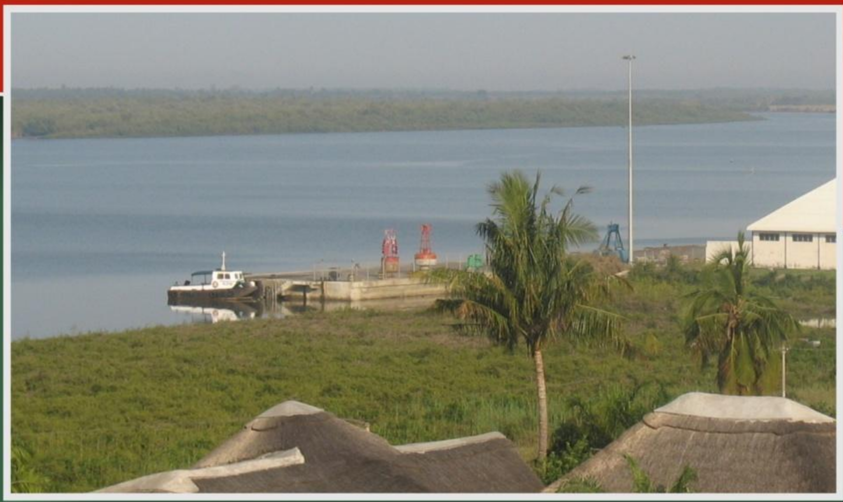
RESPONDING TO CLIMATE CHANGE IN MOZAMBIQUE

REPUBLIC OF MOZAMBIQUE
MINISTRY OF STATE ADMINISTRATION
NATIONAL INSTITUTE OF DISASTER MANAGEMENT



INGC
Instituto Nacional de
Gestão de Calamidades

THEME 5

National Institute for Disaster Management (INGC)
PHASE II

THEME 5
Water

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Abbreviations & Acronyms

AdH	Adaptive Hydraulics
AfDB	African Development Bank
AGRA	Alliance for Green Revolution in Africa
AIAS	Abastecimento de Água e Saneamento (National Water and Sanitation company for sanitation in large cities and water supply in small towns of Mozambique)
AKF	Aga Khan Foundation
API	Application Programming Interface
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AWSP	Agricultural Water Solutions Project
AVHRR	Advanced Very High Resolution Radiometer
AWM	Agricultural Water Management
AQP	Annual Work Programme
BAGC	Beira Agricultural Growth Corridor (Mozambique)
BW	Blue Water
CA	Conservation Agriculture
CAD	Computer Aided Design
CAL	Client Access License
CC	Climate Change
CCTV	Closed Conduit TV
CENOE	National Emergency Operational Centre (Mozambique)
CGIAR	Consultative Group on International Agricultural Research
CIAT	International Centre for Tropical Agriculture (Colombia)
CIMMYT	International Maize and Wheat Improvement Centre (Mexico)
CMM	Counselho Municipal de Maputo (Municipal Council of Maputo - Mozambique)
CNRM	Centre National de Recherches Meteorologiques (France)
CORDEX	COordinated Regional climate Downscaling Experiment
CP	Calibration Procedure
CRSP	Coastal Rural Support Programme (Mozambique)
CRU	Climate Research Unit
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSM	Clean Star Mozambique
CWP	Crop Water Productivity
DARIDA	INGC Drylands Programme
DAU	Departamento de Água Urbana (Urban Water Directorate – Mozambique)
DEM	Digital Elevation Model
DFID	Department for International Development (United Kingdom)
DFO	Dartmouth Flood Observatory
DGRH	De Gestão de Recursos Hídricos (Water Resources Management)
DMI	Danmarks Meteorologiske Institut (Denmark)
DNA	Direcção Naçional das Águas (National Directorate of Water – Mozambique)
DRMP	Disaster Risk Management Project
DSC	District Steering Committee
DSS	Decision Support System

DWA	Department of Water Affairs (Zambia)
EACC	Economics of the Adaptation to Climate Change
ESRI	Environmental Systems Research Institute
ET	Evapotranspiration
FAO	Food and Agriculture Organization
FdF	Fundo de Fomento (Development Fund)
FEM	Mozambique Enterprise Foundation
FFS	Farmer Field School
FIPAG	Fundo de Investimento e Patrimonio do Abastecimento de Agua (National water and sanitation company for water in large cities - Mozambique)
FRA	Flood Risk Assessment
GCM	Global Climate Model
GPCC	Global Precipitation Climatology Centre
GRanD	Global Reservoir and Dam database
GHCN	Global Historical Climatology Network
GIS	Geographic Information System
GPS	Global Positioning System
GRDC	Global Runoff Data Center
GUI	Graphical User Interface
HBV	Byråns Vattenbalansavdelning (Hydrological Transport Model)
HEC-RAS	Hydrologic Engineering Center – River Analysis System
IADP	Integrated Agricultural Development Project
ICRISAT	Institute for the Semi-Arid Tropics (India)
ICTP	International Centre for Theoretical Physics (Italy)
IDF	Intensity-Duration-Frequency
IFAD	International Fund for Agricultural Development (Italy)
IFDC	International Fertiliser Development Centre
IMS	Information Management System
INAM	Instituto Naciona de Meteorologia (National Meterological Institute - Mozambique)
INGC	National Disaster Management Institute (Mozambique)
INM	Instituto Nacional de Meteorología (Spain)
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institut Pierre Simon Laplace (France)
IRD	International Relief and Development (USA)
IRR	Internal Rate of Return
IWMI	International Water Management Institute (Sri Lanka)
IWRM	Integrated Water Resources Management
LBPTC	Limpopo Basin Permanent Technical Committee
M&E	Monitoring & Evaluation
MINAG	Ministry of Agriculture (Mozambique)
moDDS	multi-objective Dynamically Dimensioned Search
MPI-M	Max Planck Institut für Meteorlogie (Germany)
MR	Monthly Report
NCPAMP	Natural Calamities Prevention and Attenuation Masterplan (Mozabique)
NHS	National Hydrological Services (Namibia)
NGO	Non-Governmental Organization
NSE	Nash-Sutcliffe Efficiency
OIIL	Local Initiative Development Budget (Mozambique)
O&M	Operation & Maintenance
ORAM	Associacao Rural de Ajuda Mutua (Rural Association for Mutual support – Mozambique)

PAPA	Plano de Acção da Produção Agrícola (Agricultural Production Action Plan – Mozambique)
PARPA	Plano de Acção para a Redução da Pobreza Absoluta (Action Plan for Reduction of Absolute Poverty - Mozambique)
PET	Potential Evapo-Transpiration
PPFD	District Planning and Finance Project (Mozambique)
PPP	Private Public Partnerships
PPS25	British Planning Policy Statement 25
PRODER	Programa de Desenvolvimento Rural (Programme for Rural Development - Mozambique)
PROMEC	Promocao Economica de Camponeses (Economic Promotion of Local Farmer Cooperatives – Mozambique)
PRONSAR	Programa Nacional de Abastecimento de Água e Saneamento Rural (Common fund for rural water supply and sanitation in Mozambique)
Q	Flow
RBM	River Basin Model
RCM	Regional Climate Model
RCSA	Regional Centre for Southern Africa
Sb	Subbasin
SC	Sub Component of the report at hand
SCE	Shuffled Complex Evolution
SFRA	Specific Flood Risk Assessment
SPAWM	Support Project for Agricultural Water Management
SQL	Structured Query Language
SRTM	Shuttle Radar Topography Mission
SSA	Sub Saharan Africa
SSB	SPAWM Steering Body
SuDS	Sustainable Urban Drainage Systems
SWMM	Storm Water Management Model
TOR	Terms of Reference
TP	Technical Proposal
UEM	Universidade Eduardo Mondlane (Maputo – Mozambique)
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNHabitat	United Nations Human Settlements Programme
USACE	United States Army Corps of Engineers
USAID	United States Agency for International Development
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VAT	Value Added Tax
WAM	Water Allocation Module
WBM	Water Balance Module
WB	The World Bank
WH	Water Harvesting
WWF	World Wildlife Fund
WL	Water Level
YER	Yearly Evaluation Report
YWP	Yearly Work Programme
ZRA	Zambezi River Authority

SUBCOMPONENT 1: DECISION SUPPORT SYSTEM

1.1 TERMS OF REFERENCE

APPRECIATION OF SERVICE

An online, interactive water decision support system (DSS) will be developed for the Zambezi River catchment which can be used for the analysis of current and future water development scenarios. The system will allow different stakeholders in Mozambique (and also in the upstream countries) to rapidly assess the impacts of any new water resource developments and climate-induced changes on downstream infrastructure and water supplies. A possible add-on at later stages would be to extend the DSS for the Limpopo and Pungwe basins.

High priority will be given to development of a web-based application that is easy to understand and easy to use and offers high computational performance so that rapid on-line assessments of certain climate and water demand scenarios will be possible. A key to successful implementation will be the selection of the proper spatial and temporal scale which on one hand must be detailed enough to reflect the governing hydrological processes and most relevant water management activities. On the other hand the scale must be general enough to cope with the limited data available and to allow for fast assessment of climate and water management scenarios at the (national and international) river basin level.

Given the short time and budgetary framework available and considering the actual data situation the focus must be on the development of simple and robust water DSS that is able to generate results also with limited input data rather than on the development of a sophisticated software tool which requires detailed input information and can be operated only by a few experts.

A final decision on the optimum scale and spatial resolution of the pilot DSS developed for the Zambezi river shall be made during the inception stage based on the data availability, the client needs assessment as well as on the budgetary limits and the time constraints of the project.

It is assumed that all relevant data for DSS development and model calibration will be provided to the Consultant free of charge as well as in a timely manner. This shall include the following data:

- Digital river network and other GIS layers of catchment physiography
- Information on current operation of the main reservoirs in the basin (operation rules, storage elevation curves..)
- Daily or monthly series of observed flow for all gauging stations in the lower (Mozambican) part of the basin and selected gauging stations in the upper (foreign) part of the basin (> 20 years)
- Daily or monthly series of precipitation for selected gauges in the basin (preferably series from synoptic meteorological stations) (> 20 years)
- Daily or monthly series of temperature for selected stations in the basin (> 20 years)
- Information on major water users and current water demand in the different subcatchments, reservoirs and water abstraction points (monthly data)
- Climate Scenarios (regional precipitation and temperature data) downscaled and analysed in Phase I (INGC. 2009. Main report: INGC Climate Change Report: Study on the Impact of Climate Change on Disaster Risk in Mozambique, Section 1.3).

If some of the requested data cannot be provided alternative data sources will be explored by the Consultant or a simplified methodology will be applied in order to cope with the limited data sets.

METHODOLOGY:

Structure of water DSS

The components of the proposed DSS may be grouped into an information management system (IMS) and a river basin model (RBM). The IMS, which includes a web-based graphical user interface, a river basin database and a GIS component is the environment which serves the overall system, supported by a set of analytical tools.

The backbone of the system will be a river basin model covering the whole Zambezi catchment, with the two main components being a water balance module and a water allocation module.

The system will comprise the following spatial entities

- Watersheds (areas)
- River sections (linear elements)
- Reservoirs and points of water abstractions (nodal elements)

These spatial entities, will be mapped in a database, which serves as a

- Regional database for storing location and magnitude of existing and planned water demand and storage centers (who is using what);
- Watershed database of current and future climate variables including rainfall, temperature and flows for all watersheds;

RIVER BASIN MODEL

Water balance and water allocation module

Watershed runoff will be computed by a water balance module which is based on a conceptual soil moisture accounting approach. Input to the model is precipitation and temperature, output is runoff and actual evapotranspiration.

The topology of the river system and the location and seasonal demand of different water users and storage elements will be reflected in the water allocation module.

Spatial and temporal resolution

In order to allow for high system performance (as required for a web-based application) and easy use of the DSS, certain restrictions to the spatial and temporal resolution have to be made.

The total number of watersheds (subcatchments) to be considered shall not exceed 10 in the upstream part of the catchments (neighbouring countries) and shall be limited to a maximum of 20 in the downstream part (Mozambique). The number of river sections and nodal elements shall be limited to a maximum of 30.

However, design and implementation of the system will be kept flexible so that a later extension of the system to a higher number of spatial entities will be possible with reasonable effort.

It shall also be noted that the number of spatial entities depends on the availability of data. If only limited information (e.g. on observed runoff, water demand..) is available a further simplification and reduction of the spatial entities might be necessary.

For the temporal resolution of the system monthly timesteps will be applied, as this is considered an appropriate temporal resolution for regional water balance assessment and climate change impact studies. However, a certain flexibility of the system will be maintained so that upgrading of the system to higher temporal resolution (weekly, daily) will be possible in the future with reasonable effort.

INFORMATION MANAGEMENT SYSTEM

Scenario Definition

A web-based graphical user interface will be developed which will enable the user to conduct the following actions

- definition of water demand scenarios.
- selection and definition of climate scenarios
- start of simulation run
- evaluation of results (graphically and numerically)
- administration of scenario information and simulation results (saving, editing..)

Water Demand Scenarios

For each spatial entity (subcatchment, river section, nodes) water demand can be specified by the user on a monthly basis, considering

- irrigation / agricultural demand
- domestic water use and
- industrial water use.

For storage centers (reservoirs) also certain operation rules can be defined

Climate Scenarios

The database will store monthly time series of precipitation and temperature in each subcatchment for

- observed climate conditions (e.g. 1961-1990) and
- future climate scenarios

The DSS will allow defining future climate scenarios by the following options

- selection of predefined climate scenarios
- loading of new climate scenarios
- delta change approach

Selection of predefined climate scenarios

Predefined future climate scenarios (max 3 scenarios) will be loaded in the regional database by the Consultant during the development phase, which can then be selected by the user for simulation. Each climate scenario will be characterized by three constituents

- IPCC emission scenario
- Global Climate Model (GCM)
- Downscaling Method or Regional Climate Model (RCM)

Loading of new climate scenarios

The user will be able to add new climate change scenarios by loading monthly time series of subcatchment precipitation and subcatchment temperature to the system. Spatial mean values will be used, i.e. the spatial distribution of precipitation within a subcatchment will not be considered. The vertical distribution of temperature will be taken into account by considering different elevation zones derived from digital elevation models (DEMs). The necessary pre-processing of these data (downscaling of GCM data, bias correction, computation of mean values for subcatchments..) has to be done with external tools.

Delta change approach

Alternatively the user can define different climate change scenarios by specifying change in temperature (in °C) and change in precipitation (in percent) for each subcatchment and each month of the year. These changes will then be imposed on the observed climate conditions. The assumptions on the temperature and precipitation changes can (1) be taken from the literature (e.g. IPCC reports) (2) derived from analyses of GCM data (using external tools) or (3) can be any arbitrary values within a plausible range as typically applied for sensitivity studies. This method also facilitates easy analysis of what-if scenarios; e.g. "What if the temperature increases by 3 degree Celsius and precipitation decreases by 10 percent?"

Simulation Run

After having defined the water demand and climate scenarios a simulation run can be started. The user will be able to select the start time and end time of the simulation period (e.g. 2050 – 2070) for a given climate scenario. In order to allow for statistical analyses of the results (and to minimize the effect of random noise in the climate data) a minimum length of the simulation period of 20 years is proposed.

Evaluation of Results (Analytical Tools)

The application will allow to analyse the results of a simulation run for a certain climate and water demand scenario by graphical and numerical means.

For each spatial entity mean monthly runoff as well as certain statistical parameters such as maximum and minimum monthly runoff can be displayed and compared with the existing conditions (historical case). Furthermore the DSS will allow to analyse monthly values of precipitation and evapotranspiration in the different subcatchments as well as certain predefined drought indices.

SOFTWARE ENGINEERING

Open source database and GIS software such as PostgresSQL and PostGIS will be used in combination with PHP web programming language, or comparable technology. The use of open-source technology will eliminate the continuing licensing requirements of similar commercial web-based systems.

To host the web-based application developed by the consultant the following server hard- and software is proposed, and included in the financial offer:
Hardware: A standard Dell Server (Tower, not rack mounted) with Raid 1 Hard Disks (500 GB), redundant power supply, standard CPU and 4 GB RAMm (UPS for the server included). As backup an external Hard drive (Raid 1) is suggested.

Software: For the server operating system two options exist: (1) The Dell Server comes with a Windows 2008 R2 Server with 5 CAL (Client access licenses). (2) If open source version is preferred, RedHat Linux (can be bought with maintenance) or Ubuntu Server could be used. The financial proposal is based on option 1.

For installation of the server the following provisions have to be made by the client:

- Lockable room with air condition. Temperature should be around 20°C.
- Internet connection: minimum requirement for a Webserver is a 2 MBit symmetrical line, a faster line is preferred.
- Local IT experts (client), who are experienced with similar hard- and software, will be responsible for server operation and maintenance, and shall support the Consultant during system implementation.

The Client will be responsible for soft- and hardware maintenance in order to ensure future operation of the system.

WORKPLAN

Given the short time available for development and implementation a strict work plan and has to be applied in order to ensure the successful completion of the subtask. The following project milestones are proposed:

Inception workshop (conducted immediately after project start)

Meeting with the client in order to perform an assessment of the client needs and for investigation of the data availability. The draft design of the system will be discussed with the client and minor adjustments considering the actual situation can be made.

Data collection (completed 3 months after commencement date)

Data collection will depend on facilitation by the client. It is assumed that all the data necessary for DSS development and model calibration will be collected within the first 3 months of the project execution period. Based on the data collected during that period the final design of the DSS and the database will be made. It can not be guaranteed that data received at a later stage of the project will be reflected in the DSS.

The Inception and Data Collection Phase will be closed with submission of an inception report 3 months after commencement date.

Prototype development (presented 7 months after commencement date)

A prototype DSS for Zambezi will be developed and a preliminary model setup will be prepared within 7 months and presented to the client. Minor adjustments (customizing) of the graphical user interface and other DSS component will be made together with client.

Delivery of Zambezi DSS and Training (presented 9 months after commencement date)

The final version of the DSS for Zambezi catchment will be delivered after 9 months together with a training session in Mozambique. A selected team of analysts (max 8 trainees) will be trained in the use and maintenance of the system, which will be handed over to INGC. The training material provided by the Consultant will include an on-line user manual which will be delivered together with the DSS System.

The software user interface as well as the user manual will be developed in English.
It is assumed that the necessary training facilities (including training room, hard- and software with internet access, catering..) will be provided by the client.

EXPECTED RESULTS

The following outputs can be expected from SC 1

- An online, interactive water decision support system for the analysis of current and future water development scenarios of the Zambezi River (and potentially the Limpopo River and the Pungwe River as add ons), consisting of an information management system and a river basin model.
- A training session in Mozambique for a selected team of analysts
- An on-line user manual, which will allow also other users to apply the web-based DSS.
- Capacity of counterparts increased through on the job learning.

1.2 EXECUTIVE SUMMARY

In SC1, a water Decision Support System (DSS) was developed for the whole Zambezi basin, covering 1.4 Mio km². The DSS is a state-of-the-art, well calibrated, easy to use analysis tool that will serve Mozambican analysts for rapid assessment of impacts of climate change and upstream developments (irrigation, dams) on discharge. Due to its implementation as an open web-based system, the DSS is also available to the ge=neral public. The DSS has a graphical user interface and combines GIS layers, background maps and model elements, which are linked to a dynamic database and river basin model. The water balance module of the DSS simulates runoff generation from monthly precipitation and temperature inputs in 27 sub-basins of the Zambezi basin. A water allocation module considers wetlands, reservoir operations and water abstractions and aggregates discharge along the river-network at 40 locations. The user can interactively add locations of interest and add or modify scenarios including climate change, water withdrawals (irrigation), dam development and reservoir operation rules. Climatic data included in the DSS cover the period 1950-2005 for historic observations and 1960-2100 for data of three climate models, thereby enabling simulations for any time-slice between 1950 and 2100. The DSS includes an analysis tool for visualization of simulation results as time-series, seasonality or distribution (frequencies of high and low flows). Export of results enables post-processing with external software. Results of application examples of the DSS are presented, including impact assessment of climate change, irrigation and dam development. The examples show the high sensitivity and high complexity of regional changes in the Zambezi basin under various scenarios. Therefore, the DSS will serve as an important scenario analysis tool for water resources management in the Zambezi basin. The server with the installed DSS system will be located at CENOE in Maputo, Mozambique. The modular structure of the DSS software allows for future extensions to other river basins as well as other functionalities. Nine trainees from different institutions in Maputo have been trained in the use of the DSS.

1.3 AREA DESCRIPTION

1.3.1 General area description – The Zambezi Basin

The Zambezi basin is the fourth largest river basin in Africa (after Congo, Nile and Niger) and covers 1.4 Mio km². As in other studies we do not consider the Okavango River as a tributary of the Zambezi, even though in extremely wet years the Okavango system theoretically also discharges to the Zambezi. The basin is shared by eight countries: Zambia (41.9 % of total area), Angola (18.2 %), Namibia (1.1 %), Botswana (1.5 %), Zimbabwe (15.9 %), Tanzania (2.2 %), Malawi (7.5 %), and Mozambique (11.6 %). From these *Figure*s it is clear that the Mozambican share of the basin is only small, as almost 90 % of the basin is located in upstream areas, where also most of the runoff is originating from. Here, Zambia is a crucial country (more than 40 %). In some regions only very limited hydro-meteorological information is available (e.g. Angola with almost 20 %).

The source of the Zambezi River is located at Kalene Hill in Zambia and travels roughly 2600 km to the south and east before discharging into the Indian Ocean at the Mozambican coast. Along its course are world famous natural treasures (e.g. Victoria Falls) and unique ecological areas (e.g. Mana Pools). Important tributaries are the Kafue River, Luangwa River and Shire River. Floodplains and swamps (Barotse Floodplain, Chobe Swamps, Kafue Flats, etc.) are large, seasonally inundated areas of several thousand km². Lake Malawi is located in the north-eastern part of the basin and is one of the world's largest freshwater lakes (570 km long, 30,000 km²). There are also two large artificial reservoirs for hydropower generation (Lake Kariba with 5600 km² and Lake Cahora Bassa with 2700 km²). Several more hydropower plants are in planning stages.

Mean annual rainfall amounts to approximately 1000 mm, of which about 8 % generates runoff and the remaining 92 % are lost via evapotranspiration. The northern parts are wetter than the southern parts. Mean runoff at the outlet of the basin amounts to approximately 3600 m³/s, but runoff shows large seasonal and intra-annual variations. During the dry season there is practically no significant amount of precipitation. The wet season is during the austral summer from around December through March. In November and April also some considerable amounts of precipitation may occur. Seasonality in runoff is strongly controlled by seasonality in precipitation, but in addition also runoff retention in large floodplains and swamps as well as artificial reservoirs affect the seasonal runoff.

The DSS is set-up for the whole area of the Zambezi basin (excluding Okavango).

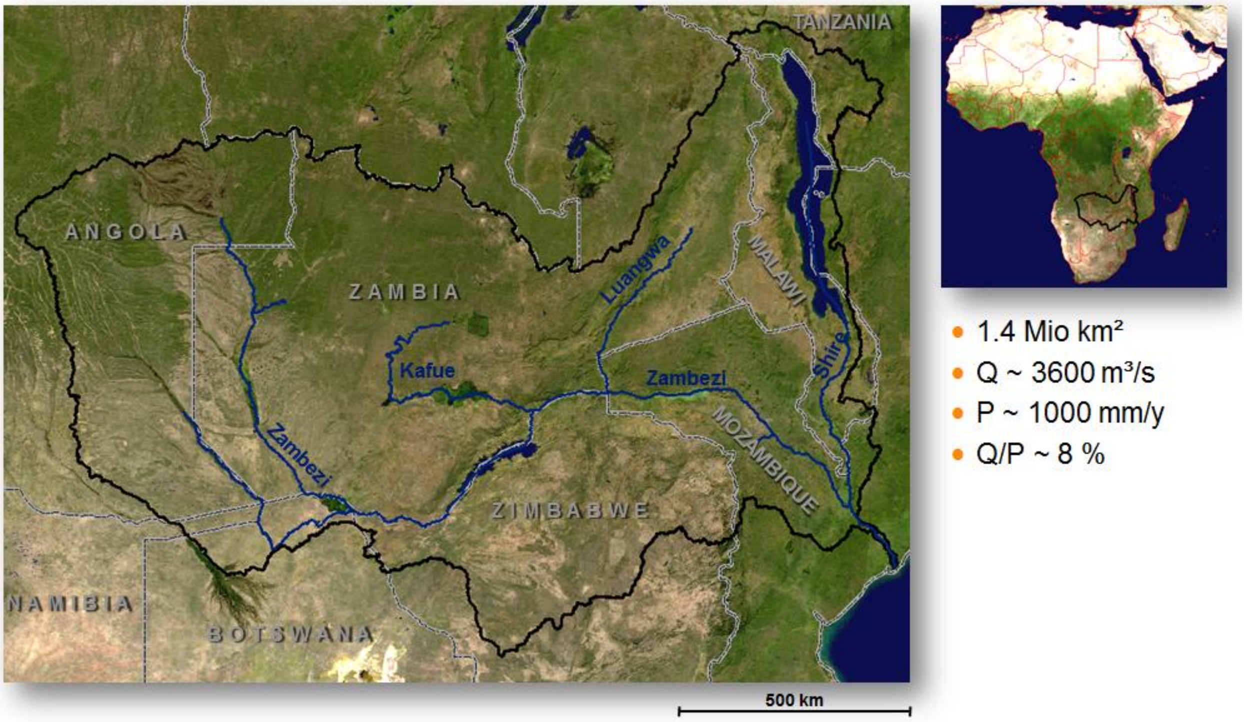

Figure 1-1: Zambezi basin.

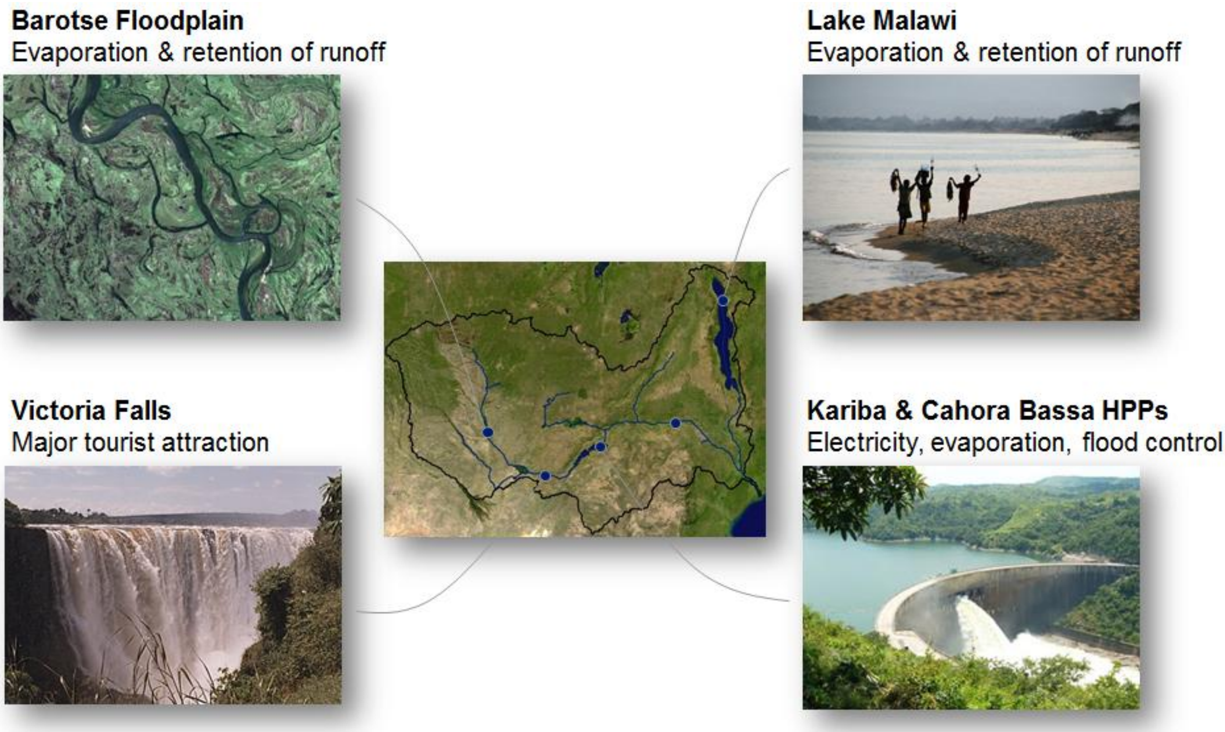

Figure 1-2: Unique features of the Zambezi basin.

1.3.2 Specific description - The Mozambican part of the basin

The Mozambican share of the Zambezi basin covers 11.6 % of the total basin area. The Zambezi River enters Mozambique from Zambia, just upstream of the Cahora Bassa reservoir. At the border the Zambezi River already includes discharge from the large tributaries Kafue River and Luangwa River.

There are several tributaries discharging into the Zambezi River within Mozambique. A few kilometres after the Zambian/Mozambican border the Panhane River flows from Zimbabwe into the upper section of Cahora Bassa reservoir. Downstream of the reservoir the Capoche/Luia River joins the Zambezi from the north. The Revubue River has its confluence with the Zambezi River at Tete and drains the area in the north-east to the Malawian border. Further downstream the Luenha River comes from Zimbabwe in the west. The last tributary is the Shire River, draining almost the entire area of Malawi, including Lake Malawi. *Table* 1-1 summarizes the Mozambican tributaries and also lists the respective areas of the basins.

Table 1-1: Zambezi tributaries in Mozambique.

River basin	Area [km²]
Zambezi at Zambian/Mozambican border	1004972
Panhane River	24404
Capoche/Luia River	28699
Revubue River	16263
Shire River at Malawian/Mozambican border	151537

1.4 METHODOLOGY

1.4.1 Preparatory work (data and info collection)

The first task for the project was an extensive literature review, to get a profound knowledge of the Zambezi basin as well as information about the latest research initiatives, institutional organization, and available data bases. The following reports and articles were used for the literature review:

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1.4.2 Stakeholder consultation

An inception visit was made from Aug. 2nd to 7th, 2011 to Maputo to meet with the client and stakeholders. Participants of the inception visit were Harald Kling (SC1) and Klaus Leroch (SC3).

15 meetings were arranged with several experts of various institutions. During these meetings the scope of the Zambezi DSS was presented, thereby raising the visibility of the project, as some of the Mozambican experts were previously not aware of the ongoing efforts. The discussions with the Mozambican experts also gave important insights to the visiting consultants (Kling, Leroch) about ongoing projects, responsibilities of different institutions (including contact persons), available data sets, etc.

During a meeting with the director of INGC (Joao Ribeiro) it was clarified that the DSS will be available online to the general public. However, it will be decided at later stages by the client if only a limited version of the DSS will be made available to the general public (i.e. restricted access to the full version of the DSS).

For the training on the DSS (Zambezi and possible extension to Limpopo) several institutions were invited (INGC, DNA, UEM, Ara-Sul). No meeting could be arranged with staff of Ara-Zambeze (located in Tete), but contact was established by e-mails after the inception visit.

Some interesting reports and data were obtained. At the same time, also some reports and data were provided to the Mozambican experts. However, not all of the existing data could be obtained (especially for the upstream countries in the Zambezi basin). After completion of the inception visit data acquisition efforts were still ongoing.

Several possible locations of the server for the DSS were discussed (INGC, UEM, Ara-Sul, external provider), but a decision was postponed.

The spatial resolution of the DSS was discussed with several experts, but no specific recommendations were provided. Therefore, a draft version of the spatial resolution was sent out by e-mail on Aug. 16th, 2011 for further comments. The received comments are considered in the final decision on the spatial resolution.

1.4.3 Data sources

Data of many different sources were collected for this study. Given the large scale of the study (whole Zambezi basin), the focus was on freely available, global data bases. The availability of these data bases greatly facilitates the data acquisition process, as otherwise national services in eight different countries would have to be contacted separately. The institutions/datasets from which data are used are described below.

A first, rough assessment of the quality of the data showed that the public domain data appear to be of reliable quality, whereas data obtained from national data bases include many data gaps and in several instances seem to be affected by considerable biases. As an example, runoff time-series data recorded at different gauges most likely have large differences in the quality, as there are unplausible discrepancies between upstream and downstream gauges. In general, all time-series data (public and national) should only be used with caution, as no information about the reliability of the data are available from the providers.

Data of INGC Phase I

Data of the first phase of INGC studies were accessed via Dropbox. However, datasets of the Phase I studies in general only cover the Mozambican part of the Zambezi basin and are therefore of limited use for the current study, which focuses on the whole basin (including the much larger upstream areas).

Data of public domain

Freely available data of the public domain are extensively used in this study. These data are either available for direct download from the internet or a free registration (or e-mail) is required before data acquisition. The used data sources include:

1. United States Geological Survey (USGS): digital elevation model, land-cover GIS data
2. HydroSheds: Digital elevation model, flow direction, river network GIS data
3. GRanD: Reservoir GIS data
4. AVHRR satellite: Land-cover GIS data
5. Global Runoff Data Center (GRDC): Runoff time-series data (at stations)
6. Global Historical Climatology Network (GHCN): Precipitation and temperature time-series data (at stations)
7. FAO: Climwat data (at stations) for use with Cropwat model (reference evapotranspiration)
8. Global Precipitation Climatology Centre (GPCC): Precipitation time-series data (spatial fields)
9. Climate Research Unit (CRU): Precipitation, temperature, potential evapotranspiration time-series data (spatial fields)
10. ENSEMBLES: Climate change scenarios for precipitation, temperature time-series data (spatial fields)
11. WATCH: Climate change scenarios for precipitation, temperature time-series data (spatial fields)

Data of national data bases

1. Direcção Naçional das Águas (DNA): Runoff, water level (Cahora Bassa) time-series data (at stations)
2. Zambezi River Authority (ZRA): Runoff time-series data (at stations)
3. Department of Water Affairs, Zambia (DWA): Runoff time-series data (at stations) were requested, but not delivered
4. National Hydrological Services, Namibia: Runoff time-series data (at stations) were requested, but not delivered
5. ZINWA, Zimbabwe: Runoff time-series data (at stations) were requested, but not delivered

Data of reports

Some reports provide valuable information, even if this data is not available in digital form for the current project. More specifically, the reports of Beilfuss and dos Santos (2001) as well as Beilfuss (2001) give important information on reservoir characteristics and operation rules. In addition, figures show the long-term behaviour of e.g. lake water levels in Lake Malawi.

1.5 DATA ANALYSIS RESULTS

This section gives an overview of the data obtained for SC1.

River network and basin divides

HydroSheds is a recently developed data set and provides global information about river topology derived from a digital elevation model (SRTM) with a 3 arc seconds spatial resolution. This data set is used for (1) delineating basin and sub-basin divides with GIS and (2) display of the river network *Figure* 1-3. Comparison of the HydroSheds data with data from Dropbox of INGC Phase I (Mozambican area only) showed a high agreement between the data sets. It is assumed that the data is of similar accuracy in the other parts of the basin.

Reservoir data

The GRanD dataset consists of two GIS layers: (1) the location of major dams and (2) the spatial extent of the reservoir water bodies (*Figure* 1-4). (1) also includes the main reservoir characteristics, such as start year of operation and reservoir storage capacity. The GRanD dataset is used for identifying major reservoirs in the Zambezi basin. By far the two most important reservoirs are Lake Kariba (185,000 hm^3 capacity) and Lake Cahora Bassa (63,000 hm^3), both located on the Zambezi River. According to the storage capacity Lake Kariba (located between Zambia and Zimbabwe) is the world's largest artificial reservoir, and Lake Cahora Bassa (located in Mozambique) is the 10^{th} largest. Another large reservoir - albeit much smaller when compared to Kariba and Cahora Bassa - is Itezhitezhi (5700 hm^3) on the Kafue River. Other noteworthy reservoirs are Kafue Gorge (785 hm^3) and Mita Hills (1500 hm^3), both located in Zambia. There are numerous smaller reservoirs in Zimbabwe. Four of them are larger than 100 hm^3 (the largest is Lake Manyame with 490 hm^3).

Additional information about characteristics of the main reservoirs in the Zambezi basin is available from the report of Beilfuss (2001). This information includes elevation-volume-area curves as well as operation guide curves for Kariba, Cahora Bassa, Itezhitezhi and Kafue Gorge.

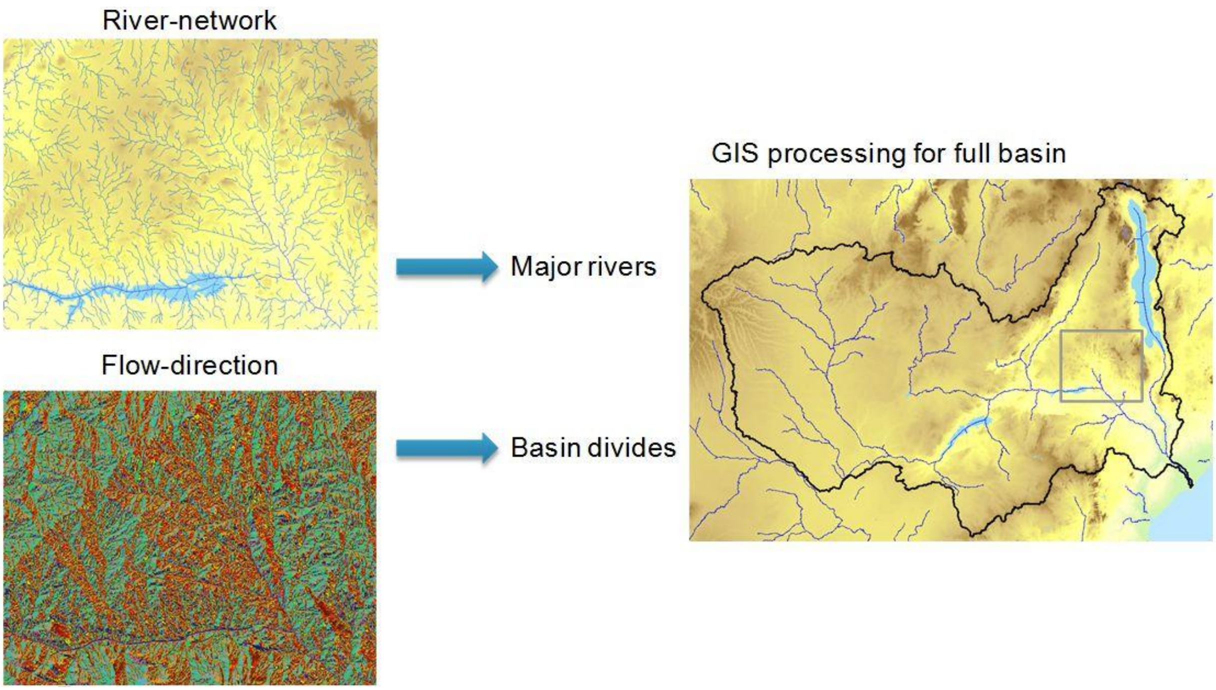

Figure 1-3: HydroSheds data set.

Left panel: detailed river network and flow direction in the region of the Cahora Bassa reservoir (grey box in right Figure). Right: example for GIS processed data (major rivers, basin divides) for the full basin.

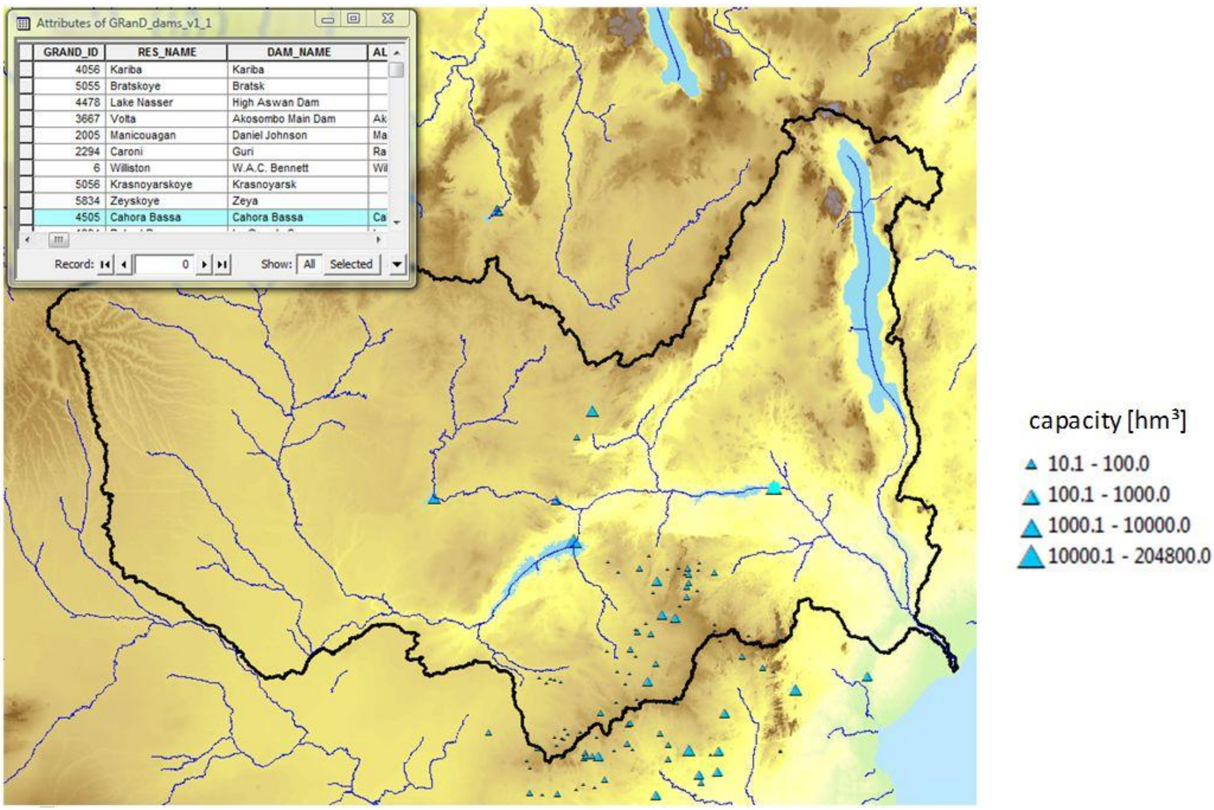

Figure 1-4: Reservoirs of the GRanD dataset in the Zambezi basin region.

Triangles: dam location. Triangle size: storage capacity of reservoir. Cahora Bassa dam is highlighted with a blue dot.

Land-cover data

The AVHRR land-cover satellite product shows *Figure* 1-5. In the Zambezi basin the dominant land-cover types are woodland, (wooded) grassland and cropland. The GIS data can be aggregated to compute the area shares of land-cover within sub-basins.

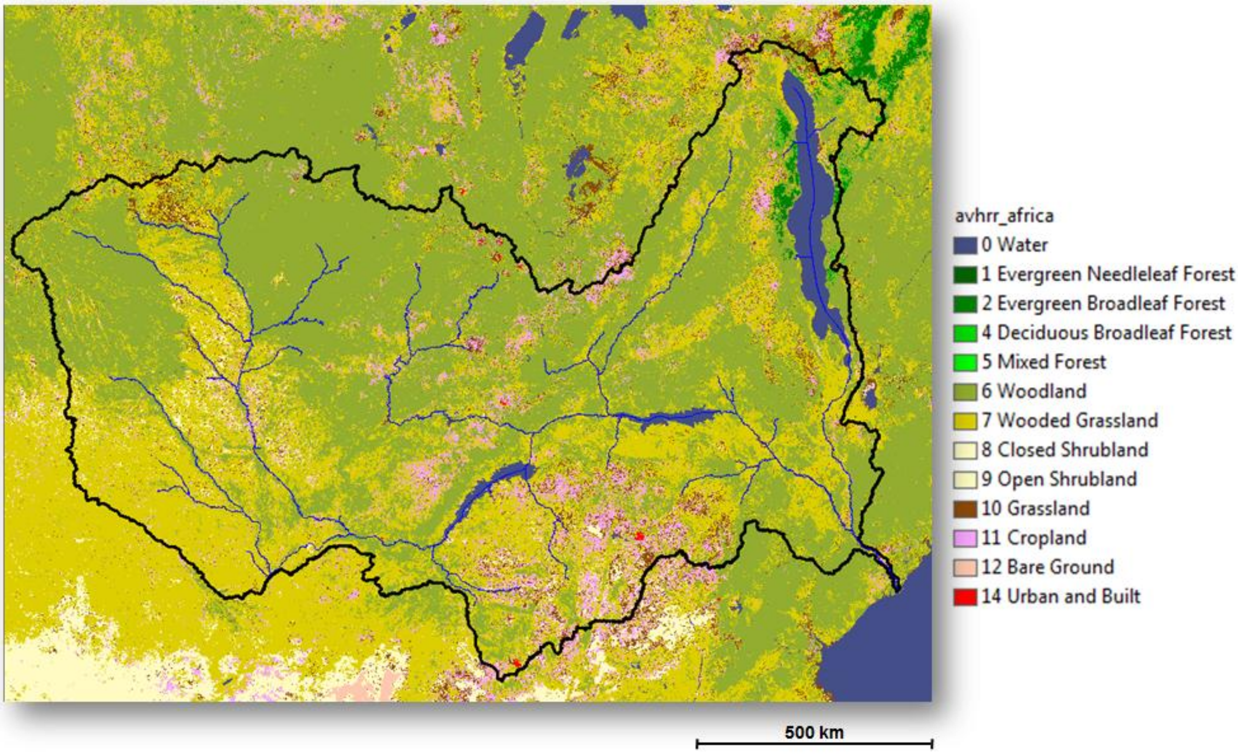

Figure 1-5: AVHRR land-cover dataset for the Zambezi basin.

Runoff data

Runoff data were mainly obtained from GRDC, DNA, and ZRA. The number of provided runoff time-series from GRDC were 76. Not all of the time-series are useful for this study due to (1) location at too small tributaries, (2) considerable data-gaps, or (3) apparent biases in the data. Data from DNA covered gauges in the Mozambican part of the basin and data from ZRA covered gauges in the upper parts of the basin. For the Luangwa River data was manually digitized from the report of Beilfuss (2001). Overall, there are 24 sub-basins outlets with available runoff data (*Figure* 1-6) and only three sub-basins are ungauged. This is a sufficient data base for calibration of the DSS. Observed runoff data are not required for simulation runs with the DSS, as runoff is a simulated variable of the river basin model. Examples for observed hydrographs in the upper part of the Zambezi basin shows *Figure* 1-7. All time-series exhibit a strong seasonality in runoff (see e.g. *Figure* 1-8).

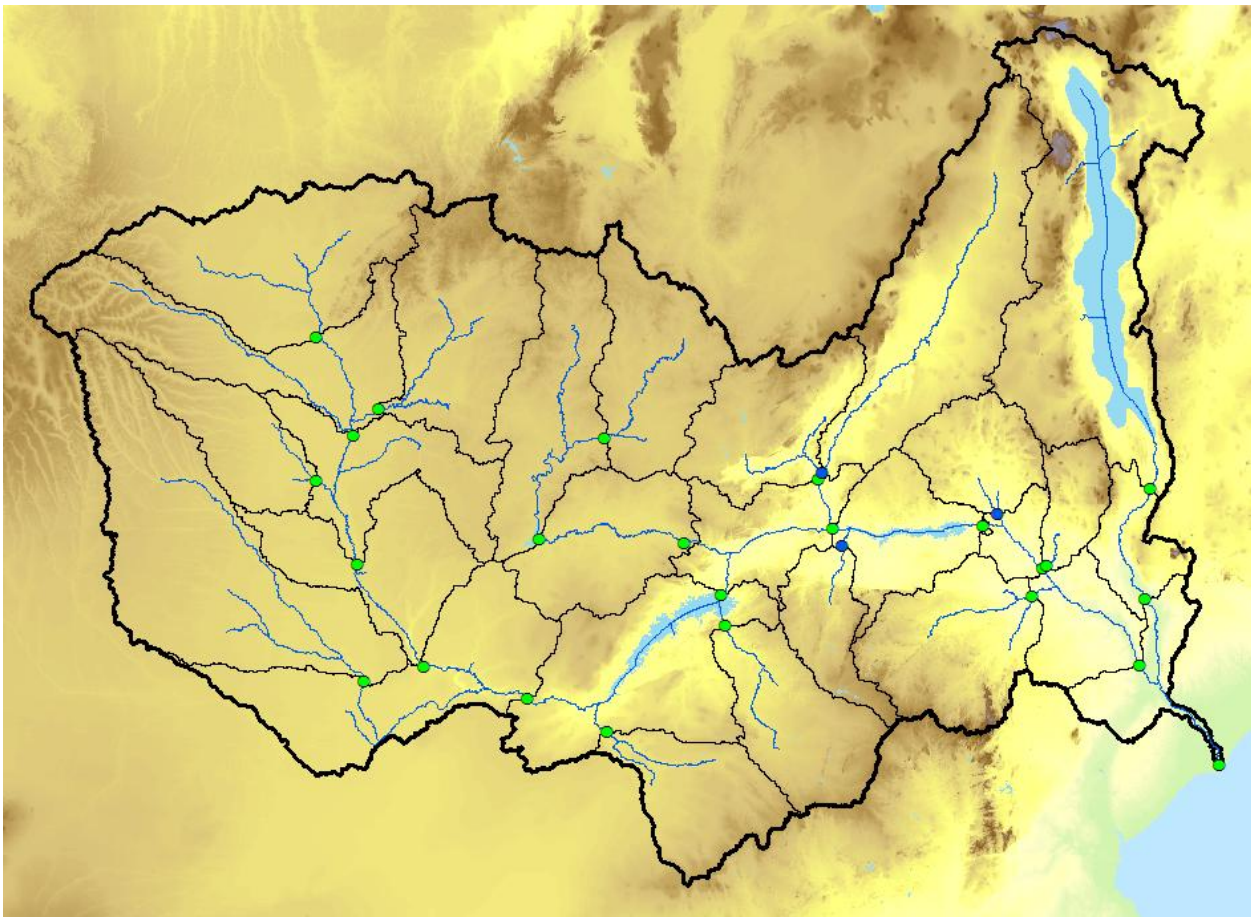

Figure 1-6: Location of used gauges in the Zambezi basin.
Green: runoff data available. Blue: ungauged locations.

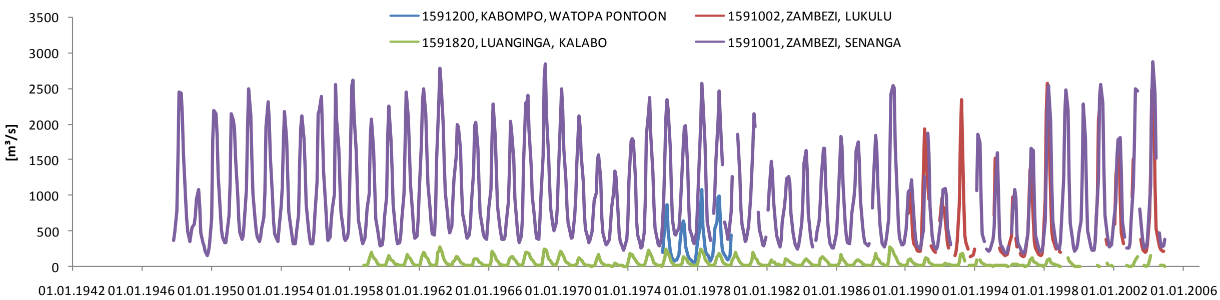

Figure 1-7: Examples of observed monthly hydrographs of GRDC for the period 1942 to 2009.

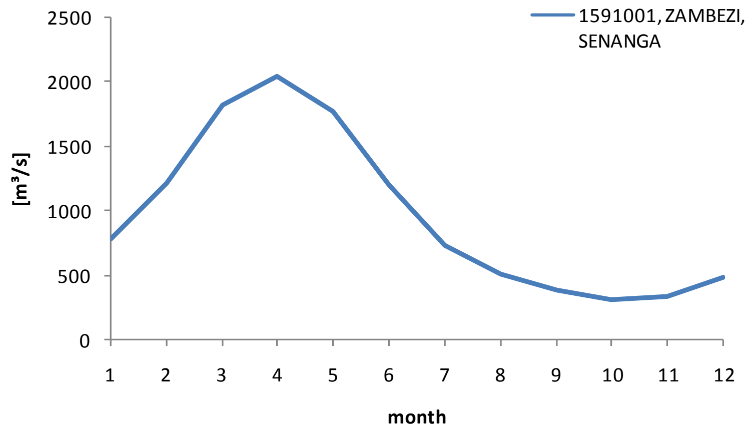

Figure 1-8: Mean monthly observed runoff of the Zambezi River at Senanga for the period 1948-2004. GRDC data.

Precipitation data

Precipitation data of GPCC is used for the historic simulation with the DSS. Other precipitation datasets (CRU, GHCN) are only used for comparison purposes. The GPCC dataset consists of global, gridded monthly precipitation for the period 1901 to 2009, interpolated from station data. The spatial resolution is 0.5 x 0.5 degree.

Figure 1-9 depicts the number of available stations for the GPCC precipitation interpolation, aggregated for the whole Zambezi basin. The period 1960 to 1990 has the highest station data availability, with roughly 200 stations. The peak 1980 to 1990 is caused by numerous stations available from Malawi. The station density is smaller in the western parts of the basin (*Figure* 1-10). GPCC used more stations for interpolation than the CRU dataset. Still, the spatial distribution of mean annual precipitation in southern Africa is quite similar between GPCC data and CRU data (*Figure* 1-11).

An analysis of the GPCC data for the Zambezi basin show *Figure* 1-12 to *Figure* 1-14. Precipitation is basically zero from June to September, but reaches monthly totals of approximately 200 mm during the wet season (*Figure* 1-12). There are distinctive long-term trends in precipitation (*Figure* 1-13 and *Figure* 1-14). Above average precipitation occurred from 1950 to 1980 (average of 969 mm/y), whereas the periods 1901 to 1915 and 1981 to 1995 were drier (average of 867 mm/y). Apart from individual years, the remaining periods were close to average conditions.

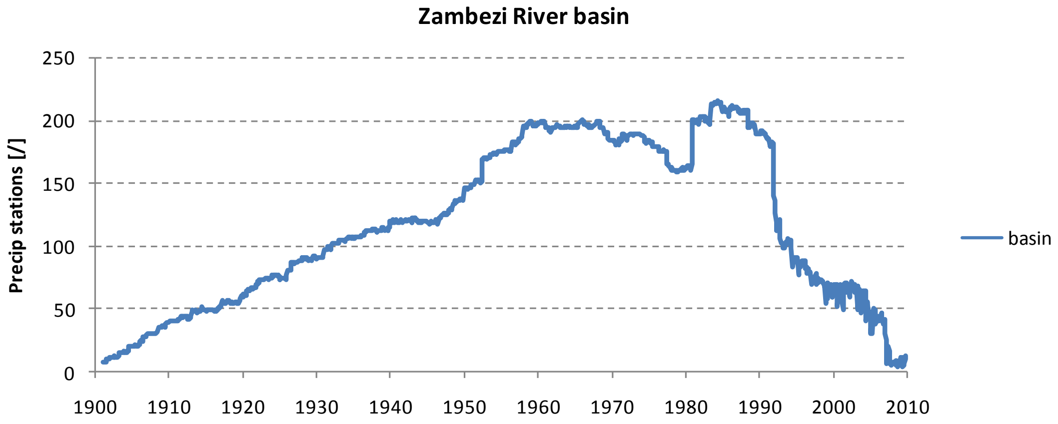

Figure 1-9: GPCC station data availability in Zambezi basin. Number of stations used for precipitation interpolation.

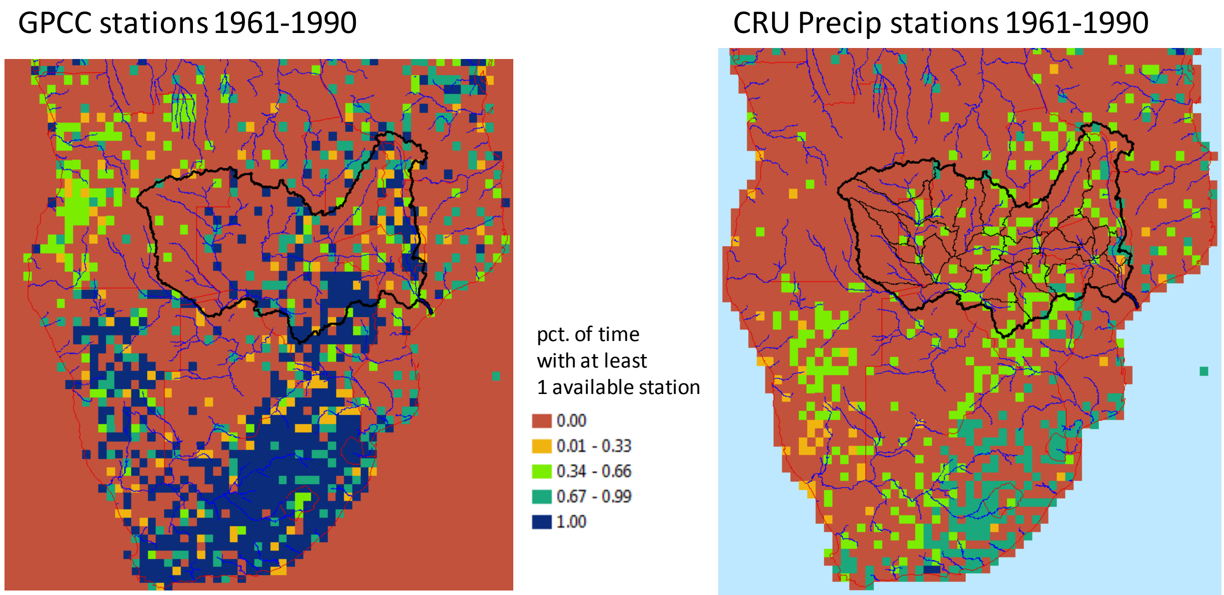

Figure 1-10: Station data availability for global, gridded precipitation products in the period 1961-1990. Left: GPCC data. Right: CRU data.

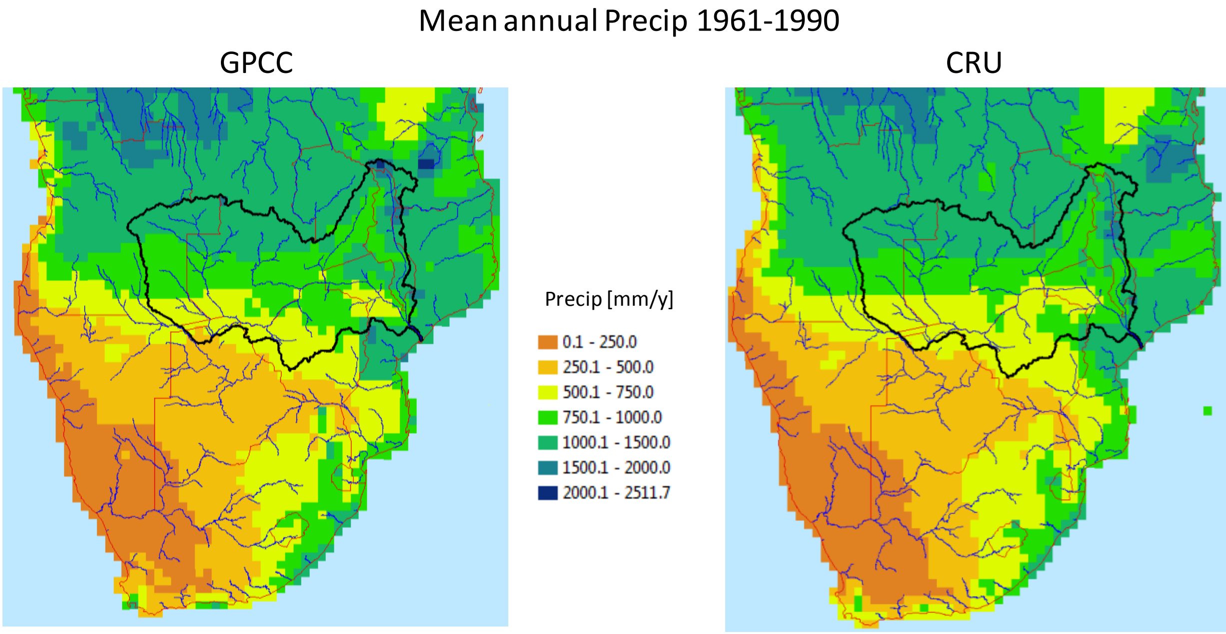

Figure 1-11: ***Comparison of mean annual precipitation for the period 1961-1990.***

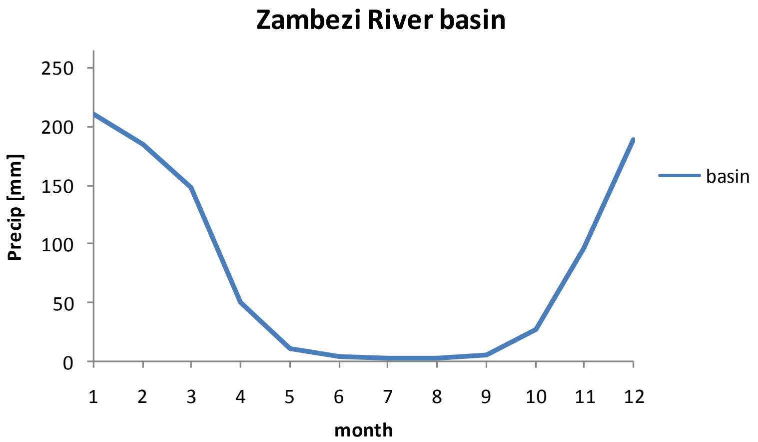

Figure 1-12: ***Mean monthly precipitation in the Zambezi basin for the period 1961-1990. GPCC data.***

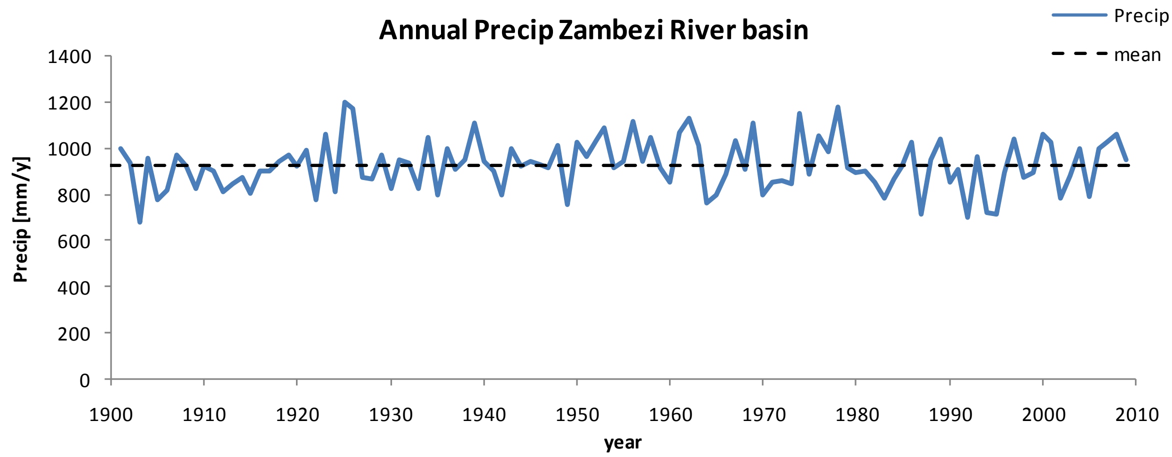

Figure 1-13: ***Annual precipitation in the Zambezi basin from 1901-2009.***
GPCC data.

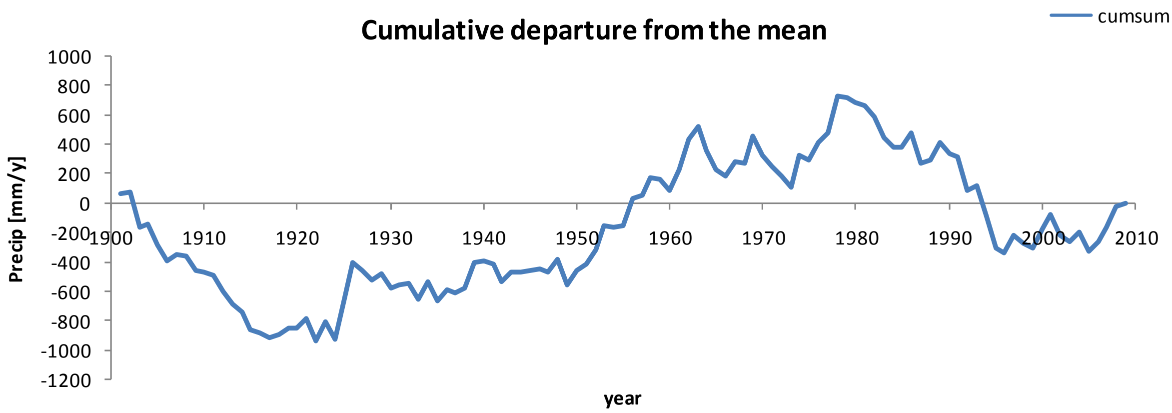

Figure 1-14: ***Long-term trends in annual precipitation in the Zambezi basin from 1901-2009.***
GPCC data. Computed as the cumulative difference between annual precipitation and long-term mean annual precipitation. Positive slope: wet periods. Negative slope: dry periods.

Temperature data

Temperature data of CRU is used for the historic simulation with the DSS. Other temperature datasets (GHCN, CLIMWAT) are only used for comparison purposes. The CRU dataset consists of global, gridded monthly temperature for the period 1901 to 2009, interpolated from station data. The spatial resolution is 0.5 x 0.5 degree.

Figure 1-15 depicts the number of available stations for the CRU temperature interpolation, aggregated for the whole Zambezi basin. The period 1960 to 2000 has the highest station data availability. However, the maximum number of seven stations is quite low. Note that also stations located outside of the basin have an impact on the temperature interpolation of CRU data. Given the fact that the interpolation of temperature is less problematic than e.g. for precipitation, seven stations is still sufficient. The stations with available data for the CRU temperature interpolation are evenly distributed in the Zambezi basin (*Figure* 1-16).

An analysis of the CRU temperature data for the Zambezi basin is shown in *Figure* 1-17 to *Figure* 1-20. Temperature is warmest in October and November with 25 °C, and coldest in the austral winter in June and July with 17 °C (*Figure* 1-18). There are distinctive long-term trends in temperature (*Figure* 1-19 and *Figure* 1-20). From 1901 to 1980 temperatures were relatively stable. After 1980 there was a considerable increase in temperature. This increase corresponds to the warming which is observed globally. On average, the period 2000-2009 was by 1.5 °C warmer than the period 1901 to 1980.

Table 1-2 summarizes the mean monthly air temperature of sub-basins based on CRU data. A map of the spatial distribution of mean annual air temperature is shown in *Figure* 1-17.

Table 1-2: Mean monthly air temperature (°C) for sub-basins of the DSS. CRU data. Period 1971-2000.

sb	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	22.9	22.9	23.0	22.5	20.9	18.7	18.6	21.2	23.7	24.3	23.5	23.0
2	22.5	22.7	22.8	21.8	19.7	17.3	17.2	19.9	23.1	24.3	23.6	22.9
3	23.0	23.1	23.3	22.6	20.7	18.3	17.8	20.5	23.7	24.5	23.7	23.1
4	23.8	23.9	24.2	23.3	21.4	18.9	18.0	20.8	23.9	25.2	24.6	24.0
5	24.1	24.2	24.2	23.0	20.7	18.2	17.8	20.8	24.5	26.0	25.4	24.4
6	24.6	24.6	24.5	23.1	20.6	17.8	17.4	20.5	24.3	26.3	25.8	24.9
7	24.0	24.0	23.9	22.8	20.3	17.6	16.7	19.9	23.0	25.5	24.8	24.3
8	25.3	25.1	24.8	23.0	20.0	17.0	16.6	19.7	23.9	26.4	26.4	25.5
9	23.3	23.0	22.6	20.7	18.0	15.3	15.0	17.6	21.5	23.8	24.1	23.4
10	23.3	23.0	22.6	21.0	18.4	15.7	15.5	17.9	21.7	23.9	24.2	23.4
11	24.9	24.8	24.5	23.0	20.4	17.4	17.4	20.1	24.0	26.7	26.8	25.3
12	22.6	22.7	22.6	21.2	18.8	16.6	16.1	18.8	22.4	24.2	24.1	22.8
13	22.9	23.0	22.9	21.6	19.2	16.7	16.4	19.2	22.9	24.6	24.3	23.2
14	23.5	23.5	23.2	21.7	19.0	16.6	16.2	19.0	23.0	25.2	25.2	23.8
15	22.8	22.8	22.9	21.9	20.0	18.0	17.5	19.4	22.6	24.5	24.9	23.5
16	22.8	22.9	22.8	21.5	19.4	17.4	16.8	19.2	22.8	24.6	24.7	23.1
17	24.7	24.6	24.5	23.1	20.7	18.4	18.0	20.5	24.4	26.7	26.8	25.1
18	22.9	22.8	22.4	20.8	18.4	16.0	15.7	17.9	21.6	23.8	24.2	23.2
19	25.8	25.9	25.6	24.2	22.2	19.8	19.5	21.4	24.8	27.4	27.7	26.5
20	24.2	24.2	24.2	23.0	21.3	19.1	18.9	20.5	23.7	25.5	26.0	24.9
21	27.2	27.0	27.0	25.6	23.6	21.3	21.1	22.5	25.7	27.9	28.7	28.0
22	23.8	23.6	23.6	22.4	20.6	18.6	18.1	19.7	22.6	24.3	25.2	24.5
23	23.7	23.6	23.2	21.5	19.3	16.9	16.6	18.2	21.3	23.8	24.5	24.0
24	27.2	26.9	26.8	25.4	23.3	21.1	20.7	22.1	24.9	26.9	28.1	27.7
25	22.9	22.8	22.8	21.9	20.2	18.2	17.7	19.0	21.5	23.5	24.4	23.7
26	25.1	24.8	24.6	23.3	21.4	19.5	18.9	20.7	23.4	25.2	26.2	25.5
27	27.2	26.9	26.6	25.0	22.9	20.8	20.2	21.4	23.8	25.7	27.0	27.2

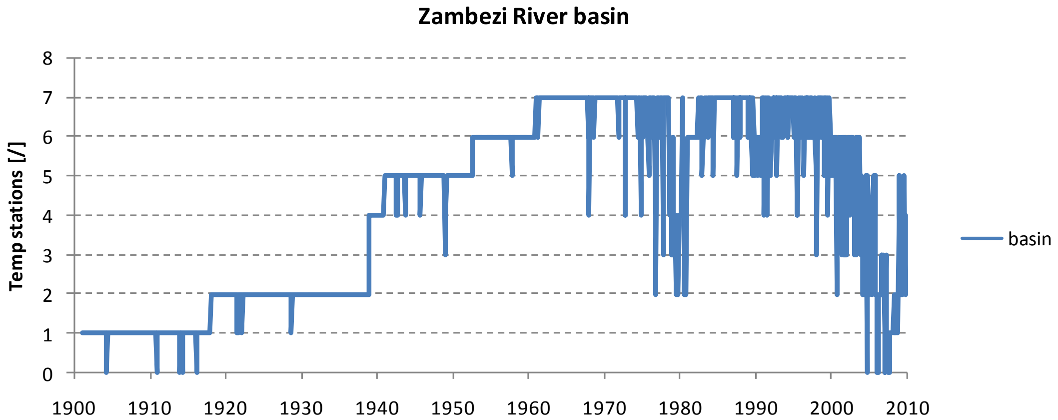

Figure 1-15: Station data availability for CRU temperature data in the period 1901-2009.

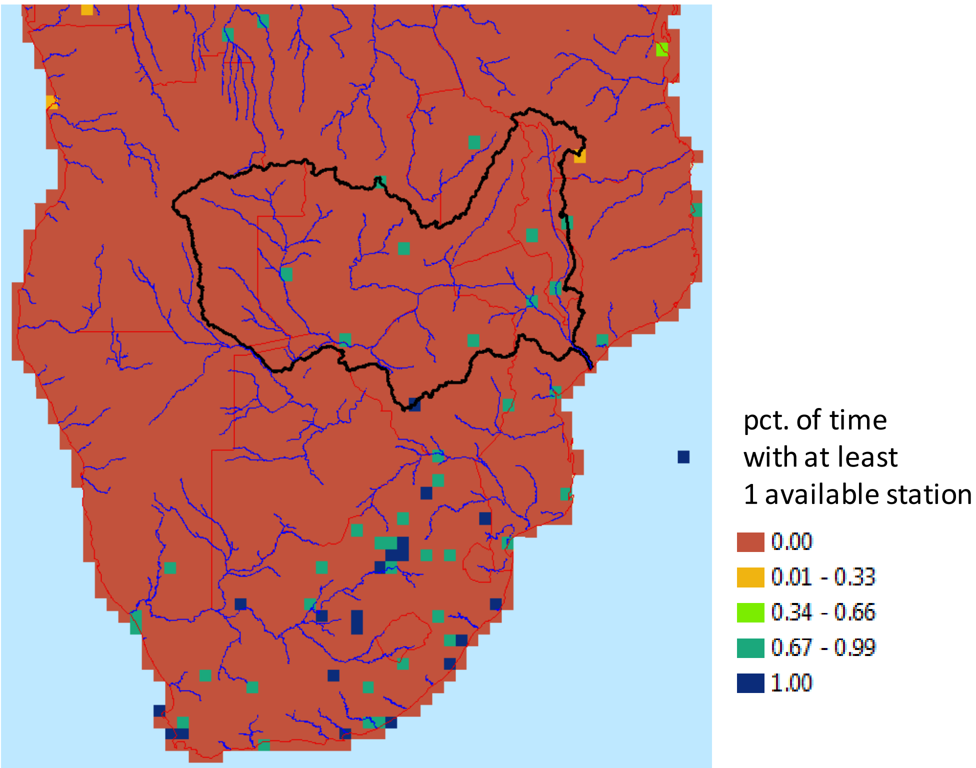

Figure 1-16: Station data availability for CRU temperature data in the period 1961-1990.

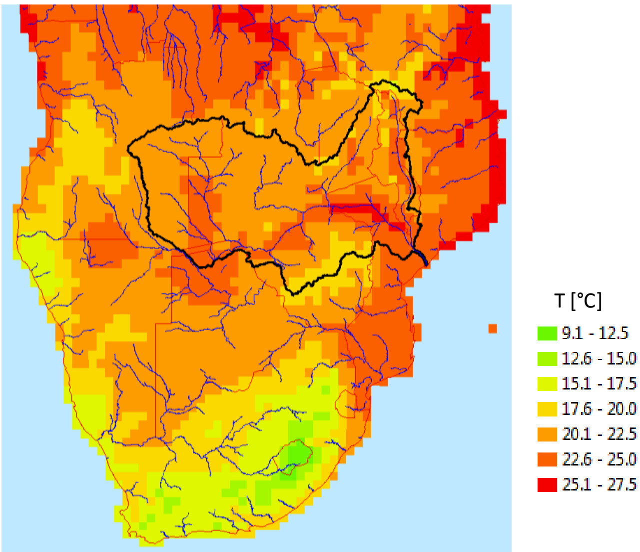

Figure 1-17: ***Mean annual temperature for 1961-1990. CRU data.***

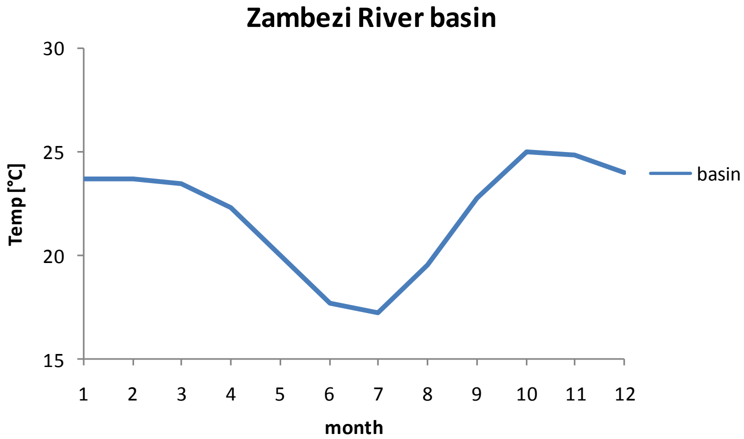

Figure 1-18: ***Mean monthly temperature in the Zambezi basin for the period 1961-1990. CRU data.***

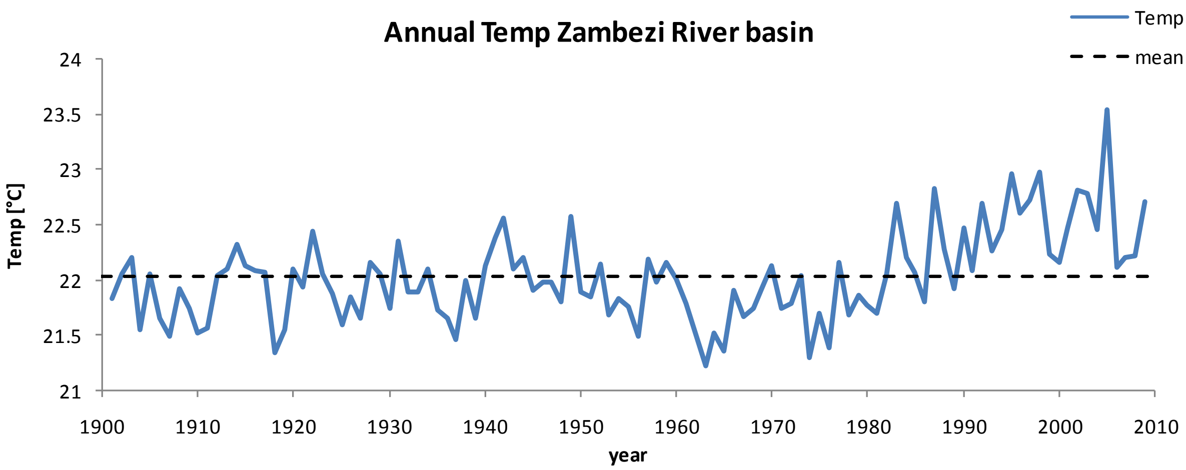

Figure 1-19: ***Annual temperature in the Zambezi basin from 1901-2009 based on CRU data.***

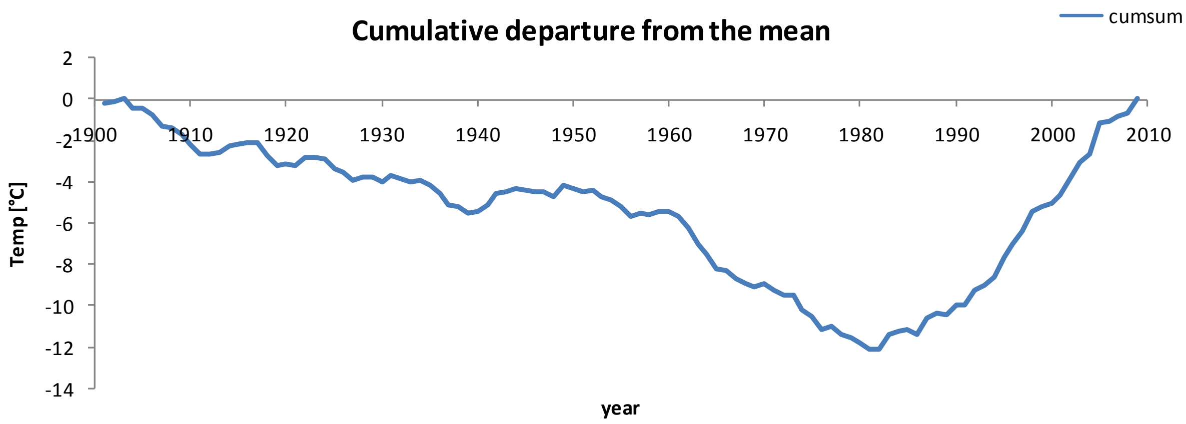

Figure 1-20: ***Long-term trends in annual temperature in the Zambezi basin from 1901-2009 based on CRU data.***

The graph shows the cumulative difference between annual temperature and long-term mean annual temperature. Positive slope: warming periods (increasing temperature). Negative slope: cooling periods (decreasing temperature).

Potential evapotranspiration

Different datasets are used to obtain information about potential evapotranspiration: CRU data, CLIMWAT data and the CROPWAT model.

Potential evapotranspiration of CRU is a derived product of other CRU datasets (temperature, relative humidity, etc.). Note, that the CRU dataset is based on very few stations for relative humidity in the region. Therefore, the CRU data about potential evapotranspiration should be interpreted with caution due to possibly large uncertainties. The data are in the same resolution as the CRU temperature dataset (*Figure* 1-21) and cover the period 1901 to 2009. Potential evapotranspiration is highest in September and October with monthly amounts of 150 mm, and is lowest from December to July with monthly amounts of 100 mm (*Figure* 1-22). The mean annual potential evapotranspiration amounts to approximately 1340 mm. However, there are distinctive trends over the 20th century, as the time-series is most likely affected by the phenomenon of global dimming (starting in 1950) and brightening as well as by an increase in temperature starting around 1980 (*Figure* 1.23 and Figure 1-24). From 1950 to 1980 there were below average values (1319 mm) and from 1981 to 2009 there were above average values (1358 mm). The relationship between annual values of potential evapotranspiration and temperature shows a positive correlation (*Figure* 1-25). However, this relationship is also influenced by variations in global radiation, which is cross-correlated with temperature. Therefore, the relationship of *Figure* 1-25cannot be extrapolated to future warming scenarios.

FAO provides the station dataset CLIMWAT for usage with the CROPWAT model. CLIMWAT itself gives information about potential evapotranspiration calculated with the Penman-Monteith method. However, potential evapotranspiration recalculated with the same method with the CROPWAT model yields slightly different results due to different model assumptions for the Penman-Monteith method. *Figure* 1-26 shows the stations used for obtaining information about potential evapotranspiration in the Zambezi basin region. The number of stations is much larger than for the CRU dataset (compare to *Figure* 1-16). The data of CLIMWAT represents long-term mean monthly values for the period 1971-2000 and consists of minimum temperature, maximum temperature, relative humidity, wind speed, and sunshine duration (*Figure* 1-27 to be used with CROPWAT. Derived data in CROPWAT are global radiation (which depends also on location) and potential evapotranspiration (reference evapotranspiration of short grass). CROPWAT can be used to compute the effect of an increase in temperature on potential evapotranspiration while assuming that all other variables are unchanged. It was found that a warming by 1 °C results in an increase of potential evapotranspiration by 2.5 %. This relationship is obtained at all stations in the Zambezi basin, with only small variations. Tests showed that this rate in increase in potential evapotranspiration is scalable also for higher degrees of warming. This relationship is used by the DSS to calculate time-series of potential evapotranspiration from historic and projected (climate change) temperature data.

As a reference the historic potential evapotranspiration of each sub-basin is estimated from a large number of CLIMWAT stations. CLIMWAT stations were grouped within regions (*Figure* 1-28) and plotted versus elevation (*Figure* 1-29) to obtain an estimate of potential evapotranspiration from the elevation of each subbasin. Even though individual CLIMWAT stations show some large deviations, the general trends in the data are plausible. *Table* 1-3 summarizes the mean potential evapotranspiration as used by the DSS for the historic reference. Together with the mean air temperature estimates from CRU (*Table* 1-2) the potential evapotranspiration of individual time-steps is computed with the following equation:

$$PET = mPET \cdot \ \Delta T \cdot F + 1$$

where

PET is the potential evapotranspiration in [mm/d]

mPET is the mean potential evapotranspiration during the reference period (Table 1-3*) in [mm/d]*

ΔT is the temperature difference between the current time-step and the reference period (Table 1-2*) in [°C].*

F is a factor specified as 0.025 [mm/(mm.°C)], i.e. PET increases by 2.5% with +1°C

Table 1-3: Potential evapotranspiration estimates for sub-basins of the DSS.

Annual values are in the units of [mm/y] and monthly values are in the units of [mm/d]. Period 1971-2000.

Sub-Basin	mm/y year	mm/d Jan	mm/d Feb	mm/d Mar	mm/d Apr	mm/d May	mm/d Jun	mm/d Jul	mm/d Aug	mm/d Sep	mm/d Oct	mm/d Nov	mm/d Dec
1	1600	3.82	3.75	3.80	4.08	4.08	3.84	4.16	5.08	6.08	5.73	4.36	3.80
2	1550	3.70	3.63	3.68	3.95	3.95	3.72	4.03	4.92	5.89	5.55	4.22	3.68
3	1550	3.70	3.63	3.68	3.95	3.95	3.72	4.03	4.92	5.89	5.55	4.22	3.68
4	1650	3.93	3.87	3.92	4.21	4.21	3.96	4.29	5.23	6.27	5.90	4.49	3.92
5	1700	4.05	3.98	4.04	4.34	4.34	4.08	4.42	5.39	6.46	6.08	4.63	4.03
6	1700	4.34	4.25	4.34	4.32	3.96	3.54	3.82	4.87	6.17	6.34	5.27	4.62
7	1600	4.09	4.00	4.09	4.07	3.73	3.33	3.59	4.59	5.81	5.97	4.96	4.35
8	1750	4.47	4.37	4.47	4.45	4.08	3.64	3.93	5.02	6.35	6.53	5.43	4.76
9	1650	4.26	4.07	4.33	4.15	3.71	3.27	3.46	4.49	5.91	6.63	5.39	4.54
10	1650	4.26	4.07	4.33	4.15	3.71	3.27	3.46	4.49	5.91	6.63	5.39	4.54
11	1700	4.39	4.19	4.46	4.28	3.83	3.36	3.56	4.63	6.09	6.83	5.56	4.68
12	1600	3.83	3.72	3.99	4.09	3.88	3.56	3.79	4.76	6.00	6.22	4.74	3.99
13	1600	3.83	3.72	3.99	4.09	3.88	3.56	3.79	4.76	6.00	6.22	4.74	3.99
14	1750	4.19	4.06	4.36	4.48	4.24	3.90	4.14	5.20	6.56	6.80	5.18	4.37
15	1750	4.06	3.93	4.18	4.29	4.10	3.78	3.98	5.00	6.48	7.20	5.93	4.57
16	1700	3.94	3.82	4.06	4.17	3.99	3.68	3.86	4.86	6.29	7.00	5.76	4.44
17	1700	4.39	4.19	4.46	4.28	3.83	3.36	3.56	4.63	6.09	6.83	5.56	4.68
18	1650	4.26	4.07	4.33	4.15	3.71	3.27	3.46	4.49	5.91	6.63	5.39	4.54
19	1500	3.99	3.92	3.96	3.76	3.30	2.84	3.01	3.84	5.03	5.88	5.20	4.56
20	1450	3.85	3.79	3.83	3.63	3.19	2.75	2.91	3.71	4.87	5.68	5.03	4.41
21	1500	3.99	3.92	3.96	3.76	3.30	2.84	3.01	3.84	5.03	5.88	5.20	4.56
22	1450	3.85	3.79	3.83	3.63	3.19	2.75	2.91	3.71	4.87	5.68	5.03	4.41
23	1450	3.85	3.79	3.83	3.63	3.19	2.75	2.91	3.71	4.87	5.68	5.03	4.41
24	1600	4.69	4.47	4.32	3.98	3.47	2.97	3.07	3.94	4.89	5.94	5.77	5.05
25	1600	3.71	3.71	3.71	3.88	3.88	3.77	3.82	4.48	5.49	6.27	5.66	4.19
26	1500	4.40	4.19	4.05	3.73	3.26	2.79	2.88	3.70	4.59	5.57	5.41	4.73
27	1600	4.69	4.47	4.32	3.98	3.47	2.97	3.07	3.94	4.89	5.94	5.77	5.05

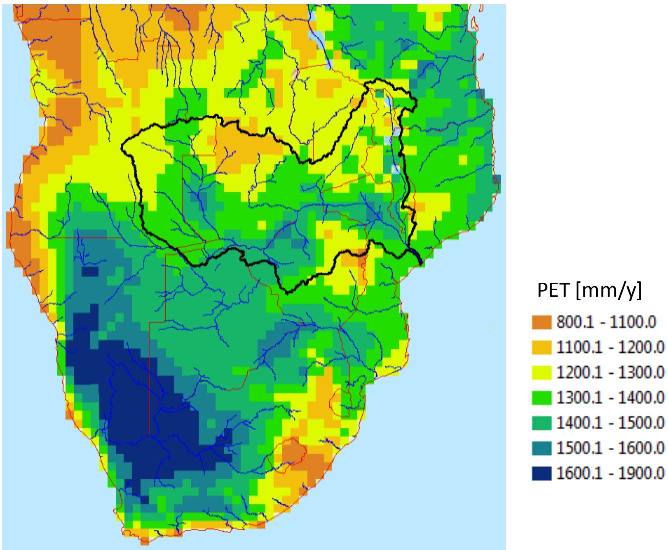

Figure 1-21: Mean annual potential evapotranspiration for 1961-1990. CRU data.

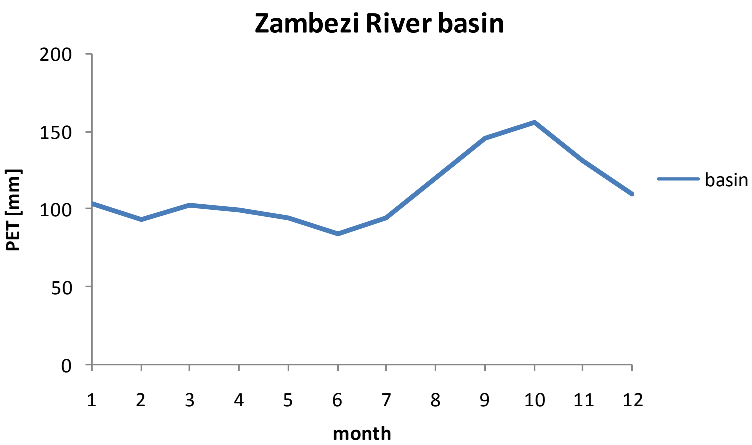

Figure 1-22: Mean monthly potential evapotranspiration in the Zambezi basin for the period 1961-1990. CRU data.

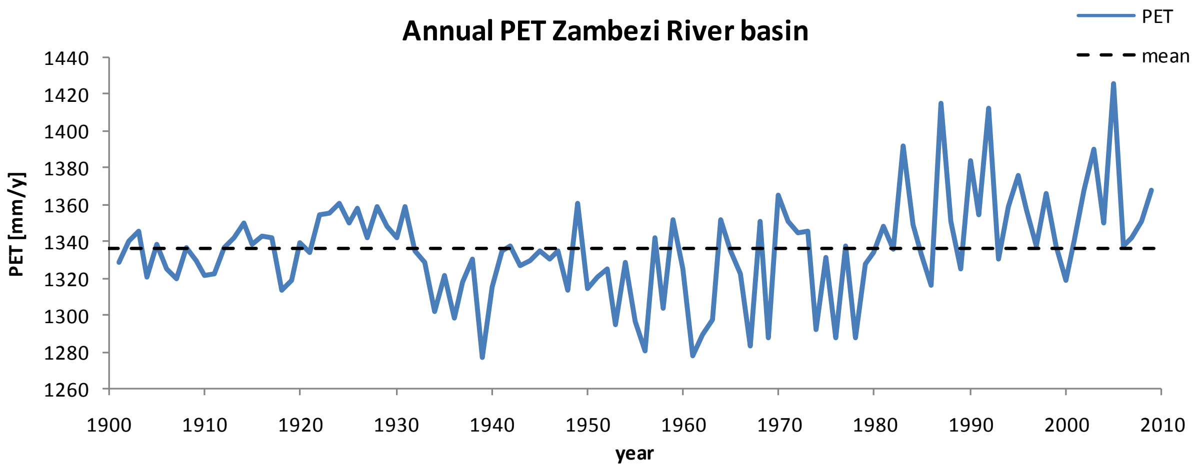

Figure 1-23: Annual potential evapotranspiration in the Zambezi basin from 1901-2009 based on CRU data.

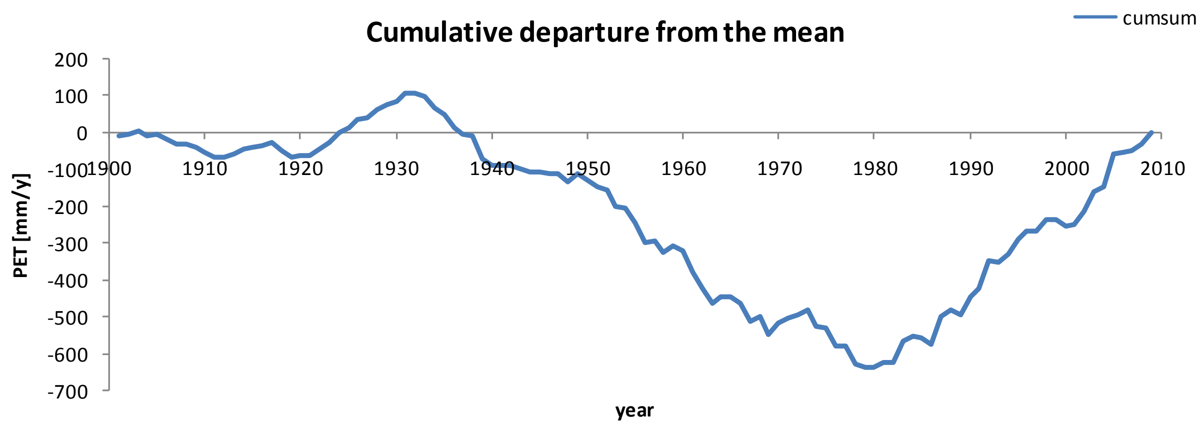

Figure 1-24: Long-term trends in annual potential evapotranspiration in the Zambezi basin from 1901-2009.

CRU data. Computed as the cumulative difference between annual values and long-term mean annual values. Positive slope: periods with above average evapotranspiration. Negative slope: periods with below average evapotranspiration.

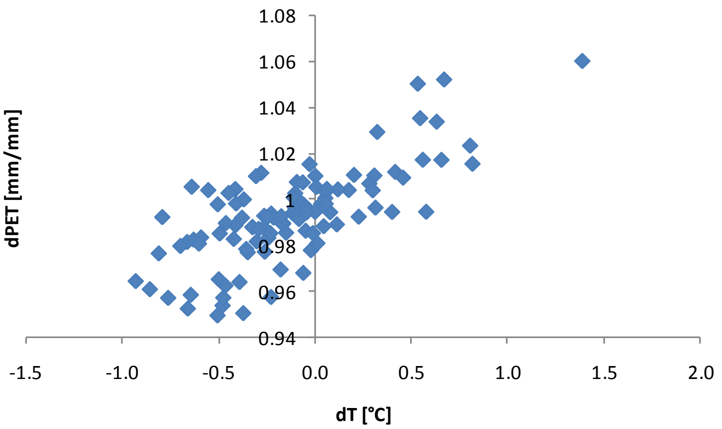

Figure 1-25: Relationship between annual anomalies of potential evapotranspiration and temperature in the Zambezi basin.

CRU data. Period 1901-2009. dT: temperature anomaly computed as difference between annual value and long-term mean annual value. dPET: potential evapotranspiration anomaly computed as ratio between annual value and long-term mean annual value.

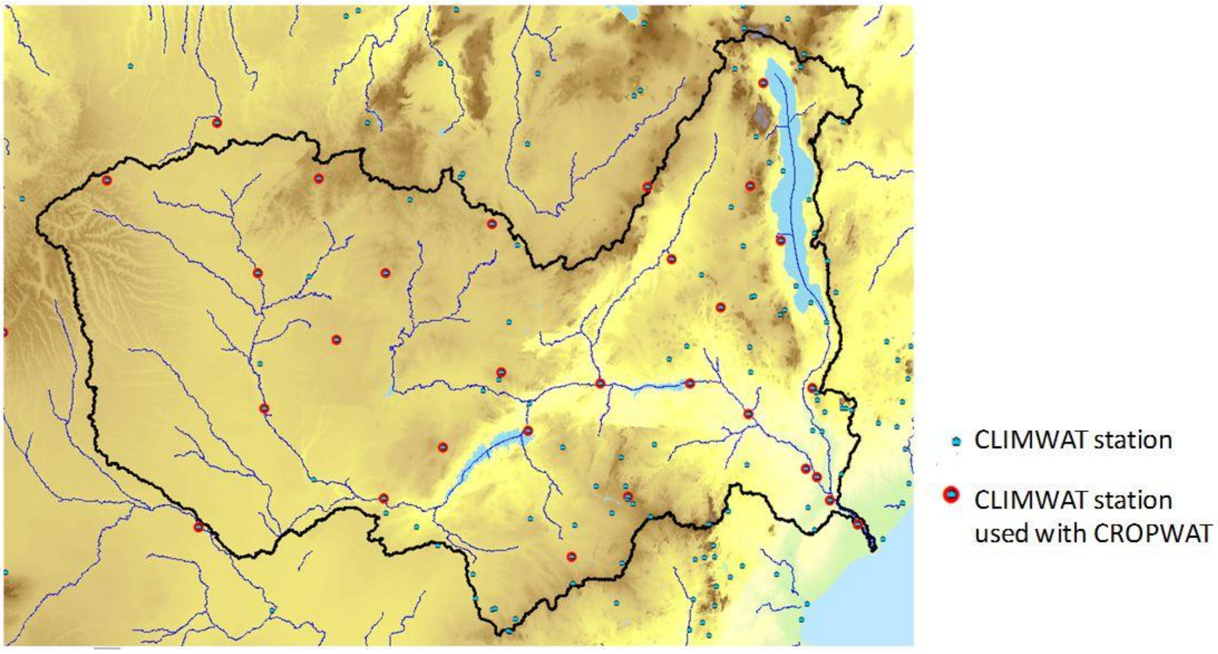

Figure 1-26: Location of available CLIMWAT stations and selection of stations used with the CROPWAT model.

Country: Location 81 Station: TETE

Altitude: 150 m. Latitude: 16.18 °S Longitude: 33.58 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	23.3	33.0	74	95	6.5	20.6	4.71
February	23.3	33.6	75	78	6.8	20.8	4.69
March	22.5	32.8	70	112	7.4	20.5	4.71
April	21.3	32.5	65	121	7.6	18.8	4.40
May	18.1	30.9	63	95	7.8	17.0	3.63
June	15.2	28.4	62	95	6.2	13.9	2.94
July	15.1	28.1	61	121	7.2	15.5	3.25
August	17.1	30.6	55	156	8.1	18.5	4.35
September	20.1	33.3	48	207	8.3	21.0	5.85
October	23.0	36.4	45	225	8.7	23.3	7.12
November	23.9	36.0	53	190	7.9	22.6	6.51
December	23.6	34.2	62	121	6.9	21.3	5.34
Average	**20.5**	**32.5**	**61**	**135**	**7.5**	**19.5**	**4.79**

Figure 1-27: *CROPWAT model for calculation of potential evapotranspiration with the Penman-Monteith method with CLIMWAT data. Example for station Tete in Mozambique.*

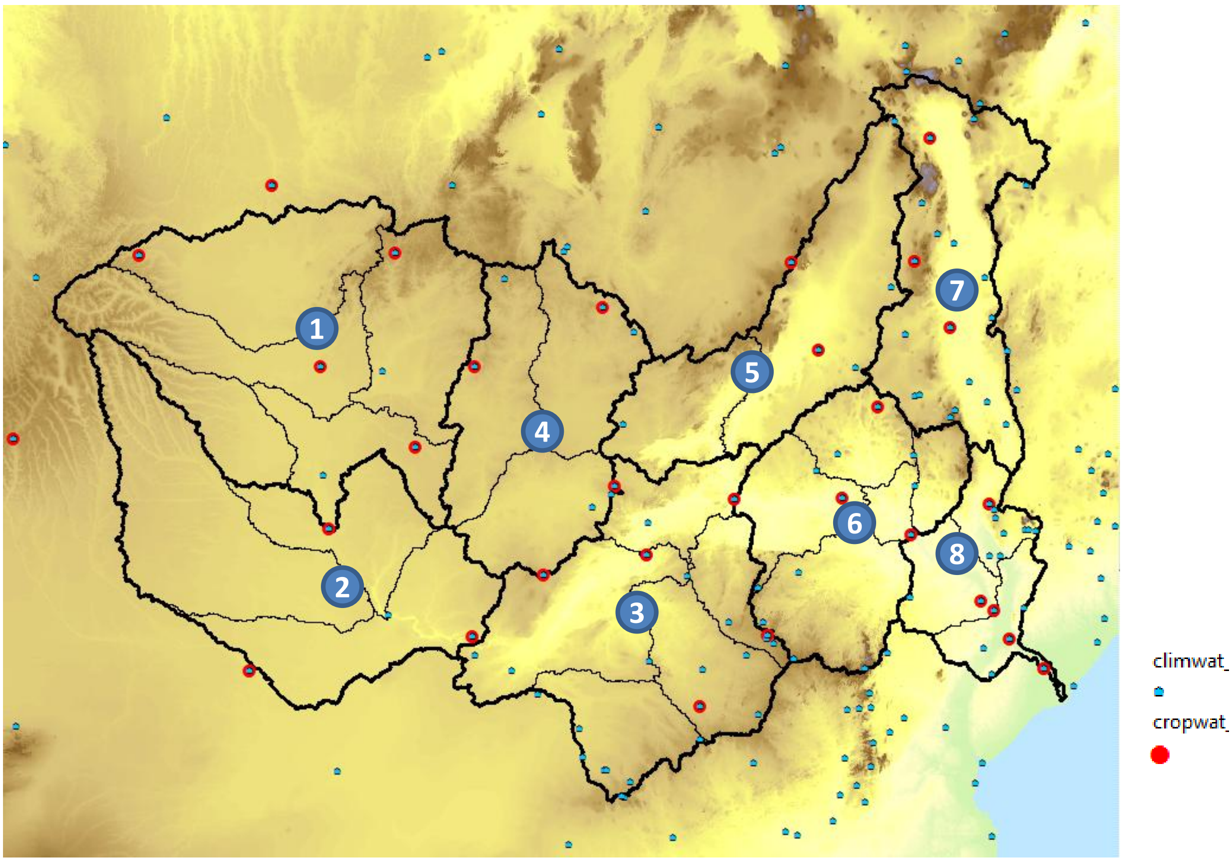

Figure 1-28: *Overview of spatial location of potential evapotranspiration data.*

Small blue circles: CLIMWAT stations. Large red circles: CROPWAT calculations. Bold black lines and numbers in blue circles: grouping of sub-basins into regions for separate potential evapotranspiration analysis.

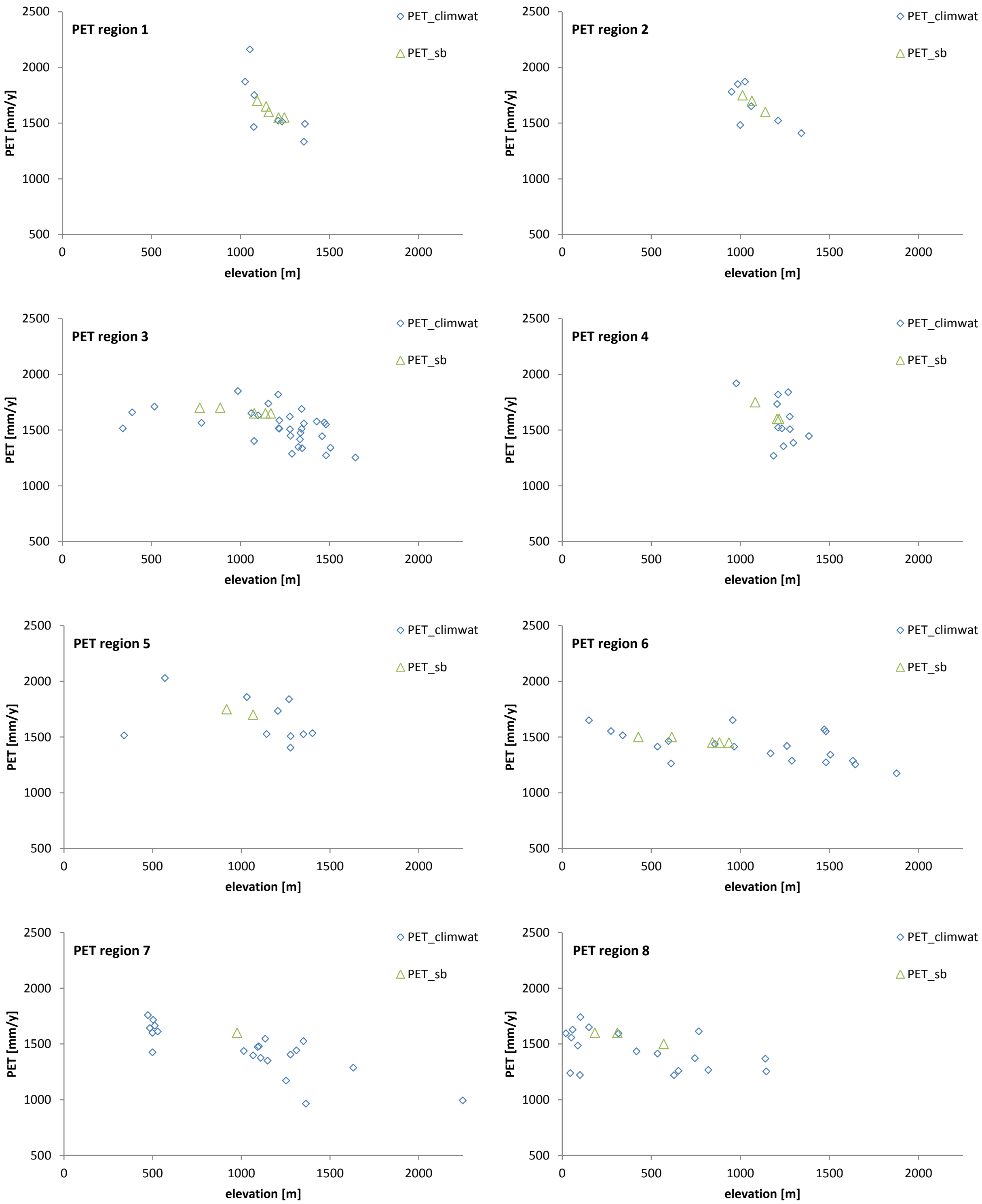

Figure 1-29: ***Analysis of potential evapotranspiration plotted against elevation in eight separate regions.***

Blue: CLIMWAT data. Green triangles: assigned estimates of sub-basin evapotranspiration.

Climate change scenarios

Climate change scenarios are available from various different climate models. In this study the climate change scenarios are based on two recently finished climate modelling projects funded by the European Union: ENSEMBLES (A1B scenario) and WATCH (A2 scenario). The anticipated usage of CORDEX Africa data was not possible, as there was a delay in publishing of the climate model results.

In the ENSEMBLES (A1B scenario) project the latest generation of Regional Climate Models (RCMs) were applied to Europe and large parts of Africa with a resolution of 50 x 50 km. Three RCMs of ENSEMBLES (A1B scenario) also cover the Zambezi basin region (*Figure* 1-25). At the boundaries the RCMs are driven by General Circulation Models (GCMs). The climate simulations are based on the A1B emission scenario of IPCC. The climate data are not bias corrected. Monthly time-step data were considered in this study.

In the WATCH (A2 scenario) project daily data of three GCMs were statistically downscaled with quantile mapping (Piani *et al*., 2010) to a half degree resolution (approximately 50 x 50 km). The climate simulations are based on the A2 emission scenario of IPCC. The data cover the whole globe and are available from 1960 to 2100. Quantile mapping is based on observational data sets from the period 1960 to 2000.

Table 1-4 summarizes the climate models used in this study. Data of these models are used to obtain future scenarios for monthly time-series of precipitation and temperature up to the end of the 21st century in the Zambezi basin. In the case of ENSEMBLES (A1B scenario) data, only the delta change signals are used, as a proper bias correction is not possible due to insufficient length of overlapping time-periods between climate model data (starting e.g. 1980) and good quality historical observations (up to 1990). In the case of the downscaled WATCH (A2 scenario) data, a correction (linear scaling) of minor biases is applied with observational data of the Zambezi basin for 1961-1990.

Through the remainder of the text we refer to the ENSMBLES climate model data as A1B scenario, and we refer to the WATCH climate model data as A2 scenario.

Table 1-4: Climate models.

acronym	project	IPCC emission scenario	institute	GCM	RCM	Period
DMI	ENSEMBLES	A1B*	DMI	ECHAM5-r3	HIRHAM5	1989-2050
ICTP	ENSEMBLES	A1B*	ICTP	ECHAM5-r3	RegCM3	1980-2100
INM	ENSEMBLES	A1B*	INM	HadCM3Q0	RCA3	1951-2098
CNRM	WATCH	A2**	CNRM	CNRM-CM3	n/a	1960-2100
ECHAM	WATCH	A2**	MPI-M	ECHAM5/MPIOM	n/a	1960-2100
IPSL	WATCH	A2**	IPSL	LMDZ-4	n/a	1960-2100

** The A1B scenario assumes a more integrated world, characterized by rapid economic growth, a global population that reaches 9 billion in 2050 and then gradually declines, a quick spread of new and efficient technologies, a convergent world with incomes and ways of life converging between regions, extensive social and cultural interactions worldwide and a balanced emphasis on all energy sources*

*** The A2 scenario assumes a more divided world, characterized by a world of independently operating, self-reliant nations, continuously increasing population and regionally oriented economic development*

Figure 1-31 to *Figure* 1-39 show an analysis of the climate model data und A1B emission scenario for the Zambezi basin. The simulated spatial distribution of mean annual precipitation and air temperature with the RCMs is plausible (*Figure* 1-31). However, there are apparent biases in the mean annual values. For example, for mean annual precipitation the observed value of approximately 1000 mm/y differs from the RCM simulations, which yield results of approximately 800 mm/y (DMI, ICTP) and 1200 mm/y (INM), respectively (*Figure* 1-32). Similar considerations apply for air temperature (*Figure* 1-36). Therefore, only the delta change signals are of interest. In general, the RCMs project a decrease of annual precipitation of up to -20% until the end of the 21st century (*Figure* 1-35). Warming is projected to lie between +3 to +4 °C as compared to 1990-2010 (*Figure* 1-39). *Table* 1-5 and *Table* 1-6 summarize the climate model projections under the A1B emission scenario.

Table 1-5: Summary of precipitation projections under A1B emission scenario. Full Zambezi basin.

Period	DMI [mm]	ICTP [mm]	INM [mm]	Δ DMI [%]	Δ ICTP [%]	Δ INM [%]
1990-2010	846	843	1188	0	0	0
2021-2050	808	818	1171	-4	-3	-1
2071-2100	/	695	1100	/	-18	-7

Table 1-6: Summary of air temperature projections under A1B emission scenario. Full Zambezi basin.

Period	DMI [°C]	ICTP [°C]	INM [°C]	Δ DMI [°C]	Δ ICTP [°C]	Δ INM [°C]
1990-2010	24.3	22.1	22.3	0	0	0
2021-2050	25.5	23.2	23.7	+1.1	+1.0	+1.3
2071-2100	/	26.4	25.8	/	+4.2	+3.4

Figure 1-40 to *Figure* 1-45 show an analysis of WATCH climate model data for the Zambezi basin. Air temperature is projected to increase significantly until the end of the 21st century (*Figure* 1-42 and *Figure* 1-43). Differences between climate models and observations (CRU) are small. This is due to the fact that WATCH data represent climate model data that was downscaled with observations. For precipitation no significant change is projected (*Figure* 1-40 and *Figure* 1-41). However, this only applies for an analysis based on an aggregation over the entire basin. In contrast, an analysis based on individual sub-basins reveals that in the upper regions of the basin precipitation is projected to decreases significantly (up to 30%), whereas in the Shire River basin (sb_25 and sb_26) projections show an increase (*Figure* 1-44). There are also regional differences in projected warming of up to 1.5 °C (*Figure* 1-45). This emphasizes the need for spatially distributed assessment of climate change.

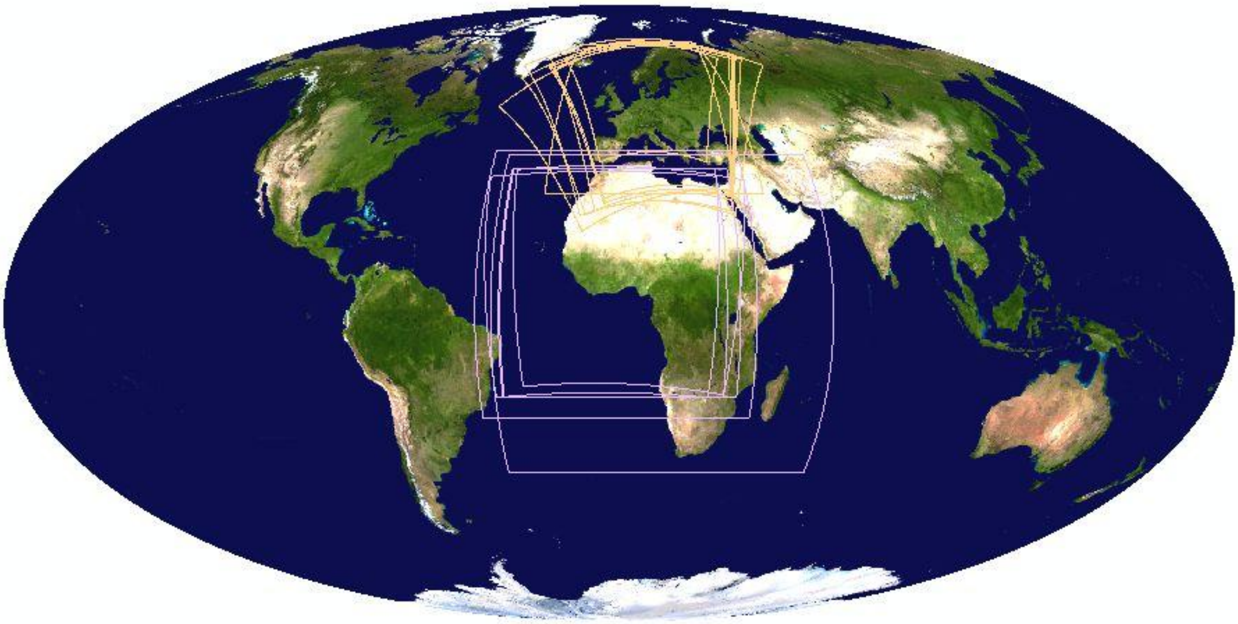

Figure 1-30: Spatial extent of RCMs included in the ENSEMBLES (A1B scenario) project.

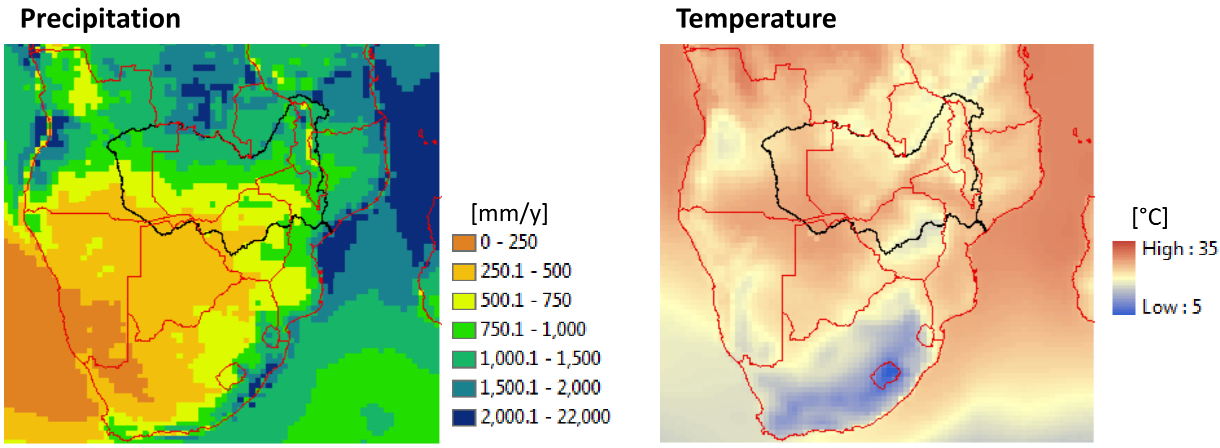

Figure 1-31: Example of spatial distribution of mean annual precipitation and air temperature (1990-2010) simulated by climate models. ICTP of ENSEMBLES (A1B scenario).

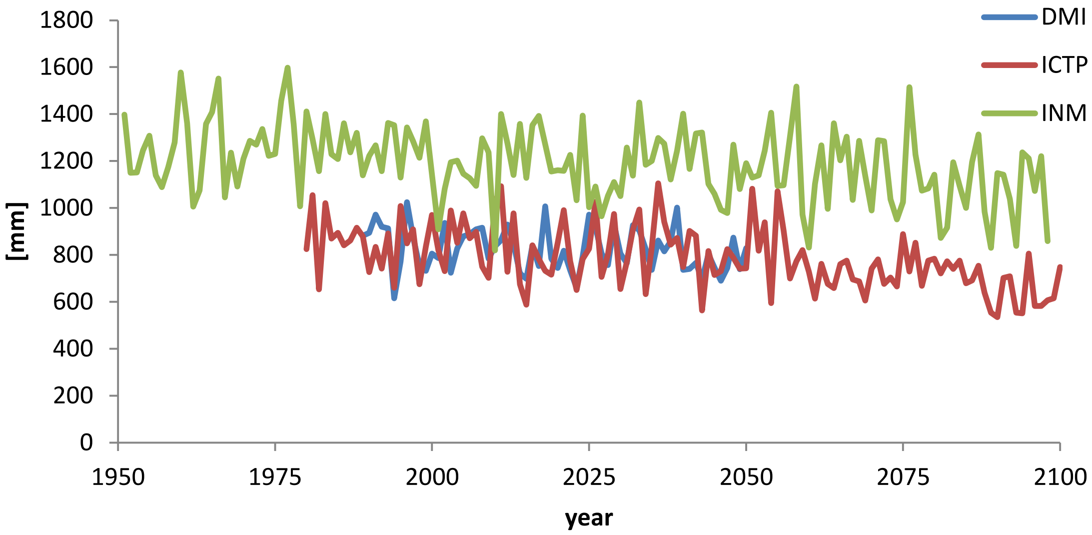

Figure 1-32: *Annual precipitation projected under A1B emission scenario. Aggregation over full Zambezi basin.*

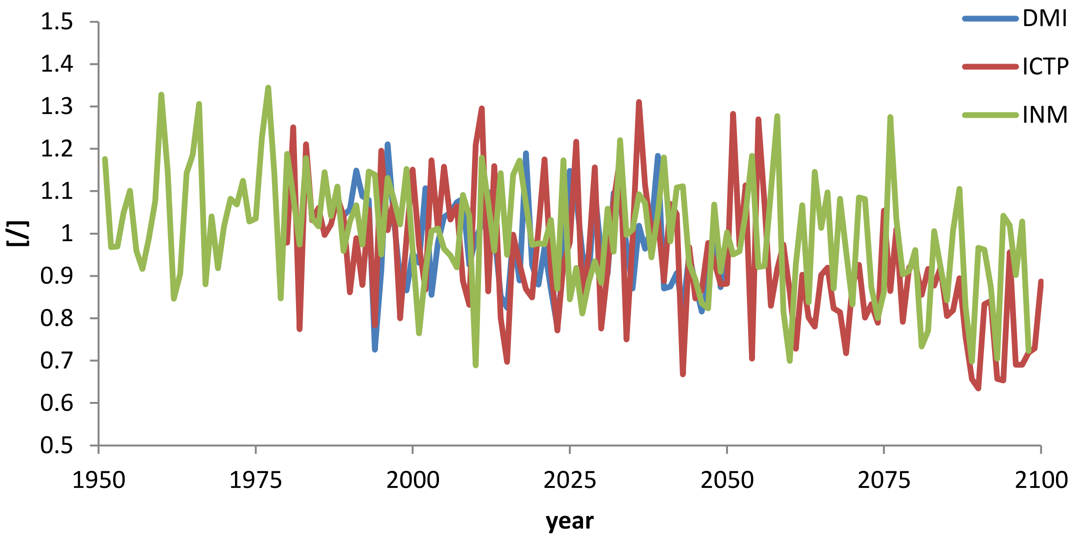

Figure 1-33: *Change in annual precipitation projected under A1B emission scenario. Baseline: 1990-2010. Aggregation over full Zambezi basin.*

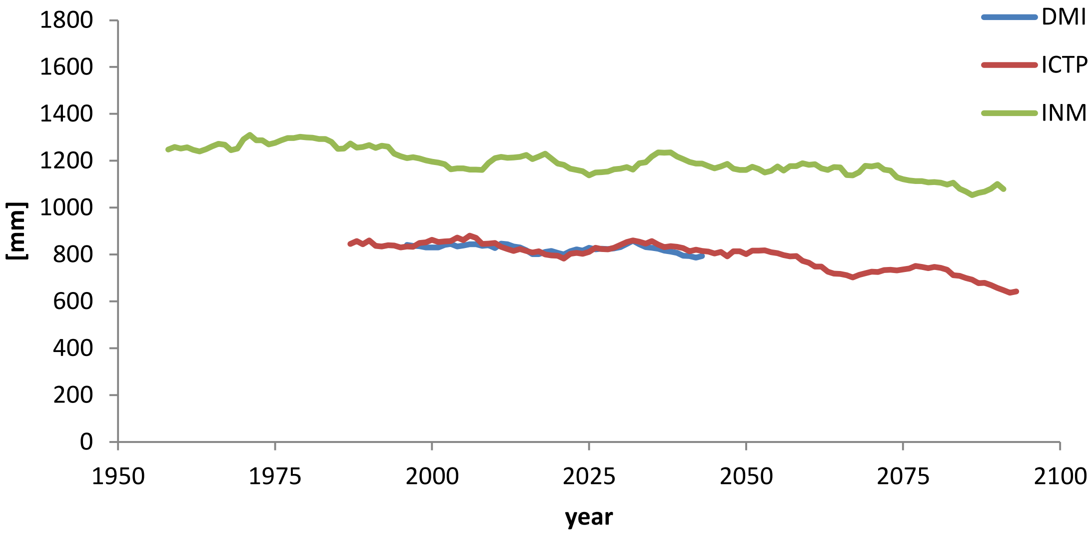

***Figure 1-34:** 15-year moving average of annual precipitation projected under A1B emission scenario. Aggregation over full Zambezi basin.*

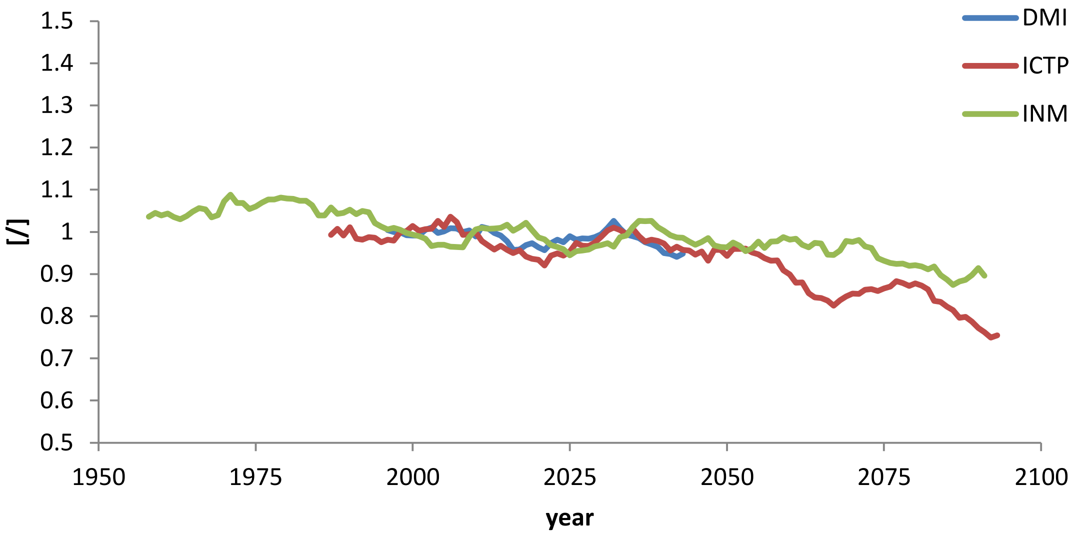

***Figure 1-35:** 15-year moving average of change in precipitation projected under A1B emission scenario. Baseline: 1990-2010. Aggregation over full Zambezi basin.*

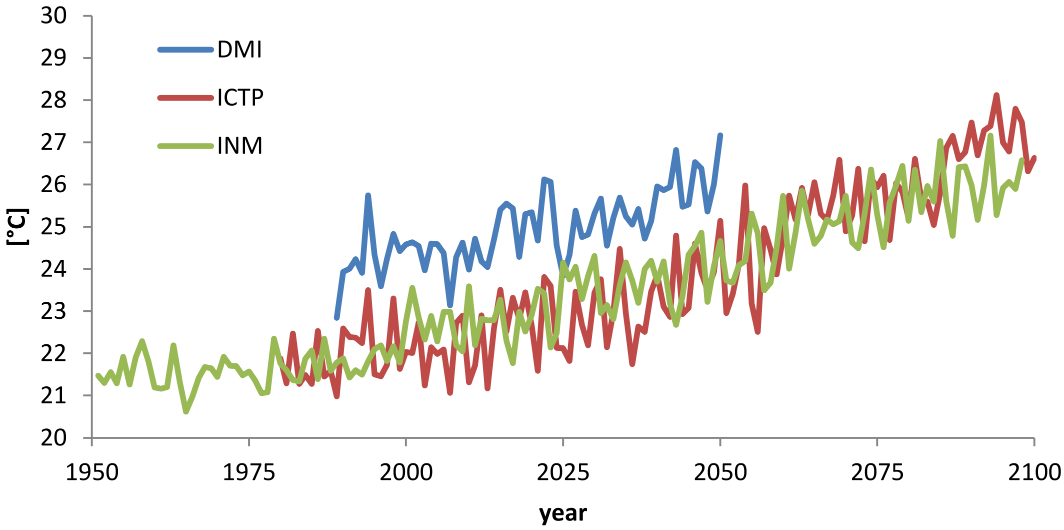

Figure 1-36: ***Annual air temperature projected under A1B emission scenario. Aggregation over full Zambezi basin.***

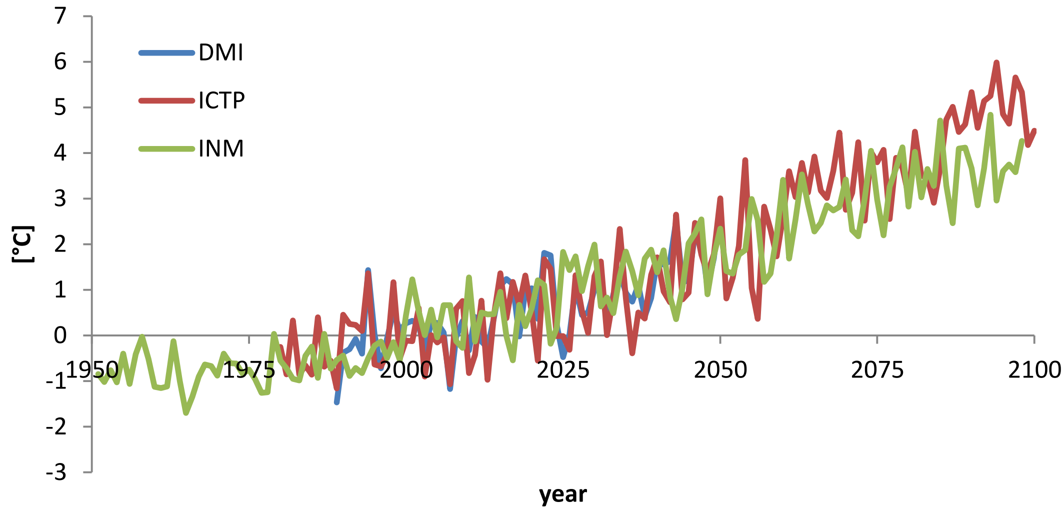

Figure 1-37: ***Change in annual air temperature projected under A1B emission scenario. Baseline: 1990-2010. Aggregation over full Zambezi basin.***

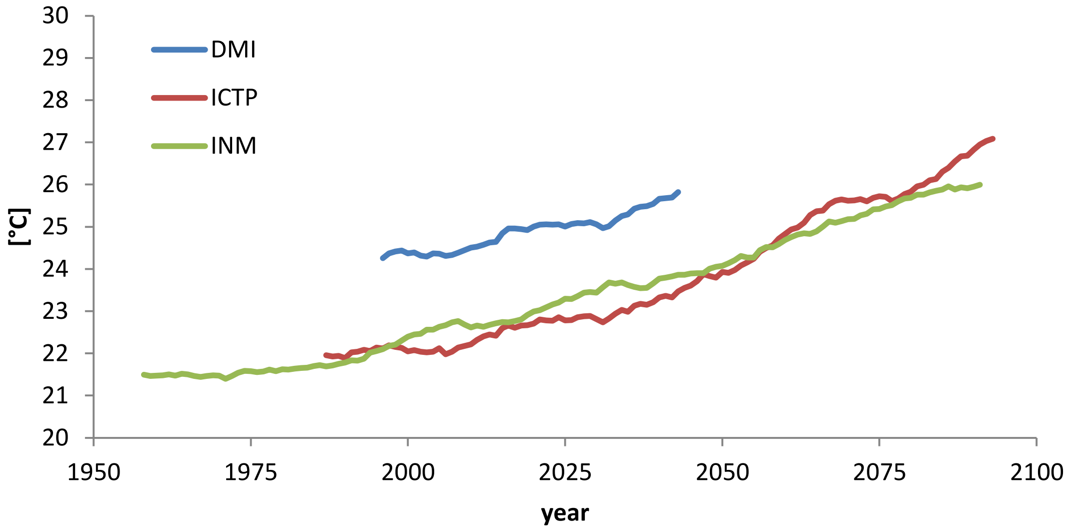

Figure 1-38: 15-year moving average of annual air temperature projected under A1B emission scenario. Aggregation over full Zambezi basin.

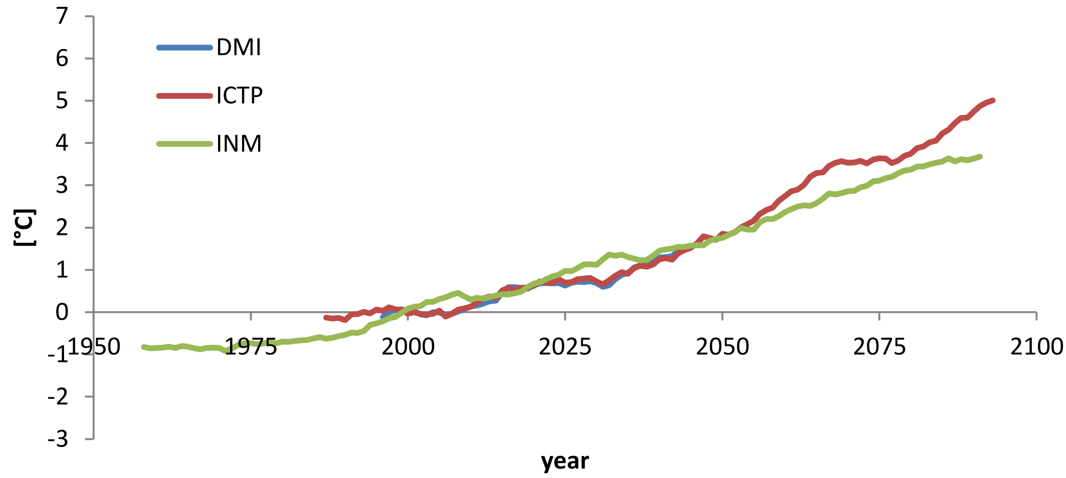

Figure 1-39: 15-year moving average of change in annual air temperature projected under A1B emission scenario. Baseline: 1990-2010. Aggregation over full Zambezi basin.

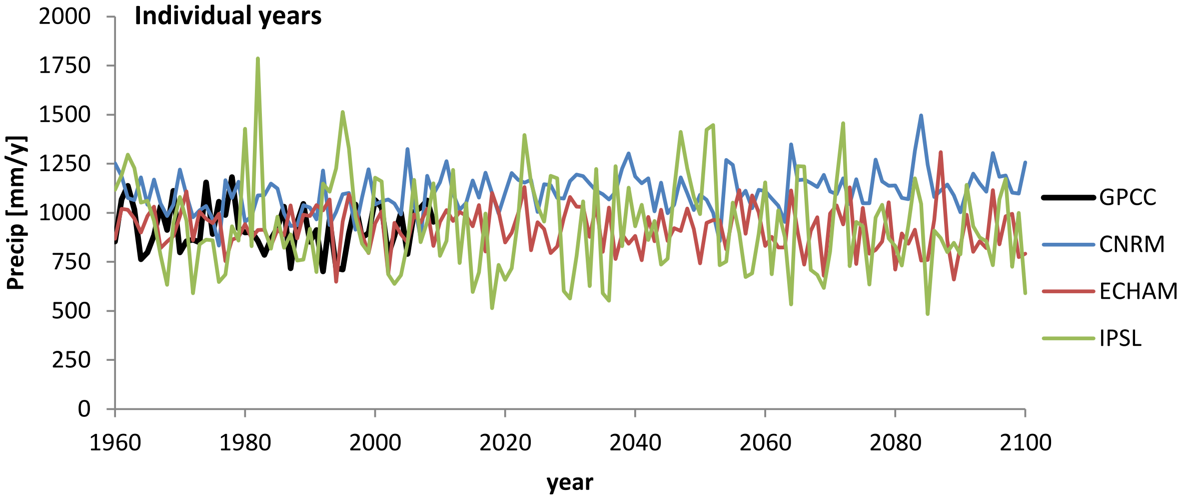

Figure 1-40: ***Annual precipitation projected under A2 emission scenario and observed GPCC data. Aggregation over full Zambezi basin.***

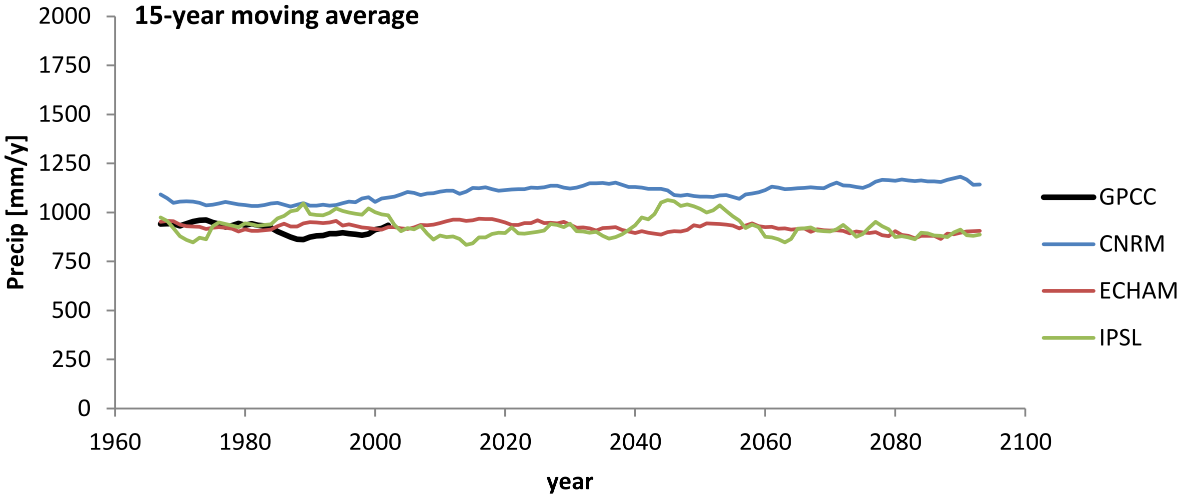

Figure 1-41: ***15-year moving average of annual precipitation projected under A2 emission scenario and observed GPCC data. Aggregation over full Zambezi basin.***

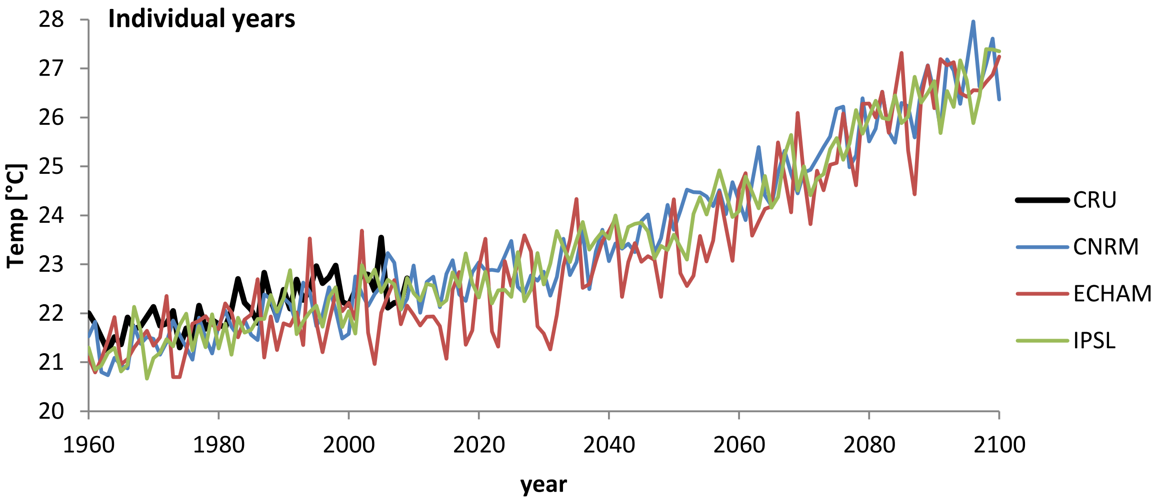

Figure 1-42: Annual air temperature projected under A2 emission scenario and observed CRU data. Aggregation over full Zambezi basin.

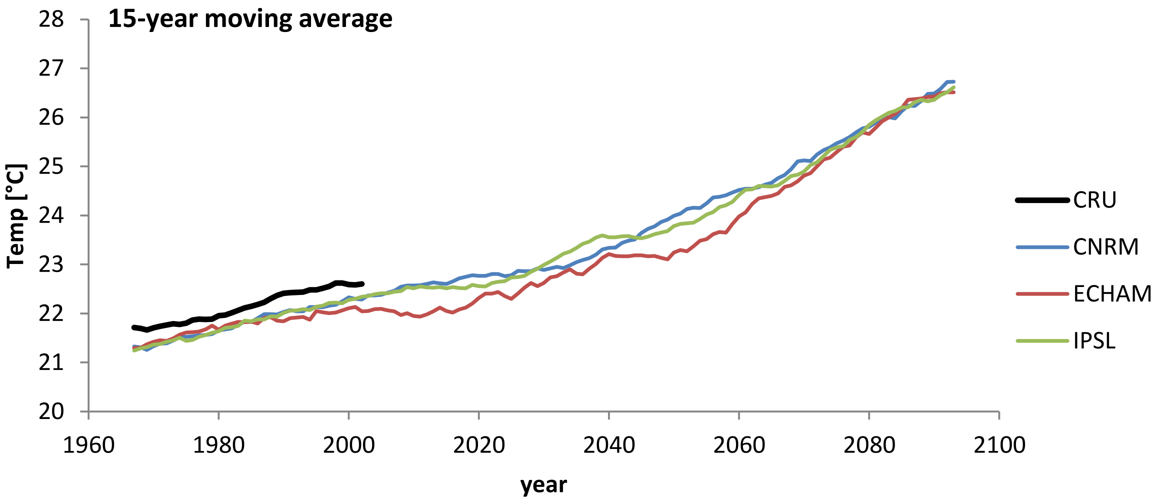

Figure 1-43: 15-year moving average of annual air temperature projected under A2 emission scenario and observed CRU data. Aggregation over full Zambezi basin.

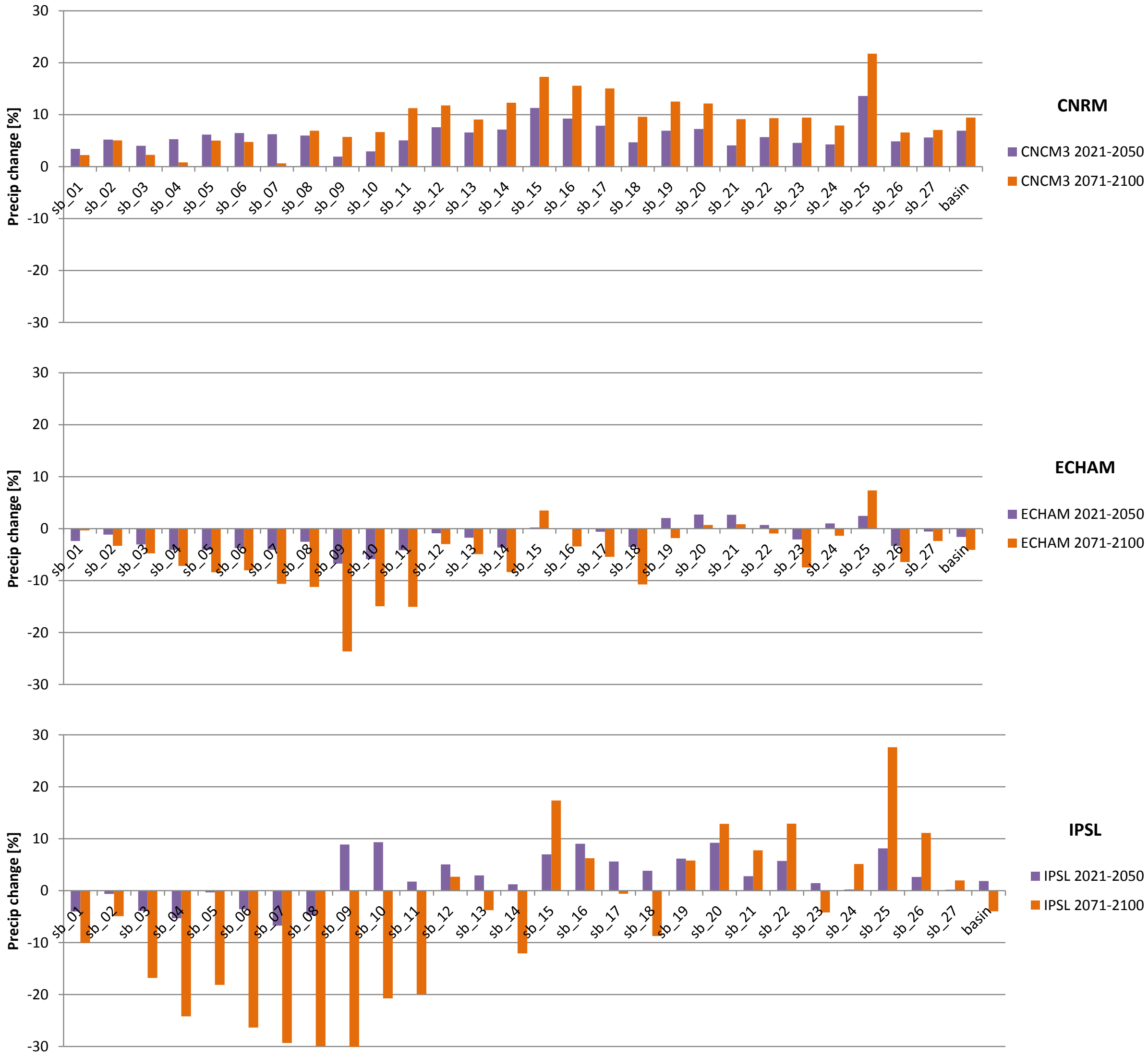

Figure 1-44: ***Change in mean annual precipitation of different sub-basins projected by GCMs under A2 emission scenario. Reference period 1961-1990. Future periods 2021-2050 and 2071-2100.***

*For sub-basin (sb) definition refer to **Figure** 1-48. Top: CNRM data. Middle: ECHAM data. Bottom: IPSL data.*

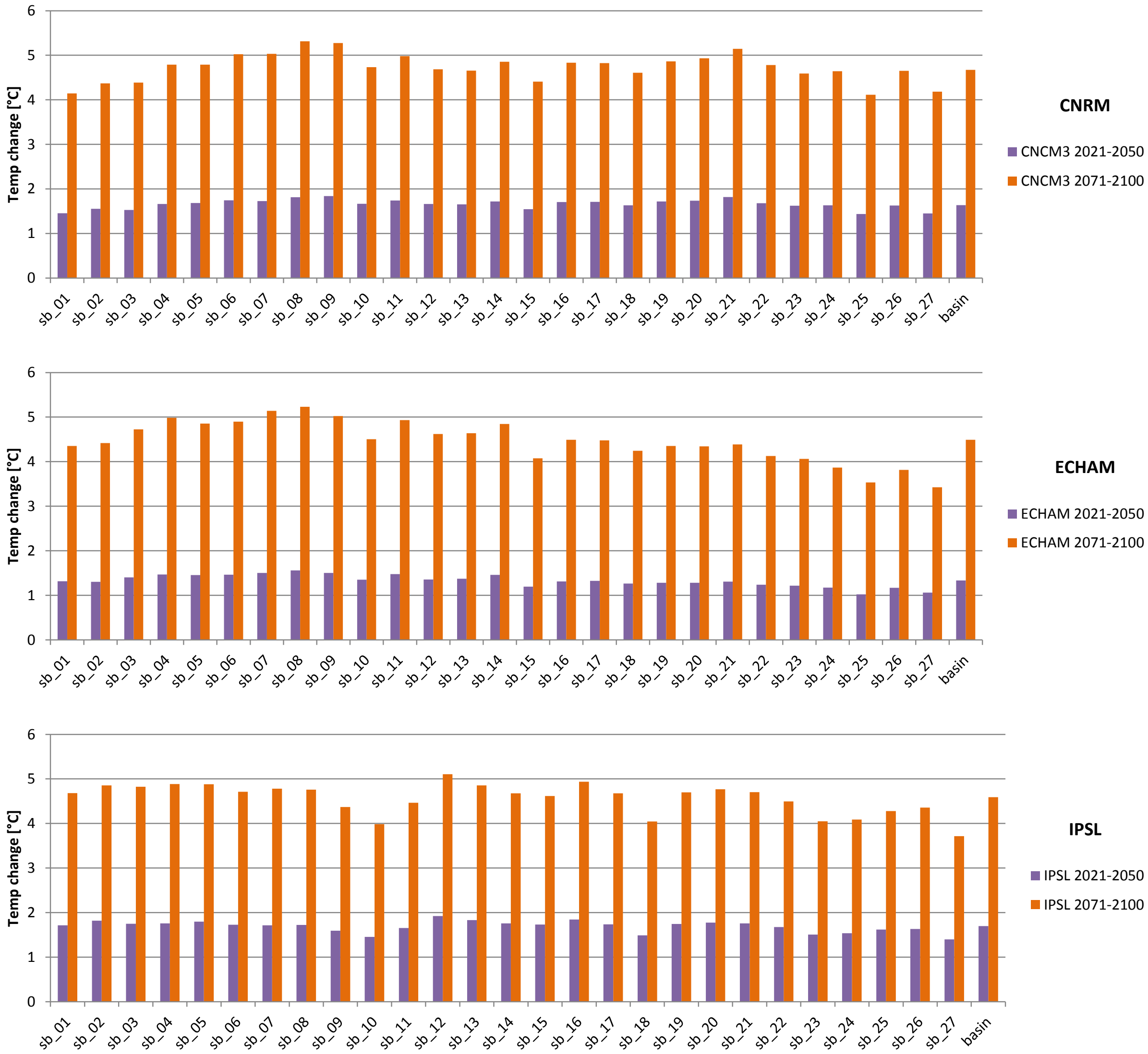

***Figure 1-45:** Change in mean annual temperature of different sub-basins projected by GCMs under A2 emission scenario. Reference period 1961-1990. Future periods 2021-2050 and 2071-2100.*

*For sub-basin (sb) definition refer to **Figure** 1-48. Top: CNRM data. Middle: ECHAM data. Bottom: IPSL data.*

1.6 MODEL AND DSS DESCRIPTION

1.6.1 General structure

The Decision Support System (DSS) is designed for online access of (multiple) users over the internet (*Figure* 1-46). The DSS software is installed on a server and consists of two parts – the River Basin Model (RBM) and the Information Management System (IMS) – as shown in *Figure* 1-47. The RBM consists of a Water Balance Module (WBM) and a Water Allocation Module (WAM). The IMS consist of a database, a graphical user interface and analytical tools. All functions of the DSS are available for the user via the graphical user interface.

The first step in the development of the RBM was to define the spatial resolution, as all the subsequent data pre-processing were based on this resolution. The spatial elements of the WBM represent sub-basins to simulate the natural processes of the water balance. Overall 27 sub-basins are defined (*Figure* 1-48). This number is fixed and cannot be changed by the user of the DSS.

In each sub-basin the same model concept is applied (*Figure* 1-49). The code was developed based on the model version used by Kling *et al*. (2012), which is similar in its structure as used in earlier studies in the Zambezi basin (e.g. Winsemius *et al*., 2008). Precipitation can be stored and evaporated from the interception storage. The remaining water falling on the ground is either stored in the soil or generates runoff as an exponential function of soil moisture (HBV-type concept). Evapotranspiration from the soil depends on soil moisture and potential evapotranspiration. Generated runoff is split into a fast and slow component representing base flow (simulated as a linear reservoir). In general monthly time-steps are used, but the interception and soil modules internally use descretization into daily time-steps to account for intra-monthly variability (interception/evaporation of individual rainfall events; inter-dependence of soil moisture, evapotranspiration and runoff generation).

The area shares of three different land-use classes are specified for each sub-basin (woodland, grassland, agriculture based on AVHRR satellite data). This enables the user to consider changes in future land-use. However, as currently set-up, there are no differences in the model parameters (e.g. crop coefficients) between land-use classes, but this can be modified by the user. Parameters of the WBM were calibrated lumped for sub-basins by a comparison between simulated and observed runoff (see next section).

The spatial elements of the WAM are represented by computation points, which account for the topology (upstream/downstream) of the river-network. Along with the sub-basins, the computation points serve as the main nodes for the user to access data of the simulations with the DSS. There are three different types of computation points: (1) river points, (2) uncontrolled reservoirs (lakes, wetlands, and floodplains), (3) controlled reservoirs (e.g. Lake Kariba). A pre-defined set of 40 computation points is used (*Table* 1-7, *Figure* 1-50). However, additional computation points at any location can be added by the user via the graphical user interface of the DSS. Such new computation points may represent either planned reservoirs (e.g. hydropower plants at Batoka Gorge or Mependa Uncua) or any specific location of interest for discharge along the river network. If the computation point represents a controlled reservoir, then the user has to specify the reservoir characteristics (storage-area-elevation curve, operation rules, diversions, etc.). The basic concept for reservoir simulation shows *Figure* 1-51 and the balance (change in storage) of a reservoir depends on the following variables:

- upstream inflow (discharge at upstream computation points)
- lateral inflow (runoff from intermediate sub-catchment)
- precipitation on water body
- evaporation from water body
- diversion from reservoir (net-consumption)
- outflow (release)

All variables above are in the units of m³/s. For the lateral inflow the area of the intermediate sub-catchment between the current computation point and the immediate (multiple) upstream computation points is calculated. This area is reduced by the lake area (which varies from time-step to time-step). This method ensures that also for large wetlands – with seasonal variations in water body area of several thousand km² - the water balance can be closed.

A key characteristic of controlled and uncontrolled reservoirs is the relationship of volume-area-elevation, where volume is the key accounting unit (hm³) for the mass balance computations of the model. Internal daily computational time-steps are used to consider gradual changes in storage and area, which is important to determine evaporation from the water body. Evaporation is computed as the potential evapotranspiration increased by 5% (according to FAO 56, Allen *et al*., 1998).

Wetlands are modelled as reservoirs with a fixed storage-discharge relationship. At most wetlands a linear relationship proved to be sufficient. The only exception is Lake Malawi, where a non-linear relationship is used.

Releases from reservoirs are modelled according to reservoir operations with storage-guide curves. Such guide curves enable to model a seasonal draw-down of reservoirs, which mimics the actual operations of e.g. Kariba and Cahora Bassa for flood control. Additional attributes are desired release as a function of storage (which is similar to the zoning-concept found in the operation of many reservoirs) and environmental flow requirements.

Diversions of water (for irrigation) can be withdrawn at all three types of computation points. In the case of river points and uncontrolled reservoirs (wetlands) the water is taken out of the river, but only if the (optional) required downstream flow (environmental flows) are maintained. In the case of controlled reservoirs the water is taken out of the reservoir storage.

The following prioritization of water is used by controlled reservoirs to determine the reservoir storage and releases:

1. environmental flow as a function of month
2. diversions (e.g. for irrigation) as a function of month
3. desired release (e.g. for hydropower) as a function of storage
4. guide curve operation (e.g. for flood control) as a function of month

The reservoir level is not allowed to rise above the guide curve; releases are increased if high inflows would result in a higher water level. Lower water levels than the guide curve are possible e.g. due to the other releases with higher priorities (1 to 3). If the water level drops below the minimum operation level (which is possible due to low inflows and high evaporation), then outflow from the reservoir ceases. Overall, the model is able to mimic the most important reservoir operation characteristics, as e.g. also used by the HEC-ResSim model.

In the model each diversion and controlled reservoir only becomes effective in the simulation after the start year (commissioning date). This enables continuous historic simulation even though the catchment properties changed over time.

The outflows from computation points are routed to the next downstream computations points with a simple lag-method. This routing is only considered at computation points at the outlets of sub-basins. In general, a value of three days is used for routing, with the exception of computation points located directly upstream of large wetlands (Barotse Floodplain, Chobe Swamps, Kafue Flats), where a value of 10 days is used for routing. This simple routing method results in approximately 5 weeks travel-time for floods from the Zambezi headwaters to Mozambique. Note, that also the retention in uncontrolled and controlled reservoirs causes an additional attenuation for floods travelling downstream.

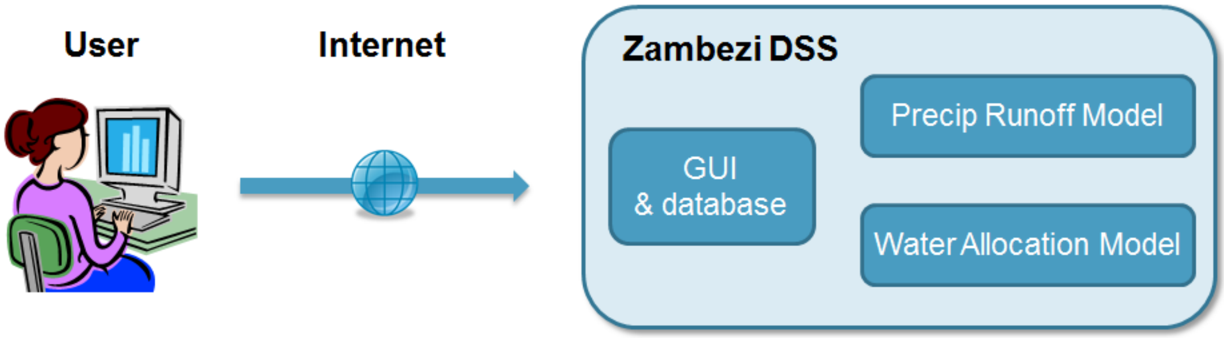

Figure 1-46: ***General design of DSS.***

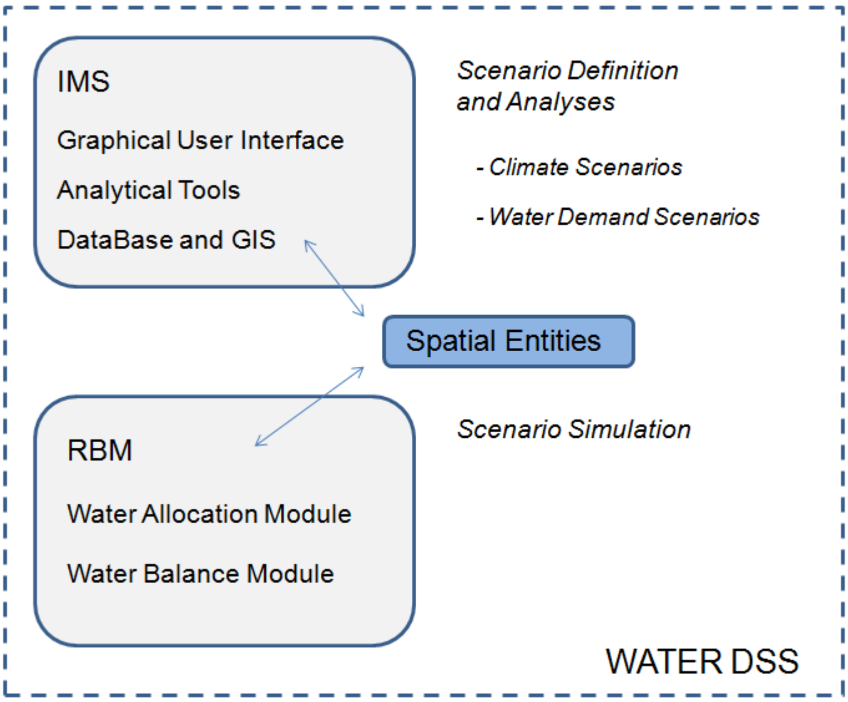

Figure 1-47: ***General concept of the Decision Support System (DSS). IMS...Information Management System. RBM...River Basin Model.***

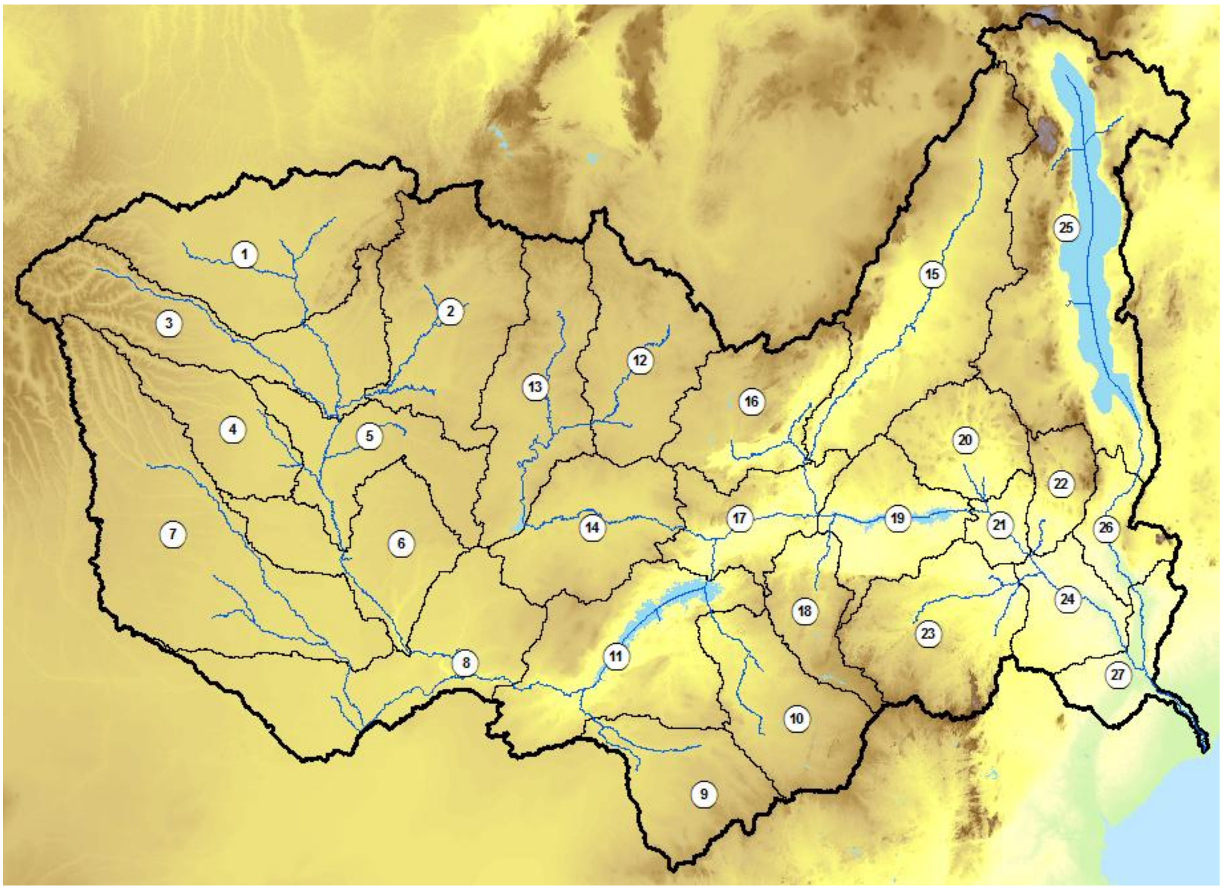

Figure 1-48 Sub-basins of the water balance module (WBM).

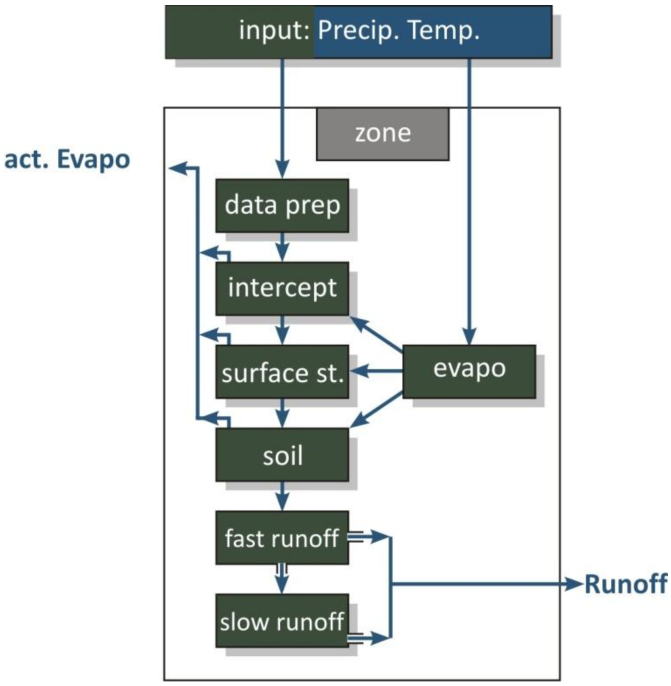

Figure 1-49: Conceptual structure of the water balance module (WBM).

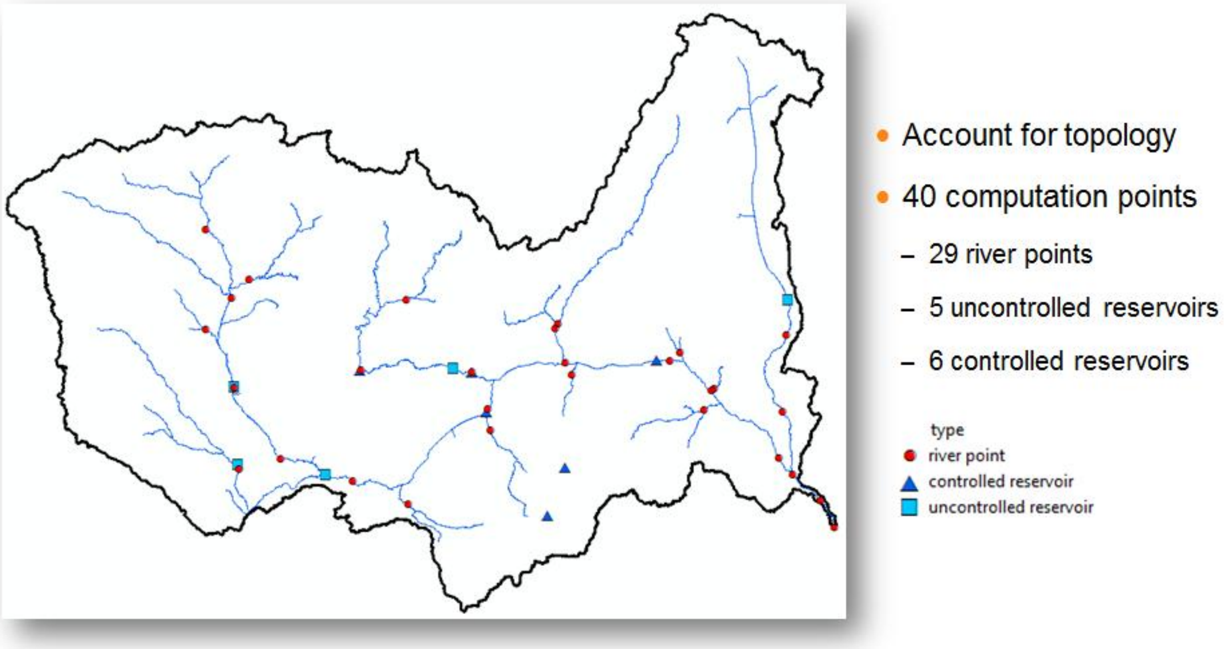

Figure 1-50: Computation points of the water allocation module (WAM).

Table 1-7: Pre-defined set of computation points of the water allocation module (WAM).

The first 27 computation points are located at the sub-basin outlets of the WBM.

CP	river	Location	type
1	Zambezi	Chavuma Mission	river point
2	Kabompo	Watopa Pontoon	river point
3	Zambezi	Lukulu	river point
4	Luanginga	Kalabo	river point
5	Zambezi	Senanga	river point
6	Zambezi	Katima Mulilo	river point
7	Kwando	Kongola	river point
8	Zambezi	Victoria Falls	river point
9	Gwaai	Kamativi	river point
10	Sanyati	Sanyati at mouth	river point
11	Zambezi	downstream Kariba dam	river point
12	Kafue	Mswebi	river point
13	Kafue	downstream Itezhi-Tezhi dam	river point
14	Kafue	downstream Kafue Gorge dam	river point
15	Luangwa	upstream confluence Lunsemfwa	river point
16	Luangwa	Luangwa Bridge / Great Eastern Rd.	river point
17	Zambezi	downstream confluence Luangwa	river point
18	Panhane	downstream confluence Duangua	river point
19	Zambezi	downstream Cahora Bassa dam	river point
20	Luia	downstream confluence Cherisse	river point
21	Zambezi	Tete / Matundo-Cais	river point
22	Revubue	Chingoze	river point
23	Luenha	Luenha 1	river point
24	Zambezi	Ponte Dona Ana / Mutarara	river point
25	Shire	Liwonde	river point
26	Shire	Chiromo	river point
27	Zambezi	Zambezi at mouth	river point
28	Zambezi	Barotse Floodplain	uncontrolled reservoir
29	Zambezi	Caprivi Floodplain / Chobe Swamps	uncontrolled reservoir
30	Kafue	Kafue Flats	uncontrolled reservoir
31	Shire	Lake Malawi	uncontrolled reservoir
32	Kwando	Kwando Floodplain	uncontrolled reservoir
33	Zambezi	Lake Kariba	controlled reservoir
34	Kafue	Itezhitezhi	controlled reservoir
35	Kafue	Kafue Gorge	controlled reservoir
36	Zambezi	Cahora Bassa	controlled reservoir
37	Sanyati	Cumulative reservoirs	controlled reservoir
38	Panhane	Cumulative reservoirs	controlled reservoir
39	Zambezi	Caia	river point
40	Zambezi	Marromeu	river point

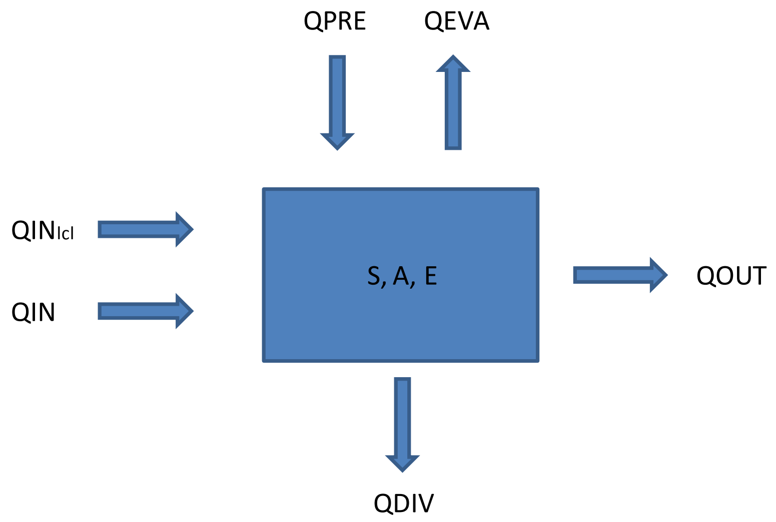

***Figure** 1-51: Variables of the Water Allocation Module (WAM).*

QIN...upstream inflow. QINlcl...lateral inflow. QPRE...precipitation on water body. QEVA...evaporation from water body. QDIV...diversion from reservoir (net-consumption). S...storage in reservoir. A...area of water body. E...elevation of water surface. QOUT...outflow.

1.6.2 Calibration

Observed discharge data measured at gauges were used for calibration of the parameters of the river basin model (RBM). The objective was to obtain a good agreement between simulated and observed discharge for the period 1961-1990. A challenge was that observed discharge data of some gauges appear to be affected by severe biases (e.g. Chavuma Mission discharge data). Such data were excluded from the calibration. In addition to the discharge data, also observed water level data of reservoirs were used for comparison with simulated water levels.

The following methods were used during parameter calibration:

- Multi-dimensional sensitivity tests.
- Shuffled Complex Evolution (SCE) optimization (Duan *et al*., 1992).
- Multi-objective Dynamically Dimensioned Search (moDDS) optimization (extension of DDS, Tolson and Shoemaker, 2007)
- Manual parameter calibration.

In addition to a visual comparison of simulated and observed discharge and water levels, model performance for discharge simulation at gauges was measured with the modified KGE statistic (Gupta *et al*., 2009; Kling *et al*., 2012) and its three dimension-less sub-components correlation, bias ratio, and variability ratio:

$$KGE' = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2}$$

$$\beta = \frac{\mu_s}{\mu_o}$$

$$\gamma = \frac{CV_s}{CV_o} = \frac{\sigma_s/\mu_s}{\sigma_o/\mu_o}$$

where

KGE' is the modified KGE-statistic [/]
r is the correlation between simulated and observed discharge time-series [/]
β *is the bias ratio [/]*
γ *is the variability ratio [/]*
μ *is mean discharge [m³/s]*
CV is the coefficient of variation [/]
σ *is the standard deviation [m³/s]*
s is the subscript denoting simulated values
o is the subscript denoting observed values

Optimization on the KGE-statistic ensures that a balanced solution for correlation (i.e. temporal dynamics), bias (i.e. mean volume of flow), and variability (i.e. distribution of flows, flow duration curve) is obtained. This would not be ensured if optimizing on e.g. the well-known Nash-Sutcliffe efficiency (NSE, Nash and Sutcliffe, 1970) or the related Mean Squared Error (Gupta *et al*., 2009).

The calibration mainly focused on four parameters of the water balance module (WBM) and the (linear) storage-release function of the wetlands (uncontrolled reservoirs) of the water allocation module (WAM). The four calibrated parameters of WBM are:

- soil storage capacity
- exponent for computing runoff generation (HBV-method)
- base-flow-index, i.e. fraction of generated runoff that percolates to the base flow storage
- base flow recession coefficient (linear reservoir coefficient)

During calibration it proved to be sufficient to use the same base flow recession coefficient in all sub-basins, whereas for the other three parameters different (calibrated) values are used in individual sub-basins, thereby implicitly accounting for the complex interplay between climate, vegetation, soils, geology, aquifers and runoff.

The calibration period was defined as 1961 to 1990, with a 1-year spinup period (for state variables of the model). The period 1961-1990 has the best quality in precipitation station availability as well as number of gauges with observed discharge. In the middle of this period in the 1970s Itezhitezhi and Cahora Bassa reservoirs were built. Therefore, the observed discharge datasets are not homogeneous. Further, frequent changes in operation rules at the large reservoirs (Kariba, Cahora Bassa) complicate evaluation of the discharge simulations in the downstream sections of the Zambezi River. In addition, the relationship between water level and outflow from Lake Malawi is affected by changes in the outlet level (e.g. due to sedimentation) and human interventions (e.g. Kamuzu Barrage just downstream of the lake outlet was constructed in 1965 to control Shire River flows). Above all, the quality of the observed discharge data is at some gauges questionable, as there are unplausible differences when comparing discharge time-series (see *Figure* 1-52 and *Figure* 1-53). A main cause of uncertainty may be an imprecise stage-discharge relationship, which comes into effect when transforming the water level data (which is actually the data measured at the gauge) to discharge.

Table 1-8 summarizes the calibration procedure and performance statistics, with the caveat that observed discharge data are unreliable at several gauges. In general the model performs well, with performance statistics similar or higher than in previous Zambezi studies (e.g. Harrison and Whittington, 2002; Winsemius *et al*. 2006).

Figure 1-54 and *Figure* 1-55 show simulated and observed monthly hydrographs at six key locations in the Zambezi basin. The observed temporal dynamics of discharge are reproduced well in the simulation. Further comparisons with observed discharge data are presented for seasonality in discharge (*Figure* 1-56), monthly flow duration (i.e. distribution of flows, *Figure* 1-57), and annual variations in discharge (*Figure* 1-58). Simulated water levels in Kariba and Cahora Bassa reservoirs as well as Lake Malawi exhibit similar fluctuations (*Figure* 1-59). However, from this figure it is also clear that actual operation rules changed over time – as exemplified by Cahora Bassa where draw-downs were smaller during the 2000s than during the 1970s after the first filling of the reservoir. Such changes over time in the operation rules are not considered by the DSS, where instead operation rules are fixed.

Table 1-8: Calibration procedure and performance statistics. CP identifies the location (see Table 1-7) and corresponds to the sub-basins defined in Figure 1-48.

CP	period	method	comment	r [/]	β [/]	γ [/]	KGE' [/]	NSE [/]
1	1961-1990	with 3	Qobs not plausible	0.87	0.55	0.66	0.42	0.39
2	1961-1990	SCE		0.94	1.00	0.99	0.94	0.89
3	1961-1990	moDDS with 8		0.94	0.98	1.07	0.90	0.87
4	1961-1990	SCE		0.87	1.00	0.99	0.87	0.75
5	1961-1990	with 8	Qobs not plausible	0.94	1.08	1.41	0.58	0.53
6	1961-1990	with 8	Qobs not plausible	0.93	0.84	0.93	0.82	0.82
7	1961-1990	SCE		0.62	1.07	0.94	0.61	0.20
8	1961-1990	moDDS with 3		0.93	1.00	0.96	0.92	0.87
9	1961-1990	SCE		0.88	1.00	1.00	0.88	0.76
10	1961-2009	SCE		0.88	1.00	0.99	0.88	0.76
11	1961-1990	manual (a)	Kariba operations	0.53	0.96	0.75	0.47	0.24
12	1961-1990	SCE		0.93	1.00	0.99	0.93	0.87
13	1961-1976	SCE		0.95	1.00	0.98	0.95	0.90
14	1961-1976	SCE		0.91	1.06	0.84	0.81	0.83
15	1961-1990	with 16		n/a	n/a	n/a	n/a	n/a
16	1961-1990	SCE		0.93	1.00	1.00	0.93	0.87
17	1961-1990	manual (a)		0.93	0.92	0.77	0.74	0.80
18	1961-2009	with 10		n/a	n/a	n/a	n/a	n/a
19	1961-1990	manual (a)	Cahora Bassa operations	0.41	0.96	0.87	0.39	-0.02
20	1961-1990	with 22		n/a	n/a	n/a	n/a	n/a
21	1961-1990	manual (a)		0.73	1.09	0.94	0.71	0.44
22	1961-1990	SCE		0.93	1.00	1.00	0.92	0.85
23	1961-1990	SCE		0.96	1.00	1.00	0.96	0.91
24	1961-1990	manual (a)		n/a	n/a	n/a	n/a	n/a
25	1961-1990	manual (b)	Lake Malawi operations	0.40	1.00	0.81	0.37	-0.01
26	1961-1990	manual (b)		0.65	1.05	1.01	0.65	0.24
27	1961-1990	manual (a)		0.73	1.06	0.84	0.68	0.50

Manual (a): manual calibration with same parameter values for sub-basin (CP) 11, 17, 19, 21, 24, 27

Manual (b): manual calibration with same parameter values for sub-basin (CP) 25, 26

changing operations at Kariba, Cahora Bassa and Lake Malawi affected observed discharge data

(Performance statistics were improved especially for Zambezi at Victoria Falls (CP 8) by including routing component in the model and re-calibration of model parameters)

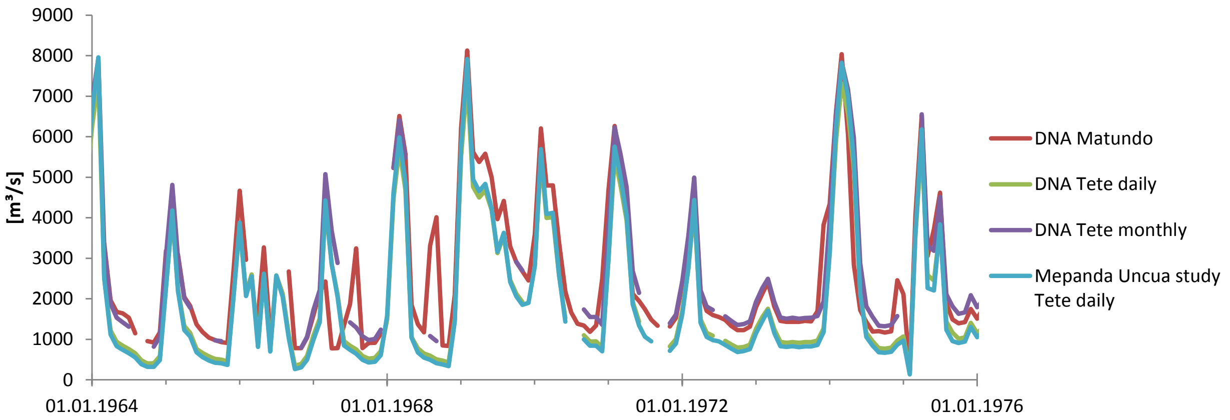

Figure 1-52: ***Comparison of four different sources of observed data for monthly Zambezi discharge near Tete. Daily data were aggregated to monthly values. Ideally, there should not be any differences in the observed data.***

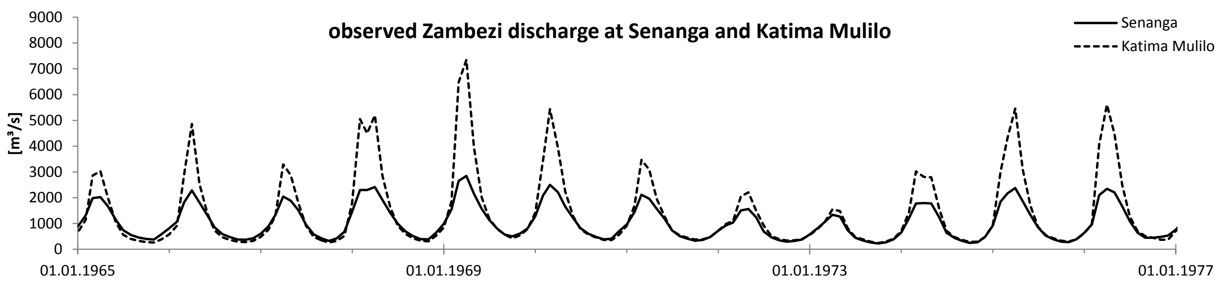

Figure 1-53: ***Observed data of Zambezi discharge at Senanga (upstream) and Katima Mulilo (downstream).***

There are no significant tributaries between the two adjacent gauges and discharge data should be quite similar, but they are not due to biased peak flow data.

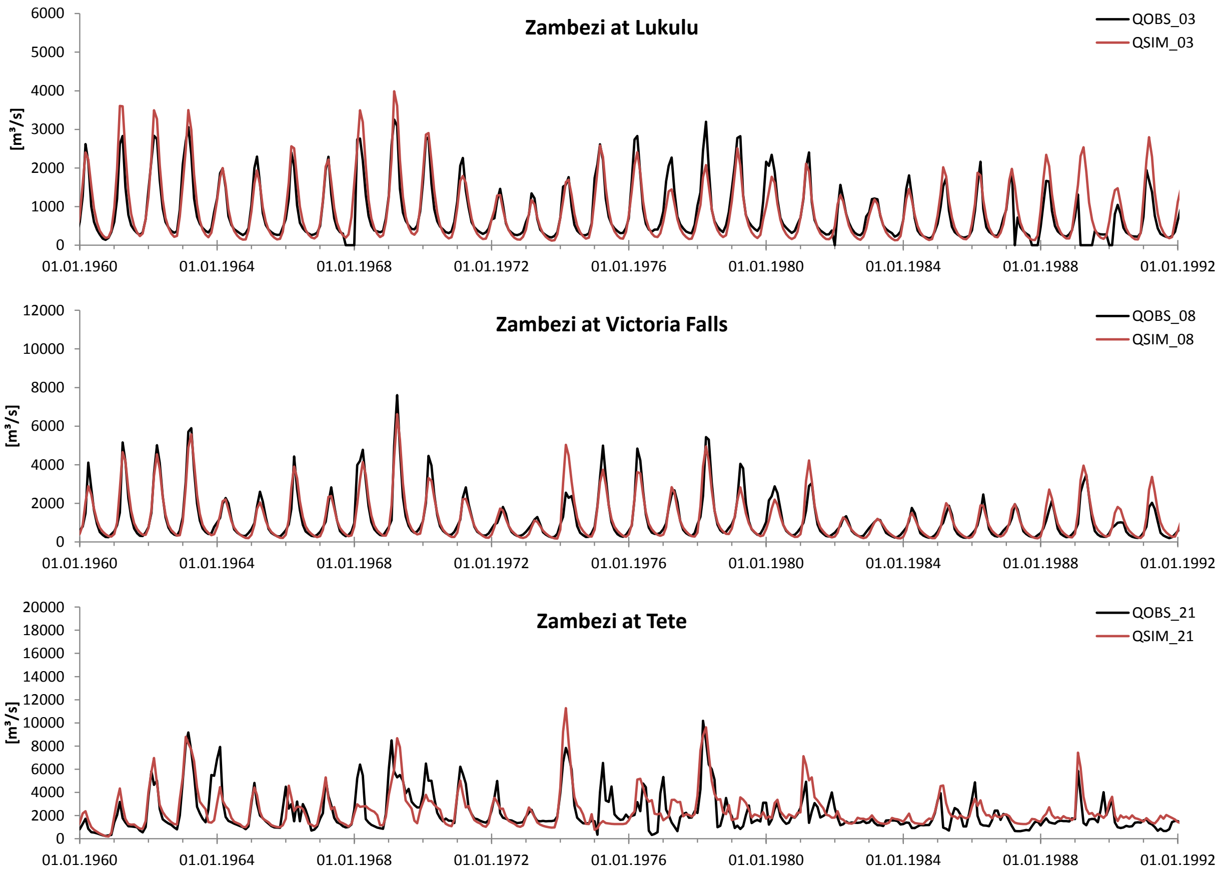

Figure 1-54: ***Simulated (red) and observed (black) monthly hydrographs at key locations along the Zambezi.***

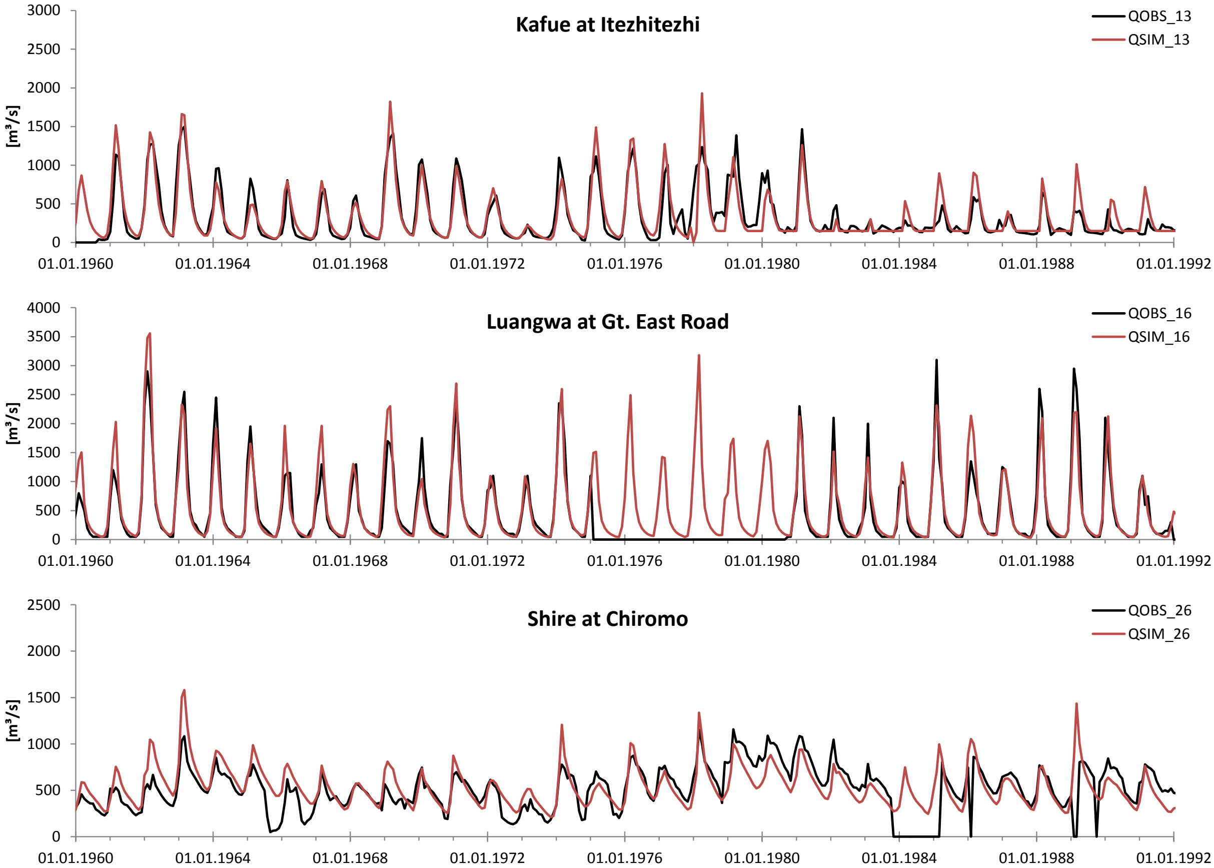

Figure 1-55: ***Simulated (red) and observed (black) monthly hydrographs of the three main tributaries of the Zambezi.***

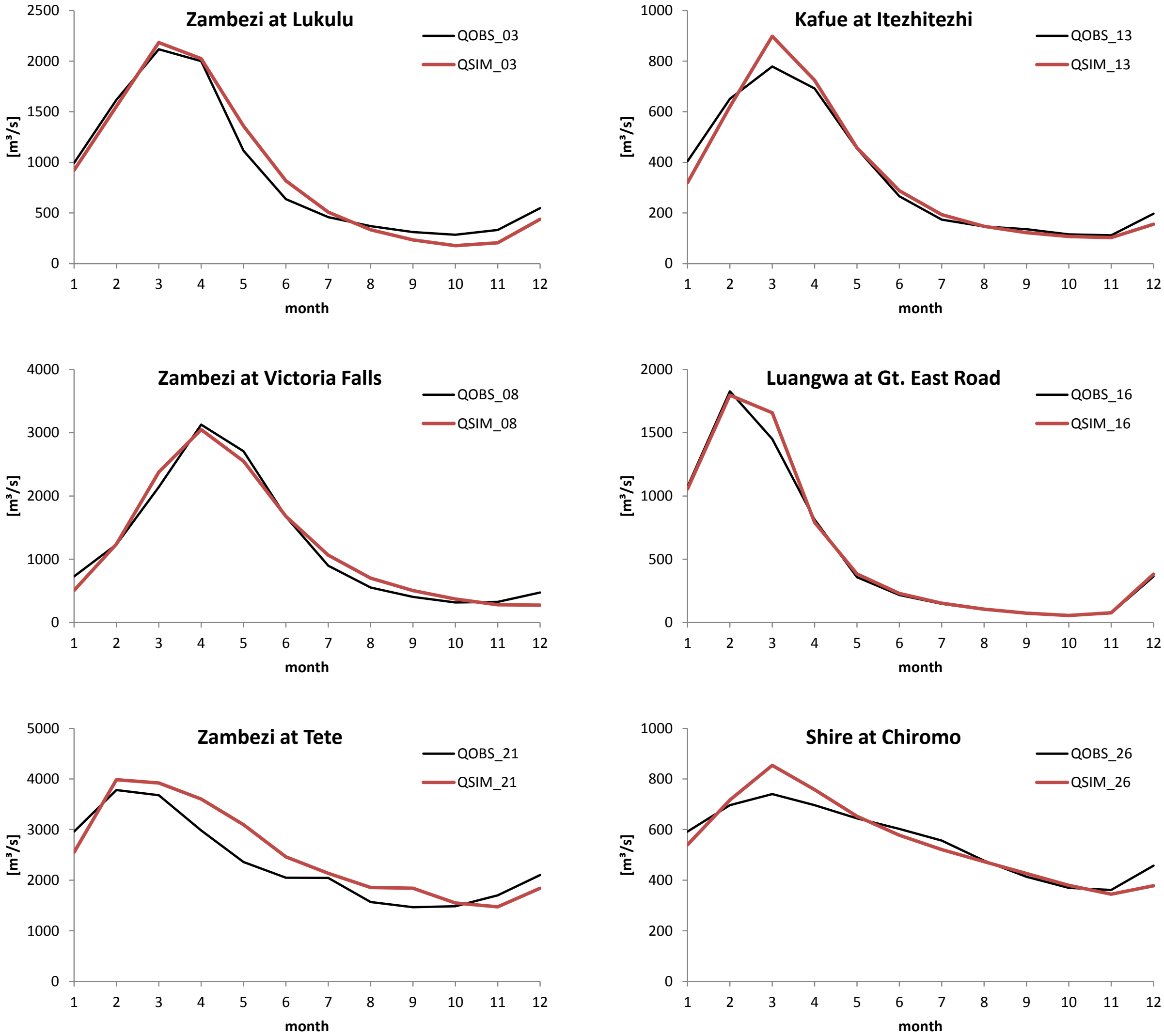

Figure 1-56: ***Simulated (red) and observed (black) seasonality in discharge at key locations in the Zambezi basin. Period 1961-1990.***

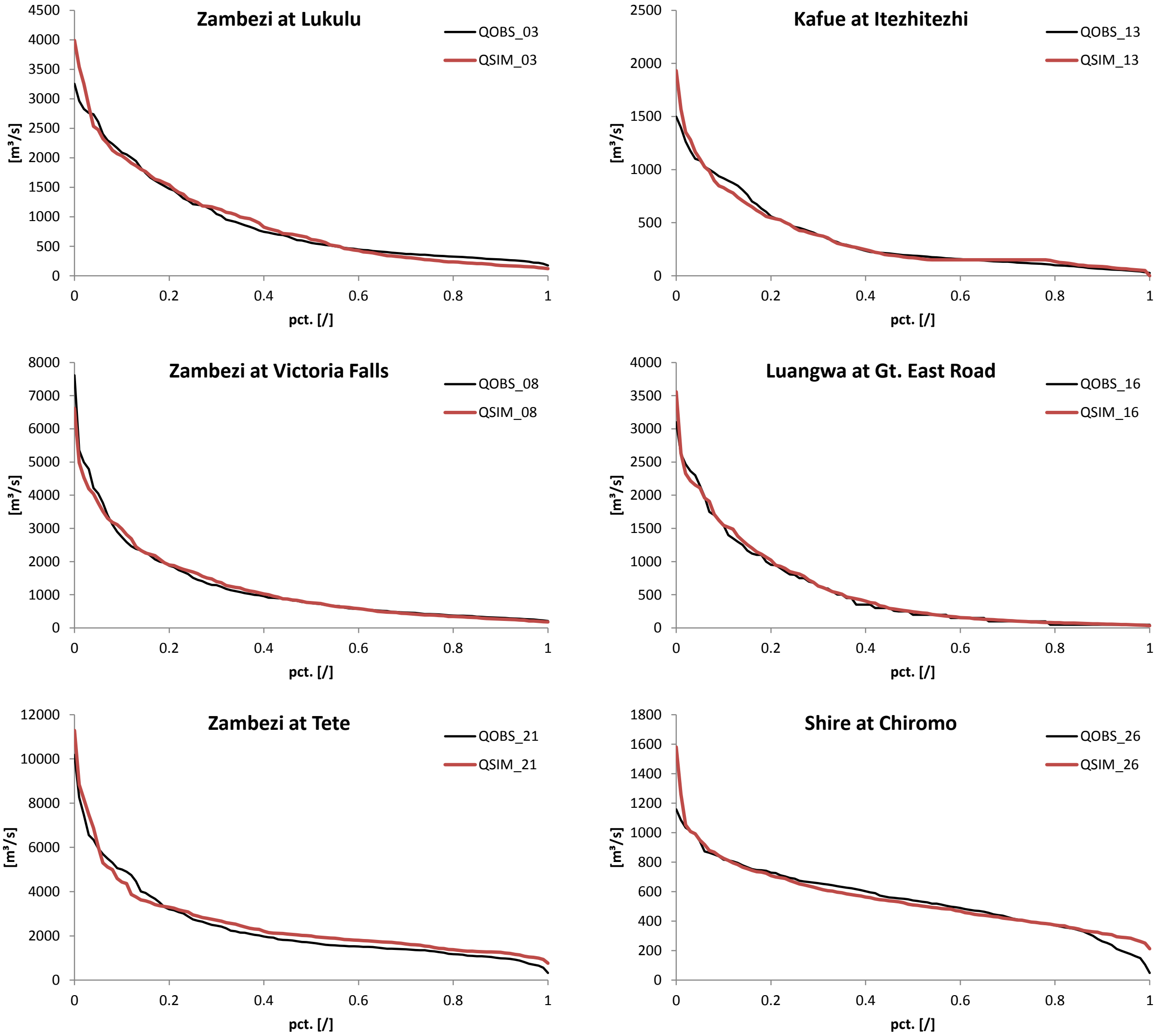

Figure 1-57: ***Simulated (red) and observed (black) monthly flow duration curve at key locations in the Zambezi basin. Period 1961-1990.***

Observed Shire low flows at Chiromo were caused by blockage of river flows during construction of Kamuzu Barrage in 1965 and other human interventions.

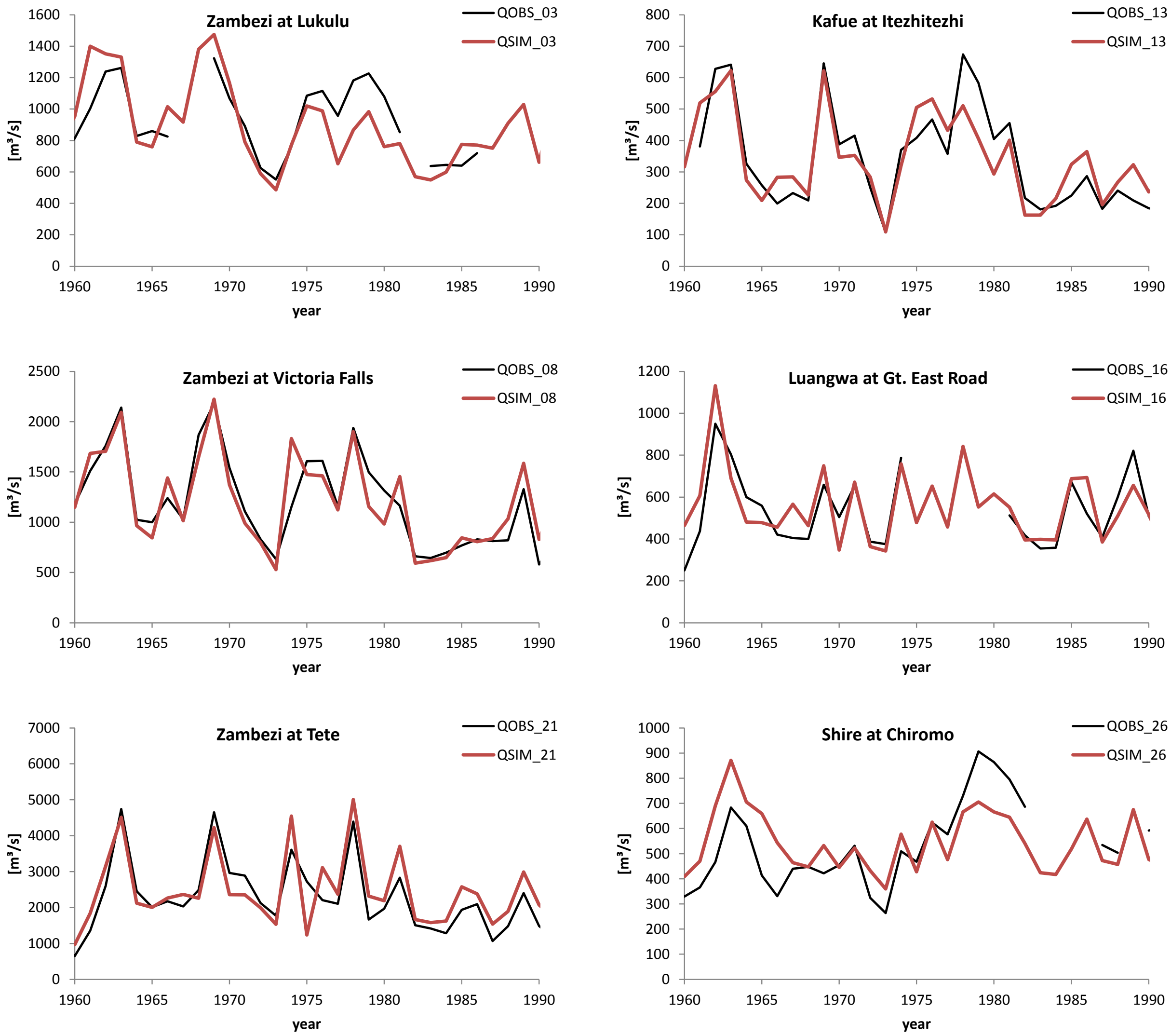

Figure 1-58: ***Simulated (red) and observed (black) annual discharge at key locations in the Zambezi basin.***

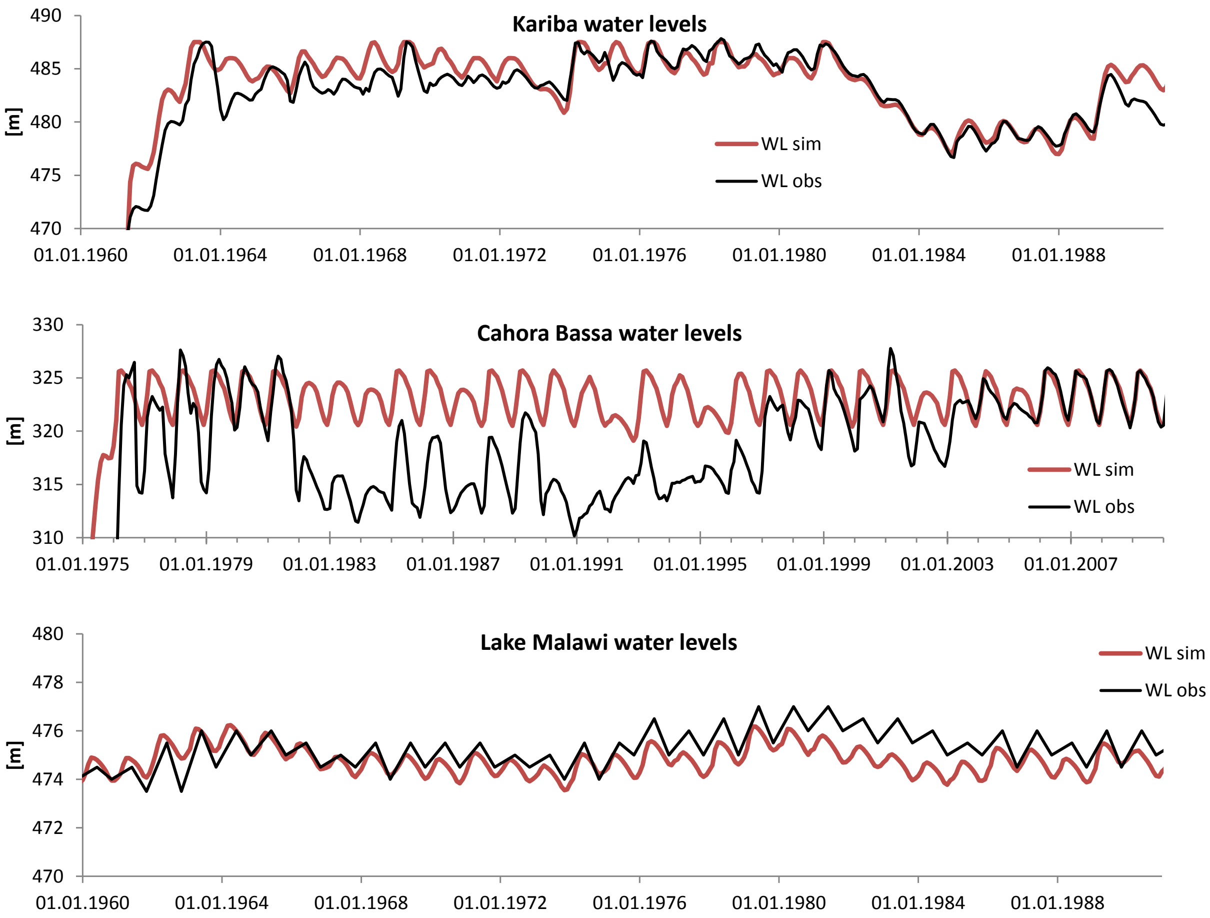

Figure 1-59: Simulated and observed water levels in Kariba reservoir (top), Cahora Bassa reservoir (middle) and Lake Malawi (bottom).

Observed Cahora Bassa water levels from 1981 to 1998 were affected by altered operations because transmission lines from the HPP were destroyed. Observed Lake Malawi water levels represent min/max levels manually digitized from the report of Beilfuss (2001).

1.6.3 User interface

The DSS uses open source technology and runs in web browsers, such as Google Chrome, Mozilla Firefox, or Internet Explorer. The user interface of the DSS was designed with an emphasis on the map of the Zambezi basin as the central focus. The map is linked to a dynamic database that manages all the data of the DSS. Access to the DSS is only possible via login with username and password, such that the database can store the current settings and modifications of each user in the DSS. Thus, if a user ends a session and logs in at a later time all data of the user of the last session are restored. Of course, multiple users can use the DSS at the same time.

This section gives a description of the main features of the user interface of the DSS.

Main view and map elements

Figure 1-60 shows the main view of the DSS after login of the user. The map of the Zambezi basin as well as GIS data and model topology are displayed in the center. In the upper right corner a panel offers several display options. The user can select one of the following base layers for display as background map.

- Open Street Map
- Google (Terrain)
- Google (Streets)
- Google (Hybrid)
- Google (Satellite)
- No Basemap

As overlay there are five different GIS layers available:

- Sub-basin boundaries
- Computation points
- Computation point network
- River network
- River network (detailed)

In the upper left corner of the map there are zoom and pan buttons for navigation within the map. Alternatively, the user can use the mouse for navigation. When hovering with the mouse over the map, the coordinates of the mouse cursor are displayed in latitude/longitude in the lower right corner of the map.

Depending on the zoom level, the base layer displays different details (from the continental to the street map level). *Figure* 1-61 to *Figure* 1-63 show example displays of base layers in the DSS for the Zambezi River and the confluence of Revubue River near Tete, Mozambique. Also displayed are the computation points of the model and the river network GIS layer.

The model elements of the water balance model (WBM) are displayed as sub-basins (see *Figure* 1-60) and the model elements of the water allocation model (WAM) are displayed as computation points (river points, uncontrolled reservoirs, controlled reservoirs) and computation point network (*Figure* 1-64).

The river network is a GIS layer that consists of 2259 river segments (6718 river segments for the detailed river network GIS layer). For each segment the upstream catchment area was pre-computed in GIS and is available for query in the DSS by mouse click on the river segment (*Figure* 1-65). The river network GIS layer includes all rivers with catchment areas greater than 10000 km^2. The detailed river network GIS layer includes all rivers with catchment areas greater than 1000 km^2.

Next to the map on the left side are a series of different modules, which offer the user different options to control the DSS. The following modules are available:

- Climate scenario
- Development scenario
- Run
- Analysis
- Help

The following sections describe these modules.

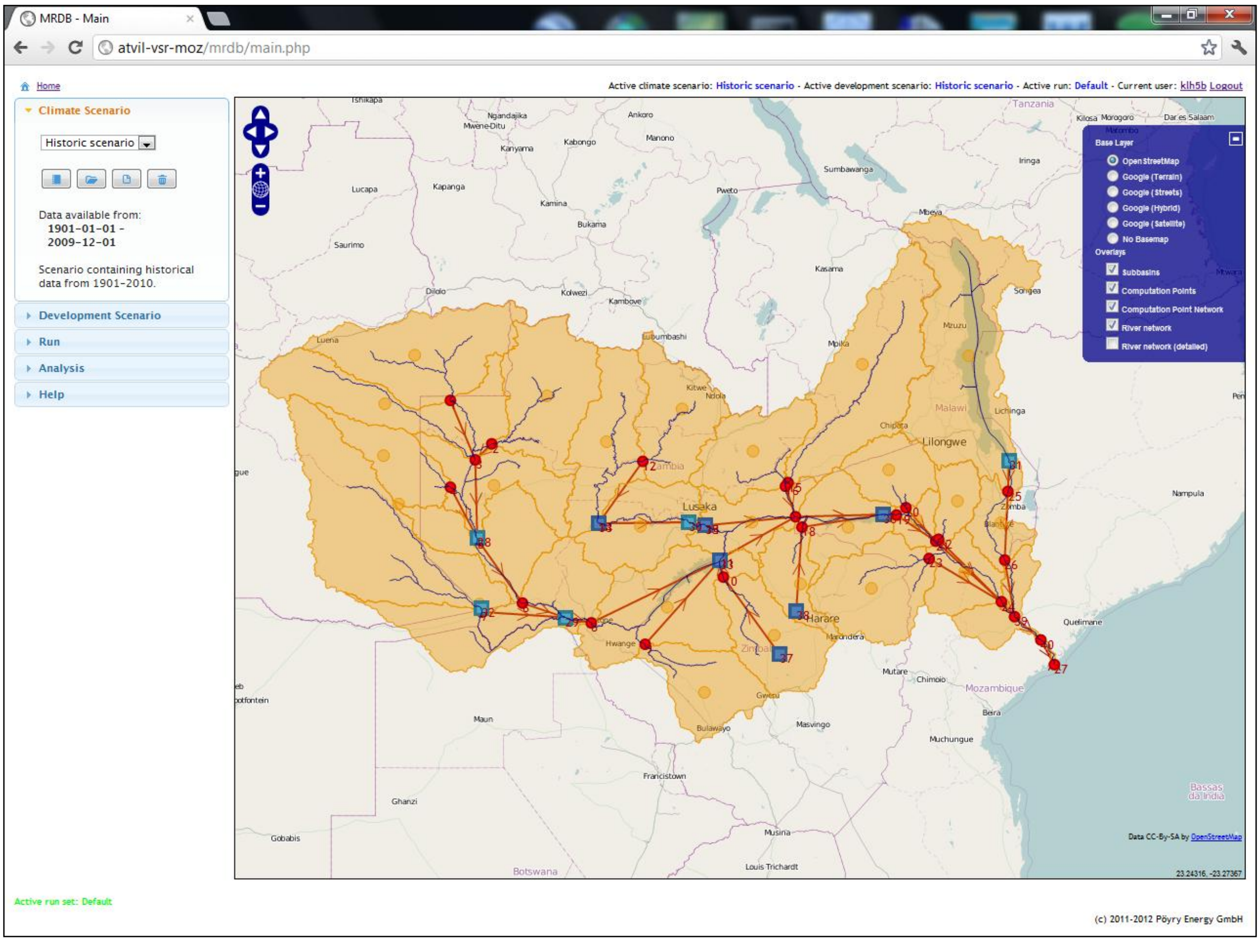

Figure 1-60: ***Main view of the DSS after login.***

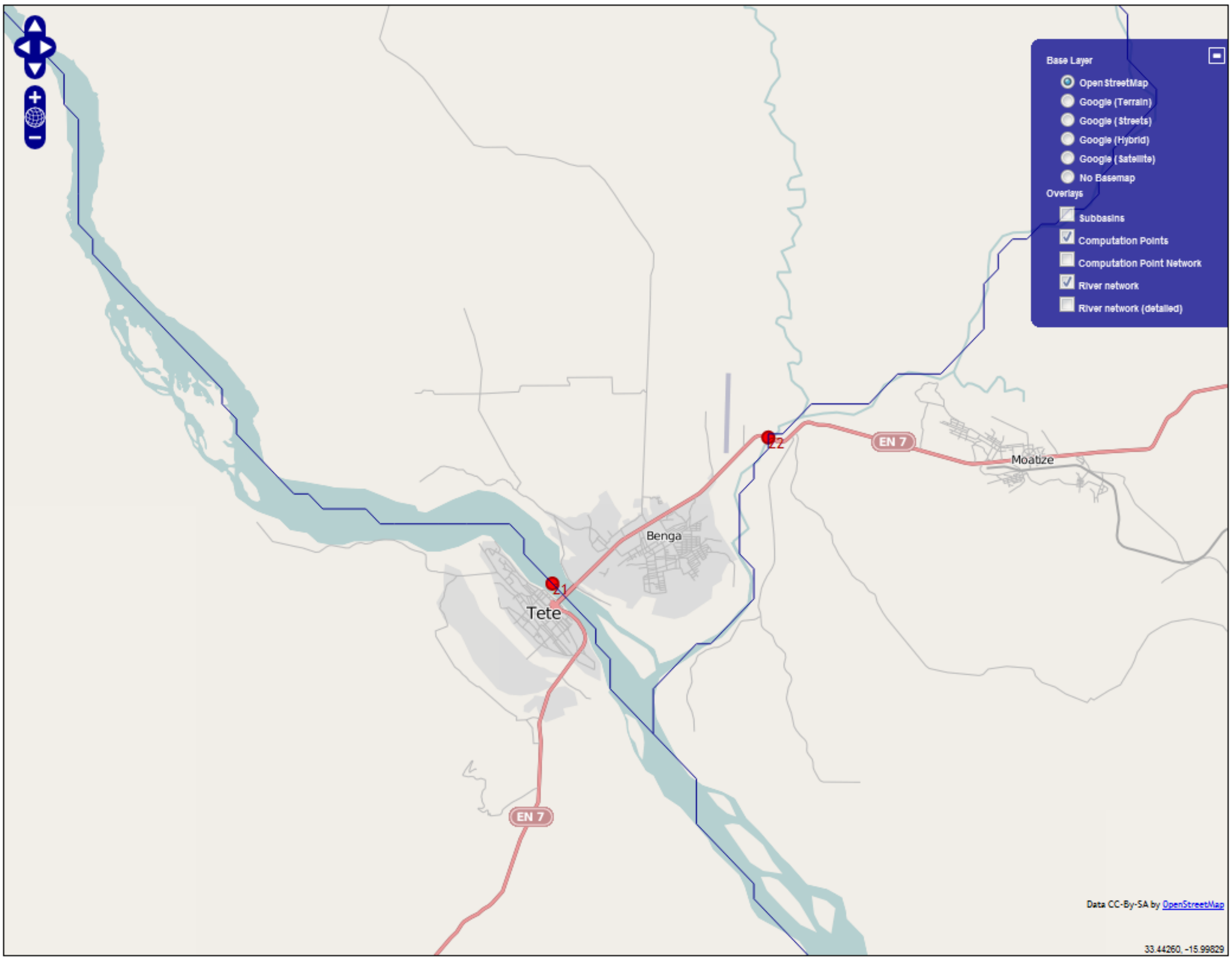

Figure 1-61: Example of Open Street Map displayed as base layer in the DSS. Zambezi River and confluence of Revubue River near Tete, Mozambique.

Red: computation points. Blue: river network.

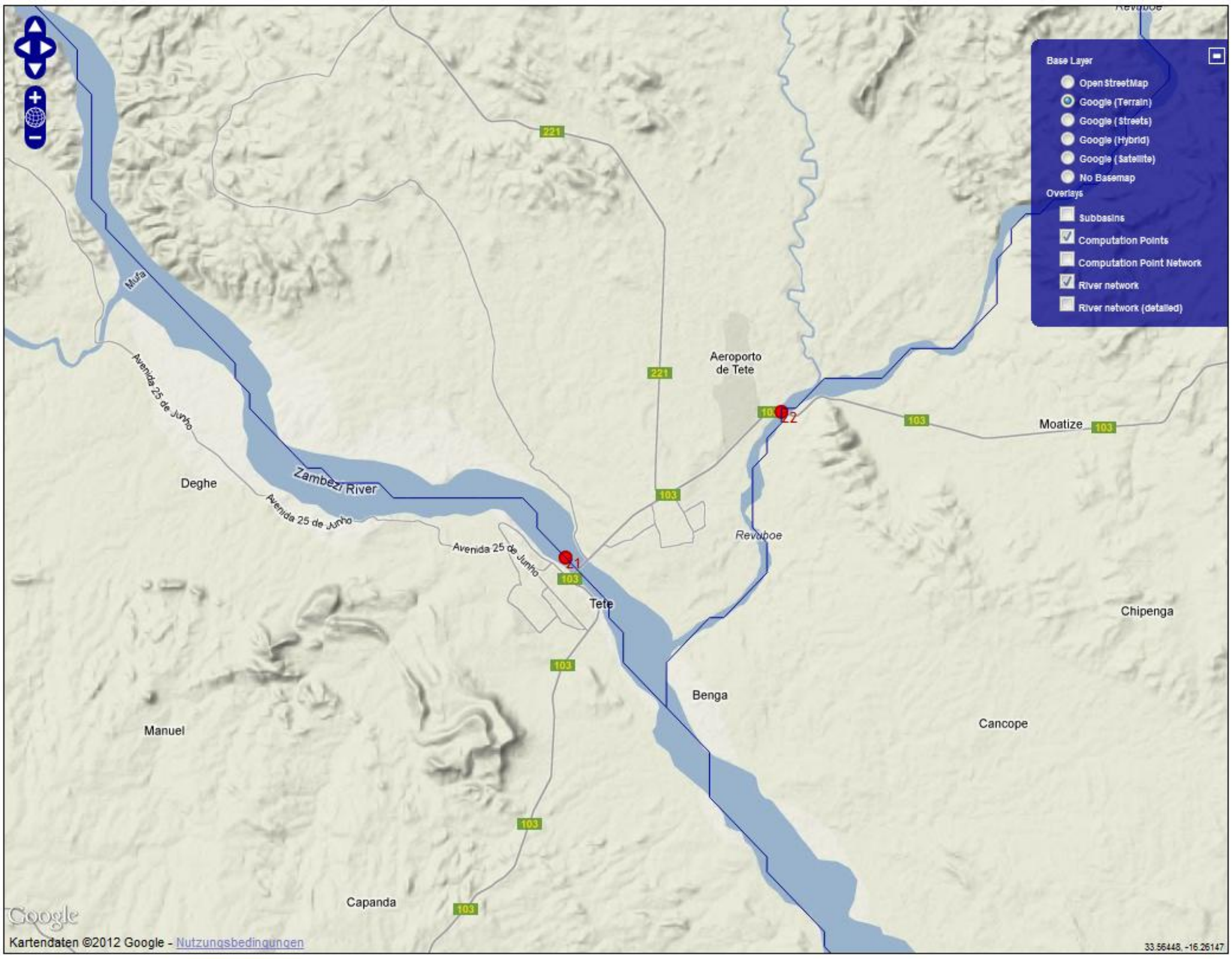

Figure 1-62: Example of Google (Terrain) displayed as base layer in the DSS. Zambezi River and confluence of Revubue River near Tete, Mozambique.

Red: computation points. Blue: river network.

Figure 1-63: Example of Google (Satellite) displayed as base layer in the DSS. Zambezi River and confluence of Revubue River near Tete, Mozambique.

Red: computation points. Blue: river network.

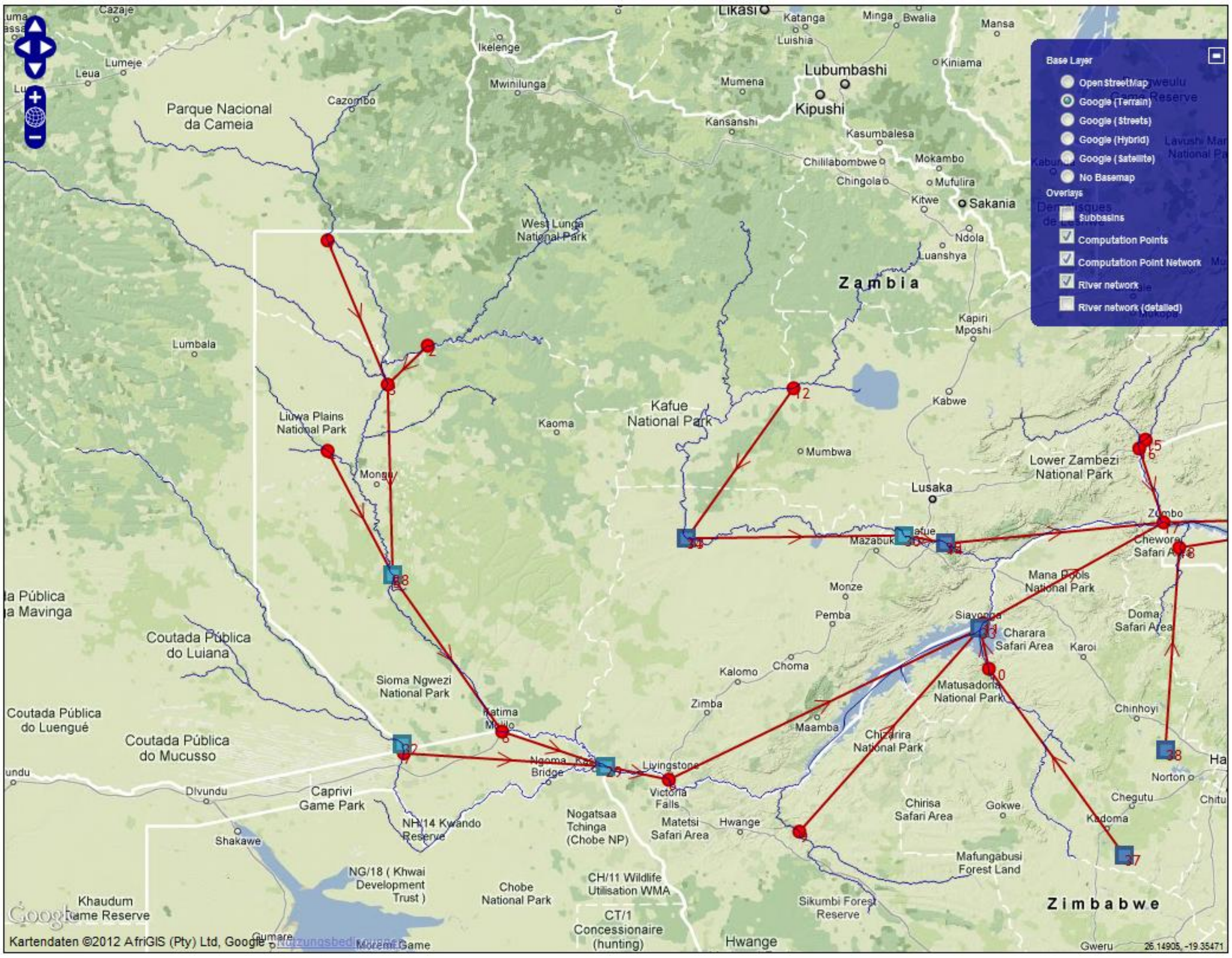

Figure 1-64: ***Elements of the water allocation module (WAM) displayed in the DSS for the upper Zambezi basin.***

Red circles: river points. Light blue boxes: uncontrolled reservoirs. Dark blue boxes: controlled reservoirs. Red lines: computation point network.

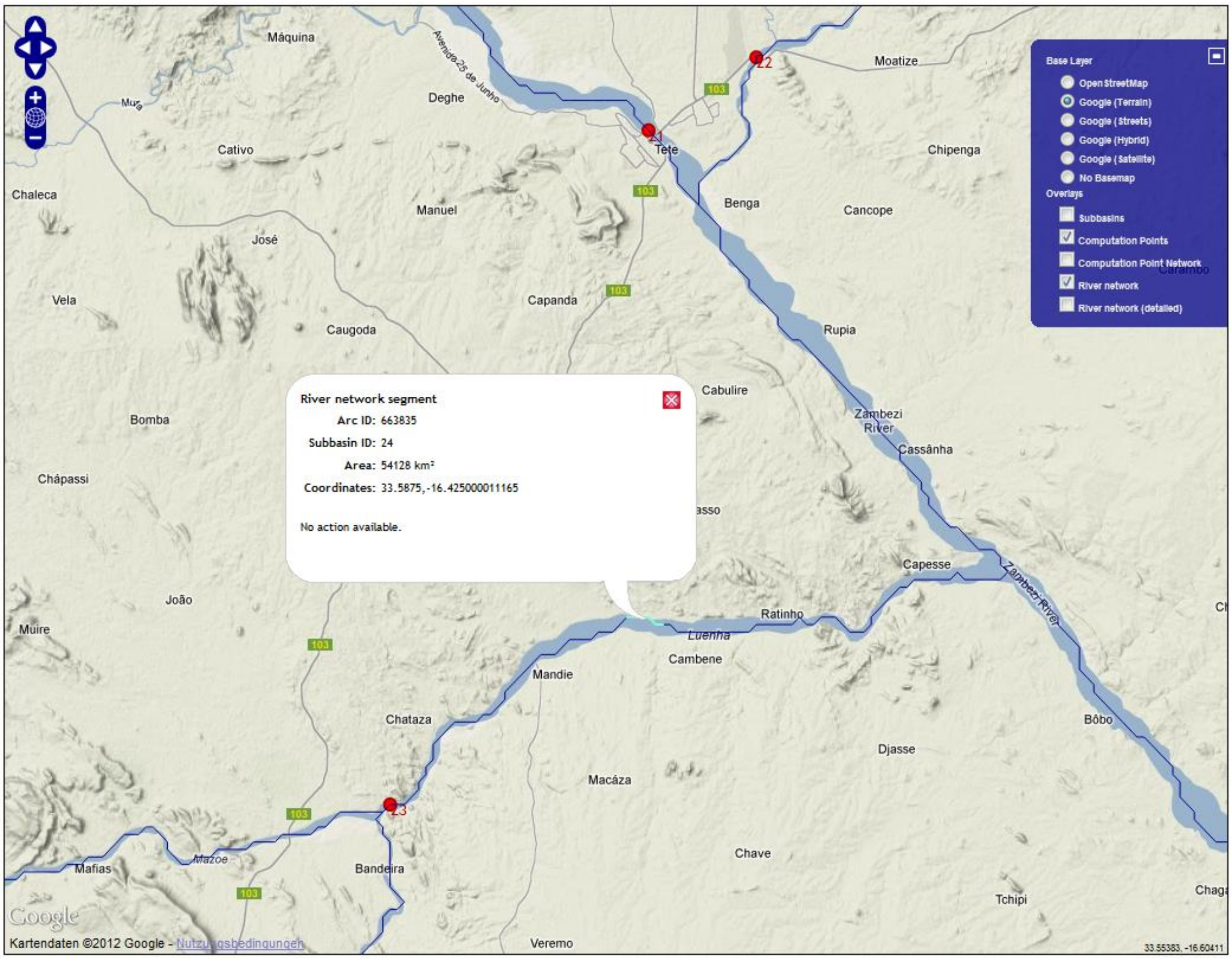

Figure** 1-65:* ***Query of upstream catchment area from the river network GIS layer in the DSS. Example for a downstream river segment of the Luenha River in Mozambique.

Climate scenario module

Figure 1-66 shows the user interface for controlling the climate scenario module of the DSS. The active climate scenario is displayed at the top in the drop-down list. Here, already existing other climate scenarios can be selected:

- Historic scenario: contains observed data 1950-2005 (1901-2009)
- CNCM3: contains data of the CNCM3/CNRM climate model 1960-2100
- ECHAM: contains data of the ECHAM climate model 1960-2100
- IPSL: contains data of the IPSL climate model 1960-2100
- user defined: any other user defined scenarios

The historic scenario contains data from 1901-2009, but due to low station coverage (see *Figure* 1-9) it is recommended to run historic simulations only for the period 1950-2005.

Four actions are available for the user via buttons:

- "Edit properties" button: Name and description of scenario can be edited.
- "Import subbasin data" button: External data can be imported to the DSS in csv format (available from e.g. Excel).
- "Create new climate scenario" button: A new scenario is created from the current scenario.

- "Delete climate scenario" button: User defined scenarios can be deleted, but not the four pre-defined scenarios.

Below these action buttons the data availability of the current climate scenario is summarized and a description of the scenario is displayed.

To query climate scenario data (precipitation, air temperature) the user has to mouse-click on the sub-basin of interest. The data display opens in a new tab-window (see "Analysis" module).

Figure 1-66: Climate scenario module of the DSS.

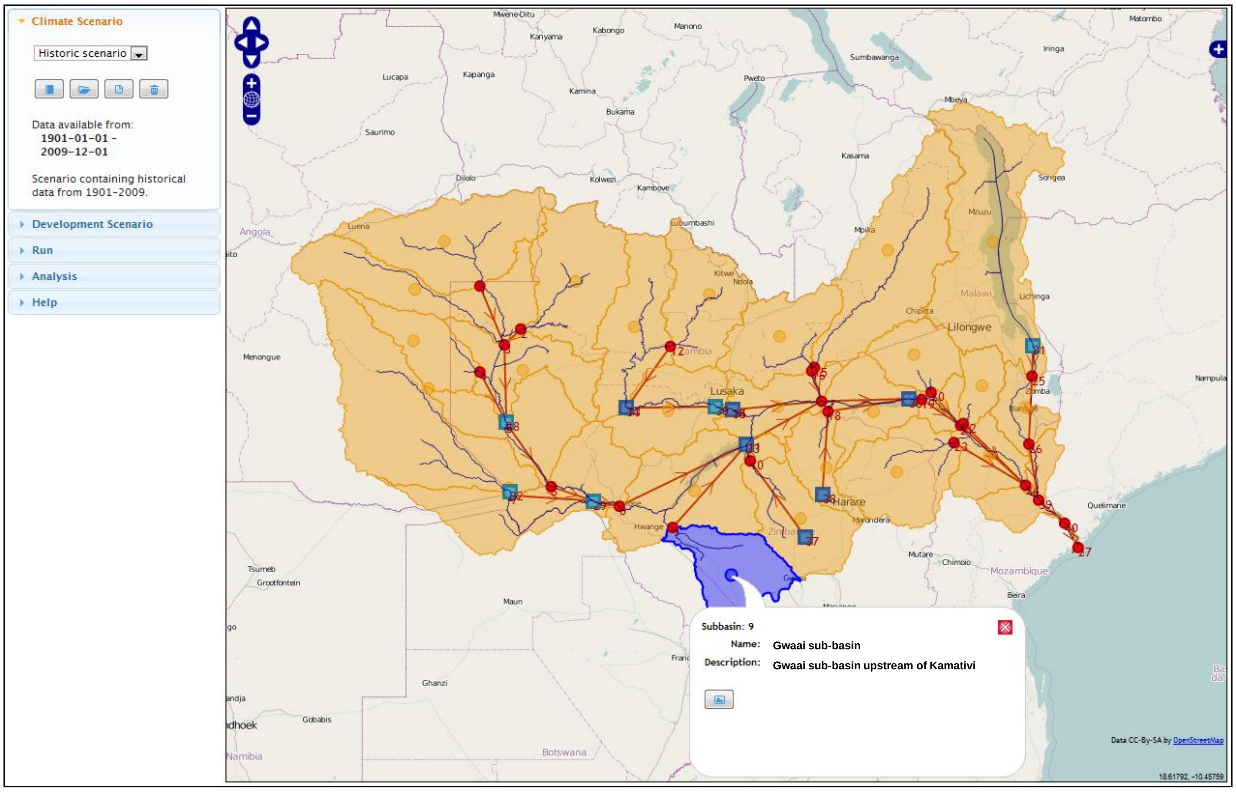

Figure 1-67: Querying climate scenario data by mouse click on sub-basins. Data display opens in new window.

Development scenario module

This module offers the user to specify the development scenario, including:

- new projects (dams)
- operation rules
- withdrawals (irrigation)

Figure 1-68 shows the user interface for controlling the development scenario module of the DSS. The active development scenario is displayed at the top in the drop-down list. Already existing, other development scenarios can be selected.

Four actions are available for the user via buttons:

- “Edit properties” button: Name and description of scenario can be edited.
- “Create new development scenario” button: A new scenario is created from the current scenario.
- “Delete development scenario” button: User defined scenarios can be deleted, but not pre-defined scenarios.
- “Refresh computation point network” button: Re-draws the display when editing the topology of the computation point network.

Below these action buttons a description of the scenario is displayed.

By mouse-clicks on elements displayed in the map several options become available, depending on the element.

By clicking on sub-basins, the model parameters of the water balance model (WBM) can be edited (*Figure* 1-69). Here, permission for such edits is limited to users with administrator rights, but not standard users.

By clicking on the river network new computation points can be added. After adding of a new computation point the user has to update the computation point network topology via the properties of the new computation point and any affected upstream computation points. The topology stores the downstream ID computation points. New computation points may represent river points, uncontrolled reservoirs or controlled reservoirs. River points can be inserted on the river network to query simulation results at locations of interests. New reservoirs require specification of properties before the model can be run. An example for a inserting a new river point shows *Figure* 1-70.

A mouse-click on computation points offers the user to either delete the computation point (only allowed for computation points that were added by the user) or to edit the attributes of the computation point. The available attributes depend on the type of computation point (river point, uncontrolled reservoir, controlled reservoir). An example for Cahora Bassa reservoir shows *Figure* 1-71. Geographic location, sub-basin location and total upstream catchment area are automatically queried by the DSS. However, important attributes to be entered by the user are:

- Topology (discharge to downstream computation point).
- Monthly values for environmental flows, diversions (withdrawals), elevation of guide curve and minimum/maximum levels for normal operation.
- Volume-area-elevation curve and the desired release (release can be set to zero if no information is available). The number of records of the volume-area-elevation curve can be selected by the user.

Figure 1-68: Development scenario module of the DSS.

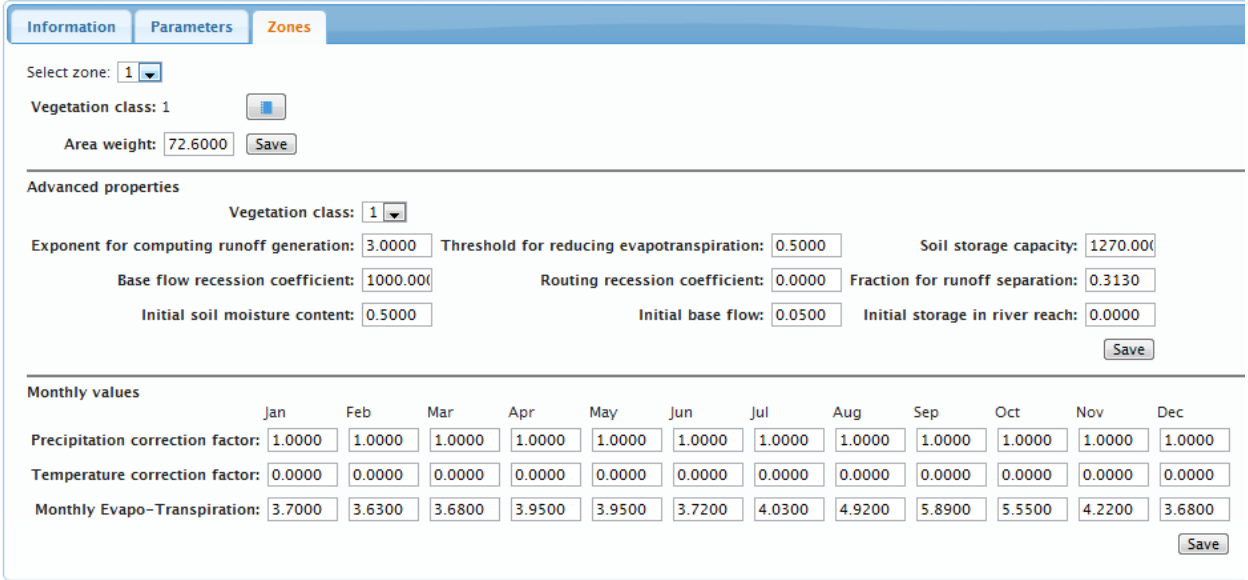

Figure 1-69: ***Interface for users with administrator permission to edit sub-basin parameters of the water balance model (WBM).***

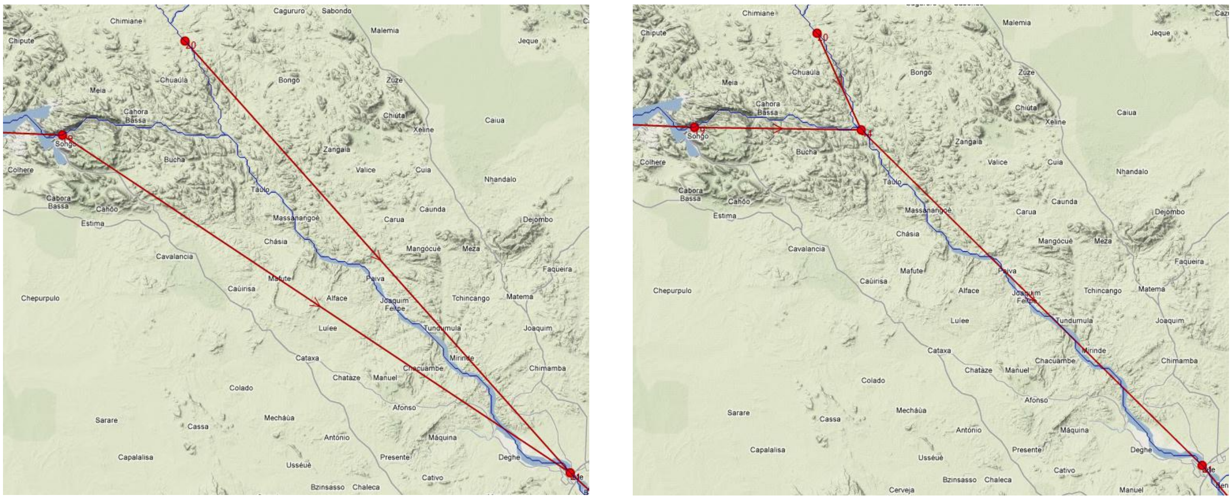

Figure 1-70: ***Refining the computation point network in the DSS. Example for inserting new computation point after confluence of Capoche River with Zambezi River below Cahora Bassa, Mozambique.***

Left: original computation point network. Right: refined computation point network.

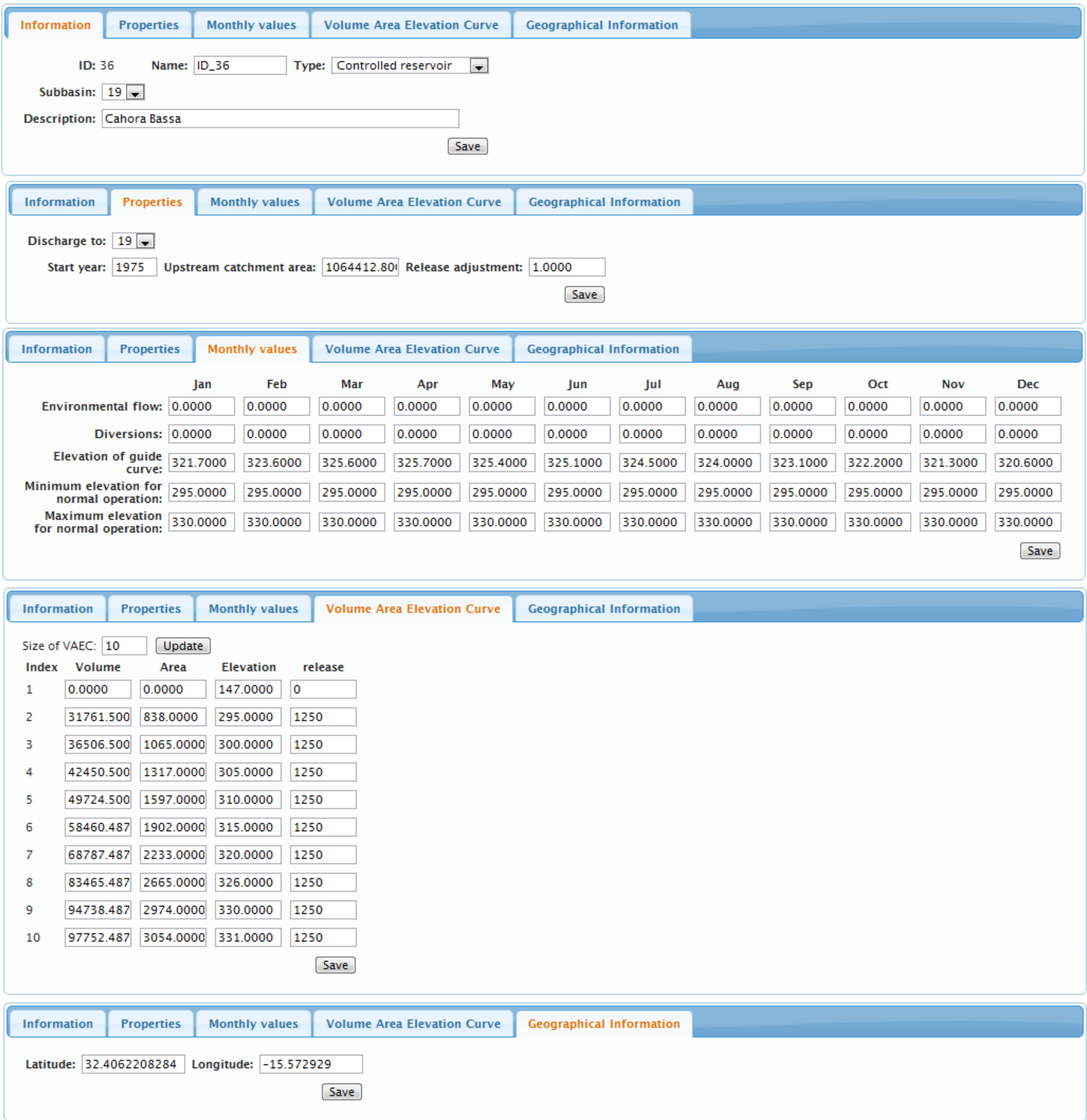

Figure 1-71: ***Specification of attributes for controlled reservoirs in the DSS. Example for Cahora Bassa reservoir.***

Run module

This module offers the user to edit specifications of a model "run". The main interface shows *Figure* 1-72. The active run is displayed in the drop-down menu at the top. The buttons offer the following options:

- "Start run" button: Executes a model run.
- "Edit properties" button: Definition of run properties.
- "Create new run" button: A new run is created from the current run.
- "Delete run" button: Removes the current run from the database.

When a run is executed with the "Start run" button the active climate scenario, the active development scenario and the settings of the active run are used. This information is also summarized at the top of display above the map. The run-status is displayed at the bottom left corner (either "running" or "finished"). After completion of a run (usually a few seconds) the simulation results are stored in the database of the DSS and can be queried by the user via the map, either by clicking on sub-basins or computation points (see "Analysis" module).

Properties of a run include (see also *Figure* 1-73):

- General information (name and description).
- Start and end date.
- Correction factors for precipitation and temperature.

The correction factors are used by the DSS to manipulate climate data during a simulation run, where the monthly correction factors are used for multiplication with precipitation and addition for temperature. Thus, the correction factors offer a quick and easy way of climate scenario sensitivity analysis. Questions such as, "What happens if precipitation decreases by 10% and temperature increases by 3°C compared to historic climate?" can be answered. Further, also climate model data can be further manipulated to answer questions such as, "What happens if warming is by 1°C larger than projected by climate model XY?" Of course, if detailed spatio-temporal patterns of climate scenarios are required, then these have to be provided via the climate scenario module of the DSS.

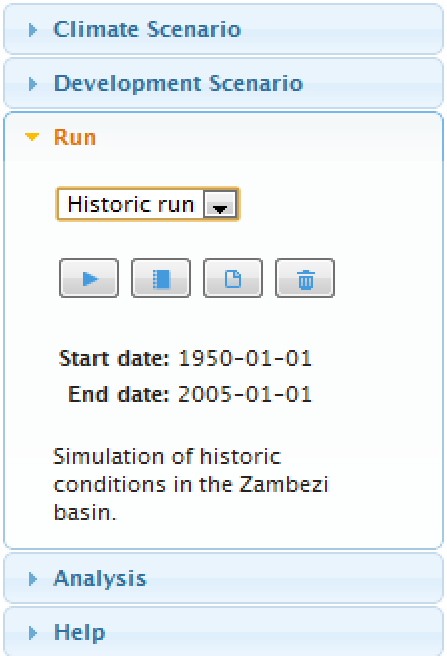

Figure 1-72: Run module of the DSS.

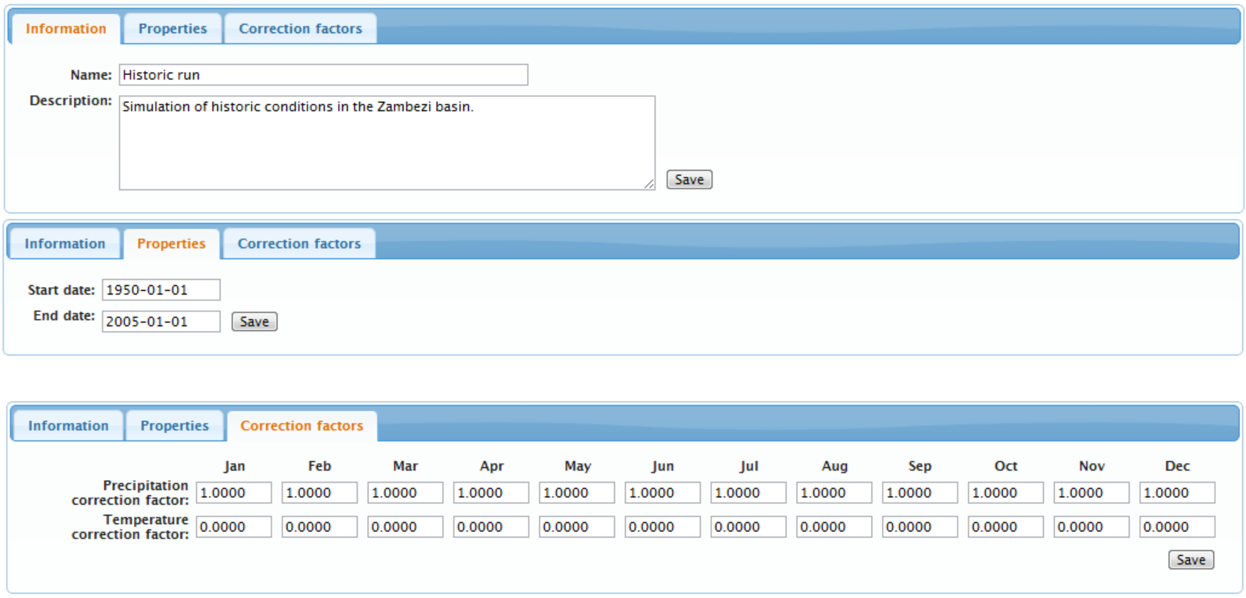

Figure 1-73: Specification of run attributes in the DSS.

Analysis module

This module offers comprehensive analysis of DSS data. There are several dimensions related to the analysis, as outlined below:

- 27 sub-basins
- 40+ computation points
- Different model runs (climate scenario, development scenario, simulation period)
- Large list of model variables.

For efficient analysis and comparison of such multi-dimensional data an analysis tool was designed for the DSS, which opens in a new tab-window. There are different ways of accessing the analysis tool. If accessed via the analysis module then the user has to select the spatial resolution of the data to be analyzed from the drop-down list (*Figure* 1-74). There are four different spatial resolutions:

- Computation points: Simulated variables of the water allocation model (WAM).
- Sub-basin local input: Original input data of the climate scenario.
- Sub-basin local output: Manipulated input data of the climate scenario (correction factors) and simulated variables of the water balance model (WBM).
- Sub-basin total output: Same variables as above, but aggregated over the full upstream catchment area.

When the analysis tool is accessed by mouse-clicks on map elements then the variables are directly displayed for this element (computation point, sub-basin local, or sub-basin total) for the active scenario (climate or run). If the analysis tool is accessed via the analysis module then the user adds data for display by the following hierarchy (left display area in “Series” panel, see e.g. *Figure* 1-75):

1. Select model run.
2. Select spatial location (computation point or sub-basin).
3. Select variable.

Additional variables can be subsequently added for different model runs, different locations or different types of variables. Thus, the analysis tool enables efficient comparisons, including:

- Upstream / downstream comparison.
- Comparison of different runs (scenarios).
- Comparison of different variables (e.g. runoff vs. precipitation).

Selected data can be displayed in different modes by specifying the temporal resolution and plot type under "Settings" on the left side of the display (*Figure* 1-75):

- Temporal resolution: monthly or annual.
- Plot type: time-series, mean, or duration curve.

Thus, there are six possible combinations for display:

- Monthly time-series.
- Annual time-series.
- Monthly mean.
- Annual mean.
- Monthly duration curve.
- Annual duration curve.

Time-series plots are used to analyze temporal dynamics and possible trends. The mouse can be used to zoom-in into sub-periods. This is especially useful when analyzing simulation results with long time-periods. Mean plots are used for plotting (monthly) seasonality or for computing long-term averages. Duration curve plots show the full distribution of the data, such that minimum, maximum, median, and percentiles (e.g. percentage of time flow threshold exceeded) are readily available for the user. This is useful when focusing e.g. on drought analysis. Also certain information about the general flood situation at large rivers can be obtained.

Figure 1-75 to *Figure* 1-78 show some example plots with the analysis tool. Plot data can be exported for post-processing in table format (*Figure* 1-79), such that the data can be further analyzed in e.g. Excel.

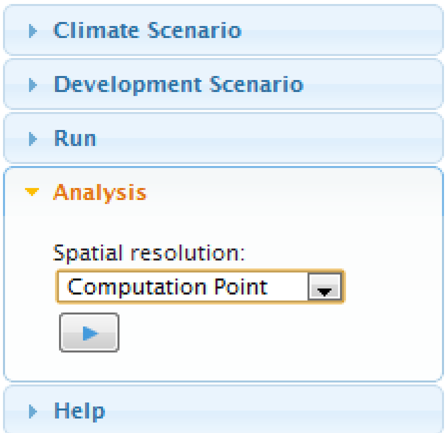

Figure 1-74: Analysis module of the DSS.

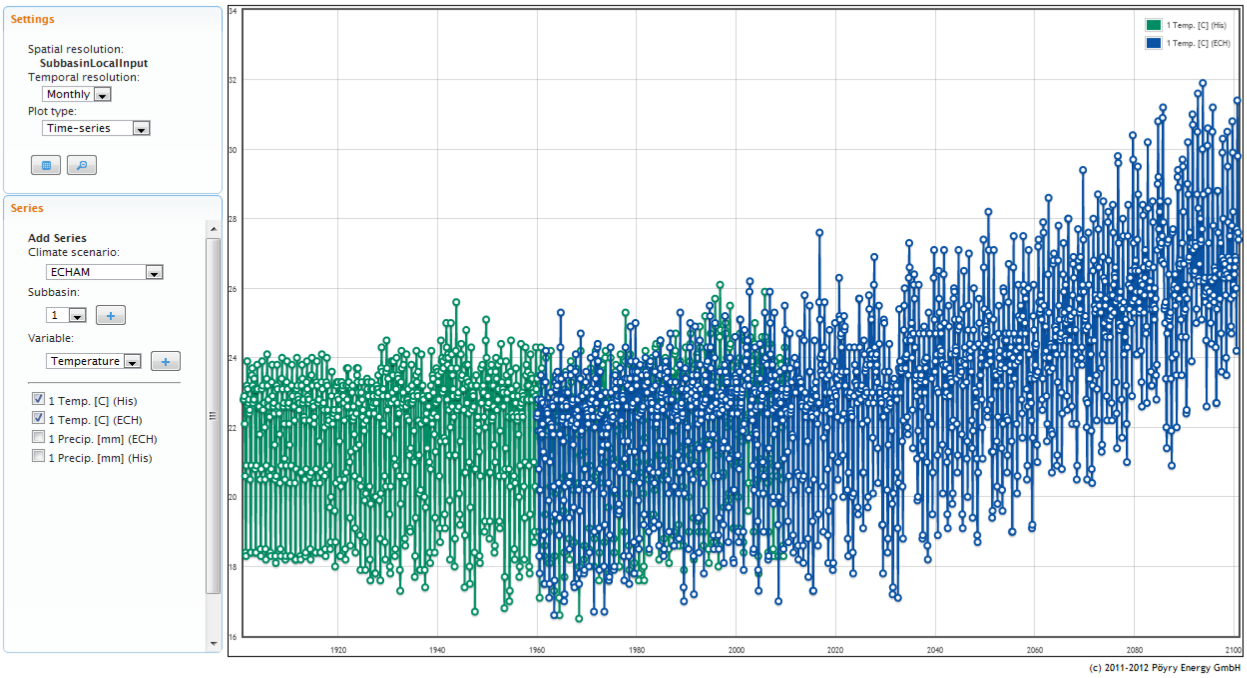

***Figure 1-75:** Analysis tool of the DSS. Example for monthly time-series of temperature.*

Historic (green) and projected (blue, ECHAM climate model).

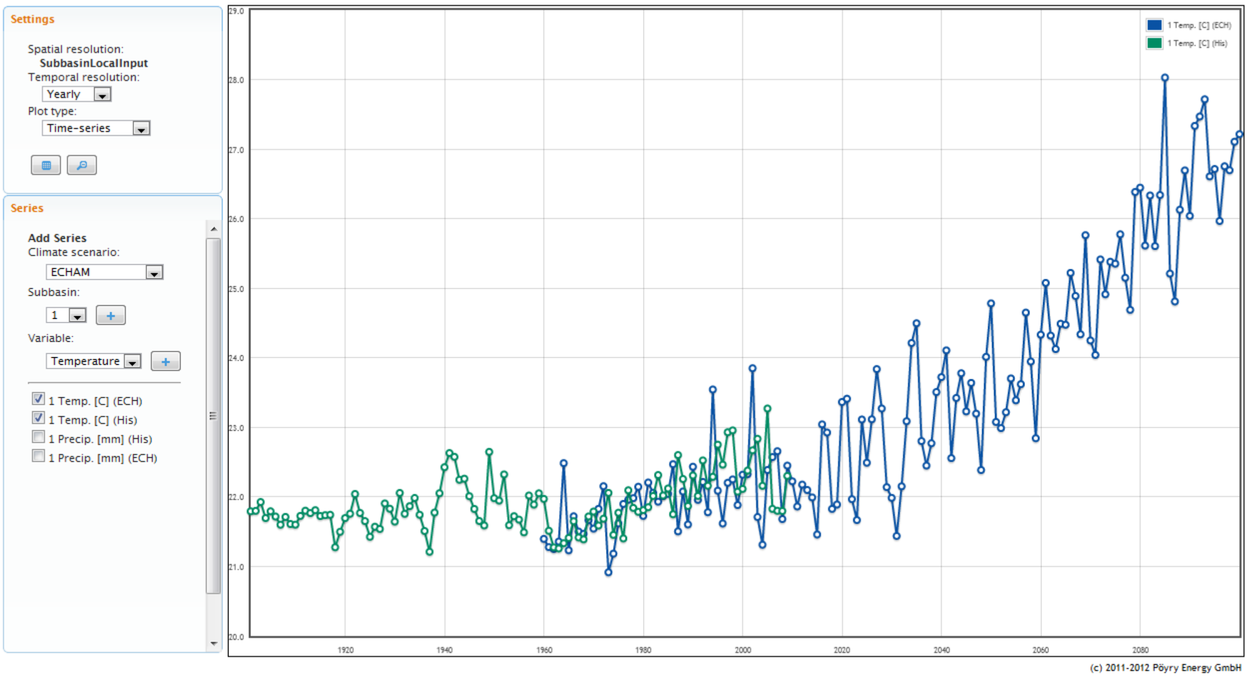

***Figure 1-76:** Analysis tool of the DSS. Example for annual time-series of temperature.*

Historic (green) and projected (blue, ECHAM climate model).

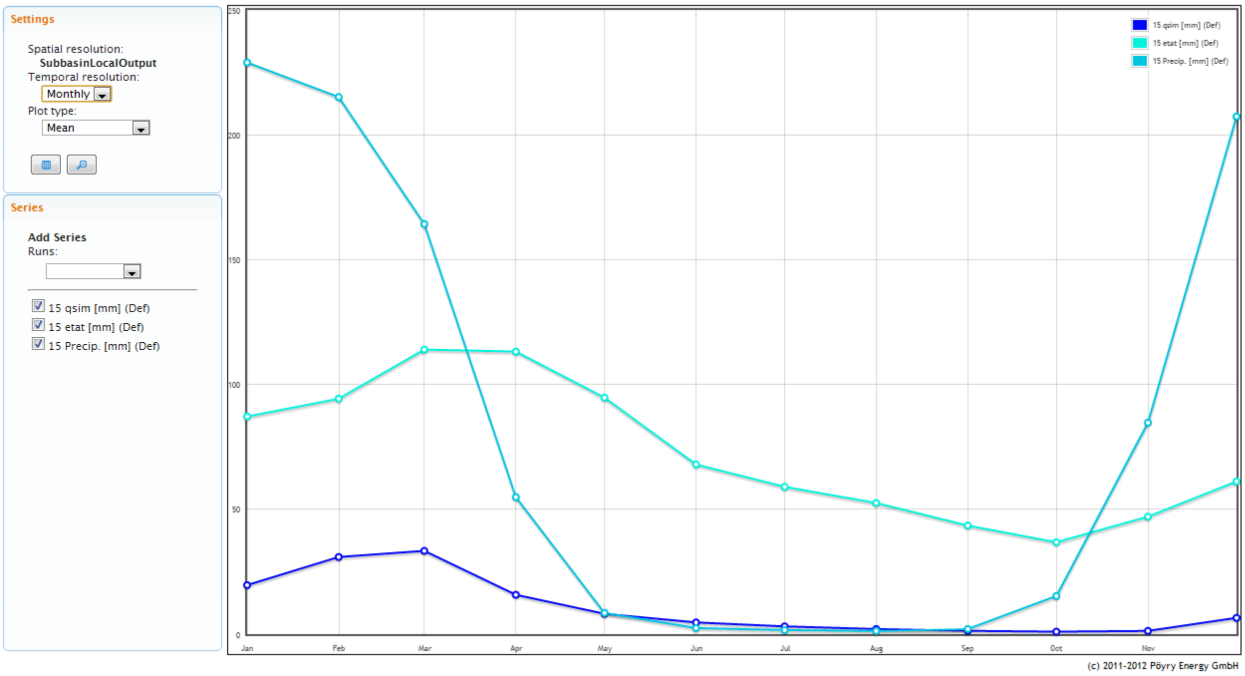

Figure 1-77: *Analysis tool of the DSS. Example for monthly mean of precipitation, evapotranspiration and runoff.*

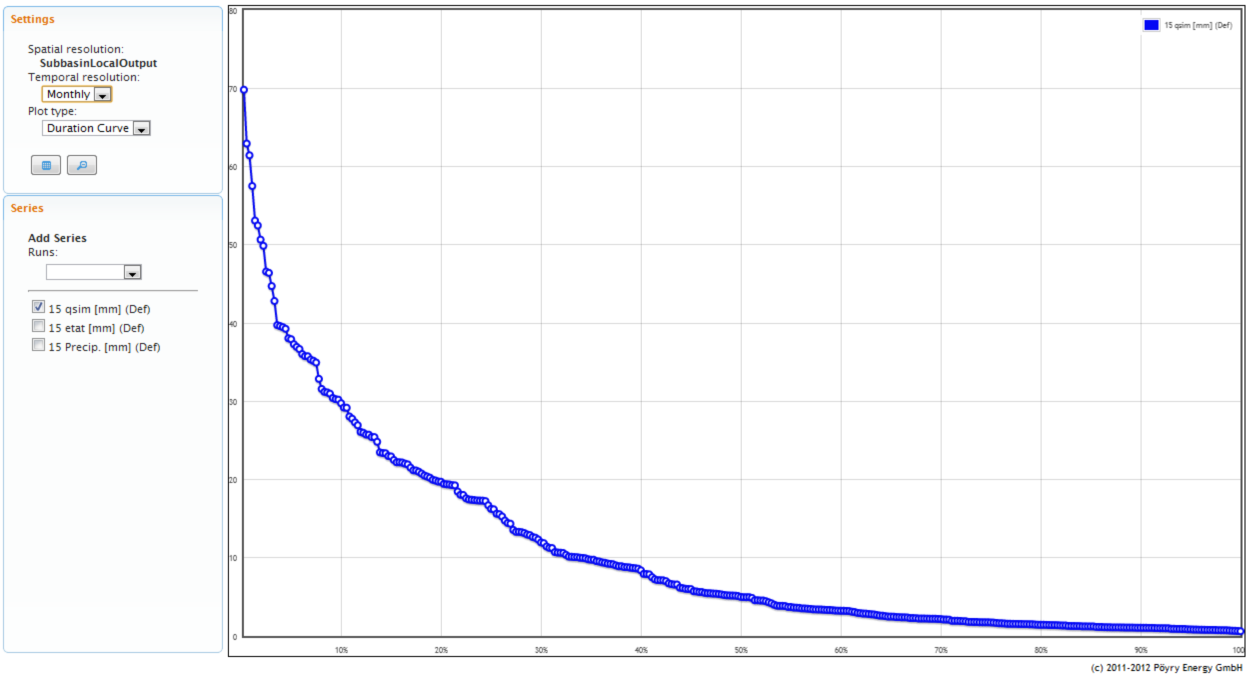

Figure 1-78: *Analysis tool of the DSS. Example for monthly duration curve of runoff.*

Date	15 qsim [mm] (Def)	15 etat [mm] (Def)	15 Precip. [mm] (Def)
1961-01-01	39.735	128.494	197.900
1961-02-01	49.868	112.102	202.300
1961-03-01	61.433	126.656	212.500
1961-04-01	26.082	132.647	64.000
1961-05-01	12.895	121.818	8.200
1961-06-01	7.141	86.427	3.000
1961-07-01	4.572	74.467	4.000
1961-08-01	2.863	64.187	1.500
1961-09-01	1.792	53.899	1.200
1961-10-01	1.278	43.123	12.500
1961-11-01	2.414	54.506	132.100
1961-12-01	17.303	75.485	306.800
1962-01-01	53.090	110.385	342.600
1962-02-01	62.934	112.676	246.300
1962-03-01	69.808	125.047	219.700
1962-04-01	31.133	131.124	71.000
1962-05-01	14.351	118.786	2.400
1962-06-01	7.923	89.733	1.100
1962-07-01	4.963	77.535	1.500
1962-08-01	3.110	69.270	1.800
1962-09-01	1.924	55.905	1.200
1962-10-01	1.386	45.561	15.500
1962-11-01	1.943	53.736	104.100
1962-12-01	9.741	68.208	238.500

Figure 1-79: Example for export table from the analysis tool of the DSS.

Help module

An online user's manual (pdf document) can be accessed via the help module. The user's manual explains all aspects of the DSS in detail, such that also non-experienced users can use the DSS.

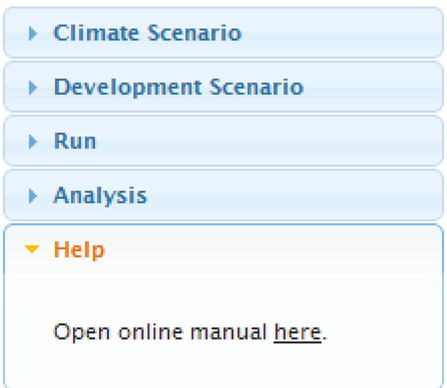

Figure 1-80: Help module of the DSS.

Administration module

Users with administrator permission can open the administration module by clicking on the user name in the upper right corner of the screen. The administration module offers basic tools for managing user accounts (passwords, permissions, etc.), as outlined in *Figure* 1-81. The administrator can create new users and also set user created scenarios (climate scenarios, development scenarios and runs) to "public", such that other users can continue working with these scenarios.

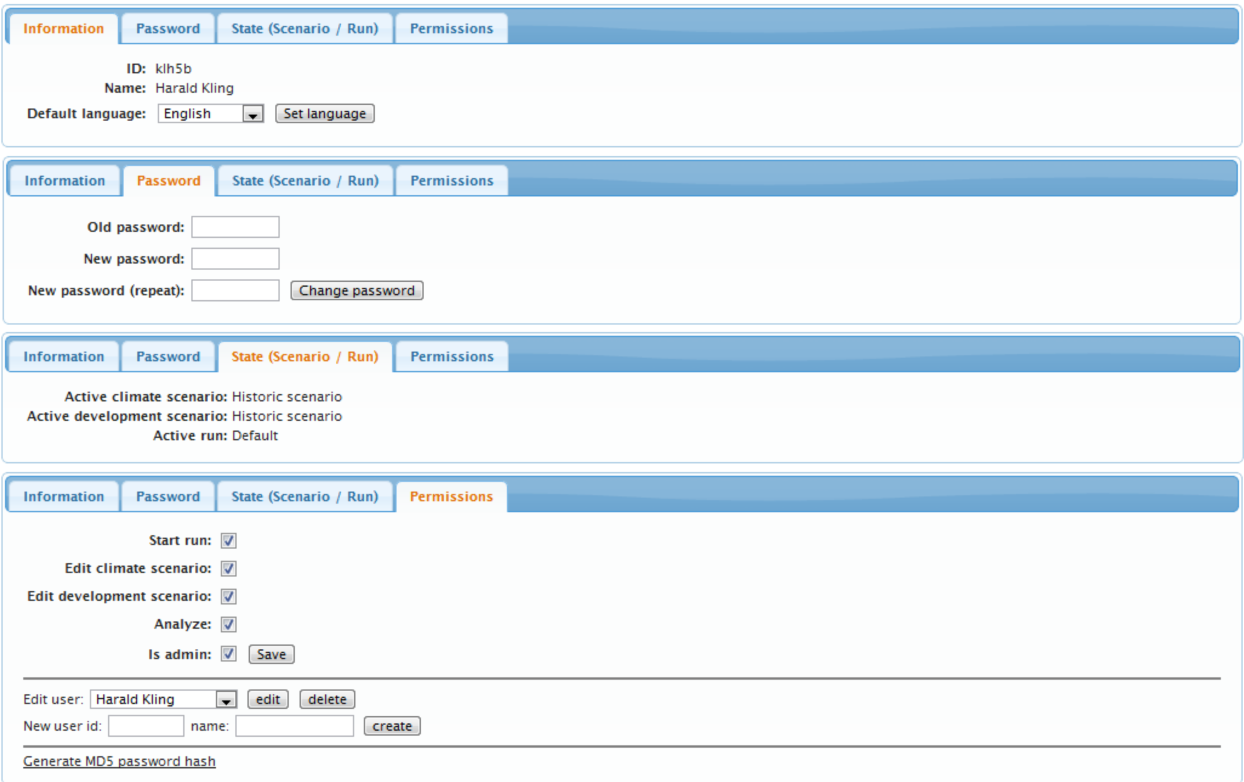

Figure 1-81: Administrator tools for managing user accounts in the DSS.

1.6.4 Application examples

The DSS can be used for various different types of analysis, as summarized in the schematic of *Figure* 1-82. This enables the user to ask what-if questions such as, "What happens if the climate changes?" or "What happens if dams or irrigation projects are developed?" It is also possible to look at the impact of a change in reservoir operation rules. In addition to these scenario analyses the DSS also offers a comprehensive analysis of the current state of the hydrology of the basin. Hence, the water balance of the whole basin or sub-basins can be assessed.

This section presents a few application examples of the DSS. Similar analyses could be conducted for different time-periods, sub-basins, climate scenarios or development scenarios. The examples include:

- Water balance study
- Inflow/Outflow analysis of reservoirs and lakes
- Climate change impact study
- Irrigation development impact assessment

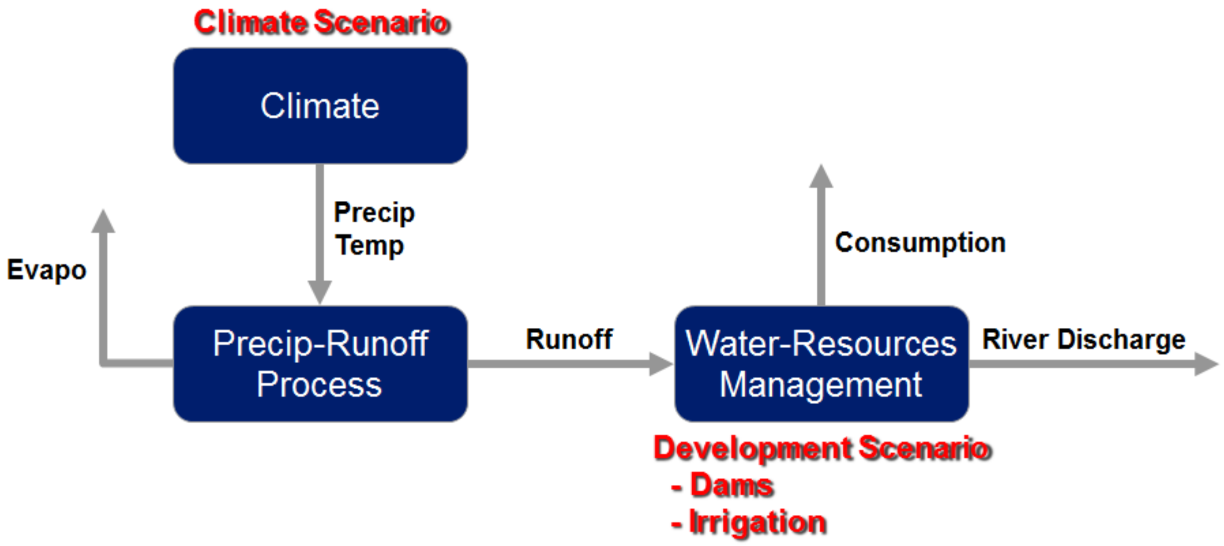

***Figure** 1-82: General concept of scenario analysis with the DSS.*

Water balance study

This example studies the water balance of the period 1961-1990 in the upper Luangwa River. The water balance is important information about the hydrology of a river basin. The basic water balance equation is defined as:

Precip = Runoff + Evapo + ΔS

where

Precip is precipitation [mm]
Runoff is runoff-depth [mm]
Evapo is actual evapotranspiration [mm]
ΔS is storage change (changes in soil moisture and ground water) [mm]

Figure 1-84 shows the seasonal water balance of the Luangwa River as simulated by the DSS. Precipitation occurs between November and March and is close to zero between May and September. During the rainy season storage change is positive, which means that soil moisture and groundwater storage are replenished. During the dry season storage change is negative due to evapotranspiration, which causes a drying of the soils. Runoff is the smallest component of the water balance and is close to zero during the dry season. In November and December precipitation is mainly stored (positive storage change) and runoff only becomes significant between January and April.

The mean annual water balance of the Luangwa basin is obtained by aggregating the monthly values. Mean annual precipitation is computed to be 974 mm, of which 854 mm are lost to the atmosphere via evapotranspiration and only 122 mm are runoff. This corresponds to a runoff-coefficient of 13 %. Annual storage change is insignificant (-2 mm).

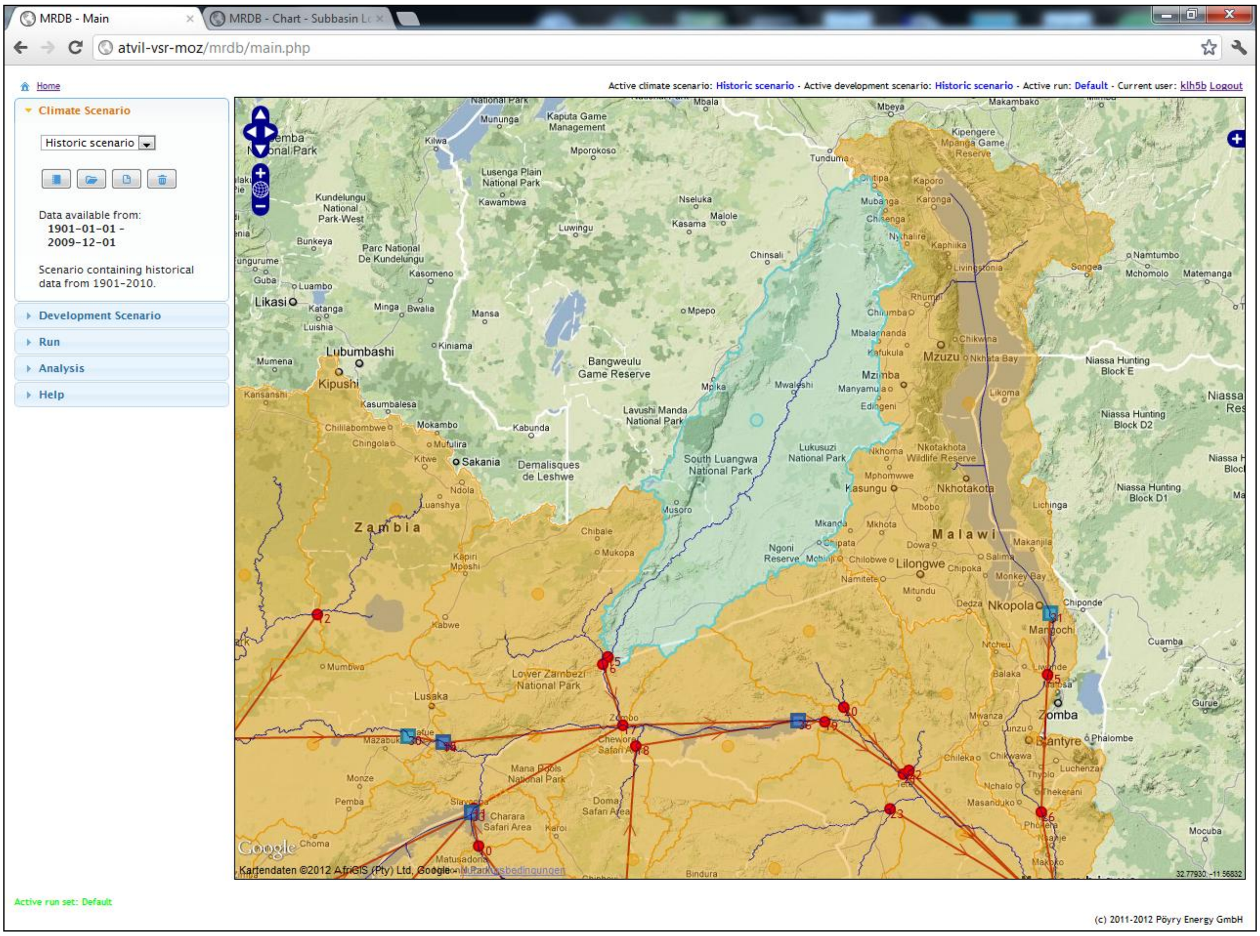

Figure 1-83: Upper Luangwa River basin in the DSS.

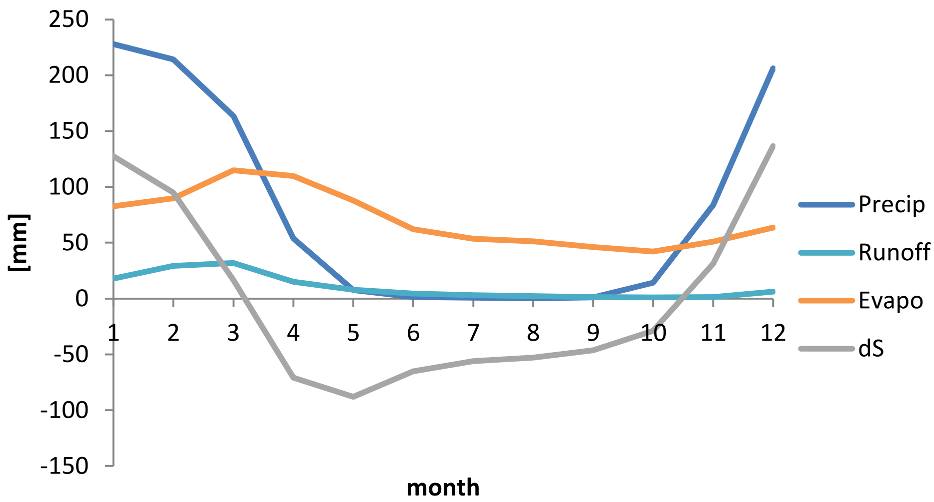

Figure 1-84: Seasonal water balance of the upper Luangwa River. Period 1961-1990.

Inflow/Outflow analysis of reservoirs and lakes

The DSS offers the user to query inflow and outflow fluxes of reservoirs. These fluxes include:

- upstream inflow (discharge at upstream computation points)
- lateral inflow (runoff from intermediate sub-catchment)
- precipitation on water body
- evaporation from water body
- diversion from reservoir (net-consumption)
- outflow (release)

As an example, the inflow and outflow fluxes of Cahora Bassa reservoir are analyzed for the period 1980 to 1990. In the current set-up of the DSS there are two upstream computation points (CP 17 Zambezi downstream Luangwa confluence and CP 18 Panhane River, see *Figure* 1-85) and there were no diversions during 1980-1990. The mean inflow and outflow fluxes of Cahora Bassa simulated by the DSS for 1980-1990 are given below:

- 1869 m^3/s upstream inflow
- 32 m^3/s lateral inflow
- 64 m^3/s precipitation on water body
- 122 m^3/s evaporation from water body
- 1835 m^3/s outflow

These numbers are completely different when e.g. analyzing the much larger Lake Malawi (*Figure* 1-86). Here the precipitation on and evaporation from the water body are larger than the lateral inflow and outflow. The mean inflow and outflow fluxes of Lake Malawi simulated by the DSS for 1980-1990 are as follows:

- 0 m^3/s upstream inflow (there is no upstream sub-basin)
- 773 m^3/s lateral inflow
- 1132 m^3/s precipitation on water body
- 1577 m^3/s evaporation from water body
- 416 m^3/s outflow

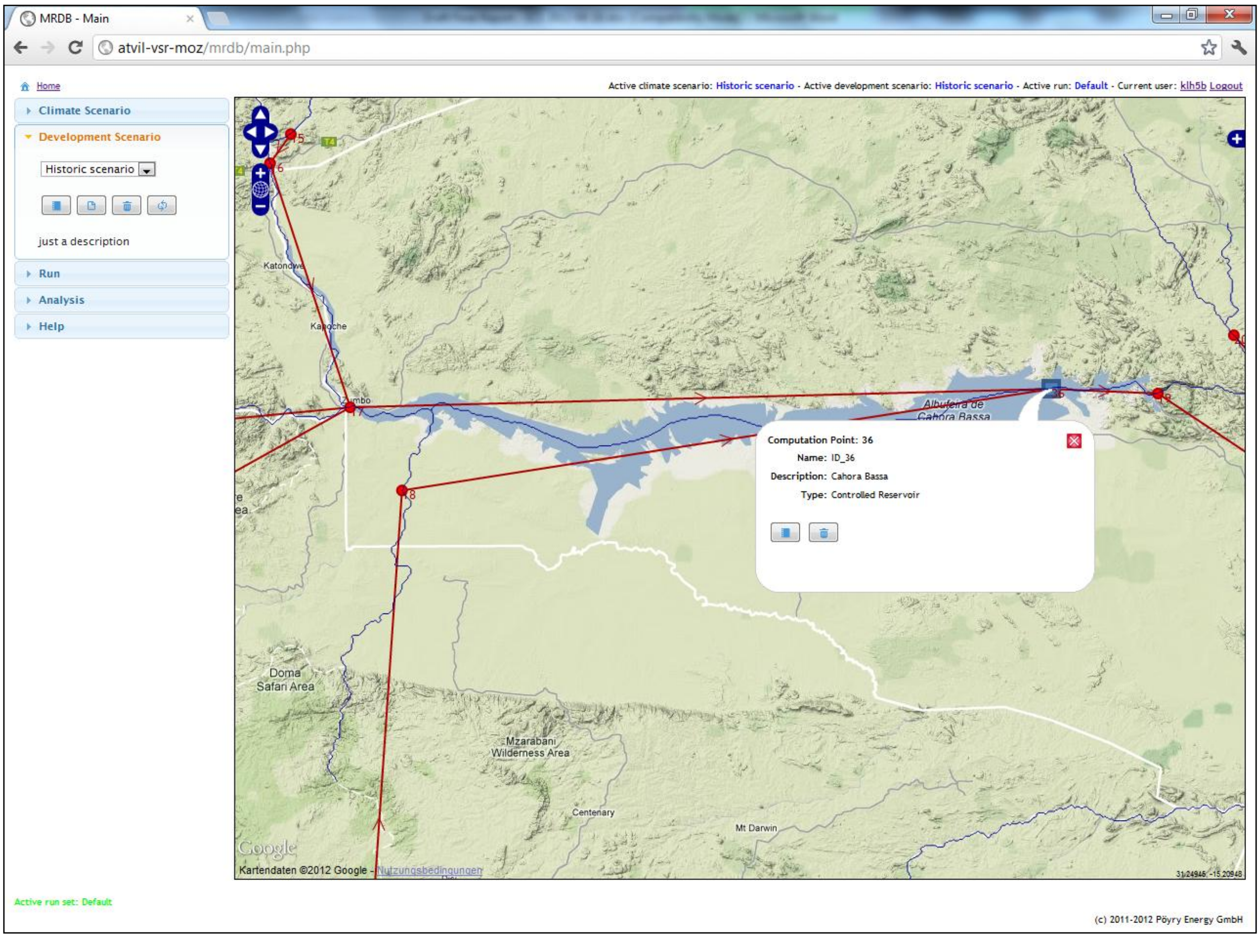

Figure 1-85: Cahora Bassa reservoir in the DSS.

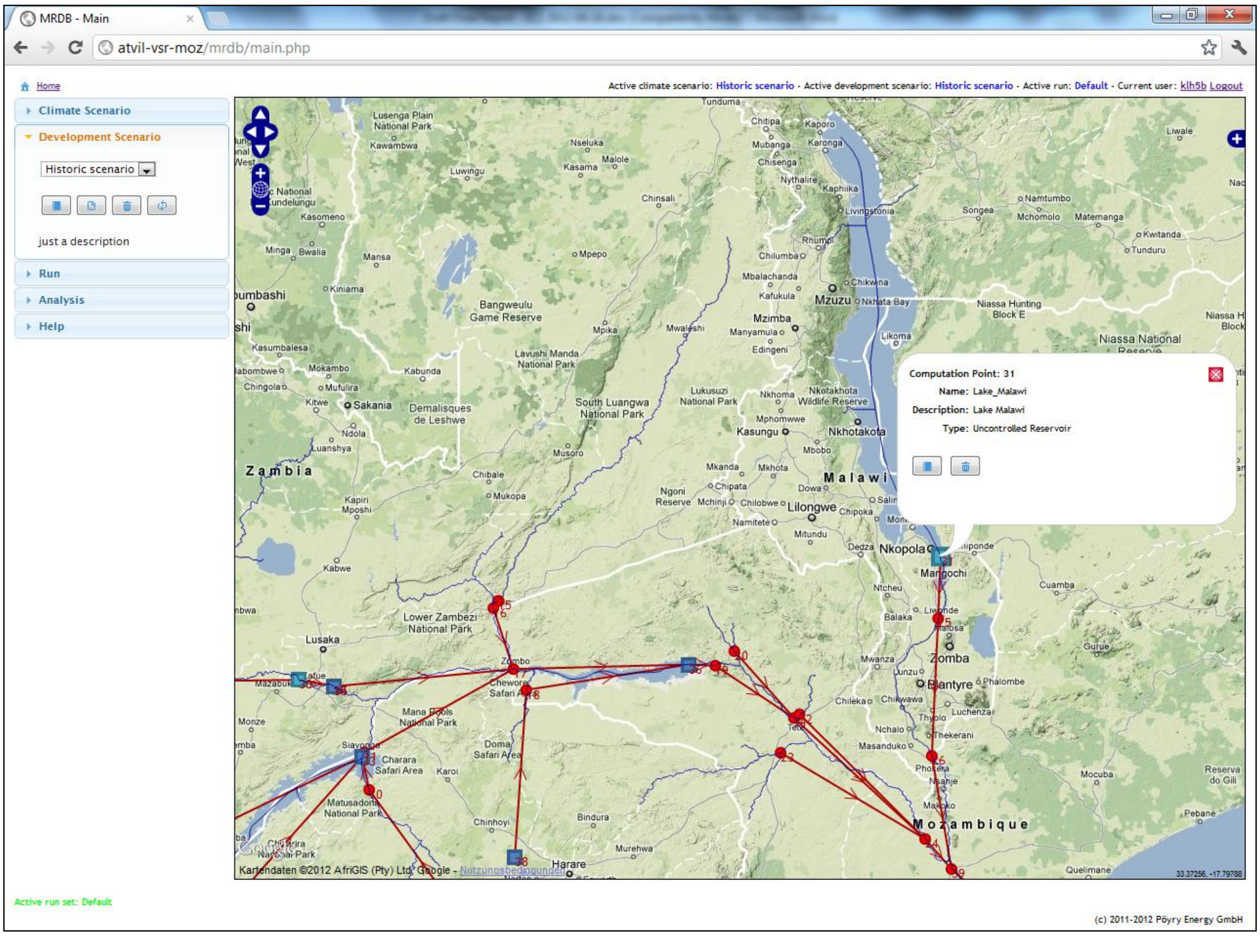

Figure 1-86: Lake Malawi in the DSS.

Climate change impact study

The DSS offers three pre-defined climate change scenarios that are based on data of the WATCH GCMs (see *Table* 1-4, page 35). The observed climate, which usually serves as reference in a climate change assessment, is stored in a separate climate scenario ("historic scenario"). In a delta change scenario, the observed time series of precipitation and temperature can be altered by the user (this is not done under the climate scenario options but by defining correction factors for run, see *Figure* 1-87). *Table* 1-9 shows an overview of the available climate scenarios in the DSS and the data sets they are based on.

Table 1-9: Climate scenarios in the DSS

Climate scenario	Data set
Historic scenario	GPCC/CRU observational data
CNRM	CNRM climate model data
ECHAM	ECHAM climate model data
IPSL	IPSL climate model data
Delta change	User defined change in precipitation (%) and/or temperature (°C)

For the example study, two climate scenarios are applied. Of the pre-defined GCM-based scenarios, the IPSL scenario is selected (A2 emission scenario). In addition, a delta change scenario is defined, with uniform changes in in temperature and precipitation over the entire Zambesi River basin. The values are based on the analysis of RCM projections under A1B emission scenario (see *Table* 1-5): -5% precipitation and +1.5°C temperature for 2021-2050 and -10% precipitation and +4.5°C temperature for 2071-2100 (*Figure* 1-87). The two periods are also used for the analysis of the IPSL scenario.

For both, the IPSL and the delta change climate scenarios, effects on discharge are analysed. For the discharge of the Zambezi at Tete (*Figure* 1-88), changes in the 30-year mean of seasonal discharge and in the resulting flow duration curves are shown in *Figure* 1-89.

Figure 1-89 reveals the high sensitivity of discharge to changes in precipitation. In the IPSL scenario, precipitation in the main contributing subbasins increases by 5-10% (see *Figure* 1-44). This leads to a drastic increase in discharge, especially in the earlier period of 2021-2050. In the later period, the higher temperature and related evaporation attenuates the increase in discharge. Seasonally, the main changes occur in the wet season, from January to April. In the delta change scenario, the decrease in precipitation of 5% in the earlier and 10% in the later period result in considerable decreases in discharge. As the same change factors are applied for all months, the decrease is distributed more uniformly within the year.

The spatial pattern of the impact of both applied climate change scenarios on discharge in the Zambezi basin is shown in *Figure* 1-90. The decrease of precipitation in the upper Zambesi basin in the IPSL scenario (from sb_1 to sb_8) has only minor effects on the – generally lower – discharge in these areas. Downstream of Victoria Falls, IPSL projects mainly increasing precipitation, which leads to high increases in discharge, notably in the Shire basin (sb_25 and sb_26). The delta change for precipitation is applied uniformly over the entire Zambezi basin, resulting in similar impacts on discharge in the various subbasins. Again, the most pronounced changes are simulated for the Shire.

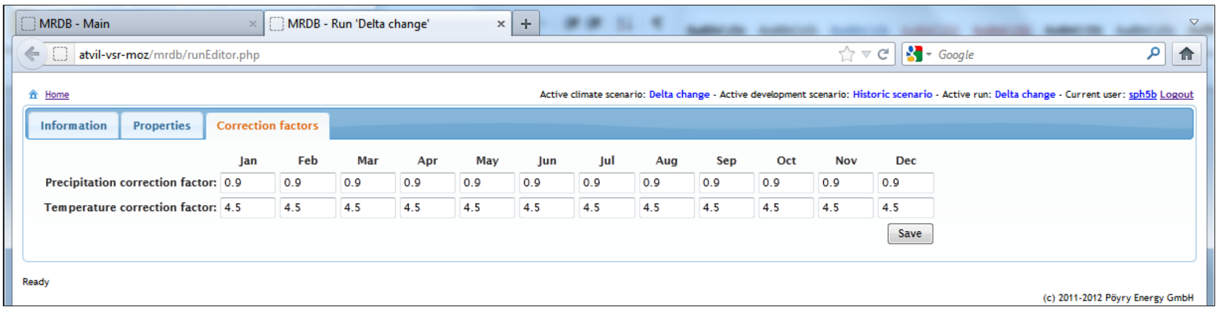

Figure 1-87: ***User-defined delta change factors for a DSS run.***

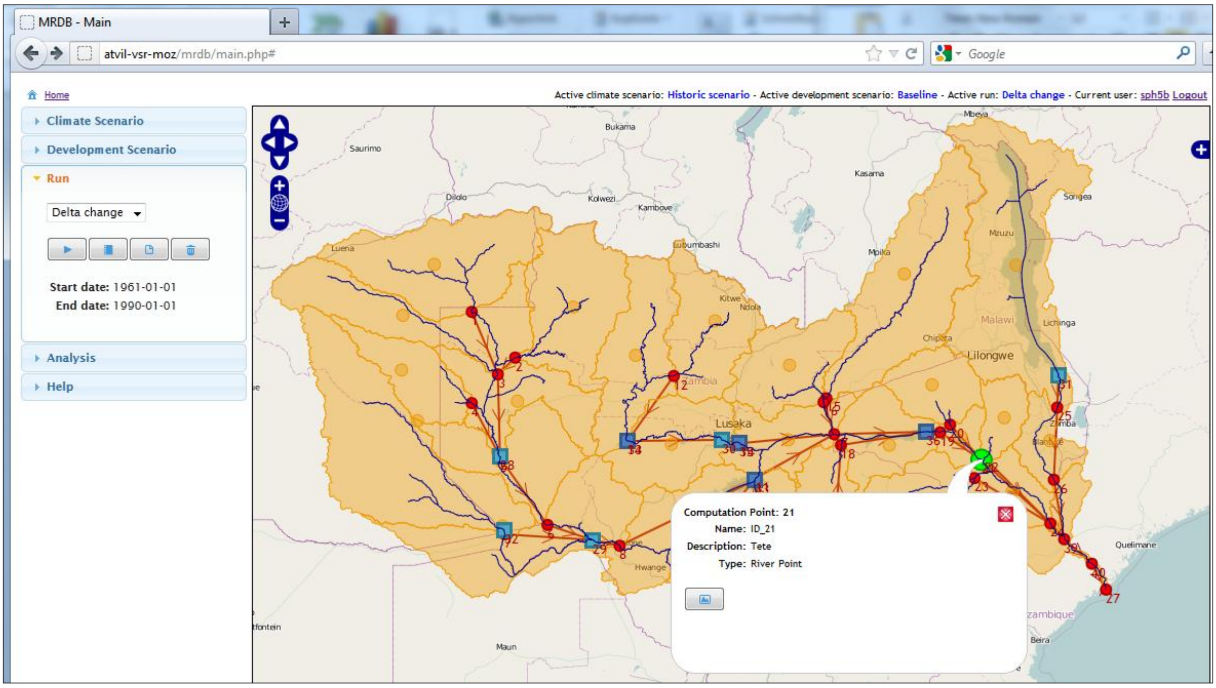

Figure 1-88: ***Tete computation point in the DSS.***

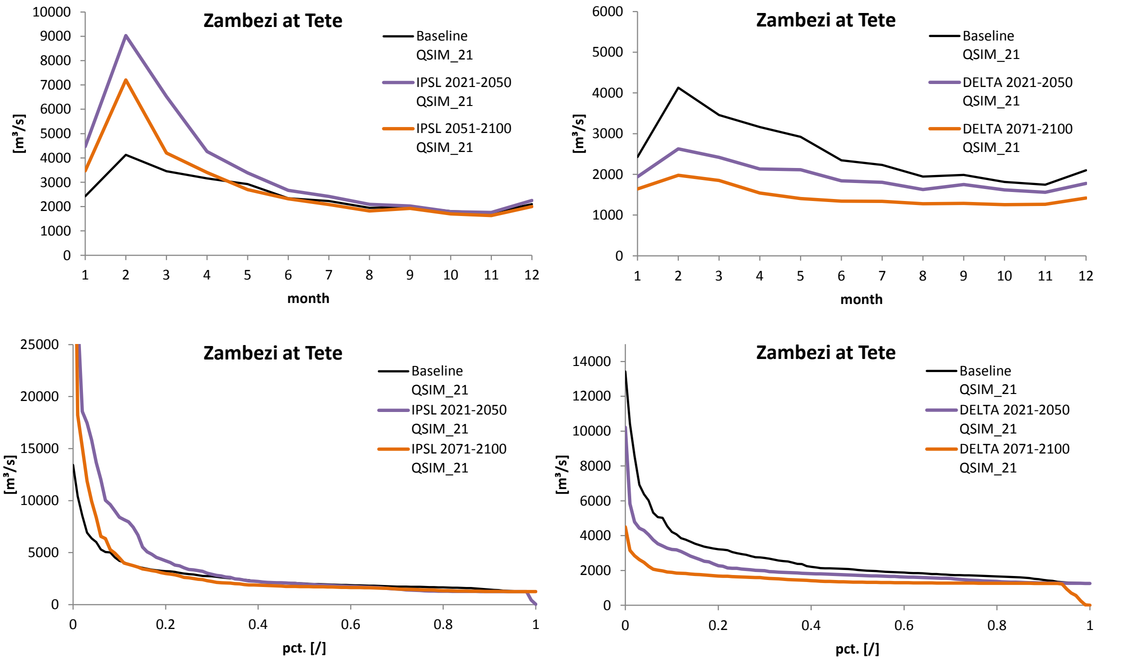

Figure 1-89: ***Long-term mean monthly discharge (top) and flow duration curves (bottom) of Zambezi River at Tete. Impact of two climate scenarios: the IPSL scenario (left) is a selected GCM projection under A2 emission scenario with increase in precipitation, and the delta change scenario (right) is a projection based on A1B emission scenario with decrease in precipitation.***

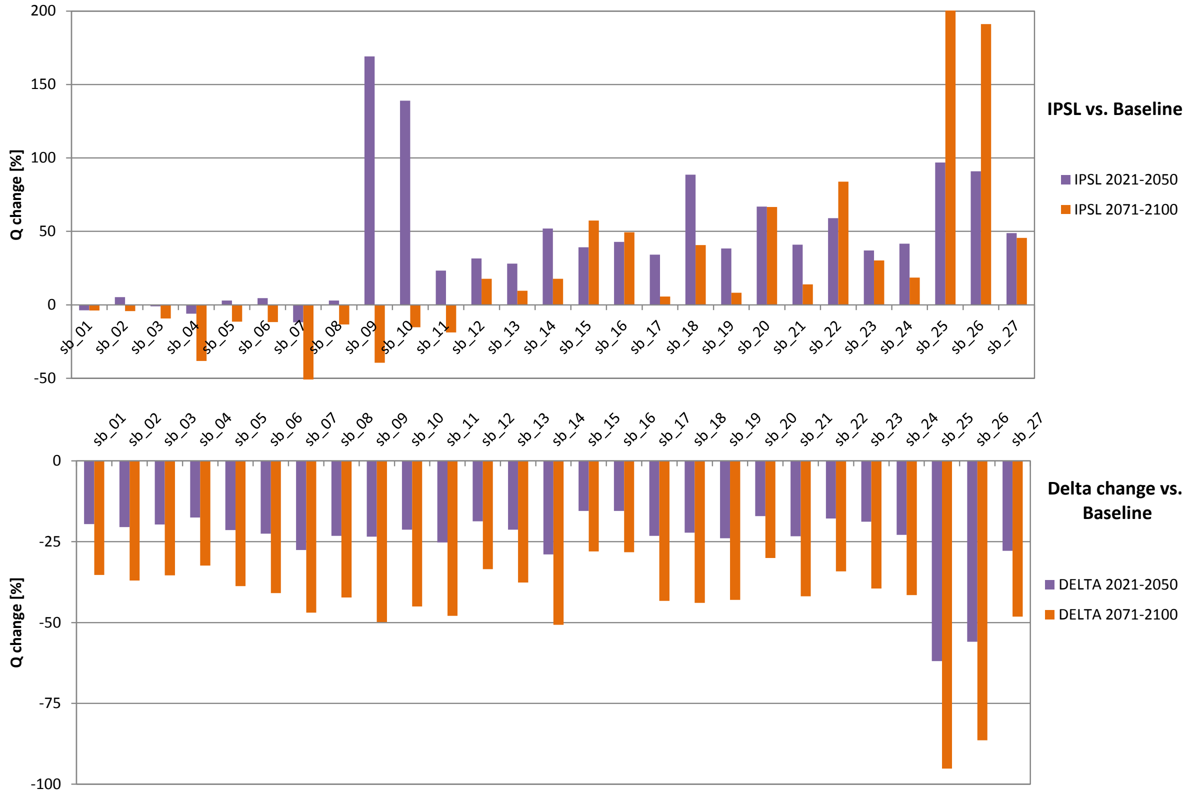

Figure 1-90: ***Change in annual discharge at the outlets of 27 subbasins in the Zambezi basin (the value of sb_27 represents the entire Zambezi River basin). Reference period 1961-1990 used for baseline scenario. Future periods 2021-2050 and 2071-2100. Impact of two climate scenarios: the IPSL scenario (top) is a selected GCM projection under A2 emission scenario with increase in precipitation, and the delta change scenario (bottom) is a projection based on A1B emission scenario with a decrease in precipitation.***

Development impact assessment

In accordance with the analysis of the World Bank (World Bank 2010), development scenarios focusing on irrigation development and hydropower development are pre-defined. Two irrigation development scenarios are defined: one for the near future with a moderate irrigation development, and one for a more distant future, with substantial irrigation development. The combination of the two irrigation scenarios and one hydropower scenario leads to two development scenarios, denominated “Moderate development” and “High development”. With the development scenarios used for calibration and the baseline scenario for scenario comparison, this adds up to the four pre-defined development scenarios summarized in *Table* 1-10.

Table 1-10: Pre-defined development scenarios in the DSS

Development scenario	Description
Calibration	Historic reservoir development, limited irrigation
Baseline	Current reservoirs, current irrigation
Moderate development	Irrigation scenario 1 + hydropower scenario
High development	Irrigation scenario 2 + hydropower scenario

Irrigation scenarios

The determination of water abstraction rates for irrigation is closely based on the calculation in the World Bank (WB) report. The values for countries and subbasins in the WB analysis were allocated to subbasins and computation points in the DSS. *Table* 1-11 gives an overview of the annual irrigation demand in the current situation and the additional water demand in two future irrigation development scenarios.

The two pre-defined irrigation scenarios in the DSS are related to the "Identified irrigation projects" and the "High-level irrigation projects" of the World Bank study. The "Identified irrigation projects" in Irrigation Scenario 1 represent specific projects that can be expected to be implemented in the short term. In the DSS, the additional abstraction for these projects starts in 2020. With this assumption of a rather late implementation, the Irrigation Scenario 1 can be considered a moderate development path. The "High-level irrigation projects" in Irrigation Scenario 2 represent ambitious long-term plans, which can also be regarded as the maximum possible irrigation development. The additional water abstraction in Irrigation Scenario 2 in the DSS starts in 2050.

The monthly water demand is assigned according to the figures of "Monthly water abstraction requirements in the Zambesi River basin" in the World Bank report. For each irrigation scenario and each subbasin and calculation point, the relative portion of monthly abstraction of the respective figure is applied (see example in *Figure* 1-91).

Table 1-11: Irrigation demand in the pre-defined irrigation scenarios

WB subbasin name	WB subbasin no.	DSS subbasin no(s).	Annual irrigation demand (m^3/s)		
			Current	**Irrigation scenario 1 (Identified irrigation projects) from 2020**	**Irrigation scenario 2 (High-level irrigation projects) from 2050**
Upper Zambezi	12	1	1.19	2.74	4.81
Kabompo	13	2	0.15	2.75	4.36
Lungue Bungo	11	3	0.50	0.25	4.97
Luanginga	10	4	0.45	3.09	6.05
Barotse	9	5, 6	0.11	3.82	5.45
Cuando / Chobe	8	7, 8 (parts of 6)	1.35	15.95	15.75
Kafue	7	12, 13, 14	19.45	5.16	10.27
Kariba	6	9, 10, 11	19.56	67.96	304.97
Luangwa	5	15, 16	3.82	2.00	8.60
Mupata	4	17	10.18	4.62	0.00
Tete	2	18, 19, 21, 22, 23, 24	21.21	14.62	83.22
Lake Malawi / Shire	3	25, 26	20.57	24.31	140.85
Zambezi Delta	1	27	4.03	39.36	51.47
Zambesi River Basin			102.58	186.62	640.75

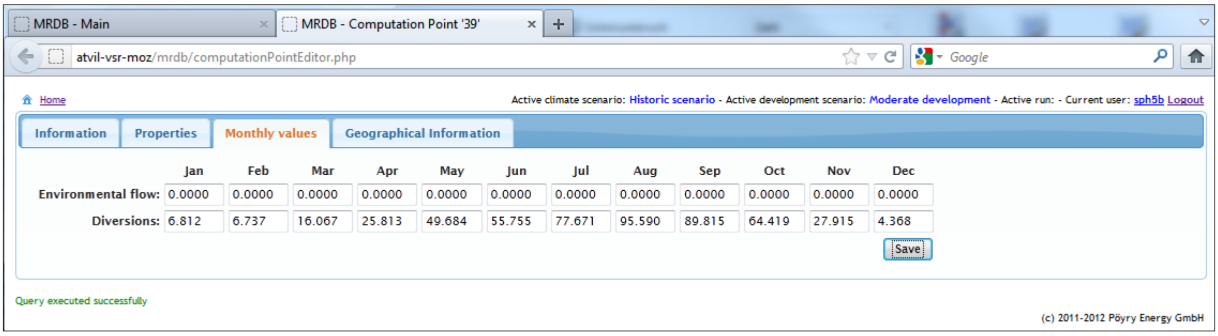

Figure 1-91: ***Monthly water abstraction requirements in one exemplary computation point (cp_39 in sb_27).***

Hydropower scenario

Several hydropower projects are planned in the Zambezi River basin, including refurbishment and extension of existing power plants and the construction of new facilities. 17 projects are listed in the WB assessment. For the pre-defined hydropower development scenario in the DSS only two projects with particularly high impact on the hydrology of the river are considered: Batoka Gorge, upstream of Kariba, and Mphanda Nkuwa, downstream of Cahora Bassa (*Figure* 1-92). Both facilities are expected to be completed by 2024. In the pre-defined hydropower scenario, the commissioning date (start year of operation) of the reservoir is set to 2020, in order to overlap entirely with irrigation scenario 1.

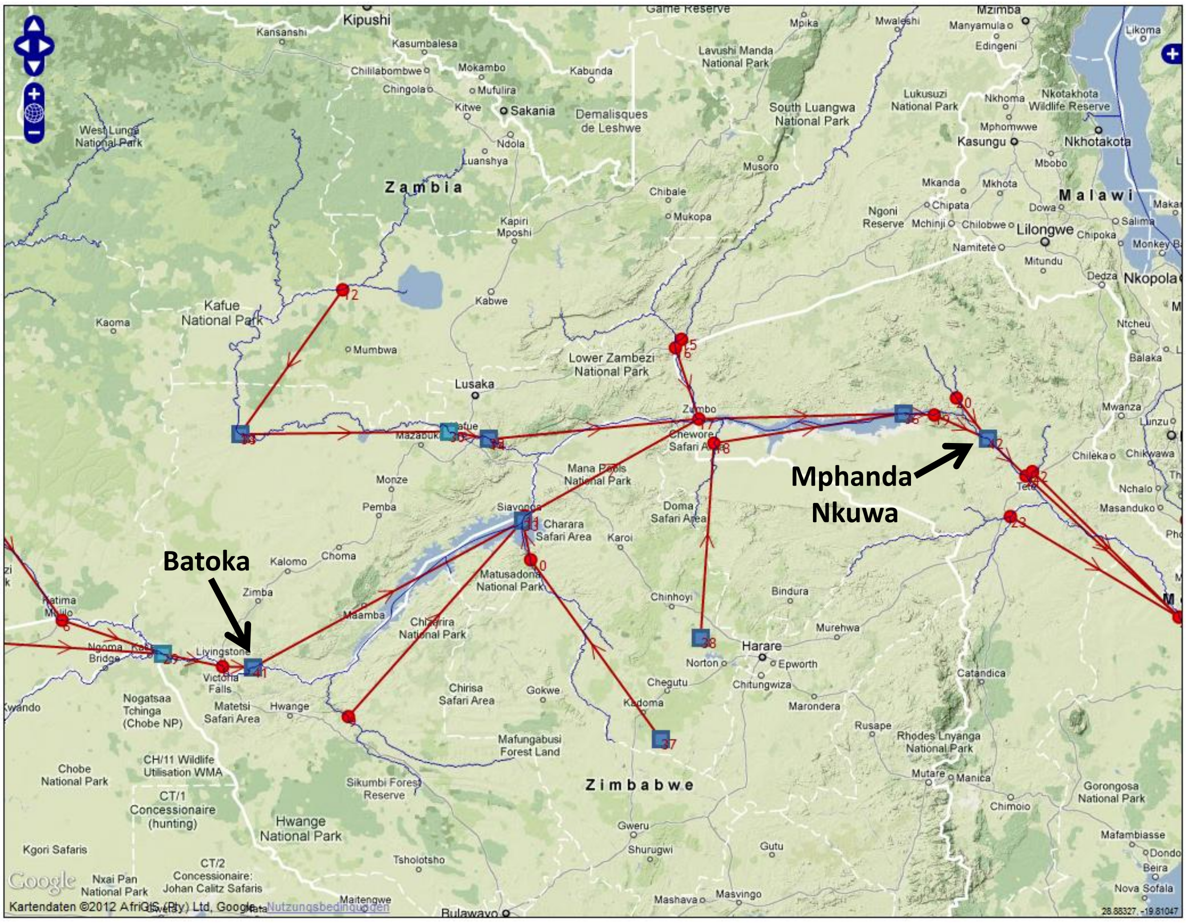

Figure 1-92: ***Computation point network including the planned reservoirs Batoka Gorge and Mphanda Nkuwa.***

For the power plant at Batoka Gorge, an installed capacity of 1600 MW is planned. The 181 m high dam will generate a reservoir with a storage capacity of 1600 hm³ and a surface area of 25.6 km² at Full Supply Level. For Mphanda Nkuwa an installed capacity of up to 2700 MW is considered. At Full Supply Level, the reservoir is planned to have a storage capacity of 2324 hm³ and a surface area of 96.5 km². These planned reservoirs are small when compared with the existing Kariba and Cahora Bassa reservoirs.

<u>*Example study*</u>

In the example assessment, the development scenarios are combined with the delta change climate scenarios described above. The moderate development scenario is analysed for the period of 2021-2050, the high development scenario for the period of 2071-2100. The results for the climate change scenarios without irrigation and hydropower development are shown in the dashed line in *Figure* 1-93.

The impact of the development scenario is clearly visible in both periods, with the highest impact in the high development scenario in low flow months (October to December, *Figure* 1-93 left) . The duration curve for the high development scenario (*Figure* 1-93 right) shows that there is almost no flow in a considerable part of the analysed time period of 2071-2100. This is due to the fact that the Cahora Bassa reservoir water levels fall below the minimum operation level in several months and no water can be released downstream. This shows that the operation rules (as implemented in the DSS) should be adapted under this scenario of climate change and high development.

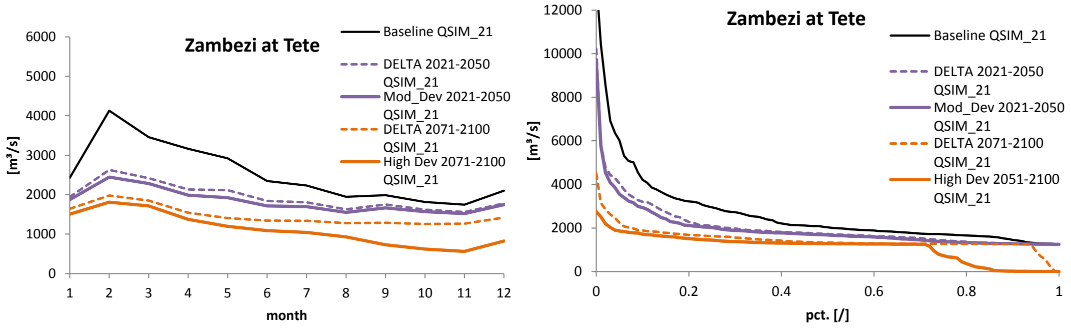

Figure 1-93: ***Long-term mean monthly discharge (left) and flow duration curve (right) at Tete, under impact of climate change only (delta change scenarios – "DELTA" – for 2021-2050 and 2071-2100) and combined climate change and development impact (Moderate development scenario – "Mod_Dev" – for 2021-2050 and High development scenario – "High_Dev" – for 2071-2100) .***

The strong impact of the high development scenarios on discharge is also shown in *Figure* 1-94 for the sub-basins of the Zambezi basin. Here, the simulated discharge of the combined climate change and development scenarios is related to reference simulations under climate change conditions only (delta change climate scenarios with baseline development scenario) – the relative change in annual discharge in *Figure* 1-94 therefore corresponds to the difference between the dashed line in

Figure 1-93 (climate change only) and the solid line (climate change and development). In several sub-basins, the impact of irrigation and hydropower development leads to a reduction of annual discharge of over 40% (07 – Kwando, 11 – Kariba, 26 – Chiromo). The impact of the moderate development scenario leads only to minor decreases in available discharge of below 10%.

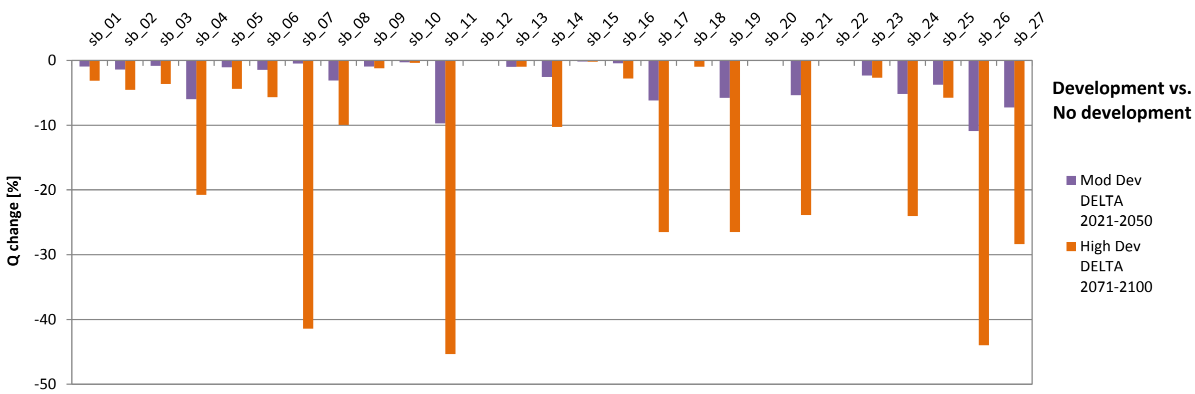

Figure 1-94: ***Relative change in annual discharge in the 27 subbasins due to development impact (Moderate development scenario – "Mod_Dev" – for 2021-2050 and High development scenario – "High_Dev" – for 2071-2100, both compared to the delta change climate scenario without development for the respective period).***

Table 1-12: Typical runs in the DSS (combinations of a development scenario, a climate scenario and a simulation period); analyses of coloured runs are presented here, colours correspond to those in Figure 1-95

Run denotation	Development Scenario	Climate Scenario	Simulation Period
Calibration	Calibration	Observations	1961-1990
Baseline	Baseline	Observations	1961-1990
CC CNRM 2021-2050	Baseline	CNRM	2021-2050
CC ECHAM 2021-2050	Baseline	ECHAM	2021-2050
CC IPSL 2021-2050	Baseline	IPSL	2021-2050
CC DELTA 2021-205	Baseline	Delta change	2021-2050
CC CNRM 2071-2100	Baseline	CNRM	2071-2100
CC ECHAM 2071-2100	Baseline	ECHAM	2071-2100
CC IPSL 2071-2100	Baseline	IPSL	2071-2100
CC DELTA 2071-2100	Baseline	Delta change	2071-2100
Mod Dev CNRM	Moderate development	CNRM	2021-2050
Mod Dev ECHAM	Moderate development	ECHAM	2021-2050
Mod Dev IPSL	Moderate development	IPSL	2021-2050
Mod Dev DELTA	Moderate development	Delta change	2021-2050
High Dev CNRM	High development	CNRM	2071-2100
High Dev ECHAM	High development	ECHAM	2071-2100
High Dev IPSL	High development	IPSL	2071-2100
High Dev DELTA	High development	Delta change	2071-2100

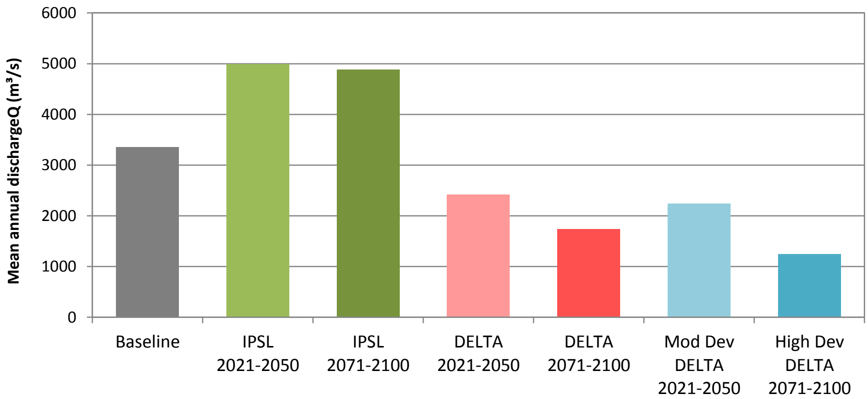

Figure 1-95: *Mean annual discharge of the Zambezi River (entire basin) under selected climate change and development scenarios.*

1.6.5 Limitations of DSS

Even though the DSS is a state-of-the-art tool there are also several limitations, as discussed below.

The DSS uses monthly data for simulation. Therefore, the potential for assessing floods is limited, as some tributaries (e.g. Luangwa River upstream Cahora Bassa reservoir) show much higher peak flows on single days than when averaging over a month.

Spatial resolution of the DSS is reflected by rather large sub-basins.. This resolution also applies to the input data (precipitation and temperature). Therefore, even though the user can insert new computation points at any location along the river network, accurate simulation results are only obtained for computation points where the upstream areas are larger than approximately 50,000 km². The DSS displays a warning message if the user wants to insert computation points for smaller areas.

The gridded input data (precipitation, temperature) are based on regionalization from only few observations at stations, especially in the upstream sections of the basin. This low station density and poor availability of observations is a source of uncertainty in the input data of the DSS, especially for observed data before 1950 and after 2005.

Precipitation and evaporation rates to/from water bodies in reservoirs are based on data that are available only on the much coarser resolution of sub-basins and not for the actual location of the reservoir. Therefore, these fluxes include some uncertainties.

The hydrological effect of large wetlands and floodplains (Barotse Floodplain, Kwando Floodplain, Chobe Swamps, Kafue Flats) generally is difficult to assess. Separate, detailed studies would be required (including site visits) to investigatet this effect, but this would be outside the scope of the present study. Apart from the Kafue Flats, the wetlands and floodplains are located in remote areas and only limited information is available. Therefore, the simulation of wetlands/floodplains with the DSS includes some uncertainties.

The parameters of the hydrological model (water balance model) were calibrated by a comparison with observed discharge data, with the objective to minimize any difference between the simulated and observed values. Any biases in the observations therefore corrupt the calibrated parameter values and affect the simulated discharge. Even though gauges with apparently biased data were excluded from the calibration, it is likely that some of the used gauges are still affected by biases, albeit the magnitude of these biases is not known.

The operation rules of large reservoirs (Kariba, Cahora Bassa) in the DSS may deviate from the actual operation of these reservoirs. In the DSS, operations apply according to fixed rules (extracted from different reports received), whereas actual operations may also consider demand, maintenance requirements, inflow forecasts, etc.

Withdrawals of water for irrigation are specified as net-consumptions (the same approach was also used in the WorldBank study, 2010). However, this does not consider that the actual amount of required irrigation water also depends on the future climate. Agricultural models about soil moisture and crop-water requirements would be needed for more detailed assessments.

The moderate and high development scenarios included in the DSS are based on the WorldBank study (WorldBank, 2010). No time horizon is attached to these scenarios and actual implementation of the projects depend on political and economic decisions.

The available projections of climate models include significant uncertainties. Therefore, interpretation of these data should be strictly viewed as scenario analysis and not as deterministic forecasts. These uncertainties stem from various sources, including emission scenario, natural climate variability, errors in the General Circulation Models, and errors in the downscaling approach. A large ensemble of climate projections would be required for a full assessment of these uncertainties.

1.6.6 Security of DSS

The DSS is an online system and might therefore be a potential target for hacking attacks. Therefore, during development of the DSS an objective was to minimize these potential threats, as discussed below.

There are different levels of users, with different permissions:

- “Standard user”: start runs, edit own climate scenarios, edit own development scenarios
- “Hydrological admin”: all permissions of “Standard user”, plus full access to hydrological model parameters and data, as well as climate data
- “User admin”: create new user accounts, set permissions of users, delete user accounts
- “Developer”: all permissions

User accounts with “Developer” permission are hard-coded and cannot be changed/hacked by online access. “User admin” can only manage user accounts and cannot access the DSS, whereas “Hydrological admin” has full access to the Zambezi DSS, but not to management of user accounts. This ensures that responsibilities and permissions are clearly separated in the DSS.

A separate web-page is available for the “User admin” to manage user accounts. This web-page has a “hidden” address that is not linked to any other pages and cannot be found with search engines (e.g. Google). Access to this page is password protected. For security reasons no screenshot of this page is provided here. For each user several pieces of information are stored, including tracking of login times, number of failed password entries (which is an indication of potential hacking attacks), host and IP address of last login failure, etc.

Each user has an account, which is protected by a password. If users forget their password they can request a new one from the “User admin”. Each user can create their own climate and development scenarios. By default, these scenarios are not visible to other users, unless the user actively wishes to make these scenarios public.

If other tools (e.g. GeoNode) are also hosted on the same server as the Zambezi DSS, this will increase traffic on the server, thereby potentially also increasing the risk of being the target of a hacking attack.

Apart from the risk of being the target of a hacking attack, the main risk is that the people who are "Hydrological admin" and "User admin" do not act responsible. Therefore, great care is required when assigning people these permissions.

As a general security measure it is recommended to make backups by copying the whole system to offline storage devices.

1.7 SUMMARY AND CONCLUSIONS

The following list summarizes the results of this project.

- A water Decision Support System (DSS) was developed for the whole Zambezi basin, covering 1.4 Mio km², which is almost double the size of Mozambique.
- The DSS was designed in a flexible way, such that it can be extended in the future with reasonable effort to other river basins (e.g. Limpopo, Pungwe) or shorter time-steps (e.g. daily resolution).
- The DSS covers the most important rivers and also the large reservoirs, including Cahora Bassa.
- The DSS can be used to analyze current and future water development scenarios. The system allows different stakeholders in Mozambique (and also in the upstream countries) to rapidly assess the impacts of any new water resource developments and climate-induced changes on downstream infrastructure and water supplies.
- The DSS is a web-based application that is easy to understand and easy to use and offers high computational performance.
- Components of the DSS include an information management system (IMS) and a river basin model (RBM).
- The IMS includes a web-based graphical user interface, a dynamic database, GIS components and analytical tools. The map display in the user interface integrates GIS layers, model elements and dynamic background maps (Open Street Map, Google maps).
- The RBM consists of a water balance module (WBM) and a water allocation module (WAM). Monthly time-steps are used by both modules.
- The WBM uses 27 sub-basins to simulate runoff generation in the Zambezi basin from precipitation inputs, soil moisture accounting, evapotranspiration and fast and slow (base) flow components.
- The WAM uses 40 elements (computation points), representing river sections, wetlands/floodplains/lakes and large reservoirs (such as Cahora Bassa or Kariba). Additional elements can be added interactively to the DSS by the user.
- For each element of the WAM water demand can be specified to consider withdrawals (net-consumption) due to irrigation, domestic water use or industrial water use.
- Simulation of reservoir operation is based on reservoir characteristics and operation rules.
- Analyzed climate scenarios include historic conditions (1950-2005) and climate model projections (1960-2100) of six different climate models. DSS simulation runs can be based on pre-existing climate scenarios, the delta-change approach, or uploading of new climate scenarios (bias correction has to be done by the user with external tools).
- DSS simulation runs can be for any time-slice between 1950 and 2100.
- The DSS includes an analysis tool for visualization of simulation results, including an

extensive list of model variables (runoff, precipitation, temperature, evapotranspiration, reservoir water levels, etc.). Changes in frequencies of flows (droughts, high flows) can be analyzed with monthly or annual flow duration curves. Export of results in table format enables post-processing with external software (e.g. Excel).
- The DSS is installed on a server that will be delivered to Mozambique. The server location will be at CENOE in Maputo.

In addition to the tasks defined in the original Terms of Reference (TOR), there are added benefits for the project including:
- Higher number of elements (computation points) in the water allocation module than originally proposed, i.e. elements included are 40 (DSS) instead of 30 (TOR).
- Data of a longer time-period included as historic scenario in the DSS, i.e. historic time-period covered is 1950-2005 (DSS) instead of 1961-1990 (TOR).
- Higher number of analyzed climate scenarios, i.e. six (DSS) instead of three (TOR).
- Application examples of the DSS are included in this report (not part of TOR). Such examples include impact assessment of climate change, irrigation and dam development.

The results of this project enable some important conclusions:
- The Zambezi River basin exhibits a complex hydrology. Along with the low coverage (and poor quality) of observations this poses a challenging situation for any hydrological modelling.
- Data pre-processing focussed on numerous different data sources. Comparison of the same type of variables from different sources showed that there are considerable uncertainties in the reported data (e.g. discharge DNA vs. GRDC, precipitation GPCC vs. CRU, potential evapotranspiration CLIMWAT vs. CROPWAT vs. CRU).
- Runoff is only a small component of the water balance, as approximately 92% of precipitation is lost via evapotranspiration to the atmosphere and only 8% generates runoff. Therefore, small errors in estimation of evapotranspiration would result in large errors in simulated runoff.
- Calibration of the hydrological model for runoff simulations focussed on key locations, whereas data of some gauges were dismissed due to apparent large biases. In general, obtained model performances are similar or higher than in previous studies in the Zambezi basin.
- As in other studies, there are some (small) deviations between simulated and observed seasonality in discharge. For example, simulated seasonality in discharge at Victoria Falls is too early compared to observations. However, there are no significant impacts downstream due to the strong dampening effect of large reservoirs along the Zambezi (Kariba, Cahora Bassa).
- Reservoir simulations exhibit similar patterns as observed data (water levels, releases). However, comparisons are complicated by the fact that operation rules changed over time.
- Application examples with the DSS showed the high sensitivity of Zambezi discharge to changes in climate and irrigation development. Irrigation development will lead to a certain reduction of discharge, whereas climate change may cause decrease or increase in discharge (depending on the climate scenario). The sensitivity of discharge is low with regard to additional upstream dam development.

The developed DSS is a state-of-the-art, well calibrated, easy to use analysis tool that will serve Mozambican analysts for rapid assessment of impact of climate change and upstream developments on discharge. Due to its implementation as an open web-based system, the DSS is also available to the general public.

1.8 RECOMMENDATIONS

Based upon the work during this project, the following recommendations are made:

- The projections of a new generation of climate models will be published in the near future (probably end of 2012) within the CORDEX Africa framework, which will be a contribution to the IPCC Fifth Assessment Report (expected in 2014). These new high resolution climate models will be a major step forward towards better regional projections for future climate in Africa. These new climate projections could be pre-processed and imported into the Zambezi DSS for a first impact assessment on future river discharge.
- The DSS could be expanded to other important rivers in Mozambique, such as the Limpopo, Save and Pungwe basins. The same user interface would be used for these basins. Therefore, Mozambican analysts who have experience with the Zambezi DSS should directly be able to also use the DSS in other river basins. Additional services to be provided by the Consultant for expansion of the system to other rivers would include data collection, hydrological model set-up, calibration and scenario definition. Building on the experience and tools of the Zambezi DSS this could be achieved in a cost-effective way.
- The DSS could be expanded to also simulate hydropower generation. This would enable to directly assess the impact of climate change and water resources development on energy generation at e.g. Cahora Bassa hydropower plant. The DSS could then be used to show the trade-offs between different developments, such as irrigation vs. electricity generation. Further, optimization of downstream flood risk mitigation and hydropower operations would be possible.
- The work of SC2 (flood mapping) could be integrated into the DSS. This would enable to assess how the flood situation changes under various scenarios, including climate change and reservoir operation rules. However, as the DSS is currently based on monthly data, statistical analyses are required to assess the relationship between monthly discharge and flood peaks.
- A pilot study could assess the possibility of expanding the DSS simulations from monthly to daily time-steps. This includes investigation of input data availability, spatial resolution, required hydrological model components, and data management issues (which are important due to the fact that the DSS is an online system). Such a study would also be an important step towards assessing the potential for upgrading the DSS to an operational (real-time) runoff forecasting system.
- It is recommended to pro-actively invite hydrologists of upstream countries to use the Zambezi DSS. For this purpose training on the DSS with hydrologists from different countries is recommended. This would foster regional cooperation and mutual understanding. A common, open tool like the DSS would also facilitate communication between stakeholders and open avenues for a better sharing of information between countries and institutions. As the Zambezi DSS is owned by Mozambique, the decisions about which information to share will be fully retained.
- Communication and knowledge exchange between DSS users could be improved by

implementing a web-based forum where users can post questions, read solutions posted by other users and start online discussions. This could be directly integrated into the Help section of the DSS, as the DSS is already an online system. However, for this to be successful the group of active users should be sufficiently large and administration of the forum would be required.

- During this project discharge data was collected from many different institutions, often with the provision that the data may not be published and distributed (consequently the data was treated confidential) Therefore, any new projects would need to go through the data acquisition process again, which is not cost-effective. It is recommended to have better data sharing agreements in the Zambezi basin.
- Observed discharge data are only available at few locations in the Mozambican part of the Zambezi basin. There are several important Mozambican tributaries with no or incomplete measurements (e.g. Luia River, Luenha River). In addition, existing measurements appear to have poor quality (e.g. discharge data during low-flow of Zambezi River near Tete differs by 100% between different data providers). Therefore, it is highly recommended (a) to assess the quality of measurements by re-evaluating stage-discharge relationships at existing gauges and (b) to install new gauges at the most important tributaries.

1.9 REFERENCES

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SUBCOMPONENT 2: FLOOD MODELLING

2.1 AGREED WORKS (TERMS OF REFERENCE AS REFINED IN ACCEPTED CONSULTANTS PROPOSAL)

Subcomponent 2 includes flood mapping and flood defence works. Expected output include the development of relationships between flow and river stage along the main stream channel using hydraulic modelling with the one-dimensional model HEC-RAS (USACE 2010). The model domain includes the main channel reach of the Zambezi downstream of Cahora Bassa Dam (604km), the Pungwe (370km) and the Limpopo (576km) within their Mozambican catchment area. Modelled flood extents are supplied for a baseline and climate change scenario. A more detailed Flood Risk Assessment (FRA) using 2D modelling will be shown with restrictions to data availability.

Works for flood defence and resilience were agreed to include recommendations for flood defence works based on findings from the flood modelling stage. A holistic approach was proposed to be taken in assessing options to avoid or mitigate flooding considering the risk, hazard potential and socioeconomic aspects. A “making room for water” concept was suggested to be preferred over rigid flood defence structures where appropriate in order to tackle and reduce the flood risk in a sustainable and holistic way for not only isolated locations but where possible for longer river stretches. Defences that may be seen as necessary will be designed in a way to have benefits for the local economy and to be low maintenance.

2.2 EXECUTIVE SUMMARY

The Zambezi, Pungwe and Limpopo are amongst Mozambique’s most flood prone rivers. The current situation of flooding is likely to shift under the pressures of climate change. Hydraulic modelling is a suitable tool for assessing changes in inundation from the status quo to projected climate scenarios.

Data have been gathered from previous reports and the public domain for conducting hydraulic simulations. A digital elevation model (DEM), landuse map, channel width information, historical flow data and climate change flow projections have been used to setup the 1D hydraulic model HEC-RAS along the main channel of the three rivers. The model areas visually cover the estuaries. These sea water level influenced regions are however not dynamically included in the simulations since high tide levels are set as fixed boundary conditions based on INGC Phase I results. The DEM was corrected in terms of elevations of cities and forests, the rivers bathymetry and channel slope using statistical measures and an empirical regime equation. Roughness values were assigned for unique land cover and channel slope classes based on literature-defined minimum-, expected- and maximum ranges. Baseline flow data to depict the current situation were not available in a sufficient quality and resolution to define distinct return period flood flows. Instead, expected return period flows were taken from former hydrological analyses and assigned with minimum and maximum thresholds. Climate change flow scenario data for 2045-2065 are available from the INGC Phase I project, consisting of 2 year and 20 year return period flows. Projected flood frequency and flood flow changes are used to define scenario flows. Scatter in the dataset was used to assign minimum, expected and maximum flow changes. All input data ranges are used as an indicator for simulation uncertainty along the rivers.

A range of flows has been run to conduct model calibration and validation. Within this process, it was found that the Zambezi Delta could not be sufficiently modelled using a one dimensional approach. The two dimensional model AdH was setup for the Zambezi delta to sufficiently account for lateral flows, changing flow paths, infiltration and evaporation processes and split flows. The models have been calibrated using channel depth as the target parameter by fitting the regime equation to bankfull flow scenarios. Model performance was tested using stage discharge measurements and inundation maps covering historical flood events. Validation results are good for the Limpopo and Zambezi and sufficient for the Pungwe.

Based on the calibrated and validated models, scenarios covering the current and future status of 2 year and 20 year return period flood flows have been setup. Inundation mapping has been carried out to produce maps of the expected flooded areas including uncertainty diagrams indicating sections of higher and lower confidence. Within this report, results for both return periods are displayed for selected target regions while the flood maps, covering the total model domains are attached as additional A0 pdf documents. The maps can be used to identify flood prone areas but cannot be used to define areas that are not under thread of flooding (i.e. the maps are designed to identify risk areas but not safe areas) due to the high uncertainties inherited in the model input data. For planning purposes in terms of development plans, mitigation strategies or regional disaster management, the results of this report are designed to be used in conjunction with detailed Flood Risk Assessments (FRAs) to be carried out for the respective area of interest. Due to lack of available data, it was not possible to carry out a FRA within any of the three river basins. To give an overview of necessary input data, the general methodology and results, an example FRA was conducted using two dimensional hydraulic modelling.

Overall, the flood maps are superior to previously produced maps in that the underlying hydraulic calculations and inundation mapping have a higher accuracy due to the incorporation of channel depth estimations and the corrections of the DEM in forest and dense infrastructure areas. Beyond that, the maps are produced for a baseline and climate change scenario and the maps contain spatially distributed uncertainty assessments. This was to our knowledge not available before this study.

For improving the flooding situation, a “making room for water” concept has been proposed. Findings from a situational analysis and stakeholder discussions show that structural flood defences and assets will be inevitable on the local scale for high value locations but efforts should be spent to minimize these and focus on holistic approaches including catchment and floodplain conservation through the development of suitable policies for which guiding principles have been provided. It is essential to understand that the increased occurrence of floods would be increased by large scale construction of defences that would increase flooding downstream Catchment conservation approaches on the other hand would have strong benefits not only by reducing flooding but by equalizing the annual flows and increasing agricultural water availability. For achieving the flood protection goals a variety of protection and mitigation measures have been discussed, described in detail and cost estimates provided. It has become clear that from a cost-benefit point of view holistic and long term catchment conservation based approaches are preferable to structural defences. Respective detailed policy suggestions are provided. Given the situation in Mozambique, implementing the policy would require efforts on administrative and enforcement level both for governmental and local administrations.

With regards to inevitable structural flood defences for areas that have already been built up on floodplains it has been stressed that investments have to be discussed on a case by case basis under consideration of a holistic view of the overall catchment situation. The best option for increasing the flood resilience of communities is seen as a combination of small scale technical interventions accompanied by large scale increase of retention area through catchment conservation. Additional multiple-benefits can be achieved by promoting the construction of weirs and small dams along the tributaries which will lead to an improvement of water supply and the creation of retention area if operated with the respective operation principles. In detail, the following combination of interventions would be advisable, following the "living with floods" concept:

1. Small dikes, wharfs for house and community protection
2. Upper catchment conservation
3. Policy development
4. Weirs and small dams for flood retention purposes
5. Adapted schedules for large dams
6. Forecasting and early warning system development in combination with alert systems
7. Promoting preparedness of the population

2.3 AREA DESCRIPTION

A brief overview of each basin and the model domains are shown here. The model extent has been derived from historical flood maps overlaid with the DEM. Where necessary, the boundary was delineated along ridges which could not be overtopped by flood waters and along borders where inundation is influenced by tributaries.

2.3.1 The Zambezi River

The 1,390,000km² Zambezi Basin is the fourth largest river basin in Africa with Zambia, Angola, Namibia, Botswana, Zimbabwe and Malawi contributing water to Mozambique (World Bank 2010).

Figure 2-1: Aerial photograph of the Zambezi at junction Namibia, Zambia, Zimbabwe and Botswana

(Source: Wikimedia Commons)

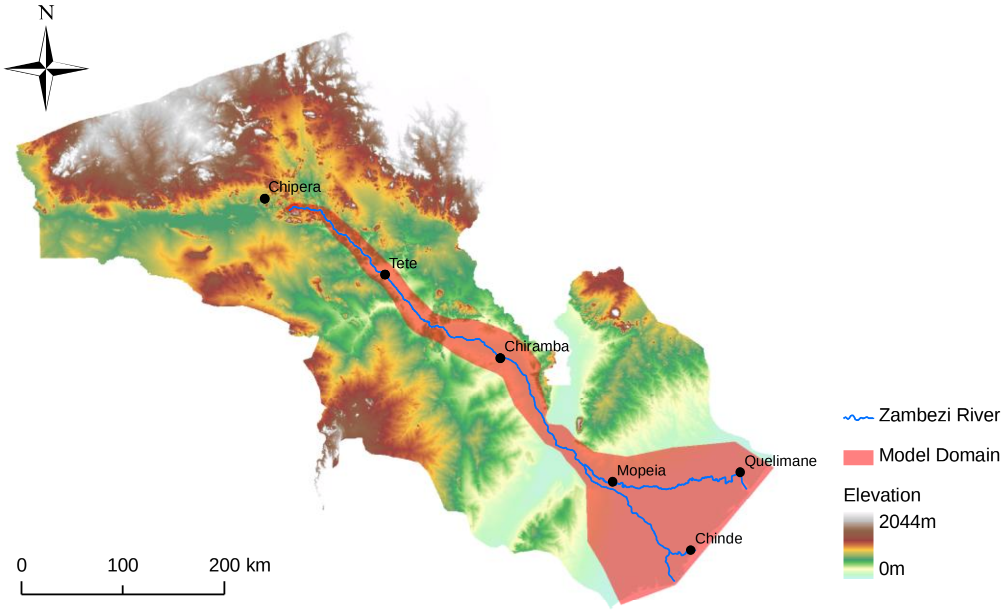


Figure 2-2: Digital elevation model, major cities and model domain of the Zambezi River

The construction of Cahora Bassa Dam in 1974 resulted in an alteration of the runoff pattern, but could not prevent flooding (Beilfuss 1999). Recent severe floods occurred in 2001 and 2008. Within a detailed hydrological analysis of the Zambezi basin, runoff monitoring in the basin is criticised, especially the lack of continuous gauging records at stable cross sections (Beilfuss and DosSantos 2001).

2.3.2 The Pungwe River

The 31,300km² Pungwe Basin is mainly located in Mozambique. The 5% of its area in Zimbabwe however, contribute considerable flow caused by excessive rainfall in that region (Van der Zaag 2000). The Pungwe has been subject to frequent flooding in recent years. In 2001, 2004, 2008 and 2010 the water level reached flood stage (DFO 2011, BBC 2001). In the Mozambican part of the Pungwe, no large dams have been constructed. Only 19 small dams for crop irrigation exist (GRM and GRZ 2006).

Figure 2-3: Flooding at the lower Pungwe River
(Source: GRM and GRZ 2006)

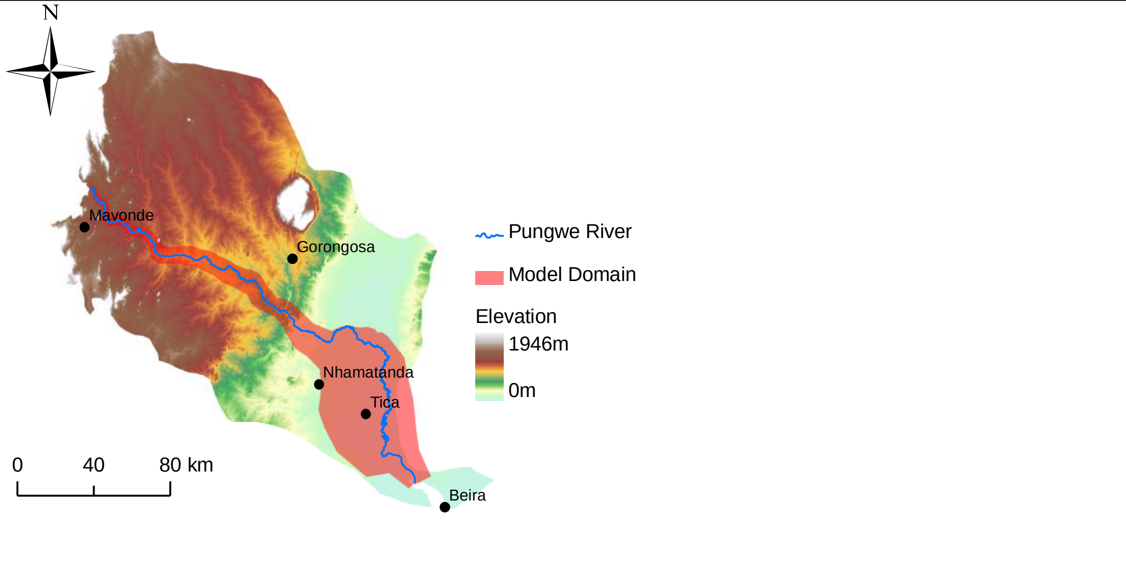


Figure 2-4: Digital elevation model, major cities and model domain of the Pungwe River

2.3.3 The Limpopo River

The 415,000 km² catchment of the Limpopo River lies in South Africa, Botswana, Zimbabwe and with one fifth in Mozambique (RCSA and USAID 2002). No major dams are located along the river (CGIAR 2003). The Limpopo has not been flooded as frequently in the recent past, but catastrophic: The flood from February 2000 caused almost 1,000 deaths and 700,000 displaced people (LBPTC 2010).

Figure 2-5: Aerial photograph of the Limpopo in March 2000 after the devastating flooding, southern Mozambique

(Source: Wikimedia Commons)

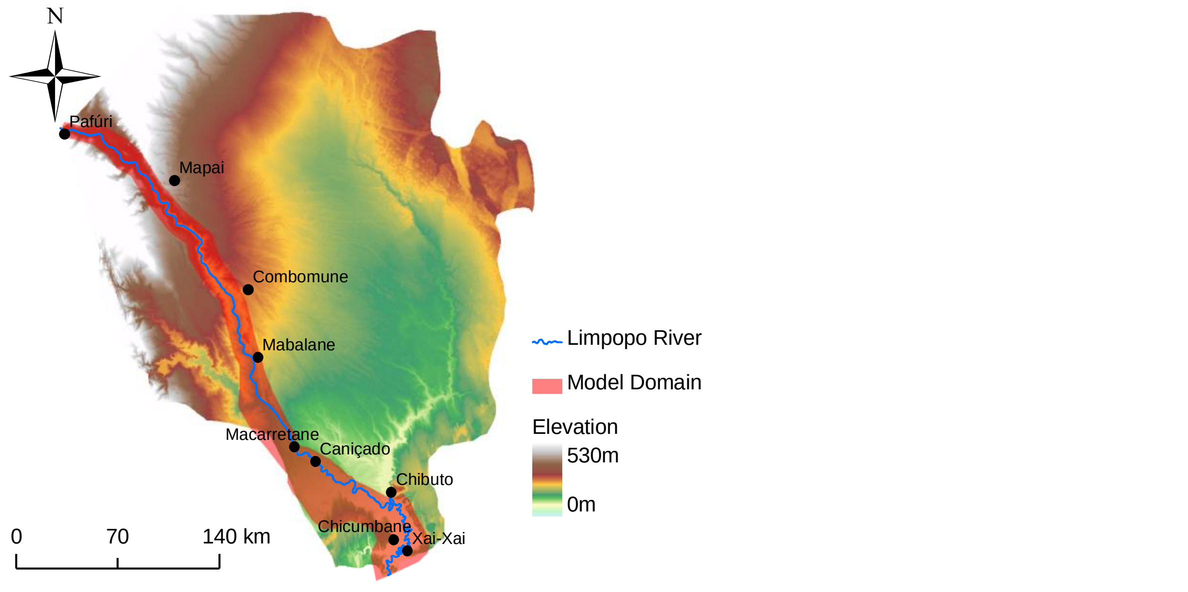


Figure 2-6: Digital elevation model, major cities and model domain of the Limpopo River

2.4 METHODOLOGY

2.4.1 Data analysis

To enable application, adaptation and usability of the model in the future, to avoid duplication of previous work and due to budget constraints, data were taken as much as possible from the public domain, remote sources and from available reports and former studies. In this section, methods are described how the data were checked for consistency and plausibility. Necessary data for the model setup are river geometry derived from topographic data, roughness values of the terrain surface, spatially distributed flow data for the baseline and climate change scenario.

Topographic data

Topographic data are used to derive river channel and floodplain geometry for the hydraulic conveyance calculations. These are the most important data for a hydraulic model (CASAS *et al*. 2006) and thus thorough checks and plausibility tests were conducted to find the optimum data source and to improve data quality. As no budget is available to obtain topographic data, access is restricted to digital elevation models from the Shuttle Radar Topography Mission (SRTM 2000, Jarvis *et al*. 2008) with 90m grid cell size or from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER 2011) with 30m grid cell size. An assessment of the SRTM and ASTER accuracy was carried out using different test methods. A comparison with 678 elevation points from SPOT data revealed that the SRTM performs slightly better on the national scale. Both datasets show strong weaknesses in the absolute elevation accuracy with a mean vertical deviation from all SPOT points of -43.5m and -48.9m for the SRTM and ASTER DEM respectively. The SRTM also performs better in depicting digitized stream networks and watershed boundaries and was thus used for the study. In October 2011 an improved ASTER dataset (ASTER v.2) became available after data assessment had already been finalized. However, ASTER v.2 was tested in the Zambezi and it was found that catchment and stream delineation performance tests led to similar results described above, with the SRTM derived dataset being the superior elevation model in that case.

However, the uncertainties in the SRTM (10m relative and 16m absolute vertical accuracy) led to a problematic depiction of the flow centerline and its elevation profile from upstream to downstream in all three basins. Implausible elevation distributions were improved using a hydrologically corrected flowpath. *Figure* 2-7 shows a comparison of the raw and processed elevation profile along the three rivers.

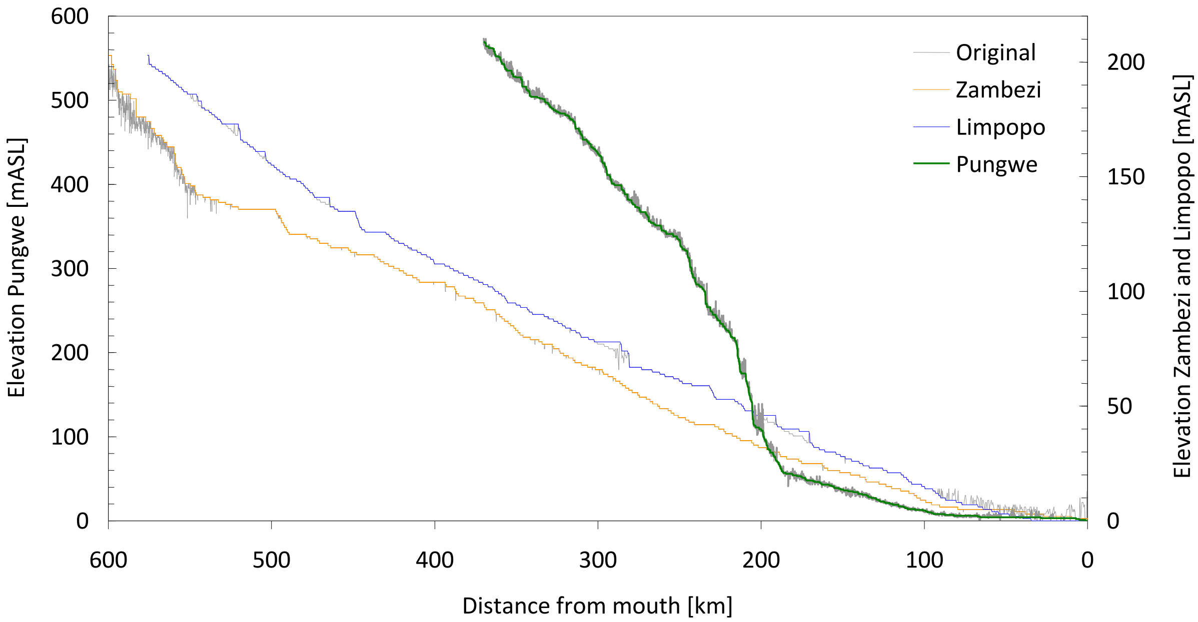


***Figure** 2-7: Corrected and raw elevation profile along the main channel of the Zambezi, Limpopo and Pungwe (all within Mozambique only), note the unnatural peaks and dents along the original profile*

Any object on the earth's surface is defined as ground level in the SRTM (and also the ASTER DEMs). This is of particular importance in densely vegetated areas and settlements with concentrated, high structures. Also the water surface is not penetrated but defined as ground level. Those DEM properties are disadvantageous for flood inundation mapping because the true ground level should be used. Elevations in vegetated areas and cities were analysed in comparison to adjacent, non vegetated areas and areas without dense infrastructure. In average, the elevation inside the forest or city boundaries is 2.7m and 2.3m higher than directly outside. Thus, elevation values inside city and forest areas have been corrected using statistical methods.

Channel bathymetry was approximated according to the following methodology: Both banks of the rivers and islands in the flowpath were digitized from Google Earth. For each cross section, river flow widths were calculated between banks and if present, multiple widths in between islands. Average river slope was calculated from the SRTM along the stream centerline at each cross section. Riahi-Madvar *et al*. 2011 assessed eight empirical regime equations which can be used to derive channel flow depth based on bed slope and width. Hey and Thorne's (1986) methodology performed best in all respects and was used for deriving channel depth. The equation is applied to each flowpath of each cross section and the resulting depth is subtracted from the lowest SRTM grid value in between the banks to gain bottom bed elevation. Additional information is supplied in Annex A2.1. Channel shape is approximated with sloping banks in an angle of 45° and a horizontal bed. *Figure* 2-8 shows a 40km part of a cross section in the Zambezi, 48km from the mouth at Marromeu, before and after the correction with an island in between the banks. Hey and Thorne's equation is an empirical function that requires plausibility checks and calibration. This iterative process is explained in the HEC-RAS calibration section (Section 2.4.6).

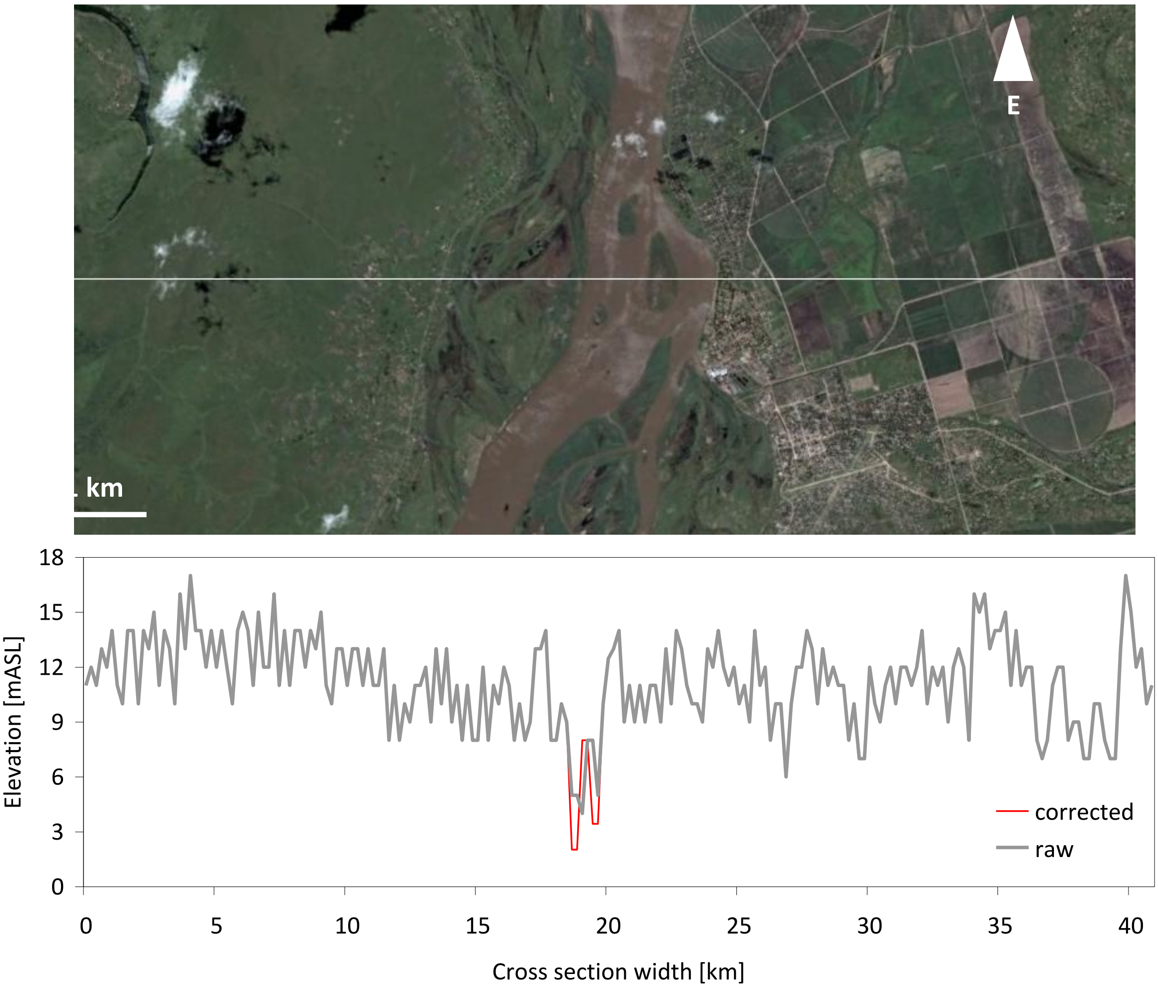


***Figure* 2-8: Google Earth image with cross section (white line) at Marromeu oriented east (top) and the elevation profile before and after the correction (bottom).**

At this station, the water depth estimate left of the island is about three meters, right of the island about two meters, while the islands elevation remains as is.

Roughness data

Manning's n values are used as the roughness factor for calculating energy losses in HEC-RAS. A Manning's n map was created in the GIS on basis of the land cover map, the digitized channel banks and the SRTM. Unique roughness values were assigned to vegetated areas, bare soils, urban areas and the river channels according to CHOW 1959. Roughness values for the channels were distinguished using three bed slope classes defined by Rosgen (1994). All classes and their according Manning's n value with an uncertainty range are displayed in *Table* 2-1.

Table 2-1: Roughness classes and their respective Manning's n value (according to CHOW 1959)

Surface properties	Mannings n	Range ±
Channel steep >4%	0.07	0.03
Channel medium 2%-4%	0.04	0.02
Channel flat <2%	0.035	0.02
Dense forest	0.12	0.04
Open forest	0.08	0.02
Water plants	0.10	0.03
Bare areas	0.03	0.01
Settlements	0.05	0.02
Crops	0.04	0.01
Grassland	0.04	0.01
Shrubland	0.05	0.02
Thickets	0.15	0.04

Baseline flow data

All available historical flow data has been screened and thoroughly assessed. The availability and quality of available discharge data is problematic. Inconsistencies have been found concerning e.g. significantly different flows at the same locations or downstream gauges having much less flow than upstream gauges. Other studies reach similar conclusions: Beilfuss and Dos Santos (2001) state that all discharge gauging data in the Zambezi must be treated as approximate. SWECO *et al*. (2004) assessed the 26 stations in the Pungwe and found that only six are operational, of which only three are in very important locations. One of them is however not accessible during flooding. Only five stations have relatively stable cross sections. According to LBPTC (2010) much runoff data is of poor quality due to unstable cross sections at the gauges in the Limpopo basin. Almost all tributaries to the main channels are ungauged. Beyond that, the flood scenarios on which the models could be calibrated have even less data coverage as some gauges have no records during these periods. It is thus not possible to simulate specific historical floods based on measured discharge.

For the most reliable and longest time series, RMSI (2009) have derived return period flood flows for the major rivers in Mozambique. Together with additional flow values derived from literature values and DNA (2011) time series, numerous baseline flow scenarios were defined. These flow values including minimum, expected and maximum thresholds are summarized in Annex A2.2 (*Table* A2.2.1).

Climate change flow scenarios

Projected flow data for a 2045-2065 climate change scenario were available from the Phase I report (INGC 2009). The climate scenario used for that analysis was the SRES A2 emission scenario calculated from seven Global Climate Models (GCM). The data from the GCMs were downscaled to the regional level and used to run a hydrological model on daily time steps. The changes between the baseline (1961-2000) and projected period were used to calculate percentage flow changes. These flow changes are available in shapefile format and cover the area of Mozambique on a subbasin level, which have an area of 1,280 km² in average. Two flood flow return periods are included in the dataset: (1) typical flood with a return period of about two years and (2) maximum flood with a return period of about 20 years.

Two different climate change impacts on these return period flood flows have to be distinguished: First, the change in flood frequency through more frequent events. A higher frequency of floods in the future means that the probability of a certain flood to hit in a particular year increases. The change in flood frequency is included in the Phase I data, albeit not distinguished for different return periods but for "floods" in general. This one frequency change value for each basin was used to assign new probabilities to the original return period flows. Back-calculating to the fixed return period (2 year and 20 year) results in a new flow value which is higher in case flood frequency increases and lower in case flood frequency decreases. In general, in the Zambezi a slight decrease of flood frequency is predicted, which amounts to a decrease in flood flows by 2.8%. In the Pungwe as well as the Limpopo the expected frequency increase leads to an increase in flows by 8.1% and 5.5%. This information is based on INGC 2009, where the difference in flood flows between the historical baseline (1961-2000) and the climate change scenario (2045-2065) is described.

On top of this flow change caused by flood frequency, the second climate change impact on the flood flows is the direct flow change through more intense events. The spatial distribution of the flow change values is displayed in *Figure* 2-9 for the 2 year and 20 year return period. As can be seen there, even neighbouring subbasins have opposite trends. It is questionable that climate change has such diverging impacts on a scale of less than 50 km. The standard deviation of the flow changes, calculated also for each point along the main channels is introduced as a measure for assessing this scatter in the dataset trends.

Terminology: Return Period

The return period is a statistical measure to define the interval between events, in this case of river flooding. The associated number in years may infer a regular occurrence of events, but it has to be stressed that it is a probabilistic value only. The inverse of the return period in years represents a probability of occurrence in any single year. For example, a 20 year return period flood event occurs with a probability of 0.05 in any year. Thus, in reality such an event can also take place in two consecutive years or not a single time in 30 years. The longer the historical time series and the better the quality of hydrologic data, the more exact is the definition of return period flood flows. Statistical probability distributions are used to extrapolate flood flows from decade-long historical time series to very rare events in the range of 500 or even 1000 year return periods.

Water Use and Runoff Generation

Downstream water availability can be influenced by many factors. In most cases downstream water availability is not so much influenced by upstream water use but rather by changes in runoff generation. Especially land use change may have strong impacts on runoff.

For the current flood analysis potential future upstream water use or land use change was not considered due to limited data availability, the uncertainty of future changes and the objective to assess the climate change driven flooding situation. Results show limited impact under the assessed return periods (2 year and 20 year). The situation may be different for other return periods. These findings point out the importance to assess these as well as to consider land use change projections for future assessments.

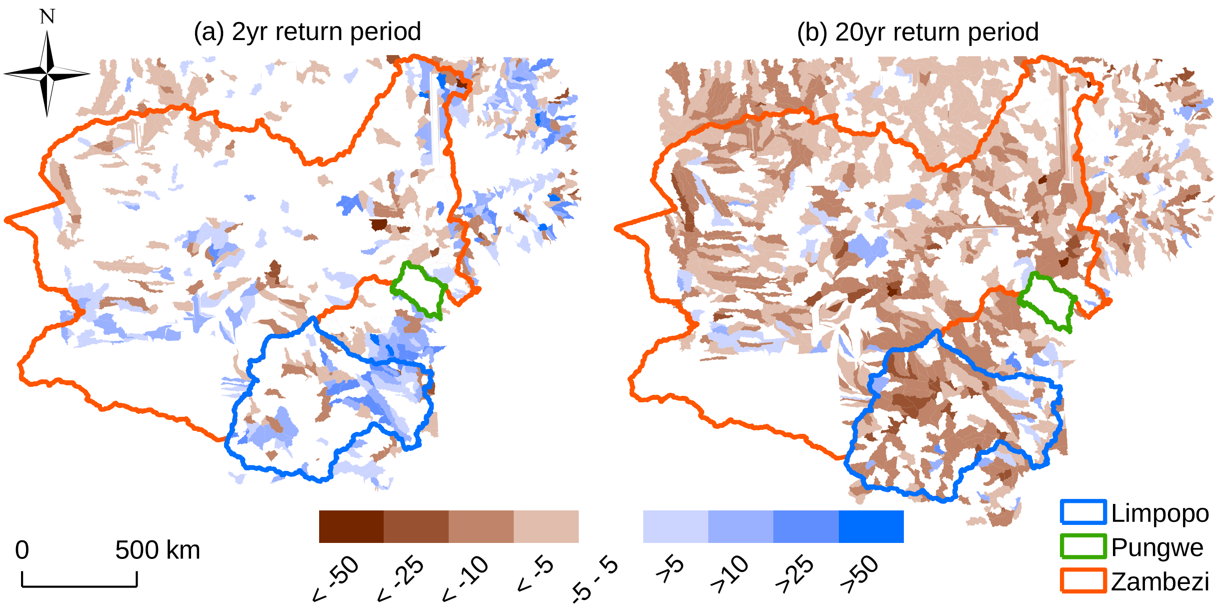


***Figure** 2-9: Change in river flows for individual subbasins under climate change compared to the historical baseline for the 2year and 20year return period flow (data from INGC 2009).*

For the 2year return period an increasing trend is visible in the Pungwe and Limpopo basin, while for the 20year return period decreasing flood flows are predicted by INGC 2009. Note the high variation over neighbouring subbasins.

The displayed dataset is used to derive flow change values for running the climate scenarios in the hydraulic models. Along the main stream channel of the Zambezi, Pungwe and Limpopo the contributing area has been calculated and the flow change values displayed in *Figure* 2-9 have been averaged over these areas. This resulted in a projected flow change for each point along the main channels. These values were set on top of the flow change caused by more frequent events described above. *Figure* 2-10 displays the result of this analysis from up- to downstream. Strong, abrupt changes are caused by tributaries whose change values averaged over their subbasin area differ from the upstream values. Generally, the larger catchments Zambezi and Limpopo are more stable due to their size while the Pungwe is strongly influenced by single subbasins. For the Zambezi, it can be seen that lower floods do not show a distinct change, while extreme flood flows are expected to decrease. The standard deviation is below 10% in the upstream reach and is increased by the Shire catchment to 10%. Many parts of the Pungwe basin, especially the upstream regions will be subject to an increased 2 year return flood flow but standard deviation is very high with more than 25% at the downstream end. The 20 year flood flows will increase slightly within a standard deviation of less than 10%. In the Limpopo basin, 2 year floods are likely to increase in flow by 10-12% while the 20 year flood flows are probably decreasing by around 8-4%. Also here, standard deviations are within 10%.

Hydrological background: Non-linearity between rainfall and runoff

The response of natural systems to rainfall is highly non-linear. A single rain event may not cause flooding during one year but may induce a flood during another year. Similarly, an increase in rainfall intensity by 50% may cause an increase in runoff by more than 50%. The reasons are different hydrological boundary conditions, i.e. the antecedent moisture conditions of the soil, vegetation properties being different over the year or varying climate conditions. Developing a direct relation between rainfall and runoff is thus generally not possible. Climate change models can give a trend in changing rainfall patterns in the future. For obtaining plausible changes in runoff based on changes in precipitation, it is useful to depict the hydrological system with mathematical models that incorporate the hydrological processes and most important boundary conditions.

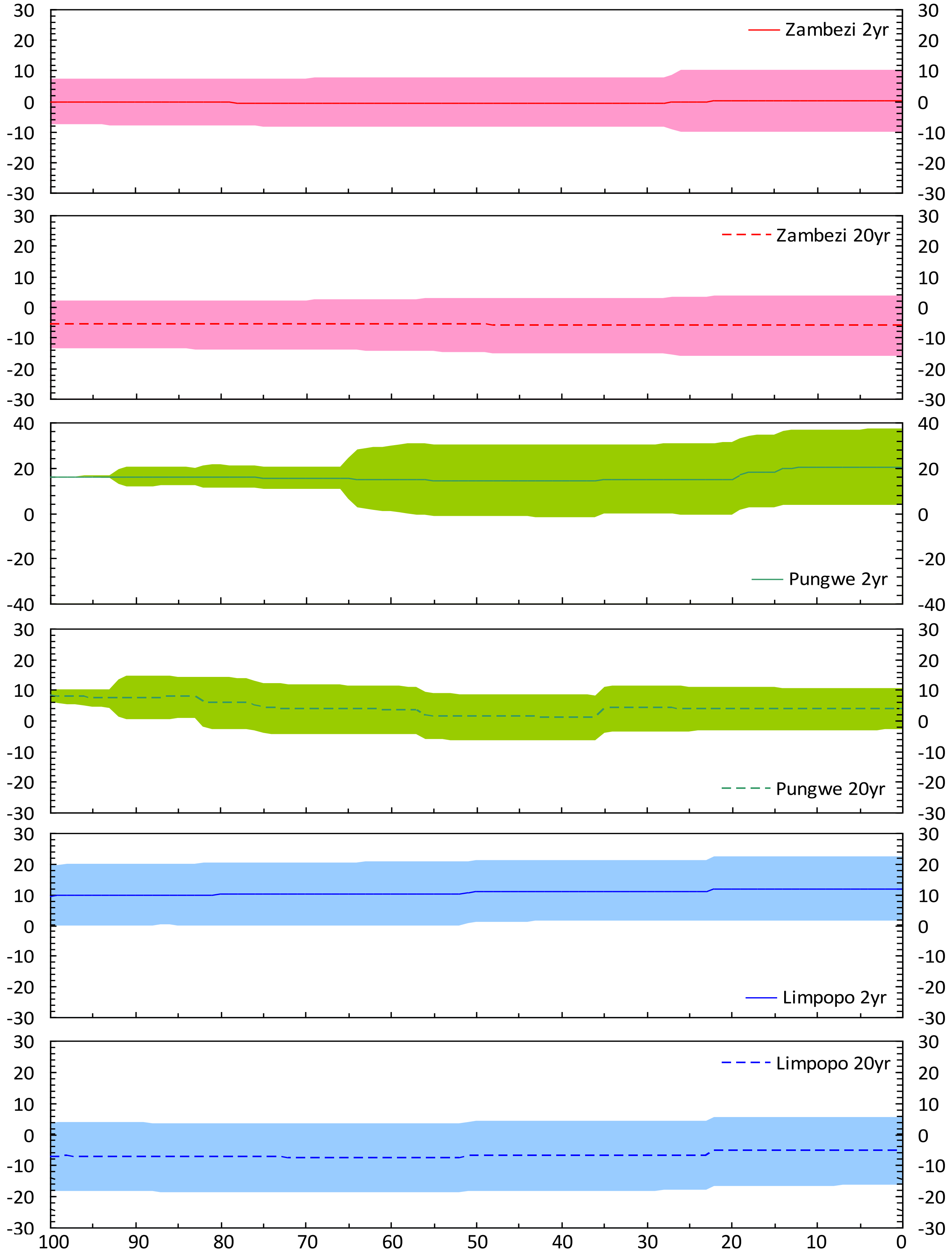


Figure 2-10: ***Predicted flow change between baseline to climate change scenario (y-Axis in %) along the main channels (x-Axis in % distance from the mouth) for the 2 year- and 20 year return periods; standard deviation range in light colours. The narrower the standard deviation band, the higher the agreement of the predicted flow change (solid or dashed lines)***

Data shown in *Figure* 2-10 are used to calculate expected, minimum and maximum climate change flows along the stream channel by multiplying the changes with the baseline flows (*Table* A2.1). The obtained climate change flows at the downstream end of the rivers are summarized in the Annex (*Table* A2.2.2).

2.4.2 Uncertainty Assessment

A methodology that incorporates two tiers was designed to objectively assess the main uncertainties in the modelled inundation extents (*Figure* 2-11).

Tier 1 considers uncertainties of the physical conditions. Average roughness (*Table* 2-1) and average return period flow values (*Table* A2.1) are considered the most likely and are used to simulate the expected baseline inundation. Upper and lower roughness thresholds and highest and lowest flow values for the return periods are used to simulate a high and low baseline inundation event. The uncertainty is defined as the relative difference between the high, expected and low event normalized over the highest deviation within each basin.

The expected baseline inundation is employed in Tier 2 for the climate change simulations. The projected flow changes with their standard deviation (*Figure* 2-10) lead to a high, likely and low climate change inundation event. Again, uncertainty is defined as the relative difference between the high, expected and low event normalized over the highest deviation within each basin.

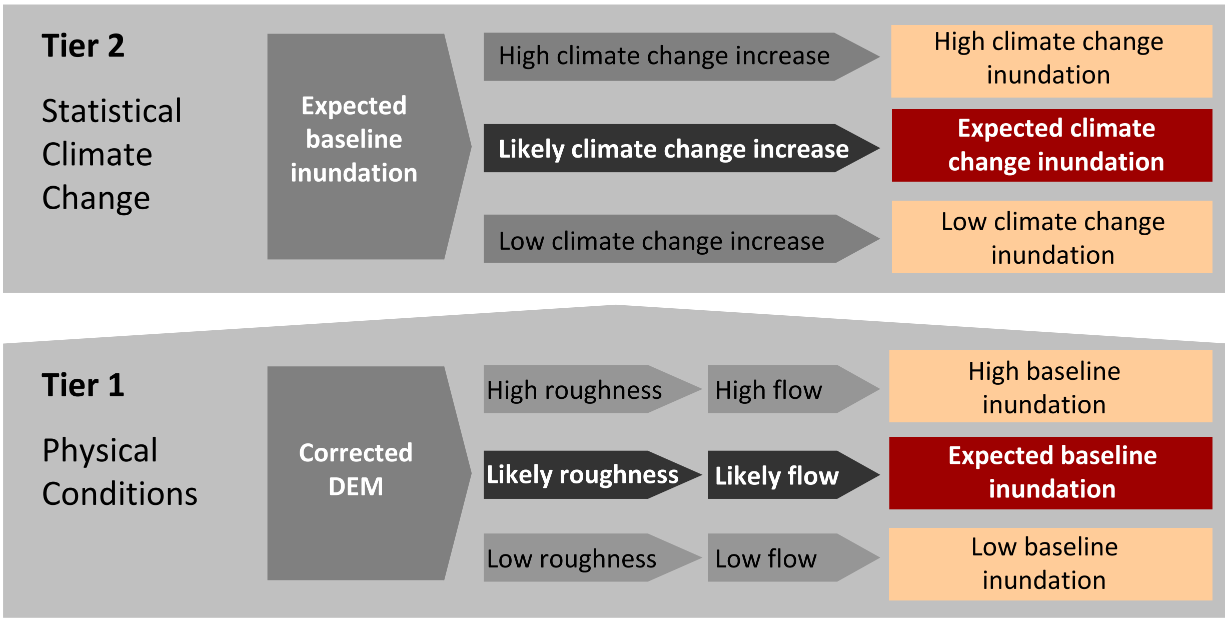


Figure 2-11: ***Low, likely and high data input values for simulating baseline (Tier 1) and climate change (Tier 2) uncertainties***

2.4.3 Model description

The model used for the analysis is the hydraulic model HEC-RAS (Hydraulic Engineering Center – River Analysis System, USACE 2010). HEC-RAS simulates one-dimensional steady and unsteady open channel flow in river networks along cross sections. For steady flow calculations it applies the momentum equation in case of supercritical flow and on hydraulic structures. For basic profile calculations it solves the energy equation with the standard step method. Unsteady flow is calculated with the 1D Saint Venant equations. In flood event calculations, HEC-RAS divides the cross sections in channel and floodplain parts and calculates conveyance separately.

HEC-RAS is widely applied in flood inundation studies world wide. The steady state one-dimensional hydraulic calculations and the user friendly interface enable relatively quick and stable simulations of long rivers. However, one-dimensional calculation procedures use important assumptions as follows. (1) Flow paths have to be defined for the model and are static throughout the model runs. In reality however, the flow path for a flood with different return periods may be different. Complex flow paths in multifaceted environments such as urban areas can not be depicted. (2) The water level is horizontal at all times in a cross section which leads to erroneous water surface calculations, especially in bends. (3) Floodplain inundation mapping using water surface elevations on cross sections produces uncertain results in between the cross sections as water surface elevations are linearly interpolated. (4) Floodplain inundation mapping using 1D model results leads to inundation of all areas of the cross section lying below the actual water level because lateral water flows and the true hydraulic connection between low-lying sections of the floodplain cannot be depicted. This leads to difficulties especially when mapping wide plains.

Two-dimensional models can overcome most of these disadvantages (Tayefi *et al*. 2007) while other studies found that these disadvantages are not severe (Hicks and Peacock 2005). Available computing power however still limits the application as cell sizes in the channel need to be sufficiently small to depict bathymetry. This leads to hundred thousands of cells for long rivers and an excessive or even impossible computation load. A simulation with both 1D and 2D models would be preferable, as steep, long and topographically distinct river sections are suitable for HEC-RAS. The wide floodplains can then be depicted by a 2D model. The Zambezi from Cahora Bassa to the Shire confluence and the Zambezi Delta would be an example for such a joint 1D-2D application. During the projects modelling phase, problems arose when modelling the Zambezi Delta one-dimensionally with HEC-RAS as the limitations described above led to unreasonable results in the delta. It was decided to split the Zambezi HEC-RAS domain and to depict the Zambezi Delta with a two-dimensional model. The model Adaptive Hydraulics (AdH) developed by the USACE Engineering Research and Development Center (Berger *et al*. 2011) is an ideal tool for that task. It will be dynamically linked to HEC-RAS in the next HEC-RAS version (Brunner 2011). AdH solves the two dimensional shallow water equations on a finite triangular element mesh. The uniqueness of AdH is its automatic adaptation of mesh resolution and time steps during model runs to account for user defined accuracy thresholds. Pre- and post processing is conducted with the Surface Water Modelling System (SMS) or ArcADH, an AdH user interface for ArcGIS9 (Kiesel *et al*. 2011). Within this report, AdH and ArcADH is used for the Zambezi Delta and the Flood Risk Assessment.

2.4.4 Model setup

This section explains the modelling methodology and processing of input and output data. Three individual HEC-RAS models have been setup for the Zambezi, Pungwe and Limpopo main river reach. Two different types of data have to be entered to these HEC-RAS models for the simulations: geometry and flow boundary condition information. A summary of the input files and data necessary for the simulations with HEC-RAS and how they are generated is given in *Table* 2-2.

Table 2-2: Summary of data used for setting up the HEC-RAS models

HEC-RAS data requirements	Type	Source
Bank lines	Geometry	Digitized from Google Earth
Flow centreline	Geometry	Derived from bank lines
XS cut lines	Geometry	Automatic generation algorithm
Elevation	Geometry	Corrected SRTM elevation data
Roughness	Geometry	Land use map with values from Chow 1959
Baseline flow	Flow	RMSI calculated return periods, regionalization
Climate scenario flow	Flow	INGC Phase I predicted flow changes
Upstream boundary conditions	Flow	Normal depth calculations based on bed slope
Downstream boundary conditions	Flow	INGC Phase I current and predicted sea level
Date of below bankfull flow	Calibration/Validation	Google Earth image time stamp
Date of flooding and flows	Calibration/Validation	Historical news reports, DNA, other reports
Stage- discharge relationships	Calibration/Validation	DNA
Flood inundation maps	Calibration/Validation	Dartmouth Flood Observatory

For the AdH model in the Zambezi Delta, the topography was interpolated from the HEC-RAS geometry file and the SRTM to a 45m cell size DEM. Surface properties are approximated from the land use map to account for spatially distributed roughness, infiltration and evaporation parameters. Upstream flow boundaries and water inflow extents are taken from HEC-RAS.

Geometry data

HEC-RAS requires the definition of the hydraulic model domain. These data are combined in the geometry file. The bank lines are digitized from Google Earth images. The cross sections should be oriented perpendicular to the flow centerline and have to fully cover the model areas with the floodplains described above. The length of the rivers and the size of the floodplains result in a high number of long cross sections. Especially in bends, overlapping lines are usually difficult to avoid and have to be drawn by hand. For automatizing that procedure, a routine has been developed for drawing the cross sections in ArcGIS in user defined spacing and assign elevation, roughness and ineffective flow areas to the cross section lines. The different roughness value ranges result in three geometry files for each river. Further information on the procedure is supplied in Annex A2.

Flow data

Due to lack of available flood hydrographs for the main channel and tributaries, no flood waves can be routed using unsteady flow calculations. Instead, steady state runs are conducted using the maximum peak flows. Tributary flows are approximated using regionalization and HEC-RAS's possibility of running different flow values along the stream channel with downstream cross sections having higher flow values than upstream cross sections. Baseline and climate change flows (*Table* A2.1 and A2.2) are entered to HEC-RAS. For the climate change scenarios, flow changes are calculated for each cross section individually depending on the spatial distribution of the predicted flow changes (*Figure* 2-10). Upstream boundary conditions are normal depths calculated from the energy slope, which is approximated from ground slope for the Zambezi (0.002), Pungwe (0.003) and Limpopo (0.0006). Downstream boundaries for the respective scenario are given in *Table* A2.1 and A2.2. The necessary assumption is that river floods with a certain return period coincide with sea floods of the same return period. Naturally, this might not always be the case, but as river flood models cannot simulate coastal flooding, this assumption is more reasonable than assuming zero sea level only.

2.4.5 Floodplain mapping methodology

Version 4.1 of HEC-RAS has an own mapping software, the RAS-Mapper. It overlays the calculated water surface elevations along the cross sections with a digital elevation model and assigns lower elevations than the water surface as wet and higher elevations as dry. Interpolation is carried out between the cross sections and the result is exported to a shapefile. The resulting shapefile has to be checked for plausibility which is done using ArcGIS. All areas of the cross section that lie below the water surface elevation are shown as inundated regardless of the true hydraulic connection to the main channel. Inundation of areas that are only poorly hydraulically connected to the main channel depends on the distance to the channel, local conditions regarding groundwater, soil and land use properties, rainfall and small scale topographic characteristics. Flooding in these areas can be caused by river waters, but also by prolonged rainfall. If soil moisture is close to field capacity, surface runoff can cause ponding of water. This phenomena is observed in Mozambican catchments where parts of floodplains become inundated through surface runoff ponding (Gosnell *et al*. 2001). During the 2001 Zambezi flood this was observed by depths of up to 2m (Beilfuss and Dos Santos 2001). As an example, *Figure* 2-12 shows a representative cross section from the Pungwe floodplain. It can be seen that the channel (at distance 13km) lies on a slightly higher elevated region. The surrounding depressional areas are shown as inundated. From a topographical viewpoint, such areas are likely prone to surface water ponding.

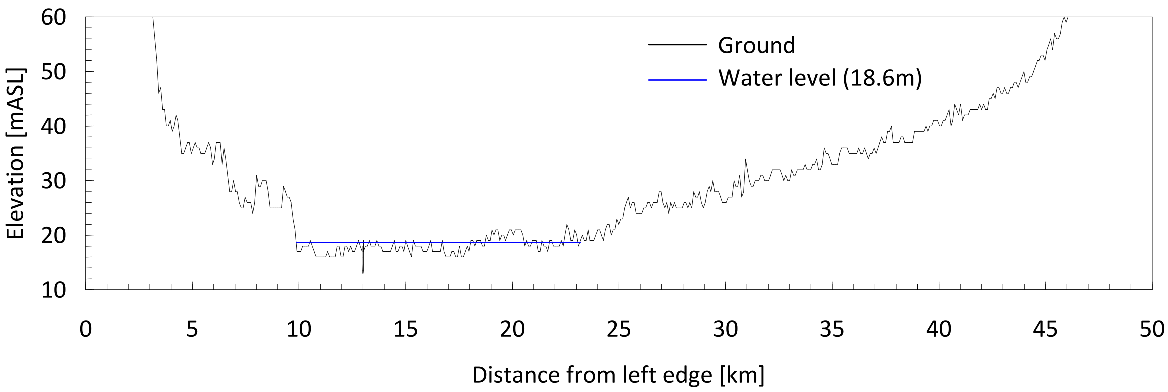


***Figure** 2-12: Cross section from Pungwe River, 116km from mouth. Note the channel at 13km, the elevated area at 20km and the inundated region indicated by the blue line.*

2.4.6 Model calibration and validation

<u>*Channel depth calibrations*</u>

The bankfull flow values (*Table* A2.1) are used to calibrate channel depths calculated through equation [2.1] (Annex A2.1). Bankfull flow is defined as the point where flow fills the channel to the top of the banks just before water flows into the floodplain. Channel depth was adapted in an iterative process to match bankfull discharge reasonably well along the three rivers. Generally, Hey and Thorne's equation overestimated flow depths in the Zambezi which seems to be shallower than predicted. The river was divided into 14 sections for which depths were adapted individually. In average they had to be reduced by 53%. The original depth values for the Pungwe matched best, with adaptations necessary only in four of the eight sections and an average reduction by 21%. The Limpopo was divided in 15 sections, for which depths were reduced by 25% in average.

Comparison with stage-discharge measurements

Stage and discharge measurements for the Zambezi, Pungwe and Limpopo have been supplied by DNA (2011) for a range of flows. Unfortunately, only 3.8% of the measurements have been conducted during the last decade. From these most recent records, the measured discharge deviates from the used rating curve by 58.4% in average. *Figure* 2-13 shows the measured data for all available stations (grey dots). The Figure is read from left to right and from top to bottom. The order of the respective gauging stations along the main channels is from downstream to upstream. The number in square brackets is the number of rating curves used over the years (number in round brackets). The range of flows represented in the measurements have been run in HEC-RAS and modelled stage-discharge relationships have been plotted in the according diagram (red squares). Model results are best for the stations in the Limpopo. Considering the poor quality of the data used for the modelling and the mostly decades-old measurements, agreement between measured and modelled values also in the Pungwe and Zambezi is satisfactory. The shape of the curves does not always match with measured data because the assumed channel geometry of 45° bank slope and a flat river bed in the model cannot match to all cross sections at different gauges. Deviations for the higher flow and stage values have been expected as measurements in such conditions are uncertain and very difficult to accomplish.

Comparison with historical flood events

Satellite images from historical flood events are available from Landsat and MODIS as well as from the Dartmouth Flood Observatory (DFO 2011). The DFO maps show corrected inundation areas and are the most suitable for comparing modelled with observed flood extents. A range of flow values is run in the three HEC-RAS models (Table A2.1) and simulated flood extent is compared with mapped inundated areas. The DFO maps have been digitized to allow for correction of implausible areas marked as inundated, which are mostly mountain shadows. Overlapping and non-overlapping areas between modelled and observed flood extents can then be calculated. *Figure* 2-14 shows the result of the simulations, the DFO map and the model domain. The visual comparison indicates good agreement in the upper and middle reach of the Zambezi for the year 2008 flood modelled with HEC-RAS. Inundations in the Zambezi Delta modelled with AdH are also depicted well. The model is capable of simulating the split flow ratios. Overestimations of inundations can be seen on the main channel. The lower part of the north eastern branch shows some weaknesses in the correct location of the flooding but generally can also be considered plausible. Apart from overestimations in the upstream 100km and a 30km long part in the lowlands, HEC-RAS can also reproduce the year 2000 flood in the Limpopo. According to *Table* 2-3, performance in the Zambezi (excluding the Zambezi delta) and Limpopo is also good, as more than 80% of the inundated area is covered by simulated inundated area and the size of the modelled and observed areas are equal. Some difficulties are however visible in the Pungwe, where the model overestimates flooding in the middle part. In total, simulated inundated area has almost twice the size of the observed (*Table* 2-3). The reason is, that flat areas which are lower in elevation than the channel bed become assigned as inundated (as discussed in Section 2.4.5) which are not marked as flooded in the Dartmouth map.

Table 2-3: Comparison of modelled (HEC-RAS) to observed (DFO) flood events

River	Year	Flow [m³/s]	Approximate Return Period [years]	HEC-RAS area covered by DFO area [%]	DFO area covered by HEC-RAS area [%]	HEC-RAS area divided by DFO area [%]
Zambezi	2008	33343	RP 500	83.3	83.3	99.9
Pungwe	2010	1703	RP 20	45.1	84.6	187.5
Limpopo	2000	9300	RP 500	81.1	80.5	99.3

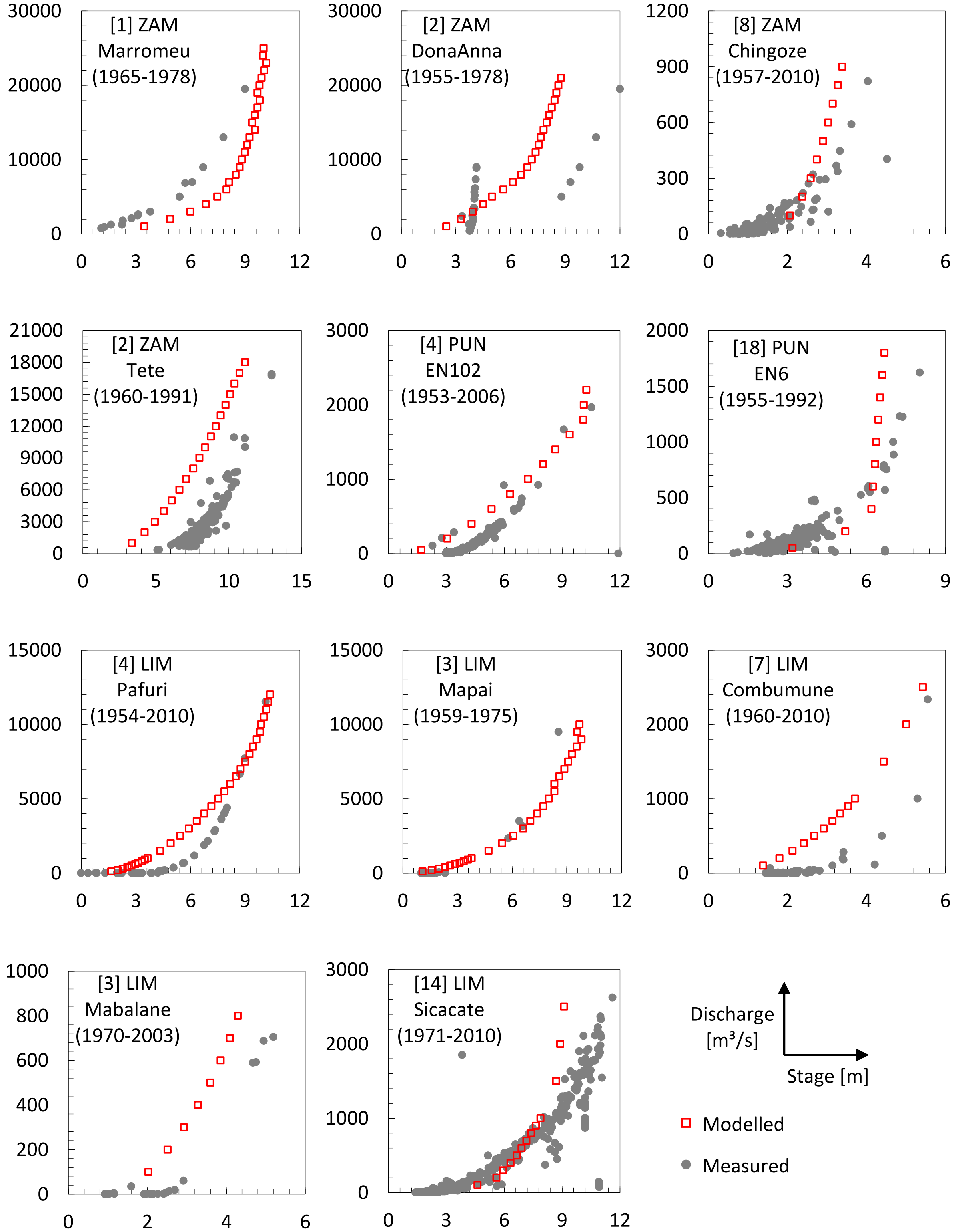


Figure 2-13: ***Comparison of modelled and measured (DNA 2011) stage and discharge at Zambezi (ZAM), Pungwe (PUN) and Limpopo (LIM) main channel gauging stations. Deviations are assumed to be a result of differences between estimated and real cross section geometry***

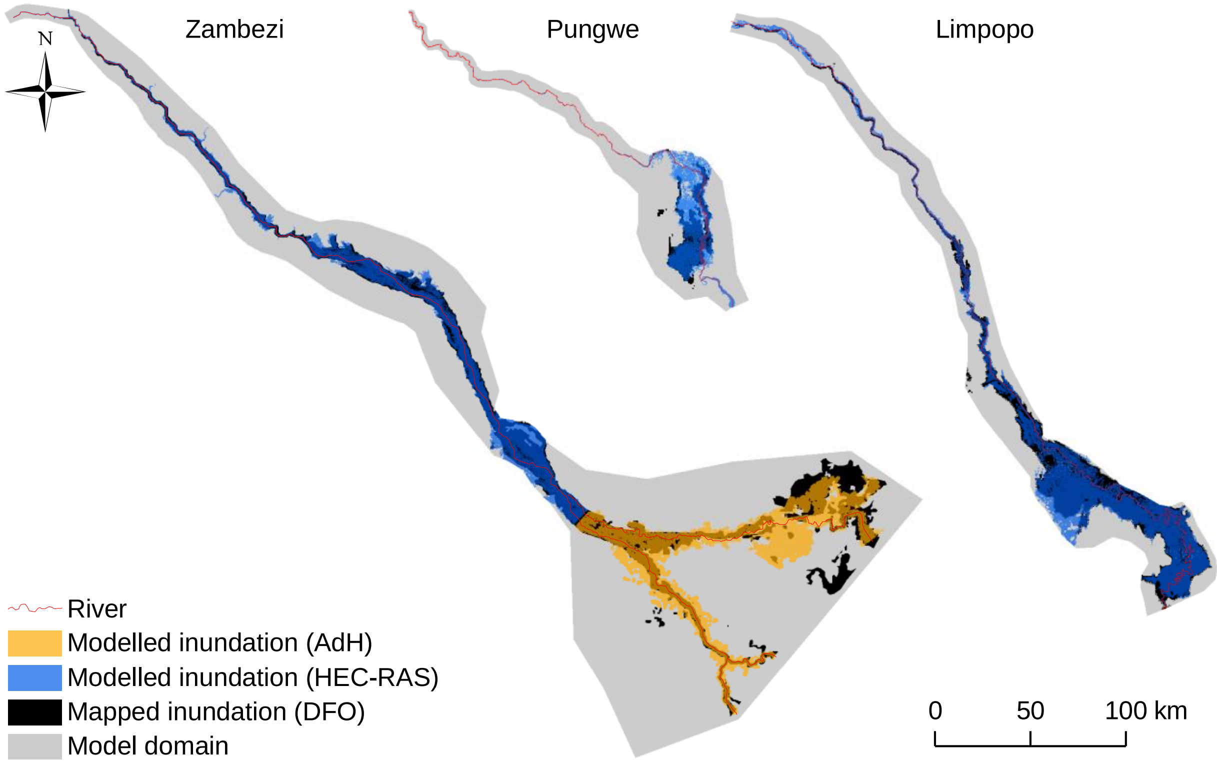


Figure 2-14: ***Mapped and modelled inundation for model calibration (historic) events (2008 Zambezi, 2010 Pungwe, 2000 Limpopo).***

Probable reasons for the deviations between predicted and observed are inundations caused by coastal flooding, surface water ponding (Zambezi) and the designation of lower lying areas as inundated (Pungwe)

2.5 FLOOD MAPPING RESULTS

Four flood inundation layers each have been created for the Zambezi, Pungwe and Limpopo main channel: The baseline (1961-2000) 2 year and 20 year flood- and the climate change (2045-2065) 2 year and 20 year flood event. The maps consist of four sheets each for the Zambezi and Limpopo (upper and lower part of the rivers for baseline and climate change events) and one sheet for the Pungwe (baseline and climate change). They are designed to be printed on A0 paper. The inundation shapefiles are overlaid with topographic maps in 1:200,000 scale from the Soviet Military, the hillshaded SRTM, the digitized channel and English names of the major cities. Areas outside the model domain which could not be included in the flood modelling are greyed out. Flooding or non-flooding of those areas can thus not be depicted on the maps. The shown inundations (blue and red) indicate that those areas are potentially at risk of flooding for the 2 year return period (occurrence probability of 0.5 per year) and for the 20 year return period (occurrence probability of 0.05 per year). The rivers stationing is shown in 10km intervals, starting with 0 at the mouth. The same stationing is applied to the uncertainty diagrams included in the maps. In that way, it is possible to relate the shown inundation along the rivers to the uncertainty inherited in the results at a particular location. The diagrams are the result of the uncertainty assessment explained in *Figure* 2-11 and show a relative uncertainty with the range between -1 and 1. Highest values (1 or -1) represent stretches with highest uncertainties for the representative river. Positive values indicate that it is more likely that the shown inundation underestimates the flood situation while negative values indicate that it is more likely that the shown inundation overestimates the flood situation. The baseline uncertainty includes flows and roughness ranges that show deviations to the expected inundation. The climate change uncertainty includes the standard deviation of the flow change predictions based on the expected baseline inundation. The flood maps are in the same projection as the Soviet Military topographic maps (Transverse Mercator, Gauss Krueger Zone 6, Pulkovo 1942) including a grid in decimal degrees for orientation. For clarity, the detailed legend description of the Russian topographic maps is not included but can be viewed in USA-WO (1958).

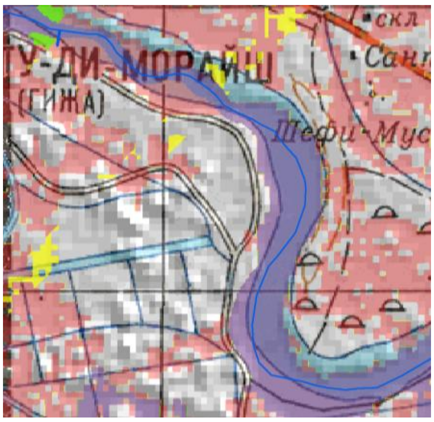
As per the clients request to focus on the three locations Tete, Caia (both Zambezi) and Chókwè (Limpopo) for investigating possible flood defences, the following figures show details of the original flood risk maps for the three regions for both baseline and climate change 2 year and 20 year return period flows.

Figure 2-15 and *Figure* 2-16 show the city of Chókwè at the Limpopo River. The city and directly adjacent areas seem not to be affected by 2 year return period flood flows. For the 20 year floods however, flood waters can reach the city area. The uncertainty diagrams at station 232 indicate that the 2 year flood inundation is relatively certain, meaning that the flow will probably stay in the river bed for the modelled flow and roughness ranges. Uncertainties between +0.5 and -0.1 for the 20 year event imply, that the expected inundations are on the lower end of the possible inundation range. For the climate change scenario, projected flows for the 2 year scenario are projected to increase by 13%, for the 20 year scenario a decrease of 5% is projected. A significant impact on the modelled inundation in the Chókwè area cannot be observed. Uncertainties due to scatter in the climate change dataset are also marginal.

Model results show that Tete at the Zambezi (*Figure* 2-17) seems not affected by 2 year return period flood flows. It is likely, that 20 year flood flows can inundate the lower lying area south west of the main city. Due to the distinct terrain, uncertainties at the stations 470-475 are low. The climate change scenario (*Figure* 2-18) with unchanged flow for the 2 year return period and a decrease by 7% for the 20 year flows shows minor changes in inundation of the 20 year event.

Caia lies approximately 5km off the banks of the Zambezi River and is displayed in *Figure* 2-19 and *Figure* 2-20. For the 2 year event inundations are marginal with few and small individual patches of water around the city. For the 20 year event, the model shows connected inundated areas around the city cutting off transportation infrastructure. Uncertainties for both events at Caia (at river station 172) show that slightly higher and lower inundation is equally possible. Climate change uncertainty as well as the change in inundation is negligible at that point.

Climate change impact comparison
Comparing baseline with climate change flows directly in a single map will not add significantly new information. The difference between the scenarios will not be very distinct. The main reason is the coarse elevation steps of the SRTM in 1m intervals. A representative example is provided from the Limpopo where it can be seen on the yellow (20 year return period differences) and green (2 year return period differences) areas, that differences between baseline and climate change scenarios are relatively small.



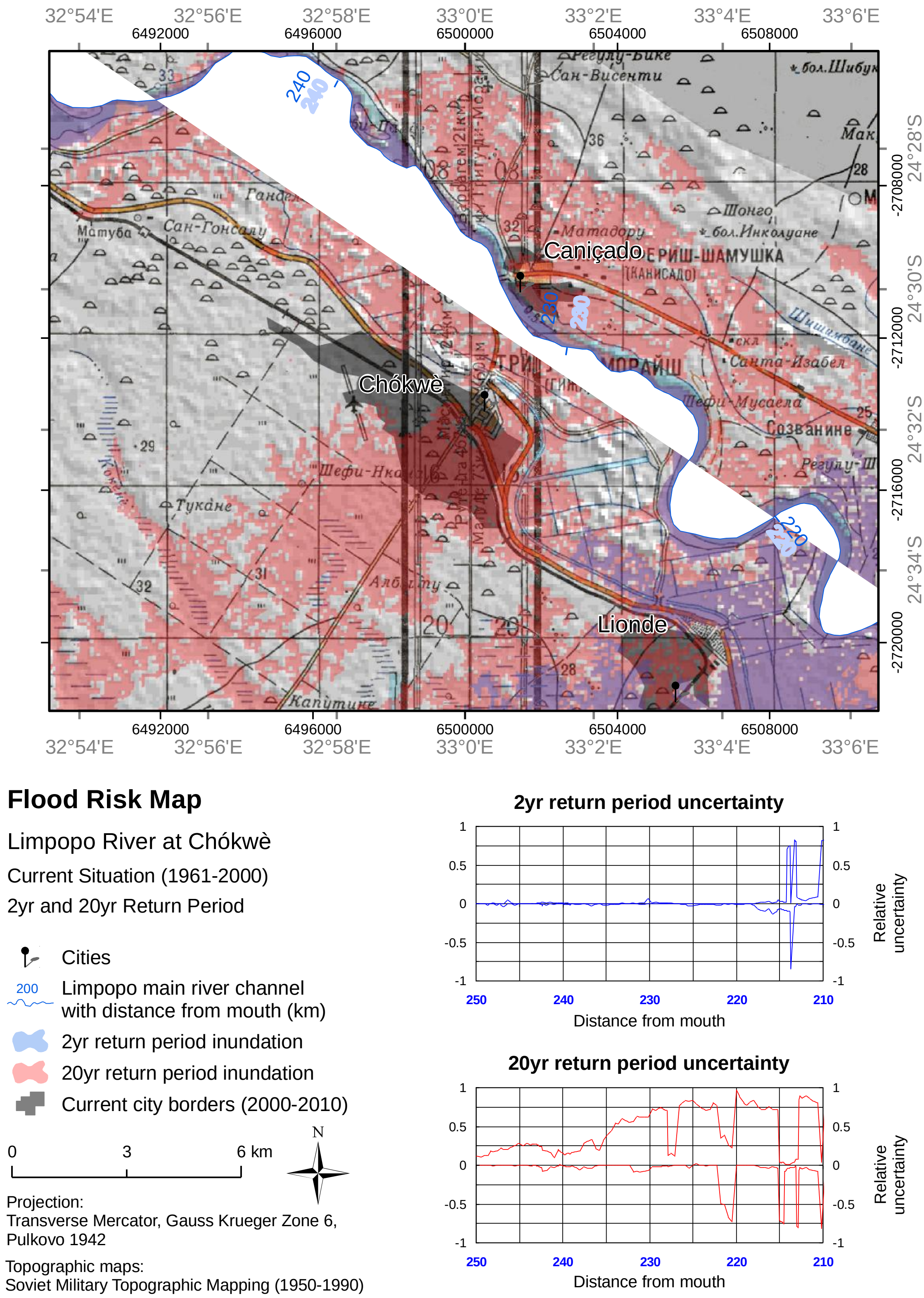


Figure 2-15: ***Flood Risk Map for the Limpopo river at Chókwè for the 20 year and 2 year return period baseline scenario including uncertainty diagrams***

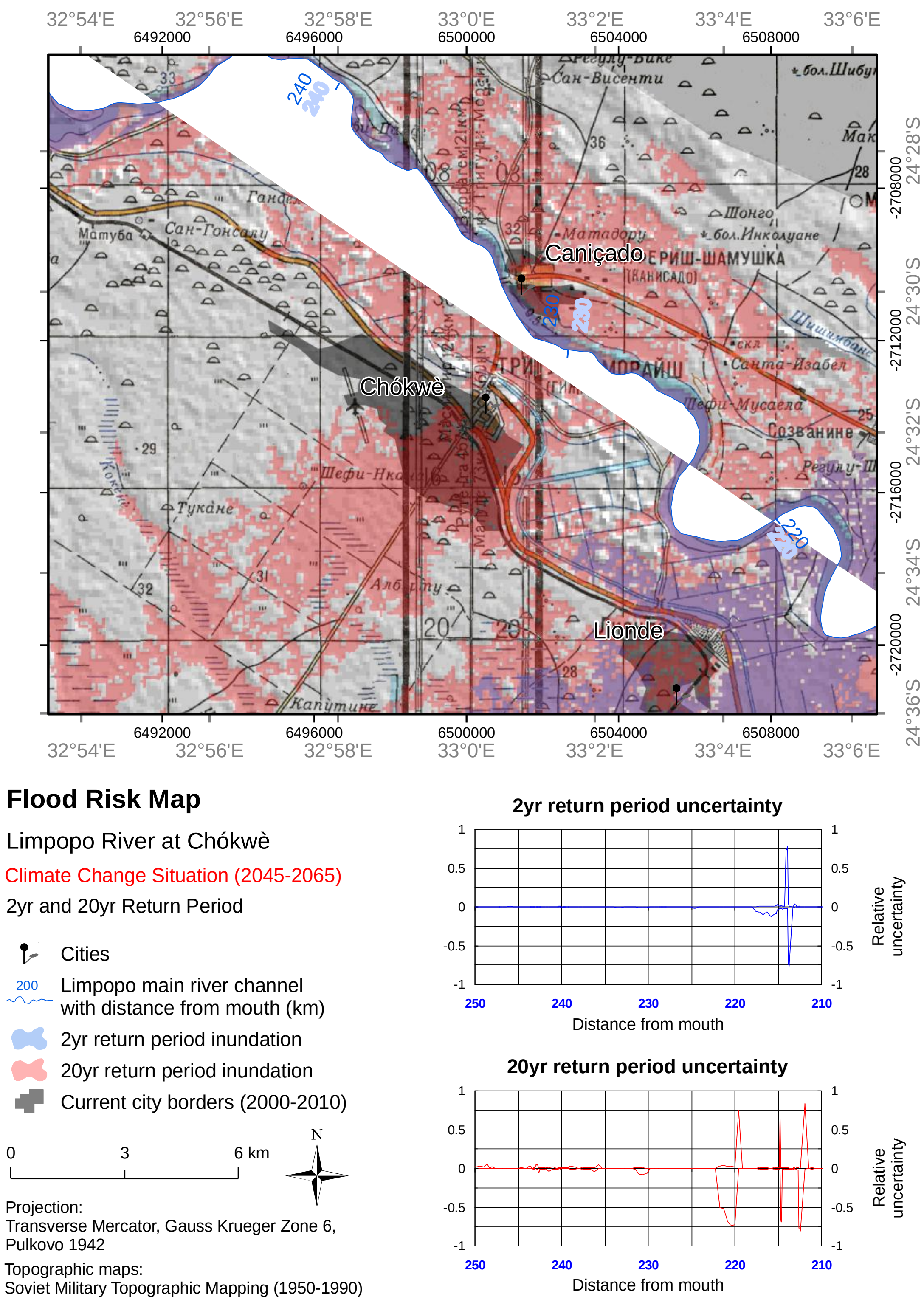
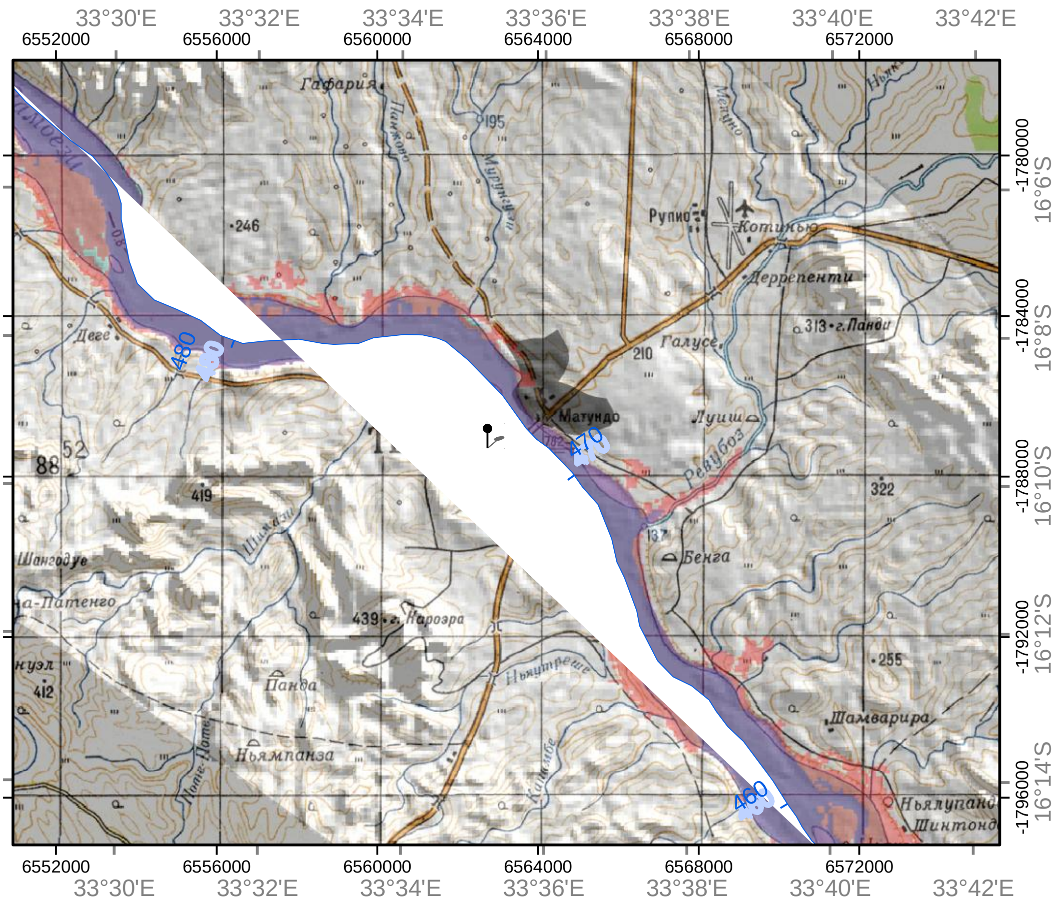


Figure 2-16: Flood Risk Map for the Limpopo River at Chókwè for the 20 year and 2 year return period climate change scenario including uncertainty diagrams



Flood Risk Map

Zambezi River at Tete

Current Situation (1961-2000)

2yr and 20yr Return Period

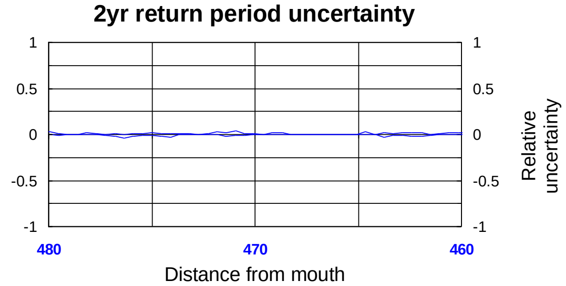
- Cities
- 470 Zambezi main river channel with distance from mouth (km)
- 2yr return period inundation
- 20yr return period inundation
- Current city borders (2000-2010)

0 3 6 km

N

Projection:
Transverse Mercator, Gauss Krueger Zone 6,
Pulkovo 1942

Topographic maps:
Soviet Military Topographic Mapping (1950-1990)



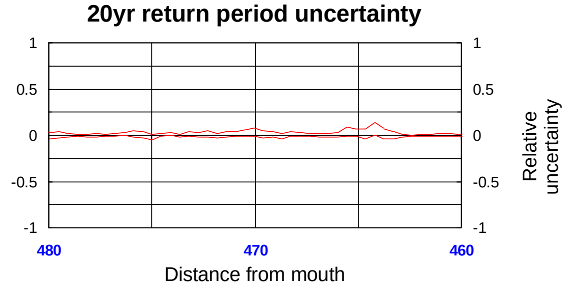


Figure 2-17: *Flood Risk Map for the Zambezi River at Tete for the 20 year and 2 year return period baseline scenario including uncertainty diagrams*

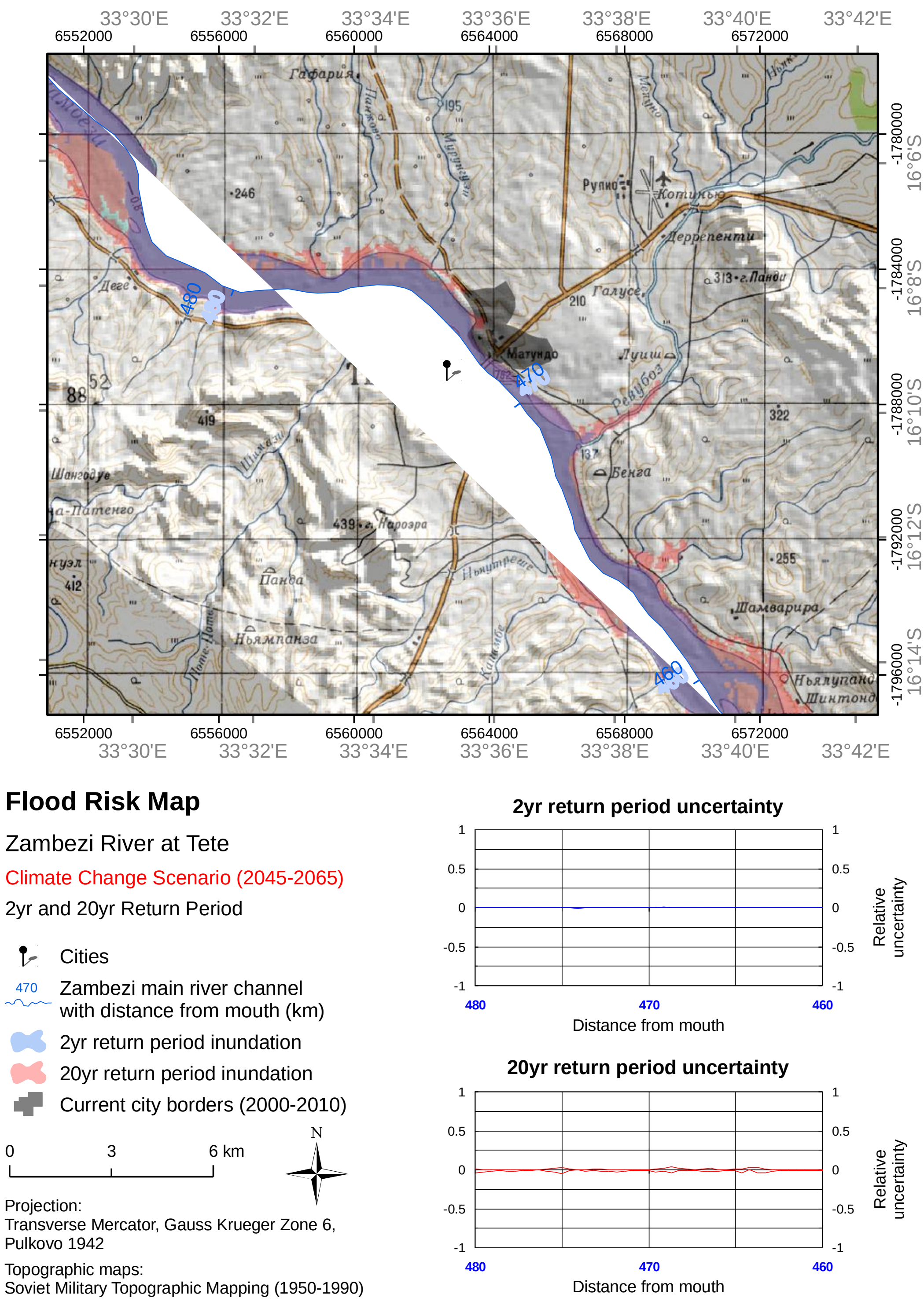


Figure 2-18: ***Flood Risk Map for the Zambezi River at Tete for the 20 year and 2 year return period climate change scenario including uncertainty diagrams***

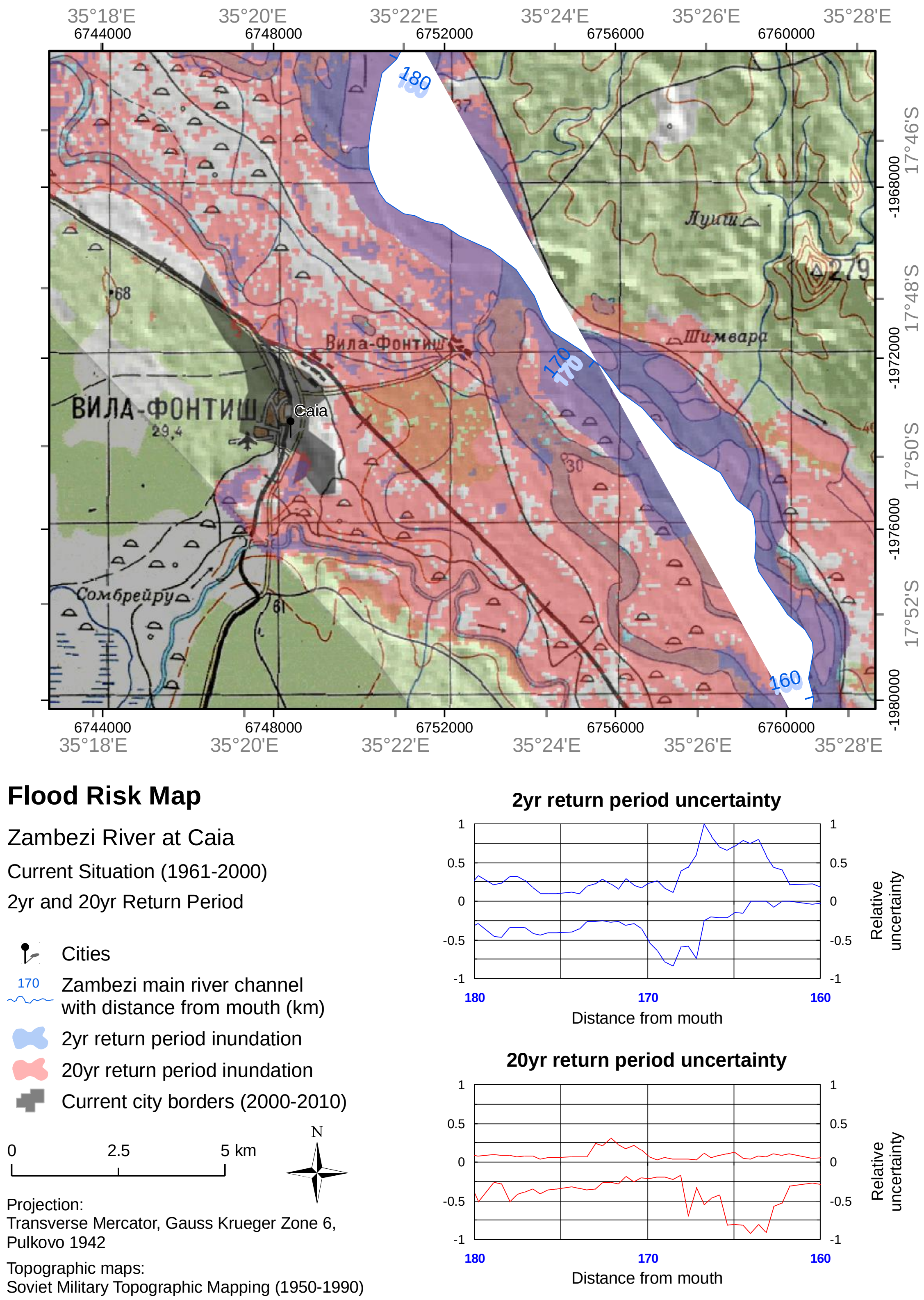
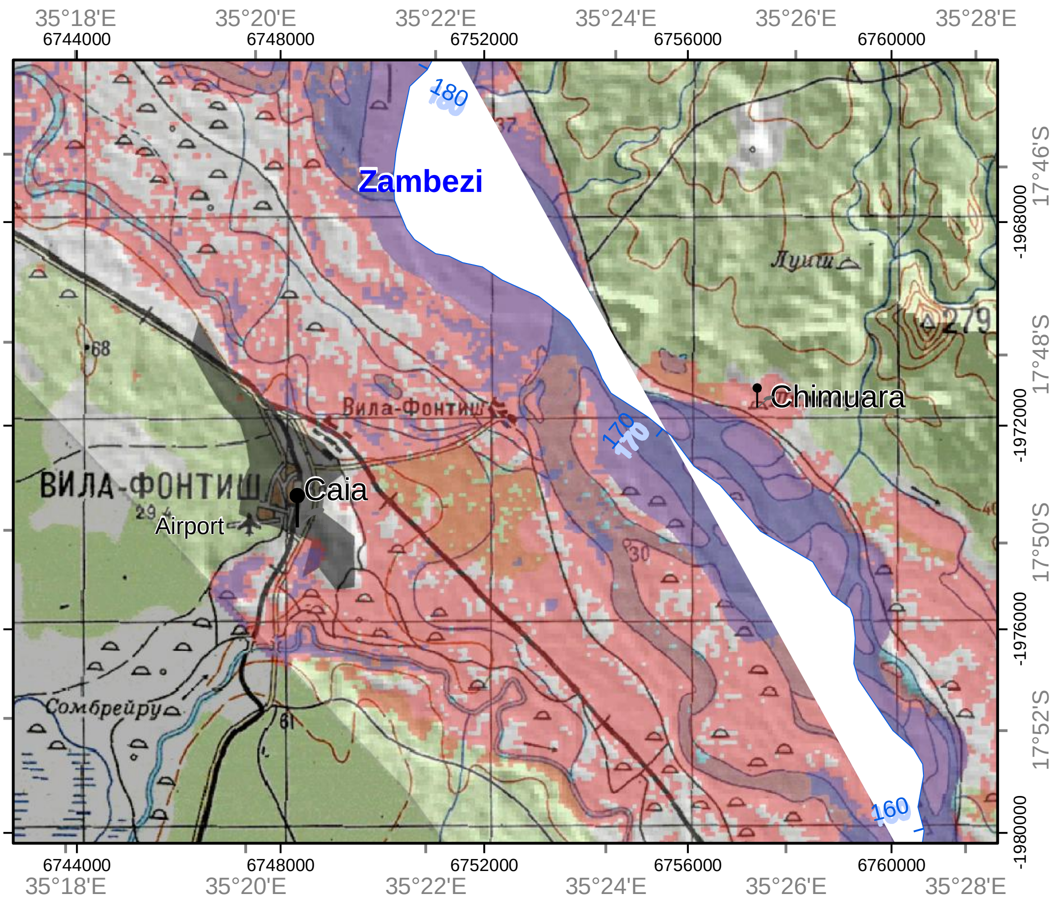


Figure 2-19: ***Flood Risk Map for the Zambezi River at Caia for the 20 year and 2 year return period baseline scenario including uncertainty diagrams***



Flood Risk Map

Zambezi River at Caia

Climate Change Scenario (2045-2065)

2yr and 20yr Return Period

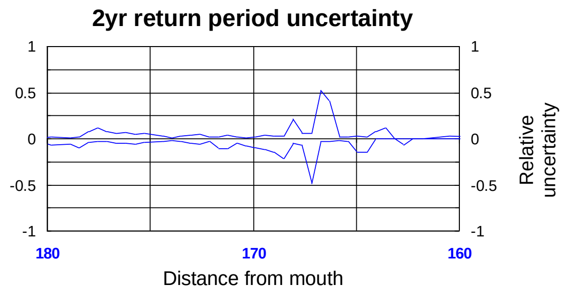
- Cities
- 170 Zambezi main river channel with distance from mouth (km)
- 2yr return period inundation
- 20yr return period inundation
- Current city borders (2000-2010)

0 2.5 5 km

N

Projection:
Transverse Mercator, Gauss Krueger Zone 6, Pulkovo 1942

Topographic maps:
Soviet Military Topographic Mapping (1950-1990)



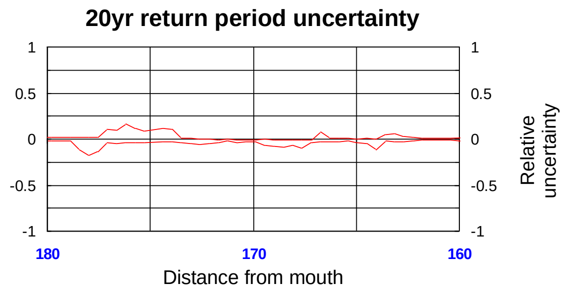


Figure 2-20: Flood Risk Map for the Zambezi River at Caia for the 20 year and 2 year return period climate change scenario including uncertainty diagrams

2.5.1 Flood mapping recommendations

Carrying out the flood modelling and mapping works, shortcomings as well as opportunities have been observed that have lead to the formulation of these recommendations.

1. The flood model and mapping results can be used as a basis for a more detailed Flood Risk Assessment (FRA) as described in Section 2.6. The developed HEC-RAS model can supply boundary conditions for more detailed localized two dimensional models and the shown inundation maps can be used to select the approximate areas (the inundation zones) where additional topographic data has to be recorded, e.g. through LiDAR flights. Section 2.6 shows an example application of a FRA including the respective data requirements. Such detailed FRA would also be the base for detailed flood defence design for which baseline information and recommendations are given in Section 2.7.
2. A strong recommendation resulting from the flood modelling and mapping would be to combine the flood model developed under this subcomponent with the Decision Support System developed under Subcomponent 1 of the water component of INGC Phase 2. The proposed extension would entail the combination and enhancement of the Decision Support System for the Zambezi and the flood model developed under the program for the Zambezi in Mozambique by including the ability to show flooding as a result of discharge scenarios into the DSS. This was not possible before the SC2 flood model was developed as no discharge related flood estimates were available. The enhanced tool would enable the use of the DSS to assess the impact of climate and anthropogenic changes in the river basin on flooding on the Zambezi. Vice versa, the enhanced tool would enable decision makers to use the DSS to assess possibilities for flood control on the Zambezi considering existing and planned dams including their operation. The flood extension for DSS would provide decision makers in Mozambique with so far unavailable knowledge about relations between river basin management and flooding and could be used to directly relief the riparian population on the Zambezi from floods through development of strategies and measures for flood relief. The DSS could be used for establishing flood risk zones (e.g. for 100/1000 year return periods) which could serve as a base for development policies as it is common practice in other countries. The DSS would allow easy display of these and respective dissemination to the public. In the same way as the current DSS, the Flood DSS could be accessed remotely through the internet which would strongly help to disseminate flood risk information.
3. Hydrometeorological data availability considering both quality and spatial coverage is an issue in the basin. It is recommended that an improved hydrometeorological monitoring and observation network will be designed and implemented through which important data can be provided. I.e. the detailed flood risk assessments in Recommendation 1. can not be carried out with sufficient station data in close proximity to the assessed area. The network should fill the current observation gaps and provide the necessary base for future detailed hydrometeorological analysis. A tiered approach could be used to ensure that priority locations would be equipped with monitoring equipment first. Parallel capacity building would be essential to ensure the sustainability of the network with regards to data collection, quality assurance and storage. Improved data collection would be a prerequisite for most detailed future studies and considering the time needed to build up usable timeseries this recommendation could be considered a priority.
4. Topographical data publicly available for Mozambique with good spatial coverage is restricted to SRTM and ASTER digital elevation models which feature a coarse spatial

resolution (90m and 30m cell size respectively) and considerable inaccuracies and uncertainties in their vertical accuracy. There are different commercial possibilities on the market (e.g. LiDAR, Quickbird) that would allow improving the situation. As these datasets are expensive a detailed analysis would need to be conducted prior to such data acquisition to identify hotspot areas or stretches for which such data should be acquired for further detailed analysis, e.g. the above mentioned detailed flood risk assessments. Acquisition of the topographical data should go in line with acquisition of hydrometeorological data in order to ensure comprehensive datasets. Details about data acquisition are provided in the Annex.

5. It is recommended that currently available but scattered data from different sources and data that would be collected from an improved monitoring and observation network as well as the acquired topographical data would be systematically collected, quality checked and stored in a data portal to ensure quality and accessibility. A good example of such a portal has been developed for Somalia and can be visited under www.faoswalim.org. The benefit of such a portal would be straightforward access to a comprehensive database which would reduce time for data searching and reduce the risks for gaps for future studies and educated decision making.
6. Coastal flooding through extreme metocean conditions is not included in the flood modelling and mapping where a “normal” tidal level was assumed. Respectively only one source of flooding – river flooding – has been depicted for the estuaries of the three assessed rivers while these areas are prone to ocean induced flooding as well. It is recommended to analyze the estuarine flood risk using a combined river/ocean model in a 2 dimensional numerical approach. The model developed in this project could provide the necessary upstream boundary conditions for such an analysis. The estuarine flood risk assessment would need to include river flow, tidal conditions, waveclimate and storm surges, also considering backwater effects. The assessment would be possible with the currently available datasets though more detailed data as described under Recommendation 3. and 4. would obviously add to the accuracy.
7. The modelling and mapping carried out in SC2 has resulted in a flood model capable of depicting the flood situation along the Zambezi. Due to data restrictions resulting from the INGC Phase 1 work only 2 year and 20 year return periods were modelled while more extreme events have not been covered. It is recommended to expand the modelling work to cover additional flood events with e.g. 100 year and 1000 year return periods. The necessary data is now available through the SC1 DSS work carried out under this project. The work would be a prerequisite (or part of) to develop the Flood DSS as described in Recommendation 2.
8. The flood model and maps developed under SC2 are a result of steady state considerations based on the existing data. With the current observation systems and system knowledge, future scenarios for different return periods have been developed and can be used for flood risk management. To increase early warning and action capabilities of emergency agencies and in this way directly benefit the riparian population, operational flood forecasting using real time data would be a logical next step. Real Time flood forecasting would significantly improve INGC´s capability to move from reacting to acting in prevention of catastrophic events. Real time flood forecasting including the respective warning measures would significantly alleviate flood impacts, reduce loss of life and property by 1. warning potentially affected population and 2. reducing catastrophic flood levels by respective preventive dam operation (i.e. preventive spilling to increase retention capacity before the flood wave hits). In addition the potential real time DSS could be used to quickly test choices for flood retention of

the upcoming flood. Methods suitable for real time flood forecasting have been described for example in the RIMAX project (Petersen, 2009), where state of the art remote sensing based monitoring has been and possible methods are described including their adaptation to conditions in developing countries.

9. Policy guidelines that could potentially be used for development control in flood risk areas have been proposed in the Annex. It is strongly recommended to further develop and implement these policy guidelines in order to prevent and control further physical developments in flood prone areas.

2.6 FLOOD RISK ASSESSMENT (FRA)

It was not possible to carry out a detailed Flood Risk Assessment within Mozambique because of lack of hydrologic and topographic data. No approximate flood inundation levels for defined return periods have been available prior to this report which leads to the problem that the exact location is not known where necessary elevation and bathymetric data would have to be recorded. As outlined in the proposal, an example FRA is conducted instead to show data requirements, general procedure and possible results. A similar study could be implemented in Mozambique if necessary data as described in the Inception Report would become available.

2.6.1 Introduction

Hypothetical scenario for the FRA: A commercial compound in a developing country had been built in the vicinity of a valley when hydrologic data have not been available. The area consists of a large factory and numerous small businesses next to the factory hall. The local authorities plan to refurbish the buildings, along with an extension of two new storage halls. Recently, statistical time series analysis of discharge measurements indicated, that the area is prone to flooding. Prior to starting the detailed planning phase, the authorities decided to investigate the hydraulic status quo and to assess the impact of the two new buildings in case the area would get inundated through a flood.

It is the scope of this flood risk assessment to (1) derive detailed predictions concerning the current hydraulic status for a 50 year and 100 year flood with climate change and (2) to assess the influence of the two structures on water depths and flow velocities in the 4ha compound. The security of people working in the area is the target parameter on which the assessment is carried out. Based on two-dimensional hydraulic modelling, recommendations will be given if the buildings should be constructed as well as if and how mitigation measures and evacuation procedures should be put in place.

2.6.2 Site description

Figure 2-21 shows the DEM with breaklines, describing the setting of the compound with the valley flowing from north-west to south-east, the large factory building on the right floodplain (north-west) with the planned storage halls. The halls have an area of 1500m² each and are 6m high, located on the eastern side of the factory (blue squares). Other small buildings on the low-lying floodplain can be seen.

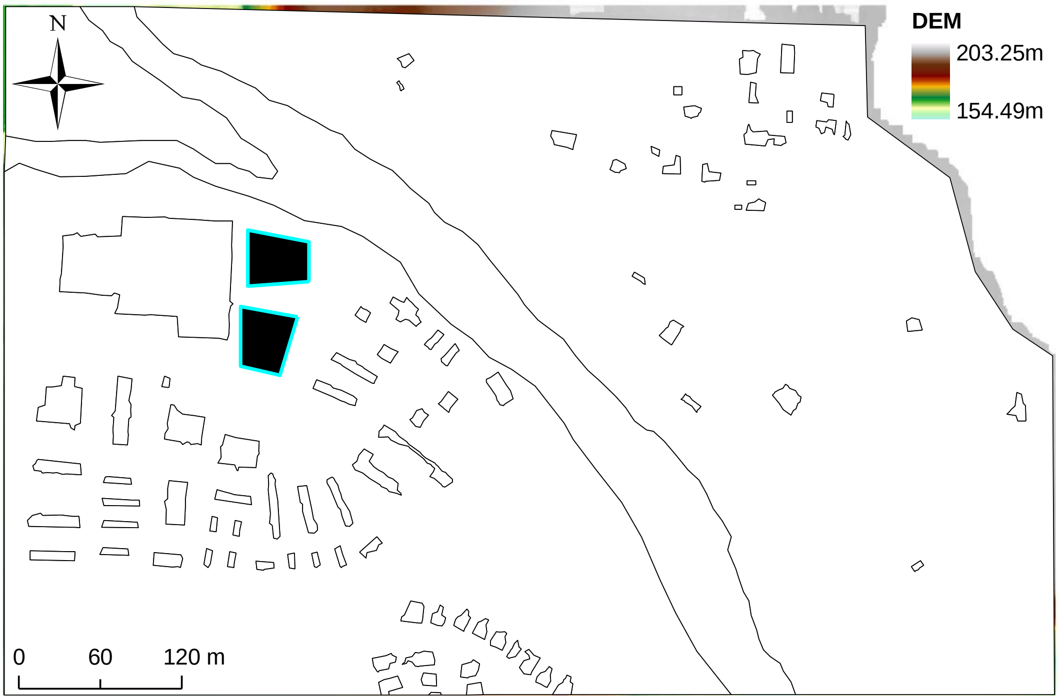


Figure 2-21: LiDAR derived DEM with building- and river breaklines (black) and proposed construction (blue)

2.6.3 Modelling

The simulations are carried out with the two-dimensional AdH model (Berger *et al*. 2011) and the GIS interface ArcADH described in Section 2.4.3.

Data input

Surface and river bed elevation are depicted through an elevation dataset generated from LiDAR with a grid size of 1m (Opentopo 2011), combined with echosounding data to cover the river bathymetry. The representation of the planned storage halls is accomplished by increasing all raster cells within the building area by 6m. These two grids are the basis for the baseline and scenario model runs. Daily discharge and water level data since 1981 are available at a gauge a few kilometers downstream of the model domain. A one-dimensional hydraulic model was used to calculate stage-discharge relationships at the downstream border of the model domain. Topographic data for the 1D model was also taken from the LiDAR and echosounding dataset. The 31-year time series was used to extrapolate the peak flood flows of a return period of 50 year (180m³/s) and 100 year plus climate change safety factor (300m³/s) using the Gumbel probability distribution. Due to the short length of the investigation area, the model can be run in steady state as the impact of the dissipation of the flood wave can be neglected on this scale. Modelled water surface elevations and flow velocities were matched to measured data through adapting Manning's roughness values.

Model results

The current state and the scenario were modelled by running AdH with the 50 and 100 year peak discharge. Water depths and flow velocities in the floodplains are used as an indicator for potential damages and hazards.

Figure 2-22 shows the results for the 50 year flood. For the current state (*Figure* 2-22a), areas in the compound around the buildings will become inundated. The water depths around most buildings range from 0 to 1m. Only five buildings in the south eastern part of the compound will become surrounded by water more than 1m deep (maximum value 1.5m). Flow velocities in the compound are mostly below 0.1 m/s with maximum values of 0.11m/s. After the construction of the storage halls (*Figure* 2-22b) current patterns of the 50 year flood have been changed as water gets diverted around the two buildings. To analyse the impact on depths and velocities in more details, the differences in flow velocity and water depth between the current state and the scenario are shown in *Figure* 2-22c and d. Positive numbers indicate higher scenario values, negative values indicate lower scenario values. Areas around buildings directly south east of the new storage halls and on the southern side in the middle of the large factory building are affected by higher flow velocities of up to 0.05m/s. Flow velocities are reduced by 0.001 to 0.05m/s for most of the other buildings. The strongest increase is found on the north-east corner of the new storage hall (0.06m/s to 0.26m/s) and on the south-western edge of a small shop in the centre of the buildings (0.11m/s to 0.12m/s). Flow velocities in the main channel are predicted to increase slightly.

Figure 2-23a shows the simulated current state in case the 100 year flood would occur before the construction of the buildings. The water depths in the floodplain around the buildings reach maximum values of 2.50m, all buildings are surrounded by 1.6m of water. Flow velocities in the compound reach a maximum velocity of 0.56m/s just west of the factory building. Flow velocities higher than 0.2m/s are found in certain flow paths in between buildings. *Figure* 2-23b shows the simulation results in case the buildings would have been constructed. It can be seen that the currents in the floodplains and the flowpaths have been considerably changed. Water depths north east of the factory building and just upstream of the new buildings will be increasing slightly by less than 1cm (*Figure* 2-23d). Water depths in the rest of the compound are predicted to decrease slightly by less than 1cm. The highest increase in flow velocity occurs in between the northern new storage hall and the factory building (0.15m/s). The already fast velocities west of the factory are increased by 0.02m/s. Apart from that, velocities are reduced, especially in the area south east of the new buildings.

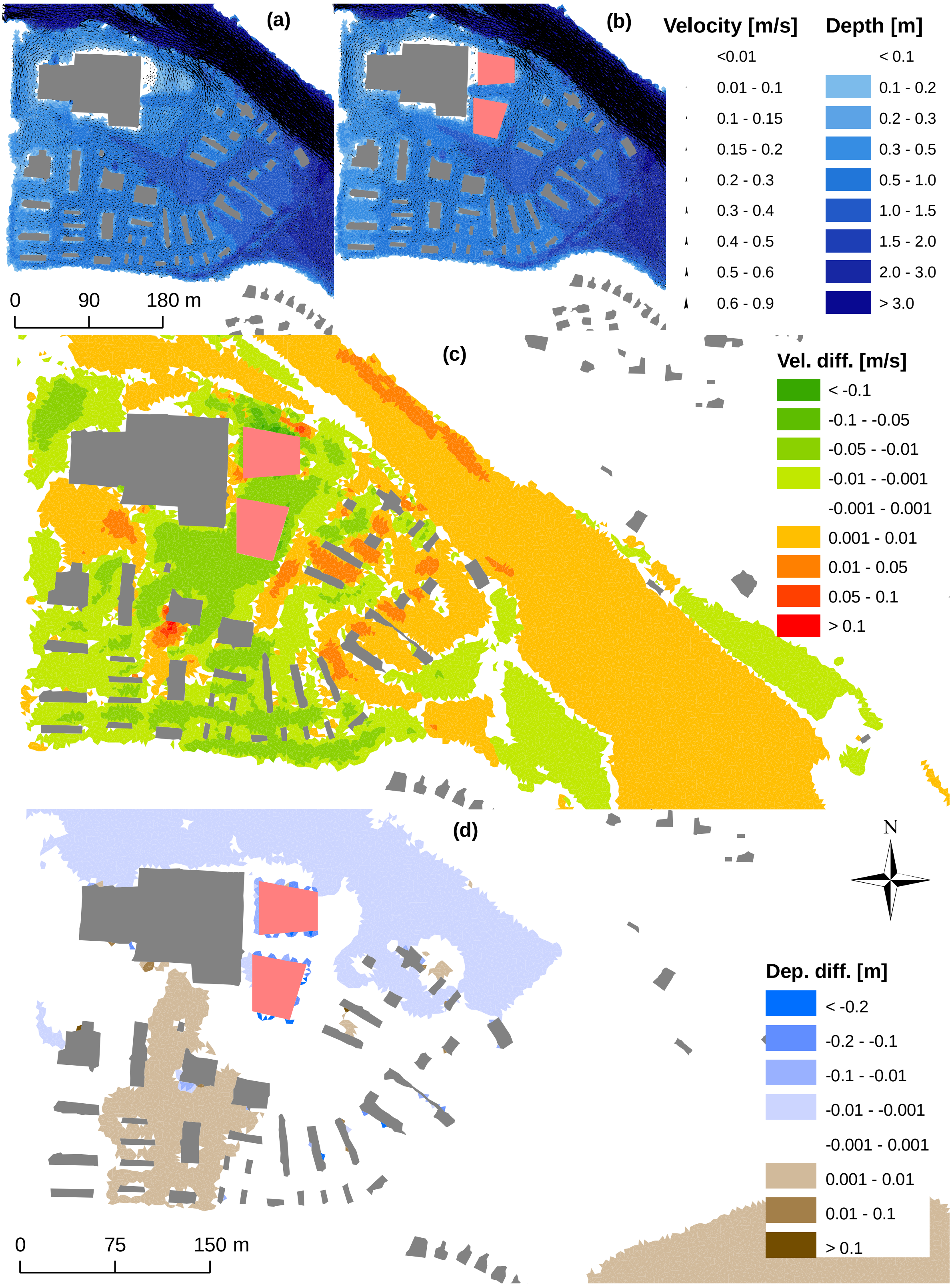


Figure 2-22: 50 year return period flow velocities and water depths before (a) and after the construction of the storage halls; for comparison, differences in velocities and water depths are shown in (c) and (d)

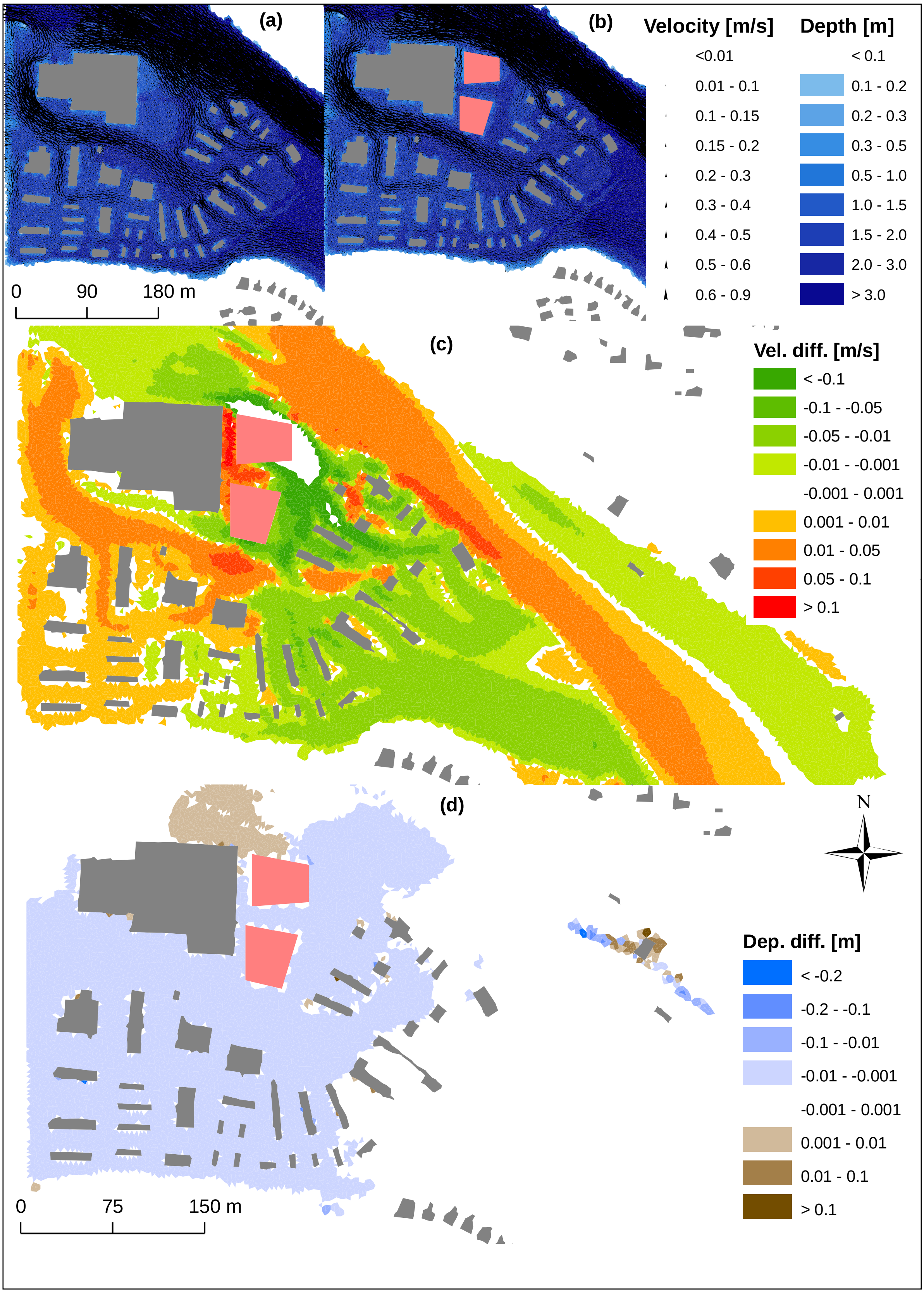


Figure 2-23: *100 year return period flow velocities and water depths before (a) and after the construction of the storage halls; for comparison, differences in velocities and water depths are shown in (c) and (d)*

2.6.4 Risk analysis

The modelled scenarios have to be analyzed according to the hazard to people. In order to leave the compound in case of flooding, people have to be able to wade through the floodwaters during business hours, usually in daylight. Guidance on the depths and velocities that cause risks to people is given by DEFRA 2006:

Hazard Value = depth x (velocity + 0.5)

So that all people are still able to wade through the floodwaters the Hazard Value may not exceed 0.7. Danger exists for some from 0.7 to 1.5 and for most people from 1.5 to 2.5. Values exceeding this limit are dangerous for all people. The model results are analysed according to these thresholds. Hazard Value maps are shown in *Figure* 2-18.

It can be seen that for the 50 year flood, all people would be able to safely leave all buildings for both scenarios (*Figure* 2-24a and b) to dry land west and south of the compound. Only at the far eastern building close to the river it is necessary to cross hazard values up to 0.8. After the construction of the halls, hazard values are predicted to increase slightly there but still a narrow escape route with values slightly below 0.8 would exists.

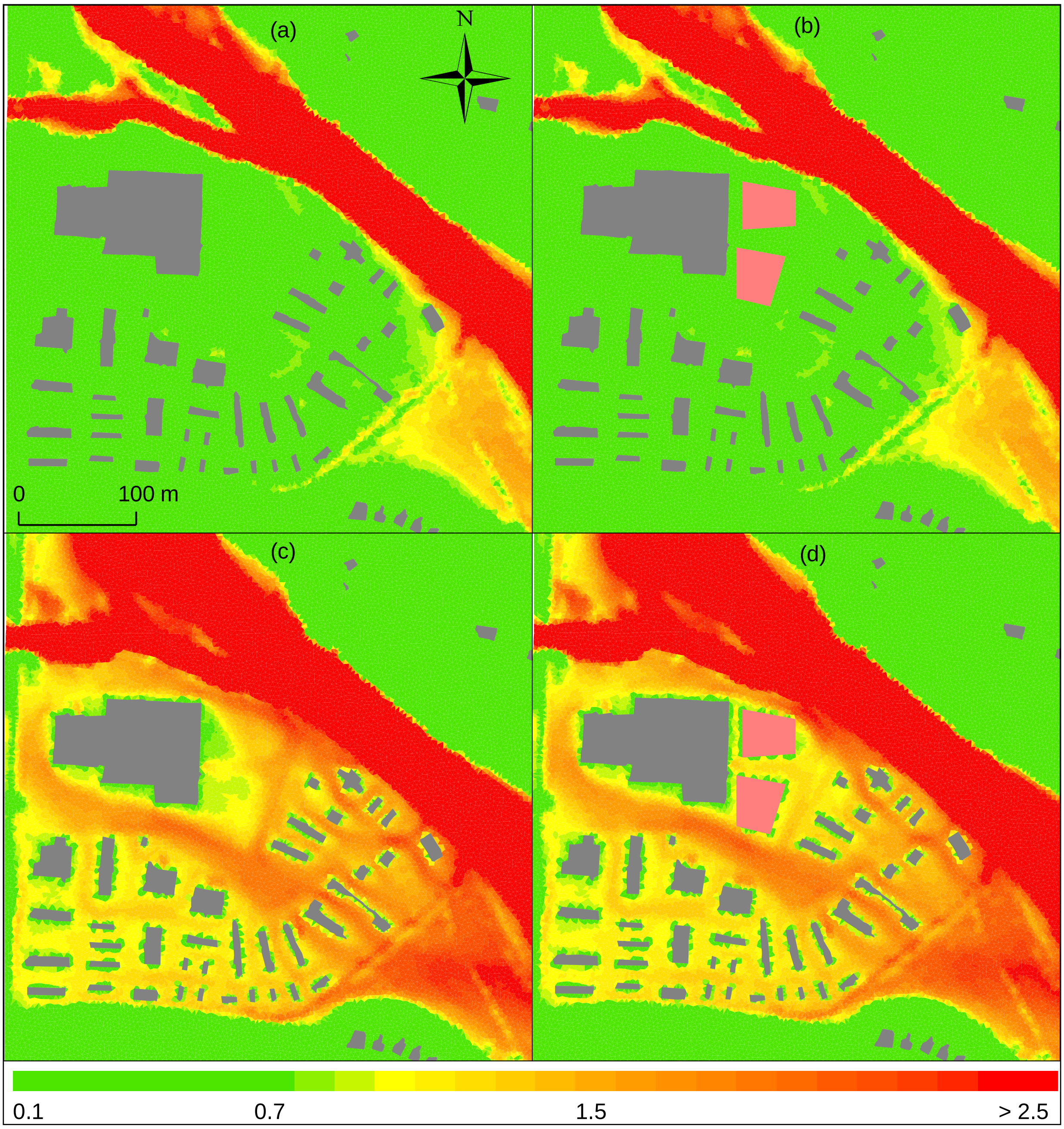


Figure 2-24: ***Hazard maps for (a) 50 year event current state and (b) after the construction of the storage halls; (c) 100 year event current state and (d) after the construction of the storage halls***

In case a 100 year flood would strike the area, a safe evacuation of the compound is not possible for the majority of people. The construction of the storage halls would lead to an increase of the Hazard Value by up to 5% in the flowpath south of the factory building. It would however also reduce the Hazard value by up to 10% in the eastern building block. Buildings can also be a place of refuge during flooding. Generally, light buildings can withstand velocity-times-depth values of 1 (Walsh and Benning 1998, DEFRA 2006). This value, being different to the hazard value mentioned above, is not exceeded anywhere in the compound for any scenario. In theory, people would thus be able to seek refuge in the buildings, which of course is highly dependent on the buildings conditions.

2.6.5 Recommendations

Model results show that the 50 year flood event does not impose a significant risk to people in the compound. Also with the construction of the two storage halls flood hazards do not increase significantly.

The 100 year flood is dangerous for all people residing in the area. Leaving the compound may be possible for some individuals, but elderly or disabled people and children will not be able to escape without a high risk of being swept away. Seeking refuge in the buildings would be a possibility if the buildings meet the standards of at least solid brick walls and a possibility to enter a second floor or the roof. The shown hazard maps can be used to identify evacuation paths and should be given to the local emergency authorities.

According to this study, it would theoretically be possible to build the storage halls as the overall technical risk would not increase (the slightly increased risk for certain parts of the compound is mitigated by supplying safe shelter in the halls in case a 100 year flood event would occur). In such a case it would furthermore be recommendable to increase the flood security of the buildings within the scope of the refurbishment.

Overall it would anyhow not advisable to allow more development in a flood prone area and construction of additional buildings should not be allowed in order to promote developments in safer areas elsewhere. In addition, in the long term, it should be aimed for to move the existing developments out of the floodplain as well. Such decisions would anyhow need to be based on detailed development codes that regulate utilization of existing developments as well as new developments in flood prone areas. The British Planning Policy Statement 25 (PPS25) would be an example for such a policy. The policy should cover both the vulnerability of the object (risk for people, risk of collapse) as well as the risk the object poses (changed flow characteristic may lead to higher risk downstream, flooded industry may cause pollution, etc.).

A further point to be addressed in a detailed FRA would be the impact of planned developments downstream. In the case above no impact is visible. Under different conditions there could anyhow be significant impacts downstream that would have to be taken into account for a decision.

2.7 FLOOD DEFENCES AND MITIGATION MEASURES

2.7.1 Introduction to flood defence and mitigation possibilities in Mozambique

Mozambique, in parts, comprise of huge floodplains that can be several kilometres wide. These plains are periodically flooded which, due to the fact that the floodplains are used for a variety of purposes, often results in the destruction of crops and assets through floodwaters. Nevertheless the floodplains fulfil a very important function in retaining floodwater and preventing higher and more destructive flooding downstream.

The current situation of flood prevention, defence or mitigation measures shows a rather less developed picture. The situation can be described as follows:

- Upper catchments are strongly deteriorating, promoting increased runoff and more peaky floods
- Operation rules for large dams are not targeted at flood retention with low operation

levels but rather on maintaining high supply levels
- Small dams and weirs along the tributaries are not numerous enough and too small to play a significant role in flood retention
- There are no land development policies in place or enforced that would prevent settling and construction in flood prone areas
- The data and monitoring situation on local level is not sufficient to conduct detailed flood risk assessments and gain thorough information of local flood conditions
- A “making room for water” concept with holistic approaches and maintaining the retention function of the floodplains for basin wide flood prevention is not followed while preference is given to local approaches
- Structural defences are mostly not in place
- Monitoring and early warning systems are not sufficiently in place
- Preparedness activities and adaptation through flood resilient construction are not promoted broadly but are only carried out locally by few NGO´s

There is a variety of options to improve the existing situation using various measures with short- and long term effects based on structural interventions, avoidance and mitigation.

Flood protection can be achieved through different means and on different levels.

On a watershed scale, upper catchment conservation and restoration works have significant beneficial effects in reducing floods. In addition preservation and restoration of wetlands and floodplains is a powerful tool for flood reduction. Utilizing existing dams in a river basin, these can be operated with synchronized schedules and flood protection being the priority, while this obviously means compromising on power output or water availability through reduced reservoir levels.

On a local level, there are several options available for improving flood resilience. Options can be low profile through preparing people for the possibilities of flooding and recommended behavioural actions in flood situations. Options can also include the development of early warning and alarm systems as well as the promotion of flood resilient designs and the inclusion of safe havens on household level where people can take refuge or valuables can be stored. Both options would benefit from development regulations that would include building restrictions based on flood risk zones as well as flood resilient construction obligations (i.e. suitability of structural integrity, electrical connections, sewage systems, etc.) at least for public buildings. Emergency planning of the respective institutional players would be of much advantage as well.

A second option for local improvement of flood resilience includes embankments which can be constructed to protect larger areas. As a detriment to a preferred holistic approach, embankments generally restrict floodplains, resulting in reduced retention capacity and leading to higher flood levels downstream. As an alternative to embankment construction efforts, properties both on large and on small scale can be constructed in a flood resilient way, either by building on wharfs or by constructing on stilts. The latter has the least impact in reducing flood retention capacity along a river but is not applicable for existing solid settlements and also depends on availability of construction material.

In general the recommendations given in the sections below as much as possible follow the “making room for water” concept in order to prevent situations where upstream flood protection measures worsen the situation downstream. Nevertheless also structural examples are given.

2.7.2 Catchment conservation

Upper and middle catchments in Mozambique are degrading to different extents. Main reasons for degradation are expansion of agriculture, unsuitable agricultural practices, uncontrolled logging and mining activities. The degradation severity for Mozambique is shown in *Figure* 2-25. While the map is more than 20 years old and at a coarse scale it provides a good baseline overview of human induced catchment degradation in Mozambique, showing the full range of low to very high degradation.

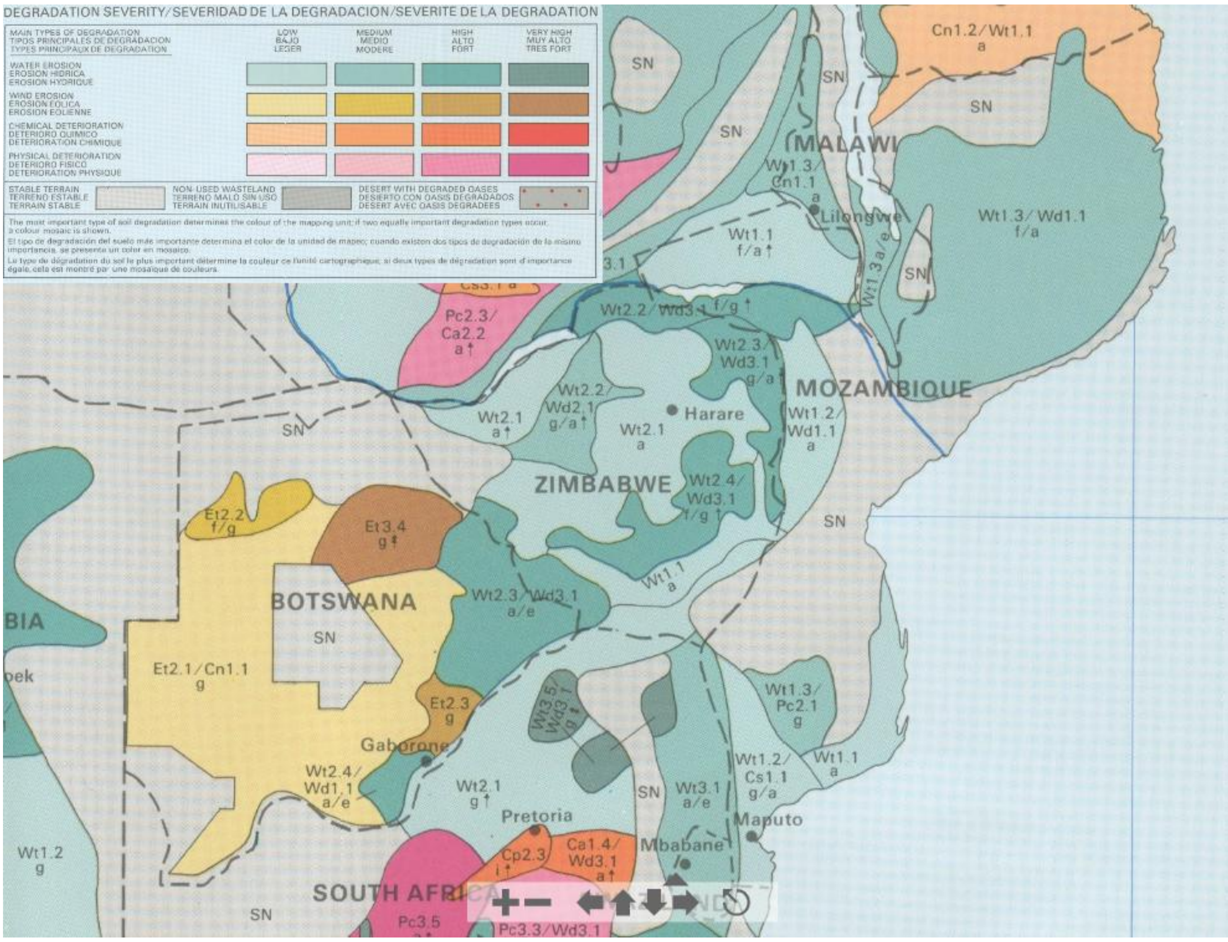


Figure 2-25: ***Degradation severity map for south-eastern Africa including Mozambique (Oldeman et al., 1992)***

Considering the ongoing population growth it can be assumed that the severity of degradation has increased as experience shows that population growth goes hand in hand with increasing land utilization, increasing farming, increasing livestock keeping, increasing logging for firewood and construction material as well as increasing other land consuming activities like e.g. small scale mining. The main factors contributing to land degradation and related increased flooding are related to farming activities, mainly agricultural production on grasslands and in wetlands causing degradation with resulting loss of retention capacity through

- Drainage and grazing of wetlands reducing the “sponge” effect

- Changed soil and plant composition
- Poor land conservation practices leading to less infiltration and increased runoff
- Deforestation for firewood, charcoal and construction materials resulting in increased runoff

Catchment conservation, rehabilitation and improvement are main aspects of successful and sustainable flood risk management with the secondary effect of increasing water availability in the dry season. If implemented before degradation takes place it is the least costly flood risk management option so it is a highly advisable solution. Main issues are the maintenance of a good groundcover in the upstream reaches which increases interception and retention as well as infiltration. In the middle river reaches wetland- and grassland floodplains are important to be maintained as they basically act as the rivers "safety valves". The well vegetated areas with a good groundcover are very effective at increasing the infiltration of rainwater into the ground. This reduces surface runoff flowing into rivers and streams during times of high rainfall, and maximises ground water seepage into these during the dry periods. The effect is most important in the upstream reaches. When rivers flood in the middle reaches of a river, the wetlands and grasslands of the floodplains spread out the water, slow it down and absorb it like a sponge, preventing the dangerously high peaking flood waves from occurring. Effectively the runoff gets retarded leading to lower waterlevels during the rainy season and higher waterlevels during the dry season.

For understanding the reasons for the hazard potential associated with floods it is also important to understand that the increase in hazard significance (considering both frequency and severity) is a consequence of two aspects. The poor management and overuse of land resources that result in increased and faster runoff and in addition the increasing population density in the downstream reaches that encroach floodplains with their settlements and thus create hazardous conditions.

Actions that are recommended to promote catchment conservation include the following:

- For the upper catchments:
  - Implementation and enforcement of logging regulations
  - Implementation and enforcement of land use regulations aiming at groundcover
  - Implementation and enforcement of land management regulations, i.e. agricultural practices aiming at contour ploughing, terracing, improved tillage and similar retention promoting methods
  - Promotion of reforestation
  - Introduction and enforcement of grazing limits
  - Introduction and enforcement of regulations for e.g. mining activities
  - Introduction and enforcement of regulations for development activities
  - Protection of altitude swamps and wetlands
- For the middle and lower catchments
  - Implementation and enforcement of building regulations to keep development out of floodplains
  - Implementation and enforcement of drainage regulations
  - Protection of wetlands
  - Implementation and enforcement of grazing and other land use regulations

Next to the necessary studies and planning activities to put the regulations in place, training and especially enforcement over a long period of time are very important aspects for successful implementation of activities. The activities would need to be planned in several steps, starting from detailed surveys and planning for the activities, the training of administrative staff in the respective administrations, the setup of administrative departments including outreach and enforcement sections and the actual implementation potentially with the help of local NGO´s or small enterprises.

Pricing the activities is difficult and would require detailed studies of which catchment areas to be dealt with, the conditions within these catchments, the situation within the local administration regarding manpower and capacity, and the suitable ways for implementation. The cost for such a study for preparation of catchment conservation activities for assumed three pilot subcatchments could range in the order of 70,000 USD.

2.7.3 Flood preparedness

In conditions where floods present a problem to a population, flood preparedness is a straightforward solution to decrease not the flood risk but the hazard potential connected to it. Studies have shown (Petersen, 2009) that injuries and the loss of life can significantly be reduced if populations are aware of the flood risk and are prepared for the occurrence of floods including suitable ways of reaction. Awareness can be created to public notification and/or community workers that conduct group trainings. Good practice examples also include the training of neighbourhood focal point persons who, after their training, can further disseminate the information within their neighbourhoods. Information that needs to be provided during such training includes correct ways of reaction when floods occur, identification of safe locations, possibilities to obtain help and information about preparing houses to make them more flood resilient but also information how to mobilize and conduct the community trainings. A baseline training for focal point persons (including the identification, etc.) carried out by a Mozambican small company or NGO could cost in the order of 3000 USD. Costs would reduce if a larger number of trainings would be carried out.

As an improvement to awareness raising activities, early warning and alerting mechanisms can be put in place. There are a variety of solutions in this regard. Simple possibilities include simple monitoring of water levels at upstream gauges based on which, when exceeding a certain threshold, flood warnings will be sent to downstream communities. More complex solutions include hydrometeorological observations and flood routing for detailed forecasting of flood levels. While the simple possibilities can be put in place fast and efficiently with limited efforts, the modelling options require severe data collection and development work. As the simple possibilities can already improve the situation significantly by providing early warning especially along long rivers, they would be the preferred solution for Mozambique in the short term. Costs for such undertaking much depend on how they would be set up. Most cost benefits could be achieved if attached to existing administrative structures in centers along the river courses for which an alerting and responsibility plan would have to be established.

As a third point, flood preparedness also includes infrastructure and building regulations for flood resilient construction and use of assets. The topic is described in more detail in Section 2.7.7.

As a last point, emergency planning is an important point for flood preparedness. While it is possible to raise awareness in the population, to forecast and to warn, floods, depending on their severity, have an impact on the population and require emergency intervention. INGC (National Institute for Disaster management) and CENOE (Central Emergency Operations Centre) are the public bodies in Mozambique who are responsible for flood emergency intervention and the related liaison with response agencies. The setup is well developed on top level (including information collection, dissemination and responsibilities) while on grassroot level response mechanism and assets are stressed when disaster strikes. It is suggested to make these agencies responsible for the above described flood preparedness activities.

2.7.4 Flood resilient design

Floods are natural phenomenons that repeatedly occur along river courses as part of the yearly hydrological cycles. Different aspects have over the recent years increased the flood risk (man-made catchment degradation and climate change) as well as increased the flood hazard potential (growing populations settling in flood plains). If there are no plans to move people and developments out of flood plains it is important to, at least in the medium term, accept to live with floods and adapt to the problems they bring. Flood resilient design is the way forward to ensure structures are better equipped to cope with floods, to avoid collapse and to allow protection of property and life. There are different levels and possibilities of flood resilient design:

1. Improvement of structural stability of existing houses to avoid collapse and to protect property
2. Improvement of flood resilience of existing or new houses by planning for flooding through
    a. Respective placement and safeguarding of e.g. power, water and sewage lines above or sealed off from flood waters
    b. Construction of safe havens to safely accommodate inhabitants and some property during floods
3. Improved design of newly planned houses by
    a. Building on stilts
    b. Building on wharfs

As Item 1. and 2. are dealt with by NGO´s on ground in Mozambique (e.g. Concern, Safe the Children), This study has focused on Item 3. the improved design for newly planned houses. Basically two options would be suitable for Mozambique, construction on stilts or construction on wharfs. While the former option is restricted to areas where suitable timber is available in sufficient quantities and to affordable prices, the latter option is suitable basically everywhere. While stilts are more capital intensive, the construction of wharfs would be more labour intensive and requiring slightly more space. Stilts have the advantage of not restricting flood waters while having the disadvantage that their lifespan is limited.

Stilt structures for single storey local houses (light structures) should be constructed from timber with minimum size 10cm diameter and anchored into the ground by a minimum of one meter. In average, one stilt per square meter house should be used and the stilts crowned by a wooden base frame of the same diameter and reinforced by cross members in triangular orientation along all axis plains (x/y/z) of the house. If larger diameter stilts are available the distance between the stilts can be increased respective to the increased diameter. Timber stilt structures can generally be built to up to 2 meter platform height. Larger heights are possible but require deeper foundation depths and more elaborate design calculations. The actual height would depend on the flood levels expected for the construction site. Impact resistance is not considered for this typical design. A typical structure is shown in *Figure* 2-26.

Based on information obtained from NGO´s that work in rural areas of Mozambique obtaining a cost estimate for a typical structure is not possible as prices strongly depend on local availability of timber and expertise of local craftsmen. While in some areas the structures are actually built, in other areas it would be very difficult to implement them.

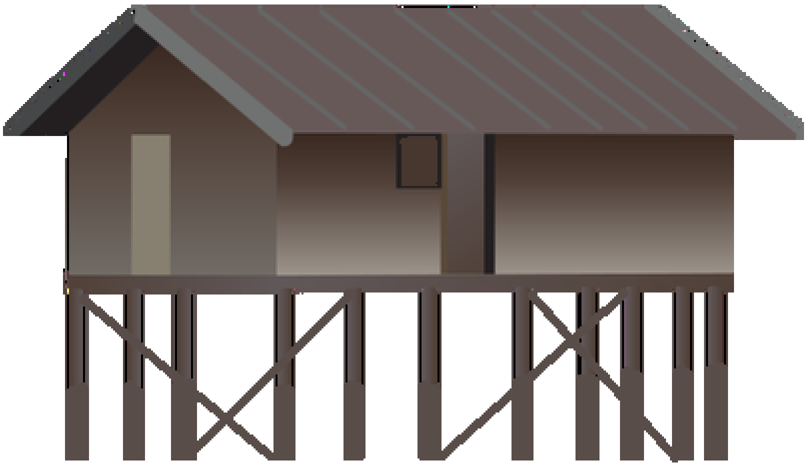


Figure 2-26: Typical design of a stilt house

Wharfs are earthen mounds that form an elevated base for a house. The wharfs are more durable than stilt structures and require significant earthmoving by more numerous but less skilled labour. Wharfs have the effect of decreasing floodwater retention area though to a lesser extent than dikes. Wharfs should be designed to a height that reflects safe levels above locally known flood levels. There is no restriction to the height of wharfs though their footprint increases with height as the slopes should be shaped with minimum 45° slope angle. The wharf should be built up in layers which are placed subsequently and compacted. Layer thickness depends on material and compaction equipment. Assuming clayey sand and hand compaction, layer thickness should be 5-7 cm. A minimum two meter fringe should be allowed around the house. Access to the house should be by a staircase built into the slope. All other areas of the slope should be prevented from access in order to minimize erosion. A typical design is shown in *Figure* 2-27. Due to the footprint area required for a wharf, they are more suitable to be constructed in scattered settlements or for isolated houses. As an alternative, wharfs can be enlarged to accommodate several houses or constructed as a village refuge separate from the normal houses to provide retreat in times of flooding. To allow for shelter, and at the same time raise awareness for floods, new school buildings could be constructed on such community wharfs. In addition, emergency supplies for the community could be stored here.

Figure 2-27: Typical design of a wharf house

Also combinations of stilts and wharfs are possible where a basement can be included in the wharf that would allow for cool storage. Depending on construction techniques used for the basement it is likely that the basement gets inundated by seepage water during floods so it can not be considered a safe storage.

Costs for wharfs differ much depending on local circumstances and the way they can be erected. Options range between promoting of community work to use of commercial contractors. Respectively costs can range between zero or incentives for community works to up to 10 USD/m^3 if material has to be transported from a distance by heavy equipment. As examples:

- Earth wharf for a single house with assumed 70 m^2 surface area (7x10m) and elevation of 2.0 m results in a volume of approximately 210 m^3. If constructed by a commercial contractor costs could be up to approximately 2,000 USD
- Earth wharf as a community refuge with assumed 10,000 m^2 surface area (100x100m) and elevation of 2.0m resulting in a volume of approximately 20,800 m^3. If constructed by a commercial contractor costs could be up to 200,000 USD

Prices strongly depend on the number of wharfs to be constructed and hauling distances for material and availability of contractors in the area. Quotes are based on quotations of a larger regional contractor; local contractors can be cheaper but this strongly depends on circumstances.

2.7.5 Improvement of existing flood retention structures

Flood retention structures already exist in Mozambique in form of large and small dams and weirs along the main streams as well as their tributaries. Both dams and weirs are generally not operated for flood retention purposes but for water storage and therefore are mostly kept at maximum supply levels as long as possible. In order to utilize dams and weirs for flood retention, storage capacity needs to be available during flood events. This can be achieved through three mechanisms.

1. A general low level of impounding that can be controlled through discharges that relate to average streamflows, i.e. water is discharged at the rate of average inflow so that under average flow conditions water is basically discharged directly and not retained. Only if the inflow exceeds the outlet capacity water is retained. This type of setup does

not need any control once the design parameters are established. No water is stored during average flow conditions.

2. A normal utilization of the reservoirs, with high impounding levels, but with an operation scheme that can react to flood warnings. In the case of floods warnings water would be released from the filled reservoirs before the arrival of the flood wave in order to create retention space. The operation has to be well scheduled and is highly control intensive and dependent on good weather- and flood forecasts in order to achieve an effect. Towards the end of the floodwave, reservoir discharge could be reduced to maintain a filed reservoir at the end of the flood.
3. Flood retentions also include floodplain areas, i.e. areas that get flooded once floods occur. In some locations the passageways for water into these areas have been restricted and floodplains have been cut off. Opening up these floodplains and thereby creating retention space would significantly reduce flooding downstream. It is therefore important to holistically view a catchment to decide which stretches along the river courses should be protected and where flooding should be allowed in order to protect downstream areas.

2.7.6 Structural flood defences

Flood defences are structural means to prevent water from a watercourse to flood an adjacent area by physically barring the water from entering this space. It needs to be understood that with these actions floodplains are cut off from the river resulting in decreased retention area and a stronger floodwave propagating downstream, leading to increased flood levels and resulting damages downstream. Talking of flood defences it is therefore very important to understand that building a flood defence in one location is likely to increase the flood risk and threat downstream. Flood defence measures therefore have to be planned with a holistic view, considering the whole catchment, and as much as possible limiting the protected or rather cut off areas.

Protection against structural failure is important for flood defences. Areas that are protected are generally considered as “safe” so that a failure of the defence could have serious consequences for the property and life of people living behind these defences. Earth dikes form the most practical and low tech solution to build defences also in light of failure risk. As dikes can not be designed to withstand “any” event, it is important to build them in a way that they are resistant against internal erosion and overtopping. Typical cross sections of dikes are shown in *Figure* 2-28. The cross sectional profile to be selected depends on material type and availability as well as space availability. Gentler slopes (1:3) are the preferred solution from a durability and stability point of view as maintenance needs are low and the gentle slopes provide good erosion stability from toe seepage and overtopping. Nevertheless, material requirements and footprint space are highest for this type of cross section making it the more costly solution. Dikes with steeper slopes (1:1) occupy less space with the same height and are less material demanding but require careful maintenance and are problematic during longer inundation times. As an example, over 1000m of dike length, with 3.0 m top width and 2.0 m dike height, a 1:1 slope would result in 10,000 m^3 of soil needed while with a 1:3 slope 18,000 m^3 would be needed.

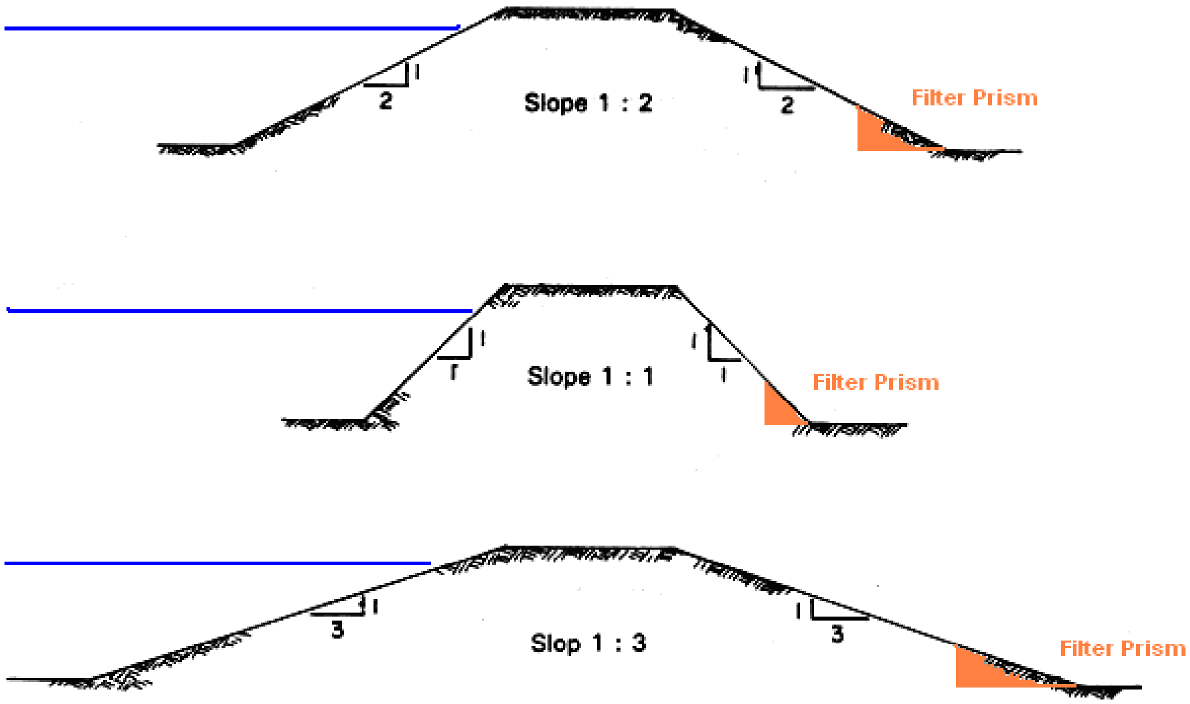


Figure 2-28: ***Typical dike cross sections.***

A good solution for dikes is a 1:2 slope. In order to resist overtopping erosion, the slopes need to be protected by a dense grass cover and should be protected from access. Any bare soil on the slopes would be prone to erosion in case of overtopping leading to risk of breaching with resulting fast flooding of the protected areas. In order to reduce the risk, sections of dike can be constructed with lower elevation where spilling would concentrate. These sections could be prepared with gentler slopes and particular surface protection.

The height of flood protection dikes would need to be established through a detailed Flood Risk Assessment (FRA) based on which dike heights would be established. The sloping nature of the waterlevels along the riverdike will need to be considered. The design should be model tested as part of the FRA. The bottom width of a dike is depending on its height in combination with the slope. For the top width a minimum width of 3.0 m should be used to allow accessibility and sufficient overtopping- and seepage resistance. In cases where the dike can serve multiple purposes, e.g. as a road dam, wider sections can be used.

Toe drains are an important feature of soil dikes that need to be considered in the design. As a standard design a filter prism of about 0.5 m height, made from well graded sand should be included in the dike cross section.

Construction of the embankment dikes needs to be carried out with suitable soil that has sufficient clay content. The dike body has to be built up in layers which are placed subsequently and are well compacted. Bonding between the layers needs to be ensured through scarifying the surface of the previous layer before placing the next layer. To achieve proper compaction the moisture content of the fill material needs to be adjusted in most cases. Before placing the first layer the foundation for the dike needs to be stripped from vegetation and topsoil and the same method applied (scarifying, adjusting moisture content) as for the subsequent layers. The exact procedure will have to be established depending on actual soil properties and construction equipment found on site.

2.7.7 Development policies

Development policies with regards to infrastructure and building regulations for flood resilient construction and use of assets are proven tools for reducing flood impacts. By providing regulations about where (and where not) and how structures and assets shall be constructed and who shall (or shall not) use them, the risk associated with floods can be reduced by ensuring structural stability and suitable use. The British Planning Policy Statement 25 (PPS 25), issued by the UK Government (2010) is a good example for a planning policy focusing on flood resilience. The document describes key planning objectives, decision making principles, a risk based assessment approach and responsibilities as part of physical development planning.

A development planning guideline suitable for Mozambique would need to take account of the local circumstances and especially focus on the baseline data situation and the implementation and enforcement of the planning guidelines. The main challenges would be to conduct baseline data acquisition including setting up and running of respective monitoring stations as well as the setup of competent regional and local departments to deal with the tasks on site.

Proposed policy principles for rural areas and smaller towns in Mozambique (applicable both for new developments as well as changes to existing developments) have been prepared based on PPS25, adapted from UK Government (2010), considering practicability in Mozambique. The policy principles are shown in Annex A2.6.

Developing a full and accepted policy with stakeholders and government agencies in Mozambique would require significant efforts and capacity of the involved governmental and local administrations. In addition commitments would need to be made in order to sustainably fund the implementation and enforcement of the new policy.

2.7.8 Case studies

Three locations in Mozambique, Caia, Tete and Chockwe where flooding is a problem due to frequency and impact of flooding have been chosen for detailed studies of possibilities to alleviate flood risk. Lengthy consultations have been held before the three sites were identified. Feedback regarding the topic has been rather vague which actually reflects the overall situation in Mozambique with flooding in many locations. Eleven individuals and stakeholders who could possibly provide information regarding suitable flood defence locations as well as suitable construction methods and in addition construction costs were contacted in January 2012. Due to the fact that flooding is a rather generic problem in Mozambique results were not explicit and the only locations specifically pointed out was around Chokwe, Lionde and Guija on the Limpopo as well as Tete and Caia areas on the Zambezi.

The locations are representative for Mozambique in that they:

1. lack data in order to carry out detailed flood risk assessments and assess real threat levels
2. lack upstream hydrometeorological monitoring that would allow for forecasting and warning

3. face worsening flooding situations due to upper catchment degradation
4. could be better protected from flooding through improved flow control assets upstream

There are anyhow chances for the locations which include
1. awareness creation in the population
2. upper catchment consercation activities
3. improvement of flow control asset scheduling for flood retention purposes
4. improvement of defences

A general recommendation given in many replies included that due to the widespread flooding issues and limited resources the priority solution should be to keep people out of flood prone areas through respective development rules. Resettlements on the other hand were reported as difficult as people tend to return.

Regarding suitable construction methods replies differed. Wharfs were overall seen as good solutions for central retreat areas in villages. Dikes were seen partly positive, partly with concerns due to the potential for breaching and flooding of areas that would be considered protected. Construction on stilts was mostly ruled out due to the limited timber or other material availability and high costs. In addition the reinforcement of existing buildings and the construction of elevated platforms inside such buildings to store valuables were proposed for areas where only shallow flooding is expected.

Regarding construction costs the strong dependence of prices depending on the site location was stressed which have a significant influence on costs.

For the first three points listed above generic recommendations have already been given in the previous sections. Regarding improvement of defences detailed information has been acquired and will be given below. Considering the local situation in the selected pilot locations, Caia, Tete and Chockwe, homogeneous soil dikes are the preferred structural intervention for flood protection. For the purpose of this study the interventions have been seen in isolation and downstream effects have not been studied due to data restrictions. Before any form of construction starts, a detailed Flood Risk Assessment with the respective input data acquisition needs to be carried out in order to assess the design parameters and the impacts of the construction works. For coming up with a quote, the following assumptions have been made:

Dikes will be constructed with a homogenous dike body, crest width 3.0 m and side slopes of 1:2. Regarding the required height two cases are assessed, with 3.0 m (Case 1) and 5.0 m (Case 2) dike height leading to cross section areas of 27 m^2 and 65 m^2 respectively. For both cases hauling distances of 4 km were assumed. Costs for such dikes including cost breakdown is shown in *Table* 2-4 and *Table* 2-5. Free access to suitable soil material assumed was assumed for the calculations, the cost estimates are based on quotes from regional contractors. Depending on circumstances local contractors may be able to offer much cheaper quotes though reliability would need to be assessed thoroughly.

Table 2-4: Cost breakdown for Case 2 dike section (3m dike height)

Cross sect.	Length	Volume	Cut to fill	Haul dist	Overhaul	Shaping area	Shaping slopes	Grassing	Total
m^2	M	m^3	USD/m^3	km	USD/m^3/km	m^2	USD/m^2	USD/m^2	USD
27	1,000**	27,000	8.67	4	0.44	16.4	1.73	0.87	218,563
Overhead cost (incl. mob, demob, supervision, etc.)*								20%	56,313
subtotal									337,875
VAT								17%	57,439
Total									395,314

Table 2-5: Cost breakdown for Case 2 dike section (5m dike height)

Cross sect.	Length	Volume	Cut to fill	Haul dist	Overhaul	Shaping area	Shaping slopes	Grassing	Total
m^2	M	m^3	USD/m^3	km	USD/m^3/km	m^2	USD/m^2	USD/m^2	USD
65	1,000**	65,000	6.5	4	0.33	25.4	1.3	0.65	677,799
Overhead cost (incl. mob, demob, supervision, etc.)*								20%	135,560
subtotal									813,359
VAT								17%	138,271
Total									951,630

*Overhead costs will much depend on the location of the site with reference to the contractors' base. I.e. local contractors may be able to offer reduced mobilization and demobilization costs.

** For comparison reasons a dike length of 1 km has been assumed. The percentage of overhead costs may reduce with increasing structure length

2.7.9 Recommendations

A variety of flood protection and mitigation options have been discussed in the above sections highlighting their benefits as well as detriments and providing cost estimates. While on a short timescale and considering the persisting problems some structural flood protection measures may be unavoidable, strong efforts should be spent to sustainably improve the flooding situation with a longer term time horizon by rehabilitating the upper catchments and providing floodwater retention areas through policy development and enforcement. A pure focus on structural flood protection by constructing of dikes should be avoided as the negative effects through a changed hydrology downstream as well as within the diked areas themselves are immense and would increase problems elsewhere. While investments have to be discussed on a case by case basis with consideration of the catchment situation, the best option for increasing the flood resilience of communities is seen as a combination of small scale technical interventions accompanied by large scale increase of retention area through catchment conservation. Additional multiple-benefits can be achieved by promoting the construction of weirs and small dams along the tributaries which will lead to an improvement of water supply and the creation of retention area. As space will be needed for such efforts, policies need to be implemented to regulate space consumption in areas allocated for water. In detail, the following combination of interventions would be advisable, following the "living with floods" concept:

1. Small dikes, wharfs for house and community protection
2. Upper catchment conservation
3. Policy development
4. Weirs and small dams for flood retention purposes
5. Adapted schedules for large dams
6. Forecasting and early warning system development in combination with alert systems
7. Promoting preparedness of the population

The measures would aim at the prevention of floods through a holistic and catchment wide approach and would require detailed catchment assessments and analysis of upper catchment conservation and -rehabilitation as well as retention potential. Potential future population growth and respective land use change and expected degradation trends would need to be considered. It can be expected that upper catchment measures would have a significant influence on flood retention and therefore alleviating flooding at hotspots with direct benefits for the riparian population

2.8 CONCLUSIONS

Current state and climate change flood maps have been produced for the main channels of the Zambezi, Pungwe and Limpopo for 2 year and 20 year return period flows. The maps are restricted to these flows since the climate change flows from INGC Phase I are only available for these two events. Available data were very limited and of poor quality for setting up 1D and 2D hydraulic models. A number of approaches were undertaken to improve topographic data quality, to find the most plausible data ranges and to consider and display the uncertainties. These efforts lead to a higher accuracy of the simulated inundation compared to using raw data. The spatially distributed uncertainty assessment is valuable for identifying areas along each channel where model results are less and more certain. Generally, it has to be emphasized that inundation mapping using the available database causes immense uncertainties in the results. It thus has to be stressed that the results should be treated with caution and should not be used in final decision making or for infrastructure design purposes. When using the maps for planning of mitigation and management strategies is it important to keep the following limitations in mind:

1) Due to lacking accuracy in flow and topographic data it is not possible to give indications of depth of flooding. The results of this study can thus not be used to derive detailed flood defence heights. The maps can only be employed to distinguish areas that are potentially under the risk of flooding from areas that are potentially not under the risk of flooding.
2) The produced inundation layers are overlaid with topographic maps from the Soviet Military Mapping as no other topographic data were available. Their accuracy is not standardized and objects and borders on the map may or may not reflect the true location. In addition towns and cities may have grown over the recent years.
3) The models are calibrated and validated to the Dartmouth Flood Observatory (DFO) maps derived from satellite images. It should be kept in mind that dense and high vegetation can mask flooded areas on such images. Thus, modelled inundation, especially in the Zambezi Delta could be underestimated due to this condition.
4) The high regional differences in the climate change flow projections, the likelihood of the A2 scenario to occur and the uncertainties involved in climate impact modelling in general (Quiggin 2008) have to be stressed here. Continuous actualizations of the flood maps towards new climate change research results should be carried out.

5) Small changes in flood flows, e.g. from baseline to climate change flows, show only very little impact on inundation. This is due to the fact that the SRTM vertical resolution is restricted to full meters. Thus, if an increase or decrease in flows does not push water depths over a meter threshold, inundation extents can be similar for different flows.
6) Weaknesses of the one-dimensional approach (see Section 2.4.3) are apparent in the wide floodplains of the rivers. Means to overcome this problem are 1D-2D hydraulic modelling together with gathering adequate datasets.
7) The shown detailed results for the cities Tete, Caia and Chókwè are based on the same data sources and model approaches as discussed above and thus have the same limitations as the river-wide flood maps.
8) The maps could only be produced for the 2 year and 20 year return period due to the limitations in the climate change flow change predictions. It is recommended to obtain climate change impact assessments on higher return flows to drive the models with more forceful events. Such climate change flows could potentially be produced by the DSS, developed in Subcomponent 1. A coupling of the hydraulic model with the DSS would thus be a meaningful step.

The supplied maps can however be used for finding promising areas/regions for development or flood defences. Those areas have to be assessed in depth individually using a local Flood Risk Assessment (FRA) after proper data gathering. The shown FRA is an example for such a detailed investigation. However, high resolution topographic and hydrologic data need to be available before similar studies can be carried out.

Overall, the flood maps are superior to previously produced maps in that the underlying hydraulic calculations and inundation mapping have a higher accuracy due to the incorporation of channel depth estimations and the corrections of the DEM in forest and dense infrastructure areas. Beyond that, the maps are produced for a baseline and climate change scenario and the maps contain spatially distributed uncertainty assessments. This was to our knowledge not available before this study.

For improving the flooding situation, a “making room for water” concept has been proposed. Structural flood defences and assets will be inevitable on the local scale for high value locations but efforts should be spent to minimize these and focus on holistic approaches including catchment and floodplain conservation through the development of suitable policies for which guiding principles have been provided. It is essential to understand that the increased occurrence of floods would be increased by large scale construction of defences that would increase flooding downstream while catchment conservation approaches have strong benefits not only by reducing flooding but by equalizing the annual flows and increasing agricultural water availability.

2.9 TRAINING IN FLOOD MODELLING

A five day training for flood modelling was conducted at Eduardo Mondlane University, Maputo from the 16th to the 20th of April 2012. *Table* 2-4 lists the trainees, identified and nominated by INGC, that participated in the course. The course objectives included the understanding of the flood modelling methodology, to gain basic HEC-RAS modelling knowledge, complete flood mapping with RAS Mapper, generate and layout a flood map with ArcGIS and understand the capabilities, uncertainties and limitations of the maps. The training was conducted in an interactive and flexible manner to encourage knowledge exchange, discussions and give opportunities to ask questions during the whole course.

Table 2-6: Participants of Flood modelling training

First Name	Surname	Employer
Agnaldo	Bila	INGC/CENOE
Anastacio	Magumane	
Brazao	Mendes	INGC
Elias	Barros	INGC
Elidio	Massuanganhe	EMU
Felisberto	Afonso	EMU
Igor	Honwana	INGC
Isac	Filimone	DNA
Isaías	Raiva	INAM
Isaías	Vilanculo	EMU
Luísa	do Céu Ricardo da Conceição	DNA

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SUBCOMPONENT 3: Urban Drainage

3.1 SCOPE OF WORK

The scope of work as defined by the Terms of Reference published in the tender documents for this assignment had been commented on by the Consultant in the Technical Proposal (TP) of this assignment and in the Inception Report, where a change of methodology as compared to the TP was suggested by the Consultant and approved by the Client.

3.1.1 Original terms of reference

Urban areas are especially susceptible to flooding. The high percentage of impervious surfaces in urban areas prevents rainfall from being absorbed by the soil, resulting in the generation of high volumes of rainwater runoff. Excess rainwater tends to concentrate in low areas or poor drainage resulting in adverse impacts such as roads impassable, houses flooded and blocked sewers. Some of these problems will intensify if climate change results in more intense rainfall, such as projected for Maputo in Phase I of the INGC project. The consultant is to conduct studies to identify the location of these problems with regards to storm water in the city of Maputo, making recommendations for structural and non-structural measures to solve or alleviate the problems.

Next to problems, excess rainwater will also mean new opportunities to reduce reliance on water supplies, particularly through its capture and reuse. The Consultant shall investigate and propose appropriate technologies to capture, process and distribute rainwater for reuse in Maputo.

It is intended that the present study to include at least the following elements:

- Urban storm water analysis to identify potential points of water concentration under the scenarios of current and future climate;
- Field surveys to verify independently the bottlenecks of rainwater and to identify potential users of rainwater partially processed;
- Recommendations for new infrastructure to solve problems with rainwater;
- Recommendations to implement systems for reuse of storm water.

The recommendations on infrastructure bottlenecks and to rainwater can be incorporated into development plans of the city and be used to manage traffic and the repair and rebuilding after major storms. [1]

[1] In Section IIIC of the Technical Proposal the Consultant remarked that "On the accuracy of outputs:

The TORs for Subtopic 3 require the Consultant to "identify the location of ... storm water runoff problems within the city of Maputo using a combination of computer-based modelling and field surveys, and recommendations will be made (infrastructural and non-infrastructural) to alleviate the problem." The Consultant would like to point out that the accuracy of outputs including any recommendation heavily depends on the data availability on the ground. Hence, it is possible that the information content of outputs (e.g. change of storm water runoff over time, effect of infrastructural and non-infrastructural measures on storm water runoff) will rather be qualitative than absolute at the end of the consultancy. In any case, the Consultant will ensure with the model design that additional data that might lead to improved output accuracy and that are not available at the time of this consultancy can easily input in the future.

Systems for the reuse of rainwater may provide new business opportunities for private investors to capture and provide adequate water for reuse. The Consultant shall work to the level of project proposal and budget of at least three of the recommendations so that when the funding of the implementation is found, the Government could proceed directly to implementation (procurement or other appropriate solution).[2]

It is intended that the study of Maputo may serve as a model for adaptation to other urban centers.

3.1.2 Methodology and workplan revised after inception phase

Based on the agreed Contract (Terms of Reference and Technical Proposal of the Consultant), the outcome of the stakeholder workshop held in Maputo on 21 September 2011, the continuous contacts with the relevant institutions of Maputo, and the resulting availability of data and information, the Consultant proposed in the Inception Report an adaptation of the methodology and workplan as described in the following sections. After the approval by the Client, the adapted workplan was consecutively pursued by the Consultant in the main phase of the project.

3.1.2.1 Adapted workplan as approved by the Client

Based on the availability of data, as it could be judged by the end of the inception phase, and based on the stakeholder consultations during the inception phase, the modelling approach was adapted as follows in coordination with the client:

- With data availability being on the low side of the consultants' expectations, the project area was reduced and detailed field surveys were carried out to collect the missing data and verify old or low resolution datasets.
- As during the inception phase it became clear that neither the Client nor the other identified stakeholders show considerable modelling experience, the Consultant was not successful inviting a "Client's modelling specialist" to accompany the Consultant during the modelling process throughout Phase three. It was therefore proposed that the Consultant would rather provide basic literature about the model and the technical prerequisites (hydrology, hydraulics, data requirements) to the Client and the stakeholders during project phase three, so the future participants for the final handover workshop and training could acquire the basic knowledge about the model principles and functionalities before the training actually took place on 21 and 22 March 2012. After some administrative delays in the project, the preparative tutorial for the identified modelling personnel started in early March 2011 with the provision

On recommendations for implementing storm water reuse systems: The TORs require that for storm water reuse systems "At least three recommendations must be worked out to project proposal and budget level, so that when funding is secured, the government can proceed to immediate implementation (through tendering as appropriate)". Due to the available budget, the Consultant assumes that "project proposal and budget level" means feasibility study level and that the output will not be projects ready for implementation"

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of reading material and was continued with the above mentioned first simple training task on a case study level.

- As already of data scarcity as anticipated in the Inception Report, technical details of the proposed interventions and measures could be elaborated only very roughly, as reliable information on the ongoing urban planning and investment schemes regarding urban drainage of Maputo is not existing or could not be obtained from the respective authorities in Maputo and could also not be measured in the limited time and budget that was available (e.g. no comprehensive underground sewer maps exist and the system is clogged with solid waste, i.e. can not even be assessed physically at the current stage.
- Not much interest for storm water reuse systems was observed. Instead of elaborating further on various opportunities, SuDS were focussed on as a good means to recharge groundwater.

The adapted workplan for the project phases two to four of Subcomponent 3 is displayed *Table* 3-1.

3.1.2.2 Final implementation of adapted workplan

The workplan as suggested in the Inception Report was implemented accordingly during the main project phase.

Table 3-1: Adapted workplan for the main project phase (Phases2-4) as defined during the inception phase (Phase 1)

Phase 2 - Data Collection and Field Survey Phase			
No.	**Activity**	**Deliverables/Milestones**	
2.1	Continued acquisition of current and future (predicted) hydrological data, spatial data, and storm water infrastructure data		completed
2.2	Detailed on site investigations on Maputo catchment area and of selected urban drainage bottlenecks		completed
2.3	Definition of catchment and subcatchment boundaries		completed
Phase 3 – Modelling and Analysis Phase			
No.	**Activity**	**Deliverables/Milestones**	
3.1	Set-up of a general urban drainage system model (input from Phase 1 and Phase 2)	General urban drainage system model set-up	completed
3.2	First model runs and validation with past bottle-neck events		completed
3.3	Improvement of the model within the selected subcatchments (input from 2.2)		completed
3.4	General documentation of urban drainage bottle-necks (input from 3.2)	Upon written request from the Client: Interim Report including overview of urban drainage bottlenecks including model Setup Scheme.	completed
3.5	Sensitivity analysis regarding uncertainty of input data		completed
3.6	Development of different scenarios for selected subcatchments (current and future climate scenarios)		completed

Phase 4 – Wrap-Up Phase			
No.	Activity	Deliverables/Milestones	
4.1	Elaboration of recommendations for (non)structural measures for storm water flooding relief and for storm water reuse systems		completed
4.2	Elaboration of recommendations for an Integrated Urban Water Management in Maputo based on the consultations with the stakeholders		completed
4.3	Preparation of draft Final Report	Draft Final Report	completed
4.4	Model handover and hands-on training with the modelling experts nominated by the Client.	Model handover	completed
4.5	Final Workshop if requested by the Client (optional)	*n/a*	
4.6	*Preparation of Final Report*	*Final Report*	

3.2 EXECUTIVE SUMMARY

Subcomponent 3 deals with the assessment of the urban drainage situation in Maputo which has proved to be very problematic with several neighbourhoods of Maputo experiencing frequent flooding subsequent to high intensity rainfall events. The key objective of this study was to investigate the actual urban drainage situation under current as well as climate change conditions, to identify problem areas and to elaborate suggestions to improve the urban drainage situation, including the consideration of stormwater re-use options.

The methodology for the implementation of the project consisted of an inception phase in which data was collected and analyzed, sites visited and meetings with institutional stakeholders conducted. These initial works were followed by an elaboration and adaptation of the workplan, based on the findings of the inception phase. The implementation phase started with the selection of Maxaquene A and Mavalane A as a catchment suitable for the planned assessments. Fieldworks then included topographic field surveys and interviews with residents, followed by the hydraulic modelling of the storm water runoff in the chosen catchment with SWMM5 open-source software. The project was concluded with a basic training for interested stakeholders and the presentation of the findings and recommendations in this final report.

During the inception phase the data availability for the foreseen hydraulic modelling was found to be weak. As a result of the data scarcity and to allow for collection of sufficient data it was agreed between consultant and client (in consultation with various stakeholders) that efforts in the main phase would focus on a selected subcatchment of the city, comprising the Bairros Maxaquene A and Mavalane A which experience frequent and heavy flooding. Detailed field surveys were carried out for these Bairros for the required topographic and structural data collection. In addition interviews with the residents regarding the flooding frequency in their respective neighbourhoods were conducted.

A detailed hydraulic model was setup and calibrated for the selected subcatchment using SWMM5 software. The model was used to simulate and assess different possible future scenarios and possible flood mitigation measures. In order to disseminate the findings and build capacity, a two day basic training on the SWMM5 model has been held in Maputo. As a result, interested stakeholders are enabled to work with the model subsequent to the finalisation of the project. Additionally a short user manual has been elaborated providing information about the use of the SWMM5 model in the project and providing the stakeholders with the necessary background information to be able to use the model on other subcatchments in Maputo and also in other cities in Mozambique.

The results of the model assessments were used to develop specific recommendations that can be used to improve the urban flooding situation in the assessed Bairros as well as, when generalized, for the overall city area. Results of the assessed scenarios are summarized as follows:

Results for Scenario 2: "Culverts cleared from solids but channels remain unchanged" indicate that the mere clearing of the culverts from solids would not have a substantial impact. The main problem, leading to flooding in the upstream areas of the study catchment is rather the partly considerable blocking of the storm water drainage channels with solids and vegetation, as this blocking leads to reduced cross sections on the one hand and to reduced flow velocities on the other hand. It could be shown that if only the culverts are cleaned and the channels not, then the total flooding would not be reduced much, only the duration of the flooding would be reduced and consequently also the water quantities inundating the study catchment.

Results for Scenario 3: "Channels and culverts cleared from vegetation and solids" show that, if the main drainage channel is cleared from vegetation and solids, the discharge capacity of the storm water channel will increase and flooding will concentrate more towards the outlet of the subcatchment because the runoff reaches the downstream part faster and with higher amplitudes. Due to the box culvert at the outlet of the subcatchment, flooding will nevertheless occur, as the capacity of the culvert is too small to discharge the whole storm water runoff. This culvert could definitely be confirmed to be a hydraulic bottleneck within the subcatchment.

Results for Scenario 4: "Opening/widening the culverts" show that depending on the structural increase of cross section area of the culverts flooding can be well avoided. Good results already occur at 50% widening of the culverts, at 100% no flooding occurs within the assessed area. Based on the two modelled scenarios with increased culvert capacity, it can be concluded that clearing the culverts from solid depositions and solid waste would already improve the situation considerably. In how far the cross sections of the individual culverts would need to be widened through either larger or increased numbers of culverts would need to be calculated based on a holistic approach considering the overall drainage system from upper catchments to its outlet in order to improve overall system performance

Results for Scenario 5: "Increased discharge in the receiving storm water channel show that flooding occurs again at the subcatchment outlet node because of the high water level in the receiving channel, which in turn is caused by backlogging from the downstream culvert in the receiving channel, which is now the hydraulic bottleneck. This situation shows that it is of utmost importance to plan interventions in a holistic way, considering the overall drainage network.

Results for Scenario 6: "Climate scenario with higher rainfall intensity" indicate that flooding increases linearly with increasing rainfall intensity. This result may appear to be rather obvious as the main factor for urban flooding is the very limited infiltration capacity of the sealed surfaces which lead to imminent runoff during a storm event.

Results from Scenario 7: "SuDS measures implemented in Maputo" show the different aspects and effects of the different potential measures.

- Storage Ponds were considered highly as very space consuming which would be difficult to implement in such a densely populated area as Maxaquene A as massive resettlement of residents would be necessary.

- Infiltration trenches would have a potential effect on groundwater levels. While recharging the groundwater is generally considered a positive effect, on local level also possible negative effects have to be taken into consideration. Groundwater levels are reported to be shallow already in the case study area so that the infiltration capacity and hydraulic conductivity of the subsoil will have to be quantified and the possible consequences of rising groundwater levels (i.e. when groundwater levels reach the bottoms of pit latrines and septic tanks in the area) on the hygienic conditions and on the structural integrity of adjacent buildings investigated. Space requirements can generally be better considered as the linear structures can follow roads. Landscape interventions are anyhow necessary. These aspects need to be decided upon based on technical and political requirements (achievable effect vs. size).

- Pervious Pavements only have an effect if implemented on a very large scale, i.e. a high percentage on the paced areas. Only a minor part of the storm water collected during a storm event can infiltrate considering the subsoil conditions and other sealed areas. While therefore not suitable as a standalone solution, the use of permeable pavements can be a valuable supplement to other measures,
- Inlet and source control are interesting from a water resources management point of view, but its quantitative effect on storm water drainage is negligible considering the enormous rainfall intensities as they are common in Maputo.

The general finding of the assessment was that the design and maintenance shortcomings of the drainage system have the largest negative effect on the urban drainage situation, and that the more extreme weather events expected from climate change will further worsen the conditions. The shortcomings in structural bottlenecks as well as maintenance are the main problems that have to be tackled to improve the situation, whereby bottleneck improvement should take downstream drainage network conditions as well as climate change impacts into consideration. Groundwater recharge through infiltration was the only accepted and sensible storm water reuse mechanism that was found.

In detail, the recommended measures include the elaboration of integrated maintenance schemes for the existing urban drainage system, the re-calculation and re-design of the existing urban drainage infrastructure, and structural measures for immediate implementation as summarized in Box 3.1.

Box 3.1: Measures to address urban flooding – Maputo case study

1. Improved maintenance of existing urban drainage system (est. cost $640,000):

- Elaboration of a digital urban drainage infrastructure inventory
- City wide cleaning campaign of all urban drainage and sanitation infrastructure;
- City-wide information campaign to raise awareness on urban drainage and solid waste management and avoiding blocking drains;
- Elaboration and implementation of a detailed Operation & Maintenance (O&M) plan for urban drainage and sanitation infrastructure.

2. Re-calculation and re-design of the urban drainage system (est. cost $520,000 – $820,000):

- New hydrological calculation of relevant design storms, incorporating climate change impacts, ideally

based on information of newly installed hydrometric precipitation measurement devices;
- 1-dimensional and/or 2-dimensional steady-state and non steady-state flow calculation of open channels;
- Steady-state and non steady-state hydraulic calculation of the piped storm water and wastewater sewers;
- Detailed citywide network calculation of the entire sewer and drainage network (e.g. with SWMM5 model).

3. Structural Measures (est. cost $50,000-$500,000):
- Extension / reconstruction of culverts, based on the results of a citywide hydraulic model;
- Concept, design and implementation of Low Impact Measures;
- Finalisation of the storm water retention basin in northern Sommerschield.

4. Further recommendations:
- Integrated land use and settlement masterplan for the whole city of Maputo (including Matola and suburbs), with a re-design of existing informal settlements in a more structured manner to allow for the installation of basic infrastructure;
- Concentration of ownership and O&M responsibility for the urban drainage infrastructure with one institution.

The choice of which recommendation will be implemented in the future will depend on budget availability and final stakeholder agreements on political level. It is recommended that the options as well as their related benefits and implications be discussed with the identified stakeholders before implementation, also considering the wider initiatives currently being carried out in the urban drainage sector. Stakeholders, including INGC, Ara-Sul, DNA – National Directorate of Water, UNHabitat, Universidade Eduado Mondlane, AIAS and the Municipal Directorate for Urban Planning and Environment have been involved throughout the project and are well informed. As an additional aspect, any changes to the system should be done with a holistic consideration of the overall drainage system in order to solve and not to relocate flooding problems (downstream impacts).

Based on the described results the highest priority for immediate action that would lead to instant alleviation of flooding is the cleaning of drains and culverts as well as the implementation of a respective maintenance plan. This intervention could be followed by structural improvements of the main identified bottlenecks. For any further interventions more detailed planning with regards to SuDS and further drainage network improvement would be necessary. These conclusions are likely valid for other subcatchments in Maputo as well as other cities as well. Where channels and culverts are clogged by solids and waste cleaning would be a first step. For structural interventions first a detailed inventory of the existing structures followed by a hydraulic assessment is necessary.

It should further be considered, that for a comprehensive approach to improving the capacity of the drainage system to absorb flooding from increasingly extreme events, a subcatchment-by-subcatchment approach is too fragmented and may lead to unwanted results and increased costs. A more comprehensive approach as outlined in Box A2.6.5 (see annex) is more appropriate for city-wide results, if sufficient funds can be made available. A main recommendation would therefore be not to replicate the approach of this study to other subcatchments of Maputo but to expand it to a city wide assessment. The approach used in the current assessment has been designed to facilitate such an expansion through the selected modelling approach.

3.3 AREA DESCRIPTION (MAPUTO AND SELECTED CATCHMENT)

3.3.1 General description

Maputo City is surrounded in the east and south by the sea. In the west the “small river” Infulene builds the frontier to the city of Matola. The area of Maputo City is generally divided through a ridge shaped hill from the north to the south in a coastal storm water runoff area and an inland storm water runoff area. The eastern coastal area is starting quite flat from the sea and rises sharply to the hill. Storm water running towards the flat area is reported to create flooding in several parts which are mainly used by agriculture. The southern coastal area, “cement city” is drained by an old storm water sewer system, the efficiency (and exact functionality) of which is unknown. *Figure* 3-1 shows the case study area (orange) within the city boundaries of Maputo (red line).

Figure 3-1: Maputo and the position of the selected subcatchment within Maputo

3.3.2 Selection of catchment

The western inland area can be divided in different basins discharging storm water by an open channel system into the Infulene River. The most southward basin with the main channel in Av. Joaquim Chissano, and in more detail the contributing area to the channel along Av. Acordos de Lusaka, was selected as the case study area for several reasons. A first case study for the area was presented to the participants of a stakeholder workshop during the inception mission in September 2012 during which the potential and the limitations of the chosen modelling approach was illustrated.

For this first rough case study a clearly identifiable subcatchment in the neighbourhood of Maxaquene A and Mavalane A was chosen for mainly technical reasons. Nevertheless, first interviews, which were conducted with residents in the neighbourhood during the inception mission, resulted in estimations that flooding occurs twice a year in the northern part of the study area and nearly 5 times per year in the southern part along the primary channel (Ertl, 2011). Subsequently the subcatchment was further investigated and based on all available data and on the findings of the site visits in August and September 2011, the Consultant suggested in the Inception Report to intensify the modelling efforts with the SWMM model for this subcatchment (for detailed description please refer to the Inception Report).

There were several reasons for suggesting this subcatchment for detailed modelling, summarized as follows:

1. For this subcatchment literature was already available due to a master thesis conducted for the University of Lund (PALALANE J. 2010: Comparative analysis of sub-surface drainage solutions in Maxaquene "A". Master Thesis. Lund University. Lund, Sweden). In this thesis not only flooding in the subcatchment is being described, but also problems with the groundwater aquifer underneath Maxaquene. This subcatchment was thus especially well suited for a joint field survey in order to collect data on all topics relevant for SC3.
2. During the site visit during the inception phase of the project it was confirmed by the local population in Maxaquene that flooding is frequent in their neighbourhood, with considerable flooding occurring almost regularly twice a year.
3. Although the available digital elevation model gave only a very rough overview of the topography of Maputo, a subcatchment with relatively clear borders could be identified in the Maxaquene A and Mavalane A neighbourhood. For many other neighbourhoods in Maputo this was not possible.
4. The size of the chosen subcatchment is well suited for the given task. The subcatchment is big enough to be subdivided in several secondary subcatchments, but is not too large to conduct a meaningful area-wide field survey in order to find out more about the properties of the subcatchment (like runoff coefficients, percentage of paved surfaces, existence of open drains and sewers, possible blocking of open drains and sewers, inclination of secondary subcatchments, etc.)
5. The housing structure of the neighbourhood is typical for many other neighbourhoods in Maputo, thus representing a good prime example for the application of the model to other neighbourhoods.
6. So far no or only a marginal sewer system is existing in the subcatchment. Construction works to construct sewers and open drains are ongoing in the subcatchment at the moment. It was thus possible to include in the model some before/after scenarios, showing the effectiveness of the measures that are currently being implemented.

7. Three major bottlenecks could be identified in the subcatchment and at the outlet of the subcatchment at the crossing of the Av. Joaquim Chissano / Av. Acordos de Lusaka respectively. It is considered crucial by the Consultant that such culverts are being included in the model in order to be able to explain the modelling of such bottlenecks with possibly transient conditions during the training course.

The selected study area (*Figure* 3-2) is located in the centre of Maputo, around the Praça dos Heróis. It includes the barrios Maxaquene A and Mavalane A and is surrounded by the barrios Maxaquene C and D in the east, Mavalane B in the southeast, the international airport in the west and Urbanizaçao in the south.

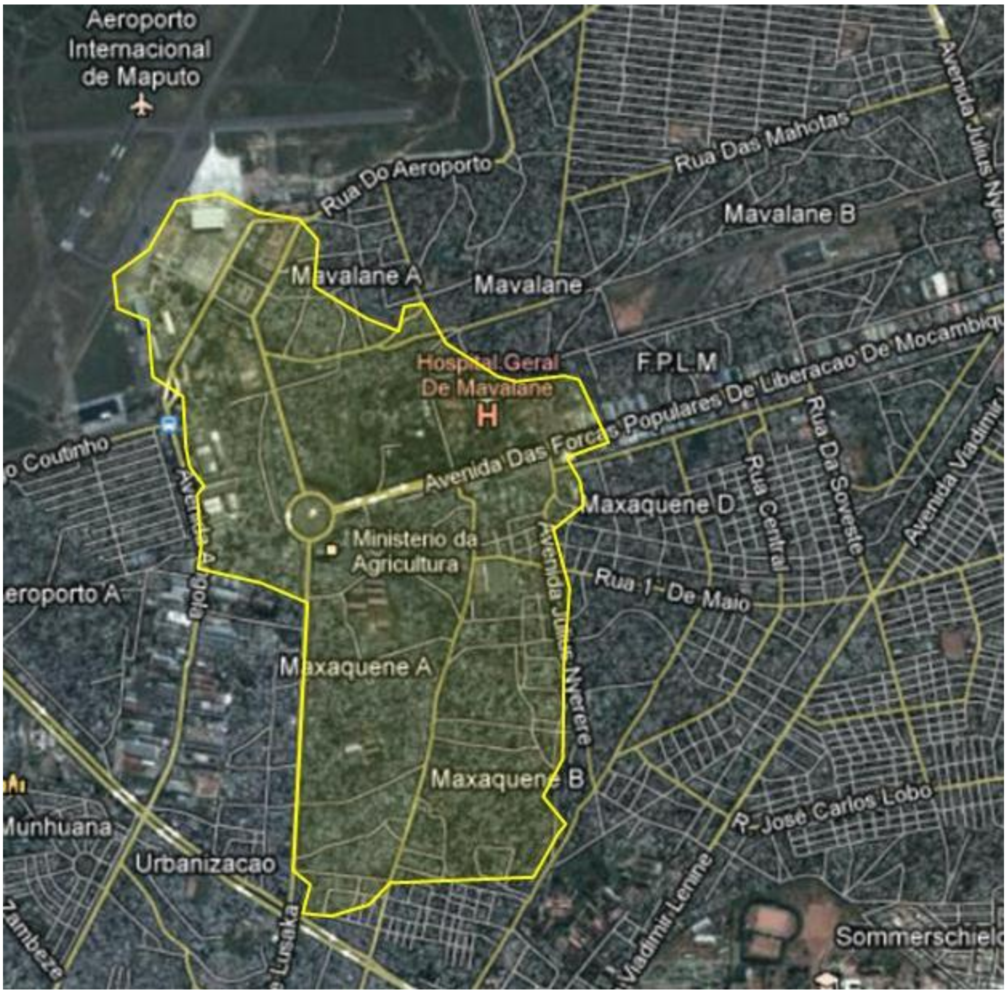

Figure 3-2: Case study area in the bairros Maxaquene A and Mavalane A

The characteristics of Maxaquene A and Mavalane A were taken from Palalane (2010). The subcatchment can be characterized as sub-urban with a high population density, with partially unplanned and informal infrastructure, with no wastewater sewer system and an incomplete storm water drainage system. The study area has an open storm water drainage channel (parallel to Av. Acordos de Lusaka, *Figure* 3-3) collecting all the storm water from the secondary storm water system in the neighbourhood. The drainage channel on Av. Acordos de Lusaka has a slope of 0.4 %.

At the junction of Av. Joaquim Chissano and Av. Acordos de Lusaka the study catchment delivers all storm water through a culvert into the primary channel (*Figure* 3-3). As the outlet of another southbound subcatchment is also located at this crossing, the confluence of storm water from three directions and several districts in this one point may be responsible for considerable backflow into all three contributories, thereby causing regular flooding in Maputo. As mentioned above, it is unclear, why these culverts have been constructed with a hydraulic capacity that is so much smaller than the capacity of the respective upstream channel. It was attempted to clarify this question with the Maputo Municipal Water and Sanitation Department during the main project phase but the respective design information was not available in the department.

At the time being, it is assumed that the under-dimensioned culverts together with the general poor condition of the some storm water drainage channels which are partly overgrown with vegetation and partly impaired through solid waste and sediment depositions are responsible for the frequent flooding in these neighbourhoods. This assumption is supported by the results of hydraulic modelling with the urban drainage model SWMM5. In the Scenarios 1-4 it could be shown that only a clearing of all culverts and storm water drainage channels will lead to a considerable increase of the hydraulic capacity of the existing storm water drainage system (refer to Section 3.4.5).

The modelling has also shown that clearing, which would be very effective to reduce the risk of inundation in the upstream part of the study catchment, would lead to a translocation of the problem towards the downstream area of the catchment as the under-dimensioned system can not discharge the flows quick enough. The bottleneck is an under-dimensioned culvert (see *Figure* 3-3 marked with a yellow circle) at the Maxaquene A / Mavalane A catchment outlet from which backlogging would occur.

***Figure 3-3: Junction of 3 main open channels at the street crossing of Av. Joaquim Chissano / Av. Acordos de Lusaka** (yellow circle: outlet of modelled subcatchment; red circles: adjacent culverts with influence on modelled outlet)*

Groundwater Situation in Maputo

Although ground water quality is reported to be good in some areas of Maputo, the groundwater pollution in Maputo is still considerable from an overall perspective. Maputo has an exposed aquifer due to its phreatic character. Some parts of Maputo show high chloride concentrations due to their historical geology (Vicente *et al*., 2006; cited to Dimande *et al*., 2001). According to another study in Moamba district of Maputo (neighbourhood of Sabíe River) high concentrations of sodium and chloride, high salinity and also fluoride are encountered, with values exceeding the limits for human use for Mozambique (DNA, 2011).

The sources of groundwater pollution are given below (Vicente *et al*. 2006):

- Industrial activities
- Pit latrines in informal settlements due to absence of good sanitation systems
- Leachate from waste-dumping site receiving all kind of waste (commercial, hospital and industrial)

3.4 METHODOLOGY

3.4.1 Methodology of inception work

3.4.1.1 Preparatory work (data and info collection, subcatchment decision)

Due to the fact that the ongoing work is part of Phase 2 of the large scale project "Responding to Climate Change in Mozambique", a large database of files and documents was available to the Consultant right from the beginning of his work, provided by the Client in the online database "Dropbox".

During the inception phase the Dropbox database has been carefully screened for respective relevant files. Additionally a thorough internet search of all relevant topics was conducted before the inception mission of the Consultant to Maputo in August 2011. The inception mission itself was supported very professionally by Mr. Antonio Queface who is acting as a liaison officer of INGC to the Subcomponent 3 consulting team.

The single steps taken in preparation for the work in Subcomponent 3 can be briefly summarized as follows:
Home office work:

- Screening of Dropbox: screening of all directories and subdirectories for relevant data, reports, articles, GIS-files, photos, maps, digital elevation models,
- Detailed search in Dropbox for all files containing the terms "water", "sanitation", "storm", "Maputo", "flood", "bottleneck", "DEM", "elevation", "sewer", "drain".
- Internet search for relevant information regarding
    - Storm water in Maputo
    - Rainwater harvesting in Maputo and other African cities
    - Integrated Urban Water Management in African cities
    - Reuse of storm water in Maputo and other African cities

3.4.2 Stakeholder consultations

As Subcomponent 3 of the present project shall provide preparative results for the implementation of recommended works, the relevant stakeholders were identified mainly on the institutional side. The following institutional stakeholders were consulted during the entire project implementation phase in order to find out about their awareness about the reasons and consequences of the urban drainage problems, their priorities, their capacities and their ideas about how the respective problems can be tackled:

- Ara-Sul: Mr. Belarmino Chivambo, Mrs. Lizete Dias, Mr. Agostinho Vilanculos
- DNA – National Directorate of Water: Mrs. Rute Nhamuche, Mr. Raul Mutivuiu, Mr. Daudo Carimo
- FIPAG: Mrs. Judite Renoldo Manhique
- UNHabitat: Mr. Paulo Conceicao Junior, Mr. Silva Magaia
- Universidade Eduado Mondlane: Mr. Jose Rafael, Mr. Antonio Queface
- AIAS: Mr. Valdemiro Matavela
- Municipal Directorate for Urban Planning and Environment: Mr. Hecrálito Mucavele, Mrs. Theresa Chissequere
- Municipal Department for Urban Drainage and Sanitation: Mrs. Circe Chaly

The results of these stakeholder consultations are summarized as follows:

1. All the above listed stakeholders were approached with a request for provision of relevant data and other respective information. While everyone was quite supportive, the results of the request showed that very little actual data (i.e. drawings or spreadsheets) is available about the exact layout and state of the existing drainage system, its total extent, the foreseen extension and rehabilitation works, or the implementation of the recommendations brought forward by DNA (2005).
2. The "Strategic Sanitation Plans for 7 Municipalities Maputo, Matola, Beira, Dondo, Nampula, Pemba and Quelimane" published by DNA (2005) was acknowledged by all stakeholders as a crucial document for the improvement of the storm water drainage and sanitation situation in Maputo. A final version of this document was not available with any of the stakeholders despite the project being concluded but a draft version was obtained by the Consultant. It was noted that none of the Consultant's counterparts in all stakeholder consultations was able to provide information about the degree of implementation of the recommendations as given in the 2005 DNA Strategic Plans.
3. The priorities as given by the different stakeholders are differing, according to the actual strategic purpose of the respective institution:

a) Ara-Sul's priority in the context of the project was on groundwater protection. The Consultant's suggestions regarding groundwater recharge via SuDS measures were welcomed and supported by the Ara-Sul representatives in the stakeholder workshop held in Maputo in September 2011. Ara-Sul played an active role during the project, provided data and documents on request and participated in the stakeholder workshop as well as in the basic SWMM training.

b) DNA also played an active role during the project, provided data and documents on request and participated in the stakeholder workshop as well as in the basic SWMM training. DNA's priority in the context of the subject project was twofold: During the stakeholder workshop DNA showed on interest on groundwater issues. The Consultant's suggestions regarding groundwater recharge via SuDS measures were welcomed and supported by the DNA representatives in the stakeholder workshop. On the other hand DNA showed no direct interest in the urban drainage agenda of the project. DNA representatives are less informed about the actual state of the urban drainage infrastructure and about ongoing activities regarding the extension and rehabilitation of this infrastructure.

c) FIPAG's main interest as demonstrated in the course of the project is to increase their water supply coverage of Maputo with piped water. FIPAG showed no intention to use the groundwater below Mapouto and rather intends to supply an increasing percentage of the population of Maputo with water brought from surface water reservoirs further inland. Therefore FIPAG showed no considerable interest in the groundwater situation in Maputo.

d) UNHABITAT was very helpful and interested and participated also in the stakeholder workshop. UNHABITAT was concerned that the choice of subcatchment and the suggested urban drainage measures would be influenced politically. After clarifying that the selection had been made based solely on technical criteria, the choice of Mafalala A and Mavalane A was welcomed and confirmed to be plausible. The priorities of UNHABITAT regarding the project were mainly to raise awareness with the Consultant about ongoing urban planning projects in Maputo, to raise awareness about the problems with the local housing market and the resulting problems of informal settlements, corruption issues and lack of capacity with the municipal institutions.

e) A representative from AIAS was planning to participate in the basic SWMM training but finally could not attend. The general priority of AIAS is on the implementation of structural measures in the field of urban drainage and sanitation. However, AIAS is not the institution concerned with conceptualisation and planning of the measures, nor is AIAS concerned with the maintenance of existing urban drainage and sanitation infrastructure. The priorities of AIAS in the context of the project were mainly on the theoretical side, i.e. the exchange of expertise with the Consultant. During the meetings it turned out that AIAS was still not fully equipped and many resources still are to be transferred from DNA. Like DNA, representatives were less informed about the actual state of the urban drainage infrastructure and about ongoing activities regarding their extension and rehabilitation.

f) The Municipal Directorate for Urban Planning and Environment provided available GIS- and CAD files from Maputo and played an active role during the project, participating in the stakeholder workshop as well as in the basic SWMM training.

g) Although being a key stakeholder in the field of work and expertise that was touched in the project, the Municipal Department for Urban Drainage and Sanitation could not be consulted. Despite several attempts by the Consultant, no meeting with representatives of this department could be arranged. Their respective priorities in the context of the project are thus unknown.

Non-institutional stakeholders were contacted mainly in the course of the field survey in Maxaquene A and Mavalane A, as a city wide stakeholder campaign was not foreseen in the scope of the project. In the course of the survey interviews were conducted in which the residents of the chosen subcatchment were consulted regarding their perception of the problem, their priorities and their ideas on how to solve the urban drainage problem and the respective other problems related to urban drainage and water resources management in general. The results of this field survey are being summarized in Section 3.4.3 with the actual interview templates and survey results being provided in the Annex of this report.

Overall, it was noted that the local population of Maxaquene A and Mavalane A believes that the best solution for the urban drainage problem would be the construction of more urban drainage channels; Improved maintenance of the existing infrastructure and reduced disposal of solid waste in the streets. The existing urban drainage channels are not perceived as effective means of handling the drainage situation.

3.4.3 Delineation of catchment area

To delineate the catchment area, two alternatives have been used. One of them is manually (via Google Earth), and the other automatically (using ArcGIS).

Delineation of catchment area via Google Earth
At first, to see the situation better, the catchment boundaries were drawn manually using Google Earth. Google Earth is a free software to view the satellite imagery, maps, terrain, 3D buildings, oceans and galaxies, based on a geographical information system.

To delineate the catchment, contour lines from GIS files provided in the Dropbox database (original source unknown) were converted to ‘kml’ format, which is necessary to open the data in Google Earth. This file illustrates the runoff flow paths, existing and proposed drainage channels and sewer system. After adding the contour lines to Google Earth, a few trials were done to obtain the best result of study area. The catchment is delineated by using the highest elevations surrounding the actual catchment.

TatukGIS Viewer **- www.TatukGIS.com**

The free TatukGIS Viewer is a slimmed down version of TatukGIS Editor (see below), without the data creation, scripting/customization, and 3D display capabilities. Both Editor and free Viewer open most ArcView, ArcExplorer, and MapInfo projects and map projects exported from ArcGIS/ArcMap (v.9x) using the free Arc2TatukGIS plug-in.

The TatukGIS Editor is a general purpose GIS desktop application and development platform with its powerful built-in Pascal/Basic scripting tools exposing an extensive object API. Features include comprehensive visual layer property, legend, and scale controls, 3,000 pre-defined coordinate systems, on-the-fly reprojection of vector/raster map layers, database joining, and native support for most GIS/CAD vector, raster, and SQL based map data formats, including advanced 3rd party spatial database formats: Microsoft Spatial, Oracle Spatial & Oracle GeoRaster, ArcSDE & ArcSDE Raster, PostGIS, MapInfo SpatialWare, SQLite Spatial..., and much more. For example, the recent version 3 upgrade added 3D viewing capabilities including DTM (digital terrain model) presentation, 3D vector rendering, automatic draping of image and 2D vector layers over a DTM, flood simulation, light/shadow control, and camera/scene control. *Figure* 3-4 provides an example for the visualisation of topography, showing the case study catchment area and the results of the hydrological analysis, while *Figure* 3-5 shows a visualisation of the mentioned contour lines shapefile with TatukGIS.

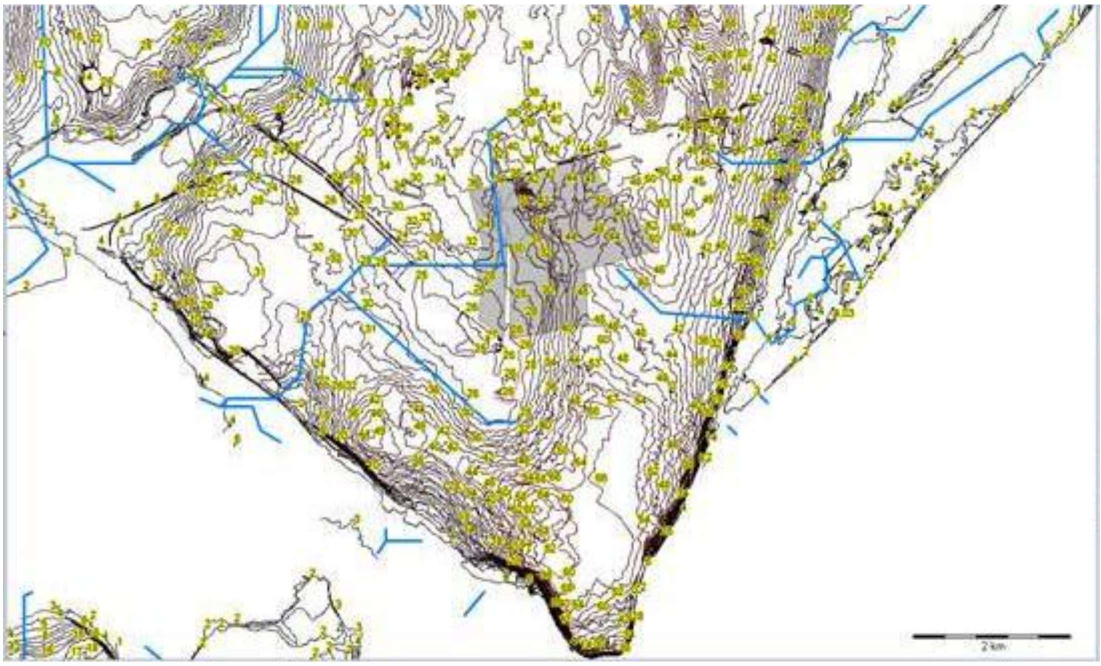

Figure 3-4: Visualisation of topography with TatukGIS software

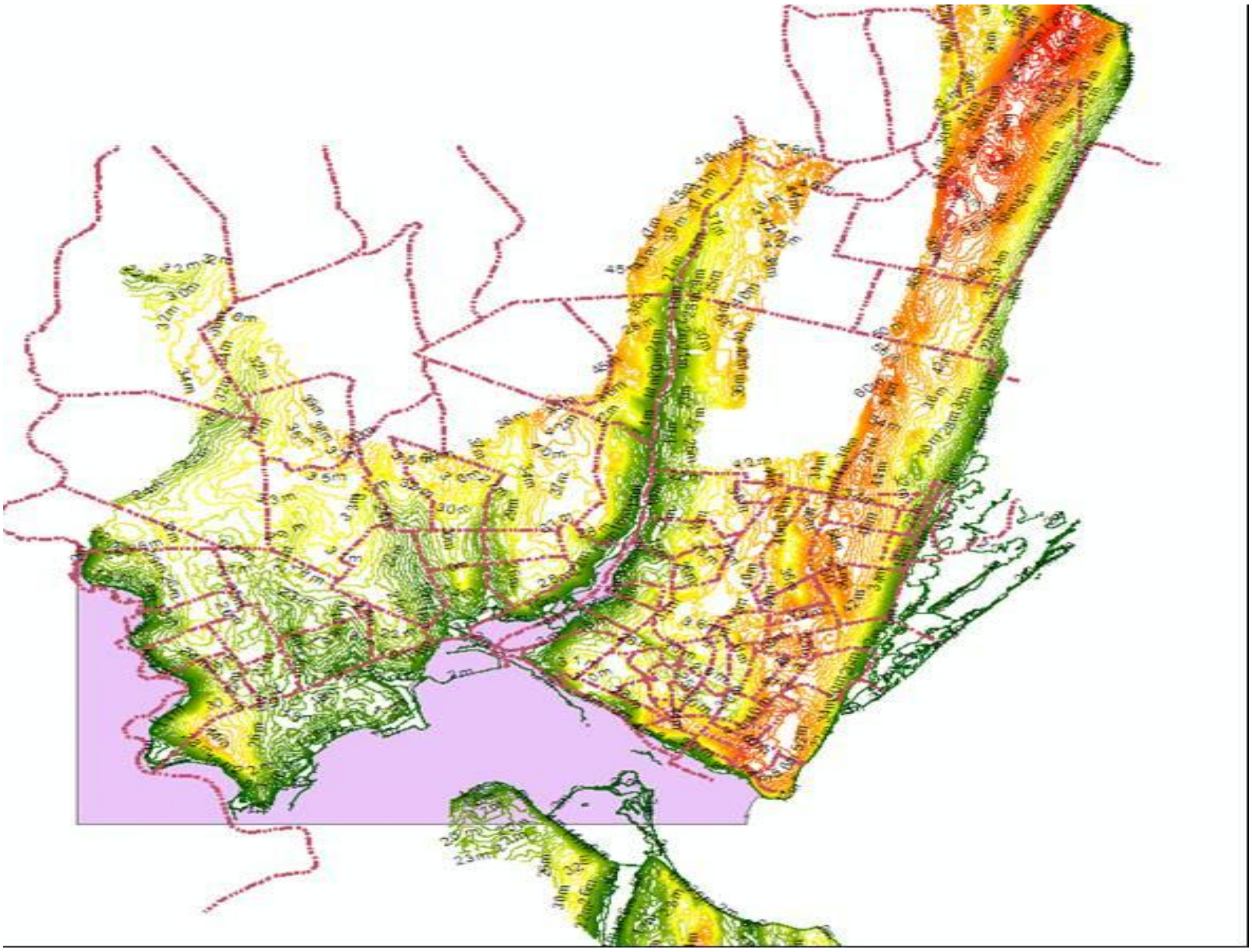

Figure 3-5: Visualisation of contour lines with TatukGIS software

3.4.3.1 Delineation of Watershed for Study Area with ArcGIS Desktop 10

ArcGIS is a group of geographic information system (GIS) software developed and distributed by the Environmental Systems Research Institute (ESRI). Basically a GIS is a tool for digital mapping and spatial analyses. Using a GIS provides, amongst others, the possibility of capture, storage, query, analysis, display and output of any kind of geographic information. For this study, to delineate the watershed accurately, the newest version "ArcGIS Desktop 10" was used on ArcInfo licensing level.

Geographic data can be represented digitally in two methods; raster and vector data structure. In this project a raster data structure was used, representing the geography of the subcatchment via grid cells. In a raster representation, every location is referenced by a grid cell in a square array. Each cell expresses a geographic attribute or property by assigning a value to them, therefore each cell has a single value. This method is stressed as the best way for representation of elevation features (Longley *et al*., 2005).

Before the delineation of a watershed with ArcGIS, some pre-processes must be completed with spatial analyst toolbox with the first step being the creation of a digital elevation model (DEM).

A digital elevation model can be created in ArcGIS Desktop 10 with an interpolation toolset and different interpolation techniques. In this study, a DEM is created using "topo to raster interpolation" technique. For the creation of any DEM some input parameters should be given. There are six types of possible input data: point elevation, contour, stream, sink, boundary and lake. For the setup of a model for the chosen subcatchment two types of them were used; contour lines as *point elevation* and polygon as the *boundary* of Maputo. Open drainage channels were integrated in a next step.

For the present project, DEM creation has been tried for different cell sizes (50, 30, 10 and 5 m). The best resolution was achieved with 5 m cell size. Thus a DEM with 5m grid size was generated taking into account that a higher spatial resolution would result in longer calculation time of the model.

Open drainage channels were not considered in the DEM generation. In a second step Reclass and Raster math toolsets were used to integrate the channels to DEM. In the flow chart below (*Figure* 3-6) all steps in the course of a DEM creation with open drainage channels integrated are shown.

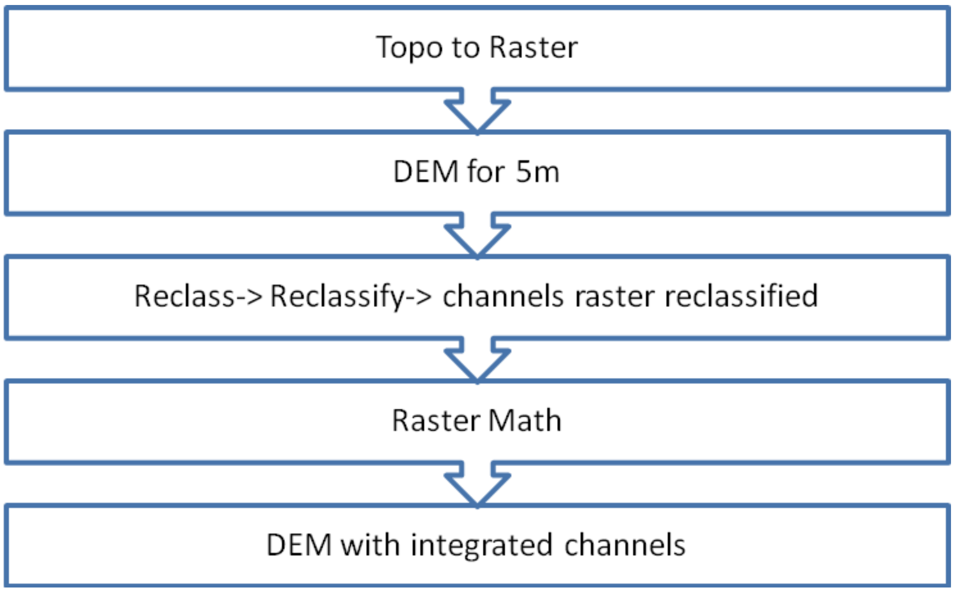

***Figure* 3-6: Steps while creating DEM**

After a DEM with a grid size of 5 m had been generated, the open drainage channels were integrated to the model. With the DEM obtained as described above, the watershed was delineated using pour points, flow direction and flow accumulation raster layers.

A sink is a cell with an undefined drainage direction and any cell around that is not lower than this cell. Because the surrounding cells have higher elevation, water stays in this lower cell and cannot flow in any direction. Sinks can be real depressions in landscape such as reservoir, levees, groundwater recharge areas and vernal pools. If there is no clear explanation about real depressions, sinks can occur by reason of data errors. To eliminate the error problems, sinks should be filled by using fill tool in the ArcGIS spatial analyst toolbox. If a sink is filled, it is filled to its pour point, which is the minimum elevation along its watershed boundary (Joseph, 2007). Once all sinks are filled, a filled DEM raster file for 5 m can be obtained.

After raising the elevation of the sinks, the general direction of water flow is determined using 'flow direction tool bar' within ArcGIS. This tool finds the flow direction of ea cell, querying the 8 cells (pixels) surrounded this cell. There are always eight values (1, 2, 4, 8, 16, 32, 64 and 128) for eight adjacent cells in this method. Each cell takes a number and each number indicates a direction. Flow directions with their codes are illustrated in *Figure* 3-7 and *Figure* 3-8. This approach was presented in Jenson and Dominigue (1988) and named eight-direction flow model (ArcGIS Resource Centre, 2011). When each cell or direction is given with different colour, it is easier to visualize in which direction water would flow.

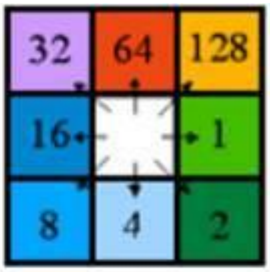

***Figure* 3-7: Direction coding**

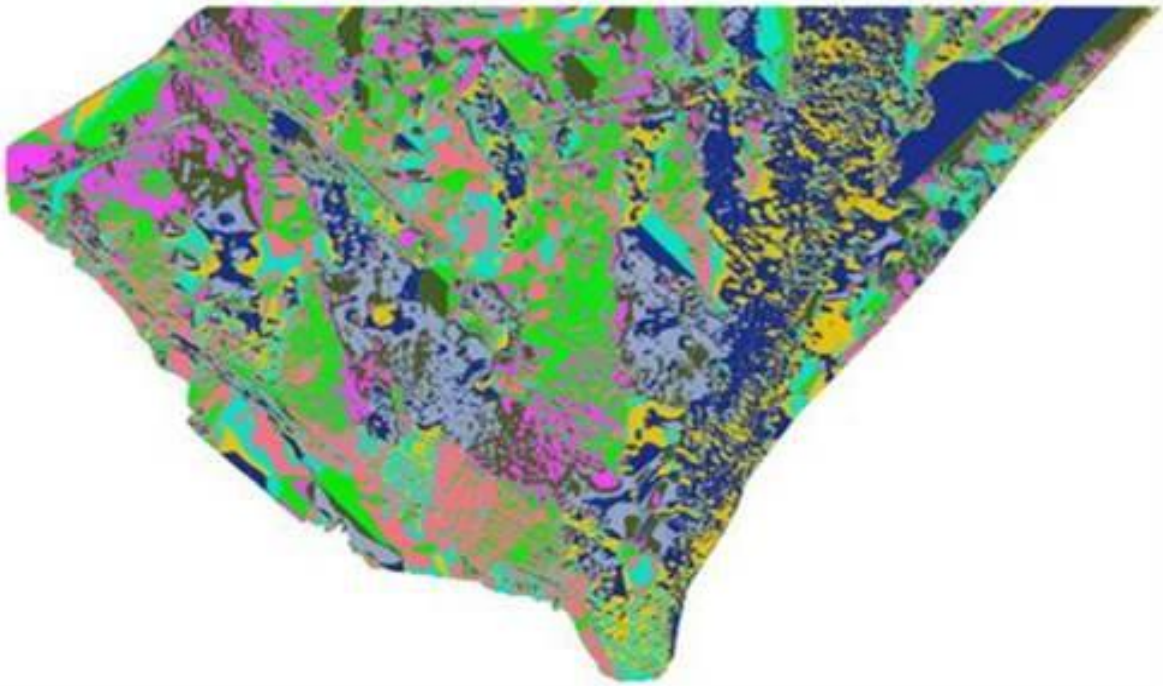

***Figure* 3-8: Flow directions calculated for the case study area**

In the next step, a flow accumulation grid is calculated using flow direction raster layer. A flow accumulation layer represents the amount of water that would flow into each cell. The accumulated flow is based on the number of cells draining into each cell in the output raster (ArcGIS Resource Centre, 2011). The cells which receive the greatest amount of water flow are lighter colours and less amount of flow is represented with darker colours. *Figure* 3-9 illustrates that water is accumulated in open drainage channels in study area.

Figure 3-9: Existing channels within the study area (red arrow: outlet of modelled catchment)

The next step was the placement of pour (outlet) points in ArcGIS. The location of pour points is the most important step in a comprehensive modelling of a watershed, as pour points essentially represent the end of sub-basins (*Figure* 3-10).

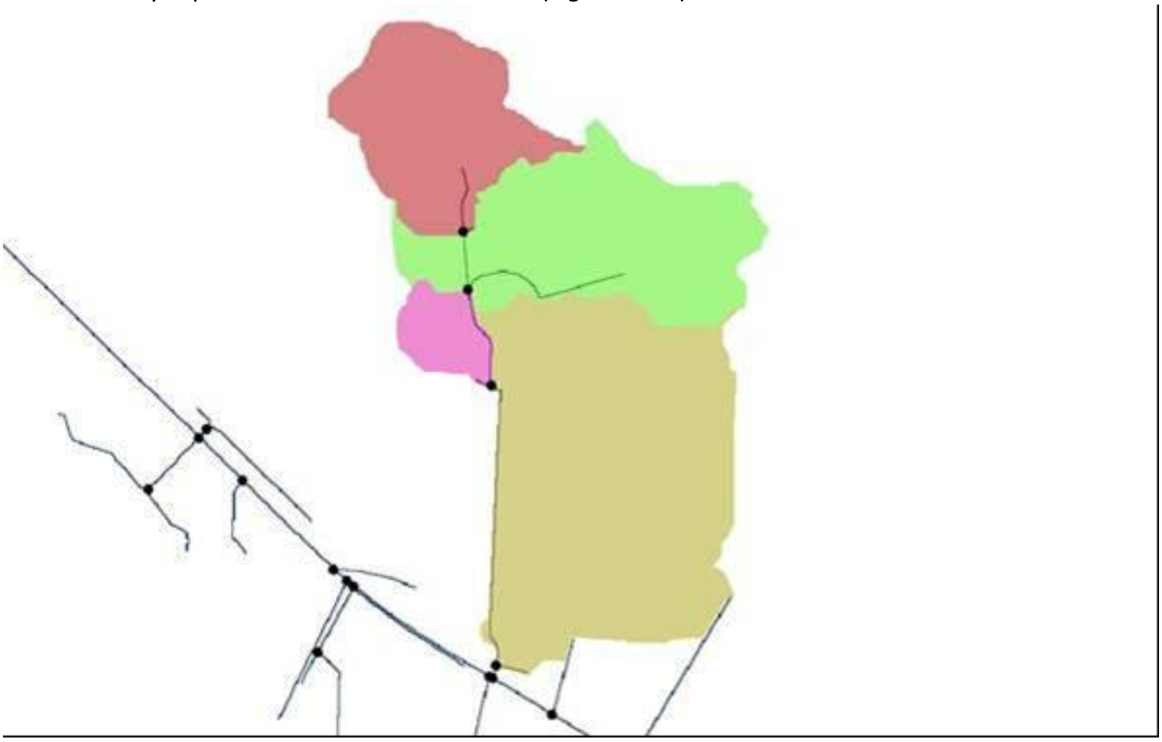

Figure 3-10: Placement of pour points for the case study area

As a watershed or catchment is the upslope area from which the water flows to a common outlet (pour point) any catchment can be delineated automatically from a suitable DEM by using the flow direction and pour points raster data (ArcGIS Resource Centre, 2011). In order to get a good catchment result, the correct positions of the pour points have been chosen with special care. Therefore, a few trials with different pour point sets have been completed before the actual delineation of the watershed was accomplished. The obtained watershed is illustrated in *Figure* 3-11. *Subcatchments* as modelled in SWMM are shown in different colours.

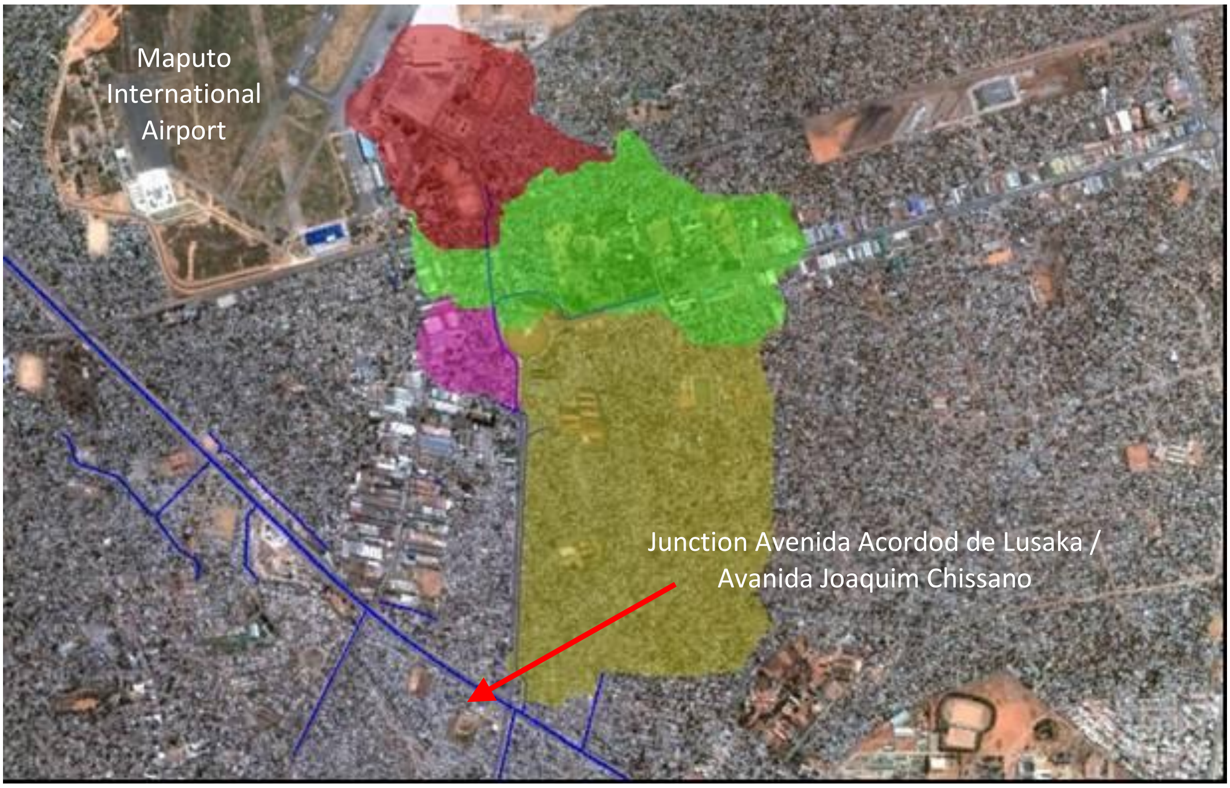

Figure 3-11: Watershed delineated via ArcGIS.

3.5 DATA ANALYSIS AND MODELLING

3.5.1 Data analysis

During three missions to Mozambique in the project implementation phase the collection of data and information was pursued. The following steps were taken:

- Meeting with Client
- Meeting with other Consultants (*McKinsey*, *Consultec*) to discuss earlier modelling results and ongoing projects in the urban drainage sector
- Visits to relevant Institutions in Maputo in order to meet with relevant experts in the field of storm water management and water resources management and to officially request the handover of relevant reports, policy outlines, masterplans, and strategy papers to the Consultant:
    - Ara-Sul: Mr. Belarmino Chivambo, Mrs. Lizete Dias, Mr. Agostinho Vilanculos
    - DNA – National Directorate of Water: Mrs. Rute Nhamuche, Mr. Raul Mutivuiu, Mrs. Luisa Conceicao, Mr. Armando Pedro Cuinhane, Mr. Daudo

Carimo
- FIPAG: Mrs. Judite Renoldo Manhique
- UNHabitat: Mr. Paulo Conceicao Junior, Mr. Silva Magaia
- Universidade Eduado Mondlane: Mr. Jose Rafael, Mr. Antonio Queface
- AIAS: Mr. Valdemiro Matavela
- Municipal Directorate for Urban Planning and Environment: Mr. Hecrálito Mucavele, Mrs Theresa Chissequere

Other organisations were contacted by telephone and email, but could not be visited due to limited availability of the respective relevant experts in these institutions. It must be especially pointed out that, despite several attempts, no consultation was possible with the Municipal Department for Urban Drainage and Sanitation

Also, despite many attempts by the Consultant, supported by the Client, the acquisition of relevant data and documents proved to be very difficult and time consuming (please refer to the Inception Report for more details). Unfortunately the Consultant could not obtain (or confirming the existence of) GIS data of the urban sewerage and drainage system from any of the involved institutions which would have formed a crucial fundament for the setup of a city wide storm water drainage model for Maputo[3].

Received data until end of March 2012:

- Rainfall: Daily rainfall (1960 – 2010)
  - Design Storm equation (DNA report)
- Topography:
  - Contour lines (shapefile, used as DEM)
  - DEM provided by INGC in March 2012
- Infrastructure files
  - Road and street network shapefile
  - Housing shapefile (for definition of runoff coefficient)
  - Study of Rainwater harvesting potential with shapefiles of buildings and roads of the southeastern part of Maputo
  - AutoCAD (.dwg) files of existing areas of sanitary sewers and storm water drainage
- Reports describing:
  - Subcatchment boundaries (without maps)
  - Districts with sewer and open channel system (no files)

In total the received data match the situation which was described as Case 2: "Weak data availability" in the Technical Proposal for this assignment: "… no data are readily available. Data including runoff coefficients land use, main drains and surface runoff waterways can only be derived from satellite images or maps and by comparison with similar climatic settings. The Consultant will strongly depend on local expert knowledge."

As some data could be acquired during the main project phase, especially by means of a field survey, the available data for hydraulic modelling has improved considerably (*Table* 3-2):

[3] While the actual existence of these files was mentioned to the Consultant several times, it could never be finally confirmed.

Table 3-2: Data availability for storm water runoff modelling in Maputo

Data	Unit	Possibilities by received data
Rainfall data	[mm]	Daily rainfall data of last 50 years show variance of rainfall.
Contributing areas and connecting points to drainage system	[ha]	By means of the newly received DEM a clear catchment delineation was possible
Runoff coefficient	[/]	By means of the newly received housing shapefiles a sufficiently exact definition of runoff coefficients was possible
Cross-section, slope and length of drains, conduits and natural waterways	[m]	Good database for the chosen subcatchment based on survey data generated by the Consultant
Storage / Treatment facilities	[m3]	No data available.
Topography (Elevation)	[m]	New DEM available

Summarizing data availability it can be stated that through the additional onsite survey the minimum standard for the catchment delineation and the modelling parameters has been fulfilled. As data or information about storage and treatment facilities in the catchment is lacking, such facilities have not been included in the modelled subcatchment.

Upon finalisation of the field survey, the available data were sufficient for the modelling of different scenarios within the subcatchment under realistic topographic conditions.

3.5.2 Model setup

3.5.2.1 Short description of modelling software SWMM5

- Storm Water Management Model (SWMM)
- Version 5 / PC / Available for free (in English language)
- Developed since 1971 by US Environmental Protection Agency (EPA)

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model that computes runoff quantity and quality from primarily urban areas. It can be used, among others, to model some of the most common types of stormwater management and design problems encountered in practice. These include: computing runoff for both pre- and post development conditions; analyzing the hydraulics of simple collection systems; designing a multi-purpose detention pond; modelling distributed low impact runoff controls; simulating the buildup, washoff, transport and treatment of stormwater pollutants; analyzing both dual drainage and combined sewer systems; and running long-term continuous simulations.

The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators.

As SWMM5 is not an inundation model, the inundation of the subcatchment cannot be simulated in the model directly, rather the exact location where flooding occurs and the exact amount of water which is spilling from the modelled drainage system is being calculated.

Setup files, manuals and all other information is available for free at
http://www.epa.gov/nrmrl/wswrd/wq/models/swmm

The purpose of using SWMM5 in this project is to create a dynamic rainfall-runoff simulation model which can be used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas of Maputo.

3.5.2.2 Study area characteristics

The study area, i.e. catchment, is located in the northeast of Maputo, which includes the barrios of Maxaquene and Mavalane. Rainwater is partly collected by channels and transferred to junction Av. Joaquim Chissano and Av. Acordos de Lusaka, where the main channel of the study area (parallel to Av. Acordos de Lusaka) discharges into the primary storm water sewer (parallel to Av. Joaquim Chissano).

The catchment area size4 is approx. 277 ha and is divided in 5 subcatchments for a better understanding and examining of the area (see also *Figure* 3-11). The main channel of the study area is enclosed by all the subcatchments. *Table* 3-3 lists the geometric properties of the 5 subcatchments and *Figure* 3-12 shows an overview of the case study area with labelled subcatchments (S1, S2, …) and labelled nodes (= junctions) along the main channel. The red line in *Figure* 3-12 denominates a new secondary storm water sewer channel crossing through Maxaquene A along Avanida Milagre Mabote. This new channel drains about the half of Subcatchment S5 directly into the receiving primary storm water sewer, thereby reducing the inflow into the a.m. main channel of the study area (parallel to Av. Acordos de Lusaka).

Table 3-3: Geometric properties of subcatchments in study area

Sub-catchment	Area (ha)	Flow Length (m)	Width (m)	Slope (%)	Imperviousness (%)
S1	51.49	944	545	0.58	80
S2	6.58	434	152	1.3	75
S3	68.20	1108	616	1.5	75
S4	12.12	520	233	0.9	85
S5	138.61	1460	949	1.4	77

[4] *Italic* printed terms denominate terms as they are named in the SWMM5 model

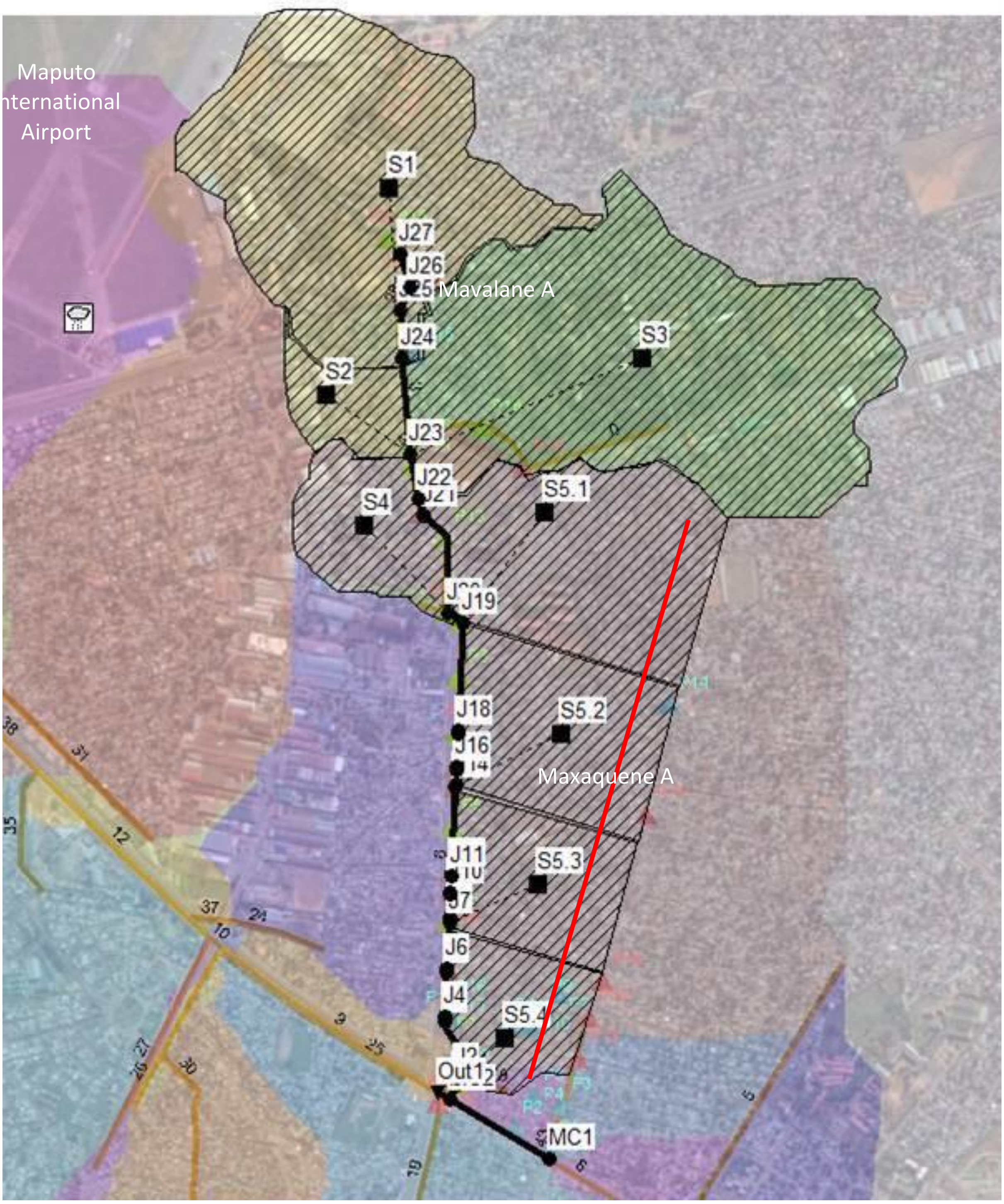

Figure 3-12: Overview of Case study with labelled subcatchments (S1, S2, …) and labelled Nodes of main channels

Figure 3-13: Typical view of Case study area

In General, the *width* of an area is calculated through the *area* divided by *flow length*. *Flow length* is the longest overland flow path that water can travel through the subcatchment (Gironas, 2009). The *slope* of each subcatchment is determined by means of a GIS (in our case ArcGIS). Ideally, the *imperviousness* of an area, i.e. the surface runoff coefficient, should be measured directly in the field or estimated from orthophotos by determining the land use (Gironas, 2009). In the present study area, the runoff coefficient is estimated based on satellite images and GIS files on the land use in the sub catchment.

Due to intensive housing in the catchment area, the imperviousness is estimated to be 75-85 %. That means that the infiltration rate in the entire subcatchment is very low. For infiltration, the *Horton* model was chosen and the routing model was set to *dynamic wave routing* in order to handle possible back flow effects.

For definition of the conveyance systems, calculation *nodes* are added. Nodes represent the location where the runoff enters the drainage system, wherever two or more channels are joined, and where *slope* or *cross section* of a channel are changing significantly (Gironas, 2009). With respect to this definition, the location of these nodes and their elevations are determined by means of a GIS. In the modelled subcatchment the maximum depths of nodes were defined according to the results of the field survey. The outlet of study area is referred to as *Out1*.

In SWMM5 the channels in which the storm water is collected and discharged are represented by links (*conduits*) in which the runoff is being routed to the catchment *outlet*. For the modelling exercise in the present project the shapes of the channels could be represented exactly in the model (e.g. trapezoidal primary open drainage channels, rectangular secondary open channels). Two of the *conduits*, located near the outlet, were designated as culverts.

Storm Water Drainage from Maxaquene A and Mavalane A

The open channel on the Av. Joaquim Chissano conveys water from Maxaquene A and Mavalane A and several other districts of Maputo towards the Infulene River and finally to the sea. In order to consider the storm water runoff from other parts of Maputo in the model, a constant flow of 4 m^3/ s has been assumed for this channel. The *Manning roughness coefficient* of all open channels was estimated to be 0.01 for *trapezoidal* and *rectangular open* channels and culverts.

Culverts were considered *rectangular closed* pipes. However, they have 45° inclined wing walls and a 90° headwall. For the entry and exit losses in culverts, coefficients were assumed to be 0.4 and 1.0.

Rainfall data

As flooding risk, being a function of possible damage and probability of occurrence, is always strongly connected to the return period of rain events, the statistical results of rainfall analysis are one of the main inputs in runoff modelling. The Consultant has received daily rainfall data from 1960 to 2010 of 1 monitoring station in Maputo. During the inception phase it was stated by Ara-Sul (and confirmed by INGC) that no other rainfall data (i.e. no higher temporal resolution) exist for the area of Maputo. Nevertheless, Intensity-Duration-Frequency Curves (IDF Curves) for Design Storms from 15 – 180 minutes have been found in a report by the National Directorate of Water (DNA 2005). For the derivation of a suitable design storm, these rainfall design storms published by the DNA were used. Storm return periods of 2 and 5 years were considered. Rainfall intensities were derived at a 10 minutes time interval. *Table* 3-4 shows an overview of rainfall intensity and duration for 2 and 5-years storm events.

Table 3-4: Intensity (cumulative) and duration for rainfall (DNA, 2005)*

Duration (hours)	Precipitation with 2 years return period (mm)	Precipitation 5 years return period (mm)	Precipitation 2 years return period + 20%[5] (mm)
9:00	0	0	0
9:10	9,47	12,95	11,36
9:20	18,94	25,90	22,73
9:30	28,41	38,85	34,09
9:40	37,88	51,80	45,46

** The table is showing design parameters for current conditions. Design data under climate change conditions do not yet exist for Maputo.*

For the first modelling attempt the rainfall data published for Maputo by Palalane (2010) were chosen, with the amounts of rainfall given in *Table* 3-5 for a return period of 2 years (according to EN 752 (1996, for housing areas) as published by DNA (2005)). A design storm with duration of 40 minutes was chosen for the first modelling attempt.

Table 3-5: Design rainfall

t (h:min)	9:00	9:10	9:20	9:30	9:40
P2a (mm)	0	9.47	18.94	28.41	37.88

source: Palalane, 2010

[5] Assumed "realistic worst case" climate change effect. Please note that this is just an assumed value, therefore also the return period is neither recalculated nor otherwise adapted.

3.5.3 Field survey

A field survey with detailed site investigations was conducted in the districts of Maxaquene A and Mavalane A in March 2012. The survey also included a set of interviews with a representative number (187) of residents in both districts. Six students were involved in the field survey over a period of three weeks of which two weeks were spent in the field and 1 week in the office for reporting. The field work included a topographic survey as well as interviews with residents of the neighbourhoods Maxaquene A and Mavalane A. For the latter, please refer to the Annex for the used questionnaires and the respective results.

Scope of services for site investigations

The agenda of the site investigations was twofold:

1. Detailed investigation on drainage structures like open channels and waterways (geographical positioning, measurement of profile and slope, documentation of operational status), also needed for detailed definition of catchment boundaries. Methods of measurement: Level surveys, photos with GPS coordinates, etc.
2. Interviews with residents of houses being flooded due to storm water. Method: Questionnaire and documentation (Photos with GPS coordinates)

Area of interest

Figure 3-14 shows the subcatchment boundaries delineated in the aerial view picture (Google Earth).

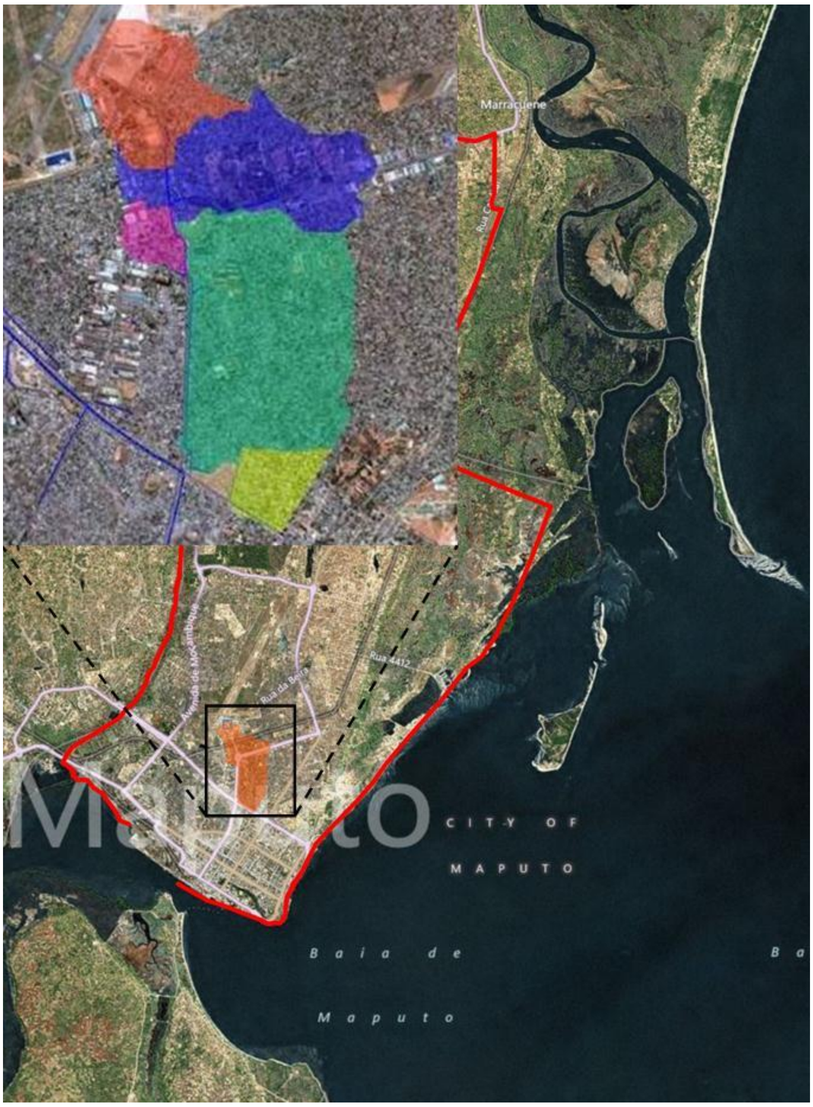

Figure** 3-14:* ***Delineation of case study catchment. The "subcatchments" as defined in the SWMM model are shown in different colours.

Detailed investigation on drainage structures like open channels and waterways

The topographic investigations started from the hydraulic outlet of the catchment, which is the main bottleneck at the end of the main channel of the catchment, see *Figure* 3-15 and *Figure* 3-16. From there the survey moved to the North along the main channel beside Av. Acordos de Lusaka.

Methods of measurement

- GPS measurements
- Measurement with measuring tape

Channels

The following measures were taken every 100 meters along the channel, as the respective data were needed for hydraulic calculations and modelling:

1) Width at the upper edge of the channel

2) Width at the lower edge of the channel (bottom width)
3) Depth of the channel

For 2) and 3): 2 different measures were taken:

a) Actual width/depth as it is at present, i.e. with vegetation
b) Theoretical width/depth as it would be if there was no vegetation. For this purpose the vegetation may have to be removed at one point in the channel.

Comment: As there are lots of deposited solids in the invert of the open channels, the aim of the survey was, amongst others, to compare the original constructed profile and the actual status with the depth of solids respectively vegetation (for defining the hydraulic roughness coefficients).

Figure 3-15: Measurements taken in the channel

Culverts

The following measures were taken at every culvert inside the subcatchment or at the boundary of the subcatchment (*Figure* 3-14). The respective data was needed for hydraulic calculations and modelling:

1) Width of the culvert
2) Clear height of the culvert
3) Depth of the channel at the culvert

For 2) and 3) two different measures were taken:

a) Actual depth as it is at present, i.e. with vegetation or deposited waste or solids
b) Theoretical depth as it would be if there was no waste or solids. For this purpose the solids may have to be removed at one point in the culvert.

As there is a substantial amount of deposited solids also in the culverts, partly reducing their clear cross section by more than 50%, the aim of the survey was, amongst others, to compare the original constructed profile and the actual status with the depth of solids (for defining the clear cross sections and the hydraulic roughness coefficients).

Figure 3-16: Culvert at crossing Av. Joaquim Chissano / Av. Acordos de Lusaka

Secondary channels

The following information was collected from every secondary channel inside the subcatchment or at the rim of the subcatchment:

1) Location of channels: Photo with GPS and/or location on map
2) Type of channel, i.e. earth channel or concrete channel
3) Shape of profile, i.e. rectangular, trapezoid
4) Width at the upper edge of the channel
5) Width at the lower edge of the channel (bottom width)
6) Depth of the channel
7) Documentation of operational status, i.e.: "fully operational" or "not operational because blocked with stones, waste etc." or "partly operational because of vegetation"

Figure 3-17: Secondary channel in Bairro Maxaquene

3.5.3.1 Investigation in the area of interest regarding possible measures of Integrated Urban Watershed Management

Questionnaires were elaborated and residents of the subcatchment area were interviewed in the course of the field survey. The questionnaires were answered by the inhabitants of Maxaquene A and Mavalene A in personal interviews conducted by the Consultant with support from the Universidade Eduardo Mondlane. It was taken care that the interviewees were distributed approximately equally within the subcatchment.
These investigations tried to cover a representative share of the population of Maxaquene A and Mavalane A.

The following questions were asked to a total of 187 households:

PART 1: URBAN FLOODING

- Question 1: How often do you experience flooding in your immediate neighbourhood?
- Question 2: How high above ground does the water level usually rise and how long does the flooding usually last?
- Question 3: In which year occurred the worst flooding you have ever experienced in this neighbourhood? How high was the water? How long did the flooding last?
- Question 4: What do you think is the main reason for the flooding in your neighbourhood?
- Question 5: Which measures would help to prevent flooding or to enforce faster runoff of the rainwater from your neighbourhood?
- Question 6: Are you informed about the ongoing construction works in your neighbourhood in order to improve the rainwater drainage situation? (i.e.

construction of new channels)

- Question 7: Do you think that the construction of new drains will help to solve the flooding problems? If no: why not?
- Question 8: Do you think that there is any space in the neighbourhood where rainwater could be collected (i.e. a retention basin) and then be released to the sea after the rainfall event?
- Do you have other suggestions about how the urban flooding problem could be solved?

PART 2 – INTEGRATED URBAN WATER MANAGEMENT

- Question 9: Where / how do you receive your drinking water? House connection to public network? Public tap? Public well? Private well? Other (if other, please specify)?
- Question 10: How reliable is your water supply? 24h per day? A few hours per day? A few days per week? Please describe:
- Question 11: Is lack of clean drinking water sometimes a problem in your neighbourhood?
- Question 12: What happens to the wastewater from your household? Is it a problem to remove the wastewater from your house/yard?
- Question 13: Is wastewater from toilets (blackwater) separated from other wastewater (greywater)?
- Question 14: Does wastewater cause hygienic problems in your neighbourhood?
- Question 15: Do you collect rainwater in your house/yard?
- Question 16: How is the solid waste collection organized in your neighbourhood?
- Question 17: Is the collection/removal of solid waste working properly? If not: which problems are there and how could they be solved?

The main findings of the interviews are summarized as listed below. For detailed results please refer to the Annex.

Regarding urban flooding:

1. Both neighbourhoods are being flooded for more than 2 days in a row approx. 1-2 times per year, with the respective inundation level between 0 and 0.5 meters. The largest flood which can be remembered by the residents was in 2000 where the neighbourhood remained inundated for more than 2 months.
2. The main reason for flooding, as perceived by the interviewees, was saturated soil and lack of drainage channels, together with unspecified other reasons. Lack of maintenance of the channels and blocking of the channels by e.g. solid waste were not considered reasons for flooding by the majority of the interviewed residents. Consequently the construction of new channels is considered the most appropriate and effective measure to improve the drainage situation.
3. The level of information regarding ongoing construction measures for new stormwater drainage channels in the neighbourhoods was low.
4. The interviewed residents could not imagine that there could be sufficient space to construct a storm water detention basin / pond within Maxaquene A or Mavalane A.

Regarding possible measures of integrated urban water management:

1. About 50% of the interviewees in Maxaquene A and 70% in Mavalane A are connected to the public water supply network with 24h water availability. The rest of the interviewed residents retrieve their water from public taps. Nevertheless, a majority of

residents claimed that there were frequent problems with water quality in the neighbourhood.

2. A vast majority of interviewees stated that there are hygienic problems in their neighbourhood caused by wastewater. While in Maxaquene A approx. 50% of the interviewees release their wastewater to adjacent channels, only 30% of the residents in Mavalane A have the chance to do so, whereas the respective rest disposes of their wastewater directly adjacent to their premises.
3. Only about 20-25% of the interviewees collect rainwater for private use, mainly by means of so-called 8-buckets (i.e. 8 x 20ltr). Such collected water is used mainly for washing (Maxaquene A) and for cooking (Mavalane A).
4. While those who do not collect rainwater gave “lack of habit” as a main reason, only approx. 5% of the interviewees claimed not to be able to afford the respective needed collection and storage equipment for rainwater harvesting.
5. A majority of interviewees is satisfied with the 2-3 times per week collection of solid waste as it is organized now, even though there is no collection directly in their neighbourhood.

3.5.4 Final modelling results

The results of the field survey (*Figure* 3-18) were used to improve the preliminary model and to carry out a plausibility check of all assumptions made so far. Additional culverts could be defined along the main channel running parallel to the Av. Acordos de Lusaka. Finally 29 nodes or *junctions* were defined in the improved model as compared to 9 *junctions* in the preliminary model.

Another improvement could be achieved by adapting the cross sections of the open channel conduits and of the culverts. Also the invert elevations of the conduits and of the culverts have been modified including plausibility checks by using the new DEM. Nevertheless, some details still remain unclear where the field survey and the new DEM differ significantly from each other (e.g. Node J24). Also the lack of any slope in the section J8-J10 seems would have to be re-checked with more accurate surveying equipment.

Table 3-6: Invert elevations of nodes/junctions in improved model according to the field survey results

Name	Invert Elev.	Max Depth	Name	Invert Elev.	Max Depth
J1	22.20	2.7	J16	26.20	2.1
J2	23.10	2.7	J17	26.70	2.1
J3	23.80	2.7	J18	27.00	1.98
J4	23.80	1.95	J19	27.70	1.98
J5	24.10	1.95	J20	27.90	1.9
J6	24.30	1.91	J21	28.00	1.9
J7	24.60	1.91	J22	28.00	1.9
J8	24.90	2	J23	28.00	1.9
J9	24.90	2	J24	28.20	1.2
J10	24.90	2	J25	28.40	1.2
J11	25.20	2	J26	29.40	1.9
J12	25.30	2	J27	29.90	1.9
J13	26.10	2	MC1	25.30	2.7
J14	26.20	2.1	MC2	22.20	2.7
J15	26.20	2.1			

The *subcatchments* in the study area have been modified according to the field survey as well. Thus the *area size* of *subcatchment 5* was reduced considering a new main channel along the Av. Milagre Mabote which leads the contributing surface runoff directly to the main channel of Av. Chissano.

Figure 3-18 gives an overview about the investigated storm water drainage infrastructure and their position within the case study area. In the following, *Figure* 3-19 to *Figure* 3-22 provide more detailed information about the results of the field survey.

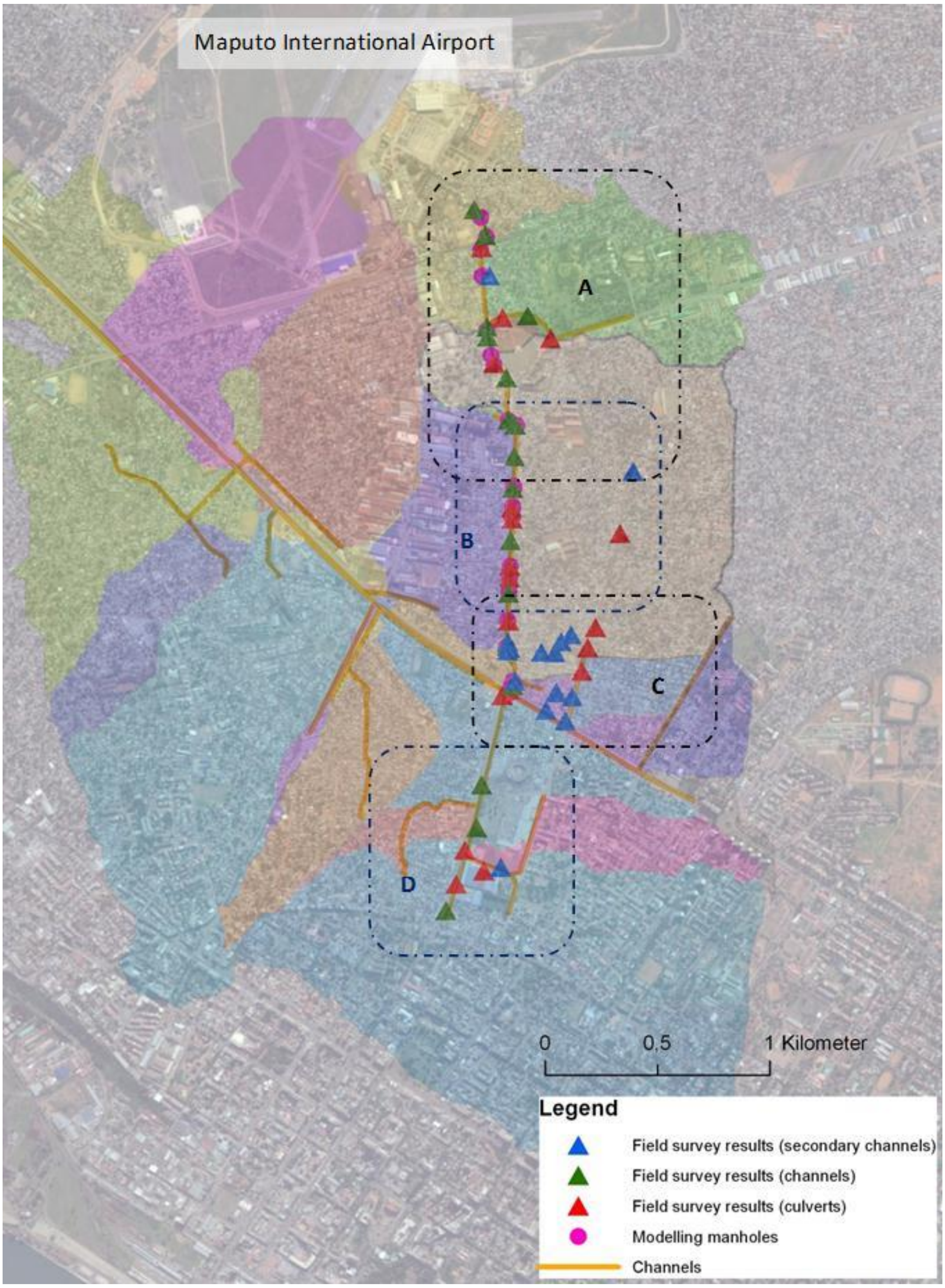

Figure 3-18: Field survey results, section overview

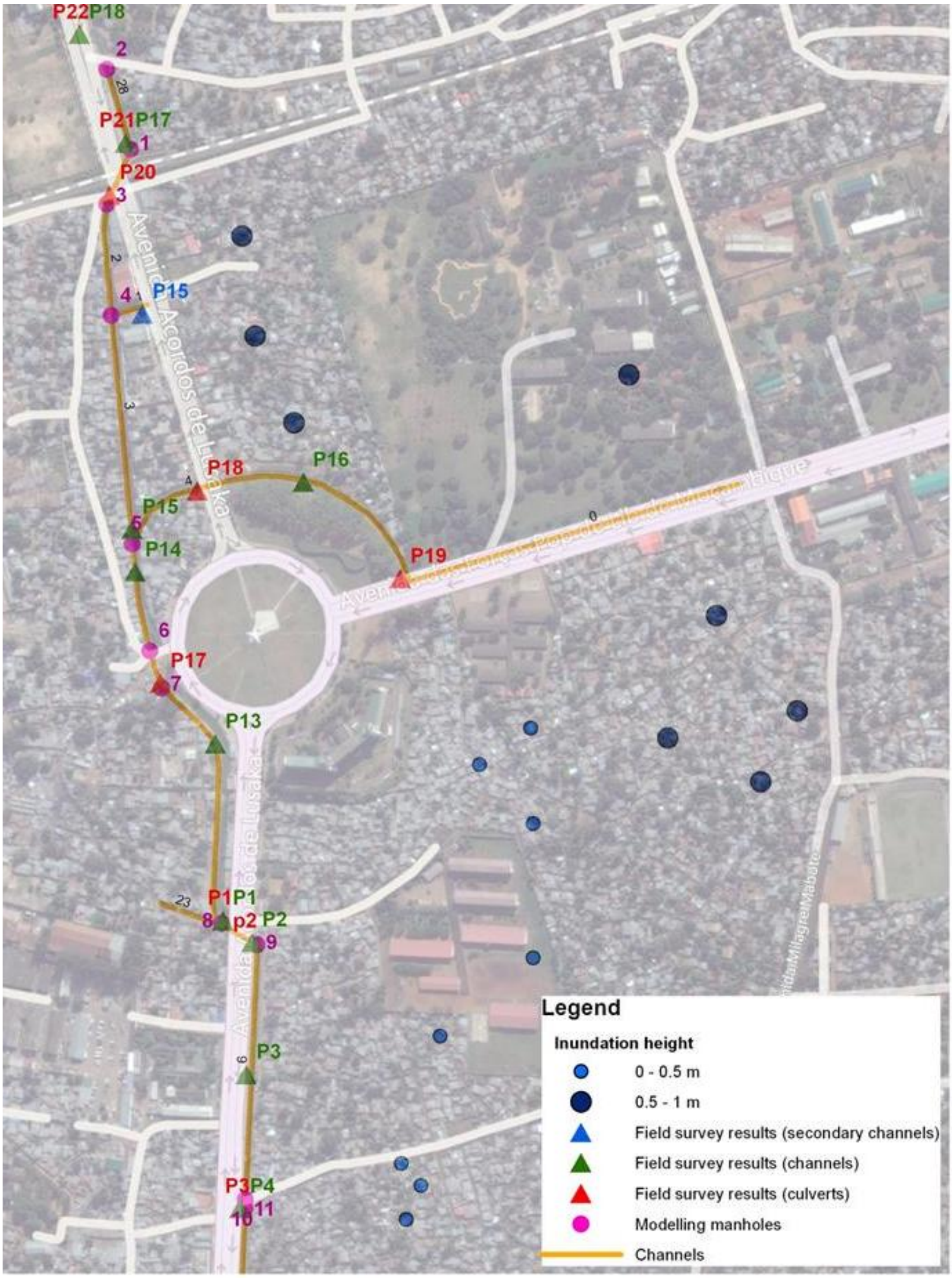

Figure 3-19: Field survey results, section A

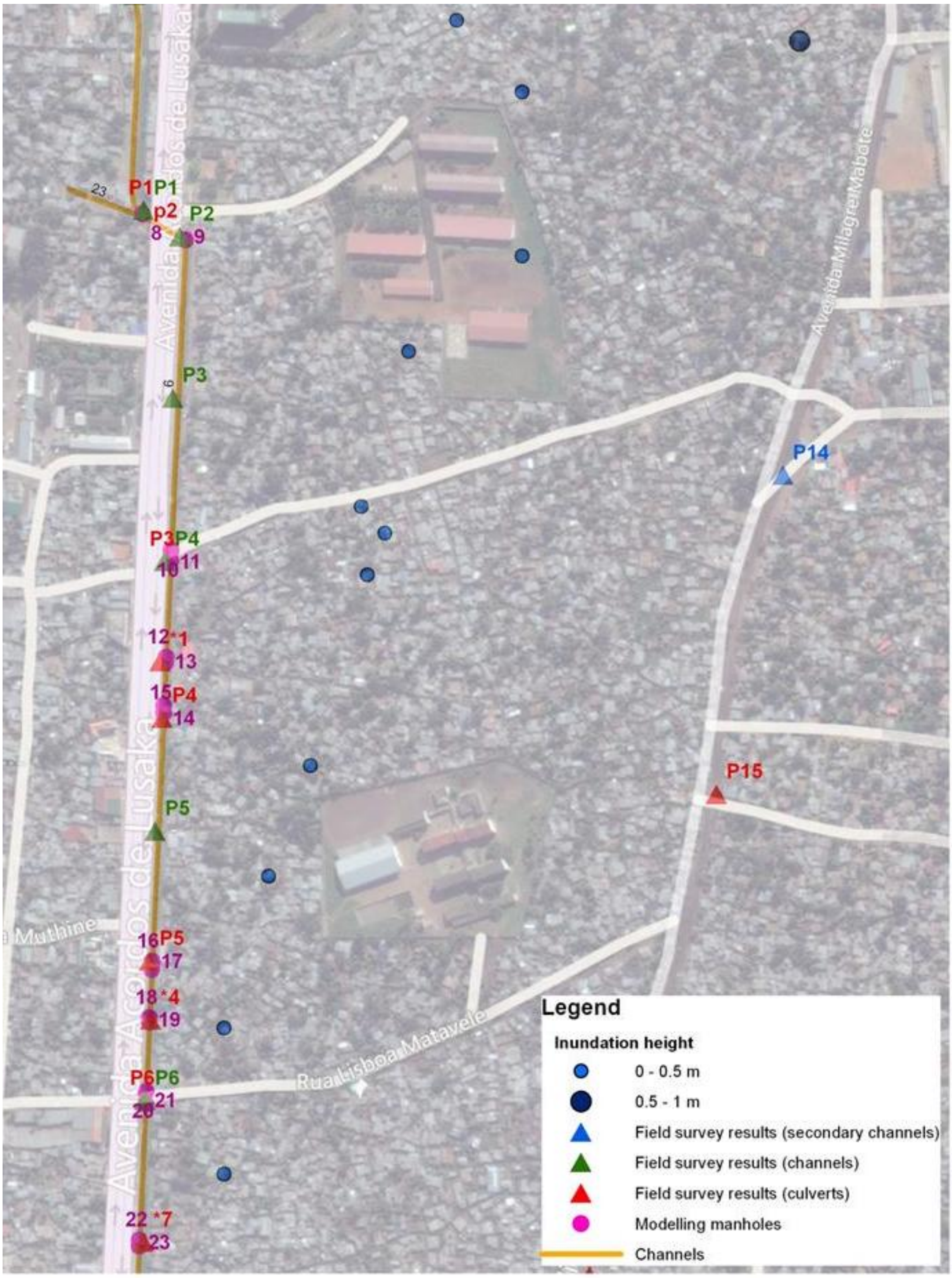

Figure 3-20: ***Field survey results, section B***

Figure 3-21: ***Field survey results, section C***

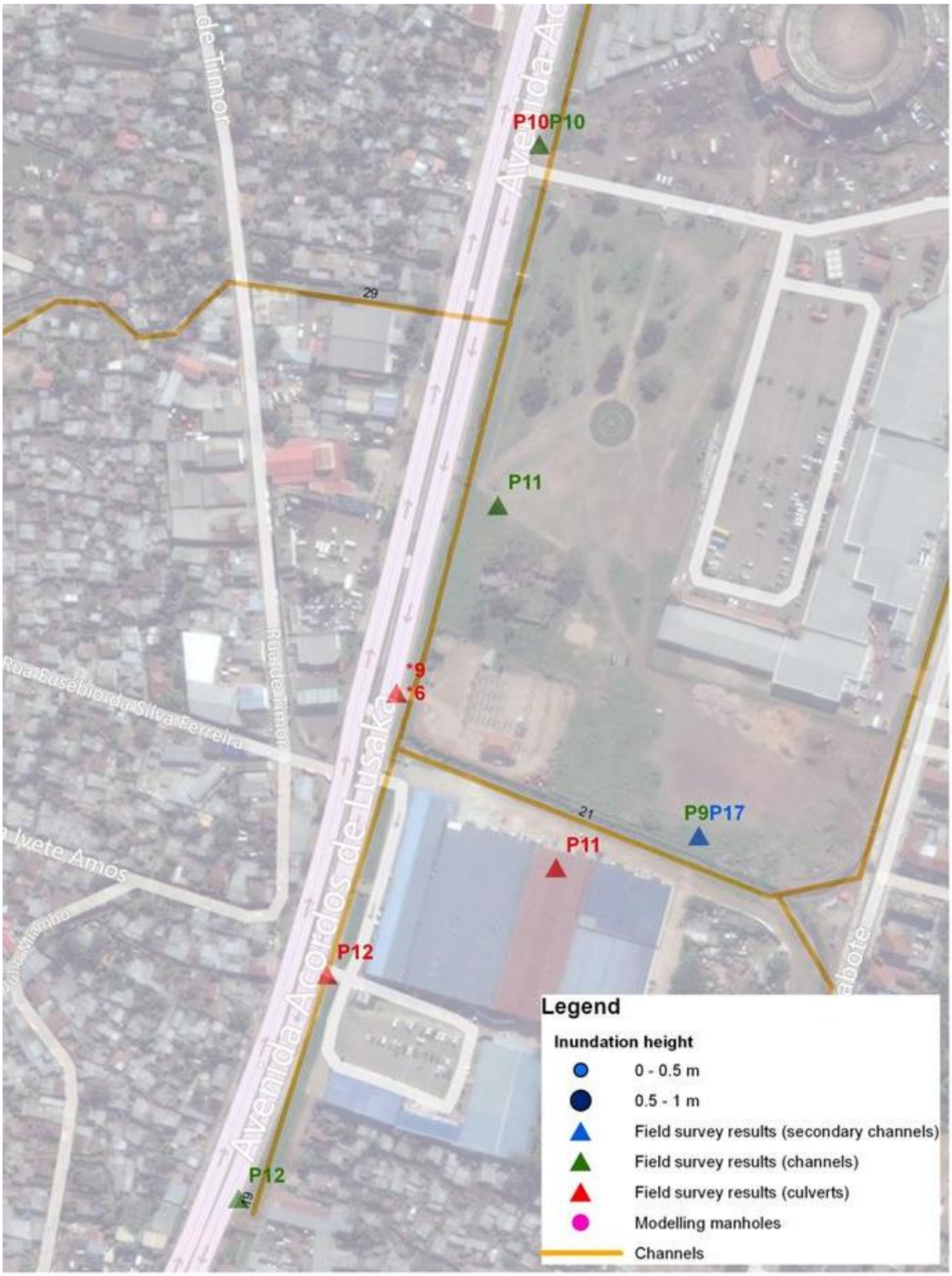

Figure 3-22: Field survey results, section D

Relating to the newly surveyed culverts, the subcatchment 5 was divided into 4 parts with 4 inlets into the main channel of Av. Lusaka instead of only 1 inlet in the preliminary model which brings more accuracy to the results. The new model setup is shown in *Figure* 3-23 with the exact invert elevations as measured in the field survey displayed in *Table* 3-7.

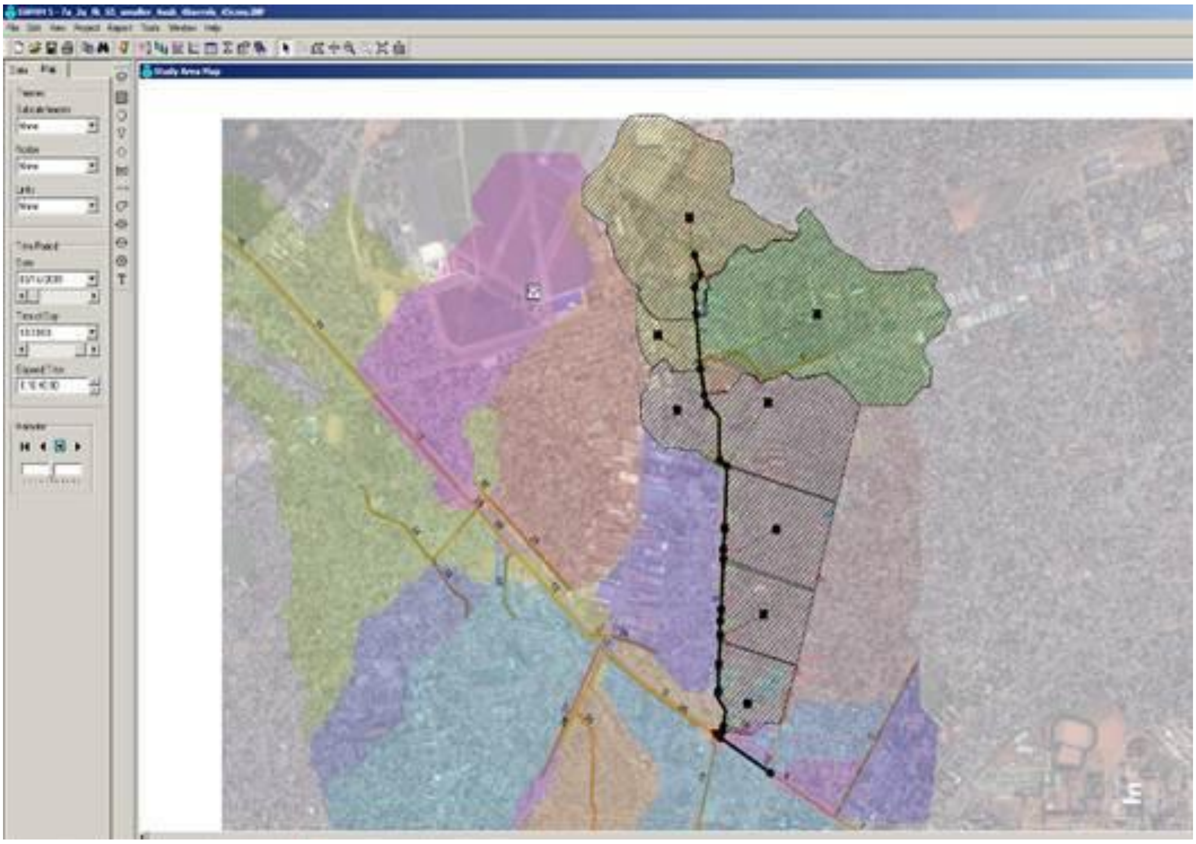

***Figure** 3-23: Overview of improved model with new structure of subcatchments*

Table 3-7: Invert geometric properties of subcatchments in improved model according to field survey

Subcatchment	Area (ha)	Flow Length (m)	Width (m)	Slope (%)	Imperviousness (%)
S1	51.49	944	545	0.58	80
S2	6.58	434	152	1.3	75
S3	68.20	1108	616	1.5	75
S4	12.12	520	233	0.9	85
S5.1	30.6	??	650	1.4	77
S5.2	20	??	530	1.4	77
S5.3	15	??	420	1.4	77
S5.4	11.8	??	330	1.4	77

The boundary conditions for all scenarios described below were:

- 2 years design storm according to EN 752 (1996, for housing areas) as published by DNA (2005)
- Continuous discharge in the receiving main Channel of Av. Chissano: 4 m^3/s

As a remark on the remaining model uncertainties after implementing the results of the field survey, all modelling results have to be seen under the following restrictions:

1. The case study area has been investigated without dynamic interaction to the neighbouring and downstream *catchments* of Maputo. It has been the right decision according to restrictions in time and budget. But for final decisions concerning the measures to be taken it must be strongly recommended that all interacting *catchments* have to be modelled in an integrated way.
2. The *subcatchments* in the model are still relatively large and thus the overland flow routing is still a theoretical one because of the long flow paths with more than hundred meters. It can be improved by further investigation in the various flow paths like secondary and tertiary channels and implementing them into the model along with further discretisation by further subdividing the *subcatchments*.
3. A special hydraulic phenomenon cannot be calculated within the model. It is to be considered quite likely that at the bridges over the modelled main channel an overflow into the downstream channel could happen in real flooding situation but not in the model. These could lead to an overestimation of flooding upstream and underestimation of flooding downstream. This problem can be solved by inserting special overflow structures into the model but makes sense only in a much more detailed model than the one used in this study.
4. The last restriction is the remaining uncertainty about certain surface and invert levels of the channels which leads to uncertainties in slopes of certain channels:

a) Node J24 Elevation unclear: this means that still after the field survey and the new DEM data the elevation of this node seems to be too low in regard to the neighbouring nodes, which can be seen in the cross-section along the main channel (see longitudinal cross section in scenarios below)

b) Nodes J9-J10 and nodes J15-J16: the slope of the downstream channel sections is apparently too low and produces backwater effects that may not happen in real. These data have to be cleared with the local agents.

SCENARIO 1: "THE CURRENT SITUATION"

The first modelled scenario was an application of SWMM5 to the current situation, i.e. with vegetation and solids in the channels and culverts, as found during the field survey. *Table* 3-8 provides an overview about the actual state of the culverts as they were also modelled in this scenario. The modelling results are displayed in *Table* 3-9 and *Figure* 3-24, which is a visualisation of the maximum water levels in the single storm water channel sections (*conduits*). In *Figure* 3-24 it is shown that the maximum water level is being reached in several sections along the channel, thus visualizing the areas where flooding occurs. The respective locations, where flooding occurs, are shown in *Figure* 3-25.

Table 3-8: Modelled culverts, their hydraulically available diameter and their actual state

No. of Point	Inlet Node	Outlet Node	Width of the culvert	Clear height of culvert without solids	Clear height of culvert with solids	% of culvert blocked	% of culvert free
P1	J20	J19	2,5m	1,34m	90cm	25	75
p2			2,14m	1,20m	90cm	75	25
P3	J18	J17	2,10m	1,30m	90cm	50	50
P4	J14	J13	2,80m	1,95m	1,55m	25	75
P5	J12	J11	3,66m	1,70m	1,20m	20	80
P6	J8	J7	2,0m	1,31m	94cm	75	25
P7	J4	J3	2,0m	1,15m	70cm	0	100
P8	J1	MC2	2,0m	1,25m	65cm	50	50
P9			2,0m	1,25m	65cm	85	15
P10			2,5m	1,45m	2,05m	35	65
P11			3,60m	1,45m	1,0m	50	50
P12			3,60m	1,50m	1,0m	50	50
P13			1,13m	60cm	40cm	90	10
P14			3,07m	85cm	60cm	60	40
P15			2,40m	80cm	40cm	50	50
P16			3,0m	60cm	40cm	50	50
P17	J22	J21	3,0m	1,30m	90cm	70	30
P18			2,50m	1,00m	70cm	60	40
P19			2,0m	2,10m	2,0m	50	50
P20			2,0m	1,50m	1,00m	65	35
P21	J26	J25	2,0m	1,20m	60cm	50	50
P22			2,15m	1,35m	1,10m	65	35
*1	J16	J15	Crossing bridge				
*2			Culvert state				
*3			Channel state				
*4	J10	J9	Crossing bridge				
*5			Culvert state (J. Chissano avenue across A. de Lusaka avenue)				
*6			Crossing bridge				
*7	J6	J5	Crossing bridge				
*8			Channel state				
*9			Crossing bridge				

Table 3-9: Node flooding summary for Scenario 1: "current situation" and 2 year / 40 minutes design storm

```
**********************
Node Flooding Summary
**********************

Flooding refers to all water that overflows a node, whether it ponds or not.
--------------------------------------------------------------------------
                                                           Total   Maximum
                                       Maximum  Time of Max  Flood   Ponded
                               Hours      Rate   Occurrence  Volume    Depth
Node                         Flooded       CMS  days hr:min 10^6 ltr  Meters
--------------------------------------------------------------------------
J24                             1.38     9.101     0  00:58   22.816     1.20
J23                             0.53     7.018     0  00:59    8.130     1.90
J20                             0.40     1.857     0  00:49    1.921     1.90
J1                              1.80     2.653     0  01:00    7.056     2.70
J4                              1.09     2.701     0  01:00    5.783     1.95
J10                             0.67     2.905     0  01:00    4.426     2.00
J19                             0.30     1.170     0  01:00    0.983     1.98
J13                             0.22     1.174     0  01:00    0.732     2.00
J18                             0.24     0.626     0  01:02    0.474     1.98
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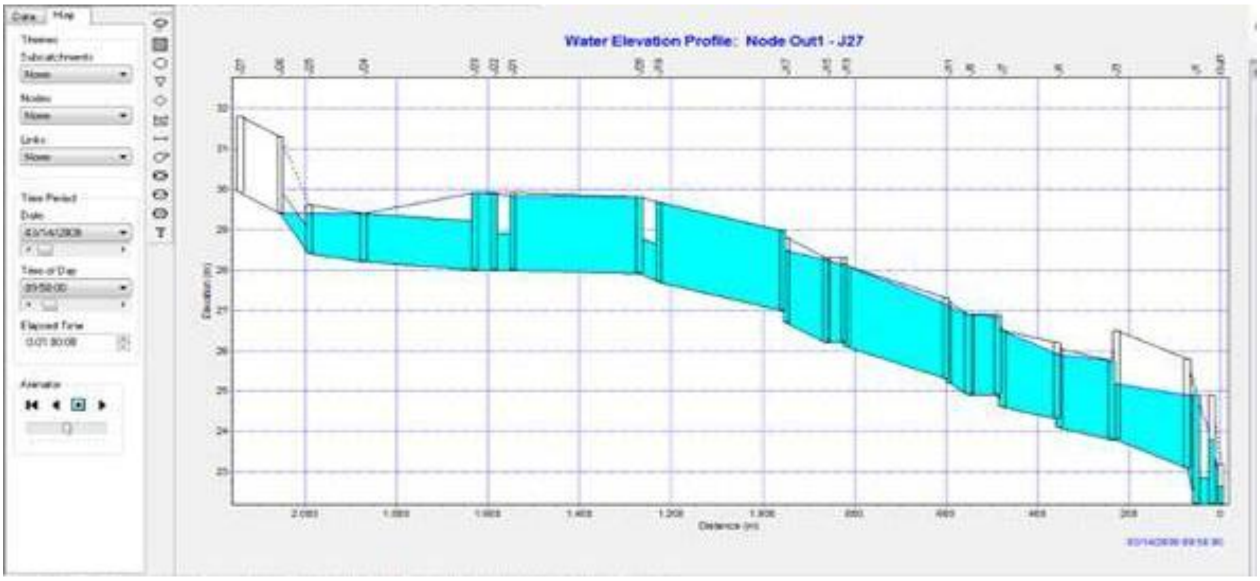
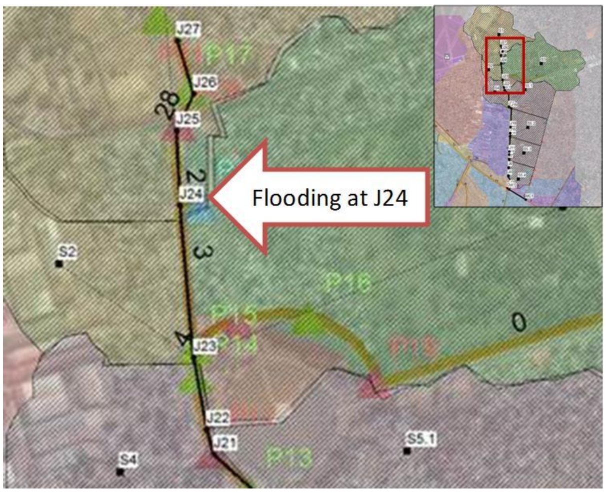


Figure 3-24: Longitudinal section through model representation of storm water channel – scenario 1: "current situation" showing water level elevations.

Result: Flooding volumes and duration are quite equally distributed along the channel. In comparison to the scenario "cleared channels and culverts" the discharge peaks are transferred from the end of the subcatchment (J1) upstream into the catchment (J24), resulting in rather equally distributed flooding in the whole *subcatchment* (see *Figure* 3-27: Flooding occurred, among others, at the junctions J1, J4, and J24.



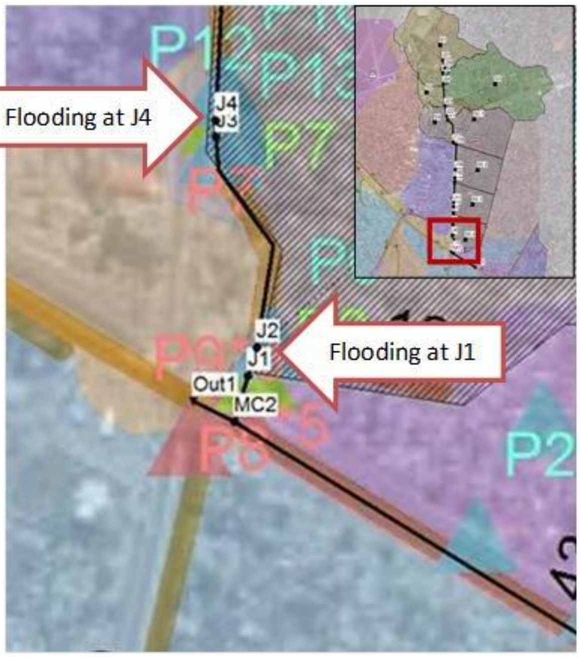


***Figure** 3-25: Flooding occurred, among others, at the junctions J1, J4, and J24 in the current situation scenario*

(see overview map for spatial reference)

The modelling results fit with the results of the interviews with the residents in the *subcatchment*. *Figure* 3-26 shows that flooding is equally distributed along the main channel of the case study area. On the other hand flooding was also reported in a certain distance from the main channel. The large blue dots in the red circle show that flooding does not only occur due to backlogging close to culverts, but likely also due to lacking urban drainage infrastructure (collection of water at low points).

To understand the model results, the model characteristics of SWMM5 need to be understood. SWMM5 is a robust one-dimensional flow routing model that can deal with low data availability and shows at which nodes spill occurs from the drainage system. It is not a spatially distributed inundation model that would simulate inundation depth and two-dimensional flood spreading. I.e. the field survey results could be used for verification (with regards to where spill occurs) but not for detailed validation (inundation extent and depth) of the model results

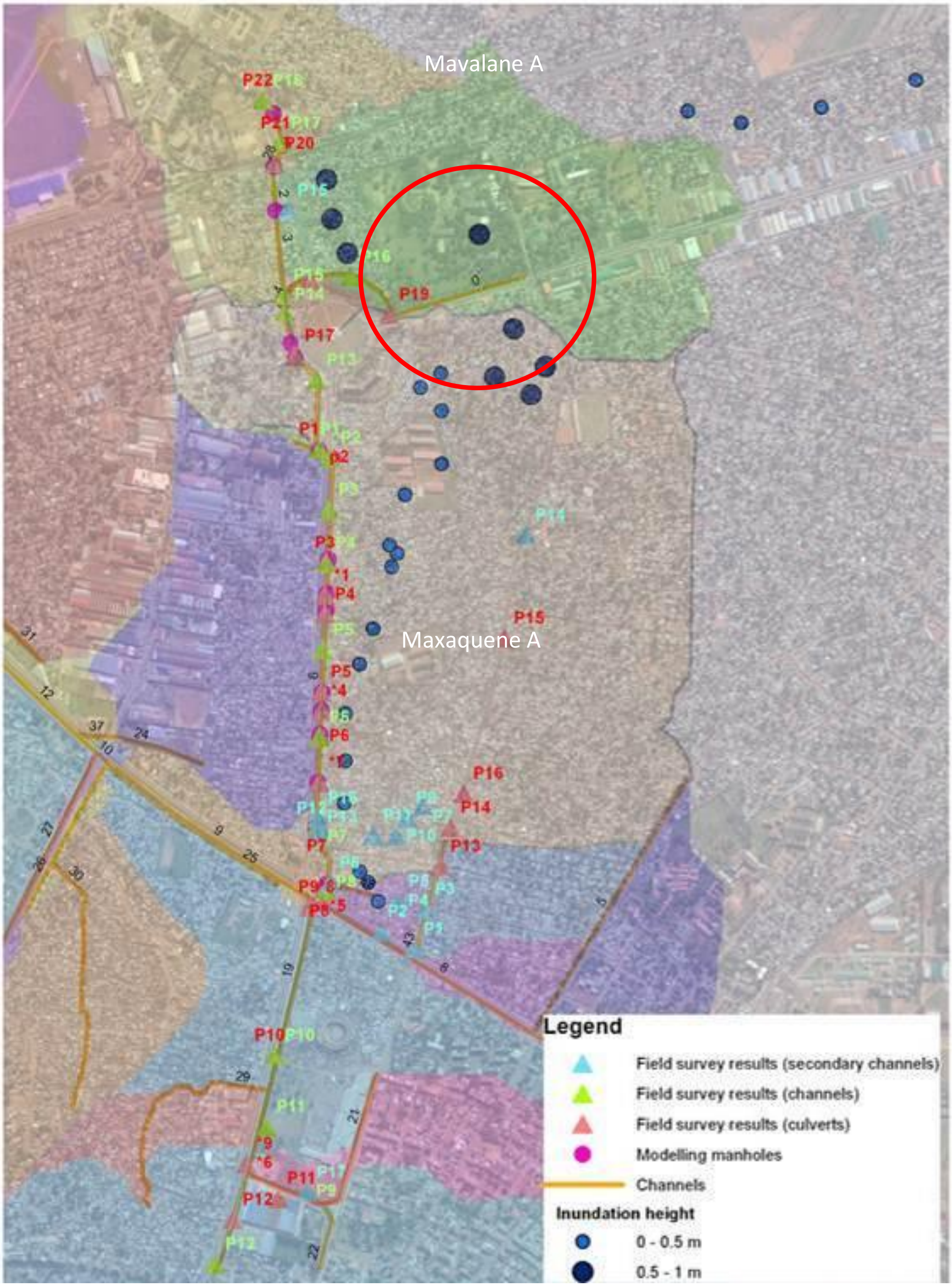


Figure 3-26: ***Results of survey interviews regarding flooding occurrence***

(small blue points 0-0.5m inundation height, big blue points 0.5 -1.0 m)

Terminology in this report:
"Inundation" means that water flows out of the channel and submerges land to a specific extent and depth.

"Flooding" is defined as overflow water from rivers, drains or sewers

"Ponding" is a term that refers to the unwanted pooling of water, especially after inundation or flooding has occurred. Overflow water may stay in local depressions even when floods retreat. In order to model these effects a 2-dimensional model would be required.

SCENARIO 2: "CULVERTS CLEARED FROM SOLIDS BUT CHANNELS REMAIN UNCHANGED"

In order to simulate the scenario with cleared storm water channels, the roughness coefficient for the discharge in the conduits was adapted accordingly. Modelling results are displayed in *Table* 3-10 and *Figure* 3-27.

Table 3-10: Node flooding summary for scenario 2: "cleared culverts"

```
*********************
Node Flooding Summary
*********************

Flooding refers to all water that overflows a node, whether it ponds or not.
```

Node	Hours Flooded	Maximum Rate CMS	Time of Max Occurrence days hr:min	Total Flood Volume 10^6 ltr	Maximum Ponded Depth Meters
J24	1.26	9.105	0 00:58	21.821	1.20
J23	0.48	6.188	0 01:00	6.919	1.90
J20	0.40	1.457	0 01:00	1.635	1.90
J1	1.03	2.448	0 01:00	4.218	2.70
J4	0.73	1.220	0 00:55	2.220	1.95
J7	0.30	1.173	0 00:59	0.976	1.91
J10	0.59	1.693	0 01:05	2.714	2.00
J19	0.36	2.008	0 01:00	2.148	1.98
J13	0.31	1.798	0 01:00	1.300	2.00

Result: The modelling results indicate that the mere clearing of the culverts from solids would not have a substantial impact. The main problem, leading to flooding in the upstream areas of the study catchment is rather the partly considerable blocking of the storm water drainage channels with solids and vegetation, as this blocking leads to reduced cross sections on the one hand and to reduced flow velocities on the other hand. It could be shown that if only the culverts are cleaned and the channels not, then the total flooding would not be reduced much, only the duration of the flooding would be reduced and consequently also the water quantities inundating the study catchment.

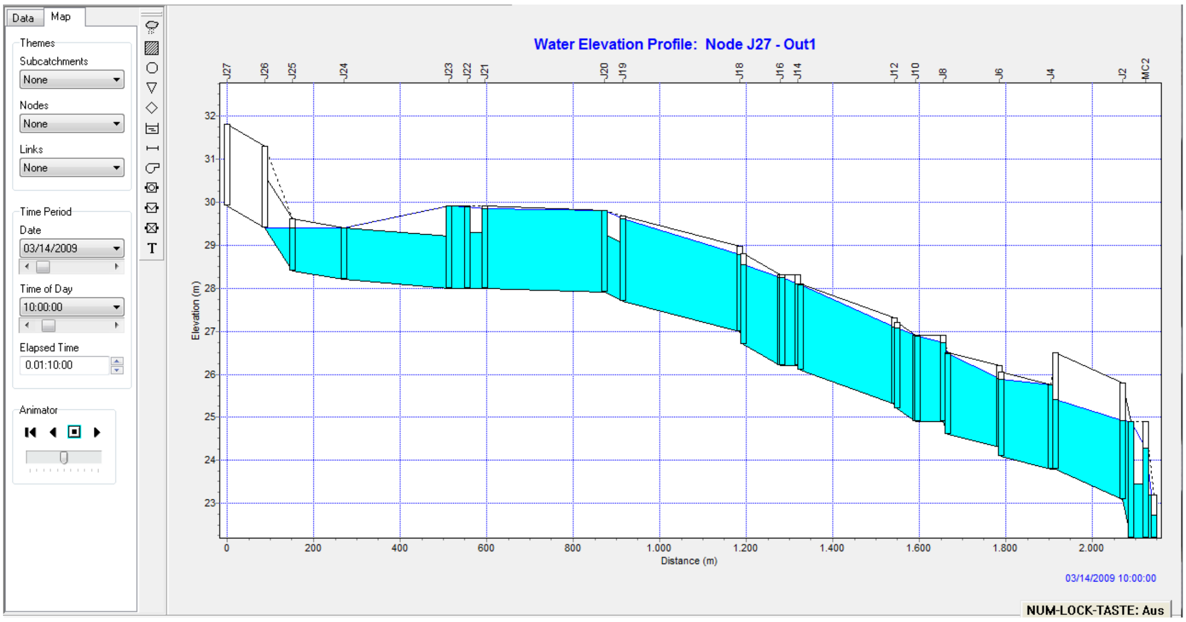


***Figure** 3-27: In the longitudinal cross section there is no apparent difference between Scenario 2: "Cleared culverts" and Scenario 1: "Current situation" at the time of peak flooding.*

SCENARIO 3: "CHANNELS AND CULVERTS CLEARED FROM VEGETATION AND SOLIDS"

In order to simulate the scenario with cleared storm water channels, the *roughness coefficient* for the discharge in the conduits was adapted accordingly. Modelling results are displayed in *Table* 3-11 and *Figure* 3-28.

Table 3-11 : Node flooding summary for scenario 3: "cleared channels and culverts"

Node Flooding Summary

Flooding refers to all water that overflows a node, whether it ponds or not.

Node	Hours Flooded	Maximum Rate CMS	Time of Max Occurrence days hr:min	Total Flood Volume 10^6 ltr	Maximum Ponded Depth Meters
J24	0.05	0.597	0 01:00	0.071	1.20
J1	0.39	19.966	0 00:58	12.859	2.70
J9	0.01	11.051	0 01:01	0.074	2.00
J10	0.09	15.852	0 00:49	2.105	2.00
J15	0.03	15.918	0 00:59	0.811	2.10
J16	0.19	14.954	0 01:00	3.452	2.10

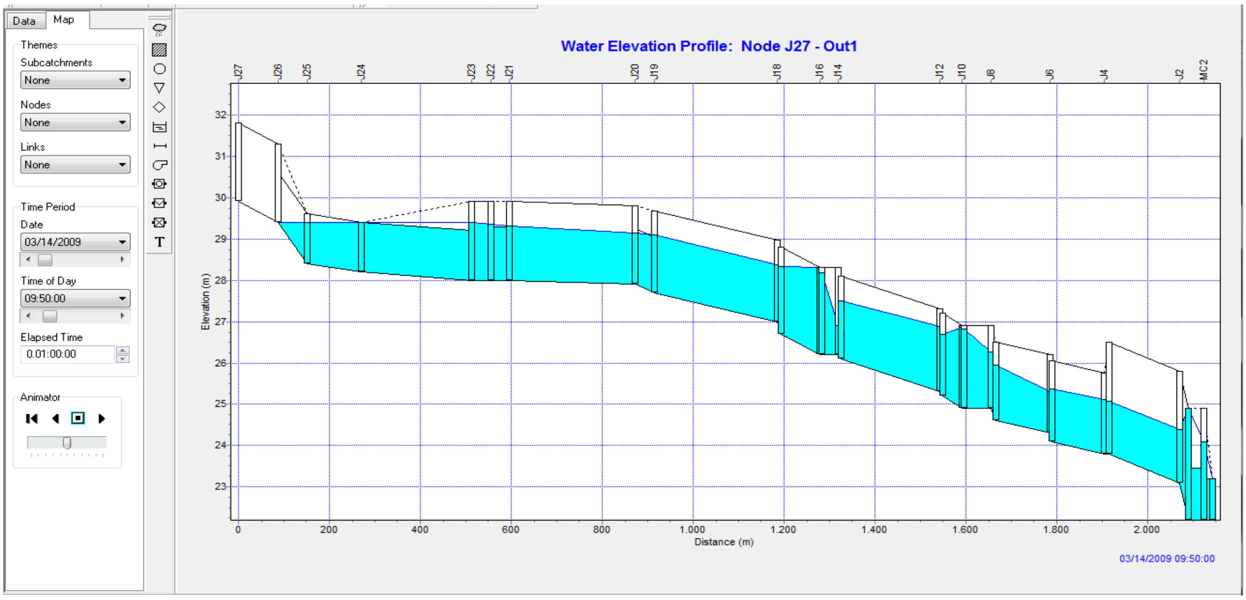


Figure 3-28: ***Longitudinal section for scenario 3: "cleared channels AND culverts" showing that flooding occurs mainly at the outlet of the model catchment (i.e. at the right end of the section)***

Result: Main flooding occurs at J1 (culvert to main channel Av. Chissano). It could be shown that, if the main drainage channel is cleared from vegetation and solids, the discharge capacity of the storm water channel will increase and flooding will concentrate more towards the outlet of the *subcatchment* because the runoff reaches the downstream part faster and with higher amplitudes. Due to the box culvert at the outlet of the *subcatchment*, flooding will nevertheless occur, as the capacity of the culvert is too small to discharge the whole storm water runoff. This culvert could definitely be confirmed to be a hydraulic bottleneck within the *subcatchment*.

SCENARIO 4: "OPENING/WIDENING THE CULVERTS"

Two different scenarios were calculated, one with an extension of the clear culvert diameter about 50% and another one with an extension about 100%.

Scenario 4a: "50% widening of culverts (3 instead of 2 barrels at each culvert)"

Like Scenario 1 but with 3 instead of 2 barrels at each culvert increasing culvert area by 50%. Please note that these calculations have been conducted under the assumption that the culverts have been cleared from solid depositions and their full hydraulic capacity is available.

Table 3-12: Node flooding summary for Scenario 4a: "50% widening of culverts"

```
*********************
Node Flooding Summary
*********************

Flooding refers to all water that overflows a node, whether it ponds or not.
--------------------------------------------------------------------------
                                                          Total   Maximum
                                 Maximum   Time of Max    Flood    Ponded
                        Hours       Rate    Occurrence   Volume     Depth
Node                  Flooded        CMS   days hr:min  10^6 ltr   Meters
--------------------------------------------------------------------------
J9                       0.01     13.159      0  00:52     0.069     2.00
J10                      0.08     17.485      0  01:00     1.822     2.00
J11                      0.01     11.013      0  00:59     0.035     2.00
J15                      0.05     17.677      0  01:01     1.222     2.10
J16                      0.22     15.127      0  01:01     4.445     2.10
```

Result: It could be shown that no flooding occurs at the *subcatchment* outlet *node J1* (culvert to main channel Av. Chissano), if the clear diameter of the box culverts is increased by 50%. Flooding still occurs at the nodes J9 to J 16. It is assumed that the latter is due to the fact that the GPS survey at the culverts was inaccurate due to restricted accessibility (refer also to *Table* 3-7). Unfortunately the invert levels which were measured on site during the filed survey could not be re-confirmed once more on site after modelling.

Scenario 4b: "100% widening of culverts (with 4 instead of 2 barrels at each culvert)"

Like scenario 1 but with 4 instead of 2 barrels at each culvert. The clear diameter would thus increase about 100%. Results are displayed in *Table* 3-13 Please note that these calculations have been conducted under the assumption that the culverts have been cleared from solid depositions and their full hydraulic capacity is available.

Table 3-13: Node flooding summary for scenario "100% widening of culverts"

```
*********************
Node Flooding Summary
*********************

Flooding refers to all water that overflows a node, whether it ponds or not.
```

Node	Hours Flooded	Maximum Rate CMS	Time of Max Occurrence days hr:min	Total Flood Volume 10^6 ltr	Maximum Ponded Depth Meters
J9	0.01	7.253	0 01:12	0.018	2.00
J10	0.08	14.282	0 00:56	1.389	2.00
J11	0.01	7.567	0 00:55	0.014	2.00
J15	0.04	16.712	0 00:59	0.724	2.10
J16	0.20	14.937	0 01:01	3.927	2.10

Result: It could be shown that no flooding occurs at the *subcatchment outlet* node J1 (culvert to main channel Av. Chissano), if the clear diameter of the box culverts is increased by 100%. Nevertheless, the reduction of flooding in the upstream nodes J9 to J 16 was inconsiderable. Again it is assumed that the latter is due to the fact that the GPS survey at the culverts was inaccurate due to restricted accessibility (refer also to Section 3.4.4.).

Based on the two modelled scenarios with increased culvert capacity, it can be concluded that clearing the culverts from solid depositions and solid waste would already improve the situation considerably. In how far the cross sections of the individual culverts would need to be widened through either larger or increased numbers of culverts would need to be calculated based on a holistic approach considering the overall drainage system from upper catchments to its outlet in order to improve overall system performance also considering SuDS. It is important to solve the overall situation considering the reduction of flood flows through SuDS if possible from a political/ownership point of view and without just reducing flooding in one place and as a result increasing flooding further downstream. In order to do this a political guideline regarding SuDS would first be needed together with a suggested budget estimate and/or a level of accepted flooding (and for which return period) to establish the level and therefore price to which the flooding problem should be solved. It would be essential to plan and build the improved drainage system in this holistic way as only individual measures or part implementation would not have the planned overall positive effect. For such detailed calculations more field measurements beyond of what has bee collected in the current study would be necessary (e.g. location, type, dimension of possible SuDS, more detailed channel and hydraulic structure dimensions, etc.). It would also be important to consider the constructive measures that are already planned or in implementation for which information has not been available for this study.

SCENARIO 5: "INCREASED DISCHARGE IN THE RECEIVING STORM WATER CHANNEL

A scenario with 4 instead of 2 barrels at each culvert was calculated, but with a considerably increased discharge in the receiving channel (Av. Chissano) of 30 m³/s instead of the only 4 m³/s as assumed in the previous scenarios.

Result: Flooding occurs again at the subcatchment outlet node J1 because of the high water level in the receiving channel, which in turn is caused by backlogging from the downstream culvert in the receiving channel, which is now the hydraulic bottleneck.

Conclusion: Widening the culvert at the subcatchment outlet node J1 makes only sense, when the following culverts in the main storm water channel along Av. Joaquin Chissano will also be widened.

SCENARIO 6: "CLIMATE SCENARIO WITH HIGHER RAINFALL INTENSITY"

The same scenario as Scenario 3 was modelled with an assumed higher rainfall intensity in 10% steps (compare *Table* 3-4), simulating a possible climate change effect. The assumption of a 10%-50% higher rainfall intensity was made mainly for modelling purposes, based on practical considerations and in the absence of solid data. An increase of the rainfall intensity by 10-20% can be considered a realistic worst-case-scenario. Referring to the INGC Climate Change Report (INGC 2009) only a minor increase in annual rainfall amounts is to be assumed according to the most Global Climate Models (GCM), except for the prediction as calculated by the CSIRO GCM. Nevertheless, as not total rainfall amounts are relevant for urban drainage problems but rather the intensity of events with a certain return period, a 20% increase of rainfall intensity for a two year design storm was given the most attention, given that rainfall variability will remain to be high in Southern Mozambique also in the future and the fact that climate change in the future is expected to lead to an increase in the intensity of tropical cyclones. There may also be an increase in their frequency of occurrence (INGC 2009). The two year 40 min design storm as published by DNA (2006) is considered international state-of-the-art and thus also acknowledged to be the relevant design event for the modelling/dimensioning of urban drainage infrastructure in Maputo.

Table 3-14: Node flooding summary for 20% higher rainfall intensity

```
*********************
Node Flooding Summary
*********************

Flooding refers to all water that overflows a node, whether it ponds or not.
```

Node	Hours Flooded	Maximum Rate CMS	Time of Max Occurrence days hr:min	Total Flood Volume 10^6 ltr	Maximum Ponded Depth Meters
J24	0.31	8.220	0 00:56	5.339	1.20
J1	0.49	20.568	0 00:56	16.690	2.70
J9	0.01	12.919	0 00:52	0.134	2.00
J10	0.12	16.016	0 00:52	2.690	2.00
J15	0.07	17.183	0 01:00	1.592	2.10
J16	0.27	16.213	0 00:53	5.114	2.10

Result: For a rainfall intensity increased by 20% main flooding at J1, but also in the other calculated junctions, rises by about 20 % (i.e. from 12.859 m³ to 16.690 m³.

This result may appear to be rather obvious and straightforward. This is actually true due to the fact that

1. The modelled subcatchment is rather small
2. The infiltration capacity within the subcatchment is very low and almost the entire storm water during the design storm event is contributing to the surface runoff and subsequently to the channel discharge.

The calculated 20% larger runoff upon the 20% more intense rainfall can be ascribed mainly to 2 facts:

1. The modelling of urban drainage problems concentrated on extreme events which cause rapid runoff upon high intensity rainfall events. Small scale effects such as interception and micro retention on the one hand, and slower processes such as infiltration and evapotranspiration thus play a minor role in the modelling of storm water runoff after extreme events. An increase in rainfall intensity will therefore in almost any cases result in an equivalent reaction in the storm water runoff response, with linear relationships being not uncommon.
2. Due to the short distances from the spot where the actual raindrop is falling to the point where it enters the next storm water drainage channel, routing effects can be neglected, especially when modelling a catchment of the size as it has been modelled here

Respectively, it can be considered that the calculated effect of any climate change scenario will be in a quite direct relation to the assumed increase (or decrease, if applicable) of rainfall intensity. Rainfall intensity increases of +10%, +30%, +40% and +50% as compared to Scenario 3 were modelled to confirm this assumption and to demonstrate the model behaviour under such conditions. *Table* 3-15 shows the results of these scenarios as compared to the standard design storm. All other settings are the same as in Scenario 3.

It can be assumed that the calculated effect is similar for all modelled scenarios, as long as the other relevant boundary conditions and model settings remain unchanged.

Table 3-15: Comparison of different increases of rainfall intensities as compared to Scenario 3

Junction / Node	Flood Volumes					
	Scenario 3	+10%	+20%	+30%	+40%	+50%
J24	0	2,07	5,34	9,86	12,2	17,97
		100%	258%	476%	589%	868%
J1	12,859	14,06	16,69	18,65	21,13	22,82
		109%	130%	145%	164%	177%
J9	0	0,07	0,13	0,19	0,13	0,18
		100%	186%	271%	186%	257%
J10	2,1	3,03	2,69	4,27	3,84	5,49
		144%	128%	203%	183%	261%
J15	0,81	1,13	1,592	1,7	1,41	1,91
		140%	197%	210%	174%	236%
J16	3,45	4,98	5,11	5,46	6,03	7,04
		144%	148%	158%	175%	204%
Total Flood Volume [*1000m³]	**19,219**	**25,34**	**31,552**	**40,13**	**44,74**	**55,41**
	1	**132%**	**164%**	**209%**	**233%**	**288%**
Flood volume difference between Scenarios		**6,12**	**6,21**	**8,58**	**4,61**	**10,67**
		32%	**64%**	**109%**	**133%**	**188%**

SCENARIO 7: "SUDS MEASURES IMPLEMENTED IN MAPUTO"

Methods of Sustainable Urban Drainage Systems are called SuDS. As the application of SuDS in the study area is considered one possibility to reduce the urban flooding problem, it was decided to include some possible scenarios in the modelling exercise.

For the application of suitable SuDS in Maputo, rather local measures would have to be preferred. It has been thought that the decentralized measures, such as large detention basins, are not adequate for the actual situation in Maputo. Therefore a storm water detention pond, infiltration trenches and pervious pavement were considered as useful measures for the subcatchment and thus also considered as a scenario in the model.

The aim of applying SuDS in the study area is to achieve additional measures against flooding and to diminish the burden to the drainage system downstream of the catchment. The measures should be chosen so that they should attenuate the storm water flow, increase the storm water runoff quality and provide groundwater recharge in a good quality.

As SuDS are generally applied in industrialized countries the selected measures would have to be adapted to Maputo's local conditions, especially as it is known, that Maputo city has no experience in the field of sustainable urban drainage systems.

The case study area Maxaquene A and Mavalane A is a former swampy area and has a high groundwater level (Palalane, 2007). This must be considered when selecting possible control measures, especially as the infiltration of storm water for ground water recharge may not be applicable in this area. Nevertheless also groundwater recharging systems were analysed for 2 main reasons:

1. Because during the stakeholder consultation process it became clear that in some districts of Maputo the groundwater level has been recorded to be falling in recent years due to overuse of groundwater resources. Groundwater recharge measures may be a suitable means to stop this negative development in these areas.
2. To show their implementation in the model in principal.

For the final selection of measures it is obligatory to consider the interactions with the groundwater system in detail. As already mentioned above and discussed with stakeholders, the following measures were considered to be the most suitable centralized systems and were thus considered in the modelling exercise:

- Storage ponds
- Infiltration trenches
- Pervious pavement

Storage Ponds

Storm water ponds can be created by excavating sinks or through the construction of embankments. Contrary to storm water detention basins, storage ponds are not supposed to be held completely empty at all times in order to be able to store a maximum volume of storm water. Instead, a storage pond is used not only for storm water retention, but also for enhancing water quality, channel protection, overbank and extreme flood protection. Additional positive effects could be the possibility of recreational use of the pond or the provision of fire fighting water. Problems may occur through mosquito breeding and rubbish disposal in the ponds and of course caused by the space requirements which are still considerable. In any case, neither a detention basin, nor a storage pond can be implemented without a very comprehensive involvement of the local population.

Ponds should be constructed so that they capture the runoff at maximum levels and minimum excavation costs (AMEC, 2001, CIRIA 2007). A storage pond should be located at a suitable point near the outlet of the catchment so they can receive the major part of the runoff from the catchment. In the case study area, a pond could theoretically be located in the southern part of study area close to the outfall at the lowest point of the study area, thereby warranting minimal excavation and construction cost and allowing easy connection to the existing drainage channels. The possible location of the pond is illustrated in *Figure* 3-29

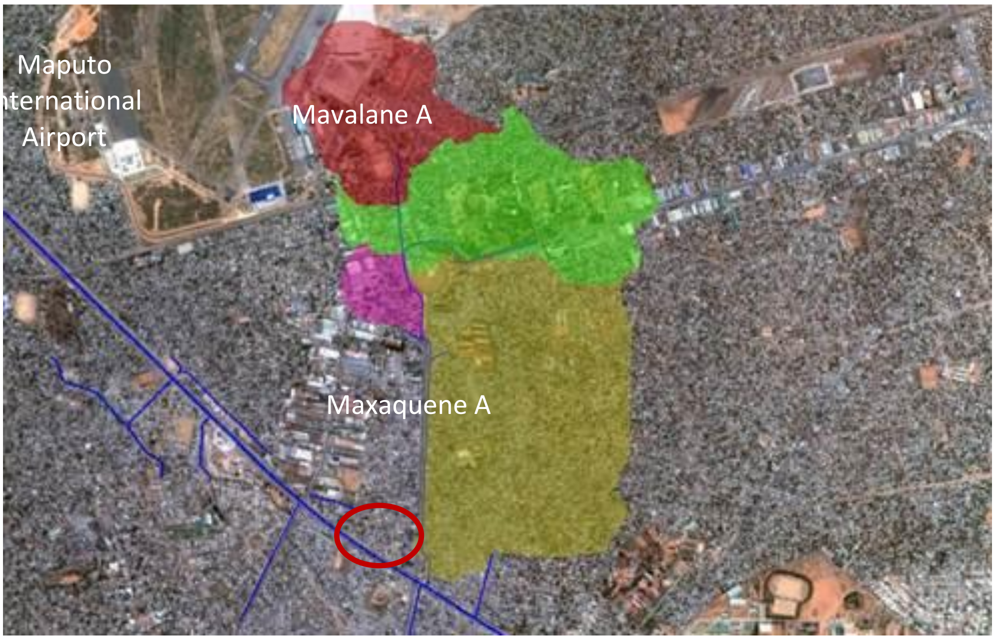


***Figure** 3-29: Possible location of a storm water retention pond. Subcatchments as modelled in SWMM are shown in different colours.*

As the suggested area is already being densely populated, it is quite unlikely that the respective necessary land could be made available for such a radical measure. The aim of the modelling exercise in this case was rather to calculate and demonstrate which size of detention pond would be necessary in the case that no other measures would turn out to be sufficient. The detention pond was assumed to be located near the outlet of the study area to receive the storm water that could be diverted upstream of the most critical node J4.

Considering the need for space and construction costs, the dimensioning of the pond must be considered an optimisation exercise. Thus, to provide the best result for the detention pond, an iterative process was used, resulting in an optimum depth of 2.5 m. The required area for a detention pond of this depth was calculated to be 30,000 m². After running the simulation, it was seen that such a detention pond could prevent the flooding in node J4 and can store 66,905 m³ of storm water runoff volume.

The technical (geotechnical conditions) and administrative (ownership) feasibility of constructing a detention pond at the mentioned location was not investigated. Possible discharge scenarios, emptying times, the location and capacity of a necessary discharge channel/sewer, the possibility to infiltrate water from the pond and the respective implications on the groundwater situation can be defined only upon a further topographic surveys which would have to deal with the specific questions as relevant for the construction of a detention pond.

In any case it can be considered highly unlikely that such a measure can be implemented in such a densely populated area as Maxaquene A, as massive resettlement of residents would be necessary additionally to the considerable construction cost, which in turn depends on the exact size of the detention pond.

Infiltration Trenches

Infiltration trenches can not only serve for reducing the surface runoff rate and volume, they can also contribute to necessary groundwater recharge (AMEC, 2001, CIRIA 2007). They should be implemented close to impervious areas such as at backsides of roads. Infiltration trenches fulfil three main functions; infiltration, depression storage, and water flow along the trench with the infiltration capacity of the trench depending mainly on the underground soil properties. A schematic view of an infiltration trench is shown in *Figure* 3-30.

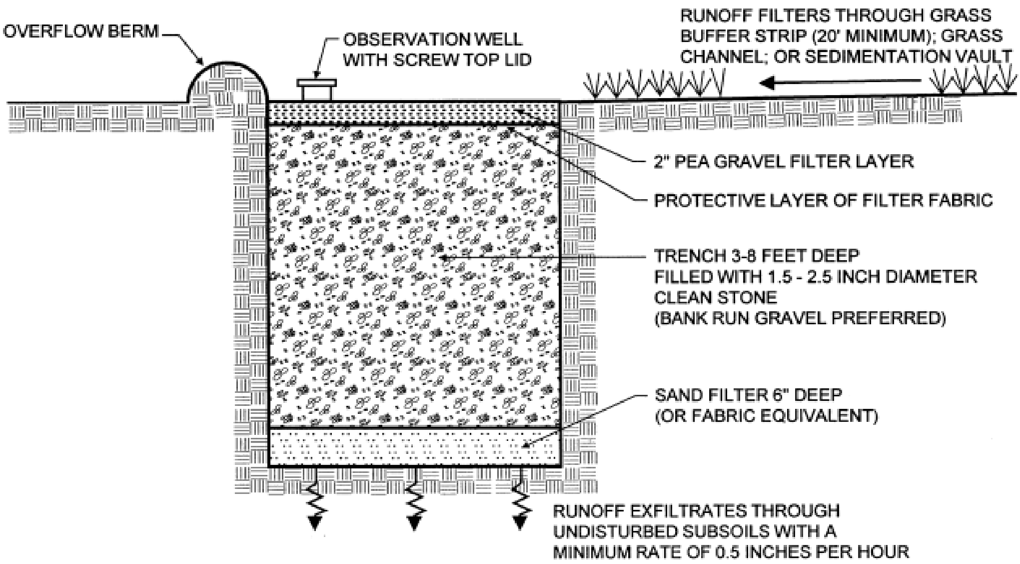


Figure 3-30: Schematic of an infiltration trench (AMEC, 2001)

Since the infiltration trenches are at risk of clogging, the installation of a pre-treatment system is strongly recommended. Pre-treatment systems can be either vegetated filter strips or vegetated buffer strips around the entire trench (CIRIA, 2007). In the study area the infiltration trenches could be implemented along roadsides. These possible locations are indicated in *Figure* 3-31**.**. The length/width of these trenches can be variably adapted to the available space, reducing them would obviously reduce their benefit. In general trenches are positioned such that as little as possible other structures, trees, and similar are impaired or have to be removed.

Please note that the red lines given in *Figure* 3-31 show only possible positions of infiltration trenches. These possible positions were not investigated for actual implementability of such a measure, as this can be evaluated only in close cooperation and consultation with the local authorities and the local residents – a process for which enough time should be reserved. Please note that the modelled areas of e.g. 5 ha in a total 67 ha of subcatchment 5 represent a considerable percentage (~7%) of the respective area.

Exact dimensions have respectively to be based on geotechnical conditions, space availability, political priorities and desired retention potential

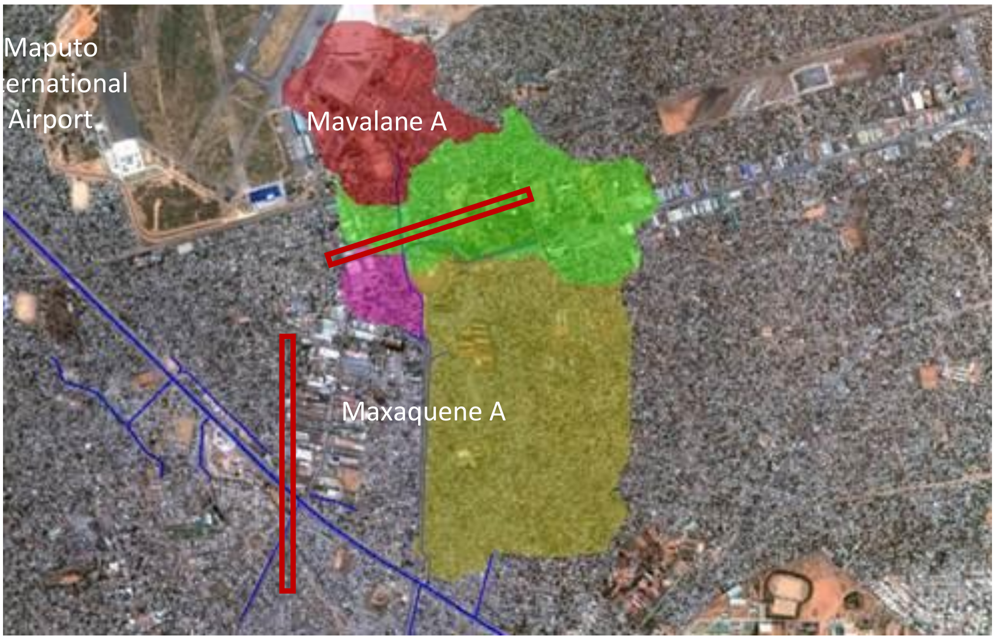


***Figure** 3-31: Possible locations for infiltration trench (red outlines).*

For an effective infiltration, the soil must be suitable to infiltrate the runoff. Hence, the most important parameter to be considered in the first place is the soil type (CIRIA, 2007) and its infiltration capacity. Palalane (2010) measured the *infiltration rates* in three different locations in the same study area and concluded that the maximum *infiltration rate* in the area is about 66mm/h and the minimum rate 30 mm/h. The decay constant was calculated to be 3mm/h, with a drying time of 7 days.

Details of modelled trenches:

In the study area, infiltration trenches with a total area of 6 ha have been modelled, 1 ha of total 67.2 ha in *subcatchment S3*. 1 ha of total 11.1 ha in *S4*, and 5 ha of total 67 ha in *S5*. The parameters chosen are: depression storage 360 mm, infiltration rates maximum 66 mm/h and minimum 30mm/h (used from the study of Palalane, 2010).

The trenches were modelled as rectangular, 100 % pervious *subcatchment* area within the *subcatchments S3, S4* and *S5*. Depression storage of the infiltration trench was set to 360 mm as effective pore volume depth of the trench. The duration of the simulation was 14 hours. The Manning coefficient was chosen to be 0.24 for all trenches (McCuen *et al*. 1996). General properties of the trenches are given in *Table* 3-16

Table 3-16: Infiltration trench summary

Infiltration Trench	Total runoff from drainage subcatchment (mm)	Total infiltration (mm)	Total surface runoff depth from infiltration trench (mm)
IT_1	2384	427	1857
IT_2	412	412	0
IT_3	974	427	392

After modelling the 3 infiltration trenches, it was seen that the flooding rate was decreased by over 70%. A comparison between flooding rates before and after implementing infiltration trenches under otherwise current but cleaned conditions is given in *Table* 3-17

Table 3-17: Comparison of flooding rates at junction J7 (near the catchment outlet) under current conditions with and without infiltration trench

Node	Flooding rate (m^3/s)	
	Before infiltration trench	After infiltration trench
J7	31.48	8.57

The considerable impact of the infiltration trenches on the modelling results make it an interesting possibility to improve the urban drainage situation in the investigated neighbourhoods. With estimated cost of USD 80 /m² they represent an affordable alternative to large detention structures where large amounts of water have to be stored.

The infiltration trenches would have a potential effect on groundwater levels. While recharging the groundwater is generally considered a positive effect, on local level also possible negative effects have to be taken into consideration. Groundwater levels are reported to be shallow already in the case study area so that the infiltration capacity and hydraulic conductivity of the subsoil will have to be quantified and the possible consequences of rising groundwater levels (i.e. when groundwater levels reach the bottoms of pit latrines and septic tanks in the area) on the hygienic conditions and on the structural integrity of adjacent buildings investigated.

In addition space requirements for the infiltration trenches will need political decisions regarding their location and size including the resulting needs for potential landscape interventions, infrastructure interventions and housing interventions /resettlement needs. These aspects need to be decided upon based on the above technical and political requirements (achievable effect vs. size).

Pervious Pavement

Pervious pavements accept the water that falls directly on its surface (AMEC, 2001). Pervious pavement systems are used where underlying sub-soils have an infiltration rate of between approximately 13 to 75 mm/h and should be adequate to support the drawdown of runoff within 24-48 hours. The slope of the area should not exceed 2 % (AMEC, 2001, CIRIA 2007). A schematic view of a pervious pavement is shown in *Figure* 3-32

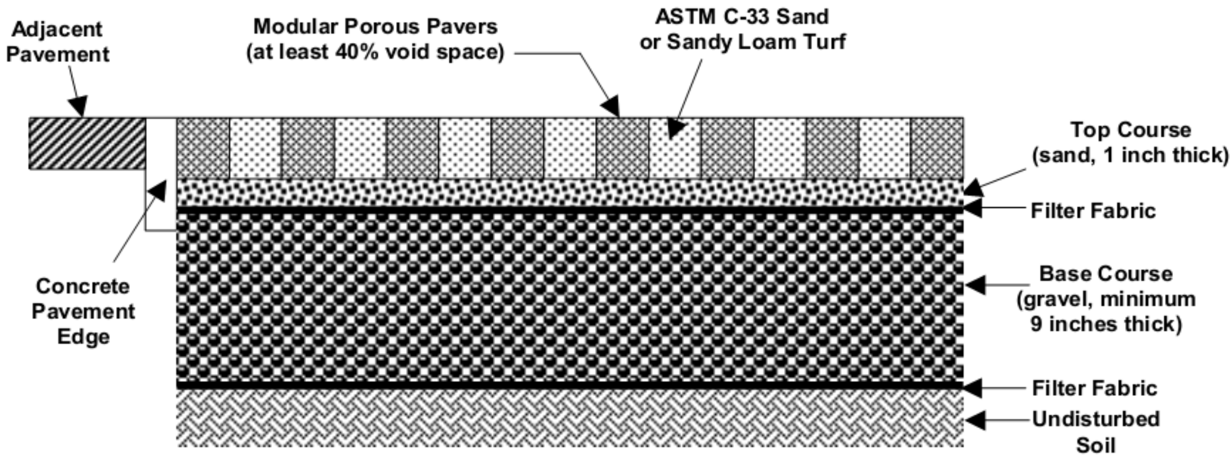


Figure 3-32: Pervious pavement (AMEC, 2001).

The general properties of the three above described SuDS are summarized in *Table* 3-18

Table 3-18: Matrix of selected SuDS objectives (adapted from; AMEC, 2001; CIRIA, 2007).

SuDS Group	Recommended maximum catchment area (ha)	Runoff treatment	Ground-water recharge	Suitability for tropical climate	Mainte-nance	Cost
Ponds	ca. 10	✓	x	✓	Medium	Medium
Infiltration Trenches	<3	✓	✓	✓	Low	Low
Pervious pavement		✓	✓	✓	Medium	Medium

For the modelling of the pervious pavement a new subcatchment was discretized on S4. It has been estimated that the area for pervious pavement could be 20% of the total area of the subcatchment which results in 2 ha. Because the pervious area is considered as part of the subcatchment S4 within which that was placed, no rain should fall on subcatchment representing the pervious pavement. Pervious pavement was modelled as having a depression storage depth of 360 mm (below this depth water is infiltrated). Imperviousness percentage was set to 35% with considering the imperviousness before implementing the pervious pavement. The results are summarized in *Table* 3-19. For the used model accuracy it is no use to define the pervious pavement in more geometric details.

Table 3-19: Runoff summary of pervious pavement

Pervious Pavement	Area of pervious pavement (ha)	Contributing drainage sub-catchment	Area of contributing drainage sub-catchment	Total runoff from drainage subcatchment (mm)	Total infiltration (mm)
S4_Pervious	2	S4	10	184.27	119.7

It could be shown that, if the pervious area is implemented only on an area of 2 ha contributing 10 ha drainage area, only a minor part of the storm water collected during the rain event can infiltrate under the current subsoil conditions. The storm water discharge in the open channels can be reduced only by 10 % or 3 m^3/s.

While not being suitable as a standalone solution, the use of permeable pavements can be a valuable supplement to other measures, especially as the slow infiltration on large areas (as compared to the linear infiltration from infiltration trenches) represents a more natural way of groundwater recharge, simulating natural conditions like the infiltration from unpaved areas.

Inlet and source control

Inlet control elements influence the runoff at or near its source (Butler and Davies, 2010). Rainwater harvesting through roof collection system is one of these measurements to reduce the runoff.

Calculation Example:

If storm water collection barrels with an average capacity of 100 litres volume are used for each roof with 50 m^2 they can collect 2 mm of rainfall from this roof before the barrels are full. In comparison to the 2 years design storm with a precipitation of approx. 40 mm in 40 minutes duration, the collected amounts of storm water must be considered irrelevant regarding storm water runoff generation. Additionally it has to be taken into account that such rainwater harvesting tanks are rarely completely empty, which they would need to be in order to be really effective.

Alternatives that would have a relevant effect on the reduction of peak runoff and volume are rooftop ponding and green roofs. These methods can be implemented in modelling the system, but for the case of Maputo have not been considered yet, also because such systems are quite costly and cannot be considered to be realistically implemented in Maputo in the next years.

Rooftop ponding

Storm water can be stored on flat roofs by using the flow restrictors (Butler and Davies, 2010). Rooftop ponding is an effective solution in order to reduce the peak runoff which flows to sewer or drainage system. On the other hand it is not recommended to control the pollutant concentrations (Maskell and Sherriff, 1992).

Green Roofs

Roofs covered with a thick layer of vegetated soil are referred to as green roof. This aims to reduce the volume and rate of runoff as soon as runoff is generated (CIRIA, 2010).

In summary, inlet and source control are interesting from a water resources management point of view, but its quantitative effect on storm water drainage is negligible considering the enormous rainfall intensities as they are common in Maputo.

3.5.5 Conclusions from modelling

Based on the modelling results, a technical solution which would lead to immediate results would be to enlarge the profiles of the culverts along the channels as these are the existing hydraulic bottlenecks in different scenarios. The enlargement of the culverts would anyhow only make sense if the downstream culverts in the Av. Chissano main channel will also be enlarged as otherwise spill and flooding may occur at those locations.

In general it is essential to thoroughly assess the overall drainage system of the city based on a sound dataset which, as technical records are not available, has yet to be established through detailed field surveys. Following these surveys hydraulic calculations or a modelling approach has to be applied to re-design the drainage system. For the time being it is unknown why the existing culverts have been constructed with such a small hydraulic capacity. The possibility that at least some of these culverts are designed to serve as hydraulic throttles are to be investigated and the respective implications discussed.

The results of the scenario assessments with and without vegetation and solids in the main channels show that cleaning the channels would set them in a better hydraulic shape and therefore the frequency of the flooding would be lower in the upstream part, but the peaks and the volume of the flooding would be higher in the downstream part of the case study area. To improve the situation in the overall area, consequently a mixture of measures would be recommendable, including clearing and maintenance measures as well as structural measures to include SuDS that reduce runoff and to increase the hydraulic capacity of the culverts near the catchment outlet.

As the interviews in the two assessed neighbourhoods Maxaquene A and Mavalane A have shown, the awareness of the consequences of open rubbish disposal is low within the local population. The respective modelling results however show that keeping the existing urban drainage infrastructure clear from rubbish and solid disposals in the channels and culverts could have a very positive effect on the hydraulic capacity of the storm water drainage channels. It can thus be concluded that awareness raising campaigns towards a more conscious and organized handling of solid waste within the modelled neighbourhoods, and in fact in all Maputo, could have considerable positive effects in reducing storm water flooding frequency and magnitude and should thus accompany the above mentioned measures.

Climate change impacts have been investigated using the best possible approximation considering the state of data availability. Climate change impacts have been found to be of secondary importance and of less impact in comparison to the current deteriorated state of the drainage system where maintenance, cleaning, implementation of SuDS and improving the identified bottlenecks in a holistic approach would have the largest net benefit in reducing urban flooding..

Overall it is essential to re-calculate the drainage network:

- Considering the whole respective source to sea drainage networks and not just those parts in which currently problems occur in order not to just relocate the problem but to holistically solve it
- Making political decisions about the allowed degree of flooding considering the importance, vulnerability and value of different locations as well as the magnitude and return period for which flooding may be allowed (e.g. there may be low value or less vulnerable locations for which more flooding may be allowed with regards to

magnitude and frequency than for high value and more vulnerable locations. The drainage system can then be designed accordingly).

- Considering where space can be made available for the implementation of SuDS
- Considering climate change impact estimates in the system analysis and design by, in the absence of solid datasets utilizing estimates if increased intensities. It needs to be understood that these estimates would not be based on solid datasets and respectively lead to a fail-proof system but would be an effort to improve the system preparation for possible climate change impacts without the exact knowledge of their magnitude

3.5.6 Elaboration of a manual for continued model use

In order to facilitate and foster the further application of SWMM5 in Maputo, a short executive manual was elaborated and included in the Annex of this report. The manual refers to detailed information sources for the necessary modelling steps for the described scenarios.

3.5.7 Basic SWMM5 training

A basic SWMM5 training was held on 21 and 22 March 2012 in Maputo. Institutions that sent participants included

- UEM, Department of Geography
- Ara-Sul
- DNA
- Municipal Administration of Maputo, Urban Planning Department

Further participants from AIAS, INGC and the Urban Drainage Department of the Maputo Municipal Administration had been invited but could not accommodate a participation in the training.

3.6 STAKEHOLDER CONSULTATION

3.6.1 Stakeholder consultation during the inception phase

In order to discuss the presently ongoing efforts and the actual priorities as seen by the national and local institutions, a stakeholder workshop was held in Maputo on 21 September 2011. In advance, the agenda of the workshop was defined as follows: To discuss on a high technical and institutional level the following points:

1. Where in Maputo does the storm water flooding cause the biggest problems? → Which are the "hottest" hotspots?
2. What is the potential future importance of the groundwater resources underneath Maputo and how can they be sustained/improved (i.e. by use of storm water infiltration for groundwater recharge)?
3. Who is interested in using the SWMM model for Maputo in the future? Which will be the main interests of using the model? Who will be the actual persons working with the model?
4. What are the large scale development perspectives in the city of Maputo in the next 5-10 years? Construction of new sewers? Construction of new drains? Enlargement of

water supply network? Diversification of water supply (rainwater harvesting, groundwater)?

The workshop was successfully held on the premises of INAM with participants of all invited stakeholders. In the workshop an overview of the project objectives was given to the participants, followed by an introduction to the storm water runoff model SWMM and an overview about Integrated Urban Water Management with examples of successfully implemented measures in other countries, mainly Brazil. The objectives and results of the stakeholder workshop are briefly displayed in *Table* 3-20.

Table 3-20: Stakeholder Workshop on 21 September 2011 in Maputo

WORKSHOP OBJECTIVE To discuss and work on the following topics: • Storm water drainage problems in Maputo / possibilities of improving storm water drainage problems • Water Resources of Maputo • Present and future infrastructure development in Maputo • Potential and limitations of the SWMM model • Future use of the SWMM model (after handover to the Client) • Importance / Relevance of groundwater as a drinking water resource in Maputo
INSTITUTIONS REPRESENTED IN THE MEETING The following institutions were represented in the workshop: • Águas da Região de Maputo (FIPAG, water supply sector, regional level) • ARA-Sul (water supply sector, national level) • CMM: Municipal Council of Maputo (local level) • INGC (emergency management, national level) • UN-Habitat (international level) • UEM (university) • DNA/DGRH (water resources management, national level) • DNA/DAU (water resources and water supply, national level)
After the introductory part, the above mentioned open questions were discussed in 2 groups, one “national” group and one “municipal group”. Subsequently the results of the group discussion were shared and openly discussed. The results of this process were compiled according to the following topics: **1) FLOODING ISSUES** **a. Maputo areas where flooding causes major problems** **b. Main causes of flooding** **c. Efforts undertaken to deal with flood problems** **2) GROUNDWATER ISSUES** **3) INSTITUTIONS POTENTIALLY INTERESTED IN MODELLING WITH SWMM** For more detailed information please refer to the Inception Report

3.6.2 Stakeholder consultation during the main project phase

In order to discuss the intermediate project results and the resulting recommendations of the Consultant, the respective stakeholders were consulted. During the final project mission in March 2012 the following institutions were consulted and informed about the project progress:

- DNA (Mr. Mutivue, Mr. Carimo)
- Ara-Sul (Mr. Vilanculos, Mr. Chaguale)
- INGC (Mr. Queface)
- AIAS (Mr. Matavela)
- UN-Habitat (Mr. Silva Magaia)
- UEM (Mr. Jose Rafael, Mr. Francisco Tauacale, Mrs. Alice Nuns)

Additionally a meeting was held with Eng. Isabel Vaz who was responsible for the design of urban drainage infrastructure handed over to DNA in 2005.

Attempts to liaise with other institutions like the Urban Drainage Department of the Municipal Administration of Maputo were not successful unfortunately. It was therefore impossible to gather conclusive information about the degree of implementation of the recommendations as given by Lahmeyer in the *Strategic Sanitation Plans for 7 Municipalities* (DNA, 2005).

It should be noted that the Sanitation Department of DND, as well as the Urban Drainage Department of the Municipal Administration of Maputo were repeatedly approached with the request to provide information about existing and foreseen urban drainage infrastructure in Maputo. These requests were unfortunately not successful.

3.7 RECOMMENDATIONS

According to the Terms of Reference, 3 possible measures were selected and elaborated in detail. Based on the site visits and the stakeholder consultations during the main project phase as well as the results of the field survey and the hydraulic modelling with SWMM5, the focus was put on mitigation measures for the reduction of the immanent urban flooding problem.

The following 3 measures are recommended for immediate implementation.

1. Improved maintenance of existing urban drainage system
2. Re-calculation and re-design of all existing urban drainage infrastructure
3. Structural in-canal Measures

The reuse of storm water was not focussed on as not prioritized by the consulted stakeholders. None of them expressed any considerable interest for the possibilities of groundwater recharge or supplementary water supply (e.g. for industrial or agricultural use).

3.7.1 Improved maintenance of existing urban drainage system

During the site missions of the Consultant the existing storm water drainage infrastructure in large parts of Maputo was inspected. The results of these inspections were very similar all over the city:

1. In many districts and neighbourhoods quite extensive storm water infrastructure is in place

2. In all districts the inspected storm water infrastructure is in a rather bad condition in terms of structural integrity or level of maintenance or both
3. Several of the open storm water drainage channels were completely blocked with solid waste or sediments and left the impression that they had not been operable for years

In the following the above listed impressions are presented in a brief photo documentation:

Figure 3-33: Culvert at the storm water channel along the Av. Acordos de Lusaka in Bairro Maxaquene A

Figure 3-34: Back view of the same culvert

Figure 3-35: Secondary channel in Bairro Maxaquene A, partially filled with solid waste

Figure 3-36: Main storm water channel along the Av. Acordos de Lusaka in Bairro Maxaquene A with a "base flow" of approx. 10 l/s household wastewater and with solid waste deposits.

Figure 3-37: ***Bridge over the storm water channel along the Av. Acordos de Lusaka which is acting like a partly blocked culvert due to deposits of bulky solid waste***

Figure 3-38: ***Secondary channel in Bairro Maxaquene A, out of operation due to blockage by solid waste***

Figure 3-39: ***Upstream part of primary storm water channel in Av. Joaquim Chissano (upstream view), completely blocked with sediments***

Figure 3-40: ***Upstream part of primary storm water channel in Av. Joaquim Chissano (downstream view), completely blocked with sediments***

Figure 3-41: Inflow of several secondary channels into primary storm water channel in Av. Joaquim Chissano, directly downstream of blocked channel shown in Figure 3-39 and Figure 3-40

Figure 3-42: Secondary channel in Bairro Maxaquene: blocked intentionally by residents in order to get access to their houses

Figure 3-43: Storm water channel, completely blocked by vegetation

Figure 3-44: Storm water inlet in the cement city of Maputo: blocked by solid waste

Figure 3-45: Storm water inlet in the cement city of Maputo: blocked, water cannot enter the sewer system

Figure 3-46: Storm water inlet in the cement city of Maputo: blocked by solid waste

Figure 3-47: ***Storm water inlet in the cement city of Maputo: blocked, water cannot enter into the sewer system***

Figure 3-48: ***Secondary channel in Bairro Mafalala. Blocked underneath the concrete slabs which were placed on top of the channel for pedestrian crossing***

Figure 3-49: Secondary channel in Bairro Mafalala. Blocked underneath the concrete slabs which were placed on top of the channel for pedestrian crossing

Figure 3-50: Drainage channel near Bairro Mafalala. The red arrow marks the position where the photo below (Figure 3-51) was taken

Figure 3-51: ***Secondary channel in Bairro Maxaquene. Almost completely blocked by solid waste***

Figure 3-52: ***Drainage channel near Bairro Mafalala, blocked by solid waste and vegetation.***

Figure 3-53: ***Same as above. The workers who are cleaning the channel do not have suitable tools for successfully clearing the channel.***

Figure 3-54: ***Secondary channel in Bairro Sommerschield / Polana Caniço A (close to the detention basin)***

Figure 3-55: ***Secondary channel in Bairro Sommerschield, blocked with sediment.***

From the distribution of the sediment in the channel it can be concluded that storm water in this channel is flowing towards the handcart, where the channel suddenly ends.

Figure 3-56: ***Secondary channel in Bairro Sommerschield / Polana Caniço A (close to the detention basin)***

Figure 3-57: Unfinished detention basin North of Sommerschield (at Av. Julius Nyerere)

As visible in the above pictures, the variety of impairment in the urban drainage infrastructure is very wide, with problems that could be solved easily if the necessary resources were (made) available. The cleaning of many of the culverts, inlets and channels does not require heavy machinery. Sufficient manpower and some trucks for the transport of the removed waste and sediments would probably suffice for most of the above displayed problems.

A problem that cannot be made visible so easily, but which can be recognized on the above pictures implicitly is the possible clogging of storm water drainage pipes in the cement city of Maputo (refer to *Figure* 3-45 and *Figure* 3-47). The degree of clogging of the respective sewer pipes can only be estimated and the problem itself can be tackled only by specialized companies with the respective special equipment such as high pressure flushing equipment and Closed Conduit TV (CCTV) for internal inspection.

Considering all the above the following measures are recommended for implementation:

1. **Elaboration of an urban drainage infrastructure inventory, providing information about exact position, technical functionality (i.e. state), operability, need for rehabilitation**
    a. City wide survey of all urban drainage and sanitation infrastructure:
        i. Exact position of infrastructure
        ii. Exact elevation of infrastructure
        iii. Exact diameters of all channels, sewers, culverts,
        iv. Exact position, elevation and volume of detention ponds
        v. Position, elevation and functionality of dams and levees
        vi. Functionality / Operability of all infrastructure
    b. Digital mapping and inventory of all surveyed information

   c. Elaboration of a database containing existing and newly surveyed information about all urban drainage and sanitation infrastructure
   d. In cooperation with AIAS and the Municipal Department of Urban Drainage include all available information about already contracted or otherwise already designed urban drainage infrastructure in the a.m. database.

→Estimated cost for international and national consultancy: **USD 420,000**

2. **Elaboration of a detailed Operation & Maintenance scheme for all urban drainage and sanitation infrastructure**

   → Estimated cost for international and national consultancy: **USD 80,000**

3. **City wide cleaning campaign of all urban drainage and sanitation infrastructure and immediately following implementation of the before elaborated O&M plan**

   → Estimated cost[6]:
   a. Clearing of channel > 3m -Heavy pollution: **USD 51/m** – Light pollution: **USD 26/m**
   b. Clearing of channel < 3m - Heavy pollution: **USD 31/m** – Light pollution: **USD 18/m**
   c. Clearing of box culvert: **USD 285/barrel**
   d. Clearing of urban drainage inlet: **USD 18 each**
   e. Clearing of sewer per meter **USD 10/m** or up to **USD 20/m** if CCTV is to be applied and a GIS based sewer cadastre is to be created

4. **Parallel to the cleaning campaign: City wide information campaign regarding urban drainage and solid waste management, informing the population on**
   a. The functionality of the urban drainage infrastructure in Maputo
   b. The immediate and mediate consequences of urban drainage infrastructure being blocked by solid waste
   c. The immediate and mediate consequences of urban drainage infrastructure being blocked by the residents/businesses on purpose
   d. Health implications of uncontrolled solid waste dumping
   e. Health implications of uncontrolled wastewater emission to the urban drainage infrastructure

   → Estimated cost for international and national consultancy: **USD 120,000**

→ Estimated total cost for international and national consultancy: <u>USD 670,000</u>

→ Estimated total cost for implementation of measures: depending on length of channels
and sewers, and number of culverts respectively. Refer to estimated rates above.

[6] All these rates are to be considered rough estimates based on the consultation with construction companies in Maputo. There are a variety of factors that will influence rates of clearing in certain areas, as for example:
- Access for truck to stop and load cleared debris – e.g. in Av. Joaquim Chissano where there is high traffic volume and no shoulder for vehicle to stop and load.
- Distance to dump site for truck to off load
- Access to mechanical drain clearing equipment for storm water drains – I suspect that the majority of drains have not been cleared for many years.

3.7.2 Re-calculation and re-design of all existing urban drainage infrastructure

Based on the results of the above described survey and the elaboration of an urban drainage infrastructure inventory, the functionality of the existing system is to be hydraulically re-calculated considering the actual state and operability of the structures. The prerequisites for this engineering task are to be provided through a field survey in advance of the works, i.e. as described above. Based on the field survey and the subsequent steps (digital mapping and inventory of all surveyed information, elaboration of a database), a detailed city wide model can be developed in order to re-calculate the hydraulics of the entire drainage system of Maputo. Such a model will have to be elaborated in close cooperation with the Municipal Department of Urban Drainage and Sanitation.[7]

This re-calculation would have to include:

1. Assessment of the existing documentation which is available for the existing urban drainage infrastructure, the design criteria applied and the experiences of the operator regarding its actual functionality.
2. New hydrological calculation of relevant design storms (ideally based on the information of newly installed hydrometric precipitation measurement devices).
3. 1-dimensional or two-dimensional steady-state and non steady-state flow calculation of open channels
4. Steady-state and non-steady-state hydraulic calculation of all piped storm water and wastewater sewers
5. Detailed citywide network calculation of the entire sewer and drainage network (e.g. with SWMM5)

→ Estimated cost for international and national consultancy:

a. **USD 120,000** if all necessary data and requested information can be provided by the Municipal Administration of Maputo
b. Up to **USD 300,000** if the respective surveys are to be organized and conducted by the contracted Consultant (no matter if national or international) and respective local sub-contractors

Based on the results of the hydraulic calculation and of the city wide hydraulic model, a **re-design[8] of the complete storm water sewer and drainage network** is to be conducted, taking into account

a) The existing urban drainage infrastructure
b) The already contracted or otherwise already designed (and not yet implemented) urban drainage infrastructure[9]
c) The political realities in Maputo, especially regarding the housing market and the realities in the peri-urban areas with its informal settlements and its insufficient possibilities to install high level infrastructure
d) Urban Development Plans and Strategic Master Plans
e) Earlier recommendations by other consultants (e.g. DNA 2005)
f) Possible extensions of the urban drainage system duly considering urban development plans, stakeholder interests and hydrological re-calculations

→ Estimated cost for international and national consultancy: **USD 400,000**

[7] Please note that the elaboration of an Urban Drainage Masterplan for Maputo is being tendered internationally at the moment. The herewith suggested measures are to be taken I close cooperation with the Consultant who is going to win this tender.

[8] i.e conceptual design

[9] It is acknowledged that there are a lot of similar projects going on already, e.g. financed by the Italian Cooperation.

→ **Estimated total cost for international and national consultancy: USD 520,000 to USD 700,000**

3.7.3 Structural measures

Based on the results of the modelling of the subcatchment Maxaquene A and Mavalane A, some structural measures at some major hydraulic bottlenecks are recommended for implementation or at least for consideration:

1. **Extension / reconstruction of culverts, based on the results of a citywide hydraulic model**: A comprehensive and reliable indicative pricing for this measure is not possible for this measure, as
   a. For each culvert several different options are feasible (extension of clear width/height of barrels, drilling of additional barrels, removal and complete reconstruction)
   b. There is a large number of differently sized culverts which are to be considered for reconstruction. As stated in the conclusions from the modelling, the re-dimensioning of culverts must be based on a citywide hydraulic modelling of the complete urban drainage system, which could not be conducted in this project phase to a level of detail which would have been necessary for such dimensioning purposes.

   →Estimated indicative cost per culvert/bridge including design, removal of old culvert/bridge and reconstruction of roads: **USD 50,000 to USD 500,000**, very much depending on agreed scope of works

2. **Concept, design and implementation of Low Impact Measures such as:**
   a. Propagation of small scale rainwater harvesting systems, especially in those neighbourhoods where there is no continuous water supply from a piped water supply network.
   → Estimated cost per household rainwater harvesting system, depending on roof size, roof shape, and required storage volume: **USD 150 to USD 500**
   b. Construction of infiltration wells, especially where the ground water level has been lowered in recent years as a consequence of overuse of the groundwater resources.
   → Estimated cost per well, depending on infiltration capacity of the subsoil and the therefrom resulting well depth and diameter: **USD 500 to USD 5,000**
   c. Construction of infiltration trenches where applicable, i.e. where the groundwater level is not too shallow
   → Estimated cost per square meter**: USD 80 /m²**
   d. Roads as Drains, e.g. in Maxaquene A and Mavalane A (compare Mafalala)
   → Estimated cost per square meter**: USD 200 /m²**

3. **Finalisation of the storm water detention basin in northern Sommerschield**: As can be seen in the above photo documentation (*Figure* 3-57), the storm water detention basin which was included in earlier designs by the local consultant *Consultec* as early as 2005 has never been finalized. Under the assumption that this detention basin is part of a large scale urban drainage concept (to be confirmed) it is recommended that the works for the completion of the detention basin should actually be re-started. The cost for this

measure depend on many factors (foreseen surface, foreseen operational options and resulting gate/weir form, foreseen storage capacity) and cannot be estimated without access to the respective detailed design documentation. In any case it should be noted that any future construction measures should be based on the results of a detailed citywide hydraulic model.

3.7.4 Further recommendations

Apart from the above mentioned detailed recommendations the following measures are recommended to be taken into consideration:

I. Immediate development and short-term implementation of an integrated operation and maintenance scheme for the existing urban drainage infrastructure.
II. Elaboration and implementation of an integrated land use and settlement masterplan for the whole city of Maputo (including Matola and suburbs), starting with new development areas and continuing with a re-design of existing informal settlements in a more structured manner to allow for the installation of basic infrastructure.
III. Concentration of ownership and O&M responsibility for the urban drainage infrastructure with one institution, e.g. the Municipal Administration of Maputo.
IV. Urban flood modelling with a 2D hydraulic model which is able to model the actual inundation of the areas adjacent to the urban drainage channels.

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SUBCOMPONENT 4: AGRICULTURAL WATER MANAGEMENT

4.1 EXECUTIVE SUMMARY

The Support Project for Agricultural Water Management (SPAWM) aims to offer vulnerable farmers increased resilience to climate change.
The project promotes improved use of water for agricultural purposes to protect farmers from increased variability of rainfall both between and within years. SPAWM will work primarily with vulnerable farmers, but will also support lead farmers, who will be emerging small commercial farmers that will demonstrate the benefits of AWM to more vulnerable farmers. The project will be limited to micro-level AWM that can be managed by individual farms or through voluntary cooperation amongst a small number of farmers. It thus complements more formal irrigation projects that support larger schemes involving shared management of water resources, including the major PROIRRI programme.

The project is prepared as part of the second phase of the 'Responding to Climate Change in Mozambique' project, coordinated by INGC.
This second phase has 8 themes, covering all the main sectors that are likely to be affected by climate change. Theme 5 deals with water and Subcomponent 4 of this theme supports the preparation of the SPAWM project. This report is the main deliverable of Subcomponent 4. The subcomponent is largely independent of the other subcomponents of Theme 5 but takes into account the work under Theme 6, which deals with food and crop production estimates.

The project will cost US$ 2.5m and will generate annual benefits of over US$ 600,000, after five years, involving 3400 farmers.
The main benefits will come from using AWM techniques to cultivate vegetables during the dry season, which will be consumed by the farm households and sold. The savings they generate from these sales will help the households survive years of drought and flood. The AWM techniques will also provide some protection from drought during the wet season, affecting both vegetables and staple crops, thus providing further protection from increased variability of rainfall. Some additional benefits will be felt by the urban population near the project activities, who will have access to improved food supplies.

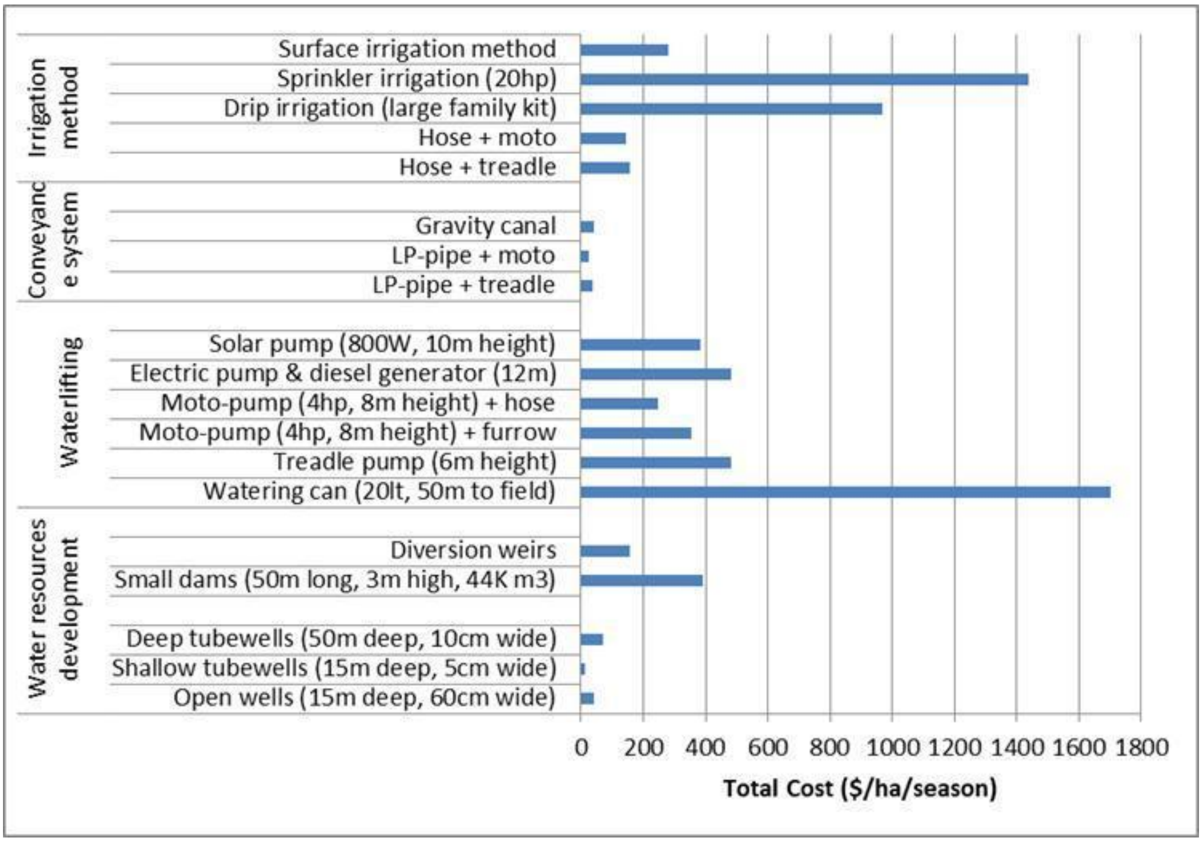
Climate change will generate increased benefits to the project.
The project is a 'low regrets' project, because it will generate good returns both with and without climate change. In most places, the returns to the project will be higher with climate change than without. Climate change is likely to result in a reduction in average yields, both with and without AWM, which will tend to reduce project returns. However, this will be more than offset by three factors that will increase returns if climate change happens: a) climate change is likely to result in a higher frequency and duration of dry spells during the wet season and the project will generate additional benefits by helping to protect farmers from this; b) climate change is likely to lead to an increase in the concentration of ground level ozone during normal wet season planting periods and this will increase the relative profits to farmers from the dry season cultivation that is made possible by AWM; and c) climate change is likely to lead to higher risks of flooding and so to higher benefits to farmers from being able to cultivate land that is just above the floodplain, using the AWM techniques provided by the project.

The SPAWM project is based on the latest AWM experience in Mozambique and internationally.

The preparation was undertaken by two international and two Mozambican experts. The work builds on experience in INGC in supporting farmers that are most vulnerable to climate change. The latest international evidence of the physical and economic performance of AWM options was reviewed in order to shortlist the most promising AWM techniques. Meetings were held with key stakeholders from government, donors and the private sector. Fieldwork involved discussions with farmers near Maputo and Beira to understand current AWM practices and farming systems and explore possible interest in new techniques. The international grey literature was searched for evidence to fill gaps and complement the evidence available in Mozambique.

Detailed analysis of unit costs for AWM techniques was undertaken.

This built on on-going international work, adapted for Mozambican conditions. In most cases, a combination of techniques is needed to extract water, deliver it to the field and apply it to crops. The unit costs of each individual technique depend on the way in which it is combined with other techniques, so it is not easy to present simple summarised figures. The unit costs of some techniques are also heavily dependent on assumptions about the cost of labour. However, the table below provides an indicative summary of the unit costs. In practice, the most appropriate techniques for a specific location depend on a wide range of conditions, including the availability of water resources, the farming practices and the circumstances of households and communities.



Six combinations of AWM techniques are shortlisted as the most likely to be sustainable and appropriate.
A shortlist has been prepared of six combinations of AWM techniques that will provide the most cost effective solutions in most circumstances in Mozambique. There are three 'blue water' options (that use water brought to the field from surface or ground resources) and three other techniques, as described in the table below:

Blue Water Options
A: surface water and moto pumps (with or without pipes and hose irrigation)
B: low cost open wells with moto pumps or treadle pumps
C: shallow tubewells with moto pumps or electric submersible pumps
Other Options
D: water harvesting (WH)
E: conservation agriculture (CA)
F: drainage control in the wetlands

The blue water combinations typically cost 500 to 700 $/ha/season, though there are quite large variations, depending in particular on the height that the water must be lifted. Water harvesting involves lower costs of about 110 $/ha/season, but provides lower benefits. Conservation agriculture has a one-off transition cost and then provides sustained yield benefits with lower costs. The costs of drainage control are site specific.

There are large variations in the benefits and costs to farmers, depending on land and water availability, weather pattern, farming circumstances, attitudes to labour and access to markets. Rough national averages are presented in the table below and are intended as indicators to assist with comparative monitoring. The returns are those to farmers and exclude the costs of extension and management support, which are dealt with in the project economic analysis.

Role of AWM	Benefits	Costs	Benefit Cost Ratio
	$/ha/season		
Blue water: dry season	2300	500	4.6
Blue water: wet season supplementary/dry spell protection	350	200	1.8
Water harvesting in wet season	270	140	2.0
Conservation agriculture in wet season	740	170	4.4

Other techniques are proposed to be tested to assess if they are cost effective in some circumstances.
In particular, the pilot testing of additional AWM techniques may be used to test the viability of treadle pumps, drip irrigation and sprinkler irrigation. However, the budget allocated for this testing will be restricted to 10% of the total budget for equipment and inputs. More widespread support for these techniques will only be considered if the tests prove that they are more cost effective than the analysis in this report.

Three areas have been chosen to represent the main agro-ecological zones in Mozambique.
SPAWM will build on the existing experience of INGC in Caia (in Zambezi) and Mabote (in Inhambane), which represent valley bottom and dryland agro-ecological zones. Both are vulnerable to climate change, with Mabote vulnerable to drought and Caia to flooding. The project will also add a third area in the Beira hinterland, which will offer insight into the AWM technologies that are successful in wetland conditions and where markets are closer. In addition,

the project operations in Beira will help to support marketing of products from Caia and a component to support micro-AWM for outgrowers will operate nationwide.

Extension and management will be undertaken by a team of national experts and field engineers, providing support to field staff.
At the national level, a Team Leader will provide overall coordination and will work with three national experts covering: agricultural engineering, agronomy and farm management/evaluation. These will be supported by two field engineers at each hub covering agricultural engineering and agronomy. Where possible, field activities will be undertaken by existing INGC field agents and MINAG extensions workers, to ensure sustainability. A budget is provided to employ six additional Extensionists, if necessary. The project will provide expenses for all Extensionists, including motorcycles and per diem.

The project will work with the Farmer Field School (FFS) approach.
FFSs are well established in Mozambique. Because they adopt a participatory approach, they are ideal for demonstrating and promoting the adoption of AWM techniques. In each of the three hub areas, the project will work with 5 extensionists, providing finance for mobility and training. Each extensionist will aim to work with 3 FFSs, many of which will have to be created. The FFSs will identify project beneficiaries and will be involved in selecting the most appropriate sites and AWM technologies. The extensionists will work closely with the FFS during the first year of contact and will provide follow-up support for the second year.

The project will support a training programme built around Farmer Field Schools and also supporting training for extensionists and project staff.
The design of the FFS training is built on the experience in Mozambique and elsewhere, with a series of 10 sessions per season and financing for training materials and expenses for farmers and trainers. In addition, there will be two training sessions per year for field engineers and two for Extensionists, both organised in Beira. There will also be two seminars per year for wider participation at the three hubs and two national seminars each year. Finally, there will be two private sector workshops each year at each hub, to provide an opportunity for the private sector to engage with project beneficiaries.

The project will aim to help about 3400 farmers to introduce AWM techniques on about 600 hectares by the end of three years.
For each FFS, the extensionists will aim to involve 25 farmers in some form of AWM. About 20 of these will be small scale vulnerable farmers cultivating less than 0.5ha, with limited experience in marketing surplus products and few household savings available to help survive years of drought or flood. About 5 of the farmers will be lead farmers, normally cultivated at least 1 ha and with some experience of marketing surplus produce. The number of AWM sites will depend on the technologies adopted. Some technologies will require cooperation amongst a group of farmers. The lead farmers will be expected to use AWM techniques on about 0.5ha, whilst the vulnerable farmers will use them on only 0.1ha. This will mean that about 4.5ha will receive new AWM techniques in each FFS. With a total of 45 new FFSs each year, this means that about 200ha of new AWM will be introduced each year.

Dry season vegetables will provide the main benefits in Caia and Beira.
In Mozambique, the margins for growing grain crops (mainly maize and rice) and legumes are not high enough to justify the costs of micro-level AWM in the dry season, unless farmers put a very low value on their labour and/or crops are valued at much higher than market prices. For

vegetables, dry season irrigation can be highly profitable, with margins of around 2000 $/ha/season, giving Benefit Cost Ratios of up to 5. In both cases, these benefits are dependent on getting crops to market and the project will provide some assistance to help establish marketing links to Beira and other major consumer centres.

Supplementary irrigation may be a useful bonus.
The benefits of supplementary irrigation will vary, depending on the extent to which rainfall is limiting. The value of the benefits will vary from the full value of the crop, in drought years, to zero in normal years. Given the probabilities of drought and damaging short dry spells in Mozambique, the average annual loss in yield from lack of rainfall in the wet season is probably between 20% and 30% of normal yields. For maize and legumes, this therefore produces benefits of about 300 $/ha/season, compared with AWM costs of about 300 to 500 $/ha/season. Thus, investment in AWM technology should not be made on the basis of its role in supplementing yields in dry years, except for high value crops. However, equipment that is bought primarily for dry season cultivation can be useful for supplementary irrigation.

Water harvesting is expected to increase yields by an average of 20%.
There is no quantitative evidence in Mozambique of the impact of water harvesting on yields and only limited evidence available internationally. In order to estimate the benefits from water harvesting and provide an indicator for monitoring purposes, it is assumed that yields will increase by 20%. This is based on evidence from Malawi and is therefore most applicable to the drier areas of Mozambique, where conditions are similar to those in Malawi. For grains and legumes, these benefits should amount to about 200 $/ha/season, compared with an average annual cost of 140 $/ha/season.

Conservation agriculture is highly varied, but most evidence suggests that yields can increase by 40%, once the new systems are established.
There are a huge range of techniques involved in conservation agriculture, with many different models and practices. Central to all techniques is the avoidance of tillage and the use of green cover crops/material and crop cycles, including the possibility of adding an additional crop to the farming calendar. Evidence was reviewed from a dozen projects in Mozambique, several reviews in Southern African and work in Sub-Saharan Africa and world-wide (see Box 4.2). This suggests that conservation agriculture can increase yields by 50% to 100%. The main costs of conservation agriculture are associated with the risks of reduced yields in the first few years. The annualised cost of providing reimbursement for these lost yields is estimated at 12% of normal crop yield, suggesting a Benefit Cost Ratio of about 3.5.

The project will provide subsidies to encourage adoption of AWM techniques.
Whilst AWM techniques do provide good returns, farmers in the project areas have very limited financial resources and few are likely to be able to afford the investments and other costs involved. For the most vulnerable farmers a 90% subsidy will be required for investments and a 50% subsidy for fuel and farm inputs. For lead farmers, a subsidy of 50% will be provided on investments, with no subsidy for operating costs. Conservation agriculture involves some labour and inputs and, in many cases, there are reduced yields during the first few years, whilst new practices are established and the soils improve and weeds are brought under control. Few farmers are able to absorb these reduced yields and there is a high drop-out rate in the first years. SPAWM will address this by providing a double pack of crop inputs to cover both the land under conservation agriculture and a comparable area of land under conventional cultivation.

It will not be possible to rely on the private sector to supply directly to farmers, but entrepreneurs will be encouraged.

Because of the financial status of most of the project beneficiaries, it is not possible for the project to rely exclusively on the private sector to supply directly to farmers during the first year of AWM adoption. However, the sustainability of AWM practices will depend on farmers making their own arrangements with the private sector for inputs, after their first year. The project will facilitate greater activity of private sector suppliers in the project areas. Some temporary and targeted incentives will be provided to traders from Beira and Quilemane to encourage them to build trust with the project beneficiaries as new sources of supply. The project extension activity will also help beneficiaries to make applications to private sources of financial services.

The full project budget is $2.5m.

Extension and management account for 49% of total costs, training 26% and equipment and input supply 31%. Farmer contributions to the cost of equipment and inputs will reduce the funding requirements by 6%. The following table summarises project costs.

	Costs ($)			
	Y1	Y2	Y3	Total
Summary				
Extension and Management	513,300	360,800	350,800	1,224,900
Training	183,630	234,170	234,170	651,970
Subsidies and Incentives	253,434	253,434	253,434	760,303
less farmers contribution to costs	0	75,540	75,540	151,080
Total	950,364	772,864	762,864	2,486,093

Smaller projects are also viable.

It is possible to adopt the same project philosophy and achieve similar returns with smaller projects. Supporting activities in only one area could reduce costs to 30% to 40% of the full project costs. Effective support and management would be provided with a team of three national experts covering the three fields and working directly with the field extension agents. The main disadvantage of this approach is that it would work in only one of the three broad agroecological zones and so would provide less evidence for broader national expansion of AWM. An even smaller approach could be undertaken with a single national expert working with a few field extension agents. This would reduce the costs to less than 20% of the full project cost. Because of the higher share of costs devoted to support and management, the returns would be lower than for the larger versions of the project. However, there would be a tendency for the national expert covered to focus on the technical viability of AWM options and to miss the full opportunities for farming systems and the implications for economic sustainability.

When the full costs of the project are taken into account, the IRR is estimated at 24%.

If the benefits of supplementary irrigation in the dry season are included, this could rise to 27%. The IRR is particularly sensitive to the yields and prices achieved with the cultivation of dry season vegetables, which provide the majority of project benefits. Assumptions about the cost of labour also have an impact on the viability of the project.

It is difficult to provide quantitative estimates of the impact of climate change on the IRR.

The projections of trends in temperature, rainfall, CO2 and ground level ozone suggest that yields will decline in most areas, although improved rainfall in some areas may lead to a small net increase. If climate change reduces national average yields of vegetables by 10%, then the

IRR would drop by 8 percentage points to 16%. However, if this drop in yields were associated with an increase in price of 10%, the reduction in IRR would be largely offset. A drop in the yield of grain and legume arising from climate change would have limited effect on the IRR. Climate change is likely to increase project IRR for three reasons:

- An increased frequency and duration of dry spells in the wet season will increase the value of protecting farmers from these risks. Climate models produce no clear estimates of the magnitude of the increased frequency and duration of dry spells in the wet season. It is therefore not possible to estimate the extent to which the project IRR will increase with if there is a rise in the risk of wet season crop losses due to drought. However, if these risks were doubled as a result of climate change, then the ability of AWM to protect yields from these increased risks would add a further 3% to the project IRR.
- Climate change is likely to increase the seasonal differential of ground level ozone concentration. This would mean that the value of dry season irrigated production would be relatively higher and would tend to increase the project benefits. Estimates are not yet available on the change in the seasonal differential in ground level ozone concentration, but it is possible that this could lead to significantly higher project benefits.
- The ability of famers to cultivate land just above the floodplain means that farmers are less likely to lose crop due to flooding. The magnitude of losses from flooding, and the ability of AWM to support cultivation off the floodplain is very site-specific and it is difficult to

The volume of water affected by the SPAWM project is very small, compared to other users. The blue water irrigation requires a supply of about 6400 m3/ha/season, leading to a total demand by the end of the project of about 1.6 mcm/year. This is extracted from rivers or from groundwater reserves and thus reduces water available for other purposes. The activities in water harvesting and conservation agriculture will reduce runoff, but the net effect of this is likely to be small, given the area involved. Thus, the volume of water involved in the project is small and is equivalent to about 1 hour's flow of the Zambezi river.

4.2 BACKGROUND

4.2.1 Introduction

This project document has been prepared by Subcomponent 4 of Theme 5 of the Second Phase of the ‘Responding to Climate Change in Mozambique’ project, coordinated by INGC. This second phase identifies 8 priority themes: 1) early warning; 2) coastal protection; 3) cities; 4) private partnership; 5) water; 6) food; 7) preparing people; and 8) the National Strategy for Climate Change. Theme 5 has the following 5 subcomponents: i) a decision support system; ii) flood resilience; iii) urban water; iv) water for agriculture; and v) water for energy.

Subcomponent 4 is largely independent of the other subcomponents of Theme 5, except that it will provide estimates of water use by AWM techniques to feed into the national water balance analysis. The subcomponent also takes into account the work under Theme 6, which deals with food and crop production estimates (Holman 2011).

4.2.2 International Perspective

There is broad agreement that agricultural development is a key pathway towards broad-based growth and poverty reduction, having the potential to benefit the poorest of the poor and to contribute to improved gender equity (World Bank 2008). There is also growing agreement that AWM is one of the key instruments for achieving sustained agricultural development (UN Water 2009; GWP 2010), especially when climate change is taken into account (World Resources Institute, UNEP *et al*. 2011; Alavian, Qaddumi *et al*. Nov 2009). Within these influential international policy statements, on-farm water management, including for rainfed crops, plays a central role.

Despite the high priority of AWM in international commitments, a recent analysis suggests that the AWM investment in Africa is much lower than in other continents and that African policy has focused too much on top down regulation and pricing of water and not enough on supporting pragmatic local initiatives and providing public investment (van Koppen, Namara *et al*. 2005). This review demonstrated the strong positive impact that AWM can have on yields in Tanzania and Madagascar and the even more marked impact on incomes.

The increased international interest in agriculture and water suggests that a project to support AWM in Mozambique is in line with international priorities. However, the challenges of such a project are illustrated by the experience gained in the early decades of development, when agriculture received a large share of total development effort. The irrigation projects of the 1970s were less successful than intended, partly because of the complex interrelation of factors affecting farming decisions, and partly because of unsustainable management costs. As a result, many donors turned to Integrated Agricultural Development Projects (IADPs). These were also less than successful, struggling to achieve any level of sustainability. Many donors then moved out of agriculture entirely and those that remained shifted to a more sectoral approach, concentrating on establishing policy and institutional capacity. This experience demonstrates the challenges faced in addressing the socio-economic dimensions of agricultural development.

There is, however, a major difference between the situation in 2011 and that in the 1980s, when the IADPs struggled to achieve impact: farming is now more profitable than it was in the 1980s, when low world food prices were coupled with distorted macroeconomic policies that resulted in very cheap food imports. The potential for a more integrated level of support should therefore be revisited. Whilst it is not be possible to establish a full-scale modern IADP based on micro-irrigation, the project design does include some targeted activities to support marketing and financial systems, to complement the support for farming techniques.

The FAO Comprehensive Assessment of Water Management in Agriculture places a strong emphasis on the importance of improvements in rainfed agriculture, including improvements in use of rainwater, soil moisture management and supplementary irrigation (FAO 2007).

4.2.3 Country Background

National Development. Mozambique has been one of the most successful countries in Africa in the last decade, with rapid economic growth and reduction in poverty, for example from 69% in 1996 to 55% in 2008. Growth has been generated both by strong public sector investment and by private investment, including a number of very large projects. Government investment has been guided by two Action Plans for Reduction of Absolute Poverty (PARPA I and II) and a third PARPA – PARP 2011-14 – was approved in May 2011. PARPA II defined a range of priorities covering: growth and poverty reduction; governance (including justice, transparency and disaster management); human capital (including education, health, water and sanitation); and the economy (including rural development, business, trade and investment). The first general objective of the new PARP 2011-14 is improved production and productivity in agriculture and fisheries and the priority actions for achieving this objective include improved access to agricultural water. Sector strategies related to agriculture are described later in this section.

This economic growth has placed pressure on natural resources, including land, forests and fisheries. Recent trends in world food and energy prices have created further pressure to expand agricultural production, both for food and for biofuels.

<u>Agro-climate Conditions.</u> The options for agricultural development are determined by agro-climatic conditions, which vary from tropical and subtropical conditions in the north and central parts of Mozambique to dry semiarid steppe and dry arid desert climate in the south. The hottest regions are located in the Zambezi basin and the coastline of Cabo Delgado, Nampula, Zambezi and Sofala. The south is the coolest part of the country, with an average maximum and minimum temperature of 30 ºC and 19 ºC respectively.

The rainy season lasts from October to April. Precipitation varies widely from the coast to the inland areas and from north to south. Average rainfall is between 800 to 1 000 mm along the coast, with values above 1 200 mm between Beira and Quelimane. The rainfall decreases inland reaching 400 mm at the border with South Africa and Zimbabwe. The north and central part of the country has annual rainfall from 1 000 to over 2 000 mm because of the northeast monsoon and high mountains. In the southern inland part of the country average annual rainfall is between 500 to 600 mm. Evapotranspiration is between 800 and above 1 600 mm, with high values in the Zambezi basin and along the coast and lower values in central Niassa and on the border with Zimbabwe. The likely impact of climate change on these figures was addressed in the Phase 1 of the current INGC project is discussed later in this section and the impact of this is assessed in Section 4.4.4

For the purposes of the project, the country can be divided into three basic agro-ecological zones with distinctly different potential for AWM technologies.

- *Dryland* areas are characterized by low and erratic rainfall, predominant rainfed crops and with no easy access to surface water sources and often limited access to good quality groundwater.
- *Wetlands*, lowlands, depressions and floodplains often have higher rainfall, seasonal flooding and shallow groundwater. There are often good prospects for agricultural development, but these have to be balanced with the need to protect fragile ecosystems.
- *Uplands and valley bottoms* have rolling lands with rainfed agriculture in the uplands. Valley bottoms may be flooded in the rainy season, but have access to surface and groundwater resources suitable for irrigation.

<u>Water Resources.</u> The Zambezi is the largest river in Mozambique, with flow rates of about 106 km^3/yr, or about half the total runoff in the country. About 88 km^3/yr is inflow from the

borders, with the Shire accounting for about 6 km^3/yr. The Cahora Bassa dam, with a capacity of about 55 km^3 stabilises flows on the Zambezi river and the Shire flows is fed by Lake Malawi.

Despite the effects of the Kariba and Cahora Bassa dams, floods do occur in the Zambezi and the last major floods in 2007/08 resulted in widespread destruction of crops and infrastructure. Many of the areas of highest potential for agriculture are the most vulnerable to floods, including the Inhangoma triangle, with about 40,000 ha.

Groundwater resources are highly varied, with good potential yields in the valley bottoms, extended outwards where there are coarser materials and deeper aquifers. In Zambezi, wells and boreholes in the better aquifers in valley bottoms have yields of the order of 10 m3/hr, which is sufficient to irrigate about 2.5 ha.

Agriculture. Agriculture accounts for nearly a quarter of GDP and over three quarters of livelihoods (MINAG 2011). There has been some success in improved productivity over the last ten years, but this is patchy and yields are low by the standards of Southern Africa. The majority of farmers have farms of less than 2ha and rely on extensively farmed rainfed crops, with low inputs and high exposure to flood and drought risks. Households use a wide variety of methods to pursue food security, including planting a range of crops and seeking a variety of sources of income. The more productive commercial farms account for only 5% of cultivated area (MINAG 2011), but nearly a third of the value of production, and provide important sources of income in rural areas.

Mozambique is highly vulnerable to climate variability and floods and drought have had a severe impact on several occasions over the past decade. The most serious impact has come from droughts, which have negatively affected yields in four years out of ten since 2002. In drier areas, crops have a 60% to 75% risk of complete failure and good yields are achieved only one in three or four years. Severe floods following extreme rainfall, such as those in 2000/01 and 2007/08, also lead to crop failure, often affecting the most fertile areas of the countries.

To reduce the risk of crop failure, farmers use a range of techniques, adapted to the local conditions. In Zambezi, techniques include intercropping, drought tolerant crops and varieties (especially of cassava and sorghum) and short cycle varieties of maize and sorghum. There is some experience with soil and water conservation techniques, including contour ridges and furrows, broad bed ridges and planting micro-basins for maize. Within the flood plains in Zambezi, flood recession agriculture is traditionally practiced during dry season to grow deep rooting crops such as maize, beans, sorghum, sweet potato and cotton. The practice of agro-forestry, combining fruit trees (mango, cashew, and banana) with field crops is also practiced in Zambezi.

Irrigation. Most of the public funding for AWM, from both domestic and foreign sources, has been devoted to irrigation development. About 100,000ha of irrigation was developed during the colonial period, by both state and private investment and a further 20,000ha have been developed by the state since independence. In 1987 two third of the irrigation schemes were under state control, 20% operated by small holder farmers and only 15% owned by private companies. The Government has been unable to effectively operate and maintain many of the irrigation schemes resulting in large scale failures of many schemes and only 50,000 ha is presently estimated to be irrigated (MINAG 2011). As a result, emphasis has been put on small scale irrigation developments, and 40% of the 50,000ha currently irrigated is now owned and run by small-holder farmers and water users associations, with only 25% still owned and run by the government and 35% privately owned.

In the Zambezi Basin, the amount of water that can be extracted from the river for irrigation and other purposes is limited by the need to maintain flows to the delicate ecosystems in the delta. The Planning and Development Office for the Zambezi Valley has an ambitious plan to develop 1.5m ha of intensive irrigated agriculture, including 0.6m ha of rice, which would require about 20% of the river flow.

Despite the investment in irrigation and the support for small scale irrigation, water users associations in Mozambique have struggled to manage and maintain infrastructure. Credit and marketing conditions have been major constraints. It is not yet clear whether the improved food prices since 2008 will have a significant effect on the viability of small scale irrigation in Mozambique. Privately owned irrigation has proved much more successful, including the large irrigated sugar schemes (accounting for 25,000 ha) and irrigated fruit and vegetables farms, including small investment in on-farm AWM by thousands of small farmers. Despite the problems faced by state and small scale irrigation, it is still considered a main pillar for agricultural development and food security. Large public investments are devoted to formal irrigation development and rehabilitation, often focussing on the smallholder schemes, with major contributions from the African Development Bank and World Bank, most recently through the PROIRRI project that aims to support 5000ha of irrigation in Sofala, Manica and Zambezia between 2011 and 2017.

Micro Agricultural Water Management. Micro on-farm AWM offers farmers a range of techniques for improving the efficiency with which water is used for crop production, thus enabling them to make best use of the limited water available. Some techniques involve storage of water that also assists farmers in surviving drought and flood. In view of this potential, AWM has featured strongly in international strategies for growth, poverty reduction and climate resilience (HLCWAEA 2008; NEPAD/CAADP 2009) and there have been several major reviews of the key issues (Turral, Burke *et al*. 2011) recent performance (World Bank 2007) and of investment needs (You 2008). The FAO Special Food Security programme also provides support for micro-level AWM and IWMI have initiated a project in 5 countries promoting the micro on-farm irrigation techniques for improved livelihood for smallholder farmers.

Little information exists to quantify the extent of use of micro AWM in Mozambique. Agricultural surveys suggest that blue water micro irrigation is not common, except in peri-urban areas, but locally adapted soil and water conservation activities are more common, as are cropping patterns that adopt some of the principles of conservation agriculture. According to dealers and importers, there has been a strong increase in imports and sales of moto pumps. Part of this is attributed to urban use, but sales to small farmers are also reported to have risen. Sales of treadle pumps are very low, but have been increasing, largely as a result of purchases by projects.

Irrigation using watering cans is very common amongst small farmers growing vegetables near to the major cities and, especially, to Maputo and Beira. Outside these areas, watering cans are used only on a very small scale for garden vegetables plots.

Efforts to provide public support for micro AWM have been limited to small scale and localised projects. In the framework of drought mitigation projects, a number of NGO's have been promoting irrigated agriculture through the introduction of treadle pumps and drip irrigation systems. Although treadle pumps appear to be attractive in theory, the experience in practice is more mixed and it is rare for farmers to choose to purchase treadle pumps from their own resources. The reasons for this are varied and not always clear. The work involved in operating a treadle pump is more arduous than a water can and is often undertaken by people who may be most able to find alternative work. In some cases, treadle pumps have been introduced with insufficient technical support and follow-up.

There would appear to be great potential to increase rice production through better water management, introducing field bunding and simple diversion structures such as practised traditional in Asia. The majority of the rice production is currently in depressions and wetland areas remain rainfed with few or no arrangements for better water control through bunding and flood control. More substantial results have been achieved in the introduction of AWM technologies through conservation agriculture (CA) and water harvesting.

Agricultural Practices. Agriculture contributes 23.5% of Mozambique's value added and provides work for 80% of the economically active population, of which 60% are female (MINAG 2011). According to official production statistics, since the end of the civil war in 1992, Mozambique has made impressive gains in restoring food production and at a national level the country is virtually self-sufficient in terms of food grain production, with the exception of wheat and rice. However, this growth has been uneven spatially and natural disasters such as flood and drought are an important cause of temporary food insecurity.

In 2002, the cultivated area was estimated at 4.4 million ha, of which 4.2 million ha arable land and 0.24 million ha were under permanent crops. Smallholder farmers account for 95% of the cultivated area and produce most of the foodcrops (MINAG 2011). Farms are small, averaging 1.8ha, and there is very limited access to irrigation, inputs, equipment and financial services. As a result, yields and margins are low. However, there is a small group of emergent farmers that are improving their farms. In addition to the smallholder farmers, small and medium private companies grow cash crops with much better access to inputs and finance, selling to national and export markets and to agro-industry. These companies also provide substantial employment. The commercial sector provides an important source of innovation and technology transfer.

In value terms, Cassava is by far the most important agricultural product in Mozambique (worth about $360m). Only four of the top ten products are food crops: cassava, maize ($130m), sweet potato ($89m) and pulses ($37m). Four are cash crops: cotton ($170m), tobacco ($120m), cashew nuts (56m) and sugar cane (51m). Two are livestock products: pork ($92m) and beef (39m). The importance of cassava reflects the high value placed by farmers on drought resilience, despite the status of cassava as a food of last resort. The crops that are growing fastest, in terms of area planted, are sugar cane, maize, tomatoes and bananas, followed by rice and cassava.

Most Mozambican crops are grown largely under rainfed conditions, using little or no agricultural water management (AWM) techniques. Rainfed crops are very vulnerable to variable seasonality of rainfall, making it difficult to plan farming activities, even in years when total rainfall is adequate. Dry spells during the growing period often reduce yields substantially and heavy rainfall can also damage crops, both directly and through flooding. As a result, crop yields have been variable. For maize, average yields in good years are over twice the level they are in bad years. Pulses are also highly variable. Other crops are affected less, either because they are more resistant to drought (eg cassava and sorghum) or because they are at least partly irrigated (eg sugar cane and vegetables). This has contributed to the volatility of food prices. Climate change is expected to increase the frequency of extreme events and the timing of rainfall.

Mozambican farmers use a range of methods to spread risks, cultivating different crops and planting at different times. Formal irrigation provides valuable protection from climate change, but only about 3% of the cultivated area is equipped for irrigation and only 1% is actually irrigated. The improvement of irrigation is being addressed by the PROIRRI project which has a main focus on the rehabilitation of small-scale irrigation project and does not directly promote micro on-farm AWM techniques. Flood control works are still largely lacking, with large fertile areas at risk of recurrent flooding.

<u>Climate Change Status.</u> Mozambique has been an important country in international initiatives to adjust to climate change. The First National Communication to the UNFCCC was produced in June 2006 and the National Adaptation Plan of Action was produced in 2007 (MICOA 2007). Mozambique is one of 9 pilot countries for the World Bank's Pilot Programme for Climate Resilience (GoM 2011).

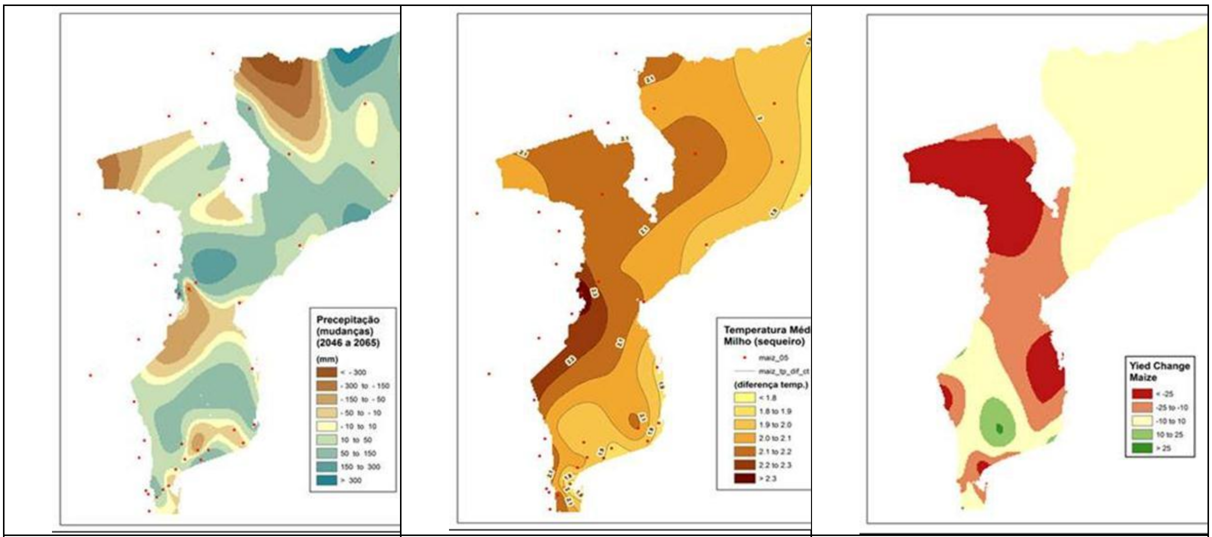
<u>Impact of Climate Change on Agriculture.</u> There have been three studies looking at the impact of climate change on agriculture:

- In 2009, the first phase of the INGC study included a section by Marques *et al* on the 'Impacts of Climate Change and Socio Economic Developments on Land Use and Land Cover - potential effects on crop yields' (INGC 2009)
- INGC collaborated with the World Bank in a study on the Economics of the Adaptation to Climate Change' (EACC), reporting in 2011 (World Bank 2010; Brito 2011)
- Theme 6 of the second phase of the INGC study has included further work on the impact of climate change on agriculture (Brito 2011; Holman 2011)

The analysis by Marques *et al* in the first phase INGC study used 3 of the 7 Global Climate Models (GCMs) run for the INGC study, selected to represent average, wet and dry projections. A crop zoning approach was used, relying on IIAM crop suitability models to show how farmers are likely to change crops rather than expected yield changes. The study concluded that further research was needed and reached the following initial conclusions: cassava becomes less suitable in the north and more suitable in the centre and south; sorghum, maize, cotton and groundnuts are all marginally more suitable across most areas; and soya becomes more suitable in the centre and south and less so in the north. The study recommends a more coordinated public response and better partnership with the private sector. For agriculture, the study recommends pilot projects to explore 'how to do more with less', focusing on responding to more variable climate, soil degradation, reduced water and less fertiliser.

The INGC/World Bank study uses all of the 7 Global Climate Models (GCMs) which produce relatively consistent projections for temperature, but a wide variety of results for rainfall, ranging from a 20% decrease to a 30% increase. This range of results is normal for countries that are on the margins of major global climate systems. Crop response is analysed using the CliCrop model with one GCM, estimating daily evapotranspiration from rainfall and temperature. The analysis suggests that the net effect of temperature and rainfall change will be more negative, largely because of the higher evapotranspiration associated with higher temperatures and the greater concentration of rainfall within the growing season. The study also suggests that groundwater recharge will be significantly higher with climate change than without, in most cases, although the middle Zambezi basin is a notable exception.

For maize, the overall effect is estimated to be 11% decrease in crop yields over the whole country, with some areas gaining and others losing by as much as 25% or more, as shown in *Figure* 4-1. The areas with falling crop yields are in the Zambezi basin in Tete, in the coast around Vilankulos, around Pafuri one of the driest places in the interior of Gaza province, and around Marracuene. The CliCrop model suggests that there will be little change in the length of the growing season, but that the sowing date will be delayed by about 10 days.



Rainfall	Temperature	Maize Yield

Figure 4-1: Impact of expected change in evapotranspiration on maize yields
Source: (Brito 2011)

Rather different conclusions are reached by Theme 6 of the Second Phase of the INGC study, which also deals with the impact of climate change on agriculture (Brito 2011; Holman 2011). The report from Theme 6 is not yet published, but suggests an overall reduction in yields of 19%, with the 14% CO2 fertilisation effect more than offset by reductions of 8% from temperature, 19% from changing ground level ozone levels and 6% from changing the (Precipitation-ETa) balance due to changes in rainfall and ETa resulting from temp increase. These figures present the average figures for all crops across the whole country and there are large differences between crops and regions.

This situation will be exacerbated by the increase in intensity and frequency of cyclones resulting from climate change. Cyclones were not modelled so their effects in crop yields were not included in the analysis. The impact of climate change in crop pests and diseases was also not included.

Sector Strategies in Mozambique. Over the past decade, public funding for agriculture in Mozambique has been dominated by PROAGRI I and II, which have coordinated expenditure in agriculture by government and most donors (with the exception of AfDB and IFAD). PROAGRI was one of the most comprehensive examples of sector budget support in the world and had a particular focus on institutional strengthening and agricultural services. The PROAGRI approach was supplemented by the Agricultural Production Action Plan (PAPA) in 2008 (GoM 2008) which was prepared by the cabinet and describes a wide range of activities designed to meet production targets for 8 major products.

PROAGRI has recently been superseded by PEDSA (MINAG 2011), which defines 5 strategic objectives related to productivity; markets; sustainable resource use; investment framework; and strengthened institutions. The first strategic objective contains 8 results, of which one is to improve AWM and four others concern improved farming techniques that may involve AWM. In addition, the Ministry of Agriculture prepared an Irrigation Strategy in 2010 (MINAG 2010).

The National Strategy for the Management of Water Resources was approved in 2006 and presents the principles for good water resource management. A National Irrigation Strategy was drafted in 2010. For small scale irrigation, this strategy recognises that government has an important role to play in financing new investments in small scale infrastructure and in supporting farmers to develop the capacity to manage small scale irrigation themselves, without government support.

The Council of Ministers approved the INGC's Natural Calamities Prevention and Attenuation Masterplan (NCPAMP) in 2006. This contains three major issues: water balance (including supplies for domestic, agriculture, energy, biodiversity, plus flood protection and reforestation); food balance (including varietal development, diversification and cash crops like biofuels); and emergency management (including readiness, search and rescue and coordination). NCPAMP defines 4 goals (drought resistance, reduced damage, minimize loss of life and suffering and quick recovery) and 14 actions, including one on irrigation water availability and another on conservation agriculture. NCPAMP has been followed by a range of disaster risk initiatives, coordinated by INGC.

The importance of AWM for agriculture is not always recognised. A recent review of the priorities for Mozambique focused on inputs, research, extension, credit and marketing and almost entirely neglected to refer to the role of AWM (Coughlin 2006).

Mozambique has a major District Planning and Finance Project (PPFD) that supports investment in local economic development. In theory, this ensures that local investment matches local priorities. However, one recent review asked questions about whether the procedures for prioritising paid sufficient attention to the importance of sustainability in local development investment (Penninkhoff 2009). This review reported that, until recently, local economic development was led by Local Economic Development Agencies and showed that the largest number of projects (26%) were devoted to economic governance, with enterprise development accounting for 22% and livelihoods development for 19%. It seems unlikely that AWM features strongly in LEDA expenditure.

In recent years, the role of local government has been stressed, and these have benefited since 2007, from the Local Initiative Development Budget (OIIL). Initially, this provided MT 7m /year (about USD 250,000/year) to each of the 128 districts in Mozambique, but allocations are now related to population and poverty. Total expenditure is now over MT 1000m and accounts for about 3% of government spending. Districts set their own priority and usually give the highest priority for local infrastructure. Districts also use OIIL to provide credit to farmers. No analysis of OIIL spending has yet been done, but the recent Agriculture Public Expenditure Review assumed that 50% of the OIIL funds were devoted to agriculture, which would mean that OIIL is the largest source of government funding for agricultural development (World Bank 2011).

Related Programmes and Projects in Mozambique. There have been a wide range of projects supporting rural development in Mozambique that have been involved to some extent in the promotion of micro-level Agricultural Water Management. None of these projects have yet produced a systematic evaluation of the impact of AWM on yields or incomes, although there is some partial evidence.

- The World Bank produced a Mozambique Country Water Resources Assistance Strategy in 2007, which led to the PROIRRI programme, with $70m funding 5000ha of irrigation (World Bank 2007).
- INGC are implementing a Drylands Programme (DARIDA) which addresses reduced water availability in dry areas and aims to benefit socio-economic conditions and the environment.
- PROMEC (Promotion of Local Farmer Cooperatives, 2001-05, €0.7m) in Buzi and Dondo Districts in Sofala, with Austrian funding. The project focused on opportunities for commercialising agriculture, often through farmer cooperation. The project was complemented by a €0.4m project to ORAM support land titling in the same districts, again with Austrian support.
- The Small Scale Irrigation Project (SSIP) was a $20.5m AfDB project that ran from 1999 to 2010 in Maputo, Sofala and Zambezi provinces and provided equipment, extension, credit and support for marketing.
- The Beira Agricultural Growth Corridor (BAGC) has received support from a range of donors and private sector investment agencies. It aims to coordinate projects in the Beira Corridor and also implements its own Catalytic Fund.
- The Programme for Rural Development of Mozambique (PRODER) was supported by GTZ and implemented by Sofala Province, with INGC. PRODER is a broad ranging rural development programme that includes climate change adaptation and a disaster risk management component.
- The government provides about $20m a year to a range of sectoral Fundos de Fomento (FdF), mainly in the form of cheap credit. The agricultural FdF (FDA) is the largest accounting for between 20% to 40% of the total.
- The CGIAR Challenge Programme on Water and Food has undertaken a range of surveys, including studies on IWRM, for example in Limpopo.
- ProAgri has been supported by regional projects to help build institutional capacity in the field, including APROS (€1.1m, in Sofala, with Austrian funding)

4.3 OBJECTIVES AND APPROACH

4.3.1 Objectives

Objective. The overall objective of the proposed project is to increase the resilience of small farmers to climate change, thereby increasing their food security and incomes. This will be achieved by helping vulnerable farmers to improve their agricultural water management (AWM), allowing them to cultivate a dry season crop and/or to achieve higher and more reliable yields in the wet season. Over the longer term, this will enable these farmers to accumulate savings and other resources to help them survive periods of drought and flood. The project will also improve the livelihoods of lead farmers, who will demonstrate the viability of AWM techniques to more vulnerable farmers.

4.3.2 Beneficiaries and Areas of Activity

Beneficiaries. The project will work with two types of beneficiaries:

- small farmers who are most vulnerable to climate change, including the changes associated with more variable rainfall, higher temperature and changes in CO2 and ground level ozone
- lead farmers, who are less vulnerable to climate change, but who are most capable of using AWM technologies in an efficient and profitable manner, partly because they have better access to inputs and to markets

This dual approach is justified because the lead farmers will demonstrate to the more vulnerable farmers the viability of AWM techniques. Where possible, lead farmers will be asked to provide technical support to more vulnerable farmers, potentially acting as mentors and/or commercial agents. In some cases, SPAWM will provide individual support to each farmer, whilst in other cases, some common structures and equipment may be owned by groups of farmers.

Areas of Activity. The suitability of the various AWM technologies will depend on the agro-climatic conditions, which will determine to a large extent the farming system and crops as well the availability of water resources for crop production, including rain, surface waters and groundwater. An important element of the agro-climatic conditions is the variability of rainfall, which will be affected by climate change. As discussed in section 4.2.3, the project recognises three basic agro-climatic zones (dryland areas, wetlands and uplands with valley bottoms) and has selected sites that represent these three types of agro-climatic zone.

The project will work in three main areas, or 'hubs', with an additional component that will operate nationwide.

- Mabote District, in the north of Inhambane is a dry area where small farmers are particularly vulnerable to drought. The options for improved AWM will be more limited. INGC have already been working in Mabote and have some useful experience on which to build.
- Caia District, in Zambezi Province, has been heavily affected by floods and INGC has assisted many farm households to resettle just outside the floodplain. These farmers are generally very vulnerable, with very few assets, but they do have access to good soils and the possibility of pumping water from the Zambezi River.
- The Beira hinterland is a lowland coastal wetland area with good access to markets and a good number of lead farmers. There should be good opportunities for the establishment of profitable improved AWM techniques that will help to build experience with the techniques and to establish the supply chain. Having a presence in the Beira hinterland will also help the work in Caia District, because it will facilitate the support needed to improve market opportunities for farmers in Caia.
- In addition to these three main areas, the project will work with a small number of selected private sector partners who are prepared to support AWM management amongst outgrower smallholders. The objective of this component of the project will be to establish models of outgrower AWM support for wider replication.

Figure 4-2 presents the rainfall patterns for the three regions, showing the differences in total rainfall and slight differences in seasonality.

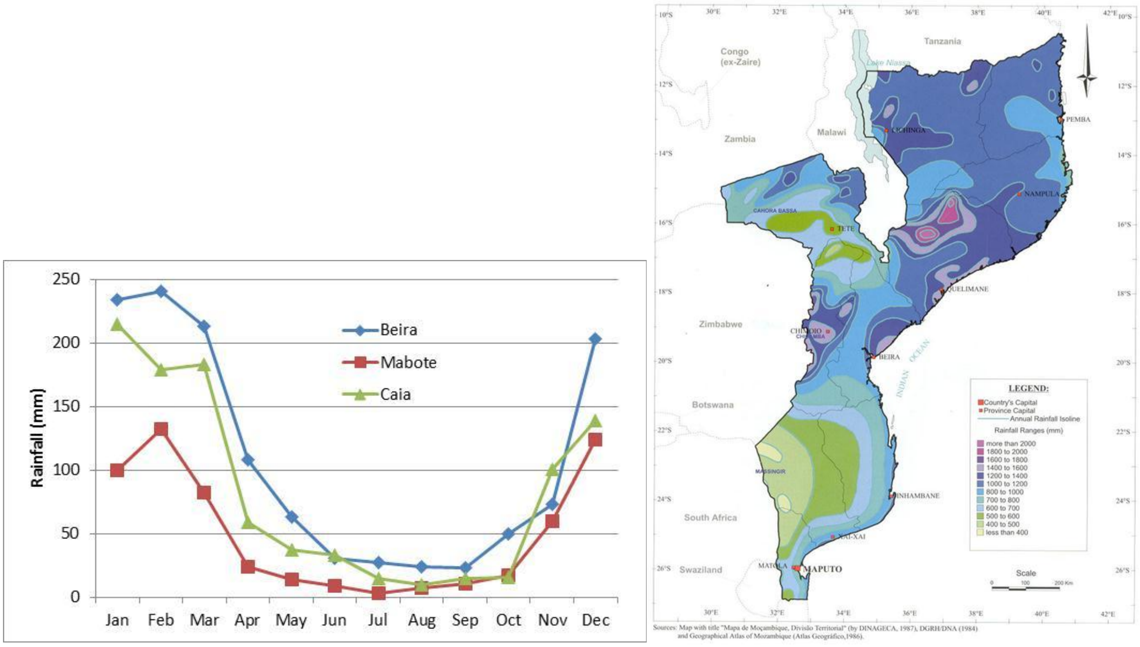


Figure 4-2: Rainfall Map and Monthly Distribution in Mabote, Caia and Beira

Source: CLIMWAT (graph) and (Brito, Holman et al. 2011)

Notes: on the map, C = Caia, B = Beira and M = Mabota

Most of the blue water AWM techniques will be used mainly for higher value crops, such as vegetables and fruit. Techniques of water harvesting and conservation agriculture are more widely applicable and should also be useful for staple foodcrops.

Production of maize is spread fairly evenly across the whole of the country, although potential yields are much higher in the north and centre than in the south, as shown in *Figure* 4-3. The two other main staples of sorghum and cassava are concentrated more in the centre and north of the country. Statistics for production by district are not available and provincial figures include a wide variety of agro-ecological zones, with many provinces covering coastal and inland areas and valley areas as well as rolling uplands that are often drier.

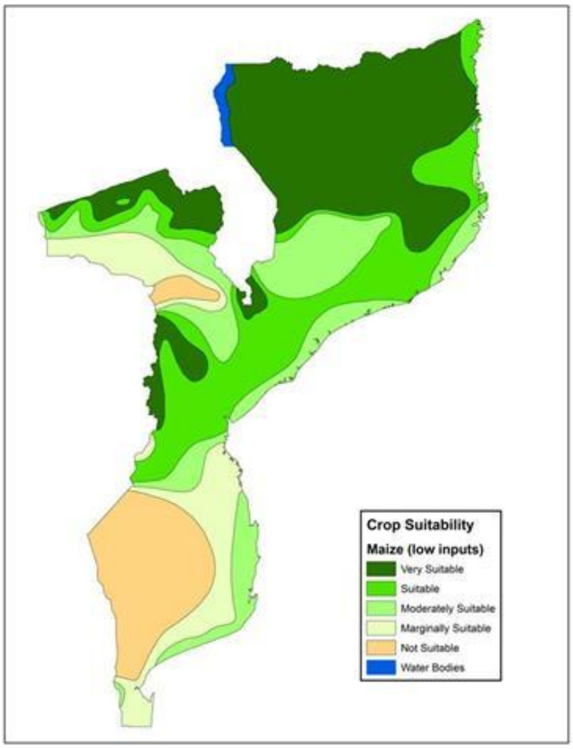


Figure 4-3: Variation in Maize Yields across Mozambique
Source: Agro-climatic suitability for maize (low input) (adapted from FAO/UNDP, 1982)

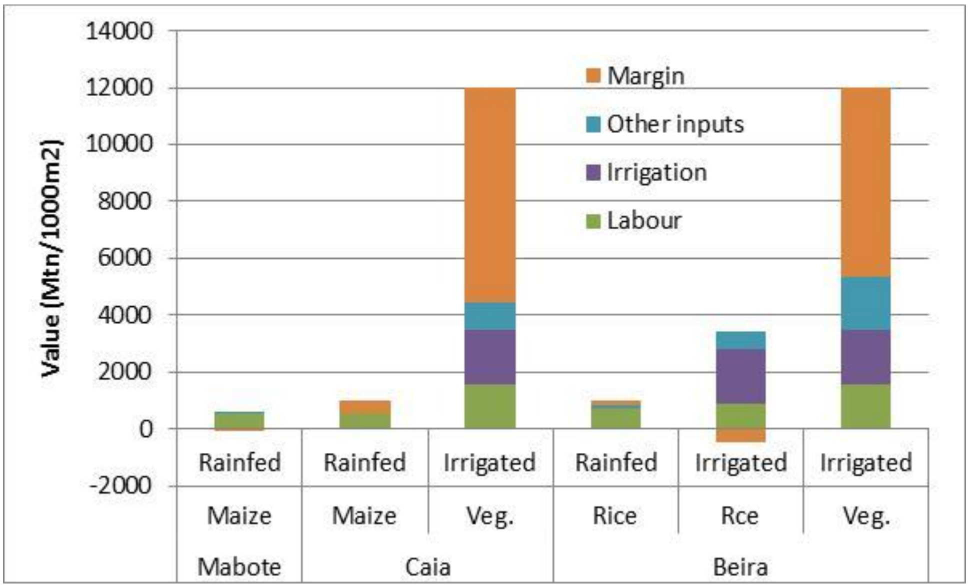


Figure 4-4: Existing Crop Costs and Margins
Source: Team estimates based on various sources

The three hubs will each operate with 15 extensionists and each extensionist will work with 3 FFSs in different locations. These will be clustered to reduce travelling times, but they are likely to be quite widely spread, in order to pick up the most promising sites. Thus, the project will be working in 135 FFSs by the end of the period. The project aims to provide support for 25 farmers in each FFS, of which 5 will be lead farmers with 0.5ha or AWM and 20 will be vulnerable farmers with 0.1ha of AWM, giving an average of 0.18ha per farmer for the whole group. Thus, the total area affected will be about 600ha. These plans are consistent with the costing and staffing programme presented in Section 4.7. This situation is summarised below:

Table 4-1: Hubs, FFSs, Beneficiaries and Hectares

			Y1	Y2	Y3
Hubs/regions			3	3	3
Extensionists			15	30	45
FFSs	3	/extensionist	45	45	45
AWM sites	3	/FFS	135	135	135
Farmers	25	/FFS	1125	1125	1125
vulnerable famers	20		900	900	900
lead farmers	5		225	225	225
Hectares	0.18	/farmer	203	203	203
vulnerable famers	0.1		90	90	90
lead farmers	0.5		113	113	113
Accumulated					
FFSs			45	90	135
Sites			135	270	405
Farmers			1125	2250	3375
Hectares			203	405	608

4.3.3 Subsidies and Cost Contribution by Farmers

Beneficiaries will not be expected to cover the full capital costs of the techniques, although the technical support provided by the project will also be available to farmers who wish to purchase AWM equipment using their own resources. For lead farmers the project will seek to obtain a 30% contribution to capital costs in advance and will provide no support to operating costs. For the most vulnerable farmers, the project will seek to obtain a 10% contribution to the capital costs and a 50% contribution to operating costs. The subsidy on operating costs will only be available for the first year. The project may agree to receive the contribution from the most vulnerable farmers after harvest. The project will not engage in formal rural credit activities, but will help beneficiaries gain access to credit for AWM from any rural finance institutions that are available.

The fact that farmers are not covering the full cost of the techniques will not prevent the project from seeking to ensure that all AWM techniques introduced have the potential to be self-financing, once the beneficiaries have worked out how best to use the techniques within their farming systems.

Box 4.1: Past experience with rural subsidies in Mozambique

The existing approach of INGC in Mabote and Caia provides inputs to farmers for free and their contribution is in terms of labour required for water harvesting and other works. This incentive is provided only during the first year, and farmers are expected to cover all future costs from revenues in the first year.

Very few small farmers benefit from formal financial services. There are about 30 micro financial institutions involved in rural finance (eg World Relief International, CCCP, CARE, Tchuma, SOCREMO and Novo Banco) but only 18% of their lending goes to agriculture and they are heavily dependent on subsidies (Coughlin 2006; Vletter 2006). However, micro-finance has been expanding rapidly and is now worth more than $50m. A recent survey suggested that 75% of operators were financially sustainable and reimbursement rates of microfinance institutions are relatively high and are often over 90% (Finscope 2009). It is therefore critical for this growing business that it is not undermined by government activities that offer quasi-credit, with little attention to securing repayment of loans. In addition to the demand for credit, there is anecdotal evidence of strong demand for services associated with savings.

The Japanese KRII programme provided about $9m annually between 1986 and 2000 to supply virtually all the fertiliser imports and about a third of pesticide imports. Recipients of the inputs were supposed to pay the full cif price of fertiliser (limiting the subsidy to the internal distribution costs) and 67% of the fob price of pesticides. The inputs were intended to benefit small farmers and were marketed by commercial farming companies. However, there was some suggestion that the companies used most of the inputs themselves and no evaluation was done of the extent to which small farmers actually received the inputs (Coughlin 2006).

4.4 AGRICULTURAL WATER MANAGEMENT TECHNIQUES

The project works with a long list and a short list of AWM techniques. The long list of techniques covers all available techniques, whilst the shortlist selects those that will be most cost effective for farmers. The majority of project effort and resources will be devoted to the techniques on the shortlist. Up to 10% of resources will be available for testing the cost effectiveness of other techniques from the long list. Any of these techniques that prove to be competitive in some situations, will be added to the shortlist and will be available for support along with the other techniques on the shortlist.

The project promotes AWM technologies for small holder farmers and does not consider small-scale irrigation schemes (5 to 200 ha) which are covered under the PROIRRI programme.

4.4.1 Available AWM techniques

AWM techniques may be classified into three groups:

- blue water (BW) techniques, which involve the capture and distribution of water to the field
- water harvesting (WH) and conservation agriculture (CA)
- brown water techniques for wetland drainage

A fuller description of the AWM techniques is provided in the Mozambique AWM Reference Book attached as an annex to this project document.

Blue Water Irrigation. A range of blue water irrigation techniques are available to the small holder farmer to supply water to his crops in periods of water shortage during dry spells and the dry season, as well to protect his crops from an excess of water from excessive rainfall or flooding (IDE 2003; Water Aid 2012). A useful summary is provided in the Review of Water Control Technologies in the FAO Programmes for Food Security, recently published by the FAO (FAO 2011).

The blue water techniques can be categorised into 5 aspects, roughly following the flow of water through the system. The following techniques will be considered by the project.

A. Water Resource

- Groundwater extraction, using ***open wells or tubewells***, which are often most efficient if lined (eg with concrete rings for open wells). These sources must be combined with some form or lifting technique, which will depend on the depth of the wells. Extraction may be constrained by seasonal changes in the water table, and this needs to be monitored to determine optimum groundwater use. These provide opportunities for off-season irrigation.
- Surface water, from ***rivers, lakes or springs***. In most cases, these require some form of lifting technique. The use of small pumps to lift water from rivers to nearby fields is the most common AWM technique. In some sites, gravity fed schemes may be possible, using diversion intake structures and with the possibility of adding small dams either as reservoirs or for supplementary spate irrigation.

B. Water Lifting

- ***Watering cans*** provide the simplest option, integrating lifting, conveyancing and irrigation in one activity. They involve little financial investment but have high labour costs.
- ***Treadle pumps*** and hand pumps are more efficient that watering cans and are relatively inexpensive. However, the rate of flow is small and they cultivate only very small areas, whilst requiring considerable labour.
- ***Moto pumps***, run on petrol or diesel, have much higher outputs than treadle pumps and are becoming increasingly cheap to purchase. Running costs are significant with high fuel costs. Moto pumps can provide suction lift up to about 7m, but can provide pressure lift (i.e. push water) up to 50m. A wide range of pumps are produced designed for different flow rates and suction and pressure lifting heights. Pumps that are used in the wrong situation can operate at very low efficiencies and can be easily damaged.
- ***Electric submersible pumps*** are more expensive to purchase than moto pumps but are cheaper to run and can be lowered into deeper wells and boreholes. They can be used at depths of more than 100m, but the volume of water produced is inversely proportional to the depth of the borehole and so it is rare for agricultural water to be pumped from more than 50m. Mains electricity is rarely available and so electric pumps can be powered either by diesel generators (which are typically used at depths of between 10m and 50m) or by solar power (which is typically used at depths of up to 20m). As with moto pumps, electric pumps are produced in a wide range of specifications and using a pump with the wrong flow rate and/or lift height can result in low efficiency and damage to the pump.
- ***Windmills*** are also able to pump from deep wells and tubewells, but are more expensive to install, are subject to variable wind regimes and can be difficult to maintain.

C. Water Conveyancing

- ***Earthen Gravity canals*** are the most common method of conveying water to the fields. They are relatively expensive and incur significant losses, especially with the small water flows involved in most micro AWM techniques. Lining the canals with bricks or cement will reduce some losses, but incur substantial operation and maintenance costs.
- ***Piped distribution*** systems provide an attractive alternative for reservoir and pumped water supply, eliminating losses and being easier to maintain. Investment is significant, but provides a good return.

D. Irrigation Methods

- Surface irrigation, with basins, borders or furrows, is the most common form of in-field irrigation, involving little investment. However, it involves high losses, due to irregular infiltration and evaporation. Land levelling and appropriate field water control can reduce losses, but involve investment. Furrows will assure a better water distribution and reduce evaporation losses.
- ***Spraying, sprinkling and dripping*** are localized irrigation methods where water is brought directly to the plants. These methods can be highly efficient. They include the watering can, as well as the well-established drip and sprinkler irrigation systems, where a pressurized pipe system water is brought to the field and crops. Losses are low, especially for drip irrigation, where fertiliser can be added to the water.

However, investment costs are high, varying from $3000 per ha for sprinkler to $6-9,000 for drip irrigation systems. Moreover pumping involves considerable energy costs, in particular in the case of sprinklers, where a water pressure of 30 meter is required.

- The ***flexible garden hose*** is an attractive alternative in the case of small pumps or a reservoir. The hose allows water to be brought to each plant from one off-take point or hydrant, with little investment. However, it requires considerable labour as the hose is moved around manually.
- A specific case of field irrigation is the ***sub-surface*** irrigation method, where through careful water level management the groundwater table is maintained within the root zone. It has been applied successful in peat soils, which require a continuous submerged condition.

E. Crop Water Management

- Irrigation scheduling is important with any blue water irrigation technique, to ensure that water is supplied to the plant at the right time and in the right quantities and depths. The design of any AWM system should start with the crop irrigation requirements. This requires detailed knowledge on climate and rainfall. There are well established procedures and computer programmes for the computation of irrigation requirements, but these are unlikely to be relevant for micro AWM. Several techniques exist to monitor soil moisture content and ensure timely irrigation applications.

Whilst farmers can adopt some of these techniques individually, it is often necessary or desirable to use a combination of techniques. Examples of such integrated schemes are presented in the table below.

Table 4-2: Examples of integrated AWM

Irrigation system	Water Resource	Lift	Conveyance & Distribution	Field Irrigation	Crop Water Management	Drainage & Flood Control
Small vegetable garden	River	Watering can	Watering can	Watering can	Calendar	Natural drainage
Vegetable garden	River	Treadle Pump	Low pressure pipe system	Hose	Calendar and conservation agriculture	Natural drainage
Dam scheme	Earthen Dam	Moto pump	Lined canal	Furrow irrigation	Rotation and calendar	Natural drainage
Wetland irrigation	Open Wells	Treadle pump	Small field channels	Short furrows	Irrigation calendar	Controlled drainage

The underlying physical performance of AWM techniques has been tested to varying degrees around the world and there is good experience of the conditions under which this performance can be achieved. However, the adoption of AWM techniques has proved to be challenging, often because of problems with integrating the techniques into existing farming systems, especially where more extensive cultivation techniques are more cost effective. New techniques have been promoted by a range of international NGOs, including: Approtec (Kenya); Enterprise Works (US); IDA (US); Practica (Netherlands); Practical Action (UK) and W3W (Switzerland). There has been some NGO activity on AWM in Mozambique (including from the Aga Khan Foundation) but most of the initiatives in the country have come from state and donor funding.

The main experience with blue water techniques in Mozambique includes: watering cans used to irrigate vegetables that have been very successful near the cities with big markets; treadle pumps which have been introduced by several aid programmes with limited success, mainly due to the technical performance and the labour needed; and portable moto pumps that have been adopted in some areas where there is a strong market but put extra pressure in terms of maintenance and running costs.

There is some experience with drip irrigation in small scale farms but usually the system is not well adopted by the farmers and is abandoned after the first or second year, perhaps because of problems with damage, maintenance or theft. Sprinkler systems are widely used in on commercial farms, as well as on some small-scale irrigation schemes. However, they are not much used by small scale farmers due to the costs and complexity and the small sizes of the farms.

<u>Water Harvesting.</u> Water harvesting involves a range of techniques to improve the proportion of rainfall that is used as crop evapotranspiration (Peacock 2005). In many semi-arid areas, over 75% of rainfall is lost to runoff and surface evaporation, but this ratio can be reduced to under 50% with effective water harvesting. Techniques include earth dams (Stephens 2010), farm reservoirs, contour bunding, circular bunds and pits. These techniques can involve micro catchments, that are easy for farmers to manage and mobilise rain falling on the fields, as well as larger schemes that bring water in from neighbouring land and often require external assistance (Awulachew, Merrey *et al*. 2005; UNEP 2005; AWF 2009; Obuobie 2010). Four broad types can be defined (UNEP 2005): i) rooftop harvesting, mainly for domestic use; ii) runoff concentration into pans or ponds; iii) storage in sand and subsurface dams; iv) in-situ storage in the soil through terracing, bunding, pitting, trenching. The FAO adopts a classification with 5 categories: micro catchments; macro catchments; flood water harvesting; storage and reservoirs; and soil and water conservation (Critchley and Siegert 1991).

There is good experience with the water harvesting in the semi-arid regions of Mozambique. This includes micro-catchment practices ranging from contour bunds, semi-circular bunds, to levelled furrows, and small basins, and the rate of adoption by the farmers that were trained is very good and they show very promising results.

The Disaster Risk Management Project (DRMP), funded by GTZ and supervised by INGC, has some experience of water harvesting. The Drought Vulnerability Reduction Component of this project has been active in Mabote and has piloted work with pitting and ridging for agriculture production, as well as with rooftop harvesting for domestic use. As of October 2011, the project had trained 570 farmers, with good signs of that many will adopt the new techniques, especially those involving trenching.

Figure 4-1: ***Ridge and Trenching***
Source: DRMP

Wider international experience with rainwater harvesting includes: projects in Tanzania with DFID support (Gowing 2000; NRSP 2007); projects in Rwanda, Djibouti and South Africa, with AWF support (AWF 2006); work in Ethiopia (Awulachew, Merrey *et al*. 2005); and research in Malawi (Chilimba and Liwimbi 2009).

Conservation Agriculture. Conservation agriculture involves a range of agricultural techniques that allow for an increase in organic matter in the soil, which improves soil moisture infiltration and retention and increased fertility. Soil texture is improved by maintaining a continuous green cover, avoiding cultivation and using mulch to reduce evaporation. Cropping intensity is increased by introducing a second or third crop, where possible. Additional benefits are also provided from reduced soil erosion and labour savings, especially on land preparation. Conservation agriculture requires a package of interdependent farming practices, taking into account the whole farming system, including livestock (Dambiro, Xavier *et al*. 2011; Mazvimavi 2011; Milder, Majanen *et al*. 2011).

Conservation agriculture is expanding rapidly in many countries, with more than half the crops in Brazil grown under zero tillage and strong growth in Australia and the US. Experience in Africa has been more mixed, but the potential is demonstrated in many projects (see Box 4.2).

A Conservation Agriculture Working Group has recently been formed in Mozambique, chaired by IIAM (with support from the Platform for Agricultural Research and Innovation, funded by USAID), with participation from DNEA in MINAG, the International Centre for Tropical Agriculture (CIAT), the International Maize and Wheat Improvement Centre (CIMMYT), the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), the International Fertiliser Development Centre (IFDC), CARE, World Wildlife Fund (WWF), International Relief and Development (IRD), Clean Star Mozambique (CSM), the Food and Agricultural Organisation (FAO), Michigan State University and the Alliance for Green Revolution in Africa (AGRA). The IIAM website now includes a section on Conservation Agriculture that includes references to 11 reports and 27 presentations. A major national seminar was held in March 2012, attended by 70 participants, and reaching conclusions on actions and research priorities (Nhamusso 2012).

The techniques that are most commonly used in Mozambique have been described in a recent manual produced by FAO. This explains the principles and the key activities and describes various models, mostly involving an early crop of beans, followed by a main crop of maize. The models also allow a third crop (typically sesame or sunflower) to be cultivated in some areas, germinating beneath the maize. The dry season can be used either for irrigated crops or for mulch.

Box 4.2: Experience with Conservation Agriculture in Mozambique and in Africa

The FAO have been supporting conservation agriculture in Mozambique for over 10 years through a series of projects supported by the Jimmy Carter Foundation and the Nippon Centre (2000 in Manica and Sofala), the Italian Food Security Programme (2005 in 12 Districts in Manica, Sofala and Maputo), the South African Government (2007 in 11 Districts in Inhambane, Gaza and Tete) and NORAD via CAADP (2008 in 12 Districts in Cabo Delgado, Inhambane, Zambezi and Tete). Projects have used the Farmer Field School (FFS) system, training over 600 extensionists and 50,000 farmers directly and a total of 150,000 (or 3% of all farmers), including indirect contact. Over 100 conservation agriculture models have been developed spanning all 10 agroecological zones. Many of these involve crop rotations that achieve 2 and even 3 crops per year from a six month growing season. FAO uses a budget of $ 300 /ha/season for establishing conservation agriculture in FFS plots and provide seeds and some assistance with equipment for participating farmers. They also provide $10 /day for the extra expenses of extension workers. There has been limited assessment of the benefits achieved through conservation agriculture.

A range of projects have been active in promoting conservation agriculture in Sofala over the last 10 years, in collaboration with the Provincial Directorate of Agriculture (Ministry of Agriculture), including: PRODER (funded by GTZ), PROMEC (2001-03 funded by Austria), PACDIB and APROS (funded by Austria). The results suggest that: yields increased up to 30%; irrigation requirements fell by 60%; weeding labour fell by up to 90%; and soil preparation labour fell by close to 75% (Taimo, Calegari *et al*. 2006).

The Aga Khan Foundation (AKF) has provided support for conservation agriculture under the Coastal Rural Support Programme (CRSP) in five Districts in Cabo Delgado that are at least partly in the Quirimbas National Park (Dambiro, Xavier *et al*. 2011). The first demonstrations were done by lead farmers in the 2008/09 season in 135 villages with 35,000 families, focusing on zero tillage and the use of mulch to increase infiltration. This was elaborated in the 2009/10 season to include micro basin water harvesting and 120 farmers cultivated a total of 15.5 ha, with each farmer supporting a Farmer Field School for the exchange of experience with neighbours. There has been an immediate increase in yields of maize from 0.8 t/ha/seasonto 1.2 in Y1, 1.8 in Y2 and 3.2 in Y3 mainly because of the improved soil moisture associated with mulching. Other crops, such as cowpea and mung bean have also experienced significant yield increases. The improved soil moisture improves resilience to dry spells and has extended the growing season by one or two months. In addition, there has been a 75% reduction in the labour needed for weeding, which previously accounted for 15% and 45% of total labour requirements.

CARE/WWF have run a project in Angoche and Meconta Districts in Nampula for four years, with two years' experience in conservation agriculture (Grabowski 2011). The yield and labour saving benefits are less obvious than with the AKF project, perhaps because of differences in soil and because the staple crop is cassava which requires the land to be disturbed during harvest. As with the AKF, the CARE/WWF projects are guided by a wider objective of encouraging sustainable agriculture in order to reduce pressures on other natural resources to were threatening natural ecosystems. In both cases, fire can destroy mulch cover and some areas have created fire breaks.

Recent research to evaluate the performance of conservation agriculture in the Angonia highlands in Tete examined two NGO projects, supported by Igreja Reformada and Total Land Care, and concluded that the net profits from conservation agriculture were mixed (Grabowski 2011). There was some suggestion that benefits were dependent on the use of inputs and that labour requirements were also higher. As a result, farmers considered conservation agriculture as suitable for small 'insurance plots' or for higher value crops.

CIMMYT and ACIAR have led the 2 year SIMLESA research project into conservation agriculture techniques in Southern Africa. This included working in 6 districts in Manica, Tete and Sofala, with collaboration from IIAM. In each district, trials were run with 6 farmers, each provided with an incentive package of inputs and conservation agriculture equipment, plus a further 5 in a local research committee. Success was strongly dependent on the quality of extension. There were early problems with the availability of mulch and problems with weeds and termites. The impact on yields is not yet clear.

A recent review of experience with conservation agriculture in Southern Africa concentrated on Zambia and Zimbabwe and concluded (Mazvimavi 2011). This found that maize yields under conservation agriculture were 42% higher than conventional farming techniques in Zambia and 105% higher in Zimbabwe. Gross margins for conservation agriculture were three times those of conventional farming in both countries. Conservation agriculture is widely known in both countries and equipment is generally available. In both countries, it is the most vulnerable farm households that have been targeted for conservation agriculture promotion. This may be appropriate, given the success of conservation agriculture in improving household food security and because vulnerable households often have severe labour shortages, especially if affected by HIV/AIDS. However, the review concludes that importance of conservation agriculture for more resources rich households should not be neglected. The experience is Brazil suggests that conservation agriculture can be very rapidly adopted by larger farmers, which would have a major impact on national food security and climate resilience.

Another review of conservation agriculture across the whole of Sub Saharan Africa (SSA) finds that it has been generally successful in increasing yields (especially in the mid to longer term but also, often, in the shorter term), increasing profits and reducing labour (Milder, Majanen *et al*. 2011). The SSA review quotes global reviews suggest that conservation agriculture yields are 20% to 120% higher than with conventional agriculture, but reports evidence from Africa suggesting that the yield increases are often even higher, with many countries reporting doubling and trebling of yields (eg in Kenya, Ghana, Tanzania, Uganda, Malawi and Zambia). Profitability increases of between 80 and 200 $/ha/season are common. Despite this success, it is still used on less than 1m hectares in SSA and this accounts to less than 1% of the global total use of conservation agriculture. Most of this use is by commercial farmers with Ghana and Zambia having the largest numbers of small farmers. The review suggests that the main problems are associated with learning new practices, integrating livestock with cropping systems and different incentives for men and women. The review concludes that the most important contribution of conservation agriculture to climate mitigation is through reduced pressure on deforestation and that conservation agriculture projects need to be of longer duration, with more flexibility than conventional projects.

There is also some useful experience in Zimbabwe and some exchange with these initiatives culd be useful for Mozambique (Twomlow, Urolov *et al*. 2008; Marongwe, Kwazira *et al*. 2010).

A recent review of 26 long term studies involving no-till practices in rainfed production considered evidence from the US, Canada, Brazil, Mexico, Nigeria, Zimbabwe, Australia, India, China and Italy (Rusinamhodzi, Corbeels *et al*. 2011). The analysis looked at the effect of soil type, rainfall, tillage, mulching and fertiliser on rainfed yield and suggested that there is a wide variation of results. Zero tillage appears to increase yields, compared to conventional tillage, when rainfall is low (<600mm) but to decrease yields with high rainfall (>1000mm). The impact of zero tillage is improved when it is combined with crop rotation. There is no clear effect of mulching practices, although some studies suggest that they have a positive effect in drier areas, but can be counterproductive in wetter areas, due to risks of waterlogging. There is some suggestion that zero tillage improves yields in loamy soils but reduces yields in clay soils. The effect in sandy soils is not marked and only starts to be felt after five years. The studies suggested that there was a very strong relationship between yield and rainfall and that the regression coefficient was not greatly different for zero tillage and conventional tillage. The most promising results from zero tillage were achieved when fertiliser was applied. The study concluded that, for Southern Africa, conservation agriculture needs to be promoted carefully and flexibly, in the right climate and soil conditions, with crop rotations and access to inputs and with sensitivity to the demands of livestock.

Wetland Development. In addition to the above techniques, wetland development includes simple water control structures, with field bunding and levelling, drainage and flood protection works, retention reservoirs, micro-irrigation technologies, shallow wells and small pumps. The designs and costs of wetland development are highly specific to the location.

Advantages and Disadvantages. The advantages and disadvantages of the main techniques are summarised in *Table* 4-3.

Table 4-3: Summary Description of Suitability, Advantages and Disadvantages of AWM Techniques

Techniques	Requirements	Constraints
Low cost well development	• favourable hydro-geological conditions, with water table less than 15m • training of local drilling teams • development market	• well development costs
Watering can	• water source close by (river, open shallow wells) • minimal investments • watering cans commercially available	• high labour input
Treadle pump	• water source not deeper that 7m • capacity building for local manufacturing • development market	• labour costs
Moto-Pump	• surface/ground water, suction lift of less than 7m • financial independence • moto pump commercially available • access to markets for produce	• investment costs • operating costs
Solar pumps	• water source not too deep • construction of water reservoir • commercially available and local services	• low discharge, small areas • high investment
Low pressure pipe distribution system	• moto pump or treadle pump available • small reservoir • assistance for installation by local technicians	• installation costs
Drip irrigation	• limited water resources available • reservoir and pressure height • trained staff for installation and management	• high installation costs (though low operating costs)
Sprinkler irrigation	• pumping from nearby water source • commercially operated farm	• high installation and operating costs
Wetland development	• adequate water resources available • technical and socio-economic feasibility studies • adequate assistance from trained advisory services • intensive farmer training for some techniques	• social conflicts • motivation of water users for cooperation • ecological damage
Water harvesting	• arid zones • no or limited surface or ground water • extension available and farmers sufficiently skilled	• high land formation costs • some maintenance costs, depending on techniques
Conservation agriculture	• strong farmer networks and extension • access to herbicides in some systems • access to mulch • ability to control competition from livestock	• potential yield losses during transition period • investment in skills and adaptation capabilities

In addition to the above table, a number of other practical issues are important in Mozambique:

- 'Divisibility' referring to the ability of the system to be used in many small plots, including both the technical suitability (eg portability) and the need for management cooperation (eg sharing of costs, depending on ownership)
- The need of outside specialist skills (eg for maintenance, management and operation) and the availability and cost of these specialist skills, for example, from local agents
- Ruggedness of the system, risk of breakdown and seriousness of implications in terms of potential crop failure

4.4.2 Costs of AWM Techniques

Blue Water Irrigation. The primary criteria for shortlisting techniques is cost per hectare, as presented in *Table* 4-4. Identifying the best options is not a simple exercise as it depends on the combination of techniques used for the different stages of water supply, which in turn depends on the physical conditions of each site. The SPAWM project identifies three blue water packages that are expected to be the most attractive, as described in 4.4.

Table 4-4: Cost of Blue Water AWM Techniques

	Investment in Equipment				Operation Costs				Total I&O
	Cost	Life	Area	Depreciation	Maint.	Labour	Fuel	Total	
	$	yrs	ha	USD/ha	USD/ha/yr				USD/ha/yr
Water resources development									
Groundwater development									
Open wells (15m deep, 60cm wide)	515	12	1.0	$43	0	0	0	$0	$43
Shallow tubewells (15m deep, 5cm wide)	397	12	3.0	$11	0	0	0	$0	$11
Deep tubewells (50m deep, 10cm wide)	7,150	20	5.0	$72	0	0	0	$0	$72
Surface water development									
Small dams (50m long, 3m high, 44K m3)	50,793	24	5.9	$361	31	0	0	$31	$392
Diversion weirs	15,000	24	5.0	$125	31	0	0	$31	$156
Waterlifting									
Watering can (20lt, 50m to field)	6	2	0.0	$91	0	1,611	0	$1,611	$1,702
Treadle pump (6m height)	140	8	0.2	$80	32	368	0	$400	$481
Moto-pump (4hp, 8m height) + furrow	1,140	10	3.7	$31	10	0	312	$322	$353
Moto-pump (4hp, 8m height) + hose	1,140	10	5.3	$22	7	0	220	$227	$249
Electric pump & diesel generator (12m)	1,908	10	2.8	$68	10	0	403	$413	$481
Solar pump (800W, 10m height)	7,940	20	1.1	$377	8	0	0	$8	$384
Conveyance system									
LP-pipe + treadle	126	12	0.3	$34	2	0	0	$2	$36
LP-pipe + moto	1,301	12	4.4	$25	1	0	0	$1	$26
Gravity canal	800	12	2.0	$33	7	0	0	$7	$40
Irrigation method									
Hose + treadle	42	8	0.3	$17	2	139	0	$141	$158
Hose + moto	194	8	4.4	$6	1	138	0	$138	$144
Drip irrigation (large family kit)	1,846	8	0.3	$923	46	0	0	$46	$969
Sprinkler irrigation (20hp)	9,000	10	2.7	$329	49	0	1,059	$1,108	$1,437
Surface irrigation method	400	4	1.0	$100	20	160	0	$180	$280

Notes: irrigation efficiencies are determined by the irrigation method – except where specified efficiencies for water resources, lifting and conveyancing assume use of piped conveyancing with hose irrigation (ie 85%).

The cost estimates require assumptions about the efficiency of irrigation and the height of water lifting. Efficiency is determined largely by the conveyancing system and irrigation method. Efficiency in a conventional gravity system with earthen canals and surface irrigation will not exceed 60%. Where conveyancing is by pipes and irrigation is by flexible hose or by drip or sprinkler, irrigation efficiency is about 85%. The cost of water lifting is directly proportional to the height lifted. Typical ranges over which the techniques operate are: treadle pump <7m; moto pump <7m, for suction height; electric pumps (by generator or solar) 10-100m.

The composition of costs varies considerably for the different techniques. For well development and conveyancing, the costs are mainly depreciation. For water lifting, the main costs are either labour (for watering cans and treadle) or fuel, for all pumps except solar, where the main cost is depreciation. Field irrigation techniques are mixed, with labour dominating for hose, capital dominating for drip and fuel dominating for sprinkler.

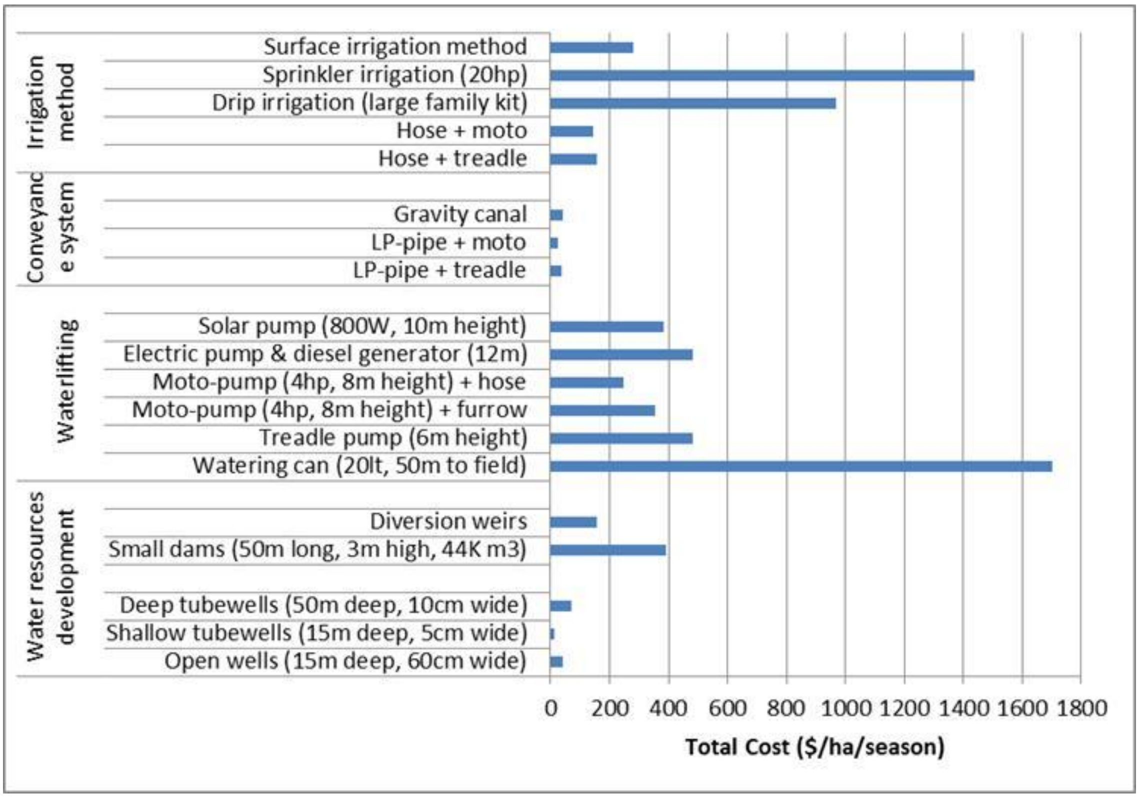


Figure 4-6: Costs of Blue Water AWM Techniques
Source: see Table 4-4

For pumps, the costs are inversely proportional to the depth from which water is pumped, but different pumps operate at different depths. The range of costs are presented in *Figure* 4-7. These figures assume that labour is valued at 1 $/day, which is lower than the market rate of manual labour in Mozambique. This reflects the fact that some households will have family members for which time is valued at lower rates, for example, if households consider that the value of children attending school to be relatively low. Farmers who have very small plots of land may consider the watering can to be the cheapest solution because they are unable to organise collaboration with other small farmers in the use of AWM techniques that are able to cultivate larger areas.

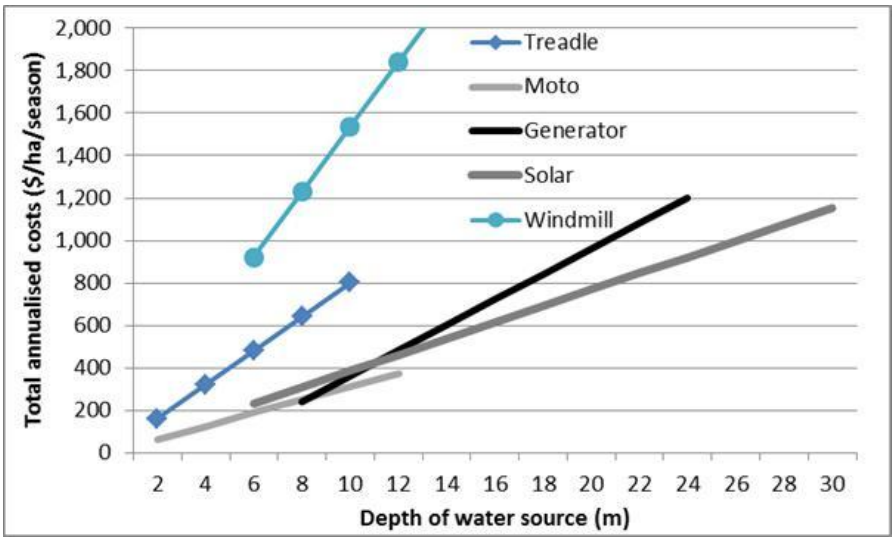


Figure 4-7: Costs of Pumping Options

The following general principles can be drawn from the above table and graphs.

- The most common AWM technique in Mozambique is the watering can. This costs about 1700 $/ha/season, assuming labour is valued at 1 $/day and water is 25m from the crop.
- Using a treadle pump, with pipes and hoses costs about 680 $/ha/season.
- The common practice of using moto pumps to lift water from rivers, combined with canals and furrow irrigation, costs about 670 $/ha/season. This can be reduced to about 420 $/ha/season, if pipes and hoses are used.
- With suction lift of 5m to 7m, plus some additional pressure lift, it is possible to use either a moto pump or an electric pump. In this range, the electric pump (powered either from a diesel generator or by solar power) is about 80 $/ha/season more expensive than a moto pump. Electric pumps can operate at much higher depths.
- The cost of wells and piping is relatively small. If surface water is not available and an open well or shallow tubewell is required, the costs are increased by up to 43 $/ha/season, but this is roughly equivalent to savings in pipes or canals.
- Drip irrigation costs nearly 1000 $/ha/season, excluding water lifting and conveyancing and sprinkler irrigation is over 1400 $/ha/season.

Water Harvesting. The DRMP project has been establishing trenches in plots of 1000m2, taking about 3 weeks for one person. The project provides a package worth Mtn 1500, including tools, 1kg of maize seed and 1m3 of cassava planting material. The investment costs are 550 $/ha, assuming that the tools account for Mtn 500 and that labour is relatively scarce in semi-arid areas and so is valued at 2 $/day. There is no need to depreciate this investment, as the water harvesting features do not require replacement. However, the investment involves significant one-off costs and the annualised cost of these is estimated by assuming that the opportunity cost of the capital involved is 20% per year, equal to 110 $/ha/year. There are also substantial maintenance demands, which are assumed to be 55 $/ha/season, giving total costs of about 140 $/ha/season.

This is roughly consistent with experience in other African countries. *Table* 4-5 summarises the results reported in a recent review (van Koppen, Namara *et al*. 2005). The capital cost per hectare of the techniques ranges from 94 to 5000 $/ha and the Benefit Cost Ratio ranges from about 0 to 1.8, at best. The review concludes that there is limited scope for successful use of water harvesting.

Table 4-5: Examples of African Water Harvesting for Crop Production

Type	Countries	Crops	Design	Capital Cost ($/ha)	Benefit Cost Ratio
Majaruba basins	Tanzania	Paddy	bunded basins of about 200m2	94	0.6
Planting pits	Kenya, Tanzania	Fruit trees	30cm diameter pits of soil and mulch		
Contour barriers	Kenya, Tanzania	Field crops	slow down runoff and increase infiltration	369	0.3
Negarim trapezoidal bunds	Kenya	Sorghum	concentrate runoff onto fields	750	-0.1
Tied ridges	Zimbabwe	Field crops	1.5m spacing between ridges		
Brick storage dams	Kenya, Burkina Faso	Vegetables	storing runoff	5000	0.5
Subsurface tanks (silanga etc)	Kenya and elsewhere	Vegetables	RELMA, Practica …	182	1.8

Source: (Peacock 2005)

Conservation Agriculture. Because of the variety of techniques involved in conservation agriculture, it is not easy to estimate general figures for the costs involved.

Experience in Africa appears to suggest that there are two types of costs in establishing conservation agriculture: in the first type, yields drop in the first few years when crops are vulnerable to weeds, soils have not yet improved and farmers are unfamiliar with all the techniques to respond rapidly to challenges; and in the second type, the costs are mainly the labour required to establish a mulch cover. With either type, there is some agreement that it take 4 to 7 years to reach the full benefits, with the transition period being shorter in hotter climates. In the first year, yield losses of up to half are common, with some reduced costs and some additional costs for weed control. The analysis assumes that a net loss of income equivalent to 40% of yields occurs in the first year and a loss of 20% in the second year. By the third year, yields have returned to those achieved with conventional agriculture and there are improved yields from year 4 onwards.

The investment costs of other AWM techniques must be depreciated because replacement equipment must be bought. However, the costs of reduced yield during the transition period in conservation agriculture are a one-off cost that does not recur and should not therefore be depreciated. It is not straightforward to express these one-off costs in $/ha/season, to make them comparable to those of the blue water and conservation agriculture techniques. The lost yield can be an extremely serious cost, especially for households that are highly vulnerable and where lost yield can pose irreversible threats to the livelihoods of the household members. The analysis assumes that the annual equivalent cost of the one-off transition costs is determined by the real opportunity cost of capital in rural areas, which is assumed to be 20%. The annualised cost of lost yield in the first two years is thus estimated to be 12% of the value of normal annual crop value. For maize in Caia, this equates to 160 $/ha/year.

There are also some investment costs required for simple equipment. The FAO have assumed that the costs of establishing a hectare of conservation agriculture are $300, including $50 for planting equipment, plus the costs of inputs and of bringing in mulch, where this is not freely available locally. These are at least partly offset by lower costs for land preparation and fertiliser, because of the higher soil fertility, so that the net effect is to reduce farm costs, at least in the medium term.

From the perspective of Mozambique as a whole, the costs of supporting farmers networks (such as Farmer Field Schools) and extension services are likely to be as large as the costs of lost yield in the transition years. These are taken into account in the project economic analysis.

Bunding and Drainage. The costs of bunding and drainage will vary according to local conditions. However, some indicative costs can be provided. Rice field bunding is comparable to water harvesting field operations, costing about 550 $/ha. Drainage and flood protection involves drainage canals and protection dikes, which will be very varied, especially if flood protection dikes and sluice gates are needed. However, it should be possible to limit these costs to about 600 $/ha. The project budget includes a total cost for bunding and drainage of about 1100 $/ha.

4.4.3 Benefits from Crop Yield and Farm Incomes

AWM in the Dry Season and Wet Season. The project will support cultivation in the dry season and will provide supplementary irrigation in the wet season.

In the dry season, the availability of blue water irrigation makes it possible to cultivate a crop when this would not otherwise be possible. As a result, the full margins achieved on the crop can be attributed as a benefit to AWM. The cultivation of irrigation vegetables is much more effective in the dry season, because wet season vegetables are much more vulnerable to pests and diseases. Where it is possible to market dry season vegetables, these provide the highest returns.

In the wet season, the project will provide blue water irrigation techniques that can increase yields in dry areas and can protect crops in wetter areas, when there are short dry spells or extended droughts.

In some cases, the same blue water investments can be used for both dry season and wet season cultivation. Water harvesting applies only to wet season cultivation. Conservation agriculture is a special case because it allows the wet season to be extended and makes it possible to cultivate two or three crops during the wet season.

Figure 4-8 summarises the margins to be achieved in the dry and wet season for vegetables and for maize or beans, assuming that irrigation is provided to meet basic crop water requirements. The cost of irrigation declines with rainfall, as less water is required and the operating costs go down. In a normal wet season, no irrigation is required. The margins for maize/beans, excluding AWM costs, are the same in the dry and wet season. However, for vegetables, the margins decline with rainfall because of the increased stress from disease and pests.

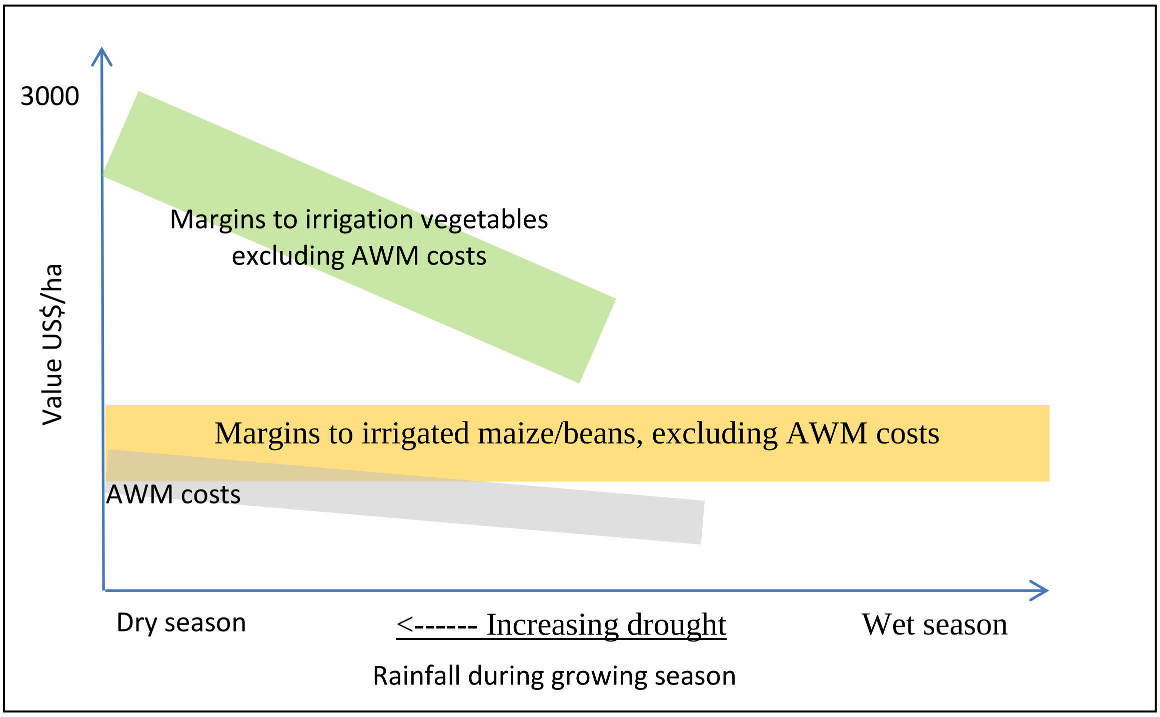


Figure 4-8: Margins and AWM Costs for Vegetables and Maize/beans

The figure suggests that irrigation is highly profitable for irrigated vegetables in the dry season. For maize and beans, the situation is more marginal. Supplementary irrigation in mid-rainfall seasons does give positive returns. However, in dry seasons, the volume of water required to cultivate maize and beans is such that AWM costs take all available margins and no net margin is made. This is consistent with findings in the literature that supplementary irrigation for maize and beans can be profitable in some circumstances (Falkenmark and Rockstrom 2004; Oweis 2009).

Crop Response to Water. Crop response to water or crop water productivity is generally expressed as a crop specific water efficiency term that quantifies productivity as the ratio of yield to water input and can be expressed in kg/m3, or kg/mm for a specific area (eg 1kg/m3 is equal to 0.1kg/mm for an area of 1 hectare, or 0.01kg/mm for an area of 1000m2). Cereal crops under high yield varieties with optimal inputs can achieve 1.0 up to 2 kg/m3. For most rainfed cereals CWP values vary between 0.4 to 1.0.

Crop water productivity typically shows a sigmoid, or S-curve, specific to each crop and variety and shows the genetic capacity to adapt to different nutrient and water regimes, as well as weed and pest challenges As shown in *Figure* 4-9, rainfed crops adapted to low and erratic rainfall patterns and low inputs have a flat CWP relationship, still producing a yield under failing rains, but have a limited production potential under optimal rainfall conditions. High input irrigated crop will achieve very high yields but are very sensitive to water stress or fertility stress and fail where rainfed crop can still produce.

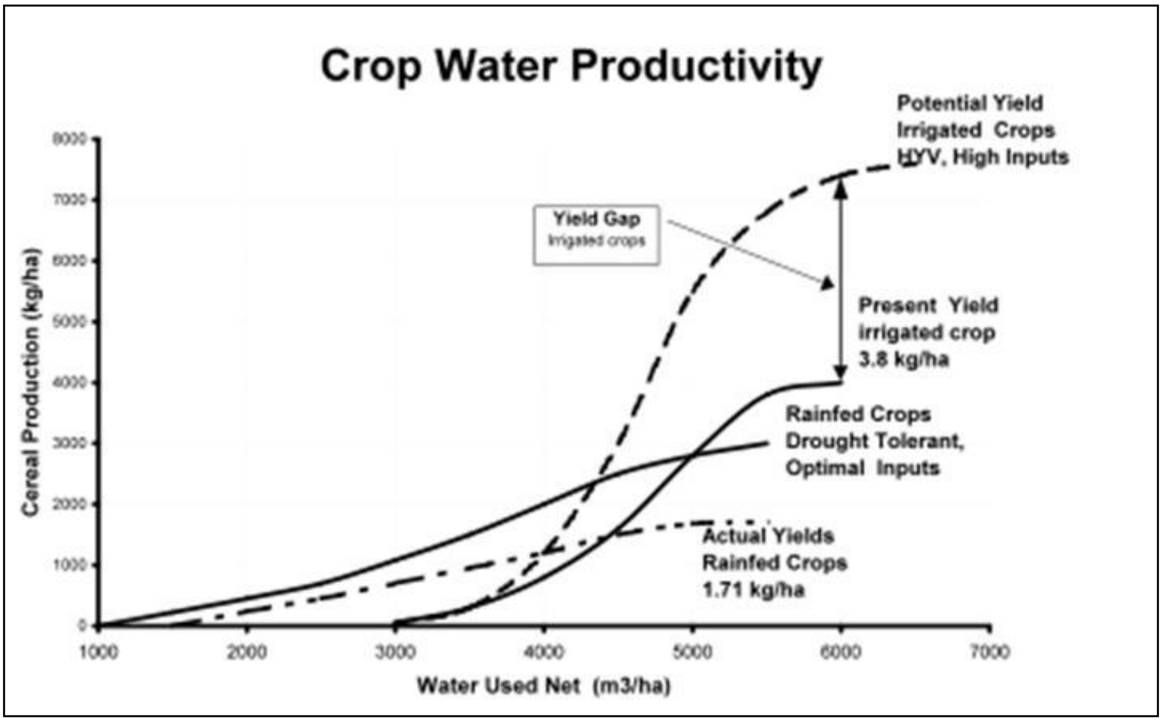


Figure 4-9: Crop Water Productivity in Rainfed and Irrigated Crops
Source: (Smith 2002)

There is limited information available on the relationship of yield to water for rainfed and irrigated crops in Mozambique. For grain crops, typical water productivity in rainfed conditions ranges from 0.4 to 1.0 kg/m3, but this can be 50% higher with improved rainfed varieties, with fertiliser and supplemental irrigation that helps crops survive dry periods of water stress (Falkenmark and Rockstrom 2004; Oweis and Hachum 2009). For irrigated vegetables, the PROIRRI crop margin tables give some evidence of expected yields and show that water productivity is typically 1.3 to 1.6 kg/m3 for rainfed vegetables and up to 3.0 for irrigated vegetables. However, crop water productivity for vegetables is highly variable, especially in rainfed conditions.

In rainfed agriculture, ETa is closely linked to effective rainfall, which takes into account rainfall losses to surface runoff and deep percolation. Although the relationship is complex, as a rough rule of thumb in Mozambique, crop water use will normally use 50% to 70% of rainfall. This means that average ETa for rainfed crops in Mozambique is about 300mm to 500mm for a growing season of 120 days. In practice, it is difficult for small farmers to calculate crop water requirements and the volume of water used for irrigation is usually either too low or, more commonly, too high. A typical dry season irrigation application of micro level AWM might involve 400mm of plant ETa (ie after accounting for losses). Depending on the location and season, there might also be small levels of rainfall available to bring total ETa to about 500mm.

Table 4-6 shows the response of yield (Y) to additional crop evapotranspiration generated from improved AWM.

Table 4-6: Crop Response to Water (1000 sq.m plot)

		Mabote		Caia		Beira	
		Maize	Vegetables	Maize	Vegetables	Rice	Vegetables
		wet	wet	wet	wet	wet	wet
Rainfed yield	kg	60	400	130	600	100	650
Yield with AWM	kg	140	700	260	1200	300	1300
Water Response							
Rainfall	mm	249	249	409	409	500	500
AWM applied	mm	100	100	300	300	300	300
Crop response							
Rainfed	kg/m3	0.24	1.61	0.32	1.47	0.20	1.30
Rain + AWM	kg/m3	0.40	2.01	0.37	1.69	0.38	1.63
AWM marginal	kg/m3	0.80	3.00	0.43	2.00	0.67	2.17

The basic principles of response to water are described in FAO Irrigation and Drainage Paper 33, introducing a simple linear relationship between yield and crop evapotranspiration, due to water stress. The linear relationship is expressed by a Yield Response factor (Ky). Crops sensitive to water stress such as maize have a Ky factor larger than 1, while more drought resistance crops show Ky values between 0.4 to 1.0.

The concepts and procedures presented in FAO24, 33 and 56 have been introduced in a series of models that allow ready calculations of crop water demand, crop irrigation requirements, effective rainfall, actual crop evapotranspiration and yield reductions due to reduced water supply (see Box 4.3).

Box 4.3: Analytical Methods for Assessing Impact of Water Availability on Crop Yield

FAO Irrigation and Drainage Paper 33 presents procedures to estimate crop yield from actual crop evapotranspiration (ETa). Procedures for crop water requirements (ETc) were first presented in the FAO I&D No 24 (1977) with potential or reference evapotranspiration (ETo) determined from climate conditions. Revised procedures for estimating reference transpiration were presented in FAO I&D 56 (1996), based on the Penman Monteith equation for estimating reference ET, with further refinements to estimate crop transpiration and soil evaporation. The FAO Penman-Monteith method has become the world-wide standard for crop water requirement calculations.

The FAO procedures have found wide applications and a large number of models have been produced, based on the FAO I&D papers, largely for irrigation management. These models have also been used to examine the implications of climate change on crop yields. The most widely used model has been the FAO CROPWAT model (FAO I&D 46), which integrates calculations procedures based on FAO I&D 33 and 56. CROPWAT has proved useful for general planning, design and operation of irrigation projects and for the rapid assessment of yield reductions under limited water supply. It has found wide applications from water supply allocation among crops during periods of water shortage to various studies at national or regional scales, where generalized crop conditions prevail. CROPWAT has now been superseded by AQUACROP, which takes into account the improvements in FAO I&D 56.

A further review to update procedures for the Yield Response functions was initiated by FAO in 2000 and will be concluded with the publication of FAO I&D paper No 66 in 2012. This includes the presentation of AQUACROP that presents a dynamic crop water response model that simulates crop growth and crop development based on crop transpiration and water availability in the root zone. A range of crop dependent parameters allow detailed simulation of the growth processes and impact of water and fertility stress on yield, but require a more sturdy calibration. Practical applications of AQUACROP for climate change studies are now starting to emerge.

Climate studies in Mozambique have used the CLICROP model (eg in the EACC study and INGC Phase II), which is similar to CROPWAT but adds more detail on surface runoff, deep percolation and waterlogging. In addition to the above, it has been common to use the DSSAT modelling framework that uses different models (eg CERES, SUBSTOR and CROPGRO) for different crops. The results of these are reviewed in Section 4.2.3.

Farm Margins. The benefits to farmers are determined by the impact of AWM on farm margins. *Table* 4-7 shows crop margins for maize, rice and vegetables in each of the three regions where the project will operate. The figures for vegetables are a rough average of onion, tomato, potato and cabbage. For each crop, the table shows the margins for rainfed and for irrigated dry season cultivation. In practice, there are wide variations in farm margins, both between and within regions and the figures in the table should be considered as indicative.

Table 4-7: Crop margins per hectare

		Mabote		Caia		Beira	
		Maize /beans	Vegetables	Maize /beans	Vegetables	Maize /beans	Vegetables
Labour price	$/day	1.00	1.00	1.00	1.00	1.00	1.00
Rainfed							
Yield	kg	600		1300		1000	
Crop price	$/kg	0.40		0.40		0.35	
Labour	days	150		150		150	
Crop value		240		520		350	
- Labour costs		150		150		150	
- Other inputs		10		100		100	
= Margin		80		270		100	
Irrigated							
Yield	kg	2800	7000	2800	12000	2800	13000
Crop price	$/kg	0.48	0.40	0.48	0.33	0.42	0.37
Labour	days	150	373	150	640	150	640
Crop value		1344	2800	1344	3960	1176	4810
- Labour costs		150	373	150	640	150	640
- Seed/fert		100	281	100	481	100	481
- Other inputs		180	324	180	556	180	556
= Margin excl AWM		914	2103	914	2283	746	3133
as % of crop value		68%	75%	68%	58%	63%	65%
- AWM costs		618	480	618	618	618	618
= Margin incl AWM		296	1623	296	1665	128	2515

Source: team estimates based on the PROIRRI appraisal (World Bank 2011) and (Oweis and Hachum 2009) adapted for micro AWM costs developed in this study and updated labour costs. The PROIRRI crop budgets are generic budgets for two areas: irrigated highlands/midlands, which are most relevant for Mabote, and irrigated lowlands, which are more relevant to Caia and Beira. In practice, a very large range of yields is achieved in any one location, dependent on the specific soil characteristic and farming skills. Thus, the crop budgets can only be treated as indicative estimates.

Estimates of typical yields, labour, seed, agrochemicals, machinery and tools are taken from the WB Appraisal document for the PROIRRI project. Irrigation costs are taken from section 4.4.2., assuming option A, with moto-pump, piped conveyancing and hose irrigation. The following conclusions can be drawn.

- Margins for vegetables in Caia and Beira are 1700 to 2500 $/ha/season for irrigated dry season production and are about 50% of the farmgate value of production.
- Margins for maize and rice are much lower and these crops give little more than 1 $/day return to farm labour. Margins for irrigated dry season grain crops are lower than for wet season rainfed cultivation.
- It is therefore much more profitable to use AWM techniques for dry season vegetables and, indeed, it is difficult to justify investing in AWM techniques purely to provide protection against drought for wet season grains and legumes.
- Crop margins are highly sensitive to assumptions about the value of labour and of crops, both of which vary by season and location in Mozambique.

Benefits for Blue Water Dry Season Irrigation. For dry season cultivation, the full crop production is dependent on AWM and the benefits derived are the full margins on that production. The margin excluding irrigation costs on irrigated dry season vegetables is about 2100 $/ha/season in Mabote, about 2300 $/ha/season in Caia and about 3100 $/ha/season in Beira. For maize the margins are between 80 and 300 $/ha/season.

Benefits for Supplementary Blue Water Wet Season Irrigation. In most areas of Mozambique, supplementing irrigation in the wet season has little impact on yields during wet years. In years where there is a shortfall in wet season rainfall, supplementary irrigation should be able to make up for this shortfall and generate some benefits. There is no existing analysis of the correlation of rainfed yields with rainfall. However, a brief analysis of the last 5 years data suggests that there is a relationship and that a 10% change in rainfall generates a 10.1% change in yield. *Figure* 4-10 presents evidence of the variability of rainfall over the last 40 years. The figures suggests that monthly rainfall during a normally wet growing season (ie from December to February) is about 200mm and that most years vary between 150mm and 200mm. The average shortfall below 200mm is 20mm, or 10%, suggesting that, on average, a shortfall in rainfall depresses yield by 10%, compared to those achievable with unconstrained water.

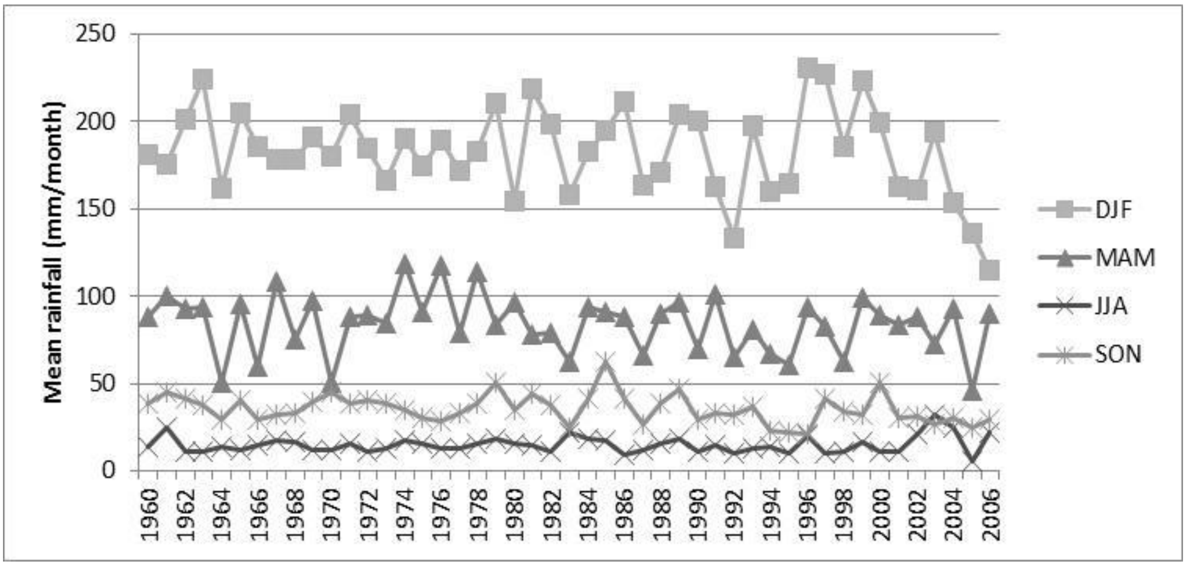


Figure 4-10: Variation in Rainfall over the last 40 years

Source: UNDP Climate Change Country Studies at http://country-profiles.geog.ox.ac.uk. Note: the recording station is not specified.

Benefits from Blue Water Irrigation to Protect against Short Dry Spells. Irrigation can also provide protection from the effects short dry spells. This depends on the timing of the drought period: if it occurs late in the growth of the crop, then AWM will be responsible for saving the whole crop and the benefits will be the full value of the crop, not just the margin, since the costs are already 'sunk' and there is no time to replant and grow another crop. No evidence is available of the frequency and timing of short dry spells in Mozambique. In the absence of any evidence, we assume that there are four different types of dry spell: i) early and modest; ii) early and serious; iii) late and modest; and iv) late and serious. The lost income from each of these types of dry spell is assumed to be 20%, 40%, 50% and 80% respectively and the frequency with which the types occur is assumed to be 20%, 10%, 20% and 10%. The average loss of income from short dry spells is therefore estimated to be 26%.

Water Harvesting. The impact on yields of the DRMP work on water harvesting in Mabote has not yet been evaluated, but there is some recent evidence from Malawi, on rainfed maize in areas that are similar to the drier parts of Mozambique and are prone to dry spells (Chilimba and Liwimbi 2009). The Malawi analysis includes a range of data from government research stations. One experiment suggests that water harvesting increases yields by 12% for ridging, 32% for pot holing and 87% for trenching. Another experiment compares only the different water harvesting techniques, suggesting that trenching and pot holing are roughly equal and are both gives yields that are about 10% to 20% higher than ridging. Some caution is needed in using these results as there is a wide variation amongst sites and the experiments were done at research stations, rather than with farmers.

Wider international reviews of rainwater harvesting support the view that significant increases in yield are normally achieved although there is limited quantitative evidence and some wide variations in results (NRSP 2007). A DFID project in Tanzania produced useful insight, showing that in-situ rainwater harvesting systems were only effective in the drier cropping season and not in the main rainy season, but that water harvesting that brought water from outside a field was more widely beneficial and much preferred by farmers (Gowing 2000). AWF have supported water harvesting in Rwanda, Djibouti and South Africa. Recent evaluations of these projects provide very limited evidence of impact on yield, but there is evidence that yields increased substantially, with margins increasing by between 130 and 230 $/ha/season in Rwanda (AWF 2006). A review of water harvesting in Ethiopia suggested that yield increases were more modest, at less than 15%, and that problems with salinization and pests could undermine the benefits (Awulachew, Merrey *et al*. 2005).

Taking into account the range of evidence above, the economic analysis of the project assumes that yields from water harvesting will increase by 20%.

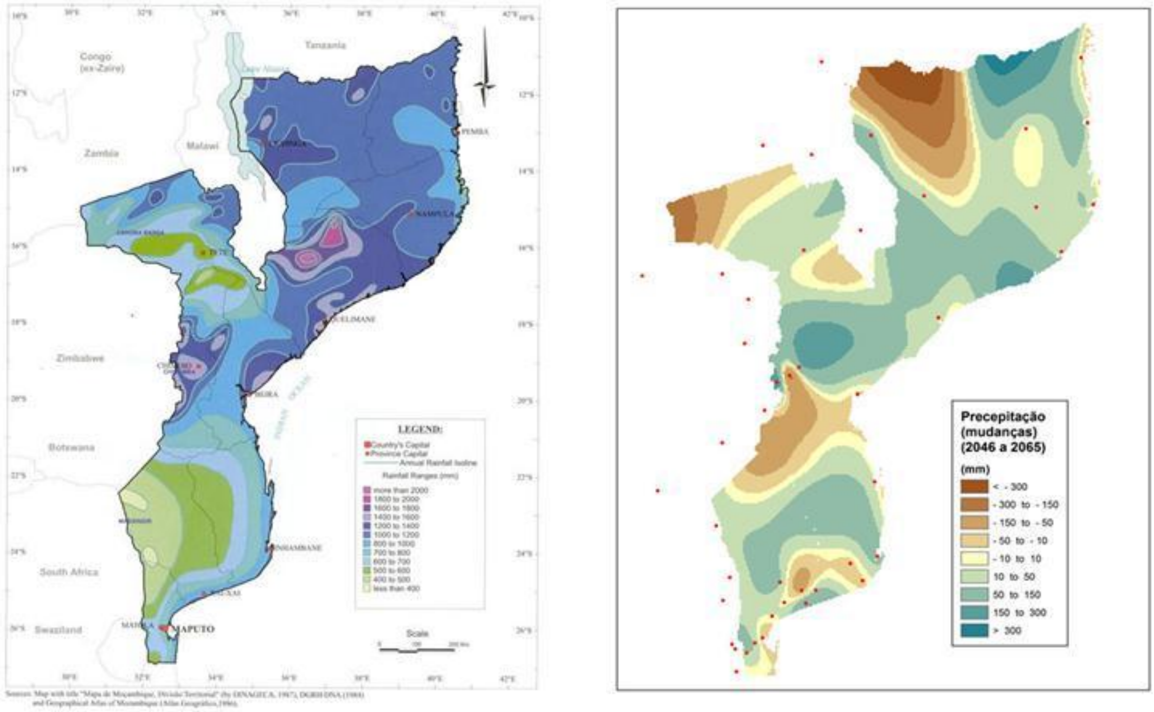
Conservation Agriculture. There is some evidence of the benefits of conservation agriculture in Mozambique and in Sub Saharan Africa more widely (see Box 4.2). This suggests that there is quite a wide variation in the impact that conservation agriculture can have on yields and on costs, but that yields generally increase by at least 50% and often 100%, with some savings in costs, notably of labour. Because of the wide variation in circumstances, generalised farm models can only aim to be illustrative and should be kept in the broadest terms.

Whilst conservation agriculture can be applied to obtain a yield response in a single crop, its full benefits are achieved with a series of crops, by direct planting under an existing crop. An early beans crop, followed by maize should be achievable in most parts of Mozambique, including Zambezi and Sofala Provinces, and some areas can also grow a third crop of sesame or sunflower, without requiring irrigation.

To estimate a yardstick of the benefits that can be achieved from conservation agriculture, it is assumed that it is used to replace a maize crop with a rotation involving both beans and maize. The yield of maize is assumed to be 40% lower in the first year and then rise to 40% higher after five years, in five equal steps. For beans, it is assumed that average yields are achieved and that the full margin on the additional bean crop can be attributed to conservation agriculture. Standard crop margins for beans were not available, but in most Southern African countries, the economics of producing beans is roughly similar to that of maize, with similar crop values, costs and margins. The benefits from conservation agriculture are thus composed of an increase in maize crop value of 40% (worth about 500 \$/ha/season) and an additional bean crop with a margin of about 200 \$/ha/season.

4.4.4 Implications of Climate Change for Yield

Implications of Changes in Rainfall. Climate change is likely to increase average rainfall in some areas and decrease it in other areas (see Section 4.2.3). Since the response of crops to actual evopotranspiration is linear, and actual evapotranspiration is strongly correlated with rainfall, all other things being equal, the total impact of changes in rainfall on production across the whole country will be limited, with the losses in some areas offset by gains in other areas. There will, however, be some areas where the changes in rainfall mean that some crops are no longer viable in rainfed conditions and farmers must either change crops or invest in irrigation. However, the areas which are both dry and getting drier are limited to Manica and parts of Tete.



Average Rainfall	Projected Change in Rainfall

Figure 4-11: Average Rainfall and Projected Changes in Rainfall

Notes: Expected changes in the future (2046-2065) in the median of all 7 GCMs for rainfall during maize growing period, expressed in rainfall mm. Source: (Brito 2011)

In practice, protecting crops from being exposed to the wilting threshold could happen either through a reduction in average rainfall or an increased frequency of short droughts arising from higher rainfall concentration, or both.

The land suitability mapping undertaken during the first phase INGC study gives some very rough indication of the area that could be shifted towards a situation when wilting thresholds threaten plant survival and result in non-linear loss of yield from lower water availability. A visual assessment of the maps suggests that about 20% of the area suitable for cassava will be subject to slight or significant change in suitability. However, the maps are presented only for Cassava, which is not a priority crop for AWM, and they present the change in suitability, rather than the areas where suitability is threatened.

- The main benefits from SPAWM come from making it possible to cultivate crops during the dry season. Where dry season irrigation is limited by the supply of water (ie away from the large permanent rivers and sustainable groundwater reserves) a reduction in rainfall arising from climate change will reduce the supply of water in the dry season and AWM investment will be able to slow or reverse the decline in dry season irrigated area.
- There are a range of reasons why yields are different between the dry and wet seasons, including ground level ozone concentration and vulnerability to pests. Recent analysis suggests that climate analysis will have a significant impact on ground level ozone, reducing yields during the wet season, increasing crop prices, margins for dry season irrigation and benefits to AWM. The net impact on pests is not yet clear.
- In areas where reduced rainfall makes rainfed crop production impossible during average years, AWM will make it possible to maintain production by supplementing rainfall.
- In areas where rainfall is still viable during average years, it may be subject to damage from the increased frequency of dry spells within the normal growing period and AWM will provide some protection for crops during these spells.
- This section on the advantages of AWM under climate change should be in the executive summary and much earlier on in the main text.

There are three main existing sources of evidence on the impact of climate change. The first phase INGC study conducted a conventional assessment of the net impact of changes in monthly temperature and rainfall on crop suitability. In the second phase, the first analysis concentrated on the effects of changes in daily water balance on yields, using a CLICROP model (Brito 2011). The climate changes were taken from 7 GCM projections models, providing evidence for temperature and rainfall and, hence on evapotranspiration. The analysis is undertaken using a daily time-step which allows the impact of increased concentration of rainfall to be taken into account. The model also takes into account the moisture characteristics of different soil types across Mozambique. No account is taken of changes in CO2 or ozone.

The analysis is done for six crops: maize, cotton, groundnuts, cassava, soya beans and sorghum. *Figure* 4-12 presents the results for maize and for soybean. The main conclusions of this study are that yields of all crops will decline, but that the decline differs from crop to crop: maize is the most affected crop, with a projected average decrease in the country of 11.1 % in crop yields; soybean has a projected decrease of 6.4 %; groundnuts 4.6 %; cassava 4.2 %; sorghum 3.5 %; and cotton 2.9 %.

The projected yield decreases are geographically differentiated, with the decrease in relative yields starting with a pocket in the west side of the province of Tete with cotton, then growing towards the coast and the south, with sorghum, groundnut, cassava, and soybean, and then maize as the most affected crop covering a wider area in Mozambique. Crop yields can decrease in the most affected areas up to 30 % of present yields as is the case of Maize in some areas of the province of Tete.

The analysis above suggests that the largest impact of climate change is likely to be felt in the Zambezi valley and in Inhambane. These therefore are the natural focus of investment to promote agricultural water management as a strategy to promote climate resilience.

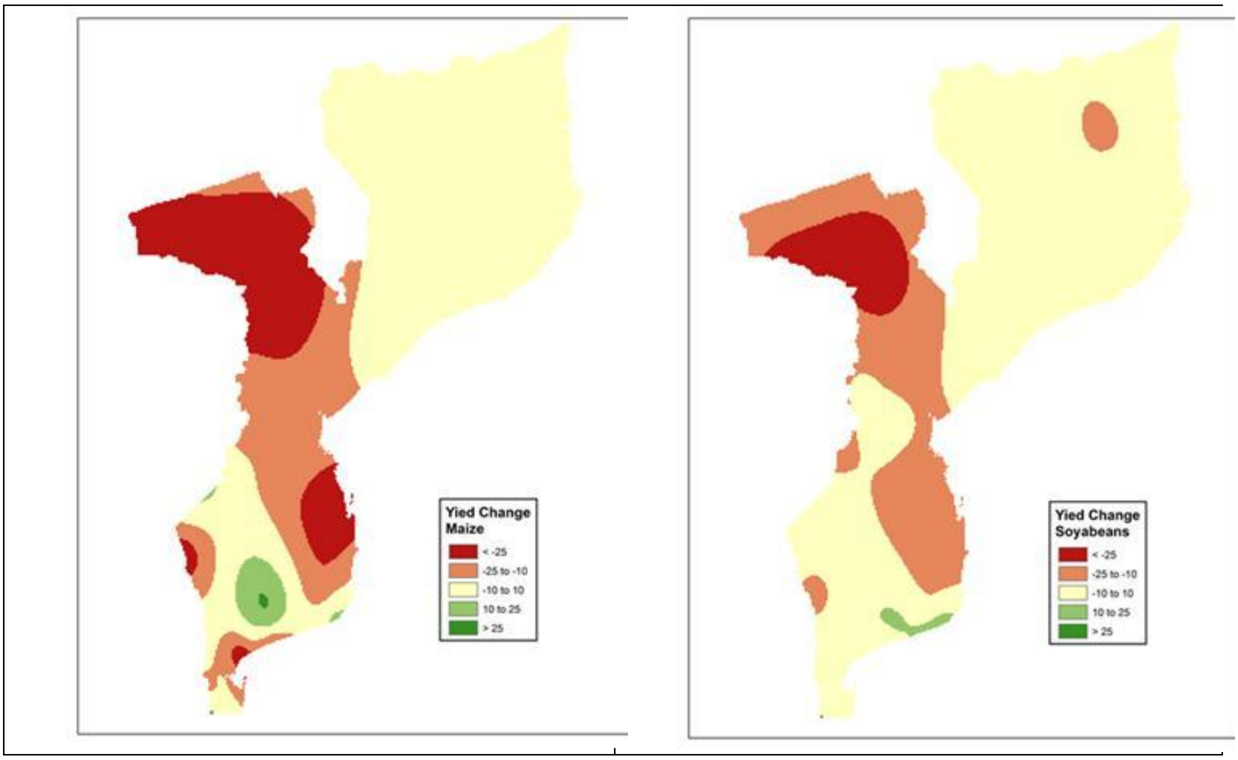


Figure 4-12: Projected changes in the future (2046-2065) of maize (left) and soybean (right) crop yields, expressed in % change of present yields

Source: (Brito 2011)

Figure 4-12 hides the fact that there are large variations in the GCM projections for rainfall. *Figure* 4-13 shows these variations, presenting the ratio between future: past national average yields.

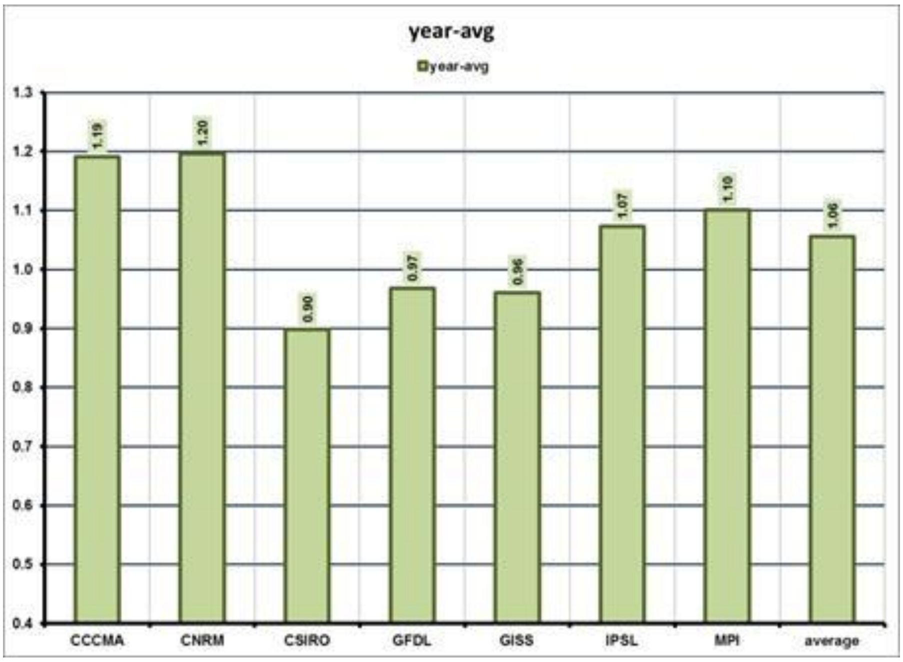


Figure 4-13: Ratios of future average annual rainfall versus past average annual rainfall for seven different GCMs and the average of all GCM models

In addition to the results from the first phase INGC study, a second study in the second phase of Theme 6 has added new dimensions, looking at the impact of CO2 and ground level ozone (O3) (Holman 2011). This work suggests that reduction in yield from increases in O3 levels will be higher than the increase from higher CO2 concentrations and the changes due to temperature. There are some regional variations in the impact of O3, but the impact is felt across the whole country. The difference between summer and winter O3 concentrations is likely to increase, resulting in even higher benefits from irrigation that allows early planting and/or cultivation in the dry season.

4.4.5 Shortlisted AWM techniques

Returns to AWM. The project will work with a short list of the AWM techniques that are expected to give the highest returns, taking into account local conditions and the need for practical concerns, such as divisibility and robustness. The ultimate objective of the project is to reduce the vulnerability of farmers to climate change and this can only be achieved if the AWM techniques provide sufficient benefits to ensure that depreciation and other annual costs can be covered, so that farmers will continue using the techniques after the end of the project. Using the cheapest options also ensures that the limited project funds available are used to benefit the largest number of farmers.

All blue water techniques provide similar benefits, assuming they meet the irrigation requirements. Thus, for blue water techniques, the best returns will be provided by the cheapest techniques. To compare the blue water techniques with water harvesting and conservation agriculture, it is necessary to consider the Benefit Cost Ratio, using the information on costs and benefits presented Section 4.8.2. *Table* 4-8 presents the Benefit Cost Ratios of different AWM techniques and uses figures from *Table* 4-22 elaborating this to distinguish between the benefits from using blue water irrigation for dry season and wet season cultivation, as discussed in Section 4.4.3. The Benefit Cost Ratios presented in the table appear high, but they are from the perspective of farmers and do not include the costs of training or of project overheads, which are included in the full economic analysis presented in Section 4.7.1.

Table 4-8: Benefit Cost Ratios of AWM Techniques, Excluding Training and Project Management

Role of AWM	Benefits	Costs	Benefit Cost Ratio
	$/ha/season		
Blue water: dry season	2300	500	4.6
Blue water: wet season supplementary/dry spell protection	350	200	1.8
Water harvesting in wet season	270	140	2.0
Conservation agriculture in wet season	740	170	4.4

Note: full conservation agriculture benefits occur only after 5 years transition

The Benefit Cost Ratio for blue water is based on a moto pump and river source, with piped conveyance and hose irrigation, which is the cheapest technique, according to the cost analysis in section 4.4.2. Using a more expensive options, such as drip or sprinkler irrigation, involves much higher costs (see *Table* 4-4 and *Figure* 4-6) and Benefit Cost Ratios fall to as low as 1.5. This is insufficient to justify public investment, when the costs of training and extension and of project management are also taken into account.

Shortlisted Techniques. Most of the activities of the project will be based around offering farmers a menu of 6 shortlisted packages that are expected to give the best returns in Mozambique. The shortlisted techniques are presented in *Table* 4-9 and are described in more detail below. The criteria for shortlisting the AWM techniques is explained in Section 4.5.2.

Table 4-9: Summary of the Shortlisted Packages

	Zone	Crops	Source	Lift	Distribution	Irrigation	Cost ($/ha/ season)
A1: Moto+surface	Valley	Veg.	River	Moto	Canal	Furrow	670
A2: Moto+pipe	Valley	Veg.	River	Moto	Pipes	Hoses	420
B: Open well	Valley	Veg.	Well	Moto/treadle		Hoses	720
C: Shallow tubewell	Valley	Veg.	Borehole	Electric pump		Hoses	660
D: Water harvesting	Upland	All	Ridge/trench				140
E: Conservation agric.	All	All	No till/mulch				135
F: Wetland drainage	Wetland	Rice/ veg	Channels				various

Notes. All options include use of irrigation calendar to optimise application of water.

A. River Source, Moto Pump, Pipe Conveyance and Hoses. The use of moto pumps to extract water from rivers and lakes is widespread in Mozambique and there are many locations in valley bottoms and wetlands where it is cost effective. The project will help to make moto pumps available to more famers.

The relatively high irrigation efficiency associated with piped conveyancing and the use of hoses in the field means that the area cultivated by each moto pump is higher than with canals and furrow irrigation and the cost effectiveness of the moto pump is higher. The cost of the moto pump plus pipes/hoses is only about 560 $/ha, compared with about 1100 $/ha for canals/furrows. The project will therefore support the installation of pipes and hoses, either for farmers who already use moto pumps or for those farmers that are being supported to purchase moto pumps.

As a variant of this option, extraction from small rivers may benefit from the additional investment in a small dam or diversion structure and gravity feed, where this is possible. If this replaces the need for a moto pump, it could be cheaper, provided the costs of the works are less than 10,000 $/ha irrigated.

B. Low Cost Wells, Treadle or other Pumps, Pipes and Hoses. Low cost wells are a cost effective water resource where the water table is sufficiently close to the surface. The annualised cost of an open well is roughly the same as the cost of pipes from water sources that are more than 100m from the field.

For small farms with limited resources, treadle pumps may be considered. However, the area cultivable with treadle pumps is very small and the net benefits are not attractive, unless labour is considered of little value and farmers are unable to raise their cost contribution for moto pumps. If considering a treadle pump, households should be aware of the labour requirements and should have suitable people willing to operate the pumps.

With labour costs of 1 $/day, the annual costs of treadle pumps and open wells are about 720 $/ha/season, assuming they are combined with pipes and houses. (If they are used with furrow irrigation, the costs are about 40% higher, because of the reduced efficiency.) Using moto pumps instead of treadles reduces the cost to about 560 $/ha/season. Farmers should thus be aware that investing in treadle pumps is only viable if they are unable to afford the extra investment in moto pumps, or if they have access to labour that is valued at significantly less than 1 $/day.

This option is not well established in Mozambique and will need to be carefully monitored and adjusted or dropped, if there are problems.

C. Shallow Tubewell, Electric Pump, Pipes and Hoses. There are a variety of techniques for developing low cost shallow tubewells, including rota-sludge, percussion and jet-bore. Rota-sludge tubewells are not yet used in Mozambique but they can be a very cheap source of water, with costs of only 11 $/ha/season, and there has been good experience in other African countries. The technique depends on developing a number of enterprises with the skills and equipment to undertake the well development. The project will support the establishment of three such enterprises in Zambezi and three in Beira. In Mabote, there is likely to be less scope because water tables are too low.

Box 4.4: Rota-sludge Tubewells

The rota-sludge drilling equipment consists of a 2 inch metal pipe fitted with a cutter bit, provided with teeth to scrape the soil. The pipe column is lifted by a lever and dropped down to hit the bottom of the well. At the moment of impact the pipe is turned about 45 degrees by means of a handle, resulting in a hammering and scraping action. The well is kept full of water and, when lifting the pipe column, the driller closes and opens the top of the pipe so that the water and scraped material is pumped up and out of the drilling pipe. To seal off the walls of the well, to prevent caving-in and facilitate the transport of cuttings, cow-dung is added to the water, making sludge.

Figure 6: : Concept of Rota-sludge borehole drilling (Practica Foundation)

The rota-sludge technique has become very successful in loamy and silty soils. It is not suitable in sandy soils or hard stone formations which require different techniques, such as a stone hammer.

Drilling sets can be made locally and teams of local drillers can be formed and trained. A team of four well trained technicians can normally drill a well in about one day. The cost of well drilling will depend on the depth and the piping, but an indicative cost is about $100 USD for a 10 m deep well.

For wells with depths of 7m or more, an electric pump is required, powered by mains electricity (if available), by a diesel generator or by a solar power. The cost of mains electricity will depend on the distance of new cabling that is required. If mains electricity is available within about 2km of the field site, then it will normally be cheaper to install new cables than to invest in a generator or solar pump. The annual costs of the diesel generator and the solar pump are similar, although almost all the costs of the solar pump are for investment, whist 80% of the generator costs are for fuel. Where farmers are able to afford the cost contribution for solar pumps, they are likely to prefer this option, partly because the 50% subsidy on inputs is lower than the 90% subsidy on capital. However, experience in Mozambique suggests that solar pumps can give more problems with theft than generators, because it is not practical to remove the panels to a secure location on a regular basis.

Assuming that pumps are combined with hose irrigation, giving an irrigation efficiency of 85%, the
cost of shallow tubewells and electric pumps is about 660 $/ha/season, which is about the same as Option A, with channels and furrow irrigation.

D/E/F. Water Harvesting, Conservation Agriculture and Wetland Drainage. These are described in Section 4.4.1.

4.5 PROJECT ACTIVITIES

Early experience with agricultural development in the 1970s led to the approach of integrated agricultural development projects (IADPs), which usually involved a wide range of complementary activities, including:

- consultation, study, extension and applied research, provided by a combination of government officials and NGOs
- facilitation of the physical supply of new equipment, either directly or through private traders and manufacturers
- financial services, including conventional credit and savings and other forms of finance, such as those offered under contract terms with private suppliers and agents
- capacity building at local levels and, potentially, at national levels

Experience with IADPs then led to questions about the sustainability of the approach and efforts to provide more selective support in those areas which were considered most limiting to development. Examples include the experience with PROAGRI in Mozambique, where support focused on institutional strengthening, without explicit match funding for investment. At the opposite extreme there have been programmes elsewhere in Africa where projects have simply provided irrigation equipment, with minimal technical support. The experience with these more selective programmes is also problematic and suggests that some degree of balance is required in project support combining both technical support and equipment.

SPAWM will concentrate on the first two elements of conventional IADPs listed above, although the subsidy programme will include an element of credit for some farmers and the programme will have an indirect capacity building element. The balance between the different types of support varies with the different AWM techniques, as presented in *Table* 4-10.

Table 4-10: Support Required for Shortlisted AWM Techniques

	AWM Shortlisted Option	Equipment subsidy	Design	Training and extension
	River extraction, moto pump, pipes, hoses	Medium	Medium	Medium
	Low cost open well, moto/treadle pump, pipes, hoses	Low	Medium	Medium
	Shallow tubewell, electric pump, pipes, hoses	High	Medium	Medium
	Water harvesting	Low	Low	Low
	Conservation agriculture	Low	Low	High
	Wetland drainage	Medium	High	Medium

4.5.1 Selection of Beneficiaries

In each village, beneficiaries will be selected in the early discussions in the FFS. The approach of the project will be presented, including the menu of shortlisted AWM techniques and the proposed arrangements for subsidising equipment and other costs. In particular, the distinction between vulnerable farmers and lead farmers will be made clear. Each farmer who is interested in participating will be asked to classify themselves as a vulnerable or a lead farmer and their judgement will be subject to approval from other FFS members. It is hoped that the social status of being classified as a lead farmer will be sufficient to encourage leading farmers to accept the lower subsidy rates offered to lead farmers.

If demand to be a beneficiary is much higher than the project's ability to provide support, then the FFS will be asked to define a method for prioritising. Options that will be suggested include the following:

- random process, by drawing lots
- request for a membership fee, with the revenue generated being used to make it possible to increase the number of beneficiaries
- definition of a simple physical criteria, such as the land per household member for vulnerable farmers or the contacts with markets, for lead farmers
- approval by a group of village elders

4.5.2 Selection of AWM Techniques

The project will aim to support the techniques which have the greatest chance of being sustainable, for each beneficiary. This will start with group discussion in the FFS on the advantages and disadvantages of each shortlisted technique. These early discussions will include consideration of the possible need for collaboration amongst beneficiaries where some investments and operations need to be shared. The group discussions will ensure that as many farmers in the locality as possible take part in the assessment and are exposed to the project and to the opportunities offered by AWM. Once the basic selection has been done, beneficiaries will move on to more detailed design, which may take place directly with extensionists.

Discussions with beneficiaries on sustainability will include both the technical and economic viability. The choice of crop is affected by both technical and economic circumstances and influences the viability of AWM techniques. The economic analysis provided in this project proposal document provides indicators of expected performance that should be discussed with farmers. However, as many of the criteria are subjective and difficult to predict, it is not possible to define a single target indicator. In particular, the way in which AWM techniques suit households depends on different exposure to risk (eg from the water source, labour availability, crop price or equipment reliability) and different vulnerability to risk, depending on access to other sources of incomes. The analysis in this proposal provides an analytical structure for assessing suitability and should make it possible to prevent completely unsuitable techniques from being used. However, it needs to be applied in a pragmatic way, to suit the local circumstances.

Technical Viability. The technical viability of AWM techniques will depend largely on soils and water sources. Soils can be classified into five types, as presented in *Figure* 4-14. This classification is based on the FAO classification of soils for irrigation suitability, which is an adaptation of the United States Bureau of Reclamation classification and addresses a wide range of factors determining the suitability of soils for sustained irrigated cultivation.

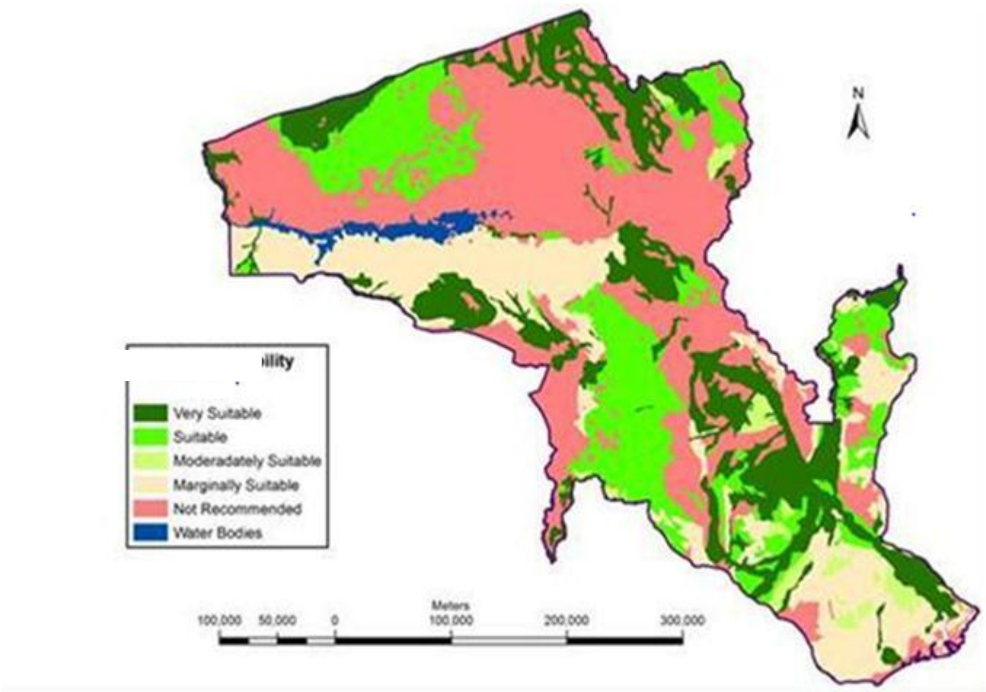


Figure 4-14: Suitability of Soils for Surface Irrigation in the Zambezi Basin

Three agro-ecological zones will be defined, with differing access to water resources.

- In dryland areas, most rivers will be seasonal and there will be only occasional access to groundwater, often from aquifers at depths of greater than 100m. In these areas, there may be some potential for supplementary irrigation through small dams and reservoirs. Conservation agriculture and water harvesting may be useful to improve soil moisture and so increase the level and reliability of yields during the wet season.
- In areas characterised by uplands and valley bottoms, there is a wider variety of possible water sources, including rivers, springs and groundwater. Many of the water sources are available in the dry season, opening up the potential for irrigating a second crop. Techniques for soil moisture management remain useful and may help extend growing seasons and options for crop rotation. An example of the areas with likely access to water sources alongside rivers is presented in *Figure* 4-15.
- Wetlands have permanent access to surface water and can use a range of AWM techniques. These may be in low-lying coastal areas or in inland valley swamps. Drainage and flood control are as important as irrigation.

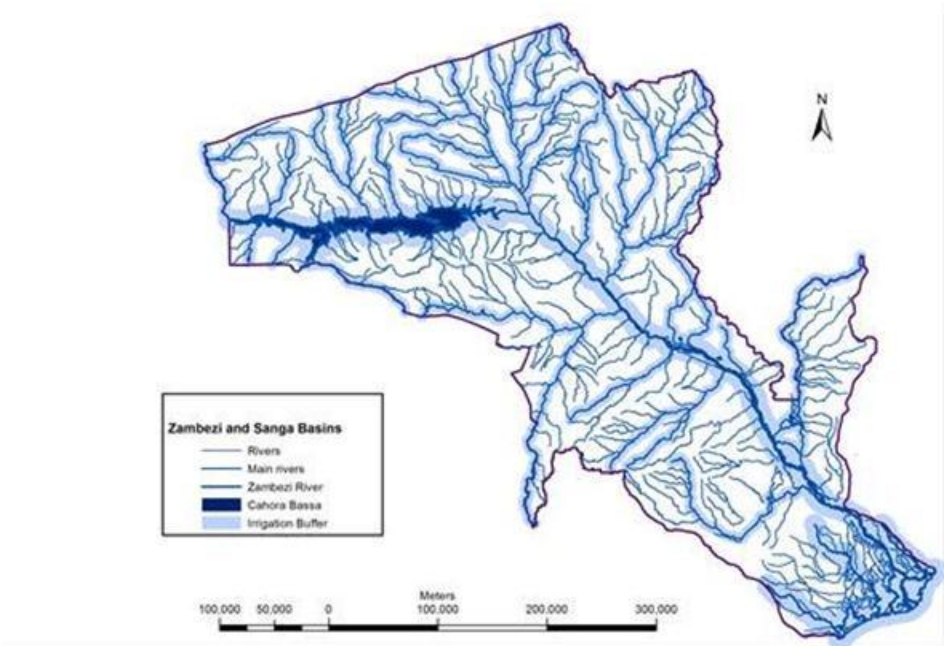


Figure 4-15: Areas with Potential Access to River Water Sources in the Zambezi Basin

Table 4-11: Technical Suitability Guide for AWM Techniques

Soils	AWM Technologies
Very suitable	• all AWM techniques viable
Suitable	• all AWM techniques viable, though with constraints that can be easily solved
Moderately suitable	• potentially viable, though with constraints that may be solved, but with difficulty
Marginally suitable	• major constraints that are unlikely to be addressed, except in special cases
Unsuitable	• never likely to be appropriate for AWM
Water Resources	**AWM Technologies**
Dryland areas, with limited rivers and groundwater	• techniques to promote soil moisture capacity, notably conservation agriculture • some possibilities for small dams, reservoirs and water harvesting • limited sites with deep groundwater, combined with efficient in-field irrigation
Uplands and valley bottoms with rivers, springs and some groundwater	• surface water extraction in valley bottoms • groundwater in and near valley bottoms • spring and river diversion, by gravity or pump • limited scope for water storage to be combined with efficient in-field irrigation • conservation agriculture in uplands
Wetlands, with permanent surface water	• drainage and flood control • bunding and diversion structure for water control • pumping from shallow wells and streams.

Crop Selection. The suitability of AWM techniques depends on the crops cultivated, which in turn depends on the technical and economic circumstances.

Table 4-12: Suitability of AWM Techniques for Different Crops

Crops	AWM Technologies
Cassava	• techniques to promote soil moisture capacity and reduce erosion, including CA • water harvesting techniques
Maize	• techniques to promote soil moisture capacity and reduce erosion, including CA • water harvesting and conservation through contour bunds • pumping from shallow wells and streams for supplemental irrigation in wet and off season production
Rice	• bunding and levelling of rice fields • low-cost inlet/diversion structures to regulate and manage water to the rice field • drainage and flood control
Vegetables	• on-farm micro irrigation technologies, especially for dry season production including: low-cost well development; small pumps (treadle, moto, solar pumps); drip and sprinkler irrigation
Fruit trees (banana, avocado, pine apple, mangos	• on-farm irrigation technologies • water harvesting techniques that exploit the deep rooting of fruit trees • low-cost inlet/diversion and water conservation structures to regulate and improve water management • drainage and flood control works
Family and School Garden plots	• rainwater harvesting or roof water tanks • small on-farm storage (eg underground tanks or drip-kit header tanks) • drip irrigation kits
Irrigated Cash crops (sugarcane, tobacco, cotton)	• river diversion and small dams • moto pumps and sprinkler • conservation agriculture
Rainfed cash crops (cotton)	• techniques to promote soil moisture capacity and reduce erosion, including CA • water harvesting techniques • drainage and flood control works in the fertile plains

Economic Suitability. About 90% of the resources will be devoted to supporting those AWM techniques that are expected to have the greatest chance of being profitable. These are expected to be mainly those techniques on the shortlist presented in Section 4.4.5 with some variations of these options. About 10% of the budget will be reserved for testing the technical viability of new techniques in locations where it is unlikely that the shortlisted techniques will be profitable, but where a test of technical viability is considered useful. If the new techniques that are tested can be shown to be viable, then they can be added to the shortlisted techniques for mainstream project support.

The suitability of AWM techniques to an individual farm will depend on a wide range of circumstances, including: farm size, farming systems, climatic conditions, local water sources and soils, farming labour and skills and a range of socio-economic issues. The project will offer the various techniques as a menu, along with guidelines about how different characteristics affect suitability. It will not aim to define optimum technologies to promote in each area of the country, although it may be useful to map likely suitability of different techniques, as a way of summarising the conclusions. *Table* 4-13 presents guidelines for the suitability of the AWM technologies to different socio-economic zones, households and farm types.

Table 4-13: Economic Suitability of AWM Techniques

Socioeconomic zones	AWM Technologies
Dynamic smallholders, with some access to inputs and farms of at least 2ha	• small diversions and dams • moto pumps and solar pumps • piped distribution • flexible hoses • micro-sprinkler • conservation agriculture
Urban fringes with strong potential for fruit and vegetable production	• improved open wells and shallow tubewells • treadle and moto pumps • piped distribution • hoses, micro-sprinklers
Mixed farming areas with good access to alternative sources of employment	• water harvesting • moto and solar pumps • drip, micro sprinkler, Californian moto
Marginal farmers in areas with reasonable social cohesion	• small dams • piped distribution • moto pump rental • conservation agriculture
Household features	**AWM Technologies**
Good access to market	• higher cost in-field irrigation for high value crops, giving greater control over water and yields
Good access to credit	• higher cost AWM technologies
Availability of household labour	• use of hoses instead of sprinklers or drip system • treadle pumps instead of moto pumps • potential labour savings from CA are still useful, but relatively less important
Good network of farming skills and access to extension	• easier to justify higher expenditure on AWM that depends on using improved seeds and inputs to obtain best yield response to water • easier to pursue CA that depends on ability to adapt to evolving problems
Easy access to new land	• usually more profitable to open up new land than to intensify existing land using AWM investment • community discussions on the environmental costs of bush clearance
Clear land rights	• pre-requisite for AWM investment
Importance of livestock	• possible need for additional costs in fencing or herding to keep livestock off crops or mulch
Existence of dealers and suppliers	• pre-requisite for wide adoption of AWM techniques

In theory, it should be possible to use the above criteria to demonstrate the areas of greatest suitability of different AWM techniques. For example, FAO have mapped the suitability of areas for AWM in the Agricultural Water Solutions Project (AWSP) in 5 African countries (Burkina Faso, Ethiopia, Ghana, Tanzania, and Zambia) and 2 Indian states (FAO 2011). The approach takes account of: water availability (surface or shallow groundwater); population density and poverty levels; and an index of the extent to which water is limiting, which is based on an expert interpretation of data about livelihood zones and farmer typologies (based on participatory data) plus data on water stress and availability per person. These indicators are applied with varying weights to moto pumps, river diversion, water harvesting and soil water conservation.

The SPAWM project will produce maps similar to those generated by the AWSP, for the three hub areas in which it will operate. The SPAWM project activities will themselves provide the participatory information gathering on livelihood conditions that is part of the FAO methodology. The project will not produce the maps as a separate baseline study because this would be expensive and time consuming and the project activities themselves provide a more rigorous and cost-effective way of gathering the information required. The requirement to provide suitability maps as part of project monitoring will help to ensure consistency in approach.

4.5.3 Subsidy for Equipment, Inputs, Contractors and Marketing

Subsidy for AWM Equipment and Inputs. The subsidy provided for equipment and inputs will be as follows:

- for the poorest farmers, 90% of the cost of equipment in the first year, 50% of the cost of inputs during the first year and 25% during the second year, with no subsidy in the third year
- for lead farmers, 50% of the cost of equipment and no input subsidy

Each hub will have an annual lump sum budget to be used for equipment, inputs and operating costs and this will be earmarked for each FFS. The allocation of this budget at the hub level will be defined each year in an Annual Work Programme (AWP) for the hub, based on the most recent evidence of results from the previous year. The AWP for the first year will be produced several months after the start of the project and before the first season. Some flexibility will be required in approval of actual spending and variations from the hub budget will be allowed provided that a clear case is made for the reasons why different AWM techniques are chosen for support. Potential reasons could include low support from farmers or problems with achieving expected yield improvements.

Where possible, the equipment and inputs will be purchased locally at the hub, to encourage local agents and suppliers. This will be done despite the fact that local prices will be higher than prices in Maputo. If there are problems with local availability, or if prices are more than 25% higher than in Maputo, then the project may consider central purchasing. However, before this is done, the project will undertake a realistic assessment of the cost of its own time in organising procurement centrally, to verify that it is cost effective.

Vulnerable farmers will have the choice of making their cost contribution on delivery of the equipment or inputs, or at the next harvest. Lead farmers will need to make their cost contribution on delivery. The revenue collected will be deposited in a project account at the hub level and will be subject to regular monthly statements and verification. If there are any questions about the

Subsidy for Conservation Agriculture. Most projects that support conservation agriculture in Mozambique provide only subsidies for the conservation agriculture equipment and inputs. In some cases, the main costs for conservation agriculture are those from extra labour needed to establish mulch layers. In other cases, the main cost of conservation agriculture is the risk of reduced yields in the first few years, whilst soils are improving and weeds are being controlled. Vulnerable farmers are not able to take the risks of reduced labour and experience with conservation agriculture suggests that there is often a high drop-out rate in the first two years. A subsidy package for equipment and inputs is typically worth only 300 to 500 $/ha/season, compared with temporary yield losses that may be worth as much as 600 $/ha/season. Therefore some additional form of subsidy is required, to sustain interest for several years and achieve the very substantial benefits that are possible in the mid term.

Providing remuneration for lost yield would be open to manipulation and abuse, especially if it was provided in cash. It would also be difficult to administer, regardless of whether it was provided in cash, in food aid or food for work, or with a voucher system.

The project will give additional subsidies for conservation agriculture by providing a 'double share' of inputs. This will not add additional administration costs and can be justified by the fact that farmers can use the extra inputs on other fields to improve yields on these fields, thus providing some protection for the lower initial yields on the conservation agriculture fields. The scheme will need to be discussed carefully with farmers, to encourage them to use the same inputs on conservation agriculture and conventional agriculture, so that there is a fair comparison in performance of the two.

<u>Low Cost Tubewell Contractors.</u> The project will provide equipment for 9 tubewell contractors, with 3 operating in each hub. The equipment to be provided will be specified by a specialist international firm or NGO and may include rota-sludge, percussion and jet-bore. The international firm or NGO will also organise for training to be provided to the contractors. The contractors will lease the drilling equipment from the project, making a payment equal to 10% of the total cost at the end of each year. The lease contract will include a clause that requires the contractor to keep records of each well drilled and will specify a minimum number of wells that must be dug for the contractor. If this level of activity is not sustained, the equipment may be withdrawn and provided to another contractor.

The cost-effectiveness of the various techniques will be monitored by the national specialist in farm management and M&E, as part of the annual reporting.

<u>Support for Marketing.</u> There is some evidence that the increased production in Caia that arose from previous INGC activities has not always found a good market and has been wasted. Investigations in Beira suggest that, if initial contacts can be made, there is good demand for new produce and traders in Beira operate with a wide network of suppliers, often from places further away than Caia. Contacts are made easily with mobile phones and traders in Beira are willing to organise transport, once they have developed trust in the farmers. However, establishing that initial trust involves a substantial investment by farmers in transport and time that needs to be sustained through several deliveries. It is likely that similar conditions apply in Quelimane, on a smaller scale.

Farmers in Caia need to demonstrate to traders in Beira that the quality and volume of products can be guaranteed, if a trader organises transport for collection. To facilitate the establishment of that initial trust, SPAWM will establish a contract with local transporters to transport product from each new village on three occasions during the first harvest season. Farmers in the village will be made aware of the terms of this contract and of the fact that it is for a limited period and that they must establish their own direct relations with Beira traders so that they can continue to sell products in future years. For the vulnerable farmers, it is likely that some form of local intermediary will be required to group their produce and provide a central and trust contact point for traders in Beira, Quelimane and other markets. A small sum of $5000 per year has been included in the project budget to provide temporary incentives to help establish contacts between traders and farmers.

Outgrower Component. The project will provide support to commercial farmers who are prepared to enter into a commitment to provide technical and marketing support for outgrowers. The subsidy provided by SPAWM should be in line with that provided in the main project areas: vulnerable farmers will get 90% of investment and 50% of inputs; and lead farmers will get 50% of investment costs. This component may operate across the whole country, taking advantage of any commercial farmer who is interested in participating in such a scheme. There are known opportunities close to Maputo, for the outgrower component.

4.5.4 Training and Extension

Organisation of Training and Extension. The training and extension programme will take place through a hierarchy of resources, as presented in *Table* 4-14.

Table 4-14: Staffing Hierarchy

	Number	SPAWM Staff	Non-SPAWM Staff
National Level	1	Team Leader AWM Specialist Agronomy Specialist Farm Management and M&E	MINAG Department Heads INGC Directors
Regions/Hubs	3 (Mabote, Caia, Beira)	3 AWM Field Engineers 3 Agronomy Field Engineers	MINAG Prov INGC Field Directors
Field level		6 Additional Extensionists	9 existing MINAG Extensionists or INGC Field Agents 45 FFS Leaders

In addition to the above project staff, the project will be provided with a budget to contract support from an international firm or NGO specialising in AWM techniques. This firm will provide support, in particular, for new techniques that are not yet well established in Mozambique, including the low cost tubewell development.

Staff Training. The National Specialists will conduct a one week training course for all new Field Engineers. They will be supported by national research institutes and the international firm or NGO providing specialist AWM support. Field Engineers will be recruited with the objective of providing both expertise in the design of AWM installations and in farm management practices. However, in practice, whilst each Field Engineers will have particular strengths, it will be important that all Field Engineers have a strong understanding of both AWM and farming systems, not least because there is often quite a high turnover of staff and Field Engineers will often have to cover both subjects with sufficient knowledge to know when additional expertise has to be bought in from national level.

The Field Engineers will ensure that all Extensionists (including both the new staff recruited by the project and the existing MINAG and INGC field workers) are also provided with at least one week's training in AWM and farm management. This training will take place in the region and will take the form of a group training session at the beginning of the project, when a significant number of Field Activists are recruited. Where replacement Field Activists are recruited, Field Engineers will be responsible for assessing the gaps in their experience and providing a tailored training programme for them, which may include being accompanies by Field Engineers during the first weeks of work and being paired with other Field Activists for a month.

Farmer Training and Farmer Field Schools. Training and extension will be organised using a participatory approach that emphasises the importance of discussion amongst farmers. This approach is now well established in Mozambique, through the widespread use of Farmer Field Schools (FFSs). The approach recognises that most agricultural problems require a combination of external expertise and local solutions. This is particularly appropriate for water harvesting and conservation agriculture. It is also relevant for micro-irrigation, where the management of new equipment may require outside instruction, but the adaptation of local farming systems to the new opportunities offered requires local adaptation.

When introducing the project in a new area, the first contact will be through a FFS. If there is no FFS in the area, then farmers will be encouraged to form a group of about 25 farmers. These groups will have the potential to become more formal FFS. The project activities will help with the strengthening of these groups, especially when they wish to establish themselves as formal FFSs. However, SPAWM will not provide significant support to FFS activities outside micro-AWM, as this would dilute the impact of the project.

Box 4.5: Past experience with Farmer Field Schools in Mozambique

Farmer Field Schools were first developed in the early 1990s in South East Asia, under the FAO Integrated Pest Management (IPM) programme. The first African FFSs were also involved in integrated pest management, first in Ghana in 1995 and then in Mali and other East and Southern African countries. The original scope was then widened and FFSs became involved in Integrated Crop Production Management (ICPM), where farmers discussed the traditional crop production practices and introduced and tested improved practices. Specialized FFSs focus on specific aspects like soil and water conservation, marketing and AWM for water users groups. The objective of FFSs is to involve farmers more in extension and research, using participatory techniques that encourage shared analysis, experience and decision-making. Evaluations of international experience tend to be positive, in terms of improved efficiency and effectiveness, compared to the T&V system. However, some questions have been asked about the cost effectiveness of FFSs, given the intensive support to weekly sessions and training of trainers. There has also been some concern about the coverage of FFSs and the risks that they can be dominated by more educated and dynamic farmers.

Farmers Field Schools were introduced in Mozambique in 2003 in Namacurra and Nicoadala Districts in Zambezi Province, where 124 FFSs were created involving 400 farmers. In 2004, FFSs were also created in Maputo, Manica and Sofala. A recent study on the effectiveness of FFSs was conducted in the Boane District of Maputo Province, covering 8 of the 38 FFSs in the District and 5 extension agents. The review concluded that the introduction of FFSs had been well managed and appreciated by farmers, with good participation and successful exchange of information. Farmers were generally in control of the activities of the FFS and more than half the farmers used the FFS to try to solve their problems. However, only 5% tried out new practices discussed in the FFS. The FFSs also encouraged some improvement in cooperative actions.

Source: (Dzeco, Amilai et al. 2010)

Discussions in the FFS will start with a participatory diagnostic of existing conditions, selection of the AWM techniques to be introduced according to farmers' priorities, selection of suitable sites and procedures for the introduction of the technologies. Agreement will be reached on inputs to be provided by farmers and by the project and procedures for the installation of the equipment and crop cultural practices. A calendar for the various FFS sessions over the growing season will be set up to monitor the full growing season operation and maintenance of the AWM techniques, as well as the various crop cultural practices.

The FFS approach involves sustained and regular support to farmers with up to 10 sessions per season and extending over several cropping seasons. The FFS sessions will be prepared and animated by the extension workers under the technical supervision of the Field Engineers. Where Field Engineers visit FFSs (eg to provide additional input on AWM design) their presence will be exploited by organising an FFS session to discuss an issue that is topical in the locality. Subjects covered will include:

- installation of the equipment and provision of inputs as agreed with farmers
- operation and maintenance of AWM equipment
- irrigation scheduling
- cropping patterns and rotations, with particular emphasis on the introduction and possible benefits of a leguminous cover crop with conservation agriculture
- options for preparing the seedbed
- use of improved seeds and additional inputs needed to exploit their potential
- use of herbicides and pesticides
- implications of changes in practices for marketing and storage
- business management, including technical support for marketing and assistance in preparing applications for loans from rural financial institutions

Particular emphasis will be placed on conservation agriculture, taking into account the full implications, including direct planting, mulching and weed and pest control.

National Workshops. SPAWM will organise a national workshop each year, for the various stakeholders of the project, including key staff of SPAWM, MINAG and INGC. Some form of representation from farmers, suppliers and contractors will be encouraged. In the first workshop, the programme will be introduced and guidance sought on how best to implement. In subsequent years, results will be presented and constraints discussed.

Regional Workshops. SPAWM will organize one day workshops twice a year at each hub. These will be attended by technical project staff, local government officials and staff from MINAG and INGC. Some form of representation from farmers, suppliers and contractors will be encouraged. The workshops will be organised to present the SPAWM seasonal programmes for the rainy season and dry season and evaluate results and constraints of the preceding season.

Low Cost Tubewell Contractors. Training will be provided to the 9 rota sludge contractors so that they are able to operate the equipment efficiently and safely. The contractors will also be provided with additional training on AWM practices so that they can provide informal advice alongside the well construction.

Equipment and Input Suppliers and Rural Finance Institutions. There are a range of private enterprises involved in the supply of AWM equipment and farm inputs and in rural banking. SPAWM will ensure their engagement in the supply of equipment and in providing adequate repair and maintenance services. Information and training sessions will be provided for these suppliers and bankers at which they will be trained in AWM techniques so that they can pass on this knowledge to their clients and can assess the viability of proposed investments more accurately.

4.6 SCALE, MANAGEMENT, MONITORING AND EVALUATION

Introduction. Support for AWM has traditionally been provided by a project approach, focusing on a limited area and providing integrated support across a wide range of activities, including technical and financial support. This approach was typical of the integrated agricultural development projects (IADPs) in the 1970s and 1980s and has been continued for irrigation schemes that are inevitably focused on a specific area. It has the advantage of offering the full range of support that farmers need and so ensuring that this support is not wasted by the lack of one critical type of support. In theory, concentrated support in one area should lead to demonstration effects that can spread to other areas. However, IADPs had high costs and the benefits were typically concentrated amongst a small number of people.

Concerns about the sustainability of IADPs led to attempts to provide support for AWM, and agriculture more generally, at a national scale using programmatic approaches. There have been two main types of

- government investment programmes, sometimes organise at a sectoral level and sometimes at local levels, are often used to provide a boost to investment over a period of several years
- sector budget support from donors (eg PRAGRI) has attempted to broaden the benefits of donor support, but has often focused on capacity building at the expense of investment and there have been concerns that the programmes do not necessarily provide strong field benefits

However, national programmes have often been problematic and there are few examples of successful national AWM programmes. One particular challenge is the integration of support for equipment with technical support, which seems difficult to achieve at a national level.

New approaches have been tried in some countries, focusing on private sector support (eg in the PROIRRI use of agents). Providing support through the private sector offers potential advantages of sustainability and of leveraging additional private investment. However, there have been problems in ensuring that directing support through the private sector benefits the wider population (eg of farmers) and private public partnerships (PPPs) do not yet have a proven track record in Africa.

Many donors have been providing more support through NGOs, recognising the skills and dedication that NGOs can offer and their sensitivity to local conditions. However, there are now concerns that some NGOs are beginning to operate more like private companies and there are risks that they may lose their grass-roots engagement if recruited for large-scale projects.

Bearing in mind the challenges faced by all the above approaches, some governments and donors have attempted to provide support direct to farmers or to farmers associations. This approach tends to have relatively low administration costs and can provide farmers with more flexibility about how to use the support offered. Vouchers have been used with some success in a range of African countries. Voucher schemes are vulnerable to manipulation, as people exploit rent-seeking opportunities and secondary markets for vouchers emerge. But there are examples of voucher schemes that have lasted for many years without excessive manipulation (eg in Malawi). There can also be some problems in providing matching technical support to complement the voucher schemes.

Nevertheless, the increasing numbers of dynamic small farmers – emergentes - and of agricultural suppliers and rural-urban family links means that there may be opportunities for an approach in-between the conventional project approach and the simplistic approach of 'dumping' equipment.

To assess the appropriate balance, the study has reviewed experience from within Mozambique (IFAD 2007; UN Water 2009; IFAD 2010) and elsewhere in Africa (Penning De Vries, Sally *et al*. 2005; IWMI 2006; IMAWESA 2007; IWMI 2007; IWMI 2009; McCartney and Smakhtin 2010; McCartney 2011).

4.6.1 Scale

In determining the scale of SPAWM, two considerations are important.

- Firstly, the project aims to demonstrate the potential value of AWM nationwide and should therefore operate in the three broad agro-economic zones (ie uplands, valley bottoms and wetlands).
- Secondly, the expertise required to support field activities includes at least two core fields (AWM techniques and farming systems) plus a third field (farm economics and monitoring) that involves less direct contact with farmers but is important for project success. It is rare to find a single national expert who can work effectively across several of these fields, especially if the full range of AWM techniques is to be covered, including water harvesting and conservation agriculture.

The full project proposal developed in this report involves working in three different hubs (one for each agroecological zone) and providing support that spans three main fields of expertise. In order to achieve this, the project provides technical support at three levels: centre, hub and village. At the centre, high level technical support covers all three fields of expertise (ie AWM, farming systems and farm economics). In each hub, mid-level technical support is provided in AWM techniques and farming systems. At the village level, the project is implemented by field agents who will have been trained to a basic level in all three fields.

The management structure described in this report relates primarily to the full project proposal. Two smaller versions of the project are also costed in 4.7: a mid-size version of the project, which is run from a single hub with two experts and 5 field extension agents; and a small version that relies on a single expert and manager supporting 3 extension workers. These smaller version may be considered as alternatives or as preparatory phases to the full project.

4.6.2 Management structure

The project will be supervised by a Steering Committee which will meet annually to approve the annual work programme and for any major strategic decisions required. The Steering Committee will delegate routine supervision to INGC, who will approve monthly progress reports and expenditure release. Daily activities will be managed by the SPAWM National Team that will be recruited and employed by INGC. The consulting company will collaborate with specialist companies and/or NGOs, as required, and will recruit and manage the project staff. The project staff will be located at national level and at the three hubs, in Mabote, Caia and Beira. Field activities will be undertaken primarily by MINAG extensionists and INGC field staff, with financial support from the project. This management structure is summarised in *Figure* 4-16.

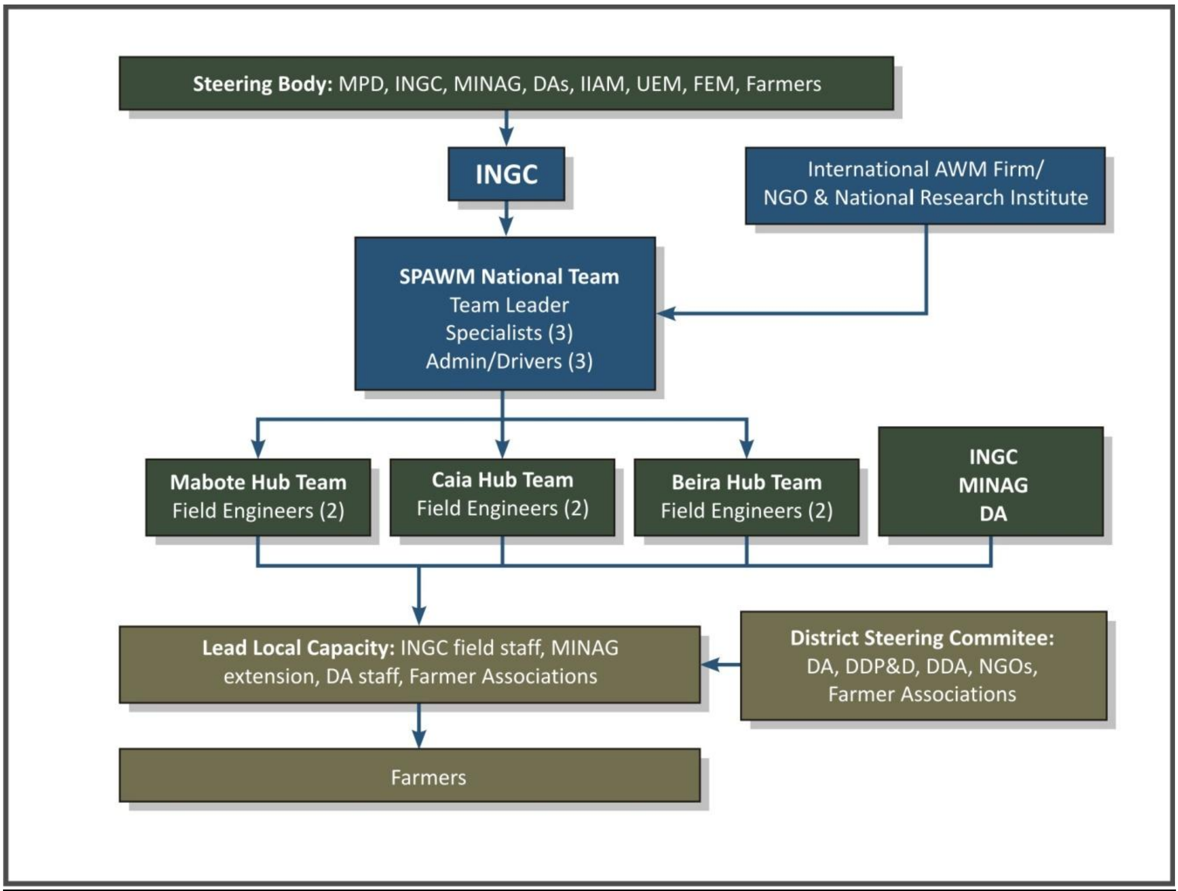


Figure 4-16: SPAWM Management Structure

Supervision. Overall supervision and leadership will be provided by the SPAWM Steering Body (SSB), which will include representatives from the following institutions:

- INGC
- MINAG
- The District Administrations in Mabote, Caia and Beira
- Mozambique Enterprise Foundation (FEM)
- Eduardo Mondlane University Rural Engineering Department
- IAMM
- MPD
- a farmers representative chosen from each of the three regions

The SSB will meet once a year to approve the next Yearly Work Programme and will also be convened at other times, if there are is a need for strategic guidance. Routine supervision will be delegated to INGC, who will be responsible for recruiting and managing the project team and will have some authority to make minor changes in the work programme (see Section 4.6.4).

Management. SPAWM requires a strong team of experts that will be responsible for driving the project forward, for coordinating activities and for the monitoring and adjustment of activities. This team needs to play the following role:

- ensuring project goals and objectives are met
- reporting to the Steering Body
- specifying AWM installations, where these require more complex design
- adapting the training materials provided in Annex A4 and training project field staff
- negotiations with the private sector to provide AWM equipment and inputs and to make contacts for marketing of produce
- analysing monitoring information and recommending changes in activities suggested by monitoring
- managing the project account

SPAWM also requires a capacity at the three hubs to support the field officers in engaging with farmers. This field capacity will need to work with the existing services in the field, but will involve human resources over and above the existing field capacity. The field capacity needs to play the following role:

- ensure that all INGC and MINAG agents are fully trained in the AWM techniques
- ensure that all agents have full access to training material provided to farmers

Project staffing is summarised in *Table* 4-15.

Table 4-15: Project Staffing

PMU Level	Expert	Experience
National Level	Team Leader	20 years
	Subject Specialist 1: Agricultural Engineer	10 years
	Subject Specialist 2: Agronomist	10 years
	Subject Specialist 3: Business and M&E	5 years
	Administrative Assistant	
	Drivers (2)	
Hubs	Engineer 1: Agricultural Engineer	5 years
	Engineer 2: Agronomist	5 years
Field Level	Extensionists, of which 9 existing MINAG and INGC field workers and 6 new extensionists recruited by the project	2 years

The Team Leader will provide overall management of the project and will be responsible for delivering the work programmes specified in the Yearly Work Programme and in the Monthly Reports. All other project staff will report to the Team Leader, who will report to INGC.

The two subject specialists will provide technical support to the field engineers at the hubs, assisting with the design of installations where necessary and ensuring that all field engineers are up to date with training. The subject specialists and the field engineers in each hub will cover two main areas of expertise: the agricultural engineer will have expertise in water management, including irrigation and the agronomist will provide advice on how to adjust crop management practices to make the best use of the improved availability of crop water.

The Business and M&E Expert will provide two functions. Firstly, the Expert will help farmers with planning the business and financing of their installations, and with applications for loans, if needed. Secondly, the Expert will be responsible for the production of the Monthly Reports and will work closely with the Team Leader and others in the team on the production of the Yearly Work Programmes and the Yearly Evaluation Reports.

District Steering Committee. Local activities will be supported by a District Steering Committee (DSC) that will meet four times a year. The DSC will approve the work programme for the district. Any variations in the work plan during the year will also need to be approved by the DSC. The DSC will be chaired either by the District Administrator or the District Director for Planning and Development and membership will include: DD Agriculture; any local INGC representative; relevant NGOs; and representatives from farmers associations and private traders engaged in input supply or marketing. The DSC will not approve daily activities of the project, such as the selection of beneficiaries or decisions about which AWM techniques to support.

Field Activities. Much of the work with farmers will be undertaken by existing extension staff at MINAG and field agents at INGC, working in collaboration with the District Administration. Salaries will not be required for these extensionists, but operating expenses will need to be provided as their existing budgets are not sufficient to allow them to travel amongst farmers. These expenses should include a motorcycle. Where MINAG or INGC field staff are not available, the project will recruit additional staff and will cover their salaries. The budget includes salaries for 5 of the 15 field staff in each hub. The reason for not providing salaries for all staff is not to save on costs, but to try to ensure the best possible engagement with any existing field staff from INGC and MINAG, and so to promote the sustainability of the project.

Good cooperation between INGC and MINAG at the field level will be essential. In most places, this cooperation takes place naturally under the general coordination of the Centres for Economic Services of the District Administration. Where both INGC and MINAG staff are active in a locality, the hub will seek to involve all staff, to encourage the spread of experience amongst as wide a range of field staff as possible. However, it will probably be necessary for each village to have only one lead contact.

Private Sector. The project will rely on the private sector in two main ways:
AWM equipment and inputs will be purchased from private sector suppliers

- the marketing of crops will be done exclusively by the private sector
- assistance to farmers in applying for loans for AWM-related investments

Suppliers of AWM equipment and inputs (including fuel and spare parts) are active in the main cities of Mozambique, including Beira. They do not have permanent representation in the rural areas of Mabote and Caia, except to supply basic farming inputs, but are interested in travelling to the areas to sell equipment and inputs. Ideally, project beneficiaries should buy AWM equipment and inputs directly from private suppliers. However, even when private suppliers are active nearby, most of the project beneficiaries are not in a position to buy AWM equipment or inputs directly from private suppliers, because they do not have sufficient financial resources. Thus, in most cases, the project will be purchasing the AWM equipment and inputs from private suppliers and making it available to beneficiary farmers, subject to agreement on receiving the farmer's cost contribution.

This arrangement will apply in the first year, when adoption is subsidised. In the second year, when there will be no further subsidies, farmers will have to make their own arrangements with private suppliers for the supply of AWM inputs. The project will work to encourage and facilitate the expansion of activities by private suppliers, especially in the more remote areas of Mabote and Caia. This could include sponsoring occasional fairs or other events at which suppliers are encouraged to sell their products and make contacts with farmers.

The project will encourage private suppliers to provide technical support to farmers, wherever possible. Whilst this support will be an important part of the longer term outlook for AWM techniques, it is not expected that private sector advisory services will be able to take over the role of public advice and extension in the medium term, especially for the most vulnerable farmers that are the target beneficiaries for SPAWM.

The project will not be engaged in importing AWM equipment and inputs, except where there is some piloting work of new technologies, that require equipment that is not available locally.

The benefits of the project depend on successful marketing of crops. This will be done exclusively by the private sector. However, the project will provide some incentives designed specifically to encourage traders from Beira to visit the project areas and establish contacts with project beneficiaries. These will be limited to a pre-defined number of initial visits and might include, for example, subsidising the cost of renting a vehicle to transport new products to Beira, for a limited period. Discussions with traders in Beira suggest that there is strong interest in new sources of supply and that traders are willing to organise transport and systems for advance purchase of crops, once a degree of trust has been built up with farmers.

The project will not engage in providing rural financial services, except to the extent that it will accept that farmers' contributions may be delayed until after harvest. However, the extension staff will work with farmers to help them access any private rural financial services that may exist. In particular, they will help farmers who are interested to prepare loan applications and will provide references, if appropriate.

4.6.3 Financial management

The project will be funded using a conventional project special account, managed by the INGC. This will receive income from donors and any funding from government. Project staff will be managed by a consulting company, with associated institutions, as required. This company will receive from the special account an advance payment covering two months of activities in the annual work programme. Further disbursement each month will be conditional on brief monthly progress reports demonstrating that the previous month’s activities have been successfully completed. The brief monthly progress reports should compare actual activities and expenditure with those defined in the annual work programme, so that any major differences can be picked up at an early stage and measures can be taken to address any problems that are emerging.

Payments from the special account for equipment provision will also be included in the monthly disbursements approved by INGC, with the possibility of disbursements at other times. These monthly payments may be made to the institution responsible for implementing each individual installation, which could include any of the following:

- the consulting company
- private suppliers of equipment
- farmers associations, where these are considered sufficiently well developed
- the local district administration, MINAG or INGC field office

In all cases, the disbursements will need the approval of the consulting company and the field staff or either MINAG or INGC. This approval will be in the form of countersignature of a standard installation form.

Farmers contributions to the cost of equipment will be made direct to suppliers. Where farmers ask for their contributions to be delayed until harvest, these payments should ideally be made direct by farmers to suppliers. If necessary, SPAWM will offer to guarantee these delayed payments. The price charged by suppliers can be expected to include a fee for delayed payments.

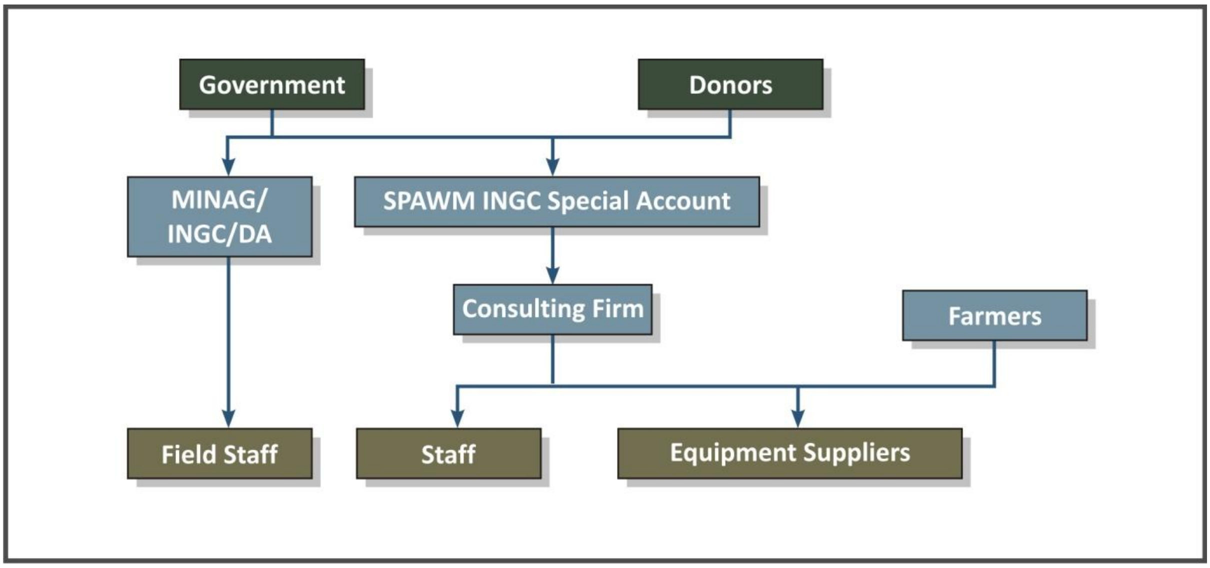


Figure 4-17: Financial Flows

The project will be recorded in the government's budget to facilitate integration into government planning and possible replication. However, the financial procedures will not be integrated in the Treasury systems, except for contributions from government.

The project will be subject to annual audit, undertaken by an independent firm of accountants. A budget of $5000 per year is included in the costing for this.

4.6.4 Reporting and adapting the programme

Yearly Work Programme. The SPAWM PMU will produce yearly work programmes (YWPs)[10] in collaboration with INGC. The YWP will include an estimate of the number of FFSs, installations and farmers that will be supported from each hub along with a monthly budget showing the expected expenditure. Approval of the YWP is the main function of the Steering Body which should be expected to question the balance and realism of the YWP proposals.

Yearly Evaluation Report. The second and third year YWPs will be accompanied by a Yearly Evaluation Report (YER). As the YER will need to be prepared about three months before the YWP needs to be approved, it will be based only on the first 9 months of the year, plus progress in any previous years. The YER will cover the following elements.

- Activities undertaken, including expenditure and outputs delivered. Data will be provided on the number of beneficiaries and the area benefiting from each AWM technique. In addition, the YER will report on training activities undertaken. The actual achievements will be compared with the targets in the YWP and differences will be explained.
- The water resources and livelihoods in each of the 45 new FFSs supported and a summary of the discussions undertaken in FFSs about the suitability of AWM techniques in each village. This information will be summarised in suitability maps, building on the methodology developed by the FAO Agricultural Water Solutions Project (AWSP) (FAO 2011). This methodology will be extended it to take account of new issues discovered during the project. The suitability maps will provide the structure required to evolve rigorous approaches to assessing suitability across the project.
- The above information will be used to analyse the cost effectiveness and expected impact of the AWM techniques on improved incomes and climate resilience. It will not be possible to report definitive quantitative evidence on production, sales and prices, since this takes several years to come to fruition and would require expensive surveys. However, the YER will report all available evidence, including reporting by project staff of estimated yield impact. Some additional survey work will be done for the YERs including consultation amongst participating and non-participating farmers to gather their views on the likely future impact of the project. This analysis will compare the actual and expected benefits with the costs of the AWM techniques for every installation supported by the project in each locality.
- Each YER will conclude by comparing the actual costs and benefits with those defined in this Appraisal Report and by explaining the differences and the implications of these differences for future project activities.

Monthly Reports. The project will also produce monthly reports (MRs) on activities, which will provide the basis for disbursement against the monthly budget in the YWP. These will present information on activities for the past month and a plan of activities for the next month. MRs will describe the number of FFSs, installations and farmers involved in in the previous month's activities and the expenditure involved, both from the project and from farmers. Where the actual activities and/or expenditure is significantly different to the plan for the previous month, explanations will be provided.

[10] The report is called a Yearly Work Programme, rather than an Annual Work Programme to avoid confusion in acronyms between AWP and AWM

Independent Input. A modest contract will be issued to an independent body to provide independent input into MPRs and YERs. This role is intended partly to provide independent verification of the monitoring information and partly to give additional insight and suggestions for the management of the project. The contract will include spot checks on the information provided in MPRs as well as a review of each YER.

Accounts and Audit. The project will produce annual accounts, which will be audited by the independent auditors.

4.6.5 Integration with water Decision Support System

The other subcomponents of the INGC Second Phase study are contributing to a Decision Support System that will help manage water resources across the country. Section 4.8.3 presents the impact of the project on the water balance and shows that micro-level AWM is unlikely to play a significant role in national water resources decision systems. However, it is possible that there will be some localised impact on sensitive smaller rivers and the project will need to monitor this locally to avoid creating any local tension.

4.7 PROJECT COSTS

4.7.1 Costs of the Full Project

The project costs include both the direct costs of working with farmers (including training and the supply of equipment and inputs for AWM techniques) and the complementary supporting costs of management and extension. Experience in other projects suggests that simply providing equipment and inputs without training and extension is ineffective and international experience offers a number of models for ensuring that sufficient central support is provided to field extension agents to ensure that farmer training and extension is effective.

The total costs are $2.49m and are presented in *Table* 4-16. Extension and management account for $1.22m, training for $0.65m and equipment and inputs for $0.76m. Farmer contribution to the cost of equipment and inputs will reduce project costs by $ 0.15m.

Table 4-16: Summary Costs

	Costs ($)			
	Y1	Y2	Y3	Total
Summary				
Extension and Management	513,300	360,800	350,800	1,224,900
Training	183,630	234,170	234,170	651,970
Subsidies and Incentives	253,434	253,434	253,434	760,303
less farmers contribution to costs	0	75,540	75,540	151,080
Total	950,364	772,864	762,864	2,486,093

Extension and Management Costs. The project will be managed be a Team Leader and three National Experts covering:

I. AWM, including the design of micro-irrigation systems and water harvesting)
II. farming systems and conservation agriculture, including the techniques required to adjust cropping practices to exploit the opportunities arising from improved access to water
III. farm management, including business advice to farmers and project monitoring and evaluation.

This national team will be supported by a contract with a specialist international organisation (such as a consulting firm, NGO or research institute), who will offer additional backstopping expertise in micro-irrigation, water harvesting and conservation agriculture. The contract will include three visits to Mozambique in the first year, two in the second and one in the third.

The project will also fund the salaries of 6 Field Engineers, with two in each hub, covering AWM and farming systems. Routine contact with FFSs and farmers will be undertaken by extension staff, including those already employed by MINAG and INGC, plus those recruited by the project.

The project will fund the salaries and expenses of the Team Leader, the 2 National Experts and the 6 Field Engineers, plus one administrative assistant and two drivers. Where MINAG and INGC have existing field agents and Extensionists, their salaries will not be covered by the project. However, the project will have a budget for two Extensionists in each hub, to fill the gaps where MINAG and INGC are not represented. The project will provide per diems and travel expenses, including motorcycles, for all field workers, including those employed by MINAG and INGC. The project will also cover the costs of the NGO contract. A 4WD vehicle will be provided in the head office and in each of the hubs. Extension Agents will be provided with motorcycles. Total costs are presented in

Table 4-17: Extension and Management Costs

			Units			Costs ($)			
			Y1	Y2	Y3	Y1	Y2	Y3	Total
Staff	$/month								
International support	5000		6	4	2	30,000	20,000	10,000	60,000
Team Leader	4000		6	6	6	24,000	24,000	24,000	72,000
National Experts (3)	2500		36	36	36	90,000	90,000	90,000	270,000
Field Engineers (6)	1500		72	72	72	108,000	108,000	108,000	324,000
Extensionists (6)	400		72	72	72	28,800	28,800	28,800	86,400
Admin support	500		12	12	12	6,000	6,000	6,000	18,000
Drivers	200		24	24	24	4,800	4,800	4,800	14,400
Audit						5,000	5,000	5,000	15,000
Total						296,600	286,600	276,600	859,800
Per Diem	$/night								
Maputo	140		30	30	30	4,200	4,200	4,200	12,600
National Experts	140		75	75	75	10,500	10,500	10,500	31,500
Field Engineers	65		100	100	100	6,500	6,500	6,500	19,500
Extension Agents	65		300	300	300	19,500	19,500	19,500	58,500
Drivers	25		100	100	100	2,500	2,500	2,500	7,500
Total						43,200	43,200	43,200	129,600
Vehicles	Invstmt	O&M							
Maputo - car	30,000	4000	1	1	1	34,000	4,000	4,000	42,000
Hub - 4WD	30,000	7500	3	3	3	112,500	22,500	22,500	157,500
Extension Agents - moto	1,500	300	15	15	15	27,000	4,500	4,500	36,000
Total						173,500	31,000	31,000	235,500
Total						513,300	360,800	350,800	1,224,900

Training Costs. The main costs of training will be those associated with Farmer Field Schools. The project will work with 45 new FFSs each year. During the first year of contact, the FFSs will be supported with two cycles of 10 sessions, one for the wet season and one for the dry season. Each session will cost $150, including the costs of farmers incentives ($50), training materials ($25) and expenses for the site, staff and reporting ($75). Cost per FFS will therefore be $3000 in the first year of contact and support will also be continued into the following year, but at 40% of the full level. The support to each FFS will stop after two years. Those FFSs starting in Y3 will not receive the second year of support as the project and Extension Agents will need to adjust the support in Y3 to take this into account and to encourage the FFSs to be as self-sufficient as possible in Y3. This may be achieved by establishing links with a nearby FFS that is better established.

Training for Extension Agents will take place twice a year, to prepare for the season's FFS training and the project activities. This session will bring together all Extension Agents for one week and will include presentations and exercises to encourage exchange of experience amongst Agents. Each session will have a budget of $7050 per season, including the costs of training materials ($1800), per diem ($3600) and expenses for site, staff and reporting ($1650).

Field Engineers will also have a training session each season with a budget of $3460, led by the National Experts. In the first season, this will last 2 weeks and will cover all the technical options and issues of project management. In subsequent seasons, the sessions will last one week and at least one day will be devoted to sharing experience of recent work, to be led by the farm management expert who is also responsible for monitoring and evaluation.

In addition to the above training activities, 2 seminars will be organised each season, with one at national level and one at each hub. These will last one day and will allow a wider group of people to be involved in strategic planning and review, including: other government officials, farming associations, NGOs, press and related projects. The national seminars will have a budget of $2430 and the hub seminars a budget of $485.

Finally, a budget of $2730 per season per hub will be reserved for support to engage the private sector in AWM activities, either through seminars or through open days.

Table 4-18: Training Costs

			Units			Costs ($)			
			Y1	Y2	Y3	Y1	Y2	Y3	Total
Training	cost/event								
Field Engineers	3,460	$/season	3	2	2	10,380	6,920	6,920	24,220
Extension Agents	7,050	$/season	2	2	2	14,100	14,100	14,100	42,300
FFSs	1,500	$/season	90	126	126	135,000	189,000	189,000	513,000
National Seminar	2,430	$/season	2	2	2	4,860	4,860	4,860	14,580
Hub Seminar	485	$/season	6	6	6	2,910	2,910	2,910	8,730
Private Sector Workshop	2,730	$/season	6	6	6	16,380	16,380	16,380	49,140
Total						183,630	234,170	234,170	651,970

<u>Farmer Subsidies and Incentives</u>. The farmers that are most vulnerable to climate change are also the poorest and have very limited access to savings and resources that can be used to fund investments or to take risks with new farming practices. Therefore, the project will provide subsidies and incentives to farmers to help with the adoption of new techniques and, hence, with improved yields. The purpose of these subsidies is to encourage the adoption of viable techniques that provide sufficient benefits to farmers to cover operation and maintenance costs and the future replacement of equipment. They are not intended to support techniques that have no chance of becoming viable and that will be dependent on continued subsidies, at least in the medium term. Because of the importance of encouraging sustainability and avoiding dependence on subsidies, the project will support a National Farm Management Expert who will work with Field Engineers, Extension Agents, FFSs and farmers to encourage full awareness of the viability of techniques and will supervise monitoring procedures that report on viability. This arrangement emphasises the fact that the aim of the project is to increase yields and climate resilience and not simply for farmers to adopt AWM techniques.

Recent experience from INGC in Caia and Mabote suggests that vulnerable farmers can provide no significant up-front contributions to investment costs. They are prepared to make a contribution after harvest, but this contribution is unlikely to be more than about 10% of the investment costs, depending on the level of investment involved in the AWM techniques. The INGC experience also suggests that, in the first year of adoption, vulnerable farmers are unable to fund the increased costs of farming associated either with the operation of AWM equipment or the purchase of inputs needed to exploit fully the potential of the new equipment. Once the yield benefits are achieved, farmers should then be able to afford on-going operating costs, although it is always difficult to wean farmers off a subsidy mentality and care will be taken in the project to ensure that farmers understand that the subsidies are provided only in the first year. For poorer farmers, the project provides a 90% subsidy on investment costs and a 50% subsidy on operating costs and the costs of selected inputs, excluding labour costs. For lead farmers, the level of subsidy is reduce to 50% of investment costs and there is no subsidy on operating costs or on farm inputs. These subsidies are paid only on the first season of operation and all farmers are expected to cover the full costs in subsequent seasons.

Table 4-19: Average Subsidy Required for Equipment and Inputs ($/ha/season)

		Vulnerable farmers	Lead farmers
A1	Moto + surface	1393	553
A2	Moto + hose	853	279
B	Well + treadle	1777	854
C	Shallow tubewell + submersible pump	1480	576
D	Water harvesting: maize/beans	545	275
E	Conservation agriculture: maize/beans	200	100
F	Bunding & drainage	1393	553

The varying subsidies required for the different options are not an indication of the economic attractiveness of the options, which is dealt with in Section 4.8.2. This is because each of the techniques generates very different net benefits.

The project will work in 45 new FFSs in each year, with an average of 3 AWM sites per FFS affecting 4.5 hectares per site, giving a total of 203 ha per year, in total. The suitability of the options varies between the agro-ecological zones. For budgeting purposes, it is assumed that water harvesting and conservation agriculture will be most popular in Mabote, with some tubewell development where water tables are not too deep. In Caia, it is assumed that moto pumps will be most popular but that conservation agriculture will also be widely adopted. In Beira, it is assumed that there will be interest in all three irrigation and drainage techniques and that conservation agriculture will also be widely popular. Because conservation agriculture can be practiced on areas that also benefit from micro-irrigation, some farmers may receive the insurance benefits for conservation agriculture as well as the subsidies for micro-irrigation or water harvesting.

The subsidy required in presented in *Table* 4-20.

Table 4-20: Costs of Farmer Subsidies and Incentives

	Area	Cost/ha	Hectares			Costs ($)			
			Y1	Y2	Y3	Y1	Y2	Y3	Total
Farmer Subsidies - all hubs									
A1: moto pumps + furrow			7	7	7	10,721	10,721	10,721	32,162
A2: moto pumps + pipes			37	37	37	38,575	38,575	38,575	115,725
B: well + treadle			7	7	7	14,775	14,775	14,775	44,324
C: rota sludge + electric			27	27	27	44,129	44,129	44,129	132,387
D: WH maize/beans			47	47	47	30,713	30,713	30,713	92,137
E: CA maize/beans			64	64	64	77,360	77,360	77,360	232,081
F: bunding/drainage			14	14	14	21,441	21,441	21,441	64,324
Total			203	203	203	237,714	237,714	237,714	713,141
Other subsidies									
Start-up for rota-sludge		2000	9	3	3	10,721	10,721	10,721	32,162
Marketing support						5,000	5,000	5,000	15,000
Mabote	33%	of project area							
A1: moto pumps + furrow	0%	1588	0	0	0	0	0	0	0
A2: moto pumps + pipes	0%	1039	0	0	0	0	0	0	0
B: well + treadle	0%	2189	0	0	0	0	0	0	0
C: rota sludge + electric	10%	1634	7	7	7	11,032	11,032	11,032	33,097
D: WH maize/beans	50%	650	34	34	34	21,938	21,938	21,938	65,812
E: CA maize/beans	40%	1206	27	27	27	32,573	32,573	32,573	97,718
F: bunding/drainage	0%	1588	0	0	0	0	0	0	0
Total	100%		67	67	67	65,543	65,543	65,543	196,628
Caia	33%								
A1: moto pumps + furrow	10%	1588	7	7	7	10,721	10,721	10,721	32,162
A2: moto pumps + pipes	30%	1039	20	20	20	21,041	21,041	21,041	63,123
B: well + treadle	5%	2189	3	3	3	7,387	7,387	7,387	22,162
C: rota sludge + electric	20%	1634	14	14	14	22,064	22,064	22,064	66,193
D: WH maize/beans	10%	650	7	7	7	4,388	4,388	4,388	13,163
E: CA maize/beans	25%	1206	17	17	17	20,358	20,358	20,358	61,074
F: bunding/drainage	0%	1588	0	0	0	0	0	0	0
Total	100%		67	67	67	85,959	85,959	85,959	257,877
Beira	33%								
A1: moto pumps + furrow	0%	1588	0	0	0	0	0	0	0
A2: moto pumps + pipes	25%	1039	17	17	17	17,534	17,534	17,534	52,602
B: well + treadle	5%	2189	3	3	3	7,387	7,387	7,387	22,162
C: rota sludge + electric	10%	1634	7	7	7	11,032	11,032	11,032	33,097
D: WH maize/beans	10%	650	7	7	7	4,388	4,388	4,388	13,163
E: CA maize/beans	30%	1206	20	20	20	24,430	24,430	24,430	73,289
F: bunding/drainage	20%	1588	14	14	14	21,441	21,441	21,441	64,324
Total	100%		67	67	67	86,212	86,212	86,212	258,636

Budgeting and Cost Allocation. Each FFS will have an indicative budget of about $4000 for training in the first year, plus a further $1000 for follow up training in the second year. Each FFS will also work with an indicative budget of about $5,500 for subsidies and incentives for new AWM techniques. Making commitments of more than this budget will be possible only with approval from the national project office. FFSs will be involved in discussing how best to use their budget and this will ensure that the best techniques are selected. The FFSs will also be aware of the target of bringing 4.5 ha under AWM techniques.

4.7.2 Smaller Versions of the Project

The full costs of the project show the minimum scale required to operate in all three broad agroecological zones, offering the full range of AWM techniques, whilst also ensuring that the techniques supported in each area are technically viable, as well as being economically sustainable and suited to farming systems. Smaller versions of the project are also possible, offering more limited coverage.

The basic building block is a single field extension worker, who supports a few villages and encourages about 75 farmers to adopt new AWM techniques on about 13ha. In Mozambique, the costs of an extension worker are about 4,000 $/year, including salary, per diem and transport[11], but excluding any training for the extension worker. The analysis in this report suggests that each extension worker needs to have supporting costs of about 17,000 $/year for farmer incentives and a further 10,000 $/year for training expenses. The total cost of this building block is therefore about 31,000 $/yr. The level of farmer incentives or subsidies required depends on the AWM techniques that are most appropriate in each location. For the main techniques shortlisted, the cost of incentives per hectare varies from just over $1000 (for moto pumps and pipes) to over $2000 (for treadle pumps and shallow wells). Supporting the more expensive techniques can add between $800 (for drip) to $1300 to the incentives needed per hectare.

The full project involves 15 field extension agents and their direct costs are therefore about 450,000 $/year. The supporting costs of management and extension are $ 460,000 in the first year and about 325,000 $/year thereafter.

Mid-scale Project in one Hub. If the operations of the project were limited to a single hub, then most of the costs of the project could be reduced roughly in proportion to the number of field extension agents. For example, if there were 5 field extension agents, then the costs would be a third of the full project costs (ie about 150,000 $/year). Operating in one hub only, the project could be managed by a team of three experts. Whilst this would eliminate the need for the middle level of management, it would mean that the costs of the relatively expensive national experts would be spread over a smaller number of farmers. Assuming that the three experts were recruited on the same terms as the national experts in the full project proposal and that they shared a single vehicle, the cost of management would be $ 150,000 in the first year and 120,000 $/year thereafter, which is roughly one third of the management costs for the full project. This suggests that it would be possible to establish the project in one hub at a cost that is about a third of the full project costs. Provided that one of the experts recruited could provide the same overall quality of supervision as the team leader, the IRR of the mid-sized project would be similar to that of the full project. However, the relevance of the results would be largely limited to one main agroecological zone. In addition, if the hub selected were Mabote or Caia, the project would not have such good links with Beira and it would therefore be more difficult to support contacts with suppliers and traders.

Small-scale Project. A small scale project could be managed by one expert and involve only three field extension agents working in a few villages each and encouraging 225 farmers to adopt AWM techniques. This is the model sometimes adopted by NGO projects. Smaller projects can be very effective, both in improving farmers livelihoods and it demonstrating new techniques and approaches. However, they are difficult to sustain and to replicate on a large scale, for several reasons.

- They depend on the availability of experienced field agents who are often scarce. In some (but not all) cases, smaller projects have to pay relatively high wages to recruit extensionists that can be relied on to deliver without an extensive network of support.

[11] These costings assume that 60% of the salary costs of field extension agents are covered by MINAG or INGC because most of the agents will already be employed by MINAG and INGC. The costs of transport are not spread evenly through the period, as they include purchase of motorcycles in the first year.

The SPAWM approach involves working as much as possible with existing field agents employed by INGC and MINAG.

- Where smaller projects depend on relatively intensive technical support, this scarce resource is spread over a relatively small overall impact. In NGO projects, the central technical support is often provided by the NGO and, although there may be no direct costs to the country or to farmers, the NGOs themselves have limited capacity and there is a high opportunity cost to their support.

In the small version of the SPAWM project, the three field extension agents would cost about 90,000 $/year and the supporting management costs would be about $ 70,000 in the first year and about 50,000 $/year thereafter. The proportion of costs associated with management is higher than in the mid-size project and full project and the IRR will therefore be slightly lower.

The main disadvantage of the smaller project is that it will not be possible to explore fully the opportunities for AWM techniques, because the single supporting expert will not have the breadth of experience that is offered by having the three experts in both the mid-size project and the full project. In particular, a small project is unlikely to be able to assess both the technical and economic sustainability of AWM techniques, unless additional overhead costs are added. The small project could be justified as a preparatory project for the full project but care will need to be taken that the lessons learnt from such a preparatory project are balanced and this will not be easy without access to the full range of experience required.

4.8 OUTPUTS AND IMPACT

4.8.1 Crop Production

By the end of the period, the project will have affected 607ha. About half of this will be under blue water techniques, which will be used mainly for dry season vegetables. This will result in an increase in vegetable production of about 3,000 tons/year, most of which will be sold in local markets and in Beira. There are no official figures for the production of vegetables in Mozambique. However, if it is assumed that households consume a similar quantity of vegetables to cereals, then Zambezi and Sofala Provinces would consume about 400,000 tons/year. Most of this will be consumed by the households that grow the vegetables. Consumption is growing at 5% a year, or about 20,000t for Zambezi and Sofala. The project will not supply all the area in both provinces, but will sell some product to other provinces. The project will therefore make a modest but significant contribution to demand, supplying 15% of the increased demand for vegetables in the region. The increased production will be greater than can be absorbed in local markets and the project will be dependent on selling to the Beira market.

The increased production will be on a sufficient scale to depress prices in the areas where crops are growing. Farmers will seek to sell outside the area in the main markets, such as Beira, where their increased production should have little effect on market prices.

4.8.2 Cost Benefit Analysis

The justification for SPAWM depends on demonstrating that the benefits are higher than the costs. This section considers the costs and benefits from an economic perspective, rather than a farmer perspective. As a result, there are some adjustments from financial to economic prices. In Mozambique's relatively open market economic the only adjustment that is made is to deduct the tax element from market prices. This affects fuel prices, in particular.

Cost and Benefits in Years of Normal Rainfall. The costs and benefits from the AWM options are summarised in *Table* 4-21 and *Figure* 4-18. The table suggests that the Benefit Cost Ratios vary from 2.0, for water harvesting, up to 5.5 for Option A2 (ie moto pumps with surface water source, pipes and hose). The costs include labour costs and, for conservation agriculture, they assume that there will be a 40% drop in yield in the first year and then a steady increase in yield to 40% above normal yields over 5 years. The costs show the BCR for the farmer and do not take into account the management and extension costs, which are considered in the estimation of overall project IRR.

Table 4-21: Costs and Benefits of Shortlisted AWM techniques ($/ha/season)

	Annual Costs	Annual Benefits	Benefit Cost Ratio
A1: moto + furrow	673	2283	3.4
A2: moto + hose	419	2283	5.5
B: well + treadle	718	2283	3.2
C: rota sludge + electric	662	2283	3.5
D: WH: maize/beans	138	269	2.0
E: CA: maize/beans	166	738	4.4
F: Wetland drainage	673	2283	3.4

Notes: costs are based on Table 4-4; incremental yield is based on crop budgets for Caia as presented in Table 4-7, assuming a blue water technique

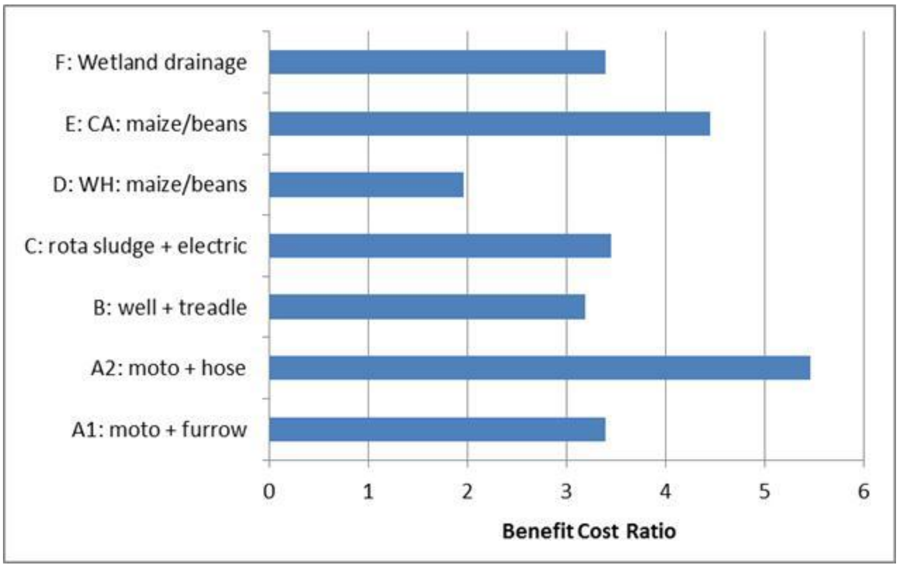


Figure 4-18: Benefit Cost Ratios for the Main AWM Options

The analysis above presents the Benefit Cost Ratio, taking into account only the costs of AWM investment and inputs and excluding the costs of training and project management. The project budget suggests the costs of investment and inputs are about 30% of the budget.

Table 4-22 shows the cost and benefits stream, taking into account all project costs and the value of increased farm margins. The analysis assumes the project costs follow the budget presented in Section 4.7. The AWM operating costs are excluded from the investment costs and are considered as operating costs deducted from farm margins. To avoid double counting investment costs, the farm margins exclude the part of irrigation costs that are associated with depreciation on investment.

Table 4-22: SPAWM Costs and Benefit Stream, excluding Climate Resilience and Replication

		Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Costs ($'000)											
Technical Assistance		513	361	351							
Training		184	234	234							
Subsidies & incentives		253	253	253							
less farmer contributions		0	76	76							
Total		950	773	763							
Farm Benefits	$/ha										
A1: moto pump	1790	12	24	36	36	36	36	36	36	36	36
A2: moto + hose	1790	66	133	199	199	199	199	199	199	199	199
B: well + treadle	1790	12	24	36	36	36	36	36	36	36	36
C: rota sludge + electric	1790	48	97	145	145	145	145	145	145	145	145
D: water harvesting	269	13	25	38	38	38	38	38	38	38	38
E: CA - maize/beans	738					47	95	142	142	142	142
F: Wetland drainage	1790	24	48	73	73	73	73	73	73	73	73
Total		176	352	528	528	575	622	669	669	669	669
Net Benefits		-775	-421	-235	528	575	622	669	669	669	669
IRR		24%									
Dry spell protection		14	28	43	43	43	43	43	43	43	43
Revised Net Benefits		-760	-393	-193	570	617	665	712	712	712	712
Revised IRR		27%									

The analysis suggests that the headline rate of return[12] (IRR) for the project is 24%. It is assumed that the benefits achieved during the three year project are sustained at the same level from Y4 onwards. Whilst this may be considered an optimistic assumption, the analysis also considers that there will be no wider demonstration effect, which is a conservative assumption with comparable potential implications.

Additional Benefits from Resilience to Rainfall Variability. The above analysis applies to years of normal rainfall. For blue water AWM techniques, the benefits are assumed to come from dry season irrigation and it is usually of little value to use the techniques in the wet season, if rainfall is plentiful. Water harvesting and conservation agriculture provide benefits by generating increases in wet season production.

However, if the investment has been made in AWM equipment, there are potential gains to be made in using this equipment in the wet season if the rainfall is below normal or if there are short dry spells that threaten to damage the crop. Section 4.4.3 considers the benefits from supplementary irrigation in the wet season, to protect against dry spells and drought and

[12] The IRR refers to the discount rate at which the discounted benefits equal the discounted costs. It is very roughly comparable with a real rate of interest on investment, but is calculated from the perspective of Mozambique as a whole, including all the actors affected by the project (ie government, farmers and private sector) and estimated in economic prices, rather than financial prices.

suggests that the average annual value of this protection is about 26% of wet season production. If these benefits are included, then the IRR increases to 28%.

It is clear that climate change is going to lead to higher rainfall variability. However, there is limited evidence, as yet, on the magnitude of this change. Some first indications are available from the preliminary SREX report recently issued by the IPCC (IPCC 2011). These are not yet in a form that can be easily used for modelling impact[13]. They suggest that Mozambique will see an increase in the frequency of longish periods of Consecutive Dry Days, but that this increase will be relatively moderate compared to some parts of the world. However, as this data appears to relate to the length of the maximum number of Consecutive Dry Days, it appears to relate more to the length of the dry season rather than to the frequency or length of dry spells in the wet season.

Without any basis for estimating the impact of climate change on rainfall variability, it is not possible to estimate whether an increased frequency and duration of dry spells in the wet season will have a major impact on the returns from SPAWM. However, some indication of the order of magnitude of the impact changing patterns of dry spells in the wet season is given by the fact that taking into account current patterns increases the IRR from 24% to 27%. Whilst this is a significant increase, it is not a large increase and the viability of the project does not depend on this increase. Even if climate change doubled the severity of the impact dry spells on wet season production, it could be expected to add only another 3% to the IRR. However, these estimates are only very indicative as the relationship between the length and frequency of dry spells and crop production is extremely complex, and depends on the timing of the dry spell in the growing season and the extent to which crops are being grown close to thresholds. The level of detail provided by climate change projections are not yet sufficient to allow stronger conclusions to be drawn.

<u>Sensitivity analysis.</u> The impact of different assumptions on the IRR is summarised in *Table* 4-23. This shows that the project is sensitive to assumptions on labour value and to crop yields and prices. The assumptions about crop yields relate to the yields that will be achieved when AWM techniques are available, both in the dry season and in the wet season, when AWM techniques protect against rainfall variability. In particular, project performance is highly sensitive to assumption on the yield and price of vegetables. Collecting data for vegetable prices is a notoriously difficult and, in common with most African governments, there is no official price data published by government. The data on prices used in this analysis was based on discussions with traders about recent trends in prices. Fuel costs are also important, but have a lower impact, unless prices increase dramatically.

[13] For Mozambique, they suggest that the maximum number of Consecutive Dry Days is likely to increase by 0.4 times the standard deviation in interannual variability of rainfall, but there is no reference data for the this interannual variability.

Table 4-23: Sensitivity of IRR to Assumptions

	Baseline value	Sensitivity Test	
		Change	Revised IRR
Headline IRR			24%
Labour value	1 $/day	+20%	20%
Fuel cost	0.9 $/lt	+20%	23%
Irrigated vegetable yield (Caia)	12.0 t/ha	-10%	16%
Maize yield (Caia)	1.3 t/ha	-10%	24%

Note: a 10% change in crop prices gives the same sensitivity results as a 10% change in yield.

4.8.3 Impact on water balance

The volume of water affected by the SPAWM project is very small, compared to other users. The project is expected to affect about 600ha by the end of year three, of which about 300ha involves blue water irrigation and the rest water harvesting and conservation agriculture. The blue water irrigation involves making about 3200 m3/ha/season of water available to plants, which will require about 6400 m3/ha/season, with a conservative assumption of 50% irrigation efficiency. By the end of the period, about 250ha will be under blue water irrigation, suggesting a total use of about 1.6 mcm. This is extracted from rivers or from groundwater reserves and thus reduces water available for other purposes.

The potential water used by the blue water irrigation technologies will be partly compensated by the water harvesting and conservation agriculture technologies, which will increase infiltration into the subsoil and reduce surface runoff in the rainy season. The increased water infiltration will recharge and raise groundwater levels and increase dry season stream discharges. The increased groundwater will ensure a better water reliability for blue water irrigation technologies as well benefiting drinking and stock watering.

The total volume of water affected by the project is about 1 hour's flow of the Zambezi river. However, the project aims to act as a catalyst for further expansion of AWM techniques. In Zambezi, for example, there are about 6m hectares of land that is either very suitable or suitable for AWM, which suggests that there is great scope for the expansion of AWM. For example, if the rate of adoption achieved in the project were to double, it would take over 50 years before 1% of the flow of the Zambezi were required. In practice, the limits to expansion will come from the expansion of market demand for products, rather than from availability of water.

In Mabote, the impact on water balance could be more significant as the volumes of surface flow and of groundwater recharge are much lower. However, much of the project will be devoted to water harvesting and conservation agriculture and the extraction from rivers and groundwater will be much lower than in Caia and Beira. The next impact of water harvesting on runoff into rivers requires further study.

Thus, the scaling up of AWM irrigation technologies requires careful monitoring of local water resources and must be accompanied by parallel soil and water conservation activities in particular the promotion of conservation agriculture techniques.

4.9 RISKS

Vegetable Yields and Prices. The sensitivity analysis suggests that the viability of the project is particularly sensitive to the yields and prices achieved for vegetables. Given the experience with past INGC projects in Caia, where it was sometimes difficult to get products to market, SPAWM will expand to operate in Beira, so that it can facilitate good market networking between traders in Beira and farmers in Caia and, to a lesser extent, in Mabote.

Non-Payment of Farmer Contributions to Costs. Because the project aims to benefit primarily those farmers that are most vulnerable to climate change, it is necessary to subsidise both AWM equipment and the inputs required to realise the full benefits of the equipment. In most cases, farmers will not have sufficient savings to afford to make their contribution to these additional costs until harvest, when the benefits are realised. Whilst INGC's experience with contributions to costs has been positive in recent years, this will become more challenging as SPAWM scales up existing activities.

The ability to recover some cost contribution from farmers will contribute to the ability of the project to afford to expand activities in the second and third years. The total farmer contribution to costs in the first year will be about $75,000 and will therefore contribute about 30% of the funding for equipment and inputs in the second year. Although 80% of the beneficiaries of the project will be vulnerable farmers, it is the lead farmers who will contribute the majority of this cost contribution, because they have larger areas and make a higher contribution to costs. Any widespread failure to collect cost contributions, especially from lead farmers, will not only reduce project spending in future years, but also undermine the approach of the project and the important distinction and complementarity of the two types of beneficiaries.

The project will aim to minimise this risk by working with FFSs and explaining the approach to cost contribution from the outset. For this reason, the project will need to operate clear and consistent rules. Farmers' contributions to costs will be made public within the FFS, thus encouraging peer pressure for contributions to be made.

Misuse of Inputs. There is a risk that farmers will not use all the subsidised inputs on land that is benefiting from new AWM technologies. This risk mainly concerns water harvesting and conservation agriculture in wet season production, as the subsidies for the blue water irrigation techniques will be provided for dry season irrigation, when there is no non-AWM cultivation. There are two elements to this risk.

- Firstly, inputs used on non-AWM land will generate lower returns, because the improved seeds are selected to give higher returns with good water availability.
- Secondly, and more importantly, using inputs on non-AWM cultivation will undermine the comparison between AWM and non-AWM performance.

The FFS approach of the project will help to address these risks, as there will be good peer supervision. In addition, the project will invest in its own supervision, with about 25% of the field staff time being used for follow-up and assessment. The central planning expert will devote half their time to monitoring and evaluation and will provide overall coordination to the supervision at hub level.

Distortion of Incentives to Favour Capital Intensive Techniques. There is a very wide variation in the capital intensity of the different AWM techniques, as shown in *Table* 4-24. The policy of subsidising the capital cost of equipment will encourage farmers to select AWM techniques that are capital intensive, even when these are the least sustainable. For solar pumps, this risk is less serious because the total annual costs are not greatly different to the other water lifting options that are less capital intensive. This risk will be addressed by limiting project support to drip and sprinkler irrigation to pilot tests, unless these pilot tests prove that the costs are much lower than estimated.

Table 4-24: Capital Intensity of AWM Techniques

	Depreciation as % of total annual costs
Water lifting	
Moto pump	10%
Diesel generator and electric pump	15%
Solar pump	98%
Irrigation	
Hose	5%
Drip irrigation	95%
Sprinkler irrigation	25%

Marketing. The recent INGC support in Caia is reported to have experienced difficulties with selling the extra produce. This risk will be addressed by project activities to support the emergence of marketing contacts with traders in Beira. The project hub in Beira will be mainly concerned with supporting AWM in farms near to Beira. However, it will also help with establishing linkages between traders in Beira and farmers in Caia. Some modest financial incentives to traders may be provided to encourage them to make a few trips to Caia to establish contacts. However, no long term subsidy for marketing will be provided.

Institutional Competition. The project will depend on good cooperation between the key institutions involved, including INGC, MINAG and local government officials. This cooperation is often effective at local level and the project should actively seek to build on good cooperation by using as Extensionists the existing INGC field agents and MINAG extension agents, wherever possible. At a national level, this cooperation will be fostered by a Steering Group that contains the main government institutions involved, as well as other representatives.

Inertia in the Field. The project will depend on having active and motivated Extensionists. This will be achieved both through training and capacity building and through the provision of funds for expenses and for mobility. The project will have the flexibility to adopt innovative approaches to recruiting new Extensionists, where these are required. For example, when recruiting any additional Extensionists that are needed, it may be possible to consider recruiting an institution, rather than an individual. Interested institutions might include an NGO or a supplier of equipment or inputs who is interested in providing complementary extension.

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ANNEX

A.2.1 Topographic data

The (re-arranged) equation [2.1] after Hey and Thorne (1986) was used for deriving channel depth. A visualization of the equation is supplied in *Figure* A2.1.1 for flow widths from 10m to 1000m.

$$\text{Depth} = 0.0638 \times \text{Slope}^{-0.1294} \times \text{Width}^{0.6287} \qquad [2.1]$$

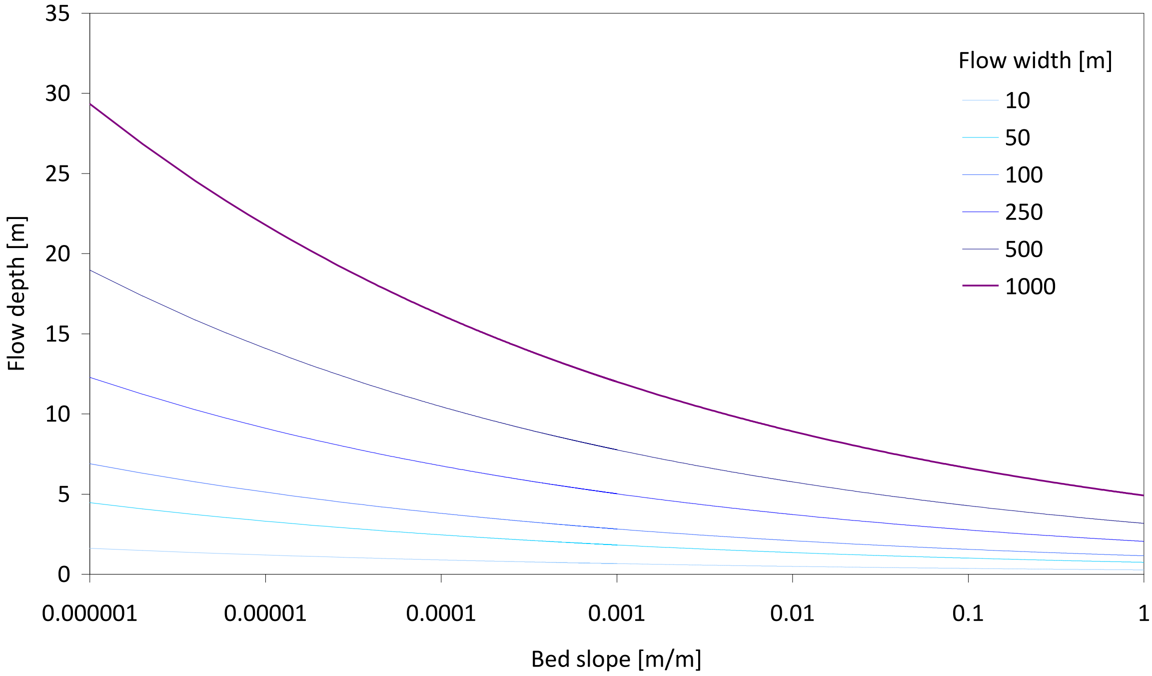

Figure A2.1.1: Diagram of Hey and Thorne's (1986) empirical equation to derive flow depth from width and slope

A.2.2 Flow data

Multiple main channel stations were available from RMSI (2009) that defined return periods. From those, minimum, average and maximum flow values are included in the baseline flow dataset. The values are defined as the discharge at the downstream end of the rivers. The bankfull flow value for the Zambezi has been taken from Beilfuss and Dos Santos (2001). For the Pungwe and the Limpopo, Google Earth images have been screened during which the river was not flooding. The maximum flow value for the dates was extracted from the DNA time series. Bankfull flow was then defined in between this highest flow value and below the 2 year return period flow given by RMSI (2009). Sea water level elevation was taken from INGC (2009) where values have been estimated for a range of return periods. The 2 year and 20 year return period are important for the simulations, because these two events act as reference to the climate change flow scenarios.

Table A2.2.1: Derived baseline flow scenarios, data source in brackets

Discharge category and data source Baseline scenarios		Zambezi		Pungwe		Limpopo	
		Flow [m³/s]	Sea water level [mASL]	Flow [m³/s]	Sea water level [mASL]	Flow [m³/s]	Sea water level [mASL]
Bankfull (multiple data sources)		5,000	3.53	500	3.53	1,050	1.87
2 year return period (RMSI 2009)	**Minimum**	**4,980**	**3.59**	**536**	**3.59**	**470**	**1.92**
	Average	**5,963**	**3.59**	**567**	**3.59**	**1,114**	**1.92**
	Maximum	**6,945**	**3.59**	**597**	**3.59**	**1,596**	**1.92**
5 year return period (RMSI 2009)	Minimum	10,462	3.78	807	3.78	1,116	2.10
	Average	10,653	3.78	1,053	3.78	2,305	2.10
	Maximum	10,844	3.78	1,299	3.78	3,476	2.10
10 year return period (RMSI 2009)	Minimum	12,790	3.92	987	3.92	1,754	2.24
	Average	13,862	3.92	1,388	3.92	3,169	2.24
	Maximum	14,933	3.92	1,789	3.92	4,787	2.24
20 year return period (RMSI 2009)	**Minimum**	**15,024**	**4.07**	**1,159**	**4.07**	**2,248**	**2.38**
	Average	**16,885**	**4.07**	**1,703**	**4.07**	**4,017**	**2.38**
	Maximum	**18,746**	**4.07**	**2,246**	**4.07**	**6,010**	**2.38**
50 year return period (RMSI 2009)	Minimum	17,915	4.26	1,382	4.26	2,681	2.56
	Average	20,655	4.26	2,093	4.26	5,128	2.56
	Maximum	23,394	4.26	2,803	4.26	7,500	2.56
100 year return period (RMSI 2009)	Minimum	20,082	4.41	1,549	4.41	3,005	2.70
	Average	23,359	4.41	2,370	4.41	5,972	2.70
	Maximum	26,636	4.41	3,191	4.41	8,539	2.70
200 year return period (RMSI 2009)	Minimum	22,240	4.55	1,716	4.55	3,328	2.84
	Average	25,949	4.55	2,635	4.55	6,830	2.84
	Maximum	29,658	4.55	3,553	4.55	9,508	2.84
500 year return period (RMSI 2009	Minimum	25,088	4.74	1,935	4.74	3,755	3.02
	Average	29,216	4.74	2,965	4.74	7,999	3.02
	Maximum	33,343	4.74	3,995	4.74	10,690	3.02
Min. flow during DFO event (DNA 2011)		4,535	3.44	871	3.73	2,504	2.16
Av. flow during DFO event (DNA 2011)		6,994	3.65	871	3.73	4,809	2.52
Max. flow during DFO event (DNA 2011)		9,310	3.73	871	3.73	7,113	2.90
Max. recorded historical flow (DNA 2011)		18,867	4.19	3,044	4.74	16,273	3.15

Based on the flow values shown in *Table* A2.2.1, climate change scenario flows have been calculated using projected flow changes. The ocean water surface elevation for climate change is obtained from INGC (2009) for the IPCC's low sea level rise scenario.

Table A2.2.2: Derived climate change flow scenarios

Discharge category Climate change scenarios		Zambezi		Pungwe		Limpopo	
		Flow [m³/s]	Sea water level [mASL]	Flow [m³/s]	Sea water level [mASL]	Flow [m³/s]	Sea water level [mASL]
2 year return period	Minimum	5,355	3.80	594	3.80	1,129	2.10
	Average	5,964	3.80	689	3.80	1,246	2.10
	Maximum	6,573	3.80	784	3.80	1,363	2.10
20 year return period	Minimum	14,156	4.30	1,652	4.30	3,345	2.62
	Average	15,818	4.30	1,768	4.30	3,782	2.62
	Maximum	17,480	4.30	1,883	4.30	4,220	2.62

A.2.3 Geometry data

A routine was developed to automatically draw cross sections for one dimensional hydraulic modelling. First, the stream centerline is calculated from bank lines and the polylines are vectorized. Non-intersecting channel vectors perpendicular to the flow direction are drawn and the A* pathfinding algorithm is utilized to obtain a unique and shortest path through the floodplains to the model domain boundary under the constraints of not being allowed to intersect previous paths or the channel bank lines. The result of the application is shown in *Figure* A2.3.1 for the lower, meandering part of the Limpopo River.

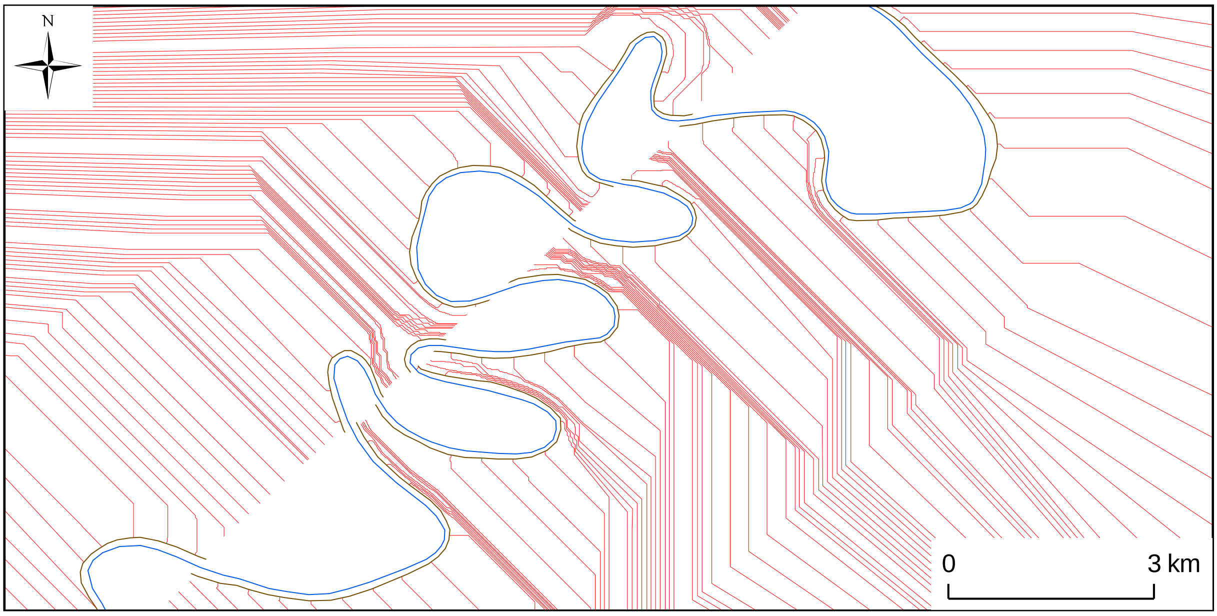

***Figure** A2.3.1: Automatically derived cross section lines (red) with computed flow centreline (blue) and digitized bank lines (brown) for the lower Limpopo River*

After that, elevation values from the corrected SRTM were assigned to the programmatically drawn cross section lines. In between the bank lines, elevation values are corrected according to equation [2.1], resulting in a distinct river channel. Ineffective flow areas are set at the first turning point in the floodplains so that deeper lying floodplain areas are not hydraulically effective as long as water elevations did not come up to the height of the ineffective area line. High, likely and low roughness values from the Manning's n map are assigned to the cross section lines, while in between the banks, roughness values are calculated based on channel slope. A HEC-RAS cross section is shown in *Figure* A2.3.2. All parameters are calculated and assembled to HEC-RAS geometry file structure using ArcObjects and Python scripting in ArcGIS.

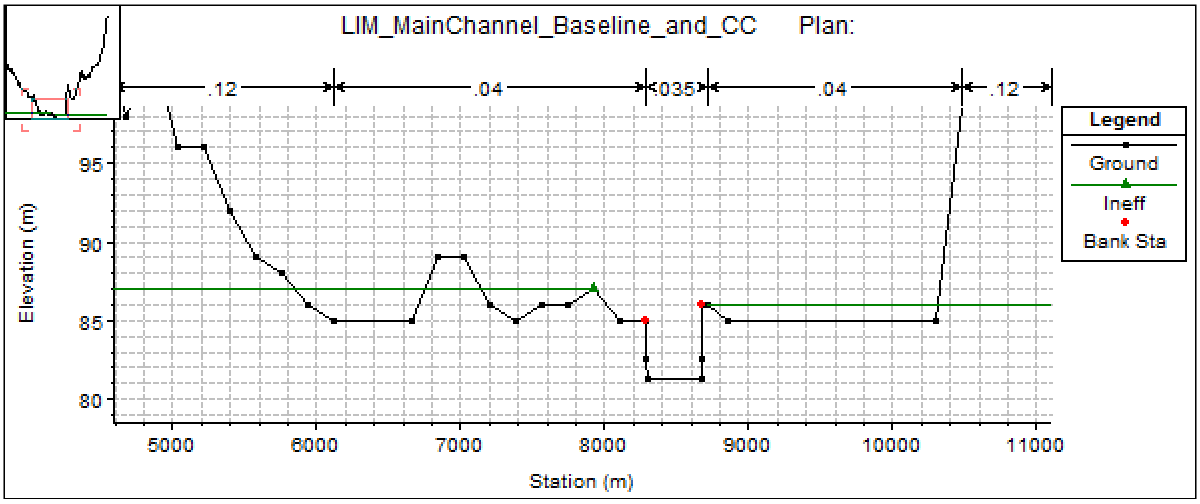

***Figure A2.3.2:** Example cross section from the Limpopo, bank points red, ineffective flow areas below green line, ground surface black, Manning's n roughness value sections on top*

A.2.4 Topography and bathymetry data acquisition

As outlined in the report, high resolution topographical and bathymetry data needs to be available for conducting a detailed Flood Risk Assessment (FRA), this data is generally not available in Mozambique. For obtaining the necessary elevation and bathymetry dataset in Mozambique, costs would arise that have been investigated and summarized below as approximate costs for a location with an area of $1km^2$ in the Limpopo (Chokwe) and the Zambezi (Marromeu).

Table A2.4.1: Approximate costs in US$ for obtaining 1 km^2 high resolution topographic data as well as respective bathymetry data for FRA

Data	Surveyor	Approximate costs (US $)		
		Limpopo (Chokwe)	Zambezi (Tete)	Zambezi (Marromeu)
LiDAR DEM, Orthophotos	African Surveyors	54,000	--	84,100
Bathymetry DEM	Underwater Surveys	15,200	22,500	22,300
Sum		**69,200**	**--**	**106,400**

Quickbird satellite images may be another source of high resolution topography data.

A.2.5 FRA data needs

Data needs for detailed Flood Risk Assessment includes the following:

- High resolution (below 1m) topographic data for the area of interest, data corrected for false ground levels (forest, houses, bridges, etc.)
- High resolution bathymetry data, matching the topography resolution
- Discharge and/or water level data upstream and downstream of the site with sufficient length of timeseries
- Alternatively model results from the developed hydraulic model could be used to estimate water levels based on short term measurements (minimum one year) at the site of interest. This would result in lower accuracy and level of confidence
- Flood hydrograph
- Roughness estimates for river channel and floodplain
- Information about structures

A.2.6 Proposed policy principles

Proposed policy principles for rural areas and smaller towns in Mozambique (applicable both for new developments as well as changes to existing developments) based on PPS25, adapted from UK Government (2010), considering practicability in Mozambique.

Key Planning Objectives

1. The aims of a planning policy on development and flood risk would be to ensure that flood risk is taken into account when new structures or infrastructure are planned or built to avoid inappropriate development in areas at risk of flooding, and to direct development away from areas at highest risk. Where new development is necessary in such areas, the policy should aim to make it safe without increasing flood risk elsewhere and where possible, reducing flood risk overall.
2. Governmental Authorities and Local Authorities should be developed to prepare and implement planning strategies that help to deliver sustainable development by:
   Appraising risk beforehand
   - ensuring sufficient data collection and liaising for data sharing
   - identifying land at risk and the degree of risk of flooding
   - preparing Strategic Flood Risk Assessments (Box A2.6.1) as appropriate, as freestanding assessments that provide baseline information for future developments on a larger scale (e.g. for river sections)

Box A2.6.1: Strategic Flood Risk Assessments

Government Agencies should carry out Strategic Flood Risk Assessments in order to assess the overall flood risk for longer river stretches. In line with the Strategic Flood Risk Assessments they would be responsible for the respective data collection. The resulting flood risk maps would be a baseline tool for judging whether or not an area is in general prone to flooding. Climate change should be taken into consideration and return periods of 10 years, 100 years and 1000 years should be modelled.

The Strategic Flood Risk Assessment forms the base for appropriate flood management policies and risk management. For areas which are indicated as being at the risk of flooding restrictions would apply that have been tackled by Site Specific Flood Risk Assessments, the Sequential Test and the Exception Test taking into account flood vulnerability aspects.

Managing risk
- framing policies for the location of development which avoid flood risk to people and property where possible, and manage any residual risk, taking account of the impacts of climate change
- only permitting development in areas of flood risk when there are no reasonably available sites in areas of lower flood risk and benefits of the development outweigh the risks from flooding
- ensure enforcement of policies
- safeguarding land from development that is required for current and future flood management e.g. conveyance and storage of flood water, and flood defences

Cooperation
- working effectively with operating authorities and other stakeholders to ensure that best use is made of their expertise and information so that plans are effective and decisions on can be delivered expeditiously
- ensuring that spatial planning supports flood risk management policies and plans, River Basin Management Plans and emergency planning

Decision making principles

3. Government Authorities and Local Authorities should adhere to the following principles in preparing planning strategies:
   - Government Authorities should ensure their Spatial Strategies include a broad consideration of flood risk from all sources and set out a strategy for managing it. This should be consistent with Strategic Flood Risk Assessments
   - Local Authorities should prepare Local Development Plans that set out policies for the allocation of sites and the way to develop them to avoid flood risk to people and property where possible and manage it elsewhere
   - where climate change is expected to increase flood risk so that some existing development may not be sustainable in the long-term, Local Authorities should consider whether there are opportunities in the preparation of Local Development Plans to facilitate the relocation of development, including housing to more sustainable locations at less risk from flooding
   - flood risk should be considered for all spatial planning issues such as transport, housing, businesses, industry, mining, agriculture, fisheries, and other developments that could be affected, or, could have an affect on flooding (e.g. runoff promoting activities). Policies should recognise the positive contribution that avoidance and management of flood risk can make to the development of sustainable communities
   - the sustainability appraisal of Local Development Plans should incorporate or reflect the findings from Strategic Flood Risk Assessments

4. In addition, Local Authorities should in determining planning applications:
   - ensure that construction and land use change actions are based on a proper application which is supported by site-specific flood risk assessments as appropriate
   - apply the sequential approach at a site level to minimise risk by directing the most vulnerable development to areas of lowest flood risk, matching vulnerability of land use to flood risk
   - ensure that all new development in flood risk areas is appropriately flood resilient and resistant, including structural stability and safe access and escape routes where required, and that any residual risk can be safely managed by awareness raising, flood management and emergency plans

Risk based approach

5. A risk-based approach should be adopted at all levels of planning. Applying the source-pathway-receptor model to planning for development in areas of flood risk requires:
   - avoid adding to the causes of flood risk, by avoiding inappropriate development in flood risk areas, avoiding reduction of floodplains and minimising run-off from new development into the river systems
   - reducing the adverse consequences of flooding on people, property, infrastructure and habitats by avoiding inappropriate development in areas at risk of flooding.

Flood Risk Assessments

6. A Strategic Flood Risk Assessment should be carried out by the Government Authority in cooperation with the Local Authority to facilitate the preparation of Local Development Plans, considering catchment wide flooding issues including downstream effects. The larger- and coarser scale assessment should yield flood risk zones of different probability level (e.g. 10 year, 100 year and 1000 year flood events)
7. Policies in the Local Development Plans should include requirements for site specific Flood Risk Assessments (Box A2.6.2) to be carried out by developers in areas of flood risk identified in the Strategic Flood Risk Assessment and Local Development Plan

Box A2.6.2: Site Specific Flood Risk Assessments

Site Specific Flood Risk Assessments should be conducted for proposed development areas that are within areas that are shown as being at risk of flooding on Strategic Flood Risk Assessment maps. The site specific assessments pick up the information provided in the SFRA´s but refine the modelling to the site in question, yielding more detailed results. Based on the FRA result the Sequential Test and Exception Test can be applied.

At the planning / application stage for developments that are planned in areas for which a risk of flooding on SFRA maps, an appropriate FRA will be required to demonstrate how flood risk from all sources of flooding to the development itself and flood risk to others that may be caused by the development will be managed now and taking climate change into account. Local Administrations should require FRAs to be submitted with planning applications in areas of flood risk identified in the SFRA.

8. Site specific Flood Risk Assessment should be carried out to an appropriate degree at planning/application stage, to assess the risks of flooding to and from the development taking climate change into account
9. Minimum requirements for all levels of flood risk assessment are given in Box A2.6.3.

Box A2.6.3: Flood Risk Assessment Requirements

The minimum requirements for flood risk assessments are that they should:

- be proportionate to the risk and appropriate to the scale, nature and location of the development
- consider the risk of flooding arising from the development in addition to the risk of flooding to the development
- take the impacts of climate change into account
- be undertaken by competent people
- consider both the potential adverse and beneficial effects of flood risk management infrastructure including raised defences, flow channels, flood storage areas and other artificial features together with the consequences of their failure
- consider the vulnerability of those that could occupy and use the development, taking account of the Sequential and Exception Tests and the vulnerability classification including arrangements for safe access
- consider and quantify the different types of flooding whether from natural and human sources and including joint and cumulative effects
- identify flood risk reduction measures
- ensure that the assessments are fit for the purpose of decision making
- consider the effects of a range of flooding events including extreme events on people, property and the environment
- include the assessment of the remaining 'residual') risk after risk reduction measures have been taken into account and demonstrate that this is acceptable for the particular development or land use
- be supported by appropriate data and information, including historical information on previous events

<u>The Sequential Approach</u>

10. A sequential risk-based approach to determining the suitability of land for development in flood risk areas is an essential part of flood risk management and should be applied
11. Governmental and Local Authorities should apply the sequential approach for allocating land uses in areas at risk of flooding.

The Sequential Test

12. Planning Authorities that allocate land in potentially flood prone areas (as indicated in the Strategic Flood Risk assessment) should apply the Sequential Test (Box A2.6.4) to demonstrate that there are no reasonably available sites in areas with a lower probability of flooding that would be appropriate to the type of development or land use proposed

Box A2.6.4: Sequential Test

The risk-based Sequential Test aims to steer new development to areas at the lowest probability of flooding (Zone 1). The Flood Zones are the starting point for the sequential approach. Flood zones Zones 1, 2 and 3 are shown on the SFRA flood maps. No flood risk could be classified as zone 0.

Zones 1, 2 and 3 reflect 10 year, 100 year and 1000 year return periods respectively. Flood Zones on the SFRA maps should refer to the probability of flooding only, ignoring the presence of existing defences while FRA´s consider defences.

The SFRA's provide the basis for applying the Sequential Test, on the basis of the Zones detailed below. Where the descriptions indicate the need to apply the Exception Test, the scope of the FRA will consider the impact of the flood risk management infrastructure on the frequency, impact, speed of onset, depth and velocity of flooding within the Flood Zones considering a range of flood risk management and maintenance scenarios.

The overall aim of decision-makers should be to steer new development to Flood Zone 0. Where there are no reasonably available sites in Flood Zone 0, decisionmakers may identify locations for development and infrastructure in the subsequent Flood Zones under consideration of vulnerabilities of land users, applying the Exception Test if required.

Within each Flood Zone, new development should be directed first to sites at the lowest probability of flooding and the flood vulnerability of the intended users matched to the flood risk of the site, i.e. higher vulnerability uses located on parts of the site at lowest probability of flooding.

Table A: Flood Zones

(Note: These Flood Zones refer to the probability of flooding, ignoring the presence of defences)

Zone 0 Low Probability This zone comprises land assessed as having a less than 1 in 1000 annual probability of flooding in any year (<0.1%). Appropriate uses include all uses of land FRA´s are not required for this area
Zone 1 Medium Probability This zone comprises land assessed as having between a 1 in 100 and 1 in 1000 annual probability of river flooding (1% – 0.1%) in any year. Appropriate uses include water-compatible, less vulnerable and more vulnerable uses of land and essential infrastructure as shown in Table B Subject to the Sequential Test being applied, the highly vulnerable uses in Table B are only appropriate in this zone if the Exception Test is passed. FRA requirements fully apply for this zone
Zone 2 High Probability This zone comprises land assessed as having a 1 in 100 or greater annual probability of river flooding (>1%) in any year Appropriate uses include water-compatible and less vulnerable uses of land in shown in Table B. Highly vulnerable uses in Table B should not be permitted in this zone. The more vulnerable and essential infrastructure uses in Table B should only be permitted in this zone if the Exception Test is passed. Essential infrastructure permitted in this zone should be designed and constructed to remain operational and safe for users in times of flood. FRA requirements fully apply for this zone
Zone 3 The Functional Floodplain This zone comprises land where water has to flow or be stored in times of flood of 1 in 10 year return period. Authorities should identify in their SFRAs areas of functional floodplain and their boundaries accordingly Appropriate uses are restricted to water-compatible and essential infrastructure listed in Table B. The structures should be designed and constructed to: – remain operational and safe for users in times of flood – result in no net loss of floodplain storage – not impede water flows – not increase flood risk elsewhere Essential infrastructure in this zone should pass the Exception Test. FRA requirements fully apply for this zone

Table B: Flood Risk Vulnerability Classification

Essential infrastructure	-Essential transport infrastructure (including mass evacuation routes) which has to cross the area at risk -Essential utility infrastructure which has to be located in a flood risk area
Highly vulnerable	-Police stations, ambulance stations, fire stations, command centres and telecommunications installations required to be operational during flooding -Emergency dispersal points -Basement dwellings -Installations storing hazardous substances
More vulnerable	-Hospitals -Residential institutions such as residential care homes, children's homes, social services homes, prisons and hostels -Buildings used for: dwelling houses; student halls of residence; restaurants and hotels -Non–residential uses for health services, nurseries and educational establishments. -Landfill and waste management sites
Less vulnerable	-Police, ambulance and fire stations which are not required to be operational during flooding -Buildings used for offices, commerce, business, industries and storage -Land and buildings used for agriculture and forestry. -Waste treatment (except landfill and hazardous waste facilities). -Minerals working and processing (except for sand and gravel working). -Water treatment works which do not need to remain operational during times of flood. -Sewage treatment works (if adequate measures to control pollution and manage sewage during flooding events are in place).
Water-compatible development	-Flood control infrastructure -Water and sewage transmission infrastructure and pumping stations -Sand and gravel workings Docks, marinas and navigation facilities.

13. In areas at risk of flooding, developments should be restricted. If development is essential, flood vulnerability aspects have to be taken into account

<u>The Exception Test</u>

14. If, following application of the Sequential Test in Box A2.6.4, it is not possible to locate a development in zones of lower probability of flooding, the Exception Test can be applied as detailed in Box A2.6.5. The Test provides a method of managing flood risk while still allowing necessary development to occur.

Box A2.6.5: Exception Test

For the Exception Test to be passed:

- it must be demonstrated that a proposed development provides wider sustainability benefits to the community that outweigh flood risk, informed by a SFRA
- the development should be within developable land or, if it is not on previously developed land, that there are no reasonable alternative sites on developable previously developed land
- a FRA must demonstrate that the development will be safe, without increasing flood risk elsewhere, and, where possible, will reduce flood risk overall.

The Exception Test should be applied by decisionmakers only after the Sequential Test has been applied and in the circumstances shown in Table A when 'more vulnerable' development and 'essential infrastructure' cannot be located in Zones 0 or 1 and 'highly vulnerable' development cannot be located in Zone 0. It should not be used to justify 'highly vulnerable' development in Flood Zone 2, or 'less vulnerable', 'more vulnerable' and 'highly vulnerable' development in Flood Zone 3.

Responsibilities

17. Responsibilities need to be clear in order to define who is responsible for data collection, data provision and conducting Strategic Flood Risk Assessments and Local Flood Risk Assessments. Additionally responsibilities for who is in charge for granting or rejecting development rights based on a Flood Risk Assessment need to be clear and the population needs to be informed about their rights and responsibilities.

The Owner/Developer

18. Landowners have the primary responsibility for safeguarding their land and property against natural hazards such as flooding. In doing that, individual property owners and users are responsible for managing their land in such a way as to prevent, as far as is reasonably practicable, adverse impacts on neighbouring land. The owner / developer is responsible for:
    - proving that his proposed development is in line with governmental and local policies
    - providing a FRA demonstrating:
    - whether his proposed development is likely to be affected by current or future flooding
    - satisfying the Local Authority that the development is safe and where possible reduces flood risk overall
    - whether his proposed development will increase flood risk elsewhere
    - If the owner / developer can not sufficiently show that his proposed development is safe, restrictions according to the risk zoning of the Strategic Flood Risk Assessment as carried out by the government shall apply
    - If the development is planned within zones of flood risk the owner / developer will have to show sufficient flood resilient measures as e.g. restriction of use and/or resilient construction adhering to government requirements (Box A2.6.1).

The Government Administration

19. The Government Administration should be responsible for Strategic Flood Risk Assessments and collection as well as provision of data at a regional scale. It should take flood risk aspects into account in their related activities and cooperate with the Local Administration for data collection, policy making and implementation.

The Local Administration

20. The Local Administration should liaise with the Government Administration for data collection and sharing purposes. They should be responsible for implementing flood risk policies on the local level and enforce (or ensure reinforcement) for adherence to the policy. In doing so the Local Administration is responsible to accept and check planning applications and accept or decline proposals.

Monitoring and review

21. Effective monitoring and review is essential to reducing and managing flood risk. Local Administrations in cooperation with Government Administrations need to monitor developments and update the Strategic Flood Risk Assessments to adjust to changed situations and consider changed conditions as well as possible adding-up effects. In addition the agencies would need to share responsibilities for maintaining and operating monitoring stations and data collection facilities as well as the related data evaluation and storing activities.

A 3.1: Questionnaires which were used for the interviews of residents during the field survey (Maputo)

Field survey in Mavalene A and Maxaquene A

Questionnaire for Interviews with inhabitants in the neighbourhoods Mavalene A and Maxaqene A

Address:
Part 1: Urban Flooding
Question 1: How often do you experience flooding in your immediate neighbourhood?
Question 2: How high above ground does the water level usually rise and how long does the flooding usually last?
Question 3: In which year occurred the worst flooding you have ever experienced in this neighbourhood? How high was the water? How long did the flooding last?
Question 4: What do you think is the main reason for the flooding in your neighbourhood?
Question 5: Which measures would help to prevent flooding or to enforce faster runoff of the rainwater from your neighbourhood?
Question 6: Are you informed about the ongoing construction works in your neighbourhood in order to improve the rainwater drainage situation? (i.e. construction of new channels)
Question 7: Do you think that the construction of new drains will help to solve the flooding problems? If no: why not?
Question 8: Do you think that there is any space in the neighbourhood where rainwater could be collected (i.e. a retention basin) and then be released to the sea after the rainfall event? Do you have other suggestions about how the urban flooding problem could be solved?
Part 2 – Integrated Urban Water Management
Question 9: Where / how do you receive your drinking water? House connection to public network? Public tap? Public well? Private well? Other (if other, please specify)?

<table>
<tr><td colspan="2">Question 10: How reliable is your water supply? 24h per day? A few hours per day? A few days per week? Please describe:</td></tr>
<tr><td colspan="2">Question 11: Is lack of clean drinking water sometimes a problem in your neighbourhood?</td></tr>
<tr><td colspan="2">Question 12: What happens to the wastewater from your household? Is it a problem to remove the wastewater from your house/yard?</td></tr>
<tr><td colspan="2">Question 13: Is wastewater from toilets (blackwater) separated from other wastewater (greywater)?</td></tr>
<tr><td colspan="2">Question 14: Does wastewater cause hygienic problems in your neighbourhood?</td></tr>
<tr><td colspan="2">Question 15: Do you collect rainwater in your house/yard?</td></tr>
<tr><td>If yes:
• How do you collect it?
• How much do you collect? (please describe)
• How do you use the collected rainwater?</td><td>If no:
• Why not?
• Do you know anybody in the neighbourhood who collects and uses rainwater?
• Do you think that collecting rainwater would bring any benefit to you and your family? Which benefit?
• What would you need to start collecting and using rainwater?</td></tr>
<tr><td colspan="2">Question 16: How is the solid waste collection organized in your neighbourhood?
• Where is the waste collected?
• How often and by whom is it removed?</td></tr>
<tr><td colspan="2">Question 17: Is the collection/removal of solid waste working properly? If not: which problems are there and how could they be solved?</td></tr>
</table>

Field survey in Mavalene A and Maxaquene A

Questionnaire for Interviews with inhabitants in the neighbourhoods Mavalane A

PART 1: URBAN FLOODING

Question 1: How often do you experience flooding in your immediate neighborhood?

1 – 2 times per year	63	>2 times per year	14	Never	23

Question 2: How high above ground does the water level usually rise and how long does the flooding usually last?

0 - 0.5m	75	0.5 – 1.0m	10	> 1.0m	0
Few hours	21	1 day	12	2 days or longer	52

Question 3: In which year occurred the worst flooding you have ever experienced in this neighborhood? How high was the water? How long did the flooding last?

2000	36	2011	34	Other Date:	15
Few days	41	1-2 Month	16	2 > Months	28
0 - 0.5m	52	0.5 - 1.0m	33	> 1.0m	0

Question 4: What do you think is the main reason for the flooding in your neighborhood?

Soils Saturation	32	Lack of channels	13	Underground Water	3
Channels blocked by waste	5	Lack of maintenance of channels	4	Other reasons	43

Question 5: Which measures would help to prevent flooding or to enforce faster runoff of the rainwater from your neighborhood?

Constuction of more channels	67	More frequent cleaning of channels	11	Others	19

Question 6: Are you informed about the ongoing construction works in your neighborhood in order to improve the rainwater drainage situation? (i.e. construction of new channels)

Yes	8	No	92

Question 7: Do you think that the construction of new channels will help to solve the flooding problems? If no: why not?

Yes	94	I do Not	6

Most given reasons why additional channels will not help

1. Falta de manuntencao das valas
2. .
3. .

Question 8: Do you think that there is any space in the neighborhood where rainwater could be collected (i.e. a retention basin) and then be released to the sea after the rainfall event?

Yes	4	I do Not	96

PART 2 – INTEGRATED URBAN WATER MANAGEMENT

Question 9: Where / how do you receive your drinking water? House connection to public network?

House connection to public network	70
Public tap	30

Question 10: How reliable is your water supply?

24h per Day	86
A few hours per day	14

Question 11: Is lack of clean drinking water sometimes a problem in your neighborhood?

Yes	57
No	43

Question 12: What happens to the wastewater from your household?

Drop in to the neighborhood	57
Drop in to Street	27
Drainage System	16

Question 13: Is wastewater from toilets (blackwater) separated from other wastewater (greywater)?

Yes	
No	

Question 14: Does wastewater cause hygienic problems in your neighborhood?

Yes	81
No	19

Question 15: Do you collect rainwater in your house/yard?

Yes	24	Pond	20	8 Bucket (20L each)	23
No	76	Bucket	4	Large tank (100 L or more)	1

How use?	Washing	1	Cooking	11
	Washing Clothes	3	Others	9

Question 15a) Why do you not collect rainwater in your house/yard?

Has house connection to public network	43	Lack of habit	27	Cannot afford tank	6

Question 15b) Do you know anybody in the neighborhood who collects and uses rainwater?

Yes	4	No	72

Question 15c) Do you think that collecting rainwater would bring any benefit to you and your family

Yes	20	No	56	Why not? Most given reason:tem torneira 24h por dia
Which benefit?	More water for household	2	Saving money	18

Question 15d) What would you need to start collecting and using rainwater?

Technical guidance	29
Money	10
Information about benefits	37

Question 16: How is the solid waste collection organized in your neighborhood?

Public waste solids collection system (Municipality)	34
No collection from the neighborhood	66

How many times

Every Day	36
2 – 3 times per week	63
Every Week	1

Question 17: Is the collection/removal of solid waste working properly?

Yes	71
No	29

Question 17a): which problems are there and how could they be solved?

Lack of accessibility	1
Collection too expensive	0
Municipality is not doing a good job	15
Others	13

Questionnaire for Interviews with inhabitants in the neighbourhoods
Maxaqene A

PART 1: URBAN FLOODING

Question 1: How often do you experience flooding in your immediate neighborhood?

1 – 2 times per year	64	>2 times per year	16	Never	20

Question 2: How high above ground does the water level usually rise and how long does the flooding usually last?

0 - 0.5m	87	0.5 – 1.0m	7	> 1.0m	0
Few hours	31	1 day	14	2 days or longer	49

Question 3: In which year occurred the worst flooding you have ever experienced in this neighborhood? How high was the water? How long did the flooding last?

2000	59	2012	9	Other Date:	30
Few days	33	1-2 Month	26	2 > Months	39
0 - 0.5m	51	0.5 - 1.0m	46	> 1.0m	1

Question 4: What do you think is the main reason for the flooding in your neighborhood?

Soils Saturation	23	Lack of channels	21	Underground Water	4
Channels blocked by waste	1	Lack of maintenance of channels	1	Other reasons	50

Question 5: Which measures would help to prevent flooding or to enforce faster runoff of the rainwater from your neighborhood?

Constuction of more channels	80	More frequent cleaning of channels	5	Others	15

Question 6: Are you informed about the ongoing construction works in your neighborhood in order to improve the rainwater drainage situation? (i.e. construction of new channels)

Yes	33	No	67

Question 7: Do you think that the construction of new channels will help to solve the flooding problems? If no: why not?

Yes	87	I do Not	13

Most given reasons why additional channels will not help

1. .nao fazem manuntecao dos canais
2. .dependera do local de construnçao e o formato do canal
3. .

Question 8: Do you think that there is any space in the neighborhood where rainwater could be collected (i.e. a retention basin) and then be released to the sea after the rainfall event?

Yes	3	I do Not	97

PART 2 – INTEGRATED URBAN WATER MANAGEMENT

Question 9: Where / how do you receive your drinking water? House connection to public network?

House connection to public network	47	Public tap	53

Question 10: How reliable is your water supply?

24h per Day	78	A few hours per day	22

Question 11: Is lack of clean drinking water sometimes a problem in your neighborhood?

Yes	69	No	31

Question 12: What happens to the wastewater from your household?

Drop in to the neighborhood	46	Drop in to channels	45	Drainage System	9

Question 13: Is wastewater from toilets (blackwater) separated from other wastewater (greywater)?

Yes		No	

Question 14: Does wastewater cause hygienic problems in your neighborhood?

Yes	96	No	4

Question 15: Do you collect rainwater in your house/yard?

Yes	19	Pond	18	8 Bucket (20L each)	19
No	81	Bucket	1	Large tank (100 L or more)	0

How use?

Washing	1	Cooking	0
Washing Clothes	10	Others	8

Question 15a) Why do you not collect rainwater in your house/yard?

Has house connection to public network	41	Lack of habit	37	Cannot afford tank	3

Question 15b) Do you know anybody in the neighborhood who collects and uses rainwater?

Yes	12	No	69

Question 15c) Do you think that collecting rainwater would bring any benefit to you and your family

Yes	44	No	37

Why not? Most given reason: tem agua da torneira que sai 24h

Which benefit?

More water for household	2	Saving money	42

A 4.1: Logical Framework

	Objectively Verifiable Indicators	Source of Evidence	Risks => Measures
Overall Objective: • improve farm resilience to CC	• crop yield and rainfall time series	• official statistics • agricultural yearbooks	• CC projections unclear, especially re rainfall => AWM viable without CC
Specific Objective: • raise farm productivity, especially in dry years	• farm margins with and without AWM	• farm surveys • project evaluation reports	• AWM variable with rainfall patterns => benchmarking for sharing experience amongst farmers • risks higher in isolated regions => incentives to suppliers to spread pilot activities to new areas
Outputs: • use of AWM techniques on farms	• number farms adopting new techniques • years techniques sustained • replicating farms	• project monitoring reports	• no standard solutions because each farm has different circumstances => project to work with a menu of options
Inputs and activities: • advice and training • pilots and demos • contracts with private suppliers • incentives to farmers and suppliers	• expenditure on activities	• project monitoring reports	• competition amongst delivery agents => checks and balances with different options for delivery

A 4.2: Training Costs

Farmers Field School Training — No of Sessions per Season: 10

	No of Farmers	No of Staff	Unit Cost	Cost per Session	Cost per Season
Training materials	25		$1	$25	$250
Farmers incentive	25		$2	$50	$500
Training site rent			$10	$10	$100
Extension staff expenses		1	$25	$25	$250
Technical staff expenses		0.5	$60	$30	$300
Report preparation		1	$10	$10	$100
TOTAL				**$150**	**$1,500**

Field Activist Training — No of Days per Season: 6

	No District Staff	No of Trainers	Unit Cost	Cost per Day	Cost per Season
Training materials	15		$20	$300	$1,800
DSA Field Activists	15		$40	$600	$3,600
Training site rent per day			$75	$75	$450
Expenses Technical staff		2	$60	$120	$720
Report preparation		2	$40	$80	$480
TOTAL				**$1,175**	**$7,050**

Field Engineer Training — No of Days per Season: 4

	No District Staff	No of Trainers	Unit Cost	Cost per Day	Cost per Season
Training materials	6		$25	$150	$600
DSA Technical Staff	6		$60	$360	$1,440
Training site rent per day			$75	$75	$300
DSA Senior Trainers		2	$100	$200	$800
Report preparation		2	$40	$80	$320
TOTAL				**$865**	**$3,460**

National Seminar — No of Days per Season: 1

	No of Participants	No Resourc Pers.	Unit Cost	Cost per Day	Cost per Season
Materials	40		$5	$200	$200
DSA Participants	40		$40	$1,600	$1,600
Training site rent per day			$150	$150	$150
Expenses Resource Persons		4	$100	$400	$400
Report preparation		2	$40	$80	$80
TOTAL				**$2,430**	**$2,430**

Information Seminar Private Sector — No of Days per Season: 1

	No of Participants	No Resource Persons	Unit Cost	Cost per Day	Cost per Season
Materials	20		$5	$100	$100
DSA Participants	20		$100	$2,000	$2,000
Training site rent per day			$150	$150	$150
Expenses Resource Persons		4	$100	$400	$400
Report preparation		2	$40	$80	$80
TOTAL				**$2,730**	**$2,730**

Consultation Workshop per Hub — No of Days per Season: 1

	No of Participants	No Resource Persons	Unit Cost	Cost per Day	Cost per Season
Materials	25		$5	$125	$125
DSA Participants	25		$5	$125	$125
Training site rent per day			$75	$75	$75
Expenses Resource Persons		2	$60	$120	$120
Report preparation		1	$40	$40	$40
TOTAL				**$485**	**$485**