2005), in Egypt flood is a main source of water supply for agriculture activities (El-Raey, 2003), and in Mozambique after 2000 flood new studies on flood forecasting and management were conducted (Denmark Hydraulic Institute, 2002) and new methods for flood forecasting are being put in place.

4.2. Flood Management

Flood management consists on execution of strategic decisions to reduce the impact and negative effect of floods trough remedial measures such as structural and non-structural. Structural measure is a type of engineering measure to solve the flood problem and non-structural measure involves non-engineering actions (Asian Development Bank, 2003; Denmark Hydraulic Institute, 2002). Table 4.1 summarises flood management measures which have been executed in most counties in world, example of United States of America on Mississippi River, Vietnam on Mekong River Delta, China on Yellow River, Egypt on Nile River, and Mozambique on Limpopo River Basin. (Jinch, 2005; El-Raey, 2003; South Regional Water Administration, 2000).

Table 4.1. Summary of flood management measures

	Structural Measure	**No Structural Measure**
Flood Management	• Constructions of dams • River diversion • Construction of river levee and embakment • Widening and deepening river bed • To retain flood water in mining ponds lakes, water-supply dam, hydroelectric dam etc	• Restriction development planning • Water proofing • Flood insurance • Flood forecasting and warning system

Source: Adapted from El-Raey (2003); Jinch (2005)

4.3. Method of estimating flood peaks

Flood forecasting can be determined by basic flow frequency analysis. This can be done using data generated empirically or by using probabilistic and deterministic methods (Chow, et al, 1988). These methods can be coded using computer-programming languages with an interface, which provides a simplified tool for viewing and interpreting results.

a) Empirical methods

Empirical methods were, initially used during the 19^{th} century. Basins are hydrologically delineated. For each hydrological homogenous region, the basin area is plotted against flood peaks to form an envelope whose upper limit is the expected flood peak. The mathematical relationship is in equation 2.1 (Kavacs, 1988; Chow et al, 1988):

$Q_{peak} = CA^n$ [Equation 4.1]

Where:
C - is the regional constant
A - is the basin area (m^2)
n - exponent, which kavacs (1988) assumes to be 1.

Kavacs (1988) appointed the following shortcomings:

- Uncertainty on the location of homogenous regions boundaries;
- Very large and very small basins cannot be accounted for in the regional approach due to different hydrological behaviours;
- The influence of primary elements (rainfall, soils, vegetation etc) is not considered in this type of assessment.

b) Probabilistic methods

These methods have been in use about 1930. These methods relate the maximum flood peak to a probability of occurrence, which is usually very low. A return period of 10,000 years is often used i.e. probability of 0,0001. Extrapolation of the theoretical probability distribution is fitted to annual flood peak records and this is usually 100 to 500 times longer than the period of record (Stedinger, et al, 1993; Kavacs, 1989; Varas et al, 1988, Clarke, 1973) in Bwanali (1999). This method also has shortcomings. Some of the weaknesses of the probabilistic method are (Kavacs, 1988):

- Theoretical statistical distributions derived for different objectives have no relationship with physical factors that influence the flood flow potential of basins.
- The return period of 10,000 years is arbitrary and too long.

c) Deterministic methods

These methods have been applied since about 1950. Deterministic methods use the unit hydrograph principle in flood flow generation (Maidment, 1993; Clarke, 1973). Equations governing the different aspects of storm-flow generation are used to define the shape of unit hydrographs. The weakness of this method is the lack of acknowledgement of the modified behaviour of storm flow response from rainfall timing in cases of storm transposition (Kavacs, 1988).

Studies Islan and Sodo (2002); South Regional Water Administration (2000); Kunel et al (1994); Walker (1993) shows that those methods have failed to predict the recent high profile flooding events at Bangladesh in 1987, 1988 and 1998, Limpopo in 2000 and Mississippi River in 1993.

Studies Guleid et al (2004); Denmark Hydraulic Institute (2002); National Directorate of Water and South Regional Water Administration (2000) also shows the weakness of the previous methods in predict the recent major flood accrued in Zambezi and Limpopo Rivers in 2000.

4.4. Hydrological models

Tucci (1998), defines the hydrological model as a useful tool that allows to represent, understand and simulate the behavior of watershed. However, it is impossible or impractical to translate all existing relationships between the different components of the watershed in mathematical terms. In fact, that these relationships are extremely complex as there is not a mathematical formulation able to describe them completely, or just a part of process involved in these relations is partially known. Thus, in most cases, the hydrological modeling becomes only an approximation of reality.

4.5. Models applied in the Limpopo River Basin

Limpopo River Basin have been tested and tested six models between the years 1979 to 2002 which have been implemented, but the results cannot be used for issues that forecasting because they all depend on the measurement of precipitation and water levels. During the floods there are many difficulties in penetrating the measuring instruments installed on the field, and they are submerged or being dragged through the water before the passage of the flood wave downstream in the basins, thus there is the lack of hydrological data to apply models. This project presents some of the models tested in the Limpopo river basin.

a) Simulation model for Massingir dam

This model was developed by H. Savenije in 1979 and was updated in 1984. It is for monthly dam water balance management, considering the major demand such as agricultural projects downstream of the dam (Chokwe and Xai-Xai). Also it is used for defining the gate operation plan and for the flood rule curve (National Directorate of Water, 1996). This model has got limitations on defining the dam discharges because it depends on the observed rainfall and inflow.

b) Flood forecasting model for Limpopo River Basin

This model was developed between the years 1978 to 1980 by H. Kranendonk for the propagation of flooding along the Limpopo River, which was intended to serve as a support system for flood warning. This incorporates three components:

- The derivation of runoff from the knowledge of rainfall occurred;
- The contribution of groundwater flow;
- The spread of the flood wave along the river, considering the time delay and damping of the peak.

In the case of the Mozambican section of the Limpopo River, the first two gates proved to be of little importance compared with the third based on the wave propagation from full flow measured at Beit Bridge and at the border (Combomune), expected tips and time delays downstream, Chokwe, Xai-Xai and Sicacate.

c) Models of flooding on the Massingir dam

Currently it is used two types of models in flood reservoir Massingir:

- A model for statistical analysis of annual maximum flows related to the dam. Derived from a long series and used the package of the Portuguese company hydro project HST to examine the adjustment of the maximum number of theoretical probability distributions and extrapolate to high return periods;

- A model for the "routing" of flooding, given its damping characteristics of the reservoir and dam, spillways and the discharges of background, using the modified method Plus. This method was designed especially for the case of Massingir.

d) Simulation model of the Limpopo basin

This model was simulated for the Mozambican part of the Limpopo river basin includes:

- The simulations consideration of Massingir discharges and runoff tributaries of Limpopo;
- Different types of demands: multiple blocks of irrigation, urban water supply, power generation and flood control Massingir, discharges to reduce the intrusion;
- Scenarios for growth in countries of abstractions upstream.

4.6. Need for hydrological model

There are many definitions of a hydrological model. This study present the concept of hydrological model as defined by Maidment (1996) because of its relevance to the topic as previously defined.

Maidment (1996) defines a hydrological model as a mathematical representation of the flow of water and its components on some part of the land surface or subsurface environment. The United States of Geological Survey (2002); Asante (2001) studies considered the natural hydrological systems as complex. Modelling them should involve the need to manipulate vast quantities of data, characterized by large temporal and spatial fluctuations. Modelling is therefore a way of integrating the numerous aspects of the real system for beneficial outputs. Other reasons for the need of hydrological model are in (United States of Geological Survey, 2002; Asante, 2001; Clarke, 1973):

- It generates information needed for planning, design, development and management;
- It provides efficient and cost effective quantitative and qualitative estimation on availability of water as well as the variation in its availability in both time and space domain;
- When computer based, a model can handle, organize and synthesize large amounts of existing hydrological data and generate useful information from limited data;
- It may be useful in filling missing and non-existent records and naturalization of records etc.

4.7. New opportunities on flood forecasting models

Many innovations in the application of information technologies began in the late 1950s, 1960s and early 1970s (Maidment, 1996). Methods of sophisticated mathematical and statistical modelling were developed and the first remote sensing data became available. Researchers began to envision the development of Geographic Information Systems and Hydrologic Model Interface as a result (Eduardo Mondlane

University, 2000; Maidment, 1996). This subsection present and discuss the integration between GIS and some of the most advanced flood forecasting models.

4.7.1. Intregating hydrologic modeling with GIS

There are many definitions of GIS according to different applications. The definitions below were selected because of their relevance to the present research. Dueker (1979) defines Geographic Information System (GIS) as a special case of information system where the database consists of observation or spatial distributed features, activities or events while Burrough (1986) defines it as a powerful set of tools for collecting, storing, retrieving, transforming and displaying spatial data from the real world for particular acts or purpose. To integrate the two definitions above, Cowen (1988) defines GIS as a decision support system involving the integration of spatially referenced data in a problem-solving environment. All these definitions include an important component, which is spatial data. Burkholder (1997) defines spatial data as a collection of existing mathematical concepts and procedures that can be used to manage and create both locally and globally spatial information. It consists of a functional model that describes the geometrical relationships and a stochastic model that describes the probabilistic characteristics of spatial data.

American Water Resources Agency (1996) noted that GIS provides numerous tools, which enhance the performance of hydrologic modelling. Djokic (2004) classified these integrated technologies as data management (manipulation, preparation, extraction, etc.), visualization, and interface development tools.

Used for flood forecasting and management there are several hydrological models that have GIS linkages. Among them are MIKE SHE, MIKE Flood Watch, Geo-spatial Stream Flow Model etc, which are being used for flood forecasting and management in Bangladesh (Islan and Sodo 2002), Kenya and Mozambique (Entenman, 2005). Below are two presentations of the applicability of them because are the most applied for flood forecast and management.

4.7.2. Mike flood watch

Denmark Hydraulic Institute (2002) defines Mike Flood Watch as a lumped and new, modern and extremely robust forecasting system, which integrates data management, forecast models and dissemination methodologies in a single system within a GIS platform.

Data requirements

According to Denmark Hydraulic Institute (2005) to run Mike Flood Watch, the following data are required: topographic data on the cross section from the field. This information is used to calculate the channel characteristics (velocity, slope and regorosity). Measured rainfall and evaporation data is also required.

Strengths and weakness of the Mike Flood Watch

A study done by Denmark Hydraulic Institute (2002) at Limpopo and Incomati River Basins shows the following advantages and disadvantages:

Strengths

- The advantages of the Mike Flood Watch include the ability to be applied successfully within following areas: real time monitoring and decision support.
- Real time flood forecasting and warning;
- Control of dam and infrastructure;
- Real time dissemination and flood mapping and integrating modelling (Denmark Hydraulic Institute, 2005).

Weakness

According to Denmark Hydraulic Institute (2005) the limitations of the model include: use of a lot of assumptions, for example for flood forecasting, the rainfall has to be assumed; the implementation is expensive in terms of finance and time, it is difficult to run, calibrated and maintain.

4.7.3. Geo-spatial Stream Flow Model

Geo-spatial Stream Flow Model is a distributed model. It has a GIS (ArcView 3.x) application based on use of satellite remote sensing, numerical weather forecast field, and geographic data sets describing the land surface (Entenmanns, 2005). It was developed by scientists at the United States Geological Survey (USGS) National Centre. The development of the model was driven by the need to establish a common visual environment for the topographic analysis, data assimilation, time series processing and results presentation activities that go into the monitoring of hydrologic conditions over wide areas.

The ArcView 3.x GIS series was adopted for the implementation because it provided a visual, customizable development environment with excellent support of raster operations.

An ArcView extension was developed (in Avenue languages) for the geospatial processing operations and for the initiation of time series analysis tasks. Routines for performing the hydrologic computations involved in mass balance and routing were developed in a mixed programming environment (C/C++ and Visual Fortran) and compiled as (DLL) Dynamically Linked Libraries (Entenmanns, 2005).

Data requirements

Many of the data sets involved in these processes are raster grids. The spatially distributed nature of the raster grids used in these processes point to the adoption of a customizable geographic information system with excellent raster functionality.

Strengths and weakness of the GeoSFM

Studies done by Entenman (2005) and Guleid, A. et al (2004) show the following advantages and disadvantages:

Strengths

- Use of global data sets that cover the whole African continent;
- Data from the rain are obtained from satellite images.

Weakness

- Difficulty to run and calibrate;
- Data processing is expensive in terms of time.

4.7.4. Waflex model

Waflex is a model based on a worksheet that can be used to analyze the interactions between upstream and downstream dam management options and water distribution and development of options (Savenije, 1995).

Model structure

Waflex is configured as a grid where each cell is used to reach the river looking for the node or reservoir. Each cell contains a simple formula for accrescentar water from adjacent cells, and to subtract any demand connected to that cell. The network is set twice, on demand and supply mode.

Entries for waflex are:

- Time series: source area where the model begins;
- Search node series, for example, a solution of water supply;
- Reservoir rule curves and dimensions;
- Time series of gauges for calibration.

The outputs for waflex are:

- Time series of specific points on the rivers: these can be calibrated against pressure gauges;
- Time series of funding and shortage of demand for each node;
- Time series of levels of the reservoir.

5. DESCRIPTION OF THE STUDY AREA

5.1. Geographical location

The study area comprises the lower Limpopo where they were considered four (4) points representing the initial conditions including Beit Bridge, which corresponds to point 1, point 3 corresponds Zinguedzi, Massingir corresponds to point 4 and Changane point 7 (Figure 5.1 below). In general, the basin of the Limpopo River is shared by four countries, namely South Africa, Mozambique, Botswana and Zimbabwe. It has an area of 412,100 km2. This portion occupies about Mozambique 79,500 km2 and is located downstream of other countries. The Mozambican part of the Limpopo river basin is an area located in the provinces of Gaza and part of Inhambane, in the southern part of Mozambique. Its boundaries are the Save River basin to the north and south Incomati River to the east is bounded by a series of small lake basins and the Indian Ocean. The west boundary is the border of Mozambique with South Africa.

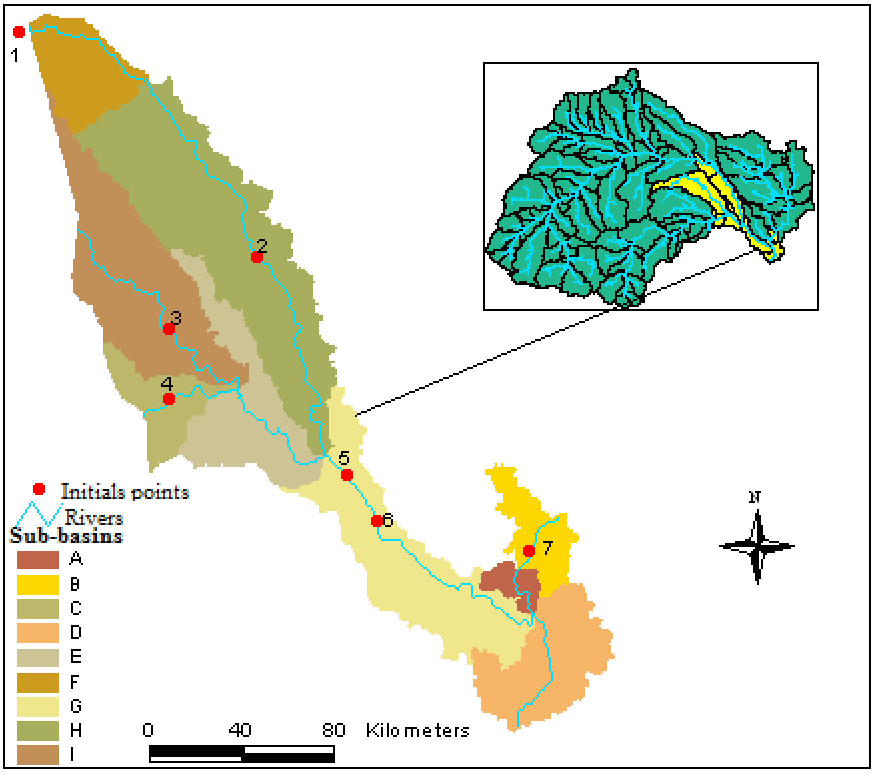


Figure 5.1: Location of study area (Source: ARA-Sul)

5.2. Topography

As the topography of general form the study area does not have a noticieable relief, high altitudes do not exceed 540 m and are located on the north and center of the basin, along the border with South Africa and Zimbabwe and the minimum altitudes ranging from 0 to 55 m are located in the southern region along the Limpopo and Changane toward the downstream DNA(1996).

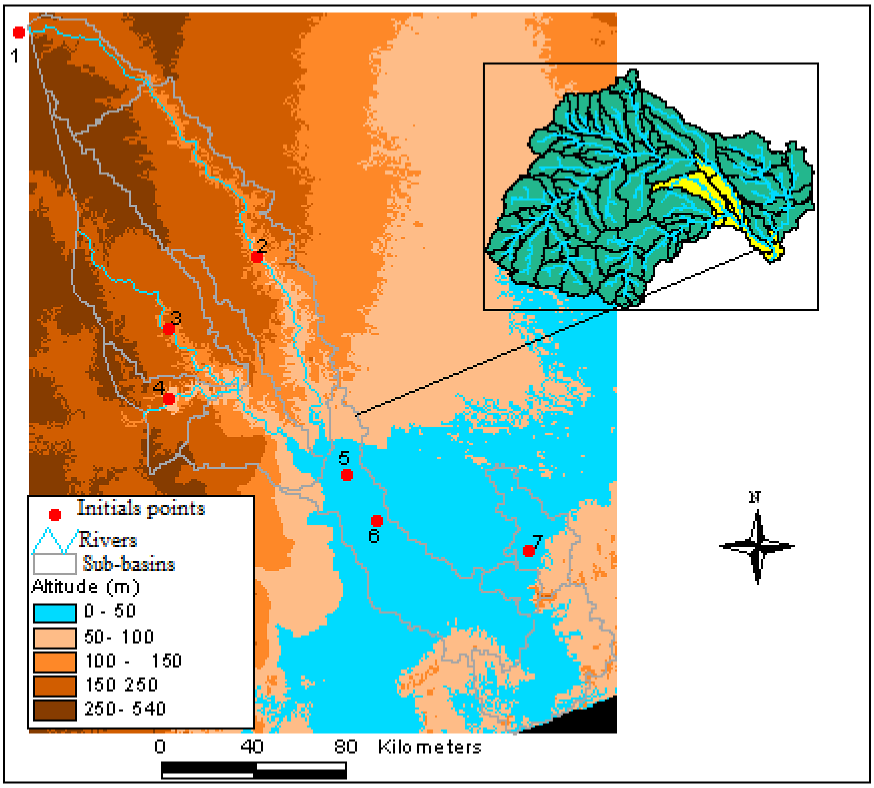


Figure 5.2: Spatial distribution of topography (Source ARA-Sul)

5.3. Clime

The following climatic variables were selected because of is influence on the process of flooding. For example, high temperatures in a certain period can cause a concentration of rainfall, excess runoff and consequent flooding of adjacent areas.

a) Temporal distribution of temperature and precipitation

The climate in this region varies essentially arid in the west, the semi-arid areas in central and semi-arid climate in the east, with pockets in the center sub-humid. Air temperatures throughout the basin show a distinctly seasonal cycle, registering high during the summer months (November to March) and low during the winter months (April to October). The maximum temperature is 26 ° C and the minimum is 19 ° C. Rainfall is also highly seasonal, raining heavily during the warm months, ranging from 12 to 126 mm.

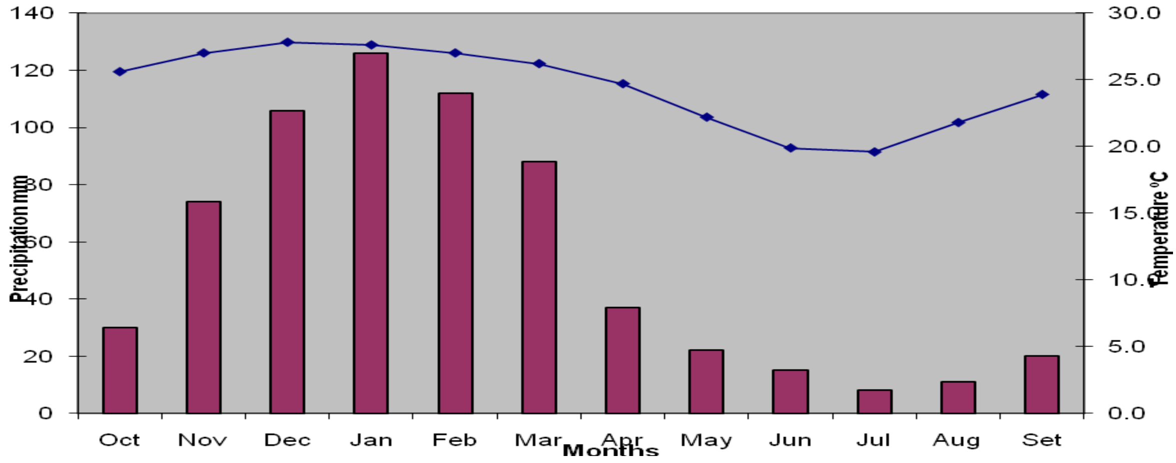


Figure 5.3. Temporal distribution of temperature and precipitation (Source: ARA-Sul, 2002).

b) Evaporation

The average annual potential evapotranspiration varies between 1257 and 1684 mm, and according to the table published by FAO (1981) and Kassan (1981) to lower evapotranspiration checked into Mabote (1257 mm) and highest (1684 mm) at Pafuri. Establishing a relationship between precipitation and potential evapotranspiration in space and inside the basin scale can be noted that the basin has a high potential evapotranspiration and low rainfall, thus having a water deficit (DNA, 1996).

5.4. Soil texture

In general the study area consists of a sandy texture along the east coast and a thin soil and the interior with a water holding capacity ranging from very poor to poor. Along the Limpopo River in the downstream direction of the soil is clayey and very capable of retaining water, these characteristics make these are poorly permeable (DNA, 1996).

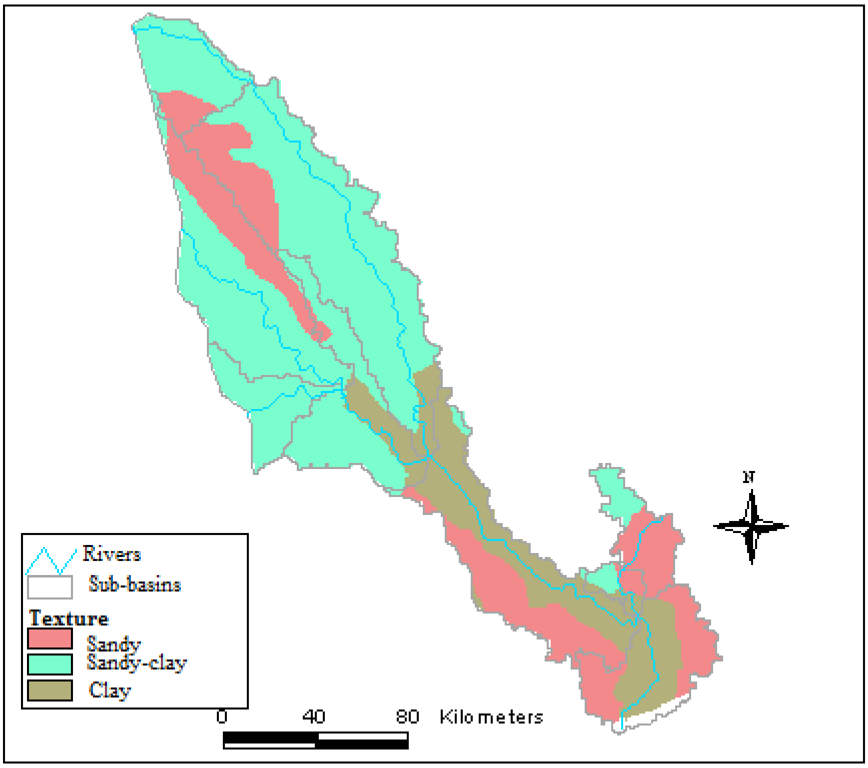


Figure 5.4: Spatial distribution of soil texture (Source: ARA-Sul)

5.5. Soil depth

Most soils in the Limpopo river basin are deeper than 100 cm, there is a sizable portion of low soil depth (less than 30 cm), located northwest of the dam Massingir. On the other hand, there are also those of moderate depths (70 to 120 cm) occurring in the South, in small proportions (DNA, 1996).

5.6. Use and land cover

The vegetation that occurs in the northern region is the evergreen forest, agriculture and grassland, occurring also in the Centre but in small proportions. Although the central region, there is a large area dominated by rainfed agriculture and agro forestry and grassland that stretches to the northern basin. The Southeast are some remnants of deciduous forests and agro forestry on a large scale. Savannas occur further east, a cluster along the coast (DNA, 1996).

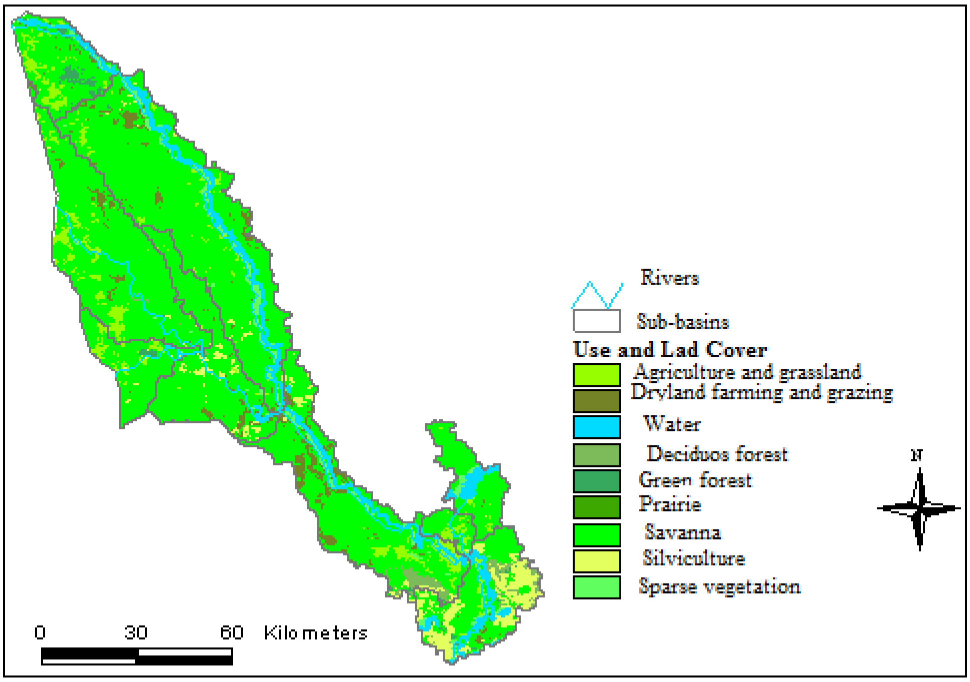
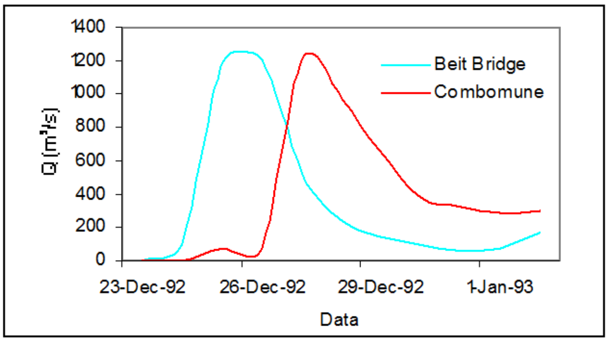


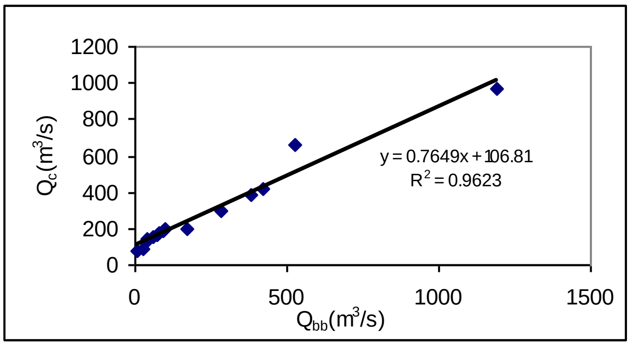
Figure 5.6: Spatial distribution of land use and land cover (source: ARA-Sul, 2002)

6. RESULTS AND DISCUSSION

6.1. Propagation time of flood wave

This analyzes explain the functionality of the model, and shows that for flows above 1,000 m^3 / s less than 1500 m^3/s the flood wave should take on average three days (Figure 6.1a) the trip from Beit Bridge to the Combomune an average speed of 1.08 m / s. Figure 6.1b explains the existence of a strong correlation between areas of Beit Bridge and Combomune, giving a linear regression coenficiente R^2 = 0.9623.





(a) (b)

Figure 6.1: Time of propagation (a) relation Beit Bridge and Combomune (b)

Figure 6.1C which is illustrated below indicates the propagation time of flood wave as a function of time, which has documented and can flow to less than 500 m^3 / s takes longer to travel to Beit Bridge Combomune with average time varies 4 days. Flow rates less than or equal to 1500 m^3 / s with an average time between two days, for flow greater than 1500 m^3 / s with a mean of 1.5 days. This is because it is considered that the soil is completely covered, and coverage of land being mostly made up of forest formations where the soil depth too high, implying that they influence the flow of water for because of water retention capacity that they have, there are major losses during the flood wave takes to reach the Combomune.

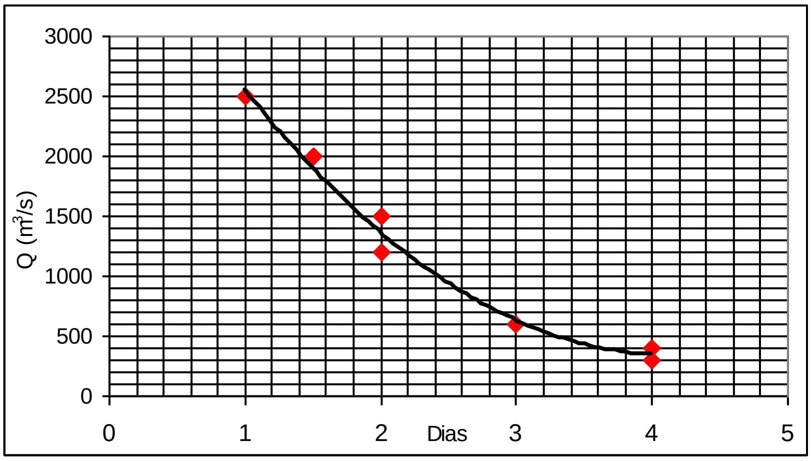
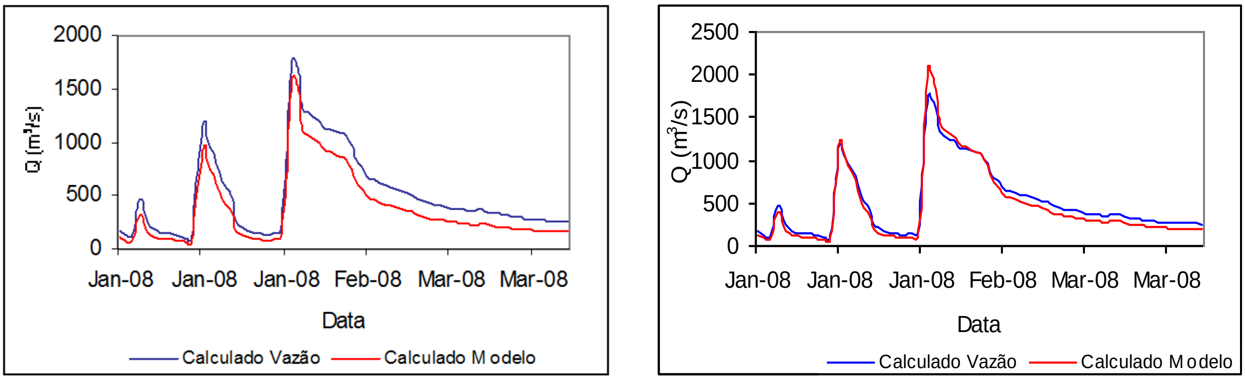


Figure 6.1C: Time of wave propagation

6.2. Verification of the model

The verification was the comparison between the results obtained by the model and the flow curve in Chokwe. For this case the ideal is given by equation H_{ch} $0.5834Q_m$ = + $c^{0.29}$ achieved after the calibration process rather than the ratio found in the initial process was given by equation 3.3. that was described in the methodology on page 7. Figures 6.2a e b illustrated below indicate the relationship between the flows generated from the flow curve and produced through the model, this relationship was made with the aim of adjusting the model to produce results that reflect those observed for this were was testing if the exponents are to optimize results.



(a) (b)

Figure 6.2: Flow in Chokwe before calibration (a) and after calibration (b)

The relationship between the results produced by the model and the flow curve which was tested by linear regression, is shown to be strongly and positively with the value of 98.9% which explains the relationship between the flows generated by the flow curve and the model, and 2.1% is not the P-value is 0 which shows the degree of confidence. 38.95 m^3 / s was taken as the value of Root Mean Square Error, which means that for the peak flow model produces an error of about 39 m^3 / s in relation to the "observed".

6.3. Model scheme

Figure 6.3 illustrates the schematic drawing of the model with initial conditions as the locals painted purple to represent the flow of Massingir, Beit Bridge, Zinguedzi and Changane. The rectangles are painted in green are the values the contributions of Combomune, Macarretane, Chokwe, Xai-Xai and Sicacate that represent the heights calculated from the flow curve. The time of three days is the period that the flood wave should take when leaving from Beit Bridge to Combomune. The main objective of this model is to calculate the losses that occur during the draining of flood, for example the flow rate went up to Beit Bridge until Combomune ranged from 3000 m^3 / s to 2402 m^3 / s, this happens due to the influence of some parameters as the inclination of the slope, texture and soil depth. The value of the flow is added to the Massingir Zinguedzi thus obtaining the value of 3900 m^3 / s that is added to the flow coming from Beit Bridge leading to 6302 m^3 / s which is in turn added to the contribution of flow of Changane where part until you reach the mouth with a value of 6752 m^3 / s.

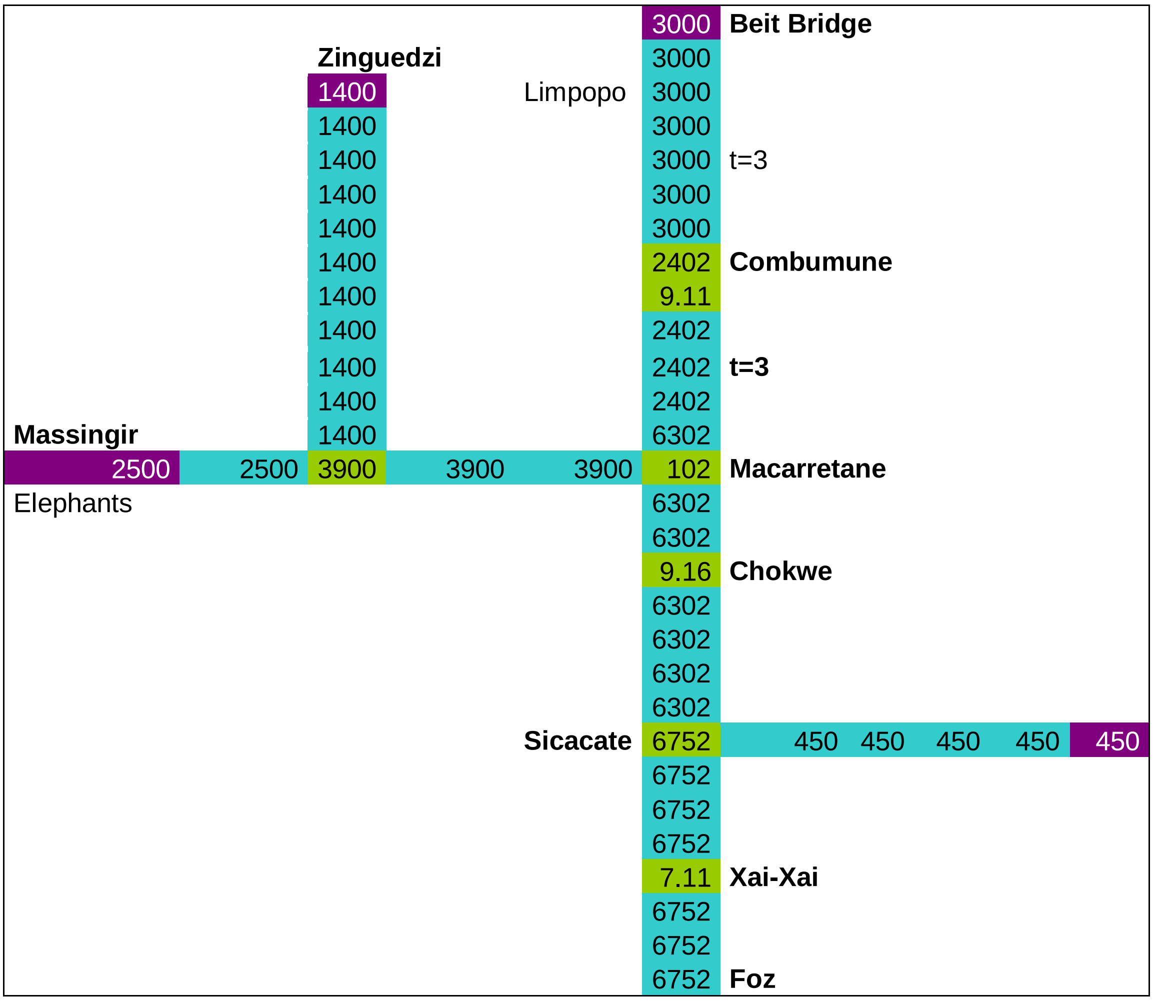


Figure 6.3: Layout of the model

6.4. Management alternatives for reducing impacts of floods

6.4.1. Flood impact assessment at Xai-Xai

In this work the sub-basin of Xai-Xai was evidenced becouse corresponds to one of the main tributaries of the Limpopo river basin, to quantify the impacts of flooding downstream villages were superimposed and the public infrastructure (such as schools, hospitals) in maps of flood risk.

a) Level 1

In flood level 1 which correspond water level at Xai-Xai between 4.5 and 6.5 m, the following villages are inundated namely: : Manhengane, Massaingue, Cumbane, Mahiele, Totoe, Gumbane, Languene, Zikai, Chilaune e Nguava. In total 103 397 people can be affected, the Figure 6.4 illustrates the map of the flood for level 1.

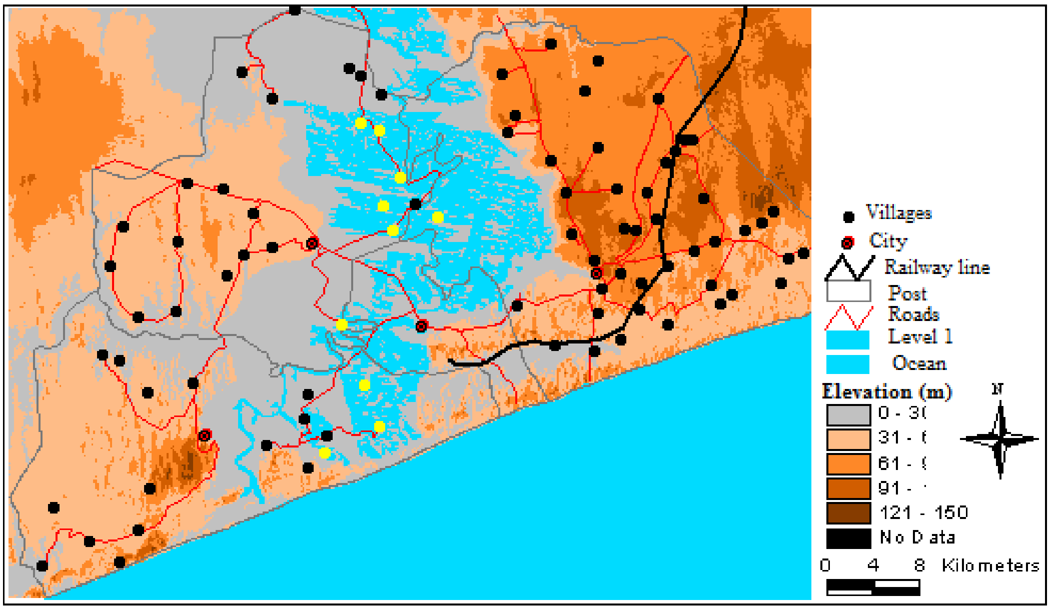


Figure 6.4: Flood area map for level 1 (4.5-6.5 m)

b) Level 2

In level 2 of floods, which correspond to the water level at Chokwe between (6.5-8.5 m), fourteen villages can be inundated as is shows in Figure 6.5. These Villages are: Totoe, Maniquinique, Cumbane, Gumbane, Languene, Madoca, Magonhane, Mahielene, Manhengane, Nguava, Massaingue, Chilaune, Phico e Zikai, e a cidade de Xai-Xai, total of 105 397 of people can be affected. The Table below is summarizing the impact of floods at level 2 (Figure 6.5).

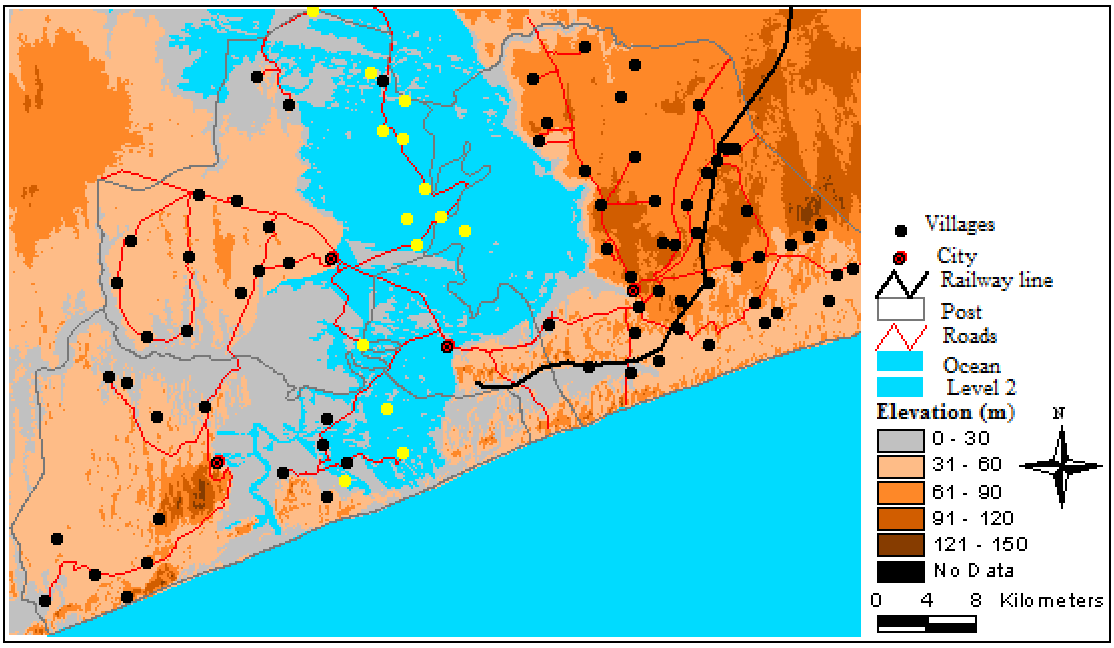


Figure 6.5: Flood area map for level 2 (6.5-8.5 m)

c) Level 3

For Level 3, which corresponds to the water level in Xai-Xai between (8.5 to 10.5 m), can be flooded fifteen villages that are: Toto, Maniqinique, Cumbane, Gumbane, Languene, Madoc, Magonhane, Mahielene , Manhengane, Nguava, Massaingue, Chilaune, Phico, Zika and Salvador Allende and two cities are: Xai-Xai and Zongoene, may be affected in total about 129 959 people, the figure 6.6. illustrates the flood map to level 3.

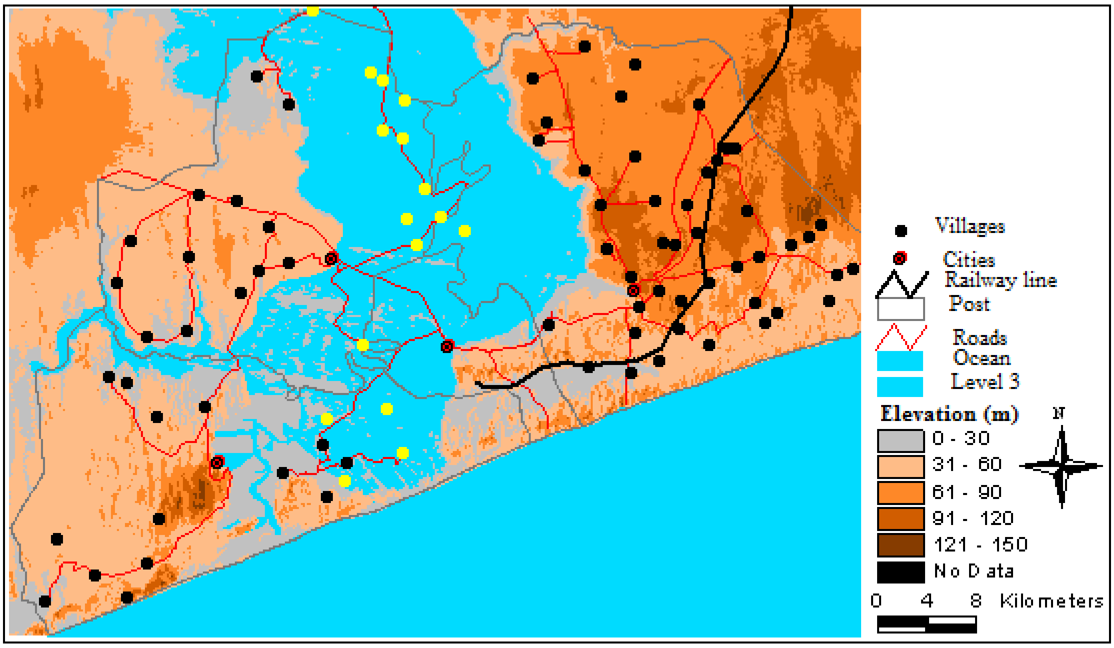


Figure 6.6: Flood area map for level 3 (8.5-10.5 m)

Table 6.4: Summary of impacts of floods at different levels

Heights measured in hydrometric station of Xai-Xai		
Level 1 (4,5-6,5m)	**Level 2 (6,5-8,5m)**	**Level 3 (8,5-10,5m)**
Locations for warning:		
Villages: Manhengane, Massaingue, Cumbane, Mahiele, Totoe, Gumbane, Languene, Zikai, Chilaune e Nguava	**Villages:** Totoe, Maniqinique, Cumbane, Gumbane, Languene, Madoca, Magonhane, Mahielene, Manhengane, Nguava, Massaingue, Chilaune, Phico e Zikai	**Villages:** Totoe, Maniqinique, Cumbane, Gumbane, Languene, Madoca, Magonhane, Mahielene, Manhengane, Nguava, Massaingue, Chilaune, Phico, Zikai e Salvador Allend
Cities: Xai-Xai	**Cities:** Xai-Xai	**Cities:** Xai-Xai e Zongoene
Flooded Area in Percentage per Seat		
Chicumbane: 19.9%	Chicumbane: 37,4%	Chicumbane: 54.5%
Chongoene: 11.5%	Chongoene: 16.2%	Chongoene: 17.1%
Cidade de Xai-Xai: 23.3%	Cidade de Xai-Xai: 33.2%	Cidade de Xai-Xai:
Zongoene: 5.6%	Zongoene: 8.1%	Zongoene: 10.1%

Table 6.5: Total population affected by post

Total Population by post in Census 2007	
Post	**Population**
Chicumbane	88.714
Chongoene	77.549
Cidade de Xai-Xai	116.316
Zongoene	31.456
Total	314.035

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

After analyzing the results obtained from combinations of data flow between the Beit Bridge, Combomune, Chokwe, Macarretane and Massingir, we can conclude that it is possible to design a simplified model for monitoring wave of floods and this model can be used with a high degree of accuracy as illustrated in this study. However from the correlation between the hydrometric station of Beit Bridge and Combomune we observed that for flows above 1000 m^3/s and below 1500 m^3/s a flood wave should take on average three days of travel in a speed 1.8 m / s, with the determination coefficient of R2 = 0.9623 and the journey time of two days is the period expected to lead to flooding Chokwe after leaving the Massingir dam. The relationship between the results produced by the model and the flow curve which was tested by linear regression proves to be positive and strong with a value of 98.9%.

7.2. Recommendations

- It is recommended that the performance verification test of the model is done in the next rainy season for ARA-Sul;
- Similar studies should be conducted in the other watersheds in order to build a strong database and more comprehensive;
- It is recommended that coaches be trained in order to work with the model;
- In study area in order to improve the performance of the model upstream dams have to be connected and validated by applying it in the future;
- Metadata tool have to be established between authorities located upstream (South Africa) and downstream (Mozambique) for quick data exchange, which is important to feed the model.

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