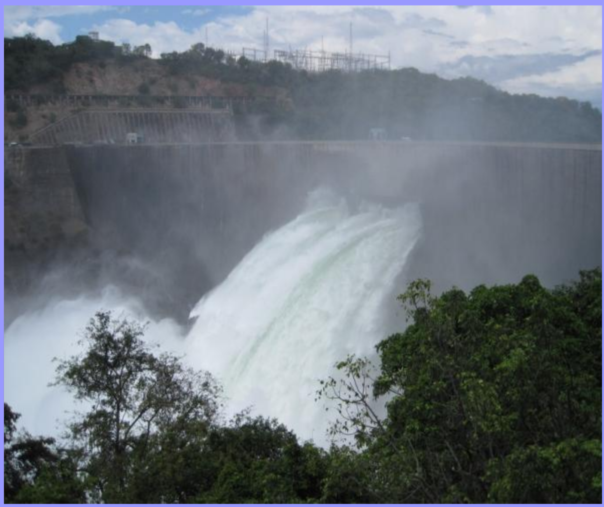
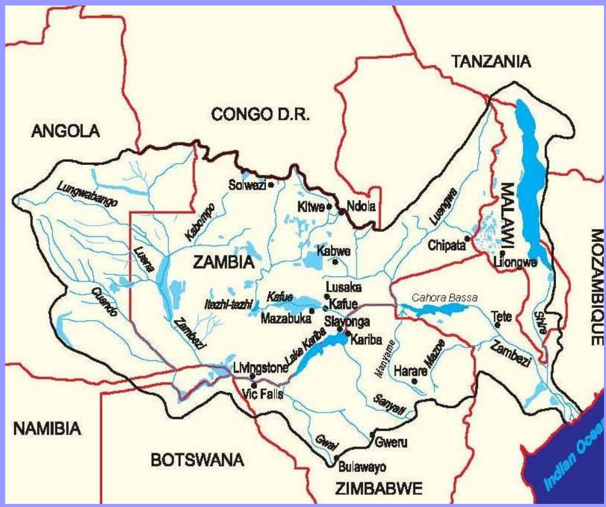
Transboundary Water Management in SADC

DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT





Annex 3

Concepts and Recommendations for Precipitation and Flow Forecasting

31 March 2011

giz

On behalf of: Federal Republic of Germany The Federal Government

UKaid from the Department for International Development

Australian Government Aid Program

SWRSD Zambezi Basin Joint Venture

SSI A DHV COMPANY | WRNA W R Nyabeze and Associates | RANKIN | SEED Sociedade de Engenharia e Desenvolvimento, Lda. GRUPO DHV | Deltares Enabling Delta Life

This report is part of the Dam Synchronisation and Flood Releases in the Zambezi River Basin project (2010-2011), which is part of the programme on Transboundary Water Management in SADC. To obtain further information on this project and/or progamme, please contact:

Mr. Phera Ramoeli
Senior Programme Officer (Water)
Directorate of Infrastructure and Services
SADC Secretariat
Private Bag 0095
Gaborone
Botswana
Tel: +267 395-1863
Email: water@sadc.int

Mr. Michael Mutale
Executive Secretary
Interim ZAMCOM Secretariat
Private Bag 180
Gaborone
Botswana
Tel: +267 365-6670 or +267 365-6661/2/3/4
Email: secretariat@zamcom.org

Table of Contents

List of Tables

List of Figures

List of Acronyms

AG	Advisory Group
ARA Zambeze	Regional Water Administration for Zambezi
CPC	Climate Prediction Center
DNA	Direcção Nacional de Águas (Department of Water Affairs in Mozambique)
DCP	Real-time data collection platform
ECMWF	European Centre for Medium-Range Weather Forecasts
EDM	Electricity de Mozambique
EFR	Environmental Flow Requirements
ESCOM	Electricity Supply Commission of Malawi
EU	European Union
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (German International Cooperation)
HCB	Hidroeléctrica Cahora Bassa
HYCOS	Hydrological Cycle Observation Station
IFR	Instream Flow Requirements
IFRC	International Federation of Red Cross and Red Crescent Societies
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standard Organization
IUCN	International Union for Conservation of Nature
METEOSAT	Meteorological Satellites
MoU	Memorandum of Understanding
Namibia DWA	Department of Water Affairs, Namibia
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NGO	Non Governmental Organization
NHS	National Hydrological Service
NMS	National Meteorological Service
NOAA	National Oceanic and Atmospheric Administration
RBO	River Basin Organization
SADC	Southern African Development Community
SAPP	Southern Africa Power Pool
SARCOF	Southern Africa Regional Climate Outlook Forum
SIDA	Swedish International Development Agency
SWRSD JV	SSI, WRNA, Rankin, SEED, Deltares Joint Venture (the Joint Venture of Consulting Firms for this project)
ToR	Terms of Reference
TRMM	Tropical Rainfall Measuring Mission
TTWW	Think Tank Work Week
TWM	Transboundary Water Management
UNZA	University of Zambia
USAID	United States Agency for International Development
USGS	US Geological Survey
UTIP	Inidade Técnica de Implementacáo de Projectos Hidroeléctricos
WB	World Bank
WMO	World Meteorological Organization
WWF	World Wide Fund for Nature
ZACPLAN	Zambezi Action Plan
ZAMCOM	Zambezi Watercourse Commission

ZAMWIS	Zambezi Water Information System
ZESA	Zimbabwe Electricity Supply Authority
ZESCO	Zambia Electricity Supply Company
ZINWA	Zimbabwe National Water Authority
ZRA	Zambezi River Authority

Executive Summary

Although there is a clear need for a basin-wide flow forecasting system in the Zambezi River Basin, such a system is yet to be established. Until now, flow forecasting has been limited to a national or bi-national focus and has been undertaken largely for the purpose of unilateral dam operation. However, the significant flooding that has occurred in the Lower Zambezi and the Chobe Swamps in recent years, the overall power deficit in the region, the growing awareness of the environmental needs of the basin and the potential gains to be achieved from synchronised operation of the large dams, all point to the importance of reliable and timely monitored and forecasted flow data for stakeholders.

This report looks at the current forecasting requirements of the Zambezi River Basin, as well as at the infrastructure and technical, financial and human resources that would be required to establish a basin-wide flow forecasting system. While the "Dam Synchronisation and Flood Releases in the Zambezi River Basin Project" (hereafter referred to as "the Project") looked in detail at the various components of the proposed flow forecasting system, the purpose of the Project was not to implement such a system, but rather to identify recommendations for the future work that would be required before implementation could commence.

Establishment of a basin wide flow forecasting system for the basin would include the following sub-components:

1. Establishment of a real-time flow gauging network;
2. Establishment of a real-time precipitation gauging network or real-time precipitation gauging network augmented with satellite rainfall estimation in areas with insufficient gauge coverage;
3. Access to timely, accurate and comprehensive precipitation forecasting information;
4. Identification of flow forecast requirements for key stakeholders within the basin;
5. Integration of existing flow forecasting models supplemented with new models (rainfall-runoff models, hydrodynamic or hydrologic routing models, etc.) where required to provide a comprehensive integrated basin-widemodel, which will allow for sufficiently accurate prediction of flows at all identified forecast locations;
6. A flow forecasting shell software program for the integration of observed flow and precipitation data, precipitation forecast information and models for the forecasting of flows at the identified forecast locations at the required lead times; and
7. A centralized forecasting location where the required ICT hardware resources and human resources (suitably qualified personnel) are available for implementation of the activities described in Item 6 above.

The following paragraphs briefly describe the key work components listed above for establishment of a basin-wide flow forecasting system in the context of the Zambezi River Basin and within the scope of the Terms of Reference for this Project. For further details, the reader is referred to the full Annex 3 Report.

Chapter 2 of the Annex 3 Report focuses on the identification of requirements for flow forecasting by stakeholders. Flow forecasts are required by a wide range of authorities and organisations including Dam Operators, Power Companies, Disaster Management Agencies, water related state agencies, and tourism and wildlife agencies. Forecast requirements include lead times, locations, timeframes (short-term, medium-term, seasonal) and data requirements (input parameters for forecasting, such as observed flow and precipitation).

Initial consultation with key stakeholders (AG members) to identify forecast requirements was undertaken using a questionnaire survey, which was emailed to designated stakeholder representatives. Further information on stakeholders and their requirements was also obtained from the 1st AG Meeting in Gaborone, stakeholder meetings and available literature.
Table 10.1 below summarises the identified forecast requirements of the various stakeholders in terms of forecast lead times, while Figure 10.1 shows the identified locations.

Table 0.1: Forecast Lead Times and User Requirements

Forecast	Timeframe	Required for:
Short	1-10 days	Dam Operation, Disaster Management, Tourism and Wildlife Agencies
Medium	10 days – 3 months	Dam Operation, Power Generation
Seasonal	>3 months	Dam Operation, Power Generation, Water Supply

Short lead time forecasts are important for flood forecasting and this forecast timeframe therefore focuses primarily on flood prone areas in the basin. Medium lead time forecast locations include existing hydropower plants (large and small), while seasonal lead time forecast locations include major hydropower plants and associated structures in the basin; i.e. Ithezi-Thezi, Kafue Gorge, Kariba, Cahora Bassa and Kamuzu Barrage.

Data requirements for each forecast location have been derived – these include observed precipitation, observed flows and levels, observed releases from reservoirs, forecast precipitation and forecast releases. The findings show in general that most forecast locations require a combination of observed flows (or levels) and observed precipitation. For catchments that have a generally fast response, such as those of the Gwayi, Sanyati and Luangwa Rivers, precipitation forecasting will also be important to meet the required lead times. Similarly, above and below major reservoirs, such as Kariba and Cahora Bassa, observed and forecast reservoir releases will be important to provide accurate information to stakeholders both upstream and downstream.

Chapters 3-5 focus on evaluation of the existing precipitation and streamflow gauging networks in the basin and identification of requirements for upgrading and extension of these networks to meet the data requirements for establishment of a basin-wide, operational forecasting system.
Current flow gauge coverage in most parts of the Zambezi River Basin is generally adequate for flow forecasting purposes. The most notable deficiency is in the portion of the Zambezi Basin within Angola, where only one flow gauge is currently operating. In developing the flow gauge network design, the following approach was generally used for the selection of gauges at required sites:

- Existing real-time gauges were selected in preference to manual gauges;
- Where an existing real-time gauge was not available, an existing manual gauge was selected, (manual gauges will need to be upgraded to provide real-time or near real-time capabilities); and
- Where an existing gauge was not available, an approximate site for a new gauge was identified (this was only the case for two new gauges in Angola).

On the above basis, 51 candidate streamflow and water level gauges were identified in the network design (Figure 1). It should be noted that one of the aims of this Project was to develop recommendations for the integration of the existing (piecemeal) forecasting models into a single basin-wide forecasting system and gauges that are currently used for flow forecasting by relevant authorities in the basin were therefore included in the network design.

Most existing flow gauges in the basin are manual gauges – the existing SADC-HYCOS network and part of the ZRA network are exceptions. For flow forecasting, real-time observations are generally needed; however, in the context of the relatively long travel times of flood peaks in the Zambezi Basin, manual readings with daily transmission of data by phone or radio would be viable in cases where sub-daily readings are not required. Due to the significant increase in GSM (cell phone) coverage in the Zambezi River Basin in recent years, satellite transmission, which is currently used by gauges within the SADC-HYCOS and ZRA networks, is unlikely to be necessary except in very remote parts of the basin. GSM transmission is significantly cheaper than satellite transmission and has added advantages due to lower risks of theft and vandalism and easier maintenance. The use of GSM technology is therefore recommended where coverage is available.

The sustainability of automatic flow gauges in the basin is currently a significant challenge. Ageing equipment, a lack of spare parts, loss of trained personnel, theft/vandalism, damage due to floods and lightning, and a general lack of funds are some of the main issues currently being faced. On-going funding and political and institutional support are therefore essential for future sustainability, as well as appropriate selection of equipment.

The existing density of precipitation gauges in the basin is generally below what is needed for accurate flow forecasting. In some areas (mostly Zimbabwe, Malawi and parts of Mozambique) current coverage was found to be adequate, but upgrading of the existing manual gauges to automatic stations will be required for operational flow forecasting. A comparison of rain gauge density in the Rhine, Mekong and Zambezi River basins indicates that the density of the Zambezi River Basin is generally significantly below those of the Rhine and Mekong.

Based on discussions with the South African Weather Service (SAWS), it is understood that some of the basin countries (Namibia and Zambia) have already purchased some of the SAWS developed Automatic Rainfall System (ARS) gauges for testing. Once installed, it is recommended that these are included in the real time network of gauges considered within the proposed flow forecasting system. As a robust tipping bucket rain gauge that reports rainfall in real-time via GPRS every 15 minutes, and which is powered by a solar panel, the ARS may be a viable and sustainable option for existing manual rain gauges requiring upgrading, as well as for additional rain gauges where current coverage needs to be extended.

A detailed investigation of currently available satellite rainfall estimation (SRE) technologies was undertaken and results from three case studies in the Zambezi River Basin indicate a generally high correlation between remote sensing output data and ground based measurement data. On this basis, it is recommended that SRE is used in the following situations:

- In areas with insufficient rain gauge coverage where the cost of upgrading existing stations and installing new stations is not justified or feasible.
- In areas with adequate rain gauge coverage as an interim measure until upgrading of manual stations to real-time status has been completed. Ground-based measurement of rainfall is still recommended over SRE in the long-term as it is generally more reliable and accurate.

It should be noted that for SRE to provide accurate estimates of rainfall, data from ground based stations is needed for ground truthing or calibration. This means that even in remote areas where SRE is proposed as a long-term rainfall measurement solution, data from a limited network of rain gauges within these areas will still be required.

Where (natural) lag times upstream of a forecast location are shorter than the desired flow forecast lead time, available information from the improved network of flow and precipitation gauges will need to be augmented with precipitation forecasts. An evaluation of the current precipitation forecasting capability in the SADC Region indicates that there are sufficient forecasting capabilities to provide the required inputs for flow forecasting in the Zambezi River Basin at the Short, Medium, and Extended to Seasonal Range time scales. The WMO Regional Specialised Meteorological Centre (RSMC) for Southern Africa, in Tshwane (Pretoria), as well as the National Meteorological Centres (NMCs) in most countries within the basin have established cooperation and these centres are additionally actively pursuing the continued improvement of forecasting capabilities. In addition, the SADC Climate Services Centre (formerly Drought Monitoring Centre) currently provides seasonal outlooks through the annual SARCOF process, and periodically updates these.

To ensure precipitation inputs are available for flow forecasting in the Zambezi River Basin, the following is recommended:

- Precipitation forecasting capabilities should not be newly developed; instead close collaboration should be established with the RSMC and SADC Climate Services Centre and through these organisations with the National Meteorological Centres in the SADC Region. This collaboration should include not only the transfer of forecast data, but also the ability for forecasters responsible for establishing flow forecasts in the basin to actively discuss precipitation forecasts with meteorological forecasters; and
- It is recommended that the information used in the flow forecasting system for establishing seasonal forecasts in the basin, which if as recommended, uses the forecasts made at RSMC with the most up-to-date meteorological forecast methods, is also made available to the SARCOF. This will provide added insight to those partaking in the SARCOF process, as well as ensuring consistency between the SARCOF outlook and any seasonal forecasts emanating from the flow forecast system.

At present, flow forecasting is only undertaken for isolated reaches of the Zambezi River and major tributaries. In the Upper and Middle Zambezi River sub-basins, flow forecasting is undertaken primarily for dam operation and power generation (ZRA and ZESCO), while in the Lower Zambezi River sub-basin, flow forecasting is undertaken for dam operation, power generation and flood forecasting (ARA Zambeze). A trigger warning system is used in Malawi for the Shire and Ruo Rivers by the Ministry of Irrigation and Water Development. Existing models or forecasting/ warning systems are therefore available for parts of the basin, but a comprehensive model or set of models does not currently exist. Establishment of a flow forecasting system will therefore require evaluation of the existing forecasting models and the development of new models to fill in the gaps between existing models. This will include the development of hydrodynamic models for the Zambezi River between Katima Mulilo and Victoria Falls and between Kariba Dam and Lake Cahora Bassa; routing and rainfall-runoff models for the Gwayi, Sanyati, Luangwa, Manyame and Luenya Rivers; reservoir operation models for Ithezi-Thezi and Kafue Gorge, Kariba and Cahora Bassa; a reservoir routing model for Lake Malawi and a water balance model for the entire Zambezi River Basin.

A consideration of the main issues that would need to be taken into account for the establishment of a centralised Flow Forecasting Centre was also undertaken as part of this Project. The main advantages of a Flow Forecasting Centre would be the timely sharing of data and information and the dissemination of short, medium and seasonal lead time forecasts to stakeholders. Provision of such information would have multiple benefits, including synchronised operation of dams, optimised power production, improved environmental flow management and improved disaster management. The main risks or threats stem mainly from the potential failure of a Flow Forecasting Centre due to a loss of sustainability (loss of funding, lack of cooperation between stakeholders, poor operation and maintenance of observation networks, etc.). Provided these issues can be addressed beforehand through the full commitment of stakeholders, Riparian states and funding agencies, then the overall risk could reasonably be mitigated.

Based on an approximate cost estimate using 2010 prices and available information, it is estimated that the capital investment cost for a Flow Forecasting Centre would be in the region of US$275 000, while the annual operating costs would be between US$800 000 and US$1.2 million. The major cost would therefore clearly be the annual operating cost and the largest component of this cost would be the salary bill for the required technical staff (60%). Costs would vary depending on the location of the Flow Forecasting Centre and the number of staff included. A number of possibilities for obtaining finance for a Flow Forecasting Centre were identified. These include donor agencies, banks and organisations involved in the establishment of flow forecasting systems. However, given the volatility of donor funding, it is recommended that the operational costs of the proposed Flow Forecasting Centre are met by the Riparian states.

Given that the role and function of a basin-wide Flow Forecasting Centre would fall within the mandate of ZAMCOM, it is likely that such a centre would be established as a subsidiary of ZAMCOM, either at the same location as ZAMCOM or at an entirely independent location. As part of this study, preliminary evaluation criteria were developed to assist with the future selection of a location for the flow forecasting centre. These include practical issues such as: internet availability, speed and reliability, power supply, transport/ connectivity; institutional issues such as independency, institutional mandate and legal status; and capacity issues, such as hospitals, schools, international airports, hotel and conference facilities, and potential connections with academic institutions and networks. While selecting a location for the Flow Forecasting Centre should ideally be based on technical criteria, a decision on the final location should be taken by the Riparian states.

As full establishment of a Flow Forecasting Centre could take some years, a number of interim measures have been proposed in this study. These include establishment of data and information sharing Agreements between Riparian states under the Interim ZAMCOM Secretariat, upgrading of the ZAMWIS database to a fully operational hydrological archive, and augmentation of the role of the Joint Operating Technical Committee to facilitate information and data sharing between key stakeholders.

As part of the Project, a demonstration pilot model of the Zambezi River Basin was developed. The model was used to simulate how sharing of observed flow data and flow forecast information could have been used during the 2000 flood event (Cyclone Eline) to reduce flooding in the Lower Zambezi in Mozambique and significantly increase power generation at both the Kariba and Cahora Bassa dams. The model demonstrated the potential financial value of a flow forecasting system and how such as system could increase power generation revenue in the basin, as well as significantly reduce flood damage and impacts on rural communities living in the basin floodplains.

The Project produced a number of important recommendations relating to the further work that would be required before a basin-wide Flow Forecasting System can be established. These are listed below according to their focus.

1. Flow and precipitation monitoring networks

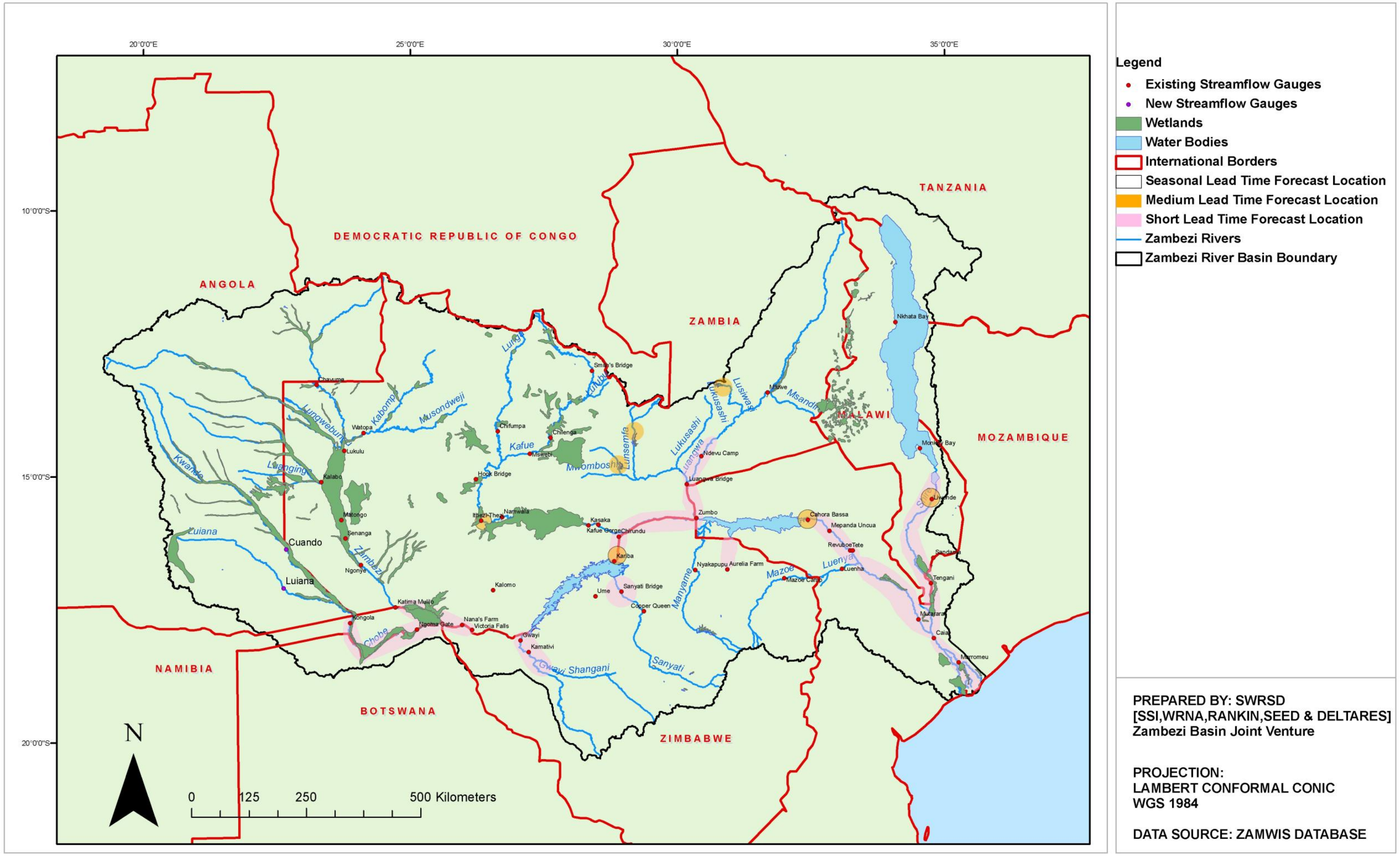
- Rehabilitate and upgrade the SADC-HYCOS network;
- Extend the network of real-time flow gauging stations;
- Establish and maintain rating curves for flow gauges within the flow forecasting network;
- Enhance procedures for collection of rainfall data;
- Upgrade the existing manual rain gauge network to real-time capability ;and
- Implement approach for use of satellite rainfall estimations.

2. Flow modeling and precipitation forecasting

- Integrate existing flow forecast models into a flow forecasting system;
- Develop new flow forecast models and integrate these with existing models;
- Investigate new forecasting capabilities with universities; and
- Expand the precipitation forecasting capability of the SADC Climate Services Centre.

3. Flow forecasting

- Review forecast locations and requirements;
- Establish a data sharing agreement between the dam operators and other stakeholders;
- Upgrade ZAMWIS to a fully operational hydrological database;
- Establish basin-wide flow forecasting centre;
- Extend the role of the flow forecasting centre to include research and education; and
- Establish a flow forecasting system using a flexible operational platform.



TRANSBOUNDARY WATER MANAGEMENT IN SADC: DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT

ZAMBEZI RIVER BASIN: IDENTIFIED FORECAST LOCATIONS AND PROPOSED STREAMFLOW GAUGES FOR FLOW FORECASTING

On behalf of:

In Delegated Cooperation with:

Figure 0.1: Identified Forecast Locations and Proposed Streamflow Gauges for Flow Forecasting

1 Introduction

This document is referred to as Annex 3 and is one of six documents that make up the report "Dam Synchronisation and Flood Releases in the Zambezi Basin". The six documents are as follows:

(a) Executive Summary;
(b) Main Report: Concepts and recommendations for improved basin wide management;
(c) Annex 1: Summary reports of compiled literature and existing studies, geodata, measuring / gauging stations and available data;
(d) Annex 2: Concepts and recommendations for dam management;
(e) Annex 3: Concepts and recommendations for precipitation and flow forecasting; and
(f) Annex 4: Recommendations for investments.

The relationships and linkages between these six documents are illustrated in Figure 1.1.

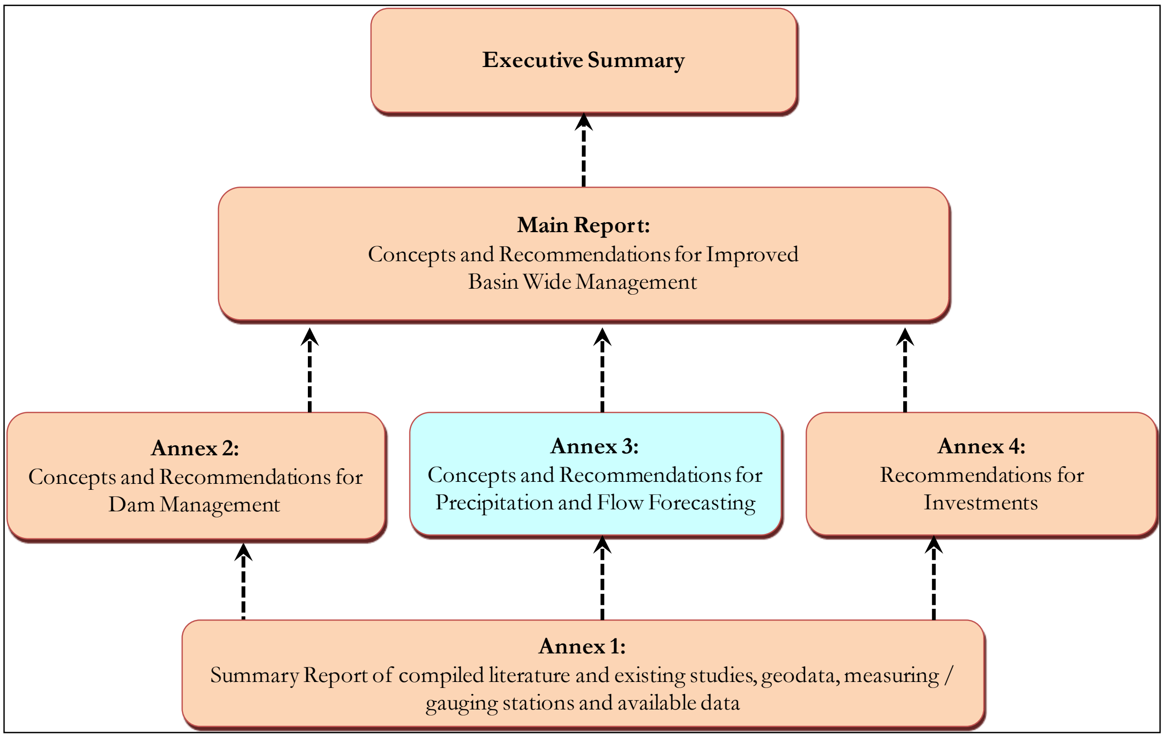


Figure 1.1: Alignment of project reports

1.1 Purpose and structure of this document

The Zambezi River basin is a complex river system that includes a number of major dams and lakes, large wetlands and several other important hydrological features. At present, most of the basin's resources are managed at a national or bi-national level. Regional or basin-wide initiatives, although important and valuable, are currently hindered by a lack of timely and reliable information on actual and predicted flows and water levels at important locations throughout the basin. Some of the current needs for real-time, basin-wide flow and water level data include dam operation, power generation, environmental flow management, drought planning and mitigation, early warning systems/ flood forecasting and disaster management and mobilization.

This document outlines the findings of an investigation into the requirements of a proposed basin-wide flow forecasting system in terms of:

- flow forecast requirements (lead times, locations, etc);
- precipitation and flow monitoring;
- precipitation forecasting;
- model requirements; and
- and establishment of centralized flow forecasting centre.

The work undertaken for this report did not include any detailed design or implementation, but did include investigation and analysis of the above listed requirements. An estimate of costs has also been provided for the establishment and operation of a centralized flow forecasting centre.

The work undertaken in this component of the project was also influenced by the outcomes of the other key components of the project, namely: Concepts and recommendations for dam management and Recommendations for investments, as shown in Figure 1.2.

This chapter (Chapter 1) presents the purpose and layout of the document. Chapter 2 outlines the identified flow forecasting requirement s and a proposed flow forecasting system design with respect to flow and precipitation monitoring. Chapter 3 presents relevant findings from an evaluation of the existing precipitation and flow gauging networks, together with recommendations for extension and upgrading of these networks for operational forecasting. Chapter 4 covers an evaluation of options for remote sensing of rainfall. Chapter 5 presents a summary of findings and implementation recommendations for extension and upgrading of the existing flow and precipitation networks. Chapter 6 addresses findings and recommendations on model capabilities and requirements for operational forecasting. Chapter 7 covers an evaluation of current capabilities in precipitation forecasting and recommendations for incorporation of available technology into the flow forecasting system. Chapter 8 presents recommendations for the establishment of a basin-wide flow forecasting centre, while Chapter 9 covers the development of a pilot forecasting system for the Zambezi River basin.

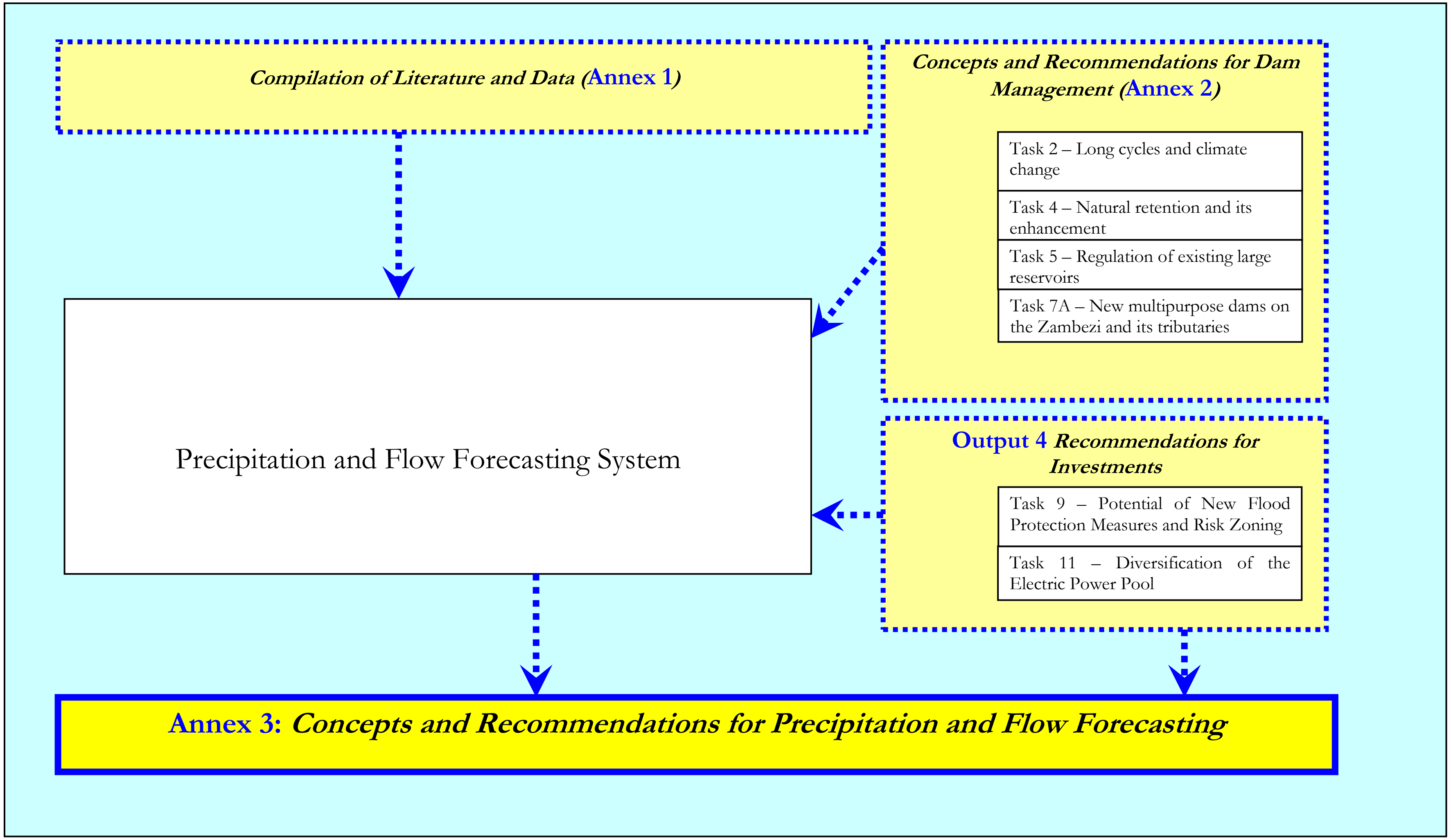


Figure 1.2: Structure of this report and the inter-relationship between the topics covered as well as the other components of this study

2 Flow Forecasting Requirements

2.1 Stakeholder consultation

Initial consultation with key stakeholders was undertaken using a series of discipline specific Questionnaires that were emailed directly to AG members (contact details were provided by SADC, but in many cases these were updated on the basis of information provided by attendees at the 1st AG meeting or through subsequent communications). Emails were later followed up telephonically, although in some cases contact persons could not be reached, even after several attempts. A Portuguese language version of the questionnaire was made available to stakeholders in Mozambique and Angola.

In general, a fair response was received from this process with the highest response rate coming from the National Disaster Management Authorities/Civil Protection Units. Information requested included minimum lead times for effective operation, details of current systems in place, their effectiveness, and potential improvements to the current system. A list of the institutions / authorities which have returned completed questionnaires to date is provided in Table 2.1 below. Further details of the process that was followed to contact individual stakeholders for this questionnaire survey are provided in Appendix 1.

With some of the stakeholders who did not participate in the questionnaire survey, subsequent project consultation meetings were held and answers to key questions were obtained in this way. The list below therefore only provides an overview of the questionnaire process and not the overall project consultation for "Concepts and Recommendations for Precipitation and Flow Forecasting".

Table 2.1: List of AG Members Responding to Questionnaire Survey

Institution	Country
Disaster Management Unit	Botswana
Ministry of Irrigation and Water Development	Malawi
Department of Energy	Malawi
Department of Disaster Management Affairs	Malawi
The Electricity Supply Corporation of Malawi Limited (ESCOM)	Malawi
National Centre for Emergency Operations (CENOE)/ INGC	Mozambique
Ministry of Agriculture, Water and Forestry	Namibia
Directorate Disaster Risk Management	Namibia
Ministry of Energy and Water Development	Zambia
Disaster Management & Mitigation Unit / OVP	Zambia
ZESCO Limited	Zambia
Civil Protection Unit	Zimbabwe
Zimbabwe Electricity Supply Authority (ZESA)	Zimbabwe

A list of the questions used in the generic questionnaires has been included in Appendix 2.

2.2 Forecast requirements

An operational forecasting system for the Zambezi River basin will cater for the needs of several stakeholders in the Basin. The primary objective of the forecasting system is to provide information on expected river flows and levels to all stakeholders in the basin to enable them to take appropriate action timeously. This overall objective of forecasting, warning and response systems is summarized by Werner *et al.*, (2005), showing the sequence of (i) monitoring, (ii) forecasting, (iii) warning, and (iv) response.

Within this sequence of steps it is important to establish the response to be taken by the different stakeholders, as well as the type of events that will lead to such a response. To be able to take an effective response, sufficient lead time should be provided by the forecasting system.

Lead time can be divided into several steps, as shown in Figure 2.1. This shows the maximum potential lead time as being the time between the event starting (e.g. excessive precipitation), and the time of the event happening (e.g. villages or towns being inundated). This maximum potential lead time is equivalent to the hydrological lead times in the basin, meaning that for the same type of stakeholder the lead times upstream of e.g. the Barotse floodplain will be very different to a stakeholder below the Cahora Bassa dam. The start of the event should be considered either the time that (excessive) rainfall is actually observed, or the time that it is reliably forecast through a precipitation forecast. The latter can then be seen to extend the lead time that can be provided.

The figure also shows that the lead time provided to decision makers is smaller than the maximum potential lead time, as data needs to be gathered and evaluated, and forecasts need to be made using models to understand if there is a threat to be acted upon. Once such a threat is clear, relevant authorities need to be notified by the forecasting service through appropriate methods of communication, following which a decision may need to be taken. An example could be the recognition of the threat of flooding, where the Disaster Management/Civil protection Units are informed of possible flooding. If the threat is judged as being real, then action needs to be take to warn those to which the flooding is a threat, which may include residents of villages and towns, national parks etc. Once warned, any action, such as evacuation of those villages and towns, should be completed prior to being inundated by flood levels.

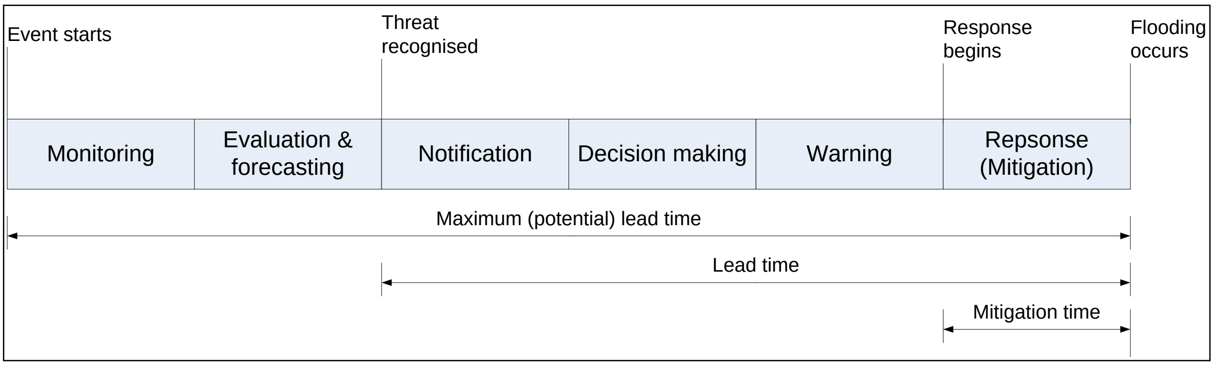


Figure 2.1: Forecasting and warning decision time line (after Carsell 2004)

It is clear that the time to take a response will differ greatly between stakeholders. For the case of flooding, the evacuation of a town will clearly take significantly more time than e.g. a tourist lodge in the Mana Pools National Park. For the operators of the reservoirs such as Kariba Dam, the information requirement is also very different, and may span a much longer lead time. Additionally the presence of the dams complicates the situation. On the one hand a dam starting to spill can be seen as an event, while the operation of the dams can also influence an event occurring downstream. In this case the mitigation action to prevent flooding may even be the operation of the reservoir to release water prior to the onset of high flows into the reservoir.

2.2.1 Objectives of forecasts at different lead times

The forecasting system will need to provide information to satisfy the lead time requirements for each of the different stakeholders identified. In this chapter an analysis is given of the forecasting requirements for each of the stakeholders. The forecast requirements are detailed in short, medium and seasonal forecast requirements per stakeholder.

2.2.1.1 Short lead time forecasts

Within the context of a large basin such as the Zambezi and its tributaries, short lead time forecasts are defined as generally having a lead time in the order of 1 to 10 days ahead. The primary variables of interest for these short lead time forecasts is the magnitude and timing of discharge and water levels peaks, as well as the timing of critical thresholds being exceeded. These forecasts focus primarily on flood flows, although for some users the volume in the flood wave is also of interest, meaning that the full flow hydrograph is required. Provision of warnings for flash floods are also considered as falling within the short term lead time forecasts.

2.2.1.2 Medium lead time forecasts

Medium lead time forecasts are considered as forecasts with a lead time longer than 10 days and up to 3 months. The variable of interest from the medium lead time forecasts will vary per stakeholder. For the operators of dams with significant storage it is the volumetric forecast that is the primary variable of interest, and the forecast should therefore cover the full flow domain, including high, medium and low flows. For more general users, the interest is primarily if river levels are expected to be higher or lower than normal, without the need for a detailed analysis of the difference in volume.

2.2.1.3 Seasonal forecasts

Seasonal forecasts are considered as forecasts providing insight into expected flows for periods ranging from 3 months up to a year, or even multiple years ahead. The primary variables of interest in these types of forecasts are the expected deviations from the normal. It also follows that as the lead time increases, these forecasts will tend towards average values for respective time period, also referred to as climatology.

2.2.1.4 Analysis of lead time requirements per stakeholder

Each of the stakeholders identified have different requirements with respect to the information the forecasts provide which can be used to inform the decisions they need to make. This information will be provided from either one of the forecasts at the different lead times, though it may be that multiple lead times are relevant. In this analysis only those requirements relevant to each stakeholder for the carrying out of their primary operations is considered. For the analysis of required lead time, stakeholders are divided into several groups;

- Dam Operators;
- Power Companies;
- Disaster Management Agencies;
- Water related state agencies;
- Tourism and Wildlife agencies;

- Other users;

2.2.1.5 Dam operators

An analysis for the primary forecast requirements for the different Dam Operators is defined in Table 2.2. This table indicates also whether the regime at the inflow is primarily regulated or if it is natural.

Table 2.2: Analysis of flow requirements for Dam Operators

Dam Operators	Basin	Description	Regime	Lead Times Required for Primary Operations [1]		
				Short	Medium	Seasonal
Victoria Falls	Middle	Run-of-the-River	Natural	-	++	-
Itezhi-Tezhi	Middle	Storage	Natural	-	++	+
Kafue Gorge[1]	Middle	Pondage HPP	Regulated	-	++	+
Lusiwasi	Middle	Pondage HPP	Natural	-	+	-
Kariba[2]	Middle	Storage	Natural	+	++	++
Mulungushi[3]	Middle	Storage	Natural	+	+	-
Lunsemfwa	Middle	Storage	Natural	+	+	-
Cahora Bassa[4]	Lower	Storage	Regulated Natural	+	++	++
Wovwe	Lower	Pondage	Regulated		+	
Nkula Falls A&B	Lower	Pondage	Regulated		+	
Tedzani	Lower	Pondage	Regulated		+	
Kapichira I	Lower	Pondage	Regulated		+	
Batoka Gorge[5] (proposed)	Middle	Storage)	Natural	+	++	++
Kapichira II (under construction)	Lower	Pondage	Regulated		+	

Notes:

1 Inflow for Kafue Gorge is regulated by Itezhi-Tezhi, and these are jointly operated. The forecast requirements are therefore considered jointly;
2 The short term variability of natural flows from the Sanyati and Shangani/Gwayi basins are important for the regulation of the Kariba dam, as these act as disturbances to the less variable inflow from the Upper Zambezi. The size of the storage in Kariba Reservoir with respect to the average annual inflow means that seasonal forecasting is an asset for long term planning;
3 These reservoirs are used primarily for hydropower generation for mining activities. As the storage is small the value of a long lead time forecast is limited;
4 The short term variability of the Manyame and in particular the Luangwa Rivers are important for the regulation of Cahora Bassa reservoir, as these act as disturbances to the regulated inflows from the main Zambezi; and

[1] The "+" and "-" symbols used in tables in this chapter denote the following:
(1) "-" – not required;
(2) "+" – required;
(3) "++" – strongly required.

5 This proposed storage dam is upstream of Lake Kariba, but will likely be operated in tandem with Kariba. The forecast requirements are therefore considered identical.

2.2.1.6 Power companies

The main power companies in the Basin (ZESA, ZESCO, ESCOM, EDM, etc.) have an obvious vested interest in the operation of the dams, as the operation of these will influence the amount of hydropower produced. As the strategy in the operation of the existing hydropower stations is primarily for the production of firm energy, they are likely to be more interested in the medium and in particular the seasonal forecasts than the short-term forecasts. All power companies are part of the Southern African Power Pool (SAPP), and therefore have a shared interest, particularly in seasonal forecasts to allow advance planning. An analysis for the primary forecast requirements for the different power companies is defined in Table 2.3.

Table 2.3: Analysis of flow requirements for Power Companies

Power Companies	Basin	Country	Lead Times Required for Primary Operations			Comments
			Short	Medium	Seasonal	
Botswana Power Corporation (BPC)	Upper	Botswana	-	-	-	No known existing HPP in basin.
Electricidade de Moçambique (EDM)	Lower	Mozambique	-	-	++	
Empresa Nacional de Electricidad (ENE)	Lower	Angola	-	-	++	No known existing HPP in basin.
Electricity Supply Corporation of Malawi (ESCOM)[1]	Lower	Malawi	-	+	++	ESCOM is not yet connected to the SAPP grid.
Zambia Electricity Supply Corporation Limited (ZESCO)		Zambia	-	+	++	
Zimbabwe Electricity Supply Authority (ZESA)		Zimbabwe	-	+	++	
Hidroelectrica de Cahora Bassa (HCB)		Mozambique	-	+	++	
MONTRACO		Mozambique			++	

Notes:

1 Most hydropower in Malawi is generated by run-of-the-river plants on the Shire River. The operators of these plants do not have direct control over river flows due to the absence of significant storage. The flow in the Shire River is largely dependent on water levels in Lake Malawi and on the operation of the Kamuzu Barrage, which only allows for limited regulation of river flows within a specific water level range. When water levels in Lake Malawi are low due to prolonged dry spells, the outflow from Lake Malawi will be equally low, with insufficient hydropower production as a result. For ESCOM it is therefore relevant to plan well in advance for such low flow periods, allowing time for negotiating alternative sources of energy through the SAPP (Malawi is not currently connected to the SAPP, but negotiations for construction of a bulk transmission line to connect the Malawi power grid to Mozambique are underway).

2.2.1.7 Disaster management agencies

The prime responsibility of disaster management agencies is to respond to flood events. This response may be initiated by receipt of flood warnings, allowing these agencies to provide warnings to local communities, and organise a response to the warnings such as timely evacuation. Generally disaster management units require short lead time forecasts, with medium range forecasts being of lower relevance. For these agencies the regime of the river is also important, as in heavily regulated reaches the occurrence of flooding will be greatly determined by the operation of reservoirs upstream. An analysis for the primary forecast requirements for the different disaster management agencies is defined in Table 2.4.

Table 2.4: Analysis of flow requirements for the Disaster Management Agencies

Disaster Management Agency	Country	Forecast Areas	Regime	Lead Times Required for Primary Operations		
				Short	Medium	Seasonal
Civil Protection Unit (CPU)	Angola		Natural	-	-	-
National Disaster Management Office[1]	Botswana	Kazungula (Zambezi), Kasane (Chobe), Ngoma Gate (Chobe)	Natural	++	+	-
Department of Disaster Management Affairs (DDMA)[2]	Malawi	Downstream of Kamuzu Barrage	Regulated, Flash floods	++		
Instituto Nacional de Gestão de Calamidades (INGC)	Mozambi que	Zambezi Floodplains downstream of Cahora Bassa	Regulated, Flash floods	++	+	
Directorate Disaster Risk Management (in Office of Prime Minister)	Namibia	Zambezi, Chobe, Linyati and Kwando floodplains and the Lake Liambezi area.	Natural	++	+	-
Disaster Management and Mitigation Unit (DMMU)	Zambia[4]	Kafue, Siavonga Luangwa, Nyimba	Regulated, Flash floods	++	+	-
Department of Civil Protection (DCP)[5]	Zimbabwe	Upstream of Victoria Falls, Kanyemba area, Areas around confluences of Sanyati/Gwayi with Zambezi, Chidodo & Muzarabani areas	Natural, Regulated, Flash floods	++	+	-
Mozambique Red Cross	Mozambi que	Zambezi Floodplains downstream of Cahora Bassa	Regulated, Flash floods	-	-	-
NGO's involved in disaster management	All basin countries	Basin-wide	Multiple	+	+	-

Notes:

1 Relevant forecast locations in Botswana are primarily on the Chobe River, which joins the Zambezi upstream of Victoria Falls;
2 Flows downstream of the Kamuzu Barrage on the Shire River are heavily regulated. However, flashy floods may occur due to unregulated tributaries;
3 Downstream of Cahora Bassa flood flows in the Zambezi are regulated. Additional flooding may result from the faster responding tributaries such as the Luenya River; and
4 Based on recent discussions with the Department of Water Affairs in Zambia, it is understood that the Department has seconded flood monitoring and warning for the Zambezi to the ZRA and that no other flood warnings within Zambia are currently issued.

2.2.1.8 Water related state agencies

There are several state agencies dealing with water resources in the basin. Generally these agencies are involved in policy development (those agencies involved in the short term management are listed in the disaster management agencies and dam operators sections). The prime interest of these agencies in forecast data is primarily the longer lead time seasonal forecast information. Some of the agencies listed in the table below are forecasting agencies in their own right (or forecasting is undertaken as a part of that agency). Additionally, hydrometric services are often a part of these agencies. Generally these agencies will have an interest at a basin wide / country wide level, rather than a specific forecast location. An analysis for the primary forecast requirements for the different state agencies is defined in Table 2.5.

Table 2.5: Analysis of flow requirements for state agencies

Facility	Country	Role	Lead Times Required for Primary Operations		
			Short	Medium	Seasonal
Ministério da Energia e Águas (MINEA)	Angola	Policy	-	-	+
Department of Water Affairs (DWA)	Botswana	Policy	-	-	+
Department of Energy Affairs (DEA)	Botswana	Policy	-	-	+
Department of Water Resources (DWR)	Malawi	Flood/Flow Forecasting Policy	++	+	+
Department of Energy (DoE)	Malawi	Policy	-	-	+
Direccao Nacional de Aguas - DNA (National Directorate of Water)	Mozambique	Policy, Hydrometry	-	-	+
Ministrério da Energia (ME)	Mozambique	Policy	-	-	+
ARA - Zambeze	Mozambique	Policy, Flood/Flow Forecasting	++	+	+
Department of Water Affairs and Forestry (DWAF)	Namibia	Policy, Hydrometry, Flood/Flow Forecasting	++	+	+
Energy Directorate	Namibia	Policy	-	-	+
Ministry of Water and Irrigation (MWI)	Tanzania	Policy	-	-	+
Ministry of Energy and Minerals (MEM)	Tanzania	Policy	-	-	+
Department of Water Affairs (DWA)	Zambia	Policy, Hydrometry	-	-	+
Department of Energy (DoE)	Zambia	Policy	-	-	+

Facility	Country	Role	Lead Times Required for Primary Operations		
			Short	Medium	Seasonal
Zambezi River Authority (ZRA)[1]	Zambia & Zimbabwe	Operation & maintenance of Kariba Dam	+	++	++
Joint Operation Technical Committee that comprises among others, HCB, ZESCO and ZRA[1]	Zambia, Zimbabwe, Mozambique	Joint operation and planning of operation of the large dams	+	++	++
Zimbabwe National Water Authority (ZINWA)	Zimbabwe	Policy, Hydrometry	-	-	+
Ministry of Energy and Power Development (MEPD)	Zimbabwe	Policy	-	-	+

Notes:

1 These agencies are responsible for the operation of the large dams (Kariba, Itezhi-Tezhi - Kafue and Cahora Bassa). The requirements are discussed in more detail in the Dam Operators section.

2.2.1.9 Tourism and wildlife

The Zambezi basin contains several pristine wildlife areas and major tourism destinations. These include the UNESCO World Heritage sites at Victoria Falls and Mana Pools, several RAMSAR sites such the Marromeu Complex in Mozambique, as well as various National Parks, Game Reserves, Conservancies and Game Management Areas. As many of these are centred around the Zambezi River and its tributaries, they are important recipients of forecast information. While information on pending floods is of some importance, longer term forecasts, particularly of low flows will provide useful information for the longer term planning of operations. An analysis for the primary forecast requirements for the major parks is defined in Table 2.6 below.

Table 2.6: Analysis of flow requirements for other tourism and wildlife

Facility	Country	Role	Regime	Lead Times Required for Primary Operations		
				Short	Medium	Seasonal
Wetland of Marromeu Complex[1]	Mozambique	RAMSAR Site	Regulated	++	+	+
Kafue National Park & Blue Lagoon National Park	Zambia	National Park RAMSAR Site	Natural	-	+	+
Chobe National Park[3]	Zambia	National Park	Natural	++	+	+
Liuwa Plains National Park[3]	Zambia	National Park	Natural	-	-	+
Sioma Ngwezi National Park[3]	Zambia	National Park	Natural	-	-	+
North Luangwa National Park[3]	Zambia	National Park	Natural	-	-	+
South Luangwa National Park	Zambia	National Park	Natural	-	+	+
Mana Pools/Lower Zambezi National Park[1]	Zimbabwe/ Zambia	National Park	Regulated	++	+	+

Notes:

1 The Marromeu site is located downstream of the Cahora Bassa dam, with the regime of the river being mainly regulated. Freshets released from Cahora Bassa as well as spilling from the dam will influence the flows and levels significantly;
2 Mana pools is located downstream of the Kariba dam, with the regime of the river being fully regulated. Freshets released from Kariba Dam as well as spilling from the dam will influence the flows and levels significantly, and information on these changes in flow is important for the safety of visitors to the area; and
3 These parks are remote and little developed. The use of forecast information is considered only relevant for the longer lead time seasonal forecasts.

2.2.1.10 Other users and agencies

There are several other state agencies that have an interest in flow forecasts for the Zambezi and its tributaries (see Table 2.7 below). The requirements of these agencies vary primarily between those agencies involved in establishing policy, and those with an operational mandate. In some cases state agencies are currently involved in forecasting flows in the basin, and provide these forecasts to, for example, the disaster management agencies discussed in the previous section.

Table 2.7: Analysis of flow requirements for other state agencies

State Agency	Country	Role	Lead Times Required for Primary Operations		
			Short	Medium	Seasonal
Ministry of Tourism, Wildlife and Culture	All Countries	Policy	-	+	++
Irrigation schemes[1]	All Countries	Operation of intakes, Policy	+	++	+
Fisheries and aquaculture	All Countries	Policy	-	+	+
Mining, Industry and Water supply[2]	All Countries	Operations	+	++	+
Navigation[3]	All Countries	Planning	+	-	-
Meteorological Services Departments	All Countries	Precipitation forecasting	Do not need flow forecast information, but rather provide precipitation forecast information to flow forecasting agencies.		
SADC Drought Monitoring Centre	All Countries	Precipitation forecasting			
SARCOF (Southern African Climate Outlook Forum)	All Countries	Precipitation forecasting			
ZAMCOM	All Countries	Basin management	Expected host of proposed Zambezi River basin flow forecasting centre.		

Notes:

1 Flow forecasts may be useful to irrigation agencies for the planning of river intakes. Short lead time forecasts may be useful for planning of responses to flooding which may require intakes to shut down, while longer term forecasts are useful for planning;
2 Several mining companies in the basin (which includes the so-called Copper belt) operate their own hydropower stations for the provision of energy to mines; and
3 Navigation on the River network is limited to the lower reaches of the Zambezi and Shire Rivers, as well as several ferry crossings throughout the basin.

2.2.2 Summary of forecast requirements

The tables above present a complete picture of forecast requirements across the basin. For forecasts at different lead times, it is clear that these are concentrated in a limited area of the basin.

2.2.2.1 Short lead time forecasts

Short lead time forecasts are required for a limited number of specific river reaches. These are summarised in Table 2.8 below, as well as schematically on the map in Figure 2.3.

Table 2.8: Forecast locations with short lead time forecast requirements

Reach/Location	Basin	Regime
Zambezi between Katima Mulilo and Victoria Falls	Upper Zambezi	Natural
Kwando, Linyati and Chobe Rivers inside Botswana and Namibia	Upper Zambezi	Natural
Lower Reaches of Sanyati & Gwayi Rivers	Middle Zambezi	Regulated / Natural
Zambezi between Kariba Dam and Cahora Bassa Lake	Middle Zambezi	Regulated/Natural
Luangwa Downstream of Great East Road Bridge to Zambezi confluence	Middle Zambezi	Natural
Zambezi downstream Cahora Bassa to the Zambezi mouth	Lower Zambezi	Regulated
Shire downstream of Kamuzu Barrage to confluence Zambezi	Lower Zambezi	Regulated/Natural

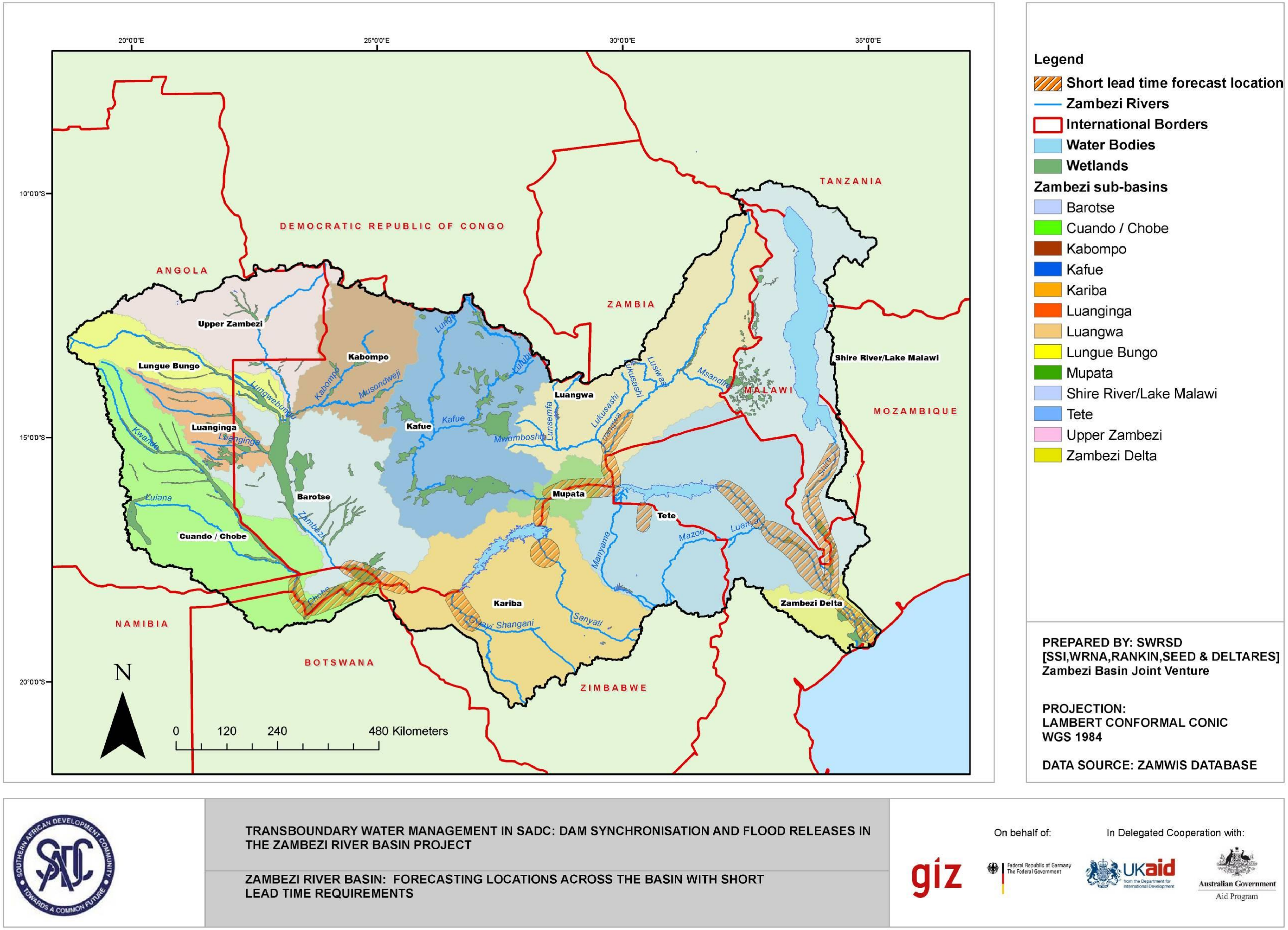


Figure 2.3 : Map of forecasting locations across the basin with short lead time requirements

2.2.2.2 Medium lead time forecasts

The locations for which detailed medium lead time forecasts are required are primarily for inflows to the larger storage reservoirs. These are summarised in , as well as schematically on the map in Figure 2.4.

Table 2.9: Forecast locations with medium range lead time forecast requirements

Reach/Location	Basin	Regime
Inflows to Lake Kariba	Upper /Middle Zambezi	Natural
Inflows to Itezhi-Tezhi and Kafue Gorge	Middle Zambezi	Natural
Inflows to Lusiwasi Reservoir	Middle Zambezi	Natural
Inflows to Mulungushi Reservoir	Middle Zambezi	Natural
Inflows to Lunsemfwa Reservoir	Middle Zambezi	Natural
Inflows to Lake Cahora Bassa	Lower Zambezi	Regulated/ Natural
Inflows/Outflows from Lake Malawi	Lower Zambezi	Regulated / Natural

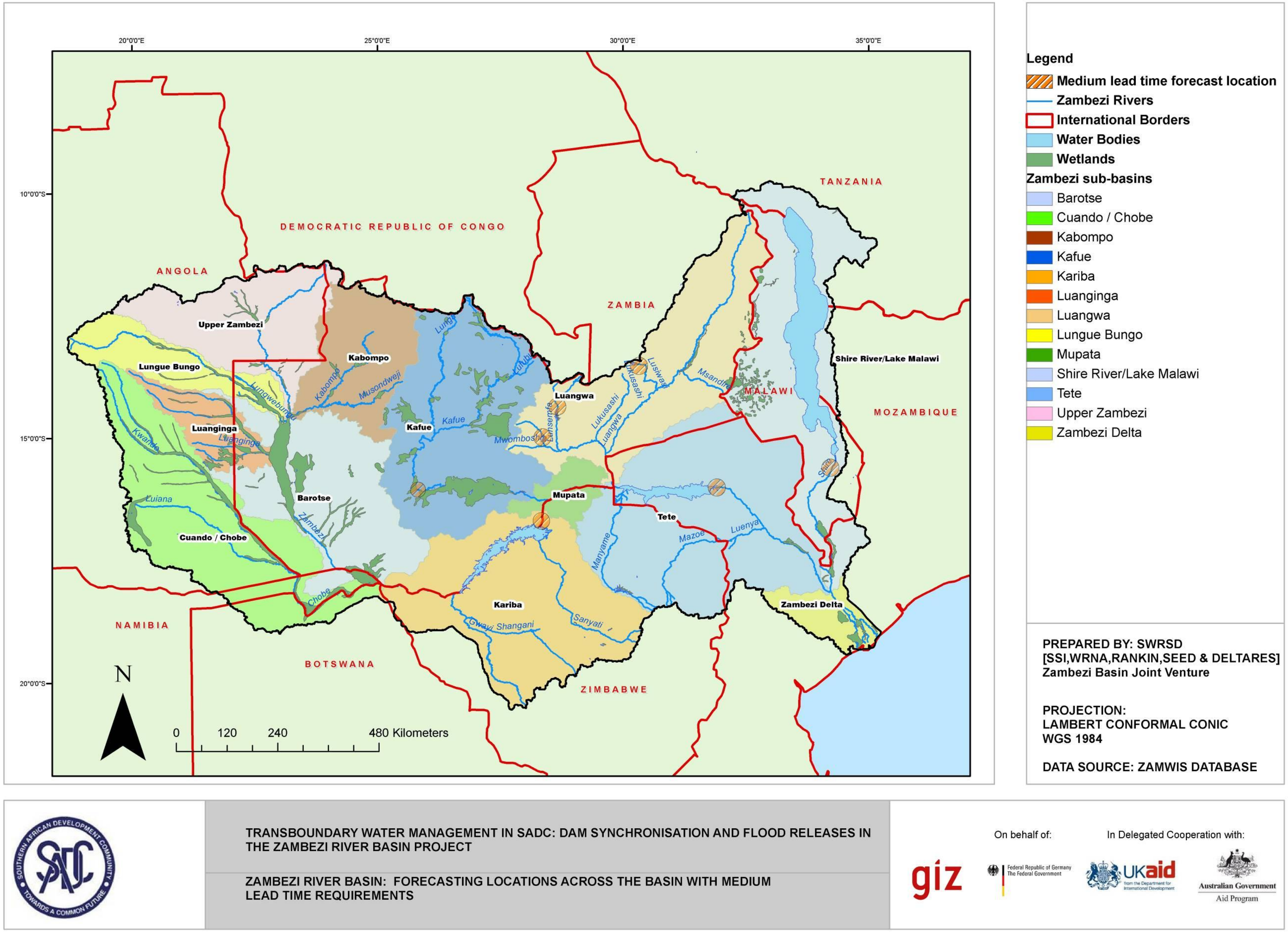


Figure 2.4: Map of forecasting locations across the basin with medium lead time requirements

2.2.2.3 Seasonal forecasts

Seasonal forecasts provide similar information as the medium range forecasts, and the most detailed information from these is again for the operators of the large storage reservoirs (refer to Table 2.10). For most other users such as policy makers and planning departments the information requirements are lower, with a general basin wide indication of lower and higher flows. Figure 2.5 provides an overview of the locations where seasonal forecasts are primarily required. However, as noted in the analysis of stakeholders, seasonal forecasts are particularly relevant for longer term planning, with an interest that is at a basin-wide/country-wide scale.

Table 2.10: Forecast locations with seasonal lead time forecast requirements

Reach/Location	Basin	Regime
Inflows to Lake Kariba	Upper /Middle Zambezi	Natural
Inflows to Itezhi-Tezhi and Kafue Gorge	Middle Zambezi	Natural
Inflows to Lake Cahora Bassa	Lower Zambezi	Regulated/ Natural
Inflows/Outflows from Lake Malawi	Lower Zambezi	Natural

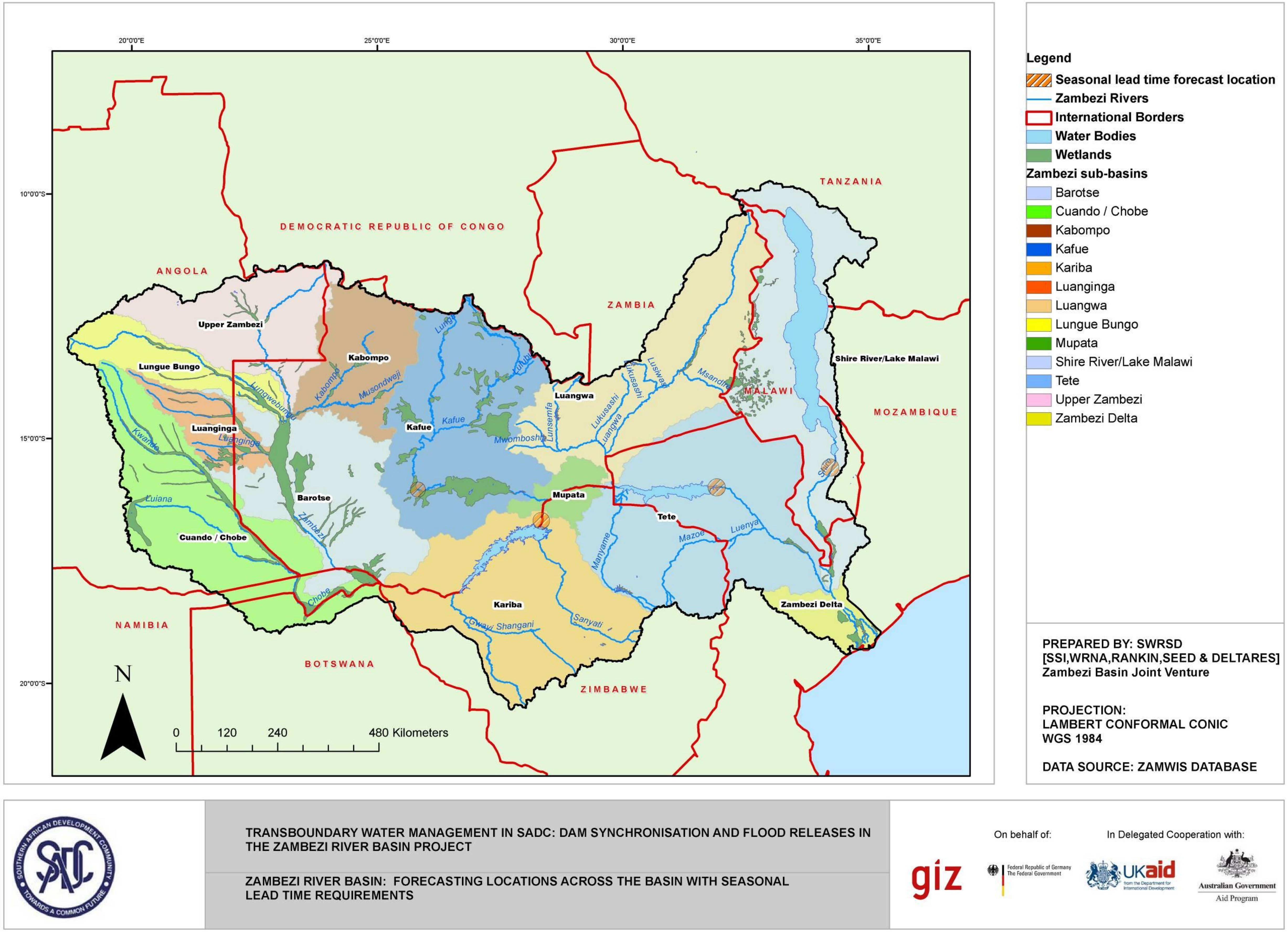


Figure 2.5: Map of forecasting locations across the basin with seasonal lead time requirements

2.2.3 Data requirements

In order to provide forecasts at any of the locations described in the previous sections, the forecasting system will require input data to enable the prediction of flow and, where required, water levels for the full lead time. The input data that is needed depends primarily on the lead time and the hydrological lag times in the basin. For a short lead time requirement of the order of a few days in a river that has a response time in the order of weeks, it is sufficient to observe flow at an upstream gauge that is at a distance upstream that corresponds with the lead time that is to be provided.

Section 2.3 provides a preliminary analysis of lead times in the basin. Through a comparison of the lead time requirements, and the lag times in the basin, the information requirement for the forecasts can be derived. Several types of data can be used in deriving a forecast;

- Observed precipitation in the upstream basins (P-obs);
- Observed flows and levels from a gauge at sufficient lag time upstream (Q-obs, H-obs);
- Observed releases from the reservoirs (Q-rel);
- Forecast precipitation over the upstream basins (P-for); and
- Projected releases from the reservoirs (Q-proj).

2.2.3.1 Short lead time forecasts

The data requirements for the short lead time forecasts are shown in Table 2.11. This shows that given the long lag times in many parts of the basin as a result of the extensive wetlands, forecasts for missed points can be easily attained through use of observed data from upstream gauges. For those reaches that are flashy in nature the provision of daily forecasts may not be sufficient, and sub-daily time steps will need to be considered. It is also important to note that for the forecast locations where observed and forecast rainfall are important, that the timing of the rainfall events may be crucial for the provision of accurate forecasts. The table also shows that generally observed flows and levels are relevant to all forecast locations. Where there are reliable gauges in such intermediate reaches, these can be used to improve forecast accuracy through data assimilation. For example having reliable data at the gauge at Senanga in the Upper Zambezi will be very useful in improving the accuracy of the forecast at Katima Mulilo, despite the travel time between the two gauges being smaller than the lead time.

Rainfall forecasts for such short range flow forecasts should be of adequate resolution in both time and space. Particularly for the provision of forecasts in the flashier catchments such as the small tributaries of the Shire and lower Zambezi, the resolution should be sub-daily. Such forecasts can be typically obtained from a well calibrated local area Numerical Weather Prediction Model. This is discussed in more detail in Chapter 7.

Table 2.11: Forecast locations with data requirements for short lead time forecasts

Reach/Location	Basin	P-obs	Q-obs H-obs	Q-rel	P-for	Q-proj	Temporal Resolution
Zambezi between Katima Mulilo and Victoria Falls[1]	Upper Zambezi	+	++	-	-	-	Daily
Kwando, Linyati and Chobe Rivers inside Namibia and Botswana[1]	Upper Zambezi	+	++	-	+	-	Daily
Lower Reaches of	Middle	++	+	-	+	-	Sub-Daily

Reach/Location	Basin	P-obs	Q-obs H-obs	Q-rel	P-for	Q-proj	Temporal Resolution
Sanyati & Gwayi rivers	Zambezi						
Zambezi between Kariba Dam and Cahora Bassa Lake[1]	Middle Zambezi	-	+	++	-	++	Sub-Daily
Luangwa Downstream of Great East Road Bridge to Zambezi confluence	Middle Zambezi	++	+	-	+	-	Daily
Zambezi downstream Cahora Bassa to the Zambezi mouth[2]	Lower Zambezi	+	+	++	++	++	Sub-Daily (Flash Floods)
Shire downstream of Kamuzu Barrage to confluence Zambezi	Lower Zambezi	+	+	-	++	-	Sub-Daily (Flash Floods)

Notes:

1 Flow upstream of these points is dominated by wetlands, which means lag times are considerable and observed flow/levels upstream can provide a good forecast. Augmenting this with an estimate of observed rainfall over the wetlands will improve the forecast.

2.2.3.2 Medium range lead time forecasts

The data requirements for the medium lead time forecasts are shown in Table 2.12. For the medium range forecasts, the primary variable of interest is the volume in the flow hydrograph. For reaches/catchments dominated by extensive wetlands, both observed flows at upstream gauges and observed precipitation over the upstream wetlands and catchments are of importance.

For catchments with shorter lag time, the precipitation forecast will become increasingly important as lead time increases. In this case the precipitation forecast can, however, be at a relatively coarse resolution in both time and space, with generally available global models likely being sufficient. This is discussed in more detail in Chapter 7.

Table 2.12: Forecast locations with data requirements for medium range lead time forecasts

Reach/Location	Basin	P-obs	Q-obs H-obs	Q-rel	P-for	Q-proj	Temporal Resolution
Inflows to Lake Kariba	Upper /Middle Zambezi	++	++	-	+	-	Monthly
Inflows to Itezhi-Tezhi and Kafue Gorge	Middle Zambezi	++	++	-	+	-	Monthly
Inflows to Lusiwasi Reservoir[1]	Middle Zambezi	+	-	-	++	-	Decadal – Monthly
Inflows to Mulungushi Reservoir[1]	Middle Zambezi	+	-	-	++	-	Decadal – Monthly
Inflows to Lunsemfwa Reservoir[1]	Middle Zambezi	+	-	-	++	-	Decadal – Monthly
Inflows to Lake Cahora Bassa	Lower Zambezi	++	+	++	+	++	Daily to Decadal
Inflows/Outflows	Lower	+	++	-	++	-	Daily to

Reach/Location	Basin	P-obs	Q-obs H-obs	Q-rel	P-for	Q-proj	Temporal Resolution
from Lake Malawi	Zambezi						Decadal

Notes:

1 These reservoirs are in the headwaters of the respective catchments. There are no gauges in the catchment upstream of these reservoirs. The accuracy of the forecast at these locations will depend primarily on the availability and accuracy of the medium range precipitation forecasts.

2.2.3.3 Seasonal forecasts

The data requirements for the seasonal lead time forecasts are shown in Table 2.13. For medium range forecasts, the primary variable of interest in seasonal forecasts is the volume of the flow hydrographs. While medium range forecasts use an actual quantitative forecast, seasonal forecasts generally use the forecast anomaly of for example the mean monthly rainfall (or climatology).

Except for the basins with significant lag times due to extensive wetlands or significant storage such as the large reservoirs, observed data will be of lesser importance. In Table 2.13, the forecast precipitation is considered as the forecast precipitation anomaly.

Table 2.13: Forecast locations and data requirements for seasonal forecasts

Reach/Location	Basin	P-obs	Q-obs H-obs	Q-rel	P-for	Q-proj	Temporal Resolution
Inflows to Lake Kariba	Upper	++	+	-	++	-	Monthly
Inflows to Itezhi-Tezhi and Kafue Gorge	Middle	+	-	-	++	-	Monthly
Inflows to Lake Cahora Bassa[1]	Lower	-	-	-	++	++	Monthly
Inflows/Outflows from Lake Malawi	Lower	+	++	-	++	-	Monthly

Notes:

1 Inflows to Cahora Bassa are dominated by regulated inflows, primarily from Kariba. The projected releases from Kariba, as specified by the operating rules used at Kariba and to a lesser extent Kafue Gorge will therefore dominate the seasonal forecast.

2.3 Basin Response Time Calculations

2.3.1 Overview

A key aspect of the process involving identification of forecast requirements for the Zambezi River basin was the calculation of response times from the headwaters of the basin in north-western Zambia to the river mouth. Figure 2.1 in Chapter 2 shows the relationship between lead time and response time. The response time is theoretically equivalent to the maximum potential lead time, but in practice the response time will always be longer than the actual lead time. The importance of response times for identifying forecast requirements has been outlined in Section 2.2.4.

To calculate response times for the main reaches of the Zambezi River basin, time series data for selected gauges was compared using a correlation approach. The method determined the statistical correlation between flows at two identified specific gauges and yielded both the average response time and the degree of correlation. The gauges chosen were usually directly in hydrological sequence on the river, with no gauges in between. As a crosscheck on the results, gauges further apart were also analysed. An advantage of this method is that it is possible to use an entire record period for the correlation analysis, giving a better estimate of response times, as the method does not analyse one isolated event. It was also necessary that the two gauges being compared had sufficient overlap in terms of record length.

Data from as many gauge pairs as possible was analysed to provide a complete picture of response times throughout the entire Zambezi River basin. However, due to lengthy gaps in some gauge records, resulting in poor correlation, some gauges were discarded. All gauge pairs analysed are shown in Table 2.17 below, together with the response times and corresponding correlation coefficients. Figure 2.6 graphically shows the calculated response times for the various river reaches in the basin for which adequate data was available.

One of the inherent limitations of the above approach is that it assumes that response times are similar during both 'flood' years and 'dry' years. Experience in the Zambezi River basin has shown this to be unlikely, particularly where there is significant capacity for natural flood storage, such as in the Barotse plains of the Upper Basin. In addition, record periods for some of the gauges were only available for periods that lie within dry cycles – periods when river flows are consistently below average for an extended period.

A more specific analysis of flow records was conducted for development of a wet season flow forecasting method at Victoria Falls and Kariba (Shawnigan Engineering, 1994), in which response times for the Upper Zambezi Basin were estimated by analysing 10 flood years between 1956 and 1978. The results of this analysis indicated that response times between Chavuma and Victoria Falls varied from 20 to 30 days, with a mean of 25 days. This figure is noticeably shorter than the figure of 37 days obtained in this study using the method already outlined.

The above discrepancy highlights two important issues:

1) Firstly, that response times within a river system vary considerably in response to a wide range of natural factors and therefore a response time range may provide a more useful impression of the natural response time of a basin than a single (average) value; and
2) That response times for flow forecasting in times of flood are likely to differ significantly from those during dry periods. Lead times will therefore vary depending on the time of the year and the magnitude of the flood being forecasted.

In light of the above situation, the response times provided in Table 2.17 and shown in Figure 2.6 should be considered to be average response times representative of both wet and dry seasons. The primary purpose in this study was to devise a preliminary forecast system.

However, for the specific case of flood forecasting, further analysis is recommended. A number of specific recommendations are proposed in this regard:

- Most of the data available in ZAMWIS does not extend beyond 2000. The period from roughly 1980 to 2000 is now generally considered to be a dry cycle in which flows in the Zambezi River were generally well below average. A more realistic overview of response times under flood conditions would be possible if the available records could be extended beyond 2000 to the present time, during which time a number of flood years occurred;

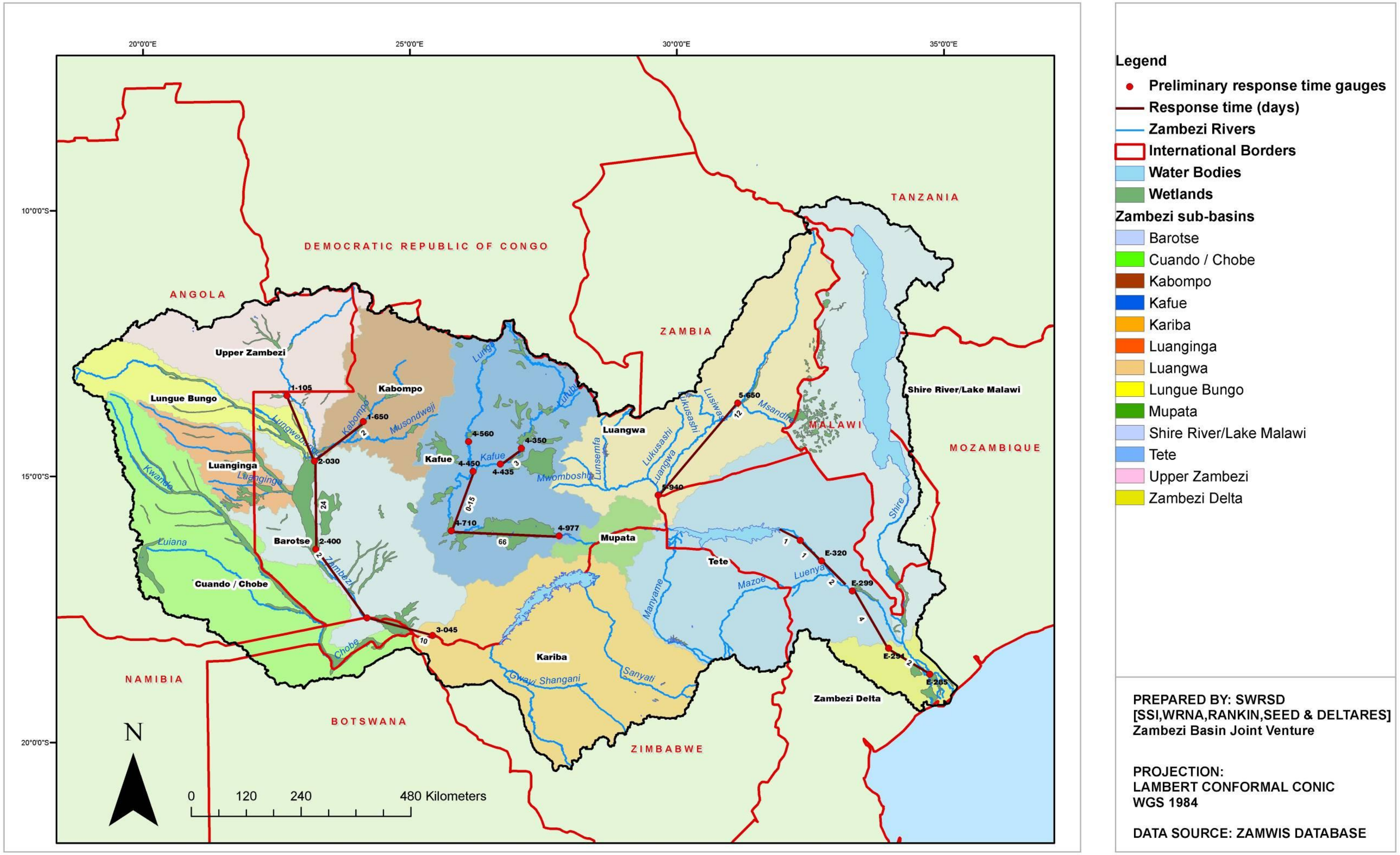
- Where possible, patching of records with missing data would allow for more detailed analysis; and
- As part of the development of the flow forecasting system, a consideration of basin response times for flood periods, as well as dry periods should be provided. This will allow forecasters to more accurately predict the response of the basin under different flow conditions.

Figure 2.7 demonstrates the concept of response times as it applies to flow forecasting at a particular location. As a demonstration, three locations have been considered. These are: Lake Kariba (blue), Lake Cahora Bassa (red) and Marromeu near the mouth of the Zambezi River (black). The concentric lines shown with an associated period of weeks in each of the above colours denote the approximate travel times to the forecast location. It should be noted that these lead times are approximate and have been shown for demonstration rather than as an accurate forecasting tool. As part of the development of a basin-wide forecasting system, specific lead time maps will be required for each forecast location; however, this level of detail is beyond the scope of the current project.

Table 2.14: Travel times for Zambezi River

Flow Gauges (Upstream Gauge and Downstream Gauge)	Record Period	Correlation Co-Efficient	Days	Comments
Upper Zambezi				
Zambezi River at Chavuma Pump House (1105) and Zambezi River at Lukulu (2030)	1990-1997	0.94	1	
Zambezi River at Lukulu (2030) and Zambezi River at Senanga (2400)	1990-1998	0.97	24	
Zambezi River at Senanga (2400) and Zambezi River at Nana's Farm (3045)	1990-2002	0.94	13	
Katima Mulilo (320100) and Zambezi River at Nana's Farm (3045)	1990-1998	0.91	10	
Katima Mulilo (320100) and Vic Falls (330090)	1968-1999	0.59	0	Possible error due to poor quality data.
Zambezi River at Senanga (2400) and Katima Mulilo (320100)	1968-1995	0.93	2	
Zambezi River at Nana's Farm (3045) and Vic Falls (330090)	1990-1999	0.97	1	
Middle Zambezi				
Lunga River at Chifumpa (4560) and Kafue River at Lubungu Pontoon (4450)	1959-2004	0.84	15	
Kafue River at Chilenga (4350) and Kafue River at Mswebi (4435)	1962-1992	0.98	3	
Kafue River at Mswebi (4435) and Kafue River at Lubungu Pontoon (4450)	1959-1992	0.95	0	Possible error due to poor quality data.
Kafue River at Itezhitezhi (4710) and Kafue River at Kasaka (4977)	1963-1992	0.27	66	Poor correlation coefficient, possible due to significant attenuation impact of Kafue flats.
Luangwa River at Mfuwe (5650) and Luangwa River at Great Road Bridge (5940)	1948-2002	0.44	12	
Munyati Flume Power on Munyati River (C94) and Copper Queen on Umfuli River (C84)	1990-2005	0.11	1	Poor result. Perhaps attributed to too large a catchment between the 2 gauges.
A 32 and A 41 (Shangani River)	1965-2006	0.59	0	Suspect data. D/s gauge tiny flows compared to u/s.
Lower Zambezi				
Cahora Bass Outflows and Zambezi River at	1976-1992	0.96	2	

Flow Gauges (Upstream Gauge and Downstream Gauge)	Record Period	Correlation Co-Efficient	Days	Comments
Tete (E-320)				
Zambezi River at Tete (E-320) and Zambezi River at Tambara (E-299)	1991-1992	0.97	0	Possible error due to poor data. Alternative technique also 0. Short record period.
Zambezi River at Caia S.S (E-291) and Zambezi River at Marromeu Sana Sugar (E-285)	1999-2001	0.98	2	
Zambezi River at Tete (E-320) and Zambezi River at Morromeu Sana Sugar (E-285)	1999-2001	0.84	6	
E-299 and E-285	1962-1981	-0.07	4	Possible error due to poor data or gauges being too far apart.
(E-375) and Zambezi River at Tambara (E-299)	1962-1966	0.94	3	

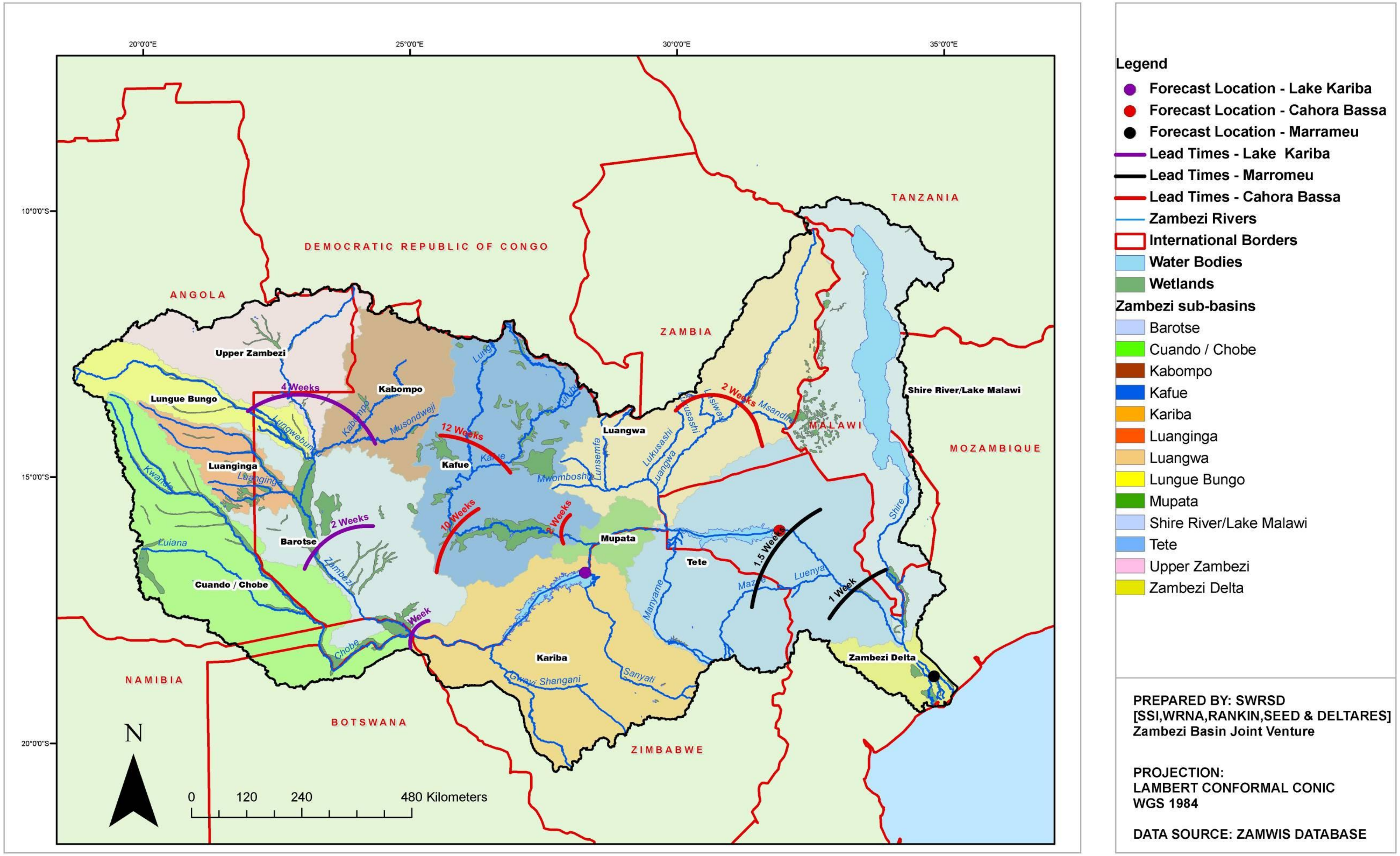


TRANSBOUNDARY WATER MANAGEMENT IN SADC: DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT

ZAMBEZI RIVER BASIN: PRELIMINARY BASIN RESPONSE TIME

On behalf of: In Delegated Cooperation with:

Figure 2.6: Map showing gauges used in preliminary response time calculations



TRANSBOUNDARY WATER MANAGEMENT IN SADC: DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT

ZAMBEZI RIVER BASIN: CONCEPT MAP OF FORECASTLEAD TIMES ESTIMATED FROM APPROXIMATE BASIN RESPONSE TIMES

On behalf of: In Delegated Cooperation with:

Figure 2.7: Concept map of forecast lead times estimated from approximate basin response times

2.4 Summary of Flow Forecasting Requirements

In this section, an analysis of flow forecasting requirements in the Zambezi River basin is presented, together with the required forecast information for each stakeholder group within the basin. A broad range of stakeholders have been identified, including disaster management units, dam operators, power companies, and tourism and wildlife agencies. Stakeholders across the basin from these different groups were interviewed through specific meetings and a questionnaire survey to identify the information needs. These needs were divided into three typical lead times: short range forecasts (1-10 days), medium range forecasts (10 days – 3 months), and long range or seasonal forecasts (3 months – 1 year). Short range forecasts are typically utilised by those involved in responding to flood issues, such as disaster management units, whilst the medium range and seasonal forecasts are generally of use in long term water resources planning (e.g. dam operators). The key output of the above process is concise information which summarises the user's requirements across the Basin, including identification of forecast locations and the lead times at which flow forecasts are to be provided.

In Section 2.3, response times within the Basin were analysed, providing an understanding of the time of travel through the river system. It was found that in some case the information requirement can be easily fulfilled through gauged data from flow gauges upstream of the site of interest, given that the response time from that gauge is longer than the length of the lead time required. This is, for example, the case upstream of Lake Kariba, where the slow response time of flood flows through the Barotse plains means that flow data from the river system upstream of the plains (e.g. the Kabompo River) is useful in predicting flows into Lake Kariba for the first 1-2 months. In the fast responding system of the Luangwa River, on the other hand, a forecast with a lead time in the order of ten days will require the modelling of rainfall-runoff processes in the basin, as well as observed and forecast rainfall over the catchment.

The combination of the analysis of forecast lead times and the basin response times presented in this chapter forms the foundation of the design for the proposed basin-wide flow forecasting system. Whilst the analysis presented considers the needs of the stakeholders across the basin, once the flow forecasting system has been designed to a greater level of detail, each of the stakeholders will need to establish procedures through which the information provided by the system will be utilised. Through development of these procedures, the information requirements will again be refined. A recommended approach in developing these procedures and refining the requirements is through an interactive process, where options are demonstrated to the stakeholders through pilot forecast products, and subsequently refined prior to incorporation into a fully operational forecasting system.

3 Evaluation and Design of Flow and Precipitation Network

3.1 Overview

A prerequisite for an accurate flow forecasting system is an adequate flow and precipitation monitoring network. The network has to be reliable, sustainable, have a suitable system for data transmission, and needs to have sufficient coverage in the right catchment areas to meet the required forecasting lead times. This section of the report outlines the preliminary work that has been undertaken to evaluate the existing networks in the 8 countries that lie within the Zambezi River basin.

The evaluation and design process has principally involved the following key steps:

1) Obtaining data and information on existing flow and rainfall networks currently in operation in the Zambezi River basin. This step involved the following sub-steps:

    - Review of the ZAMWIS database to obtain relevant and available data/ information;
    - Obtaining information on existing monitoring networks from National Water Ministries or subsidiary authorities in each of the Basin countries through a questionnaire response process (refer to Section 2.1 of this report for further details of this process);
    - Review of relevant and available literature and reports covering flow and rainfall monitoring networks in the Zambezi River basin. Documents reviewed in this sub-step were principally sourced from the Client (SADC Water Division), relevant websites on the internet, important funding agencies such as the World Bank, the ZAMWIS database and directly from stakeholders; and
    - Meetings with relevant stakeholders, particularly those who are part of the Project Advisory Group. Summaries of the main discussion points of these meetings have been prepared as part of this Project.

2) Identifying key features of existing networks in terms of coverage (gauge locations), instrumentation (automatic, manual, etc.), data transmission (satellite, GSM, phone, radio, post, etc.), reliability and sustainability and preparing inventory overviews for each country;
3) Evaluating the capability within the Zambezi River basin with respect to coverage, communication of data, reliability and sustainability, particularly with respect to preliminary forecast requirements;
4) Evaluating the SADC-HYCOS flow gauging network and considering arguments in favour and against the adoption of this network as the core network of a future flow forecasting system;
5) Preparing a flow gauging network design for a basin wide flow forecasting system taking into consideration both the expected requirements of a fully operational flow forecasting system, and the practical constraints of establishing a real-time flow gauging network in the riparian countries of the Zambezi River basin;
6) Identifying recommendations for further steps required to establish a monitoring network for a real-time operating system;
7) Evaluating the suitability of the existing rainfall gauging network in the Zambezi River basin on the basis of readily available rainfall data and preliminary forecast requirements using numerical gauge correlation methods;
8) Identifying required rain gauge densities in each sub-basin on the basis of preliminary forecast requirements. Comparing the existing rain gauge density in the Zambezi River basin with that of other large basins worldwide, such as the Mekong River Basin in South-East Asia and the Rhine River Basin in Europe;

9) Evaluating the potential suitability of existing satellite rainfall estimation technologies using three sites within the Zambezi River basin and available ground-based daily rainfall data. Recommending further steps for the use of such technologies in a real-time flow forecasting system and evaluating the advantages of such an approach in comparison to the establishment of a ground based monitoring system; and
10) Proposing strategies and/or recommendations for measurement of rainfall in the Zambezi River basin on the basis of preliminary forecast requirements.

3.2 Inventory of Monitoring Networks by Country/Authority

While each of the countries within the Basin operate and maintain flow and rainfall gauging networks within their respective national boundaries, operators of dams within the basin either have their own monitoring networks for flow forecasting or they manage gauges belonging to the respective National Hydrological Service (NHS). The following section summarises relevant details relating to the networks within each of the eight countries of the Zambezi River basin. Although the SADC-HYCOS flow gauging network is a largely real time network spearheaded by SADC-HYCOS on behalf of the member states of SADC, the individual gauges within each country are owned and operated by the respective NHS under the National Ministries of Water. For this reason, a description of this network is not provided here. However, a detailed overview of the SADC-HYCOS network is provided in Section 3.5.2.

Angola

Flow gauging activities in Angola were active in the Zambezi River basin until the mid-1970s, before they were severely disrupted by the civil war. Consequently, very limited flow gauging has been undertaken since then. To this day, the establishment of new gauges or re-establishment of old ones is severely hampered by the high incidence of land mines within the Angolan portion of the Zambezi River basin. For this reason, the ZAMWIS database currently has data for only one flow gauging station in Angola, which is located on the upper reaches of the Lumege River near Canhague. The Lumege River is a tributary of the Luena River, which in turn, discharges into the Upper Zambezi River. The available record in ZAMWIS extends from 1964 to 1972. However, according to Mr Musariri Musariri (per com), who was until recently the Chief Hydrologist for the SADC-HYCOS Project in Pretoria, a SADC-HYCOS (real-time) gauge is currently operating on the Luena River in Angola, although the exact location of the gauge is unknown. With respect to rain gauges, the ZAMWIS database contains data for three3 sites.

Zambia

Zambia, together with Zimbabwe, has the most comprehensive network of both rainfall and flow gauging stations in the Basin. The Zambia Department of Water Affairs, Zambia Meteorological Department (refer to Figure 3.1), ZESCO and ZRA (Zambia and Zimbabwe) all operate monitoring networks, although it is understood that data capture resources are shared between the three authorities for some flow gauges. ZRA has its own network of 14 runoff stations as shown in Figure 3.2. All stations are manned by gauge readers, who take manual readings off gauge plates. Gauge readers undertake an annual course and their stations are visited by technical staff every year.

Regarding the Kafue River, a number of flow gauges in the Upper Kafue and Kafue Flats have been analysed as part of a separate project by the Consultant entitled "Decision making system for Improved Water Resources Management for the Kafue Flats". Most of these stations are providing valuable data, with the exception of a few. A visit was made by Mr Allan Bailey to Lusaka on 12-14th April 2010 to obtain updates to rainfall and flow data, which only went up to

2006 at best for rainfall data and 2002 at best for flow data (from the ZAMWIS database). The quality of the streamflow data appears to have deteriorated noticeably in terms of the number of missing months in a year with the exception of station 4669 at Kafue Hook. The method of transmission appears to be the main problem in recording the flows accurately with the postal service being the most problematic. A number of radios appear to be out of order. Rainfall also appears to have deteriorated over the past decade with a relatively large number of missing or unreliable values and with most of the records lacking data for recent years.

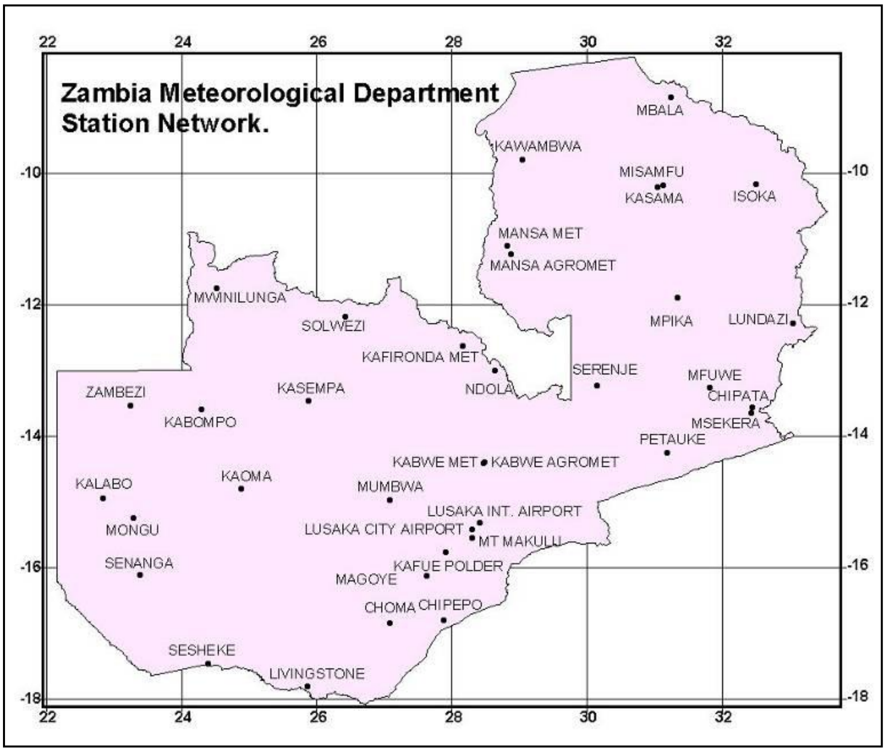


Figure 3.1: Zambia Meteorological Department Station Network (source: http://www.wmo.int)

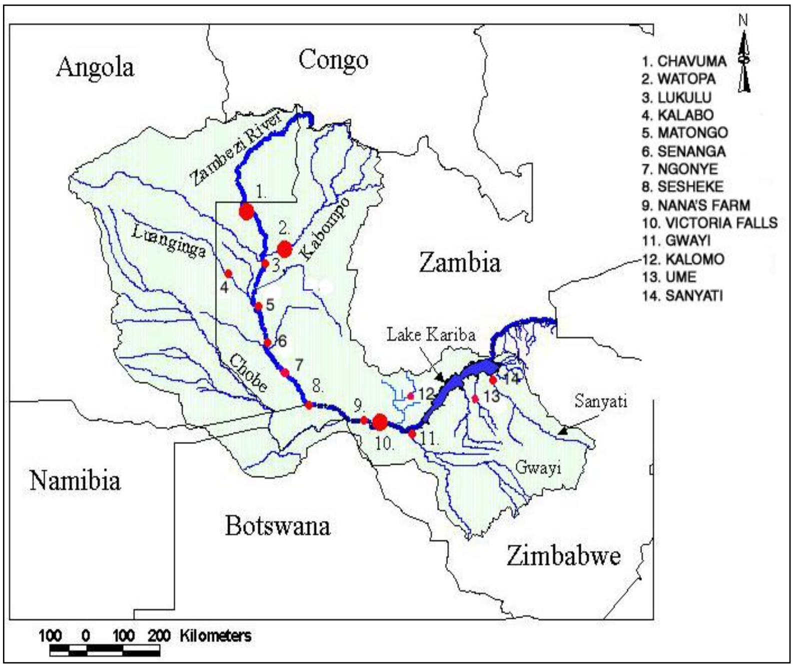


Figure 3.2: ZRA Flow Gauging Network

Namibia

The Namibia Department of Water Affairs and Forestry currently operates and maintains automatic flow gauges at Katima Mulilo (Zambezi), Kongola (Kwando), Ngoma Gate (Chobe) and Bukalo and has a de facto role in flow forecasting and early warning of floods. The Namibia Meteorological Service operates a number of rainfall stations in the Basin, including Katima Mulilo.

Botswana

Botswana covers a very small part of the Zambezi Basin, but through the Botswana Department of Water Affairs it operates a flow gauge with a data logger at Kasane, which is part of the SADC-HYCOS network. It is understood that Botswana also receives flow data from Namibia and Zambia for flows in the Kwando, Chobe and Zambezi.

Zimbabwe

Zimbabwe has extensive coverage of both rainfall and flow gauging stations. Meteorological stations are operated by the Zimbabwe Meteorological Services Department (ZMSD), while the flow gauging network is operated by the Zimbabwe National Water Authority (ZINWA). 24 hour rainfall data is collected from 60 synoptic meteorological stations and some volunteer stations spread around the country. ZAMWIS includes data from 52 of these stations. Other data sets collected include; evaporation, temperature, cloud cover, humidity and wind velocity. As can be seen from Figure 3.3 below, a number of SADC-HYCOS stations are currently operated by ZINWA in Zimbabwe's portion of the Zambezi Basin and additional gauges are planned under Phase II.

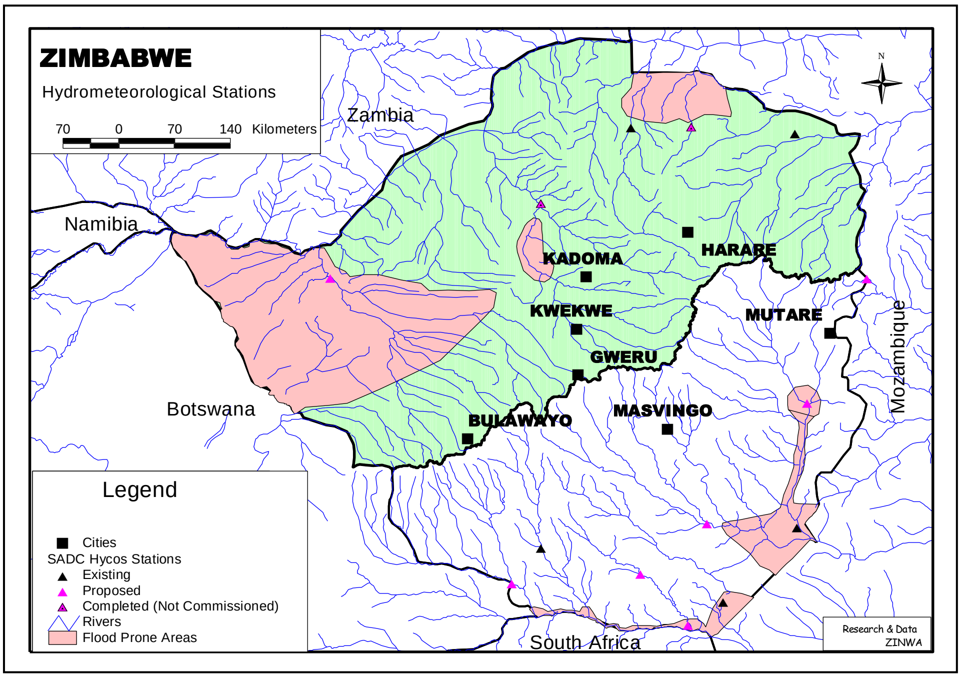


Figure 3.3: Zimbabwe SADC-HYCOS Stations (source: www.wmo.int)

Malawi

In water resources terms, Malawi is dominated by Lake Malawi and the Shire River which impact on the Zambezi delta. The Department of Climate Change and Meteorological Services operates 22 full meteorological stations, 21 subsidiary agro-meteorological Stations, 9 automatic weather stations, well over 400 subsidiary rainfall stations scattered across the country, a satellite receiving station and the Meteosat 2nd Generation, capable of accessing satellite imageries at 15 minute intervals and at more wavelengths (12 channels) (ZAMWIS includes data for 29 rainfall stations). In addition, the Department of Water Resources is currently responsible for the maintenance of 168 flow gauging stations, 23 of which are water level stations and 6 are SADC-HYCOS stations. The Department of Water Resources also has a trigger based flood warning system for the Shire and Ruo Rivers.

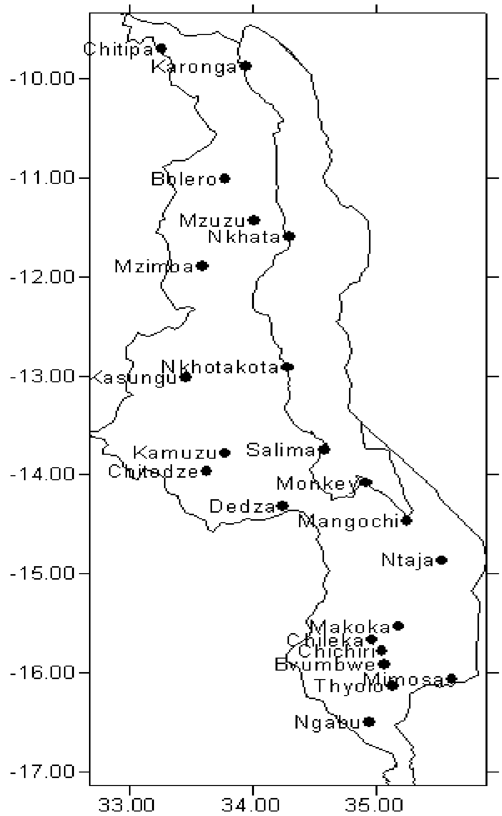


Figure 3.4: Malawi Meteorological Station Map (source:www.wmo.int)

Tanzania

The south-western part of Tanzania includes a small part of the upper reaches of the Shire River Sub-Basin, which is part of the overall Zambezi River basin. ZAMWIS includes data for 27 flow or water level gauging stations and 8 rainfall stations, including a SADC-HYCOS flow gauge on the Ruhuhu River, which discharges into Lake Malawi.

Mozambique

Cahora Bassa Dam is one of two major dams in the Zambezi River basin and therefore rainfall and flow gauges relating to this dam are extremely important. However, the country has a relatively small proportion of the overall Zambezi River basin. Although relatively few rainfall and flow gauges have been included in the ZAMWIS database, ARA Zambeze currently manages a network (ZAMWAT) of 29 water level gauges and approximately 48 rainfall stations. Flow records in ZAMWIS contain water level data only and it is understood from discussions with ARA Zambeze that rating curves for existing Lower Zambezi gauges are generally of poor quality. ARA Zambeze is responsible for flow forecasting. An early warning system for the Lower Zambezi was setup by DHI Consultants in 2008. It is understood that the system includes collection of real-time data from both flow and rainfall gauges in the Lower Zambezi Basin.

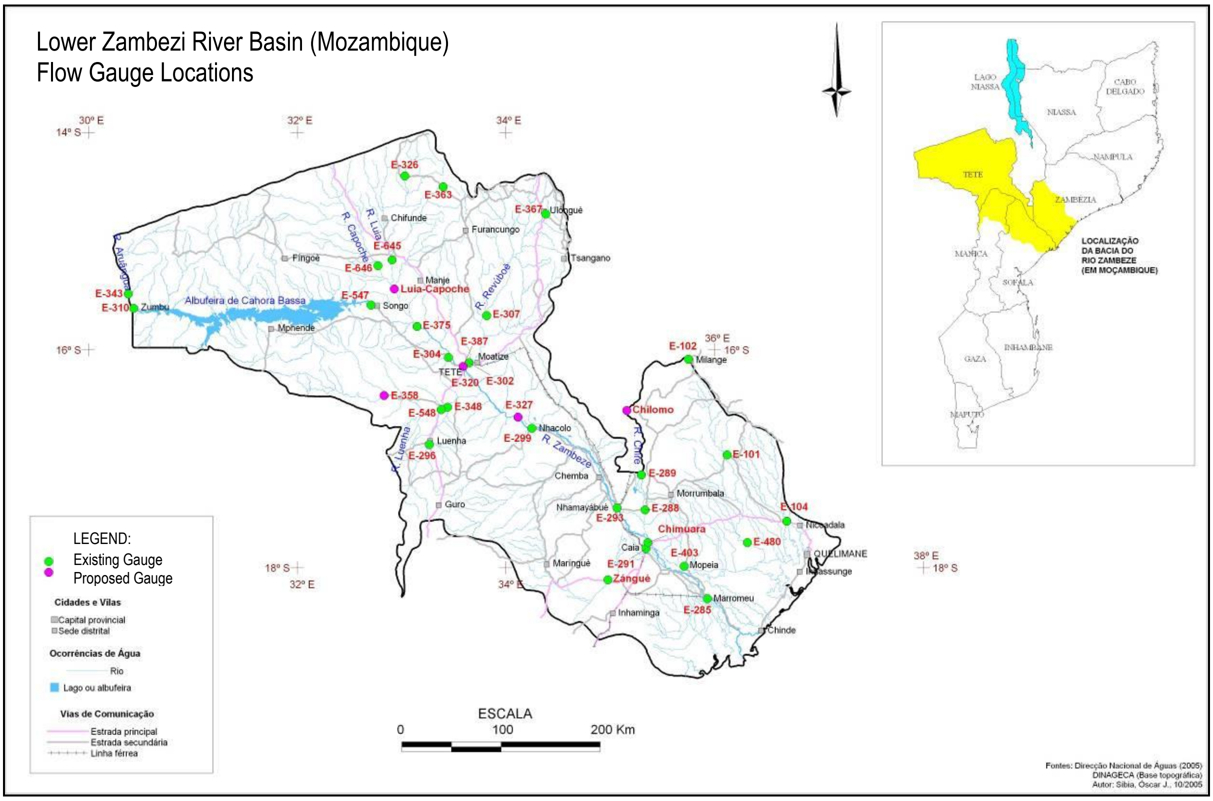


Figure 3.5: Flow gauging network managed by ARA Zambeze (including proposed stations), (source: http://www.wmo.int)

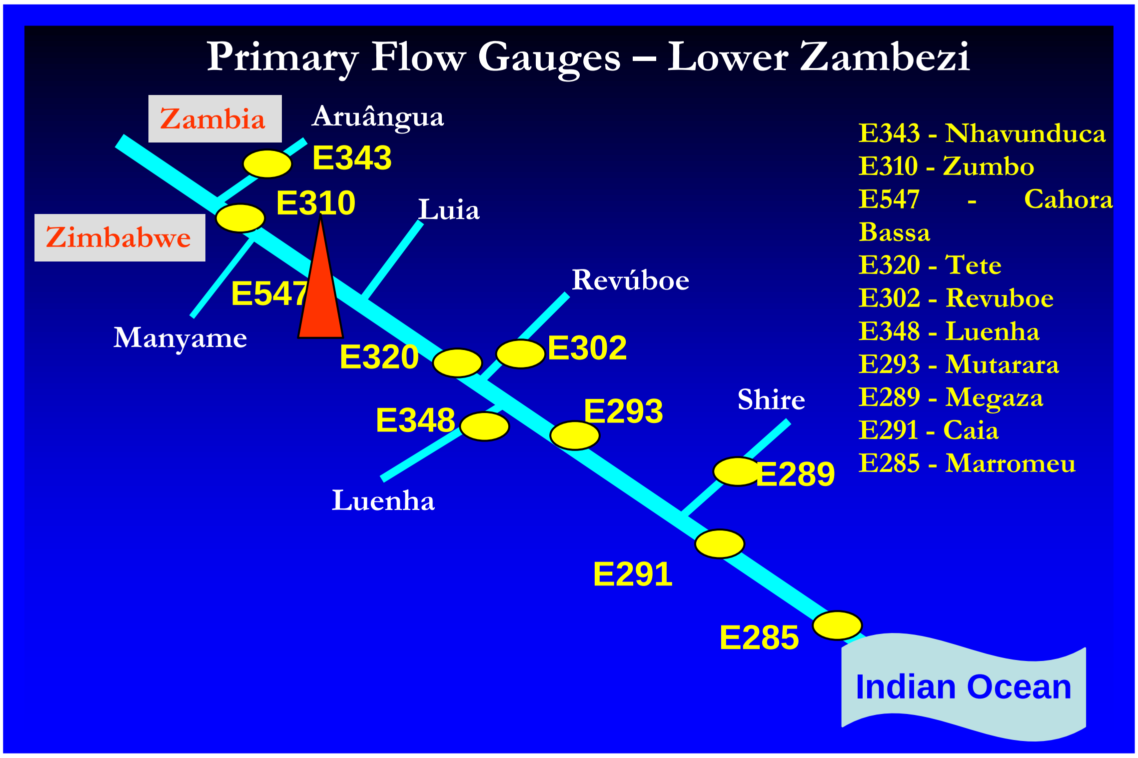


Figure 3.6: ARA Zambeze Principal Hydrometric Network (source: http://www.wmo.int)

3.3 Criteria for Evaluation of Flow and Precipitation Networks

The adopted criteria for evaluation of the existing network of flow and meteorological stations for the purpose of flow forecasting were as follows:

- *Coverage* – it is essential that precipitation, as the 'driver' of flow, and flow itself as the principal input and output of a flow forecasting system, are accurately measured both temporally and spatially. In the context of a flow forecasting system, coverage refers to the density and/ or location of gauges within a precipitation and flow gauging network, as required to meet the designated lead times at the desired accuracy. For example, if a lead time of 10 days is required for disaster management operations at Katima Mulilo (Namibia) in the Upper Zambezi Basin, then observed rainfall data will only be required for the portion of the basin that lies less than 10 days away in terms of response time. In practical terms, this means that measurement of rainfall in the portion of the Basin upstream of the Barotse Flooplain will not be required as the travel time for flows through the Barotse Floodplain is generally in the order of one month, which is greater than the required lead time. Flow gauging alone will therefore be adequate for accurate flow forecasting. However, measurement of rainfall in the catchment area immediately upstream of Katima Mulilo will be required as this area will have a response time of less than 10 days. The concept of coverage is therefore closely related to the requirements of the forecasting system and cannot be undertaken in isolation of the forecasting system requirements;
- *Reliability* – rainfall and flow gauging stations are required that will provide sufficiently accurate data so that they can be developed for use in forecasting models. Reliability in the context of forecasting therefore refers to the ability of chosen stations to consistently provide the required data at the required accuracy;
- *Communication of data* – it is imperative that data from key flow and rainfall gauges is communicated promptly and effectively to a central forecasting location and correctly transferred to electronic format for dissemination to users. In most cases, it is desirable that this is achieved via automatic measurement and transmission; however, manual readings often serve as an important check and backup option for automatic gauges, which may be subject to theft and vandalism; and
- *Sustainability* – in the context of flow forecasting, sustainability refers to the ability of stations to deliver accurate data on a continual basis, without interruption. This is an important consideration in remote areas where breakdowns due to faulty equipment or vandalism can take weeks or even months to repair. Sustainability should also be considered in the context of institutional arrangements and funding. Water resources projects in developing countries often fail because funding for on-going operation and maintenance of essential equipment is not provided due to political, economic or social constraints.

3.4 Evaluation of Flow Networks

3.4.1 Introduction

The ZAMWIS database formed the starting point for evaluation of the existing flow gauges in the Zambezi River basin. Data from the database was used to prepare a basin map (refer to Figure 3.7) showing major rivers and tributaries, major catchment boundaries, major dams and lakes, significant wetlands, country divisions and flow gauging stations. Flow and water level data for selected gauges were also obtained from the database.

In order to obtain an overview of the relative contributions of the various sub-basins to flows in the Zambezi River basin, approximate mean annual runoff (MAR) values for most major sub basins were calculated. Data was obtained from a number of sources. These MARs are presented in tabular form in Table 3.1 below, as well as graphically on Figure 3.7.

Table 3.1: Contribution of Zambezi Rivers to the Total Mean Annual Runoff (MAR)

Description	Incremental Catchment Area (km²)	Incremental MAR (10^9 m³)	Total Catchment Area (km²)	Total MAR (10^9 m³)
Northern Highlands (inflow to Barotse Wetland)	220 570	27	220570	27
Upper Zambezi at Victoria Falls	507 200	33	507 200	33
Sub-catchment to Kariba Dam	156 600	7	663 800	40
Kafue River	154 200	9		
Luangwa River	151 400	18		
Sub-catchment to Cahora Bassa Dam	80 600	10	1 050 000	77
Luia River	28 000	4		
Revúboe River	15 540	3		
Luenha River	54 140	5	1 147 680	89
Shire River	154 000	17	1 301 680	106
Zangue River	8 500	1	1 310 180	107

Note: MARs are given to the nearest 10^9 m³.

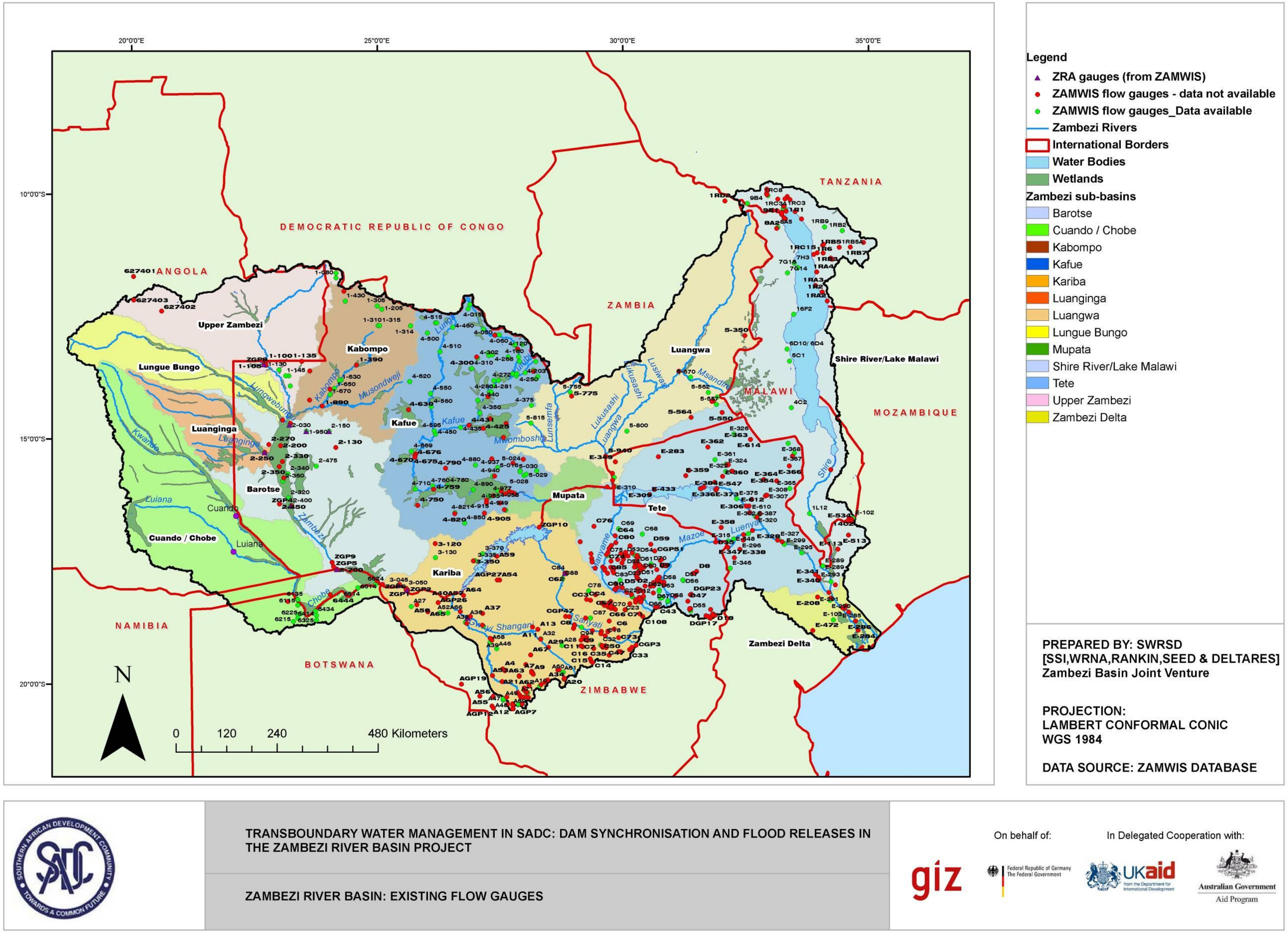


Figure 3.7: Zambezi River Basin Flow Gauge Map (source: ZAMWIS)

3.4.2 Coverage

As can be seen from Figure 3.7, the Zambezi River basin is covered by a wide geographic spread of flow gauges. The following paragraphs outline the gaps in coverage in the Upper, Middle and Lower Zambezi River basins, respectively. However, it should be noted that ZAMWIS includes data for historical gauges and not all of the gauges shown on the map are currently operational.

3.4.2.1 Upper Zambezi Basin

The Upper Zambezi River basin (Upper Basin) extends from the source of the Zambezi River to Victoria Falls. A noticeable gap in the flow gauging network in the Upper Basin is the portion that lies within Angola. Although it accounts for close to half of the entire area of the Upper Basin, ZAMWIS includes data for only one historical gauge in Angola.

The above problem is partly compensated for by the fact that flow gauges have been installed on some of the tributaries (Luanginga & Southern Lueti Rivers), inside Zambia and upstream of their confluences with the Zambezi River. Other major sub-catchments in the Upper Basin include:

- The Kabompo, Dongwe and Luena Rivers in north-western Zambia;
- The Kwando / Linyati / Chobe Rivers in Angola, Namibia and Botswana; and
- The Gwayi / Shangani and Sanyati Rivers in Zimbabwe;

All of the above sub-basins are covered by at least one gauge (based on ZAMWIS and other data) and therefore gauges within these sub-basins could potentially be made available for the purpose of operational forecasting.

3.4.2.2 Middle Zambezi Basin

The Middle Zambezi River basin (Middle Basin) extends from Victoria Falls in Zambia/ Zimbabwe to Cahora Bassa Dam in Mozambique. Although this section of the Zambezi River is shorter in length than the reach of the Zambezi River in the Upper Basin, the overall basin area is not significantly different. This is primarily due to the very large tributaries that contribute to the Zambezi River flow in this part of the Basin, such as the Kafue and Luangwa Rivers. As can be seen from the MAR values shown in Table 3.1, the Kafue and the Luangwa Rivers alone provide almost a third of the Zambezi River's flow at the downstream end of the Middle Basin.

Flow gauge coverage in the Middle Zambezi River basin is relatively good. The Kafue River has a number of gauges, and as a result of the regulation of flow at Itezhi-Tezhi Dam and Kafue Gorge, as well as the considerable lag through the Kafue Flats, coverage appears to be adequate. Similarly, the Gwayi, Sanyati and Manyame River Sub-basins in Zimbabwe are generally well covered and coverage in the Luangwa River Basin is adequate for the purpose of forecasting of inflows from this sub-basin into the Zambezi River.

Between Kariba and Cahora Bassa, there are relatively few historical gauge sites on the Zambezi River with only the downstream end of this reach being covered. Although flows are measured at Kariba, there is a deficiency in gauges in the upper part of this reach (it is understood that the Department of Water Affairs in Zambia operates a manual gauge at Chirundu, although this gauge is not included in ZAMWIS).

3.4.2.3 Lower Zambezi Basin

The Lower Zambezi River basin (Lower Basin) extends from Cahora Bassa Dam to the mouth of the Zambezi River. Major tributaries in this portion of the Basin include the Shire, Mazowe / Luenha, Luia and Revuboe Rivers. As can be seen from Figure 3.7, the Lower Basin narrows considerably in its lower reaches, with the majority of inflows entering in the top half of this reach of the Zambezi River, as well as from the Shire River Sub-Basin. From the map it can be seen that flow gauge coverage for the main Zambezi River, as well as the major tributaries listed above is reasonably good. Therefore, from the perspective of general gauge coverage, no obvious deficiencies are apparent in the Lower Basin.

3.4.3 Reliability

In order to evaluate the historical reliability of gauges in the ZAMWIS database, a summary table showing record lengths, gaps in the record and other anomalies for a sample of gauges was prepared. From this table, it was found that some records are long and continuous, while others have numerous gaps. Reliability therefore varies significantly from one gauge to another. However, it can concluded that reliability is a problem with most gauges and therefore establishment of a real-time monitoring network may require that other measures are put in place, such as the approach undertaken by ZRA, in which real-time gauges are assigned a gauge reader, who undertakes manual measurements and communicates these by phone or radio to the forecasting centre. This would also allow for cross-checking of real-time data with manual data.

From the point of view of flow forecasting, it is generally preferable to select gauges that have relatively long and continuous records. This allows for more accurate calibration of flow forecasting models and therefore improved forecasting. Missing data reduces model accuracy. In many cases, missing values often occur due to rating curves being exceeded in times of flood and for flood forecasting these are generally the more important flows.

Of significance to the issue of reliability is the fact that some AG members and other stakeholders have reported that many existing gauges on the Zambezi River and other large tributaries do not have accurate rating curves. Rating curves are particularly difficult to establish in areas where insufficient elevation data currently exists, which is the case for most of the Zambezi River. Problems are also encountered in areas with very wide floodplains, such as in the lower reaches of the Zambezi River in Mozambique, where floodplains are often several kilometres wide. In addition, as most gauges are located at natural control sections, rating curves often change and therefore regular updates are required. A comprehensive programme will therefore be required to establish and update rating curves for key gauges as part of the implementation phase of the flow forecasting network.

3.4.4 Communication of data

For a real-time forecasting system, on-going communication of data from individual gauges to a centralised forecasting location is of paramount importance. For the Zambezi River basin, where response times are relatively long, it is likely that transmission of data once a day will be adequate. However, for some gauges where response times are shorter, sub-daily communication is likely to be required. Like reliability, communication of data could affect the accuracy and ultimately the effectiveness of the forecasting system, as on-going real-time data is required to continuously update forecasting models and therefore to achieve the highest possible forecast accuracy.

Because data is likely to be required at daily intervals from most stations, the only suitable forms of communication are likely to be automatic transmission (telemetry, satellite, GSM, GPRS, etc.) or manual transmission by radio or phone. Postal communication is not suitable for obvious reasons. Investigations for this study benefited from the experience of the Kafue River System where a study was carried out on the *Decision making system for Improved Water Resources Management for the Kafue Flats Project (*WWF and ZESCO, 2004). In this study it was found that flows at stations which are communicated by postal delivery are generally erratic, whereas flow records for stations which are communicated by radio/telemetry are generally of much better quality.

At present, measurements from most gauges in the Zambezi River basin are transmitted manually, either by phone, radio or post. Very few networks currently have real-time transmission capability. The only exceptions that the Project Team are currently aware of include: a network of real-time gauges operated by the Department of Water Affairs and Forestry in Namibia (it is understood that these gauges use GSM technology). In addition, there is the network of satellite transmission gauges in Zambia and Zimbabwe operated by ZRA, as well as the SADC-HYCOS network of flow gauges, which relies on satellite transmission in the Zambezi River basin.

Based on the experience of the SADC-HYCOS project as discussed in Section 3.5.2, GSM technology is substantially cheaper and a more sustainable alternative to satellite transmission. The SADC-HYCOS Project has started replacing damaged satellite transmitters in some countries, such as Malawi, Lesotho and Swaziland, with GSM transmitters where coverage is available, as these can operate on a battery without maintenance for a period of approximately 3 years. A solar panel is therefore not required, which significantly reduces the risk of theft or vandalism.

The map below shows GSM coverage in Southern Africa as of January 2009. As can be seen, coverage is patchy along most parts of the Zambezi River, with the result that only some areas such as Malawi, Kariba/Chirundu, and Victoria Falls to Katima Mulilo appear to have sufficient GSM coverage to allow this technology to be an alternative to the much more costly and complex satellite transmission. However, as can be seen from Figure 3.9, which shows GSM coverage for the Zain network in Zambia (www.zm.zain.com), coverage has increased considerably in Zambia since the 2009 map in Figure 3.8 was produced. The entire Upper Zambezi River from Chavuma to Victoria Falls now has coverage, where there was previously only very limited coverage. At the time of writing this report, detailed coverage maps of all basin countries were not available and therefore an updated coverage map for the entire basin could not be prepared. However, internet research suggests that the trend of rapidly increasing coverage has been followed in other basin countries, which suggests that GSM or GPRS transmission will be a viable alternative for a flow forecasting system, particularly in view of the likely timeframe that would be needed to establish such a project.

Figure 3.8: GSM Network Coverage for Southern Africa, January 2009. Coverage is shown in dark brown (www.gsmworld.com).

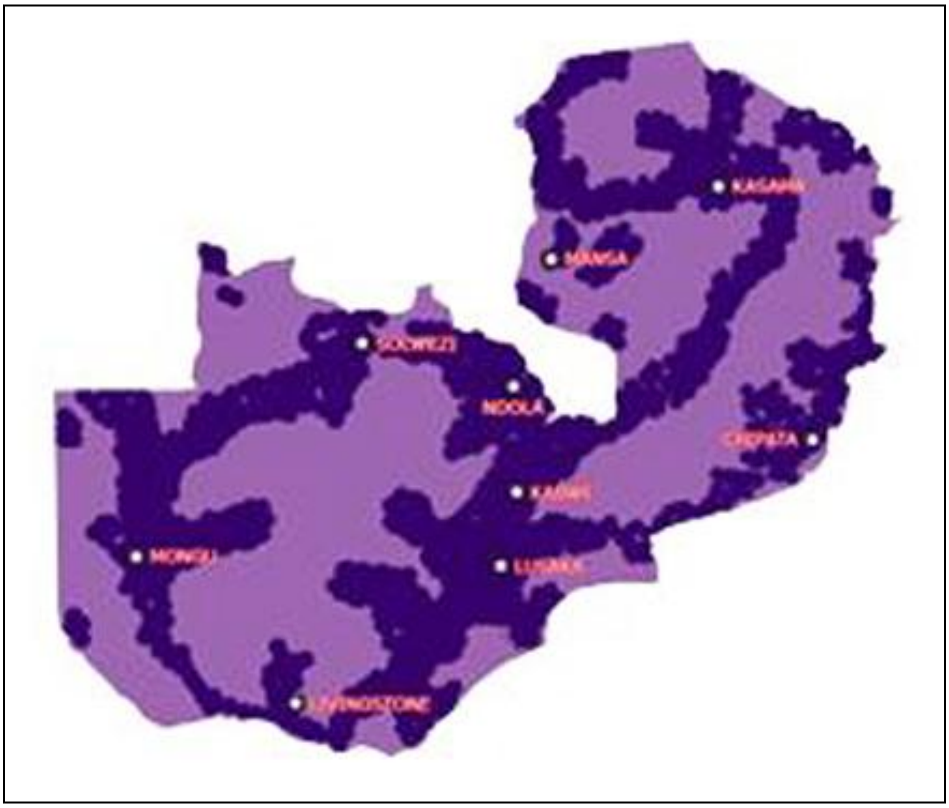


Figure 3.9: GSM Network Coverage for the Zain Network in Zambia. Coverage is shown in dark blue (www.zm.zain).

3.4.5 Sustainability

There are numerous problems relating to the establishment and on-going maintenance of meteorological and flow stations, including cost of installation and maintenance, cost and logistical problems related to monitoring and documentation, communication, vandalism and other obscure issues, such as political priorities and active landmines (Angola). The location of stations is therefore important. Some stations are located where they can be protected and well managed, whereas others are in very remote areas where protection is difficult and access for service and repairs can be very restricted and costly. Theft and vandalism are also not the only source of damage to stations, with weather related risks, such as lightning being prevalent in many parts of the Zambezi River basin, as well as risks of damage associated with high concentrations of wildlife. These have historically sometimes been a cause of erroneous readings or damage. Automatic stations are generally preferable as they reduce reliance on human beings but they still require checking and maintenance and unmanned stations are usually ripe targets for theft or vandalism.

The ZRA system in Zambia and Zimbabwe appears to have been successful as some ZRA gauges have both automated measurements with satellite transmission, as well as manual readings communicated by a gauge reader by radio or phone. This system offers the benefit of automatic readings and data transmission, with the added benefit of manual readings to confirm or refute potentially erroneous readings. The gauge reader usually lives near the gauging station and therefore his/her presence reduces the risk of theft or vandalism.

In addition to the above problems, which relate more to the setup of the system, equally important are the institutional arrangements which are essential for the long-term support and funding of the project. The following excerpt from the SADC-HYCOS Phase II Implementation Document (June 2002) highlights some of the potential challenges:

"Experience in many developing countries indicates that it is impossible to assure the long-term sustainability of a development project. In the water resources sector, many projects have been implemented but have had little or no lasting effect. A range of reasons can be identified, including the frequent loss of key staff, the higher priority placed by governments on other areas of expenditure, government restructuring, inadequate provision for ongoing operation and maintenance, and so forth. Fundamentally, projects are more likely to be maintained if they clearly meet a need of which the government is acutely aware, and the benefits of post-project expenditure clearly exceed the costs and the benefits of other possible expenditures".

Considering the above points, an important issue for this project is the collective commitment of all countries, particularly those in the upper parts of the Zambezi River basin, for whom an accurate flow forecasting system is a lower priority than for downstream countries. Coupled with this is the issue of maintenance and on-going costs and whether these costs should be borne solely by the respective member states or shared with those downstream states that require flow forecasts. In order to address these potential challenges, it is imperative that decision makers in each of the member states understand and appreciate the benefits of a basin-wide flow forecasting system and further that they agree upon an equitable arrangement for sharing of costs that guarantees the long term sustainability of the project. While it appears that this commitment has been achieved in some of the Basin States for the operation and maintenance of the SADC-HYCOS network, the experience in other countries has been less positive, with the result that some gauges are no longer operational. Unless this commitment is obtained for the proposed Zambezi River basin flow forecasting system, there may not be a long-term future for such a system, even if the initial setup and installation is successful.

3.5 Design of Flow Gauging Network

3.5.1 Overview

This section outlines the work that was undertaken to identify key gauges for operational forecasting and to undertake a preliminary gap analysis. It should be noted that a very important issue for the success of this project is the acceptance of recommendations by the affected stakeholders in each of the basin countries. At project inception, an approach for development of a real-time hydro-meteorological network was proposed by the Consultant that did not adequately take into account the considerable effort that has already been undertaken to establish the SADC-HYCOS network. The final proposed approach being presented here was therefore adapted to take this into account.

3.5.2 The SADC-HYCOS Network

3.5.2.1 Overview

The World Meteorological Organization (WMO) and the World Bank initiated the World Hydrological Observing System (WHYCOS) in 1993. The main objective was to strengthen National Hydrological Services (NHS's). WHYCOS subsequently spearheaded regional initiatives in various parts of the world including SADC. This resulted in the setup of the SADC-HYCOS Phase I flow gauging network in 1998, with a plan for the installation of 50 Data Collection Platforms (DCPs) equipped with real-time monitoring and transmission equipment, the establishment of a Pilot Regional Centre, and the training of regional personnel from participating countries. Installation and setup for Phase 1 was completed on 31 August 2001. However, for a variety of reasons, only 43 DCPs out of the planned 50 were eventually installed. The SADC-HYCOS Phase II project commenced in 2006 and was designed to consolidate and expand on the project activities that were initiated during Phase 1. An additional 41 DCPs are planned under this phase. Phase II is mostly complete, although gauge installation has been delayed in some countries due to a lack of funds for the construction of civil works. Figure 3.9 shows the locations of the flow gauges installed under Phase I and Phase II (not yet complete). As can be seen, the number of SADC-HYCOS gauges in the Zambezi River basin compared to other river basins in the SADC region is relatively high.

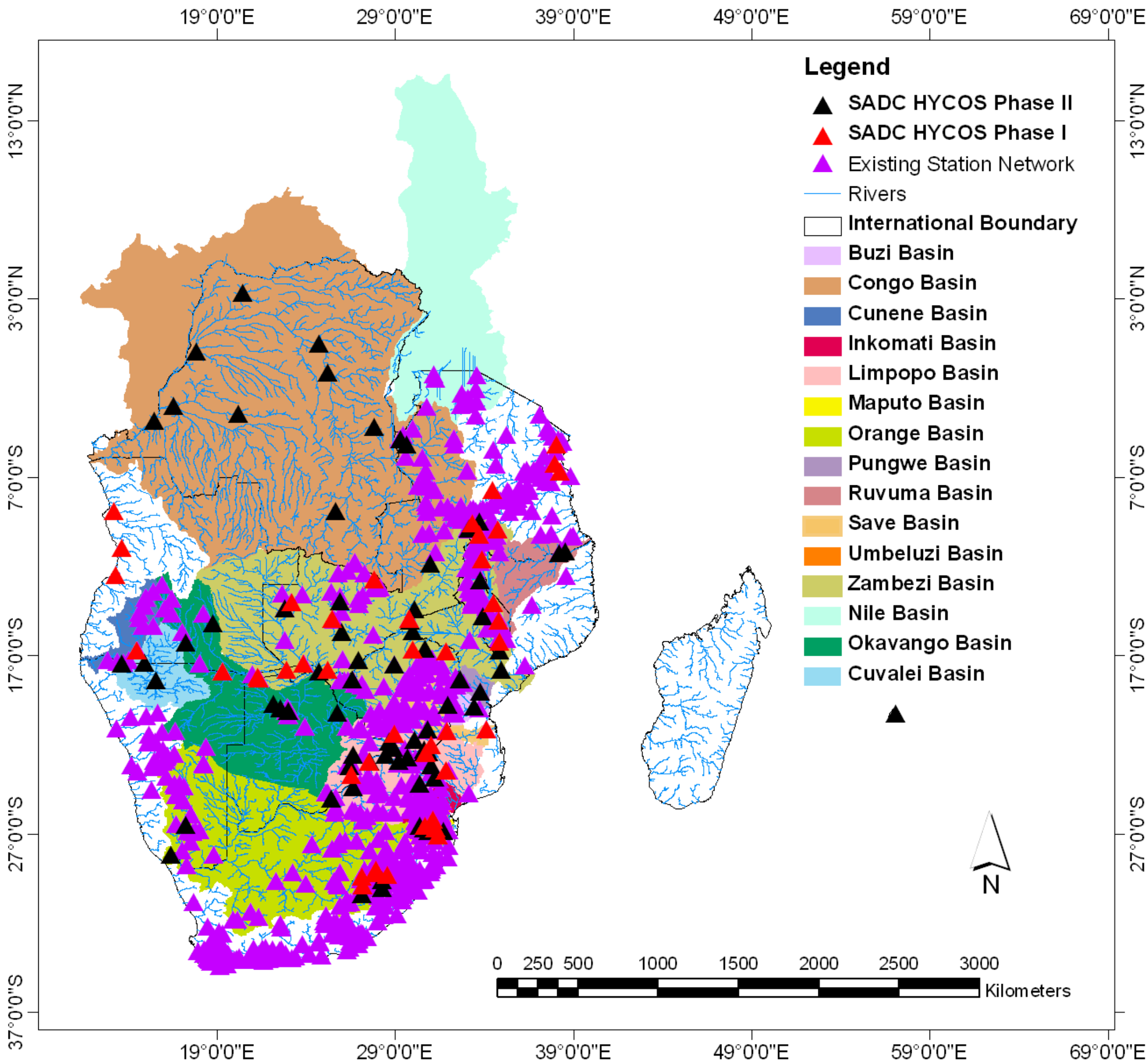


Figure 3.10: SADC-HYCOS Network (source: www.wmo.int)

Funding for the SADC-HYCOS Project (Phase I and II) was set up such that donors provided funding for purchase of gauge equipment (monitoring and transmission), while funding for civil works and operation and maintenance costs were/ are provided by the respective Member States.

3.5.2.2 Lessons Learnt from the SADC-HYCOS Network

Based on information from reports on the SADC-HYCOS project, as well as both verbal and written contributions to this Project by Mr Musariri Musariri (formerly of the SADC-HYCOS project), several important and relevant lessons can be learnt from the experiences of the SADC-HYCOS project (refer to Appendix 4 for further details of the technical aspects of the SADC-HYCOS Project). These include:

- *Equipment Damage* – Of the 43 DCPs that were eventually installed under Phase I, not all are currently operational. Due to equipment limitations such as maximum cable lengths, some stations were installed below high flood levels and were subsequently washed away. Improvements in equipment technology should prevent this problem in future installations. Some were damaged by lightning strikes and others were damaged by theft and vandalism. To address this latter problem, improvements to civil works were implemented under Phase II to make it more difficult to steal or damage the monitoring and transmission equipment.

In addition, local stakeholder consultation has been successful in some areas, whereby protection of equipment is vested with local village leaders;

- *Equipment Selection* - Many of the stations installed as part of Phase I are now reaching the end of their design life, with the result that breakdowns are frequent. The situation has been exacerbated by a lack of spares, due to the fact that the original equipment manufacturer is no longer operating. In addition, experience has allowed different types of equipment to be tested in the Southern African environment, with the result that the most suitable options have been identified. For example, air bubbler gauges have been found to be the most suitable option for river sites within the SADC-HYCOS network, as these gauges are reliable for most situations and are not subject to damage by lightning;
- *Communication of Data* – The DCPs installed under Phase I all used satellite technology for data transmission. In comparison to GSM (cell phone) technology, installation costs for satellite transmitters are approximately 5 times higher. In addition, stations with satellite transmitters are much more likely to be targets of theft and vandalism, due mostly to the fact that they require solar panels for power requirements. GSM installations, on the other hand, do not require satellite transmitters or solar panels and can survive for *approximately* 3 years on battery power without the need for re-charging. They are therefore much less prone to theft or vandalism. GSM installations in Swaziland, Lesotho and Malawi have been successfully operating for a period of years;
- *Database Software* – HYDATA was provided to all participating NHS's and staff were trained on the use of this software. This provided a platform for data management, exchange and dissemination at a regional level. However, it would appear that support for HYDATA, which was developed by the UK Centre for Ecology and Hydrology, is no longer available. This has resulted in difficulties in NHS's where staff members originally trained in the use of the database has left or are no longer available. To address this problem, a decision was made to transfer data management from HYDATA to HYDSTRA, and a number of Basin countries are in the process of implementing this change. The benefit of HYDSTRA is that it is a commercially developed software program with technical support, which is expected to assist Member States with capacity challenges;
- *Internet and Email* – As part of Phase I, a regional electronic network was established and some NHS's were provided with computers and email facilities. This network is a positive step forward and would complement the objectives of the current project, *although* internet speed and email reliability continue to be a significant problem for many NHS's in the region. This has been confirmed by the numerous difficulties that have been experienced by the Project Team in contacting the NHS's in the Basin by email for this project. Improvement of this system will be a key issue for the success of a basin-wide forecasting system, when implemented;
- *Staff Turnover* – loss of trained staff has been a problem in some countries. Many of the technicians / hydrologists trained by the project and involved in the operation and maintenance of SADC-HYCOS equipment are no longer available. Some NHS's also felt that the initial training was not detailed enough. Training is therefore an important issue and on-*going* training is likely to be required where staff turnover is high. The Zambezi River Authority (ZRA) (Zambia/ Zimbabwe) runs a number of real-time stations with equipment similar to those of SADC-HYCOS Phase I and currently has a number of technicians who are proficient in maintaining these stations. It is understood that preliminary negotiations have been undertaken by the SADC-HYCOS Project team to transfer responsibility for maintenance of some SADC-HYCOS stations to the ZRA, which would result in reduced costs and increased sustainability;
- *Stage-Discharge Relationships* – Although most SADC-HYCOS gauges accurately record water levels, stage-discharge relationships (rating curves) have in most cases not been *accurately* determined. Funding for establishment of stage-discharge relationships should be included in capital cost estimates for gauge establishment and allowance should be made for

recalibration of stage-discharge relationships every few years due to the often significant changes that occur in the geometry of natural control sections;

- *DCPs vs DLs* – Not all stations in the SADC-HYCOS network have been equipped with data collection platforms (i.e. automatic data collection and transmission facilities). Some *stations* that were considered to be necessary for water resources planning, but not for flood warning, were installed with data loggers (DLs) rather than data collection platforms (DCPs). However, based on the findings of this project, it may be necessary to upgrade some of the DL sites to DCPs, such as the Lukulu flow gauging station on the Upper Zambezi River in Zambia, which has been allocated a data logger under SADC-HYCOS Phase II; and
- *Funding and Progress* – The SADC-HYCOS Phase II Project is currently underway, with installations completed in Botswana, Namibia, Tanzania, Swaziland, Lesotho and Mauritius. In Malawi and Zambia, equipment has been received and is awaiting installation, while in Zimbabwe, a lack of resources for civil works construction has *delayed* progress. However, donor funding for the project was suspended at the end of May 2010 and therefore the future of the project is currently unclear.

3.5.2.3 Reasons for Adoption of the SADC-HYCOS Network

Several reasons exist for adoption of the SADC-HYCOS flow gauging network as the core network for establishment of a future flow forecasting system. These include:

1) The SADC-HYCOS network was developed through a transparent and participatory approach that included a questionnaire survey, participatory workshops and presentations at Project Steering Committee meetings. A list of proposed stations was provided by each of the member states and representatives of these states were then invited to a number of workshops where the focus group discussion method was used for the selection of stations. This approach had certain advantages:

    - Representatives of member states could exchange views regarding critical water resources management issues in each basin;
    - Prioritisation of stations by the group facilitated development of an optimum and strategic network that was acceptable to the participating countries; and
    - The method led to the development of consensus regarding stations to be included; hence acceptability and ownership of the process by the member countries.

2) The final network was approved by the Project Steering committee mostly composed of representatives of Member States. The stations selected are expected to serve the following requirements:

    - Basin-wide water resources assessment and planning;
    - Flood and drought monitoring;
    - Supporting environmental and ecological management; and
    - Monitoring compliance with agreements between basin states.

    Figure 3.10 shows the location of the finally selected stations by purpose. It can be observed that most of the stations that were chosen principally for "flood warning" lie within the Zambezi River basin. In addition, most of the stations either already have or will be equipped with real time transmission equipment, which is also a likely requirement of the proposed flow forecasting system.

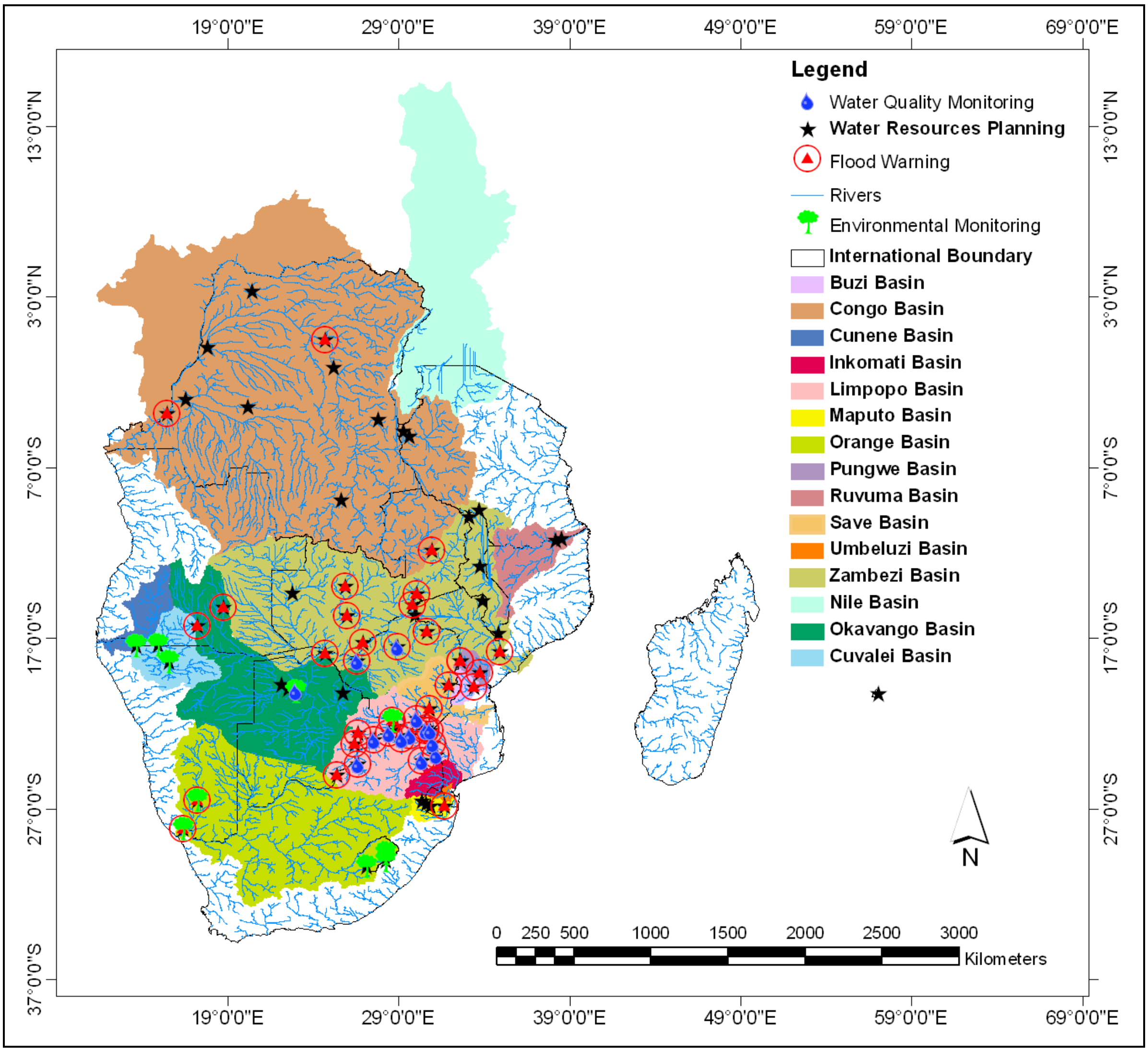


Figure 3.11: Stations classified according to main purpose selected for equipping with DCPs and DL's in the SADC-HYCOS Phase II project

3) Development of the SADC-HYCOS project has followed a process that has had similar objectives to those of this project. These include institutional strengthening and information sharing between the riparian Member States, education and training and improvement of data collection for integrated water resources management;

4) There is already an agreement between the Member states, SADC Water Division and the SADC-HYCOS project that SADC-HYCOS network stations are owned by the Member States and therefore the operation and maintenance costs are borne by the member states. Most of the Member States have, as of now, a budget allocation through their respective Treasuries for the SADC-HYCOS project;

5) The SADC-HYCOS project already has a data transmission arrangement with WMO and EUMETSAT, as well as data transmission facilities and a regional database at the Project Regional Centre in Pretoria, South Africa. These agreements have reduced both capital and operating costs substantially from what would have been required had the assistance and cooperation of the WMO not been obtained;

6) Selection of new stations outside the SADC-HYCOS network will entail:

- Basin States incurring extra costs for the construction and upgrading of the selected stations and procurement and installation of new equipment. This will depend on funding arrangements for establishment of the proposed flood forecasting system. However, it is likely that the on-going operation and maintenance costs will need to be borne by the Basin States or ZAMCOM, when fully established; and
- Commitment and agreements will also have to be made with the Basin States. Although new agreements will be required as part of the flow forecasting system, it is hoped that under the expected establishment of ZAMCOM, this authority will take over ownership of this process. However, the institutional arrangements set up as part of the SADC-HYCOS project could form a foundation for this process.

7) Issues such as site access (for installation and maintenance of gauging and transmission equipment), historical reliability (length of historical record available and record quality), stability of the rating curve for the site (for natural control sections) have already been addressed for gauges in the SADC-HYCOS network.

3.5.3 Network Design

3.5.3.1 Overview

This section of the report describes the adopted network design methodology and a preliminary list of selected stations and sites. For the reasons that will be given later, it was decided that the SADC-HYCOS network should form the core of the required flow gauging network. However, although the SADC-HYCOS network includes gauges in most parts of the basin, additional gauges will be required for flow forecasting. In order to identify gaps in the SADC-HYCOS network and prepare a preliminary network design, the following process was generally followed:

- An independent network design was undertaken using the linear distribution technique. A gap analysis between the SADC-HYCOS network and the resulting designed network was then undertaken;
- As part of the SADC-HYCOS Phase II network design, National Hydrological Services (NHS's) were requested to nominate gauges for inclusion in the Phase II network and not all of the nominated gauges were ultimately selected. A review of the nominated gauge locations from this process was subsequently undertaken as an additional check of the initial network design; and
- A partial review was also conducted of the gauges used in the existing forecasting systems (ZRA and ARA Zambeze).

The main outcome of the above process is a list of proposed existing stations and possible new stations. New stations will require the approval of the respective NHS's, as it is likely that each NHS will ultimately be responsible for the operation and maintenance of new gauges within their respective borders.

3.5.3.2 Design Methodology

The major limitation with the SADC-HYCOS network design was that it had to cater for a limited number of stations to be upgraded to either real-time stations with transmission equipment or automatic stations with data loggers. Consequently, gaps within the network were inevitable. The linear distribution technique was therefore used to identify gaps in the SADC-HYCOS network design and identify possible candidate gauges which could be used to fill these gaps. For cases where there are no existing stations, recommendations have been made to investigate the feasibility of establishing new stations.

The guidelines for design of flow gauging networks as expressed in the *Guide to Hydrological Practices, Volume 1* (WMO, 2008) were generally adopted. These include the following main principles of relevance to this study:

- That a sufficient number of flow gauging stations are needed along the Zambezi River and its major tributaries to allow for interpolation of flow between these stations (if the difference in flow between two points on the same river is less than the limit of error of measurement at the station, then an additional station is not required);
- That gauges are needed at locations where significant changes in flow can be expected, such as downstream of major tributaries, at significant geological or topographical features and at the outlets of major wetlands or natural storage areas; and
- That flow measurement at dams can be used in lieu of establishing new gauges provided calibration of control structures and turbines is undertaken with periodic checking of such calibrations.

The network design approach undertaken in this study focused on flow forecasting. Special cognisance was therefore taken of required lead times, forecast requirements and identified forecast locations as presented in Chapter 2 of this report. As these criteria may differ from the requirements for other water resources applications, the proposed network design may not cater for all needs and applications.

Flow data in the ZAMWIS database is listed by country and therefore a similar approach was adopted for the network design. As already noted, a basin map was prepared showing all flow stations in ZAMWIS (Figure 3.7), and following completion of the initial network design a second map was prepared showing the designed flow network (Figure 3.11).

3.5.3.3 Details of Network Design

This section presents an overview of the network design according to the Upper, Middle and Lower Zambezi River basins, as well as a brief outline of the rationale behind the selection of individual stations. The reader is referred to Figures 2.3, 2.4, and 2.5 in Chapter 2, which graphically show the identified forecast locations according to short lead time, medium lead time and seasonal lead time, respectively. It should be noted that the network design outlined here was undertaken strictly for the purpose of flow forecasting at the identified forecast locations. Other issues, such as water resources planning and environmental monitoring, have different needs and therefore may require additional gauges.

As one of the goals of this project was to retain existing forecasting expertise by integrating existing flow forecasting models rather than replacing them, an important consideration in the network design has been the inclusion of gauging stations that are currently used by forecasting authorities (forecasting models are currently used by ZRA and ARA Zambeze).

Upper Zambezi

The Upper Zambezi River basin (Upper Basin) extends from the headwaters of the Zambezi River basin to Victoria Falls. As can be seen, from Figure 2.3, the most upstream forecast location on the Zambezi River for short, medium or seasonal lead time forecasts is located at Katima Mulilo in Namibia. Preliminary response time calculations (refer to Figure 2.6) indicate that the average response time of the Basin from the upstream end of the Barotse Floodplain to

Katima Mulilo is in the order of 26 days. Considering an estimated required lead time of 10 days, observed flows upstream of the Barotse Floodplain (Lukulu) are unlikely to be required. However, for medium lead time and seasonal lead time forecasts, additional upstream gauges will be needed and existing ZRA gauges upstream of Lukulu have therefore been included in the network design. Only some of the existing ZRA gauges are currently equipped with real-time equipment. These are Chavuma (Zambezi), Watopa (Kabompo), Kalabo (Luanginga) and Ngonye (Zambezi). As an alternative to the manual ZRA station at Sesheke, it is recommended that the real-time SADC-HYCOS gauge at Katima Mulilo is used.

There are currently SADC-HYCOS gauges at Kongola and Ngoma Gate on the Cuando River in Namibia (the river changes name downstream to the Kwando, Linyanti and finally the Chobe before discharging into the Zambezi River); however, these gauges do not provide any advance warning of significant flows from Angola, which does not currently have any operating flow gauges in the Cuando River basin. It is therefore recommended that additional gauges are installed on the Cuando River and its tributary, the Luiana River, within Angola. Suitable locations for gauges still require identification; site selection should take into consideration the natural response time of the Cuando Sub-basin and the estimated required lead time of 10 days for issue of flood warnings at Kongola. For the reasons given above, two new gauges have been included in Table 3.2, with the locations shown in Figure 3.12. Both should be equipped with real-time DCPs, due to the remoteness of this part of the Basin and the difficulties with access. Although the high incidence of landmines in eastern Angola is a major factor restricting the establishment of new flow gauges, it is expected that this situation will improve in the future. At that point, the establishment of new gauges in this part of the basin will need to be urgently considered.

Below the Chobe/ Zambezi confluence, ZRA uses two gauges for flow forecasting. These are at Nana's Farm and Victoria Falls. Nana's Farm is equipped with a real-time DCP, while Victoria Falls is a manual gauge. Due to the close proximity of Nana's Farm to Victoria Falls and the lack of any major tributaries between these gauges, upgrading of the Victoria Falls gauge to a real-time DCP is not considered to be necessary. However, due to the extremely long record available for Victoria Falls (>75 years), data from this station will be useful in the calibration of forecast models.

Middle Zambezi

The Middle Zambezi River basin (Middle Basin) extends from Victoria Falls to Cahora Bassa Dam and includes the major dams of Kariba, Cahora Bassa and Itezhi-Tezhi . Forecasting requirements in this part of the Zambezi Basin are therefore predominantly focused on Dam Operation, although, as can be seen from Figure 2.3, the Middle Basin includes a number of other areas that require predominantly short lead time forecasts. Table 3.2 shows the proposed gauges and sites for inclusion in the Middle Basin forecasting network. Most of the gauges shown have been included primarily for quantification of flows from major tributaries, particularly the Gwayi, Ume, Sanyati, Manyame, Kafue and Luangwa Rivers.

ZRA's network in the Middle Basin includes manual gauges on the Kalomo and Ume Rivers, and real-time gauges on the Gwayi and Sanyati Rivers. All of these tributaries have relatively short response times and coupled with their close proximity to Lake Kariba, the absence of accurate flow data for them can cause operational problems at Kariba Dam. Thus, these rivers have all been included in the proposed network design. In addition, as completion of the SADC-HYCOS Phase II network will result in upgraded real-time gauges on each of the Gwayi and Sanyati Rivers (at different locations from the ZRA gauges), these future gauges have been provisionally included in the network design to improve forecast accuracy and increase the available lead time, although not strictly essential.

The two largest tributaries in the Middle Basin are the Kafue and Luangwa Rivers, both of which rise in Zambia. The Kafue River is heavily regulated by the Itezhi-Tezhi and Kafue Gorge Dams and, in addition, passes through several large wetlands, including the Kafue Flats. Both of these dams are managed by ZESCO, which uses a network of nine flow gauges for monitoring of upstream flows, seven upstream of Itezhi-Tezhi and two downstream. Given that ZESCO's network does not include all SADC-HYCOS gauges in the Kafue River Sub-basin, the network design was based on a combination of ZESCO and SADC-HYCOS gauges. Based on information obtained directly from ZESCO through email communication and a project meeting, it is understood that ZESCO's current network does not include any real-time gauges.

The Luangwa River contributes approximately twice the mean annual flow of the Kafue Sub-Basin to the Zambezi and, furthermore, is unregulated. The Luangwa River is therefore an extremely important tributary from a forecasting point of view, particularly for operations at Cahora Bassa Dam. At present, the only real-time gauge on the Luangwa River is at Luangwa Bridge, but on completion of SADC-HYCOS Phase II, an existing gauge at Ndevu Camp will be equipped with a real-time DCP. However, given the flashy nature of the Luangwa River (response times are in the order of days), its considerable flow, and its close proximity to Lake Cahora Bassa, it is recommended that an additional real-time gauge in the middle reaches of the Luangwa Sub-Basin is established. There is currently an existing manual gauge at Mfuwe, near the road entrance to South Luangwa National Park. Based on the previous experience of the Consultant's team, it is proposed that a real-time gauge be established on the existing road bridge at Mfuwe – this would be a safe location both in terms of vandalism and flood damage. A gauge at this location would increase lead time substantially over the Ndevu Camp and Luangwa Bridge gauges and would therefore greatly assist operations at Cahora Bassa Dam.

In order to quantify outflows downstream of Kariba Dam, the outlet (turbines and flood gates) of the dam has been included in the network design (it is understood that calibration of the turbines is undertaken on a regular basis). However, for real-time monitoring of flows downstream of Kariba Dam, it is recommended that the existing manual gauge at Chirundu is equipped with real-time equipment. The only other significant tributaries in the Middle Basin are the Manyame and Musengezi Rivers in Zimbabwe, both of which discharge directly into Cahora Bassa. SADC-HYCOS currently operates a real-time gauge on the Manyame River at Nyakapupu and an existing gauge at Aurelia Farm on the Musengezi River will be upgraded with real-time equipment as part of SADC-HYCOS Phase II. Both of these gauges have been included in the network design.

Lower Zambezi

Flooding in the lower reaches of the Zambezi River downstream of Tete generally affects large numbers of people and occurs relatively frequently even with regulation of flows at Cahora Bassa Dam. The following gauges have been included in the network:

- Cahora Bassa Dam outlet (gates plus turbines) for monitoring of outflows from the dam;
- Gauge E-375 (Mpanda) downstream of the Luia/ Zambezi confluence for monitoring of flows from both Cahora Bassa and the relatively large Luia River (this gauge may become obsolete with the planned construction of Mpanda Ncua Dam);
- An existing SADC-HYCOS real-time station on the Mazowe River in Zimbabwe, as well as an existing manual ARA Zambeze gauge on the Luenya River at Luenhai, downstream of its confluence with the Mazoe (a.k.a Mazowe) River;

- An existing ARA Zambeze manual gauge on the Revuboe River, a major tributary that enters the Zambezi River downstream of Tete; and
- Existing gauges on the Zambezi River at Tete, Mutarara, Caia and Marromeu, which are part of ARA Zambeze's flow forecasting system.

Flows in the Shire River Sub-Basin (Malawi) are determined largely by water levels in Lake Malawi/ Nyasa and the Kamuzu Barrage at Liwonde. Existing SADC-HYCOS real-time gauges at Nkhata Bay, Monkey Bay and Liwonde have therefore been included in the network design, the Nkhata Bay gauge being included as a standby option for the Monkey Bay gauge. In addition, real-time gauges at Tengani on the lower Shire River and at Sandama on the Ruo River (a tributary of the lower Shire River) have also been included. Figure 3.12 shows the locations of these gauges. Although accurate real-time flow data for the Shire River is required for operation of existing run-of-river hydropower stations, the overall lack of major tributaries between Liwonde and Tengani suggests that an intermediate flow gauge between these stations is not required. However, a possible candidate for an intermediate gauge would be Gauge IL12. The gauge at Tengani will facilitate monitoring of flows in the lower Shire River, which sometimes experiences backwater effects from the Zambezi, when this latter river is in flood.

Table 3.2: Proposed Flow Gauges and Sites for Flow Forecasting Network

No.	Country	River	Place	Existing Instrument Type	Lat	Long	OWNER	COMMENT
	UPPER ZAMBEZI							
1	Zambia	Zambezi	Chavuma Pump St.	DCP			ZRA	SADC-HYCOS station washed away. ZRA station damaged by lightning, but under repair. Part of ZRA forecasting network.
2	Zambia	Kabompo	Watopa Pontoon	DCP	-14.03	23.62	Zambia (HYCOS)/ ZRA	Part of ZRA forecasting network.
3	Zambia	Zambezi	Lukulu	DL	-14.383	23.232	ZRA	Part of ZRA forecasting network.
4	Zambia	Luanginga	Kalabo	DCP	-15.000	22.7552	ZRA	Part of ZRA forecasting network
5	Zambia	Zambezi	Matongo	Manual			ZRA	Part of ZRA forecasting network.
6	Zambia	Zambezi	Senanga	Manual	-16.1200	23.2477	ZRA	Part of ZRA forecasting network.
7	Zambia	Zambezi	Ngonye	DCP			ZRA	Part of ZRA forecasting network.
8	Namibia	Zambezi	Katima Mulilo	DCP	-17.48	24.27	Namibia (HYCOS)	Use instead of manual ZRA gauge at Sesheke.
9	Angola	Cuando	Identification of suitable location required.				Department of Water, Angola	Establishment of new real-time station on Cuando River recommended for advance warning of flows within southern Angola and at Kongola (Namibia).
10	Angola	Luiana	Identification of suitable location required..				Department of Water, Angola	Establishment of new real-time station on Luiana River recommended for advance warning of flows within southern Angola and at Kongola (Namibia).
11	Namibia	Kwando	Kongola	DCP	-17.79	23.34	Namibia (HYCOS)	Existing real-time gauge on Kwando (Cuando) River in Nambia.
12	Namibia	Chobe	Ngoma Gate	DCP			Namibia (HYCOS)	Existing real-time gauge that allows for monitoring of flows both from Chobe into Zambezi, as well as Zambezi into Chobe.
13	Zambia	Zambezi	Nana's Farm	DCP	-17.82	25.65	Zambia (HYCOS)	Part of ZRA forecasting network.
14	Zambia/ Zimbabwe	Zambezi	Victoria Falls	Manual	-17.82	25.65	Zambia/ZRA	Part of ZRA forecasting network.
	MIDDLE ZAMBEZI							
15	Zimbabwe	Gwayi	Kamativi	DCP	-18.345	27.035	HYCOS	Gauge earmarked for upgrading to real-time under SADC-HYCOS Phase II (for monitoring of flows from Gwayi River into Zambezi).
16	Zimbabwe	Gwayi	Gwayi	DCP			ZRA	Part of ZRA forecasting network.
17	Zimbabwe	Ume		Manual			ZRA	Part of ZRA forecasting network.
18	Zimbabwe	Sanyati	Copper Queen	DCP	-17.494	29.398	HYCOS	Gauge earmarked for upgrading to real-time under SADC-HYCOS Phase II (for monitoring of flows from Sanyati River into Zambezi).
19	Zimbabwe	Sanyati	Sanyati Bridge	DCP	-17.217		ZRA	Part of ZRA forecasting network.

Table 3.2: Proposed Flow Gauges and Sites for Flow Forecasting Network

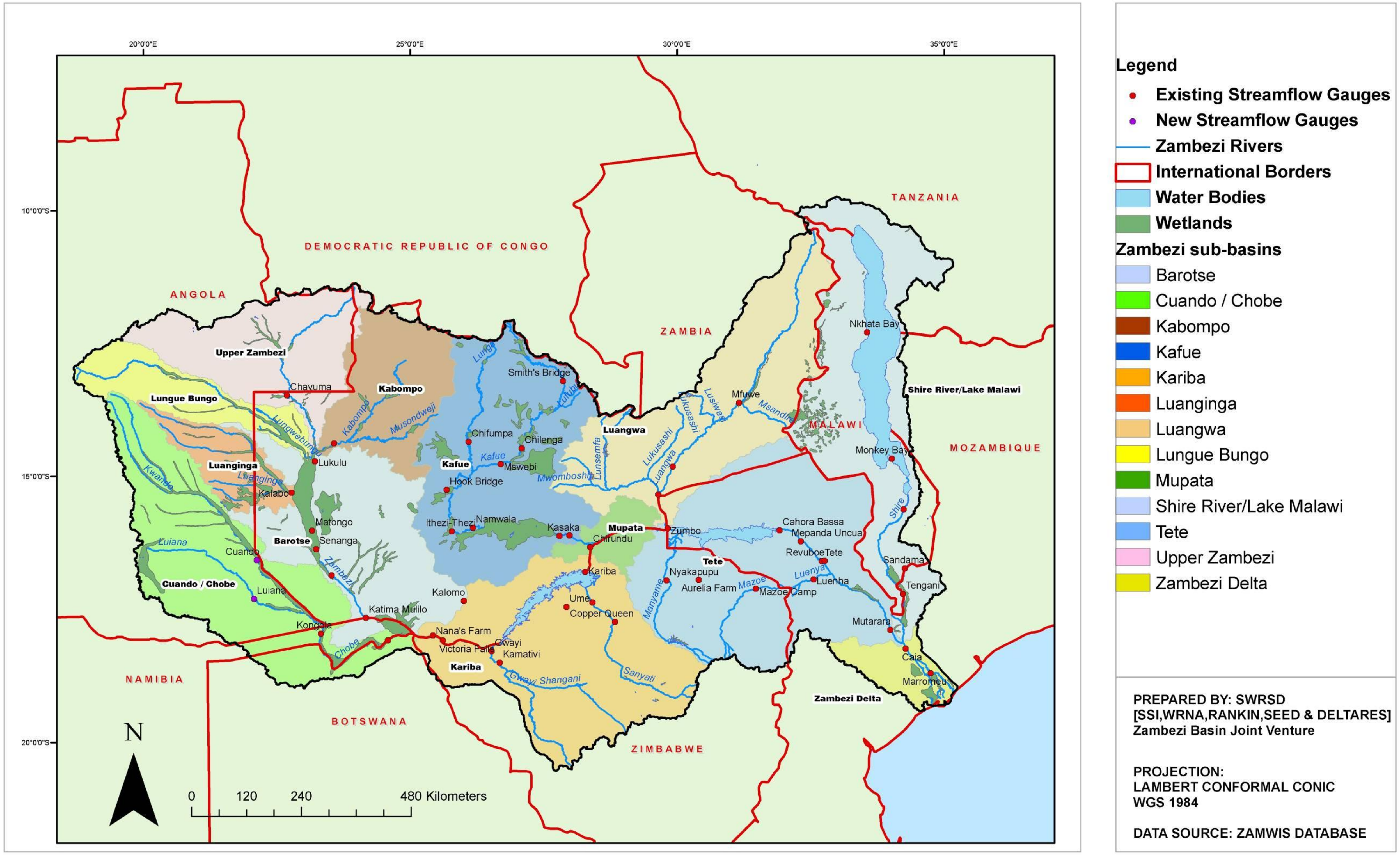
No.	Country	River	Place	Existing Instrument Type	Lat	Long	OWNER	COMMENT
20	Zambia	Kalomo	Kalomo	Manual	-17.221	26.478	ZRA	Part of ZRA forecasting network.
21	Zambia/ Zimbabwe	Zambezi	Kariba dam	Turbines/ gates	-16.522	28.762	ZRA	Regular calibration of dam outlets recommended.
22	Zambia	Zambezi	Chirundu	Manual	-16.030	28.850	ZAMBIA DWA	Upgrading to real-time or near real-time status recommended (for monitoring of flows downstream of Kariba).
23	Zambia	Kafue	Smith's Bridge	DCP	-12.76	28.23	HYCOS	Allows for monitoring of flows in Upper Kafue River.
24	Zambia	Kafue	Chilenga	Manual			ZESCO	Candidate gauge: 4350 (Chilenga) – measures flows upstream of Lukanga Swamp.
25	Zambia	Kafue	Mswebe	Manual			ZESCO	Candidate gauge: 4435 (Mswebe) – measures flows downstream of Lukanga Swamp.
26	Zambia	Lunga	Chifumpa	DL	-13.986	26.344	HYCOS	Major tributary of Kafue River. An alternative to this gauge would be the existing ZESCO gauge at Kelongwa.
27	Zambia	Kafue	Kafue Hook Bridge	DCP	-14.94	25.91	HYCOS	Important gauge with long record upstream of Itezhi-Tezhi Dam.
28	Zambia	Kafue	Itezhi-Tezhi Dam	Manual			ZESCO	Candidate gauge 4710 (Itezhi-Tezhi) - measurement of flows discharged from Itezhi-Tezhi Dam.
29	Zambia	Kafue	Namwala Pontoon	DCP	-15.683	26.450	HYCOS	Existing real-time gauge upstream of Kafue Flats (major wetland).
30	Zambia	Kafue	Kasaka	Manual			ZESCO	Candidate gauge 4977 (Kasaka) – provides information on water levels at Kafue Gorge Reservoir.
31	Zambia	Kafue	Kafue Gorge Dam	Turbines/ gates	-15.806	28.422	ZESCO	Measurement of flow through spillway gates and turbines.
32	Zambia	Luangwa	Mfuwe	Manual	13.097	31.787	ZAMBIA DWA	Zambia DWA currently operates a manual gauge at Mfuwe, which, if upgraded to real-time or near real-time status, would provide valuable advance warning of flows from the Upper Luangwa Basin. The existing bridge to South Luangwa NP would provide a safe location for an automatic gauge.
33	Zambia	Luangwa	Ndevu Camp	DCP	-14.395	30.491	HYCOS	Earmarked for upgrading to real-time under SADC-HYCOS Phase II. Would provide improved monitoring of flows between Mfuwe and Luangwa Bridge.
34	Zambia	Luangwa	Luangwa Bridge	DCP	-14.96	30.21	HYCOS	An alternative option to this gauge would the new Luangwa River gauge (DCP) to be established on the Mozambique side of the River, 10km downstream as part of SADC-HYCOS Phase II.
35	Mozambique	Zambezi	Zumbo	DCP	-15.622	30.424	HYCOS	Required for measurement of flows into Cahora Bassa.
36	Zimbabwe	Manyame	Nyakapupu	DCP	-16.65	30.43	HYCOS	Major tributary with historical flooding problems where river drops into Zambezi Valley.
37	Zimbabwe	Musengezi	Aurelia Farm	DCP	-16.619	31.089	HYCOS	Significant tributary with historical flooding problems where river

Table 3.2: Proposed Flow Gauges and Sites for Flow Forecasting Network

No.	Country	River	Place	Existing Instrument Type	Lat	Long	OWNER	COMMENT
								drops into Zambezi Valley near Muzarabani.
	LOWER ZAMBEZI							
38	Mozambique	Zambezi	Cahora Bassa	Turbines/ gates	-15.585	32.705	HCB	Measurement of outflows from dam via spillway gates and turbines.
39	Mozambique	Zambezi	M'panda Uncua (E-375)	Manual			ARA Zambeze	Part of existing flood forecasting model used by ARA Zambeze (allows inflows from both Cahora Bassa and Luia to be quantified). Due to proposed new dam at M'panda uncua, may be superseded by outflows from future dam.
40	Mozambique	Zambezi	Tete (E-320)	DCP			HYCOS	Important gauge on Zambezi River upstream of main flood prone areas.
41	Mozambique	Revuboe	E-302 (near Tete)	Manual			ARA Zambeze	Candidate gauge E302 – important for monitoring of flows from Revuboe River (major tributary) upstream of confluence with Zambezi River.
42	Zimbabwe	Mazowe Camp	Mazowe Camp	DCP	-16.75	32.26	HYCOS	Major tributary downstream of Cahora Bassa.
43	Mozambique	Luenha	Luenhai	Manual			ARA Zambeze	Candidate gauge E348 – important for monitoring of flows from the Mazoe/ Luenha River system into the Zambezi.
44	Mozambique	Zambezi	Mutarara (E-293)	Manual			ARA Zambeze	Part of existing flood forecasting model used by ARA Zambeze (and Principal Hydrometric network).
45	Malawi	Lake Malawi	Nkhata Bay	DCP	-11.60	34.30	HYCOS	Existing station on Lake Malawi for monitoring of lake levels – alternative to Monkey Bay station.
46	Malawi	Lake Malawi	Monkey Bay	DCP	-14.07	34.92	HYCOS	Existing station on Lake Malawi for monitoring of lake levels.
47	Malawi	Shire	Liwonde	DCP	-15.06	35.21	HYCOS	Liwonde weir controls outflows from Lake Malawi (up to certain level).
48	Malawi	Ruo	Sandama	DCP	-16.22	35.30	HYCOS	Important tributary of Shire River.
49	Malawi	Shire	Tengani	DCP	-16.726	35.283	HYCOS	Important gauge for monitoring of Shire River flows into Zambezi River.
50	Mozambique	Zambezi	Caia	DCP	-17.807	35.399	HYCOS	Existing station in flood prone reaches of Lower Zambezi River and downstream of Shire River confluence.
51	Mozambique	Zambezi	Marromeu (E-285)	Manual	-18.280	35.933	ARA Zambeze	Part of existing flood forecasting model used by ARA Zambeze.

[2]

[2] Text in blue denotes proposed new gauges.



TRANSBOUNDARY WATER MANAGEMENT IN SADC: DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT

ZAMBEZI RIVER BASIN: PROPOSED STREAMFLOW GAUGES FOR FLOW FORECASTING

On behalf of:

In Delegated Cooperation with:

Figure 3.12: Locations of Proposed Flow Gauges in the Zambezi Basin

3.6 Evaluation of Precipitation Networks

3.6.1 Overview

The required evaluation of existing precipitation networks was conducted on the basis of currently available information. While the ZAMWIS database does include details of most rainfall stations within the Basin, only monthly data is provided. Daily data is required for some short lead time forecasts. For this reason, data from ZAMWIS was supplemented with additional data from some National Meteorological Services (NMS's), as well as other sources. Figure 3.13 shows the gauges that were included for evaluation of coverage, and unfortunately, daily data was not available for all of these gauges.

3.6.2 Coverage

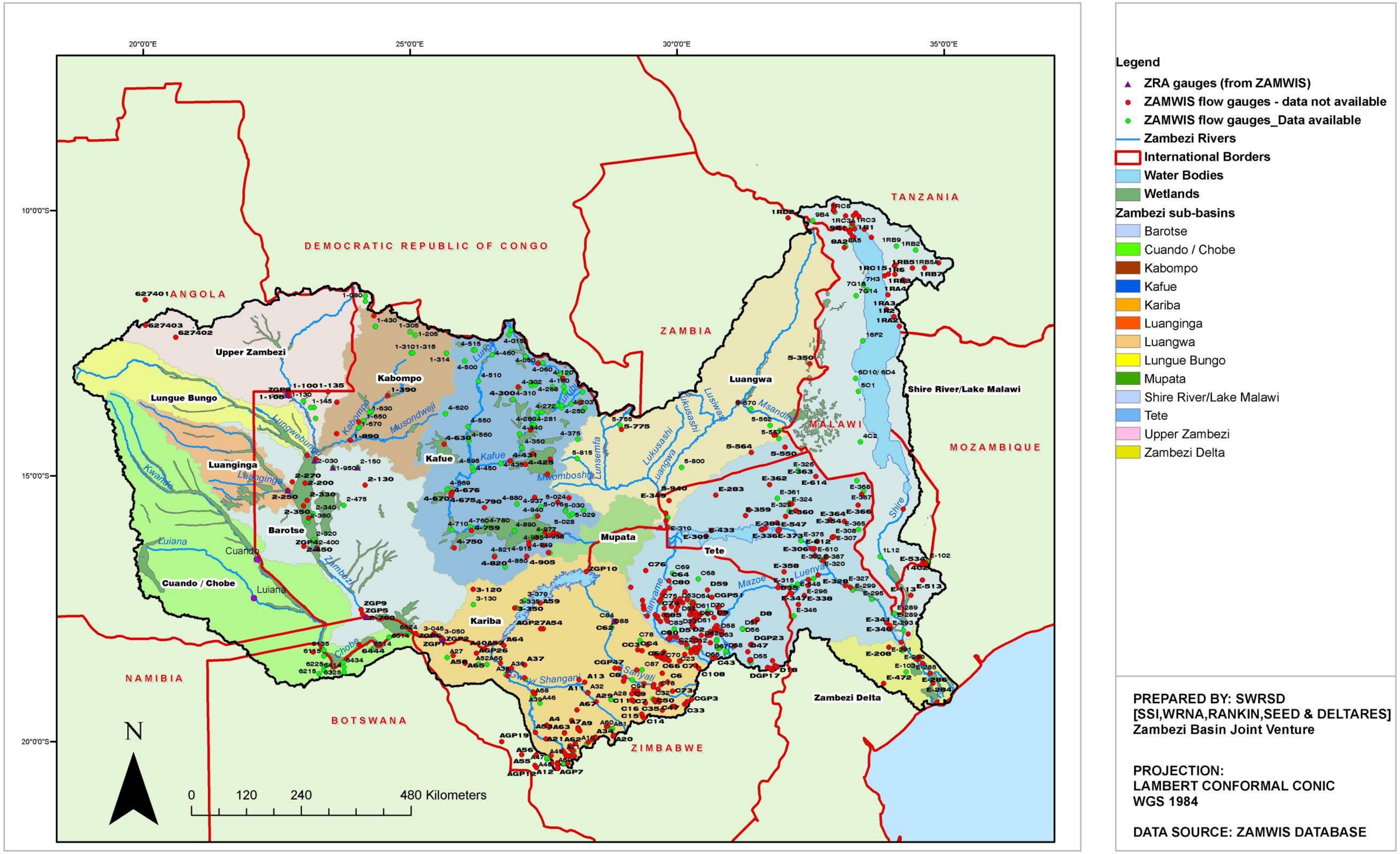
ZAMWIS appears to only include data for selected stations, as in the case of Zimbabwe, the Zimbabwe Meteorological Services Department (ZMSD) provided details of additional stations not included in the database (some of these stations are primary stations operated directly by ZMSD staff, while others are stations operated by volunteers). The number of rainfall gauges per country included in the current ZAMWIS is as follows: Angola - 3; Botswana – 4; Malawi – 29; Mozambique – 10; Namibia – 2; Tanzania – 8; Zambia – 58; and Zimbabwe – 52.

The issue of coverage with respect to rainfall stations cannot truly be viewed in isolation of the requirements of an operational forecasting system. Coverage requirements differ for each of the particular applications; for example, water resource studies or water balance models based on a monthly time-step will not require the same coverage as a forecasting model using a daily or sub-daily time-step for short lead time forecasts. Coverage requirements for daily forecasting are generally extremely high, particularly in areas where there is a high spatial and temporal variability of rainfall. The issue of coverage for rainfall networks therefore needs to be evaluated in the context of forecasting requirements and for this reason this issue is dealt with in Sections 4.8 and 4.9.

3.6.3 Reliability, communication of data and sustainability

Although the issues affecting rainfall stations differ to some extent from those relevant to flow gauging stations, many of the problems and pitfalls are relevant to both. The siting of rainfall stations is generally more flexible than that of flow stations in that locations can often be chosen according to where protection of these stations can be guaranteed. Flow stations on the other hand need to be situated at more specific locations where conditions within the particular river are suitable for accurate gauging.

Nevertheless, the issues of reliability, communication of data and sustainability in the context of this project are not significantly different. For this reason, the issues already discussed under flow gauges will not be repeated here. The reader is therefore referred to Sections 4.5.3, 4.5.4 and 4.5.5, *supra*, for more information on the issues relevant to the above criteria.



TRANSBOUNDARY WATER MANAGEMENT IN SADC: DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT

ZAMBEZI RIVER BASIN: EXISTING FLOW GAUGES

On behalf of:

In Delegated Cooperation with:

Figure 3.13: Overview of station locations in the Zambezi Basin, available for this Project

3.6.4 Measurements of temperature and evaporation

An operational forecasting system will need, besides rainfall measurements, estimated values of potential evaporation as well[*]. Such estimates are needed to determine the antecedent wetness in rainfall-runoff models. The wetness largely determines how much of the rainfall is converted into runoff, low wetness resulting in low amounts of runoff, high wetness resulting in high amounts of runoff. The wetness is determined by preceding rainfall and evaporation, of which the latter strongly depends on potential evaporation.

Many measurement networks in the past made use of Class A Pan evaporation estimates as a proxy for potential evaporation. This measurement method makes use of a circular basin ("pan"), filled with water. The changes in water level are recorded as an estimate of potential evaporation. However in arid or semi arid regions, the wet surface of the pan, located in a generally dry area, will cause overestimation of potential evaporation estimates. Furthermore, reading of Class A pans is generally done manually which is not desirable in an operational setting.

Therefore, potential evaporation estimates can better be derived from measurements of the meteorological conditions. In practice, estimates of the following variables are required to estimate potential evaporation (see Allen *et al.*, 1998 for more information):

- Solar radiation;
- Relative humidity of the air;
- Wind speed; and
- Temperature.

Automatic weather stations can, with relative ease, be equipped with sensors that estimate the above-mentioned variables.

3.7 Coverage of Precipitation Networks with respect to Forecasting Requirements

3.7.1 Detailed analysis of meteorological stations

The ZAMWIS database, currently only holds monthly rainfall records. In some regions monthly rainfall may however, be sufficient for forecasting of flow. This is particularly the case in regions that have a large natural lag time due to wetland retention and where forecast requirements are met even when monthly time scale predictions can be made. A good example is the inflow forecast for the main stem of the Zambezi for the operators of Lake Kariba, as shown in Chapter 2. For other regions, having a faster natural response and a more advanced forecast requirement, higher temporal scale rainfall values may be required for forecasting.

[*] *Potential evaporation* is an estimate of the amount of energy available to evaporate water from the land surface and is determined by the meteorological conditions. It is in most cases not equal to the actual evaporation, because actual evaporation is limited by the amount of water available.

Therefore, efforts have been put into the collection of daily rainfall records besides the monthly data already available in ZAMWIS. In particular the Zambia Meteorological Department (ZMD) has been generous in data supply and most of their records cover a long period up to 2005. After 2005, either the records stop or significant gaps seem to appear in the time series.
Additional records have been retrieved from a global database, the "Global Historical Climatology Network – Daily" database, which can be found on http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/. The records in this database are compiled using data from meteorological organizations all over the world. Figure 3.14 indicates the locations where daily records have been collected.

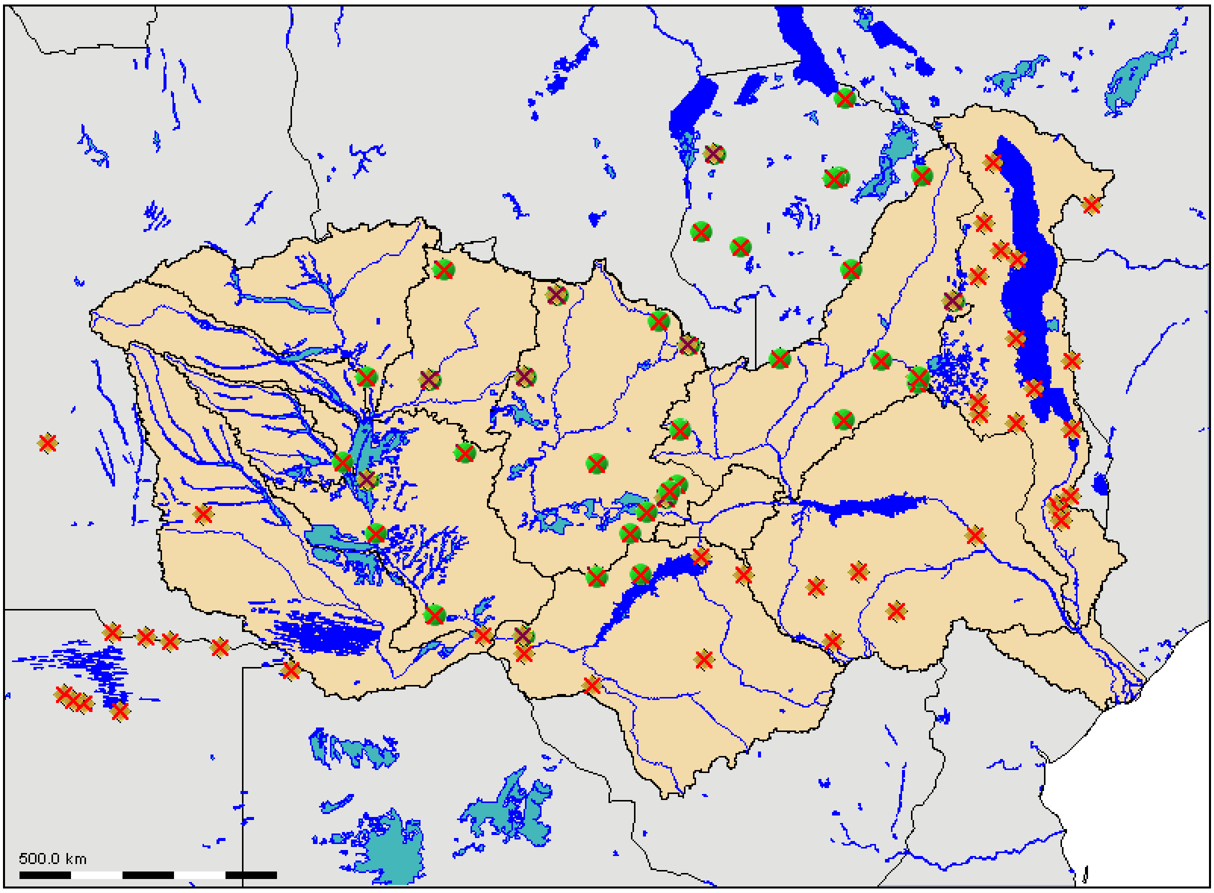


Figure 3.14: Locations of rainfall stations with available daily rainfall values

3.7.2 Required coverage of meteorological stations

In this section, the available daily rainfall station records in the basin have been used to answer the following question:

- How many rainfall stations are required per forecast area to provide adequate areal rainfall estimates for the purpose of forecasting?

It is assumed in the analysis described in this section, that all the available rain gauges can deliver data in an operational context. Furthermore, the analysis has been performed on gauge data currently available within this study. Most of the available data comes from the measurement network in Zambia from the ZMD. It is likely that there are more daily rainfall records available in Malawi, Zimbabwe and Mozambique than used in this study.

General approach

To determine whether the spatial coverage of the present rain gauge network would be adequate, the relationship between the distance between stations and the correlation was investigated. If the correlation declines rapidly with distance, this means that a high density of stations is required to provide a good estimate of areal rainfall. How rapidly this correlation declines with distance, can be expressed in a so-called "correlation distance". This is the distance from a station at which the variability in the rainfall at that station cannot be explained by the observed rainfall at another station and can be approximated by doing pair-wise correlation analysis between the station of interest and as many surrounding stations as available. The more stations are available, the better one can sample the different conditions around the station of interest that may impact on the correlation – distance relation.

One can expect that in areas with convective rainfall, the spatial variability in rainfall is very large. Additionally, in mountainous regions this variability can be expected to be higher than in the plains areas. This will hence result in a low correlation length which indicates that a high station density is required to provide a good areal rainfall estimate.

In addition, when one averages rainfall over longer time scales, the variability of the records will decrease considerably. This means that if forecast requirements need a long time scale rainfall estimate, a much higher correlation length is likely to be found and the station density can be much lower. Therefore the analysis outlined above needs to be done on different time scales. The analysis has been performed on daily, decadal (10-daily) and monthly time scale.

Results

To deal with stations that have poor quality of data, an assumption was made that if for a certain station the correlation length is lower than a certain threshold, (i.e. the records in the station itself are very poorly correlated with surrounding stations), that it is likely that the records are either of insufficient quality or not appropriately handled by the data provider. For monthly to decadal data, a threshold of 200 km was chosen and for daily data, 100 km was used. For each station in the basin, the spatial correlation distance was established. Appendix 3 provides a brief description of how this was done based on the available data.

The results of the spatial correlation analysis are displayed in the form of spatial maps on daily, decadal and monthly time scales. The maps are displayed in Figure 3.15, Figure 3.16 and Figure 3.17. The results are discussed in the next sub-section.

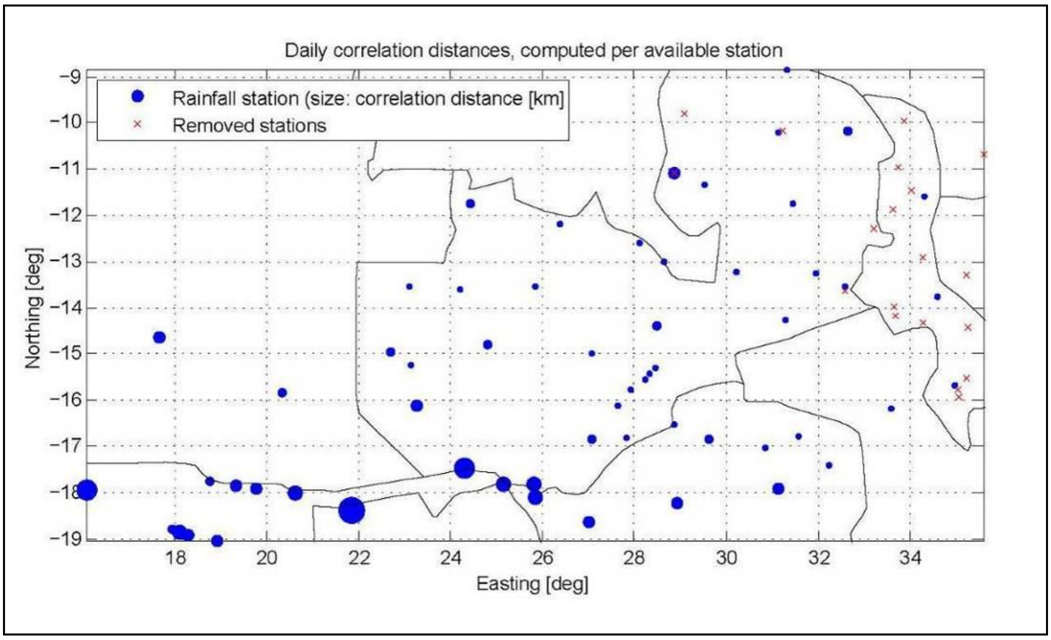


Figure 3.15: Spatial correlations distances at a daily time scale, computed for each station.

The size of the blue circles shows the magnitude of the spatial correlation distance. Stations marked with a red 'x' were removed because the data was found to be poor.

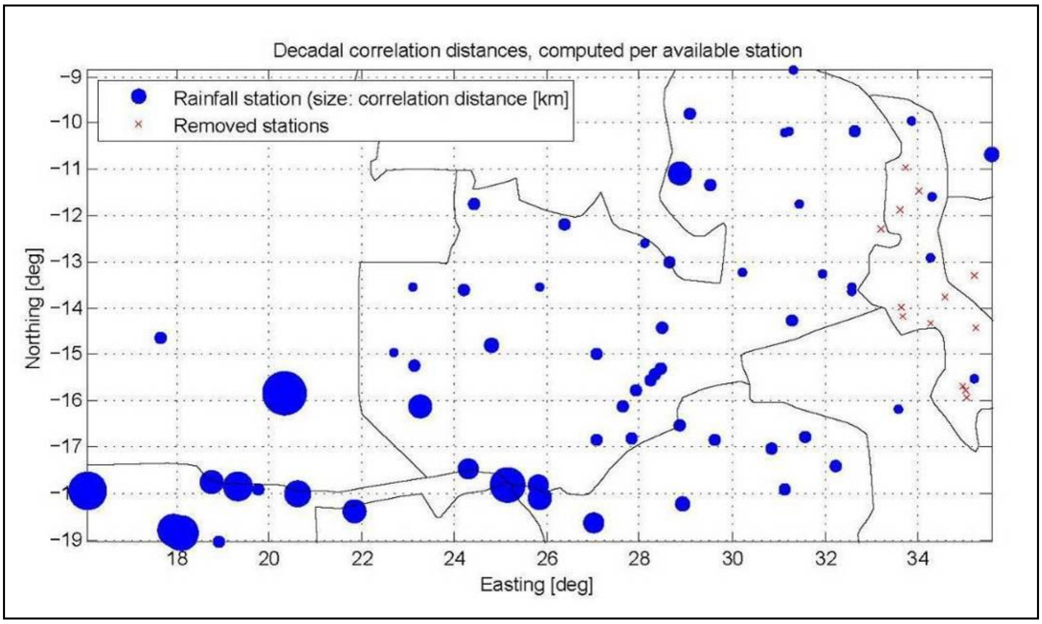


Figure 3.16: Spatial correlations distances at a decadal time scale, computed for each station.

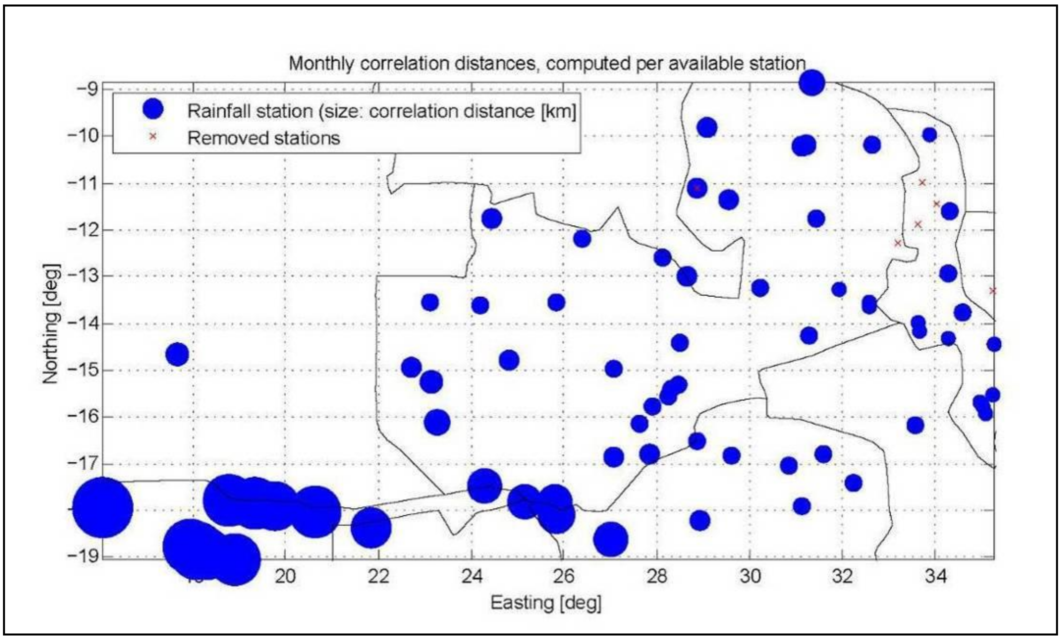


Figure 3.17: Spatial correlations distances at a monthly time scale, computed for each station.

Discussion

The above results are interpreted below for several sub-catchments in the upper, middle and lower Zambezi.

Upper Zambezi

Zambezi source and upper sub-catchments

In the north-east near the source of the Zambezi, in the Lungwebungwu, Luanginga and Kabompo sub-catchments, the correlation lengths are generally smaller for all time scales considered, compared to the southern regions. This suggests a higher spatial variability in rainfall. This area receives considerably more rainfall than the south and therefore also exhibits higher variability. This pattern is also shown in Figure 3.18 which presents the annual rainfall map, retrieved from ZAMWIS.

Senanga – Victoria Falls

The Zambian rainfall stations along the banks of the Zambezi between Senanga and Victoria Falls have a higher correlation distance than the upper regions of the Zambezi. They are slightly lower however than in the Kwando region, probably because there is more rainfall (see 3.18).

South-western region, Caprivi Strip and lower Kwando/Luiana River

All maps show clearly that stations near the Caprivi Strip have a very high correlation distance, indicating well correlated records, even when stations are far apart, compared to stations in the north-east. This can be explained by the fact that there is little relief in this region and relatively low rainfall (see Figure 3.18 and Figure 3.19).

Middle Zambezi

Luangwa sub-catchment

Over the Luangwa catchment, the correlation distances are very small, indicating high variability. This is a mountainous area which explains the high spatial variability. Moving north from the Luangwa escarpment (Southern Congo and Lake Bangweulu area), the area consists of a relatively flat highland area where the rainfall is again less variable in space which is reflected by higher correlation distances.

Gwayi/Sanyati Rivers

The Gwayi River is close to the Caprivi Strip and has little relief and low rainfall. Therefore, correlation distances are high in this region. The Sanyati River receives slightly more rainfall and has more relief, leading to slightly lower correlation distances.

Lower Zambezi

Shire River/Malawi

Almost all stations in Malawi had to be removed during the process, because their correlation with surrounding stations, even stations that were in close proximity, was very poor. However, it is expected that the characteristics of rainfall are similar to or slightly more variable than the Luangwa region. The relief is similar and rainfall amounts are slightly higher as shown in Figure 3.18 and Figure 3.19.

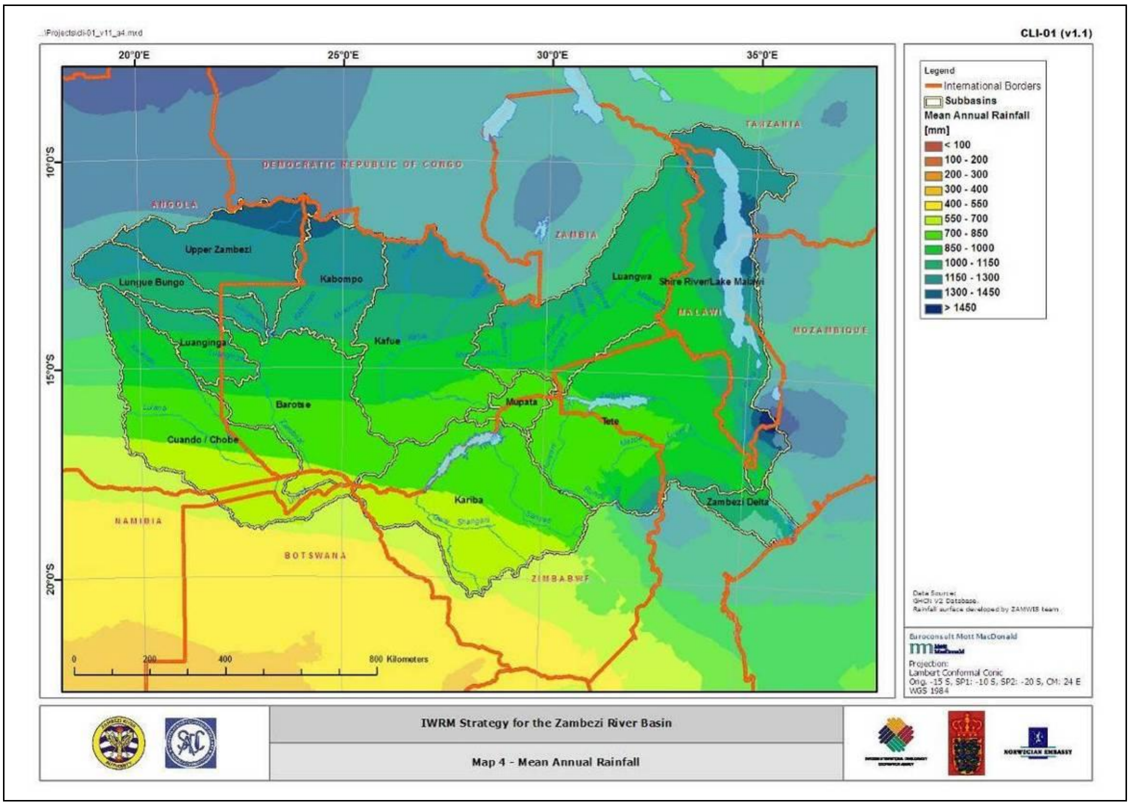


Figure 3.18. Annual rainfall map (source: ZAMWIS)

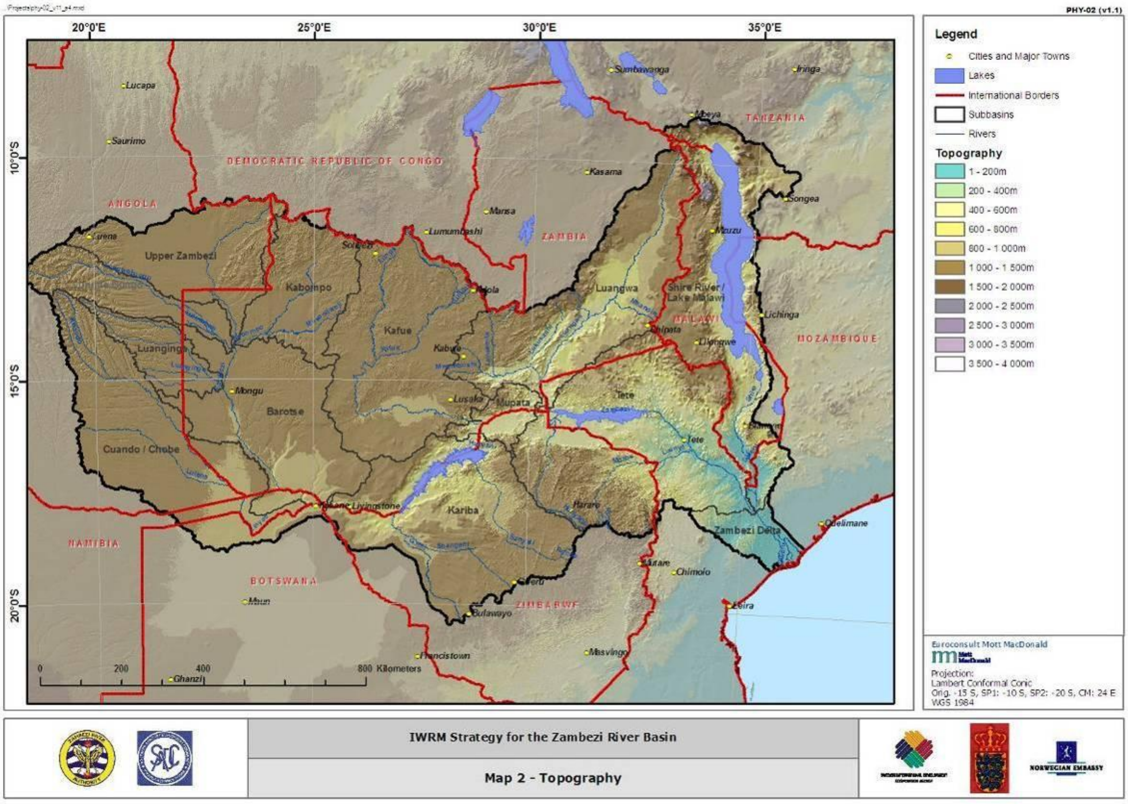


Figure 3.19: Elevation map (source: ZAMWIS)

Required station densities in relation to the forecast requirements

The required station density is strongly dependent on the forecast requirements, determined in Chapter 2 and the physiological characteristics of the targeted area of interest. This, in turn, determines the spatial scale at which forecasting models need to be run, as well as the temporal resolution. For example, the operators of Lake Kariba are primarily interested in the forecasting of monthly to seasonal flows and therefore need relatively long lead times. Given the physiological characteristics of the basin, a large part of the inflow in this time scale will be from rainfall that is already on the ground at the moment of forecasting, in particular, the rain falling upstream of the Barotse flood plains. The lag of the flow from the Barotse plains to Kariba is approximately 1 month (Figure 2.7). Therefore monthly rainfall values provide adequate resolution. Rainfall data would be required for up to 2 months prior to the start of the forecast for the area upstream of Barotse, and in the month prior to the start of the forecast for the area between Barotse and Lake Kariba.

In this manner, for each particular area, the requirements for rainfall observations in terms of temporal resolution (in the example monthly), spatial resolution (example: sub-catchment level) and moment of acquisition (in the example the area upstream of Barotse for 1-2 months prior to forecasting and downstream for 1 month prior to forecasting) will be deduced.

To estimate the number of required stations in a given area, an empirical law defined by Kagan (1972) that uses the correlation length and the size of the given area as input (further information on the methodology is provided in Appendix 3) was used. This method assumes that the stations are more or less evenly distributed in space. The equation underlying the law is given below as:

$$Z_{areal} = C_v \sqrt{\frac{1}{N}\left(1 - r_0 + \frac{0.23}{d_0}\sqrt{\frac{S}{N}}\right)}$$

where:

Z_{areal}:	the relative root mean square error of the area averaged rainfall estimate in the forecast area of interest;
C_v:	the coefficient of variation of the station rainfall;
N:	the number of stations in the forecast area;
r_0:	the correlation that station values would have if stations would be placed exactly next to each other;
d_0:	the correlation length, which is defined above for each station;
S:	the surface area of the forecast area.

For each forecast location, a required relative error (Z_{areal}) of 15% and the average of C_v and d_0 over the stations that lie within the forecast area was assumed. If no stations were available in the forecast area, stations in the direct surroundings were used to estimate C_v and d_0. r_0 was estimated to be 0.9 for daily values and 0.95 for decadal and monthly values. Below, the station requirements and the extent to which the requirements can be met by the currently available coverage are described. This is done per forecast area and per required lead time. While the spatial correlation analysis has been performed using a limited amount of daily ground measurements, the gap analysis has been performed assuming that the current rainfall station coverage of daily stations consists of the locations found in:

- ZAMWIS (monthly stations);
- Zambia Meteorological Department stations;
- Zimbabwe Meteorological Services Department official stations; and
- Global Historical Climate Network-Daily database.

This analysis specifically considers the availability of adequate gauging locations. Therefore, the availability of voluntary station locations has also been taken into account. Data transmission issues have not been considered. This is addressed in Section 6.3.

Short range lead time forecasts

Where short lead times are required, the area where rainfall impacts on the forecast location within the required lead time (*S* in Kagan's equation) is dependent on the response time of the river itself. If this response time is very small (e.g. in flashy catchments), then rainfall estimates are needed over the upstream catchment area, because part of this rainfall will reach the forecast location within the required lead time. If there are large wetlands, the flow upstream of the wetland provides a lot of the forecast power, which can be augmented by rainfall observations within the wetland rather than upstream. This has been analyzed in Chapter 2 and this information is used below. Note that in areas where precipitation only is an augmentation to provide more accuracy, the station density can perhaps be lower, because a higher relative error than 15% is acceptable. Table 3.3 shows the requirements per forecast area for short term lead times.

Table 3.3: Precipitation requirements for forecast locations with short lead time requirements

Forecast area	Temporal scale needed (lead-time)	Target area where rainfall is needed	Required station density [total amount in target area] *	Is requirement met?
Zambezi between Katima Mulilo and Victoria Falls	Daily	Intermediate catchment (~50.000 km²)	30	Yes, local surrounding station rainfall is needed and available.
Chobe between Ngoma Bridge and Zambezi Confluence (~25.000 km²)	Daily	Wetland in intermediate catchment (~10.000 km²)	15	No, there are however 4 stations available directly bordering the wetland which could be used (Kasane, Sesheke, Ngoma Bridge and Selinda Spillway)
Lower Reaches of Sanyati & Gwayi rivers	Sub-Daily	Contributing catchments areas (~100.000 km²)	Gwayi: 35 Sanyati: 35	Gwayi: Yes, 58 stations present Sanyati: Yes, close to 200 stations present
Zambezi between Kariba Dam and Cahora Bassa Lake[1]	Sub-Daily	Intermediate catchment area (~20.000 km²)	35	Around 15 stations available in the Zimbabwean part of this area. There are no stations in the Zambian part of this area.
Luangwa Downstream of Great East Road Bridge to Zambezi confluence	Daily	Upstream contributing area (~150.000 km²)	45	No, 8 stations available but not evenly distributed over the catchment. 6 are on the boundaries and only 2 within the catchment
Zambezi downstream Cahora Bassa to the Zambezi mouth[2]	Sub-Daily (Flash Floods)	Intermediate catchment area	50	Yes, Luenya catchment is well covered (southern part) with about 70 manual stations, within Mozambique, 48 stations are present.
Shire downstream of Kamuzu Barrage to confluence Zambezi	Sub-Daily (Flash Floods)	Contributing catchment area (~200.000 km²)	Not known, no reliable station records available, if similar coverage to that of Luangwa is assumed, 60 stations are needed	Over 100 station locations are known, however no information is known about whether these locations are operational and reliable in quality.

* Note that this number is valid when stations are evenly distributed over the area considered. The right-column of this table also indicates where the distribution is not adequate.

This table shows that for almost none of the identified short term forecast locations is the station density high enough to provide an accurate enough rainfall estimate.

Medium range lead time forecast

In most medium range areas, the number of rainfall stations is generally adequate. Table 3.4 shows the results of the analysis per forecast area for a medium range lead time. Some of these forecast locations have very small catchment areas where rainfall influences the forecast such as for the smaller reservoirs Mulungushi, Lunsemfwa and Lake Lusiwasi. It appears that these areas require a disproportionate number of rainfall stations. This is caused by the fact that over a small target area, it is easy to make a large relative error. Consider for instance the example where a local thunderstorm causes a great deal of rainfall in the catchment area but rain gauges miss most of the event. Over large areas, the effect of multiple storms will be smoothed out over the whole area, leading to a much smaller relative error. However, when the variability in rainfall is more important to the user of the observations than the absolute accuracy, fewer rainfall stations, sometimes only a single station, may be sufficient.

Table 3.4: Precipitation requirements for forecast locations with medium range time requirements

Forecast area	Temporal scale needed	Target area where rainfall is needed	Required station density [total amount in target area] †	Is requirement met?
Inflows to Lake Kariba	Decadal	Catchment area from Barotse to Victoria Falls (~120.000 km²)	4	Yes, 5 stations are available, quite evenly distributed in space
Inflows to Itezhi-Tezhi and Kafue Gorge	Decadal	Kafue catchment area (~100.000 km²)	5	Yes, there are 7 locations however only 6 are evenly distributed. There are two stations in Kabwe very close to each other.
Inflows to Lusiwasi Reservoir[1]	Decadal	Lusiwasi lake (~5.000 km²)	1	Only to measure rainfall on the lake
Inflows to Mulungushi Reservoir[1]	Decadal	Mulungushi catchment area (~20.000 km²)	4 (see note)	The only stations available are in Kabwe. Note that the contributing area is very small and that if the interest is in day to day variability of rainfall, far fewer stations are needed.
Inflows to Lunsemfwa Reservoir[1]	Decadal	Lunsemfwa catchment (~5.000 km²)	4 (see note)	No, zero stations available. Note that the contributing area is very small and that if the interest is in day to day variability of rainfall, far fewer stations are needed.
Inflows to Lake Cahora Bassa	Decadal/Monthly	Intermediate catchment between Kariba and Cahora Bassa (20.000 km²)	5/3	Around 15 stations available in the Zimbabwean part of this area. There are no stations in the Zambian part of this area.
Inflows/Outflows from Lake Malawi	Decadal/Monthly	Contributing catchment area (~200.000 km²)	If similar coverage to that of Luangwa is assumed, about 10 stations are needed	Yes, over 100 stations available

† Note that this number is valid when stations are evenly distributed over the area considered. The right-column of this table also indicates where the distribution is not adequate.

Seasonal lead time forecasts

Table 3.5 shows the requirements for areas with a seasonal lead time requirement. Only the areas where observed rainfall is needed or useful to augment a forecast are shown. The inflows into Lake Kariba can benefit from measurements of rainfall upstream. Theoretically there are enough gauges, however they are not well distributed. As was pointed out earlier, no data is available for Angola.

Table 3.5: Requirements for forecast locations with seasonal lead time requirements

Forecast area	Temporal scale needed	Target area where rainfall is needed	Required station density [total amount in target area] ‡	Is requirement met?
Inflows to Lake Kariba	Monthly	Catchment area from the source to Vic falls (~500.000 km^2)	4	No, although 8 stations are available, they are not evenly distributed in space. There are no gauges in Angola.
Inflows to Itezhi-Tezhi and Kafue Gorge	Monthly	Kafue catchment area and Kafue wetlands (~100.000 km^2/50.000km^2)	4/2	Yes, there are 7 locations upstream Itezhi-Tezhi and 6 surrounding the Kafue flats.
Inflows/Outflows from Lake Malawi	Monthly	Contributing catchment area (~200.000 km^2)	If similar coverage to that of Luangwa is assumed, 4 stations are needed	Yes, over 100 stations available

3.7.3 Conclusions

The coverage of the available daily rainfall station network was evaluated to determine what could be expected from this network in terms of precipitation forecasting; and whether this would be adequate for the identified forecasting requirements. In many areas where daily rainfall observations are required, the current coverage is too low. Therefore, to reach a reliable area-averaged ground-based rainfall estimation, a considerable number of stations will need to be added in these areas. In particular, the Katima Mulilo – Victoria Falls flood prone area and the Luangwa catchment area would need more rain gauge information to meet the identified forecasting requirements. The other large forecast areas, Gwayi/Sanyati and the Lower Shire, have adequate rainfall station coverage. The quality of forecasts in smaller intermediate catchment areas with daily forecast requirements, are more dependent on upstream flow gauging than on rainfall estimation and in these areas improvement of the rainfall network is therefore less important.

Many of the forecast locations that have a medium range lead time requirement need observation values in the order of every 10 days or month. In most of these locations, the current station

‡ Note that this number is valid when stations are evenly distributed over the area considered. The right-column of this table also indicates where the distribution is not adequate.

density is adequate to reach a relative error of less than 15%. Exceptions are the smaller reservoirs in the Luangwa tributaries (Lusiwasi, Mulungushi and Lunsemfwa), which have none or very few stations in the forecast area at present. Inflows into Lake Cahora Bassa are, excluding flows from the Luangwa River, impacted by rainfall in the intermediate catchment between Kariba and Cahora Bassa. Again, this impact is much smaller than the impact of the releases from Kariba and the natural flow from the Luangwa. Therefore improved rainfall observations in the Luangwa River Sub-basin are more important.

For the seasonal time scale, monthly rainfall is adequate in all forecast areas. In the area upstream of Victoria Falls, for inflow into Lake Kariba, the density is theoretically high enough, although the stations are spatially poorly distributed. Since there are currently no stations at all in Angola, improvement of rainfall measurement in Angola is recommended.

The accuracy of forecasts from the recommended rain gauge network could be further improved using rainfall data from remotely sensed rainfall estimates, which is of particular interest in areas with a far too low coverage, or areas that have unfavourable conditions for a dense measurement network. In Chapter 4 of this report an analysis is done on the potential of such remotely sensed rainfall.

3.8 Comparison of Rain Gauge Coverage

To put this discussion into perspective, the coverage of rain gauges in the Zambezi basin was compared to the coverage of rain gauges in other river basins in the world, namely, the Mekong River and the Rhine River basins.

3.8.1 Rain gauge coverage in the Mekong Basin

The Mekong River Basin is the largest river basin in South-East Asia. Similarly to the Zambezi basin, the Mekong River Basin is a trans-boundary basin, with its headwaters in China, and the countries of Myanmar, Laos, Thailand, Cambodia and Vietnam contributing to the basin. Commonly the basin is divided into the Upper Mekong Basin (UMB), which is the basin in the mountainous reaches in China, and the Lower Mekong Basin (LMB) which covers the entire basin downstream of the Chinese border.

Operational forecasting is undertaken within the basin at the national level, with Thailand and Vietnam having the most developed operational forecasting systems developed. Additionally, the Mekong River Commission operates a basin-wide forecasting system during the flood season. The countries of Laos, Thailand, Cambodia and Vietnam are full members of the Mekong River Commission, with China and Myanmar being observer members. The forecasting system also covers the LMB.

Observed rainfall data is obtained through three networks of rain gauges. This includes the relatively new network of Automatic Rain Gauges (ANHYP), a network of manual rain gauges across the basin, as well as gauges from the Global Telecommunication System (GTS) network. There is some overlap in the second two sets of gauges though data is obtained independently. Table 3.6 provides an overview of the rain gauge network used in the operational forecasting system for the Mekong basin as operated by the Mekong River Commission (status 2009). It is estimated that some 50% of the manual gauges in the LMB are at the same site as the GTS stations, and therefore do not contribute to the coverage. It must be pointed out that the coverage reported in the table considers the number of rain gauges, though those actually reporting during the operation of the forecasting system may be fewer. Observed rainfall in the system is augmented by rainfall data estimated from satellite images.

Table 3.6: Coverage of rain gauges in the Mekong River Basin

Basin	Area 1000 km² S	ANHYP Network	Manual Network	GTS Network	Total N	Coverage km⁻² S/N
Upper Mekong Basin	162	2	4	19	25	6480
Lower Mekong Basin	630	18	168	93	232	2715
Complete Mekong Basin	792	20	172	112	257	3082

3.8.2 Rain gauge coverage in the Rhine Basin

The Rhine Basin, which is the largest river basin in western Europe, is truly an international basin, with headwaters in Switzerland and Austria, Liechtenstein, Germany, France, Luxemburg, Belgium and the Netherlands. Within the basin there are several forecasting systems in operation, including one in each of the basin countries (for forecasting of flows within each national territory), as well as in some of the federal states of Germany. The main reason for this is that safety of the riparian population is the mandate of each of the national countries, or the federal states of Germany. Although there is a well established river basin commission, this does not undertake operational forecasting at the basin level. Exchange of data is, however, very well established within the basin, with an extensive network of operational rain gauges. These generally report at hourly intervals, although there are also some synoptic gauges that only report at 6-hourly intervals. Table 3.7 shows the coverage of rain gauges used in the operational forecasting system that is used by the Dutch Centre for Water Management (part of the Ministry of Public Works and Water Management), which has the mandate for forecasting flows in the Rhine within the Netherlands. This shows that the coverage of rain gauges in the basin is extremely high. Rainfall in the Rhine basin is predominantly frontal, meaning that the required coverage of rain gauges would be lower for the same area as for basins where rainfall is primarily convective such as in the Zambezi and Mekong basins. Worthy of note, however, is the fact that the Rhine basin is only slightly larger than the Luangwa basin, which is much smaller than the Zambezi basin.

Table 3.7: Coverage of rain gauges in the Rhine River Basin

Basin	Area 1000 km² S	Total Gauges N	Coverage km⁻² S/N
Rhine	162	668	242.5

3.8.3 Rain gauge coverage in the Zambezi River Basin

Based on information provided in ZAMWIS, an approximate estimate of coverage in the Zambezi River basin can be obtained. ZAMWIS includes data for 166 rainfall gauges. Given that the Zambezi River basin has a total area of approximately 1,350,000 km^2, this translates into a basin coverage (in terms of the average area commanded by each gauge) of approximately 8130 km^{-2} per gauge Compared to the values of 3082 km^{-2} and 242 km^{-2} for the Mekong and Rhine River basins, respectively, the coverage in the Zambezi River basin is significantly lower than these two other basins, even if one were to assume that there are other gauges that have not been captured by the ZAMWIS database.

4 Evaluation of Remote Sensing Technology for Rainfall Estimation

4.1 Scope

In Chapter 3, deficiencies in the number of rainfall stations in the Zambezi Basin were identified. This was done from the perspective of forecast requirements. In forecast areas where the station coverage is too low to meet forecast requirements, additional information on rainfall distribution may be obtained by installing new rain gauges. This must be done at locations that are suitable and safe for the installation of sensitive equipment and that are also easily accessible for maintenance and collection of data.

The Zambezi Basin contains many remote regions where access and suitability cannot be guaranteed. For instance, in Angola, there are currently no operational rain gauges installed and there has not been any recording of data since the beginning of the civil war in the early 1970s. In these regions, remotely sensed rainfall products may prove useful to bridge the gap between the status quo and the forecast requirements in terms of rainfall observations. Additionally, such remotely sensed data may be useful as a backup to observed data, and may often even be available before observed data becomes available. Remotely sensed rainfall products are generated by analyzing satellite imagery from several satellites, carrying different types of instruments. One of the most famous satellite missions that delivers information on rain rates over the whole world is the Tropical Rainfall Measuring Mission (TRMM), which carries on board a precipitation radar, very similar to the radars used on the ground for measuring rain rates, and a microwave imager, which infers rain rates by analyzing the microwave backscatter from clouds. The signatures of this backscatter give information on rain rates. By combining several rain rate estimates, all inferred by different instruments, the best guess of rain rate can be established. There are several remotely sensed rainfall products available now, all slightly different with respect to the satellite data that they use, and how they process it. Many of the products are made available through the internet in the form of geographical raster maps. Some of the products have reached operational status by delivering data in near real-time. This makes these products interesting for use in operational forecast systems. An example of a resulting rainfall map of a recent event (15 February 2010 23:00-00:00) over the Zambezi River basin is given in the figure below.

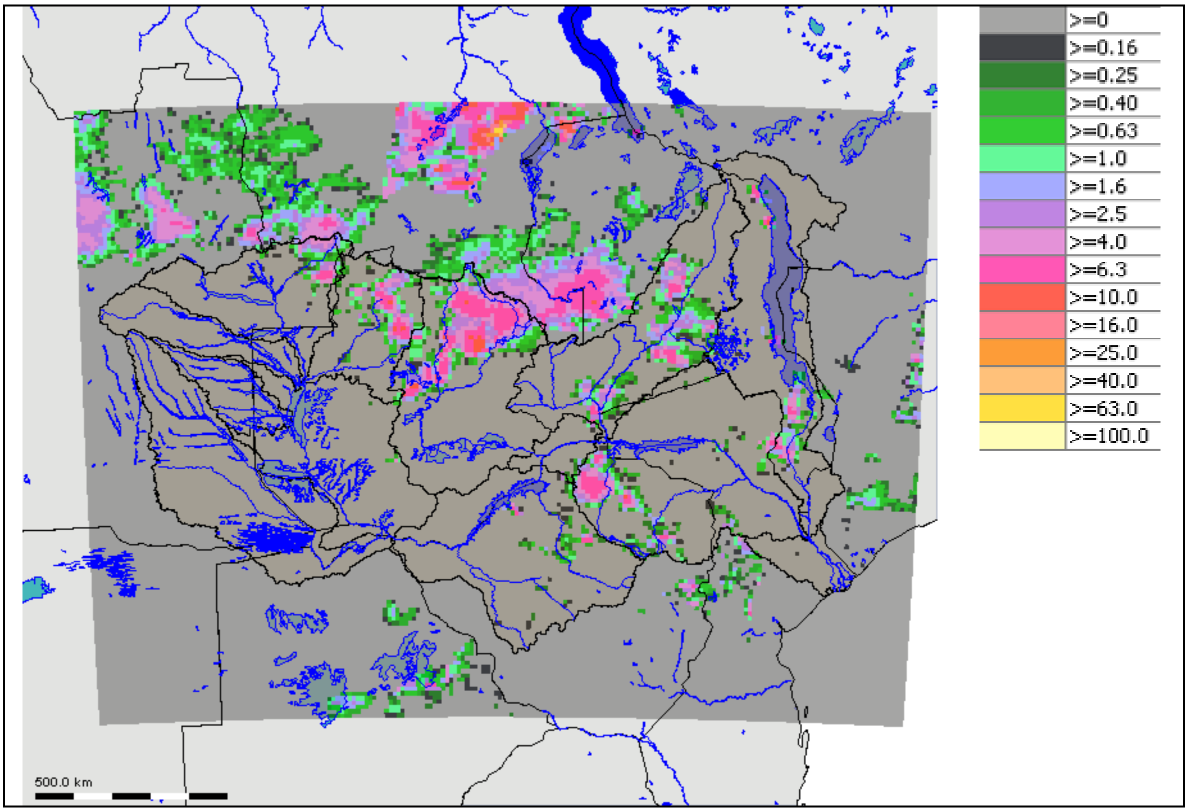


Figure 4.1: Example of a remotely sensed rainfall map of the GSMaP product over the Zambezi. This is the rainfall depth [mm] on 15 February 2010 from 23:00 until 00:00.

In this chapter, the potential of a number of these products is for use in operational forecasting in the Zambezi River basin is investigated, on the basis of the following aspects:

- Spatial-temporal resolution;
- Time elapsed between the satellite observations and the availability of the product on the internet;
- Typical file sizes requiring download via the internet on a daily, if the product is to be used for forecasting; and
- The accuracy of the product, based on several comparisons with ground-measured rainfall.

The accuracy of this technology using comparative analyses in the Kabompo, Kafue and Luangwa catchments has been investigated, and a satisfactory number of ground observations were available for this analysis.

The ground observations used, the rainfall products, and the assessment methods and results are presented below. In the last section, an overall assessment of the potential for remotely sensed rainfall measurement in the Zambezi River basin is made.

4.2 Available data

4.2.1 Ground records

The ground records used for this analysis were all within the boundaries of Zambia. Rainfall station data inside and in the vicinity of the investigated Kabompo, Kafue and Luangwa sub-catchments was used. Data was kindly provided by the Zambia Meteorological Department. Most of the records overlap the available satellite product time series in the period 1998 to 2007/2008.

4.2.2 Remote sensing products

The products listed in Table 4.1 have been investigated. The longest available time series for each product has been downloaded and processed. The lengths of the databases are considerably different per product. For each product, the longest possible time series, overlapping with the available ground observations has been used. Table 4.1 gives the required information about *spatial-temporal resolution*, the *delay between observations and delivering of the product* and the *download requirement* per day.

Note that TRMM 3B42 (as opposed to PERSIANN and TRMM 3B42RT) is a research product that is not available in near real-time. It is therefore less suitable for an operational forecasting system. TRMM 3B42 data (without 'RT') has been corrected with globally available rain gauge values. It has therefore been included in this analysis to establish whether there is a difference between the real-time product (TRMM 3B42RT) and the gauge-corrected product. The product GSMaP is relatively new. The GSMaP team delivers both a research reanalysis product and a near-real time product. Only a short time series was available for the freshly developed near real-time product (October 2009 until April 2010), which did not overlap with ground observation data. For this reason, a comparison with ground observation data was not possible. However, to establish an indication of the accuracy of this new product, data from the reanalysis GSMaP product was compared with data from the near real-time product of GSMaP in the most recent wet season (October 2009 until April 2010).

Table 4.1: Investigated Satellite Rainfall Estimation Products

Rainfall product (time series)	Provider (ftp-site)	Spatial resolution [deg.]	Temporal resolution [hours]	Availability delay [hours]	Internet load [MB/day]
TRMM 3B42RT (2002-2010)	NASA ftp://trmmopen.gsfc.nasa.gov/pub/merged/mergeIRMicro/	0.25 x 0.25	3	5	2
TRMM 3B42 (1998-2010)	NASA ftp://disc2.nascom.nasa.gov/data/s4pa/TRMM_L3/TRMM_3B42/	0.25 x 0.25	3	Not an operational product	3

Rainfall product (time series)	Provider (ftp-site)	Spatial resolution [deg.]	Temporal resolution [hours]	Availability delay [hours]	Internet load [MB/day]
PERSIANN	UC Irvine ftp://hydis8.eng.uci.edu/pub/PERSIANN/tar_6hr/beta/	0.25 x 0.25	6	65 (Pre-operational status)	2.5
GSMaP NRT (2007-2010)	JAXA	0.10 x 0.10	1	4	25
GSMaP MVK+ reanalysis (2003-2006)	JAXA	0.10 x 0.10	1	Operational product available (4 hours delay) but not overlapping with available ground records. A research product for investigations was also used.	25

4.3 Sub-catchment-averaged time series

To investigate the accuracy of the various remote sensing products, comparisons were performed between rainfall measured on the ground and rainfall observed by satellite. In an operational system, data from satellite rainfall products would be used at the sub-catchment scale. For this reason, sub-catchment averaged time series data from ground observations were compared with data from the previously listed satellite products. Three sub-catchments with available daily rain gauge data were selected, as follows:

- The Kabompo basin (upper Zambezi, deep Kalahari sand area, slow response due to wetlands);
- The Luangwa basin (mountainous, fast responding, about 2 response time); and
- The Kafue basin (intermediate area, slow responding due to wetlands).

First, a ground-observed rainfall estimate was produced for each sub-catchment. This was done by weighted averaging of the rain gauge time series data in and in the neighbourhood of the catchment using the Thiessen (nearest-neighbour) approach. Then satellite-based time series for the same period have been produced from each satellite product, by averaging all the pixels of the satellite product that lie within the sub-catchment of interest. These time series have been used in further analyses.

4.4 Assessment of Product Accuracy

To assess a product's accuracy, the time series are compared visually by means of double mass curves, time series plots and scatter plots. The scatter plots are made on daily, decadal and monthly basis to inspect how the quality changes with time scale. Averaging over larger time scales reduces the variability in rainfall, which means the ground observations and satellite products will become better comparable.

The number of stations in each sub-catchment is too low to provide a good daily catchment-averaged time series (refer to Section 3.7). However, they may be used to assess whether a rainy day or a dry day occurred. Therefore a verification analysis has been performed that assesses how well the satellite product is able to estimate whether a day was rainy or not.

4.4.1 Volumes and time series

Double mass curves

Many studies have found that that although satellite rainfall estimation is reliable for predicting the spatial variability of rainfall, it is not as successful with estimating actual rainfall intensities and volumes. A frequently used analysis method which assesses how well a rainfall product reproduces these rainfall volumes is the double mass curve.

A double mass curve is constructed by accumulating all the overlapping records of the reference time series (in this case, the ground-based rainfall time series data) and the time series data that is to be evaluated (in this case the different rainfall products). These accumulations of the reference series are then plotted on the horizontal (x-) axis and the accumulations of the test series on the vertical (y-) axis. If the values along the horizontal and vertical axes are the same at all points (x=y), then the time series match perfectly and therefore produce exactly the same volumes in every time step. If the plot deviates from the x=y line but the line is straight, there is a consistent bias, which can be corrected with relatively ease. If the line is not straight, there are non-systematic deviations, which are more difficult to correct.

Figure 4.2 presents double mass curves for each sub-catchment, one for each satellite product investigated. Each product has a different time series range. This is because the available time series data differed for each satellite product considered. For GSMaP for instance, only about 4 years of overlapping data were available – this is why the curve is smaller.

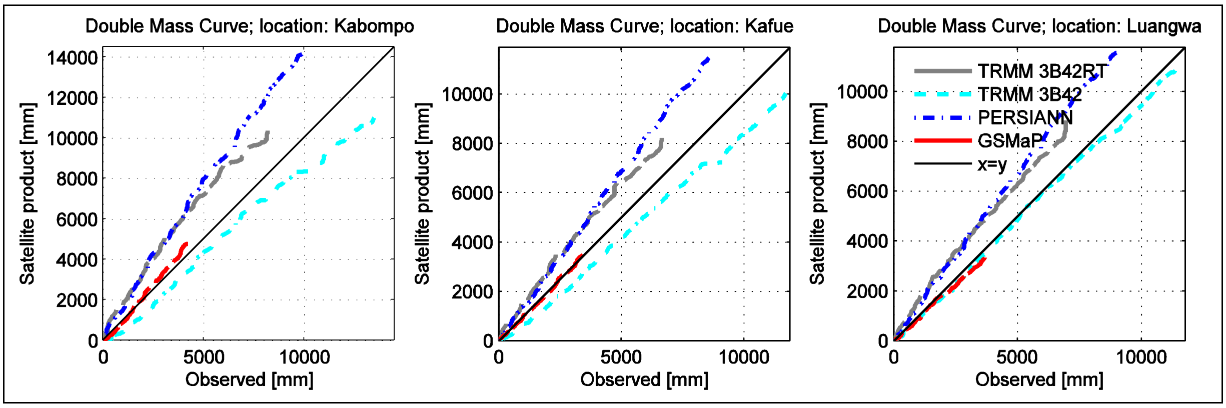


Figure 4.2: Double mass curves showing accumulated rainfall (mm) from ground observations versus estimates from satellite rainfall products (plots are given for three different sub-catchments).

It is evident that most of the products evaluated reveal a considerable bias. Both TRMM 3B42RT and PERSIANN show a similar positive bias over the first 4000 mm of rainfall for the period up to 2005-2006, which means that these products in general over-predict the total rainfall during this period. After 2005-2006, PERSIANN continues to deviate from the x=y line with the same offset meaning that the bias is more or less constant, while TRMM 3B42RT appears to end up parallel with the x=y line from 4000 mm onwards. This means that TRMM

3B42RT follows the observed rainfall intensities more closely from 2005-2006 onwards. This could be due to changes in the rainfall algorithm in 2006. Some new satellite rainfall intensity estimates were incorporated in the algorithm (derived from the AMSU-B and AMSR-E satellite instruments) on 3 February 2005 (see ftp://meso-a.gsfc.nasa.gov/pub/trmmdocs/rt/3B4XRT_doc.pdf). This could be an explanation for the sudden improvement in volumetric skill.

TRMM 3B42 under predicts rainfall and reveals a less constant bias. GSMaP is the only product that shows a negligible bias in all catchments. Note that the ground observations consist of only a few gauges per sub-catchment. This could mean that the GSMaP product actually outperforms the ground-based gauges, as GSMaP samples the area more effectively. However, a firm conclusion on this cannot yet be drawn due to the limited ground observed data available. The total bias over the full period is given in Table 4.2.

Table 4.2: Bias scores for each product (a lower bias indicates a more accurate estimate of rainfall volume)

Rainfall product	Kabompo	Kafue	Luangwa
TRMM 3B42RT	27%	23%	26%
TRMM 3B42	-18%	-15%	-4%
PERSIANN	40%	32%	25%
GSMaP	9%	-1%	-9%

Time series

Another way to assess rainfall quality is by looking at the time series themselves. This can be done by plotting all of the time series together in one plot. In Section 3.7 it was concluded that the existing spatial coverage of rainfall stations across the reference sub-catchments is not adequate for estimation of *daily* (ground-observed) rainfall. For this reason, only *decadal* and *monthly* rainfall values have been plotted in the figures below. Figure 4.3 displays the time series for the Kabompo catchment, Figure 4.4 for the Kafue catchment, and Figure 4.5 for the Luangwa catchment.

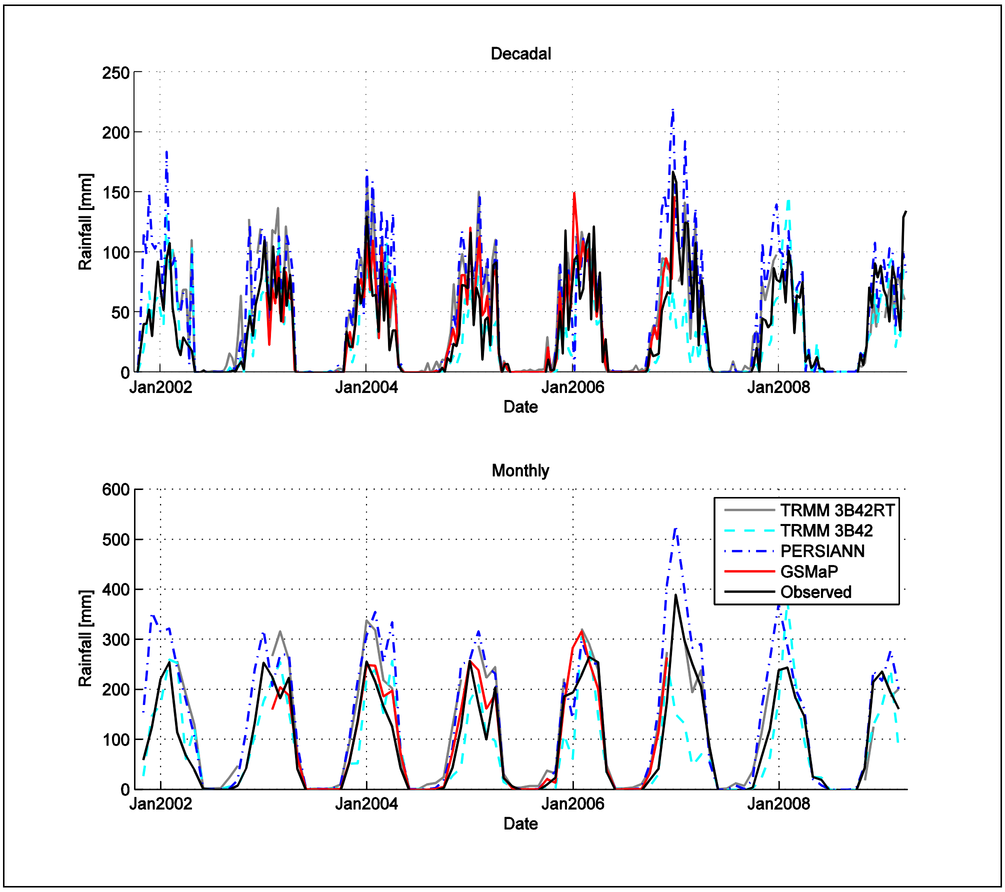


Figure 4.3: Time series plot showing satellite product data and observed data in the Kabompo catchment.

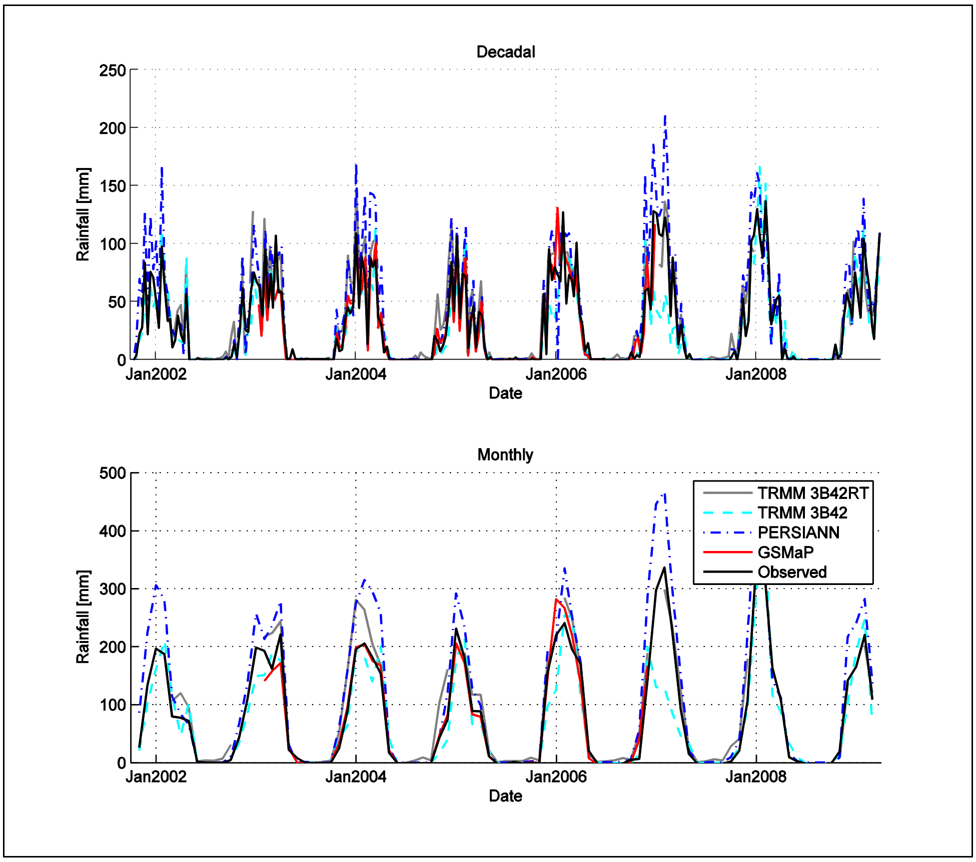


Figure 4.4: Time series plot showing satellite product data and observed data in the Kafue catchment

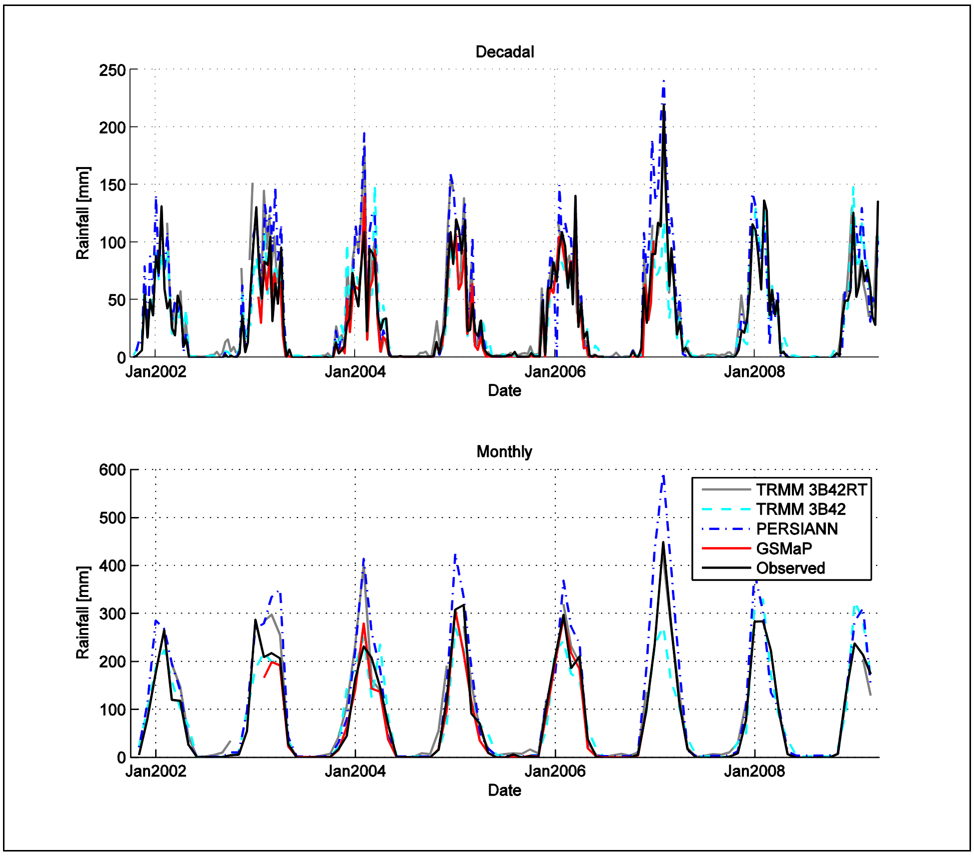


Figure 4.5: Time series plot showing satellite product data and observed data in the Luangwa catchment

The time series graphs in Figures 4.3, 4.4 and 4.5 clearly indicate how well the evaluated satellite products are able to follow rainfall variability from time step to time step. The best correlation with the observed data is shown by the GSMaP product, both at decadal and monthly time scales. This is true for all three sub-catchments investigated. The pattern of each rainy season is represented well by GSMaP compared to the other rainfall estimates.

As was mentioned earlier, a significant change to the TRMM 3B42RT algorithm occurred at the end of the 2004-2005 dry season. To be precise, the change occurred on 3 February 2005, which may explain why the product shows improved performance in 2005-2006.

Because of the close resemblance between the GSMaP reanalysis product and TRMM 3B42RT in recent years, a comparison of these products was undertaken for the short period of available overlapping time series to determine whether these products show consistent behaviour. The resulting scatter plot and time series is shown in Figure 4.6.

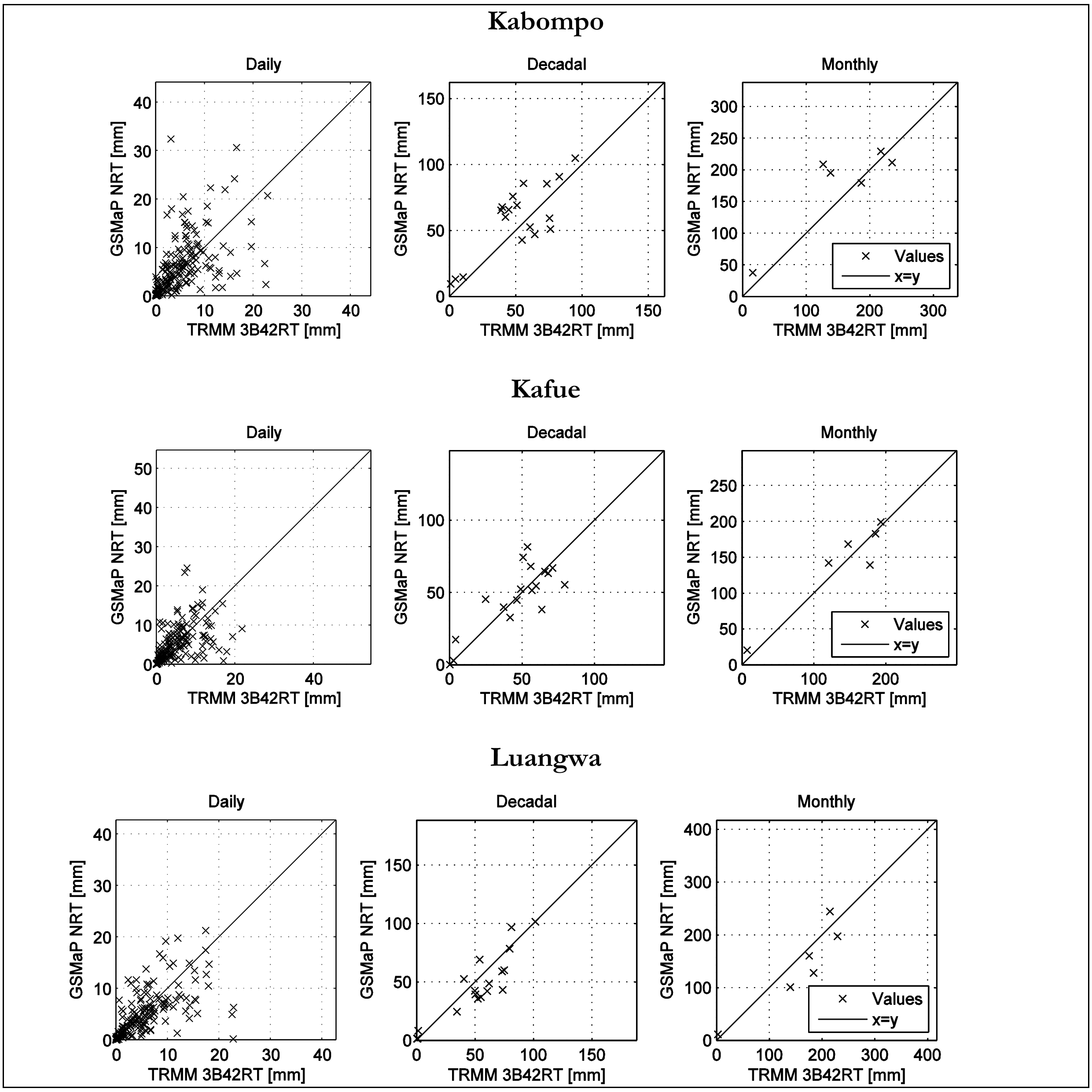


Figure 4.6: Scatter plots of TRMM 3B42 (x-axis) against GSMaP Near real-time (y-axis) at daily, decadal and monthly time scale

Although the two compared time series are relatively short, including only one wet season, the comparison shows a clear consistency between the two products.

4.4.2 Verification

Verification is used to test the ability of a rainfall product to estimate whether rainfall occurred or not on a given day. This has been tested by determining for each day on which data is available for both the observations and the rainfall product, whether this was a rainy day or a dry day. A dry day is taken here as a day where rainfall is below 0.3mm and a wet day where rainfall is above 0.3mm. The following were counted:

- *Hits*: the number of days on which both the ground observations and the satellite product indicated a rainy day;
- *Misses*: the number of days on which the ground observations indicated a rainy day but the satellite product indicated it is dry;
- *False Alarms*: the number of days on which the ground observations indicated a dry day but the satellite product indicated a rainy day; and
- *Correct negatives*: the number of days on which both the ground observations and the satellite product indicated a dry day.

The hits, misses, false alarms (FA) and corrected negatives (CN) are displayed as percentages of the total amount of available in the time series in tabular form in Tables 4.3 – 4.6.. This is called a *contingency table*.

Table 4.3: Contingency tables for the TRMM 3B42RT product for each investigated sub-catchment. Events that were correctly estimated by the satellite product (i.e. hits and correct negatives) are given in white boxes.

		TRMM 3B42RT					
		Kabompo		Kafue		Luangwa	
Hit	FA	ground observed		ground observed		ground observed	
Miss	CN	yes	no	yes	no	Yes	no
satellite estimate	Yes	41%	14%	38%	10%	37%	16%
	No	3%	42%	4%	48%	4%	43%

Table 4.4: Same as Table 4.3 but for TRMM 3B42.

		TRMM 3B42					
		Kabompo		Kafue		Luangwa	
Hit	FA	ground observed		ground observed		ground observed	
Miss	CN	yes	no	yes	no	Yes	no
satellite estimate	Yes	39%	7%	37%	5%	38%	9%
	No	6%	48%	5%	53%	3%	50%

Table 4.5: Same as Table 4.3 but for PERSIANN.

PERSIANN							
		Kabompo		Kafue		Luangwa	
Hit	FA	ground observed		ground observed		ground observed	
Miss	CN	yes	no	yes	No	Yes	no
satellite estimate	Yes	38%	7%	35%	4%	35%	5%
	No	6%	49%	5%	55%	5%	55%

Table 4.6: Same as Table 4.3 but for GSMaP

GSMaP							
		Kabompo		Kafue		Luangwa	
Hit	FA	ground observed		ground observed		ground observed	
Miss	CN	yes	no	yes	No	Yes	no
satellite estimate	Yes	40%	7%	37%	4%	37%	5%
	no	5%	49%	5%	54%	4%	55%

The contingency tables show that all rainfall products are more or less equally capable of distinguishing between wet and dry. All products estimate this correctly for over 85% of the time. The only exception is TRMM 3B42RT, which predicts wrongfully 17% of the time (3% misses and 14% false alarms = 17% wrong predictions). All products give around 5% amount of misses. Considering that also the ground records do not give a perfect rainfall estimate, this is a very good score. It can be seen that generally the false alarms are higher than the misses. This may be expected, as the likelihood of the satellite rainfall detecting rain in a catchment is higher than observed rainfall in convective events that are typical to the Zambezi River basin. In some cases it may be that the observed rainfall 'misses' the event simply because there was no rain over the rain gauges, while it did rain in other areas within the catchment.

From the number of hits, misses, false alarms and correct negatives, a number of skill scores can be defined as:

- Accuracy: this skill score describes how well in general the rainfall product predicted dry and wet events. A value of zero indicates no skill, a value of one perfect skill in predicting whether it rains or not. Accuracy is computed as follows:

$$\text{accuracy} = \frac{\text{hits} + \text{correct negatives}}{\text{total number of days}}$$

- Probability of Detection (POD): this score describes how often a rainy day was correctly predicted as rainy by the satellite product. A value of zero means the product is not able to detect rainy days. A value of one means that every time a rainy day occurred, the satellite product also predicts this as a rainy day. POD is computed as follows:

$$\text{POD} = \frac{\text{hits}}{\text{hits} + \text{misses}}$$

- False alarm rate (FAR): this rate indicates how often a rainy day is predicted by the satellite product, while the observation did not indicate a rainy day. A value of 0 means that the product never gives a false alarm. A value of one means that the product is not able to detect dry (i.e. it always rains a bit). FAR is computed as follows:

$$\text{FAR} = \frac{\text{false alarms}}{\text{hits} + \text{false alarms}}$$

Table 4.7 gives the skill scores, described above for each rainfall product and over each investigated sub-catchment.

Table 4.7: Skill scores for each investigated rainfall product

Rainfall product	Kabompo		Kafue		Luangwa	
TRMM 3B42RT	Accuracy:	0.83	Accuracy:	0.86	Accuracy:	0.8
	POD:	0.93	POD:	0.9	POD:	0.91
	FAR:	0.26	FAR:	0.21	FAR:	0.3
TRMM 3B42	Accuracy:	0.87	Accuracy:	0.9	Accuracy:	0.88
	POD:	0.86	POD:	0.88	POD:	0.92
	FAR:	0.15	FAR:	0.11	FAR:	0.19
PERSIANN	Accuracy:	0.87	Accuracy:	0.9	Accuracy:	0.9
	POD:	0.87	POD:	0.87	POD:	0.88
	FAR:	0.16	FAR:	0.11	FAR:	0.12
GSMaP	Accuracy:	0.89	Accuracy:	0.91	Accuracy:	0.91
	POD:	0.9	POD:	0.88	POD:	0.9
	FAR:	0.14	FAR:	0.1	FAR:	0.12

The skill scores show that GSMaP again gives the best performance although it is only marginally better than the remainder of the rainfall products. In particular the false alarm rates are slightly better for GSMaP than for the other products (e.g. only 0.10 in the Kafue).

4.5 Conclusions

The potential of using remotely sensed rainfall for operational forecasting in the Zambezi River basin was assessed according to the following criteria:

- Spatial-temporal resolution;
- Amount of time between the satellite observations and the availability of the product on the internet;
- Amount of megabytes of data that would need to be transmitted via the internet on a daily basis, if the product is to be used for forecasting; and
- The accuracy of the product, by several comparisons with ground-based rainfall.

Sections 4.5.1 to 4.5.5 summarise the main conclusions that can be drawn from this analysis.

4.5.1 Spatial-temporal resolution

The forecast areas are very large compared to the spatial resolution of the satellite products. For instance, the Kabompo catchment covers an area of about 70,000km^2. Around 70 raster cells of

0.25°x0.25° fit in this area and about 450 of 0.1°x0.1°. This means that the resolution is adequate for the purpose of this study in every product investigated. The same is true for the temporal scale. The forecasts require a temporal scale of a day or higher everywhere, while the temporal resolution of all products is an order higher (3 hours or even 1 hour). This means that also the temporal scale of rainfall products is more than adequate.

4.5.2 Delay time between observations and product availability

In Section 5.2.2, an overview of the typical time delay required by the various processing centres for posting of data on the internet was provided. This time delay directly influences the lead time. If a forecaster has to wait a month before rainfall estimates of rainfall falling at this moment become available, this leads to a reduction of lead time of one month. Therefore, besides the accuracy of the rainfall product, this is one of the most important parameters to consider when assessing potential for operational systems.

Table 4.1 shows that TRMM 3B42RT becomes available 5 hours after the satellite observations, PERSIANN about 65 hours and GSMaP NRT 4 hours. TRMM 3B42 is not an operational product. TRMM 3B42 is based on TRMM 3B42RT but makes a monthly-based correction based on global ground measurements from the Global Telecommunication System (GTS). This means the processing centre needs to wait for at least a month before the correction can be made and before the product can be delivered to end-users.

GSMaP delivers both a reanalysis product and an operational near real-time product. Their specifications are very similar. Unfortunately, overlapping time series data for the operational product and ground observations were not available for this study. However, to provide an indication of the accuracy of the GSMaP real-time product against observed data, the following approach was adopted. The reanalysis product was compared with ground observations and a comparison of the GSMaP real time product with the TRMM 3B42RT product was then undertaken to determine whether their behaviour was consistent. The spatial-temporal behaviour of the near real-time product was also visually examined and it was noticed that this behaviour is somewhat different from the reanalysis product. The quality of GSMaP near real-time, compared to the reanalysis product should therefore also be investigated with an overlapping set of ground-observations and satellite records, before using it in an operational system.

It can be concluded that GSMaP, given the short delay of only 4 hours, has great potential, but the user must be aware that the near real-time product is requires testing against an overlapping ground-based rainfall series. The fast delivery time of the product makes it useful, especially in forecast areas where considerable lead time is required and in fast responding catchments. This is the case in the Gwayi/Sanyati catchments for prediction of inflows into Lake Kariba, the Luangwa catchment for inflows into Cahora Bassa and for the Shire River. These catchment areas respond quickly to rainfall.

4.5.3 Internet load

Table 4.1 lists the estimated download data sizes that would typically be required for the use of each satellite product. The maximum load is about 25 megabytes per day for the GSMaP product (on average 0.3 kb/s). This transfer speed is in generally manageable for most internet connections. A dial-up connection for instance can manage up to 5 kb/s, which is an order of magnitude higher than required. Therefore, internet speed is in principle high enough everywhere in the world. It is, however, recommended that an operational system makes use of a dedicated internet connection that is not shared amongst other users besides the forecast system. In fact the download should occur at a central forecast location. If other users would use the same connection the download stream of data may become too slow or may even stall due to overload of internet traffic.

4.5.4 Product accuracy

Next to the delivery delay time, the product accuracy is of crucial importance to the potential of satellite rainfall in operational forecasting. It has been shown that, in particular, the GSMaP product is well suited. This product gives very accurate volumes, compared to ground-observations (bias ~10% in all sub-catchments). In the analysis, it is assumed that the ground observations provide a good reference time series. Given the fact that the station coverage used to estimate the ground-based values is rather poor, the 10% bias can be both due to ground observation inaccuracies and satellite product inaccuracies.

All other satellite products show more bias, but all, except TRMM 3B42 are very consistent in bias. This can also be seen in the time series plots. The bias can therefore easily be corrected for. The time series of GSMaP follows the ground observations best.

All rainfall products are highly suited to determining whether a day was rainy or dry. Again here GSMaP is better than the other products, although the difference is very small.

4.5.5 Potential of satellite rainfall

From the analyses carried out it can be concluded that satellite rainfall products, in particular the GSMaP NRT product, are promising for use in operational forecasting systems. The volumetric differences between GSMaP and ground observations is so small that differences between the two could be either due to poor station coverage or due to inaccurateness in the satellite product. The delay time of delivery of GSMaP is the shortest which also makes this product the most attractive to use from an operational perspective. However, the GSMaP NRT product has not been validated yet, because no overlapping ground-truth time series was available. Until this validation has taken place, use of the TRMM 3B42 RT is recommended, as this product has been shown to have reasonable performance and it is also available at a sufficiently short time delay. However, TRMM 3B42RT should be bias-corrected before being used in rainfall-runoff modelling. PERSIANN rainfall has too long a delay in availability for operational use.

Although there is strong potential for the use of remotely sensed rainfall determination, ground observations remain crucial. Satellite observations provide an indirect estimate of rainfall as opposed to direct ground measurements. Where rainfall estimates are needed on a decadal or monthly basis, it is recommended that an extensive rain gauge network is established wherever the coverage is too low, rather than relying on satellite rainfall. Furthermore, collection of recent rainfall observations is necessary for continuous ground-truthing of the satellite rainfall estimates.

Rainfall station coverage throughout most of the Zambezi River basin is currently too low to provide reliable daily estimates on sub-catchment basis. However, in the Luangwa and Shire river basins, daily estimates are required to meet the forecast requirements. If extension of the rain gauge network is deemed non-feasible in these areas (for instance because too many stations would be required at too many remote locations), the use of remotely sensed rainfall estimates is recommended as an alternative to ground-based measurement. The best product tested is the reanalysis product of GSMaP. However, it is recommended that a similar analysis as done here using the near real-time product of the GSMaP service is performed before considering its use in operational systems. If the near-real time product shows similar performance as the reanalysis product, it is recommended that the GSMaP near real-time product is selected as the preferred option.

However, as long as such a validation has not been carried out, or in case the performance appears to be poor, it is recommended that TRMM 3B42RT, which comes available with a lag time of only 5 hours, is used. TRMM 3B42RT however, needs a bias correction since it overestimates the rainfall by about 25% in the Zambezi.

For all other forecast areas, the remotely sensed rainfall products can also be used as a backup in case the ground station network fails or as an addition to ground gauges by merging ground observations with satellite observations.

5 Recommendations for Upgrading of Flow and Precipitation Gauging Networks

5.1 General

Chapter 3 of this report presents the results of an evaluation of the existing rainfall and flow gauging networks in the Zambezi River basin, and concludes with a list of proposed flow gauges for inclusion in a flow forecasting system, as well as estimates of the required rain gauge density for accurate ground measurement of rainfall. Chapter 4 outlines the analysis undertaken and results of an evaluation of existing remote sensing technologies for rainfall estimation.

The current chapter summarises the main findings presented in Chapters 4 and 5 and also lists key recommendations for the establishment of real-time or near real-time flow and rainfall gauging networks through the upgrading and extension of the existing networks for operational flow forecasting in the Zambezi River basin. Due to the inherent differences in the existing flow and rainfall networks with respect to physical factors, technology, operation and management, conclusions and recommendations for these networks are presented separately.

5.2 Flow gauging network

5.2.1 Network evaluation

The main findings of the flow gauging network evaluation were:

1. *Coverage:*

- Existing flow gauge coverage in the Zambezi River basins is generally adequate, with the exception of the Angolan portion of the basin, which currently has just one operational (SADC-HYCOS) gauge on the Lumege River.

2. *Reliability:*

- An evaluation of the reliability of existing gauges (using historical records) revealed that while a few gauges, such as the existing gauge at Victoria Falls, have relatively long and continuous records (high reliability), most have records with numerous gaps and missing values (low reliability). A summary of the above evaluation is provided in Appendix 5;
- Reliability appears to be related to the method of data transmission. Gauges that rely on postal communication were generally found to have poorer records than those with either automatic communication or manual communication by phone or radio;
- The practice used by some authorities whereby measurements are recorded both manually by a gauge reader (communicated by radio or phone) and automatically (by real-time equipment) appears to be an effective option that offers the combined benefits of operational flexibility and reliability, while reducing the risk of damage caused by theft or vandalism; and
- As most gauges in the Zambezi River basin are manual gauges, an evaluation of reliability with respect to different types of measurement and transmission equipment was not possible. However, some relevant lessons from the SADC-HYCOS project should be applied in the selection of gauge equipment.

3. *Communication of Data:*

- With the exception of the SADC-HYCOS project network and some of ZRA's flow gauges, the majority of existing flow gauges in the Zambezi River basin are manual gauges with both manual measurement and manual data transmission;
- The SADC-HYCOS network and ZRA currently use satellite transmission (EUMETSAT) for real-time communication of data, but capital and operational costs for this equipment are high;
- The current rapid expansion of GSM (cell phone) coverage throughout the Basin presents a great opportunity for the improvement of data transmission for future installations or upgrades to be undertaken at a significantly lower cost and at significantly reduced risk of theft and vandalism; and
- Manual measurement with data communicated by phone or radio is a viable alternative to automatic transmission in locations where daily measurements are adequate for flow forecasting.

4. *Sustainability:*

- Sustainability needs to be considered in the context of the gauge location (access, flood risk, lightning risk, etc.), the gauge technology (type and suitability of gauge, data transmission equipment, risk of theft, etc.), maintenance challenges (personnel training, availability of spare parts, etc) and political/ institutional challenges (political will for funding, long-term commitment to project, etc.);
- In general, the sustainability of existing automatic flow gauges in the Zambezi River basin is a major challenge. Equipment maintenance issues and a lack of spare parts are a major issue. On-going funding is also a problem, as well as the availability of suitably qualified maintenance staff. Experience from the SADC-HYCOS project has shown that selection of gauging equipment (measurement and transmission) should be limited to suppliers who have local service agents (within Southern Africa) and who are prepared to guarantee the availability of spare parts; and
- With respect to data transmission, experience from the SADC-HYCOS project indicates that GSM technology is more sustainable than satellite technology. GSM transmitters are cheaper to install and maintain, and being battery powered are less prone to theft or vandalism. Satellite transmitters, on the other hand, are relatively expensive, both for installation and operation, and in addition, are often attractive to thieves who are usually interested in the solar panel.

5.2.2 Network Design

The following findings and recommendations summarise the main outcomes of the flow gauge network design:

- 51 flow gauges have been identified for inclusion in a basin-wide forecasting network:
    - 49 of these are existing gauges;
    - 2 are new gauges proposed for establishment on the Cuando and Luiana Rivers in southern Angola;

  - 28 either already have real-time equipment or are earmarked for upgrading to real-time status under the SADC-HYCOS Phase II project;
  - 23 gauges do not have real-time equipment, although two of these have been equipped with automatic data loggers;
  - 3 sites are dams and use other means for measurement of outflows; and
  - The remaining 20 gauges are manual gauges and will require equipping with real-time systems. Some additional equipment will be required for upgrading and repair of existing gauges. Where GSM coverage is available, it is recommended that the existing systems are modified to allow communication of data via both satellite and GSM transmitters;
- The network design requirements are closely related to the various forecast model requirements and therefore fine tuning of the network is likely to be required during the implementation phase (not part of this project).
- The network design focused primarily on utilization of existing real-time gauges in the Zambezi River basin (SADC-HYCOS and ZRA). The expected institutional and financial investment required for establishment of the forecasting network will therefore be substantially lower than would have been the case for the establishment of a completely new network;
- Although real-time observations are generally preferred for operational flow forecasting, due to the long response times of some parts of the Zambezi River basin, not all gauges will necessarily require real-time equipment. However, a significant number of key gauges will definitely require upgrading from manual to real-time status;
- Many of the existing gauges in the SADC-HYCOS network will require repair or upgrading to become functional for operational forecasting;
- Gauges in the existing SADC-HYCOS real-time gauging network use satellite transmission for communicating data. However, the advent of better and cheaper, more robust and more theft proof GSM technology after their installation presents an opportunity for reequipping these gauges with GSM transmitters where coverage is available. It is also recommended that all new gauges are based on the GSM data transmission system where coverage exists; and
- Most of the existing gauges on the Zambezi River and other large tributaries do not have accurate rating curves. Although stage readings will be adequate for some gauges, establishment of accurate rating curves and on-going updating of rating curves at key gauge locations will be necessary for accurate forecasting.

5.2.3 Sharing of data

The SADC-HYCOS project established links between the National Hydrological Services of the 15 SADC member countries. As the Zambezi Basin is shared by 8 of these countries, communication, sharing of data and the development of basin-wide hydrology initiatives are important for many reasons including the establishment of a flow forecasting system. Many of the benefits of a basin-wide flow gauging network will accrue to the basin as a whole, rather than to individual countries. In some cases the main beneficiary of a particular gauge is not the country where the gauge is located but rather a downstream country. For this reason, it is important that agreements are set up between the basin countries to facilitate the sharing of data, and where necessary the sharing of costs. Although some informal arrangements between countries currently do exist, formal agreements that spell out the protocols for sharing of data do not. It is therefore recommended that an agreement be established between the basin countries to formalise and extend such arrangements. Such an agreement could be established as an Addendum to the main ZAMCOM agreement.

5.2.4 Estimation of costs

The costs associated with establishment of a real-time flow gauging network are multiple and can include institutional costs, civil works costs, equipment costs and installation costs. Quantifying direct civil and equipment costs will require detailed investigations, while institutional costs are very difficult to estimate. For this reason, it has not been possible to prepare a detailed cost estimate as part of this study. However, where approximate costs could be estimated on the basis of available information, these have been provided. An overview of the main costs likely to be required is given below (for implementation details, refer to Section 5.2.3):

- *Institutional costs* – the setting up and operation of a hydrological information system normally involves a number of institutions where in most instances, although their contribution is vital, it is almost impossible to quantify their contribution in monetary terms. In most cases the cost of the hydrological information is part of their broad activities, shared amongst the participating institutions or is substituted by agreements;
- *Repair of existing civil structures or construction of new structures* – cost estimates for repair of existing structures will be determined as part of the proposed condition assessments. Costs for design and construction of new structures will require specific design (this will vary according to the site);
- *Procurement of gauge equipment* – preparation of a procurement schedule for gauge equipment will require detailed condition assessments, as outlined in Section 5.2.3. Under this item, allowance should also be made for customs charges (if applicable) within the respective member state, as well as transportation costs to the country and site;
- *Installation* – in addition to the above costs, there will be equipment installation costs, both for existing real-time gauges (requiring repair or upgrading) and for new real-time stations. Installation costs will vary according to the country, the remoteness of the site and the ease of access;
- *Rating curves* – establishment of rating curves will be required at most gauges to provide flow data for calibration and operation of forecast models. An evaluation of existing rating curves, as well as information on currently available equipment, will be required before likely costs can be determined. A number of countries in the basin are currently upgrading their rating tables and this has included the procurement of Acoustic Doppler Current Profilers (ADCPs). The average cost of an ADCP with the accessories such as a boat and engine is roughly US$ 80 000; and
- *Operation and maintenance* –One of the most important costs to quantify for the long-term sustainability of the network will be the operation and maintenance costs (these include maintenance of the station and equipment, labour charges (observer), and training of staff in the operation and maintenance of the station). Various measures have been proposed in this report to reduce maintenance costs and in particular to minimise the risk of vandalism. However, operation and maintenance costs nevertheless remain very important. At present, costs for operation and maintenance of real-time gauges established under the SADC-HYCOS Project are provided by the basin states. It is recommended that this system continues unless management of these costs by ZAMCOM is considered to be a more effective approach.

The following section itemises in general terms, some the costs related to establishing a new station, operating and maintaining the hydrological network, setting up and running a data transmission facility and the related databases. These costs and the associated information were provided by Mr Musariri Musariri of the SADC-HYCOS project and are therefore based on practical relevant experience.

The main cost item for establishing new stations are the civil works costs (.i.e. the cost for construction of the gauging station and the DCP shelter). Table 5.1 gives an indication of the typical total costs for construction of a weir, a natural control section equipped with a stilling well and gauge posts and the housing of the DCP.

Table 5.1: Flow gauging station structure costs

Type of Structure	Cost in USD
Gauging weir	200 000
Natural control section	35 000
DCP shelter	15 000

Satellite transmission equipment is generally more expensive as compared to the GSM equipment. Figure 5.1 shows an invoice billed to the SADC-HYCOS project for the purchase of the OTT DCP equipment (satellite transmitting). The average cost of a GSM transmitting system is around US$7 000 as compared to the satellite which is US$17 500.

INVOICE: H0032010 CURRENCY: ZAR

DESCRIPTION	QTY	UNIT COST	COST TO THE PROJECT	TOTAL
OTT DCP Housing including: Logger Logosens PCU12 (Regulator) GPS Antenna HDR METEOSAT Transceiver w cable	3	50 262.95	150 788.85	No charge to D R C
Antenna "Patch" (Satellite), Bracket & Cable	3	4 500.00	13 500.00	
Solar Panels 12V - ±20Watt	3	2 257.20	6 771.60	
Solar Panels Housings	3	5 465.80	16 397.40	
Lead Sealed Batteries 12V - ±40Ah	3	860.00	2 580.00	
Pressure probes with Accessories (PLS)	3	10 260.00	30 780.00	
Hygro-Thermo Transmitter-compact	3	4 824.00	14 472.00	
Rain gauge	3	7 017.00	21 051.00	
Thalimedes D/Logger + Float & counter weights & Cable	5	8 525.00	42 625.00	
Personal Data Assistant (PDA) & Cable	1	8 938.67	8 938.67	
YSI KIT (Multi-Probe System with barometer)	1	22 858.00	22 858.00	
DuoLink & RS232 link	1	3 060.00	3 060.00	
Hydras 3	1	1 268.92	1 268.92	
		Sub-total	335 091.44	0.00
		VAT 14%	46 912.80	0.00
		TOTAL	382 004.24	0.00

Figure 5.1. Sample invoice showing costs for SADC-HYCOS flow station equipment

Establishment of additional satellite data transmission system gauges will require the engagement and signing of agreements with the World Meteorological Association (WMO) and EUMETSAT to enable data transmission through the METEOSAT facility. The costs related to this exercise are dependent on the nature of the agreement. The SADC-HYCOS project signed an agreement with the WMO for the unlimited use of the METEOSAT facility at a total cost of about US$50 000. It should be noted that the SADC-HYCOS project is a WMO initiative and thus the nature of the agreement and related cost may be discounted and not reflective of the actual cost for establishment of an independent network. Further details of the technical aspects of the SADC-HYCOS Project are provided in Appendix 4.

There is also a need to identify a Project Regional Centre (PRC), which would host among other things the METEOSAT receiving station, computer server, web site and database. The cost of establishing a PRC is difficult to quantify as this will depend on the facilities already available at the centre location (if hosted by an existing organisation). For hosting the SADC-HYCOS website and regional database the cost to the South African Department of Water Affairs was around US$ 35,000 per year, whilst the total cost for the entire centre for the three years that the South African Government hosted the project was about US$ 270 000. It must be noted that these costs are much less than would be applicable for establishing a new centre, as in most cases the project was utilizing the existing DWA facilities. Until such time as ZAMCOM is established, it would seem most practical and cost-effective to use the existing facilities in Pretoria for the receiving and storage of hydrological data. However, negotiations with the South African Department of Water Affairs would be required to confirm whether this would be an acceptable to them.

The HYDSTRA database has already been installed in most of the basin countries, with the exception of Zimbabwe and Angola. Therefore, an additional cost will be required for a consultant to install the database in these countries and for the training of relevant staff. Most of the countries in the SADC region who received training in the use of HYDSTRA were of the opinion that the training offered was not adequate and that training should ideally be an on-going activity that accommodates important issues that may arise during the operation of the system. For the smooth exchange of data there is currently a need for upgrading of the internet facilities in each of the NMSs in the Basin. In addition, as the HYDSTRA licenses are only currently valid for a period of five years, a commitment should be obtained from each of the NHSs that the cost of re-licensing will be borne by them. Alternatively, external funding will be required.

5.2.5 Implementation plan for flow gauging network

A detailed implementation plan for upgrading and improvement of the flow gauging network has not been prepared as part of this study. However, key details and actions have been identified and these are summarised under specific proposed recommendations or interventions in Chapter 10 (Recommendations). Further consultation with stakeholders and development of specific implementation details may be required before these interventions can be implemented.

5.3 Weather Monitoring Network

5.3.1 Overview of current ground observation capabilities

In Chapter 3, an investigation of whether the current rainfall station coverage meets the identified forecast requirements was conducted. Below, an overview of the relevant findings from this study regarding the current ground observation capabilities is provided.

In the Upper Zambezi region, the rain gauge network is sparse. This region is much more remote than the Middle and Lower Zambezi River basins. In the Zambian portion of the basin there are currently 10 rain gauges in place, which includes coverage over the Kabompo catchment and the contributing areas between the town of Zambezi (close to the boundary with the Democratic Republic of Congo located along the banks of the Zambezi River) and Sioma Ngonye Falls. Especially in Angolan territory (Lungwebungu, Luanginga and Cuando catchments), the rain gauge network is virtually non-existent and currently difficult to extend, mostly due to a risk of land mines.

The current capabilities in rainfall monitoring are concentrated in the Middle and Lower Zambezi Basins. In particular the Zimbabwe Meteorological Services Department (ZMSD), Malawi Department of Climate Change and Meteorological Services (MDCCMS), the Zambia Meteorological Department (ZMD) and ARA Zambeze have an extensive monitoring network available in these parts of the Zambezi River basin. The ZMD has 26 primary stations in the Middle Zambezi, the MDCCMS about 50 in the Lake Malawi surroundings and Shire catchment, of which 9 are automatic and equipped with GSM transmission. ZMSD has about 17 primary stations located in the Gwayi/Sanyati area. Mozambique owns 48 rainfall stations as part of the ZAMWAT network, some of which are equipped with cellular or HF radio communication. Besides an operational monitoring network, ZMSD and MDCCMS also have a significant number of voluntary or subsidiary gauges available in the region. Although such locations typically report with a delay of 1-3 months, they may provide enough secure locations to contribute to an operational forecasting system in the near real-time. To realise this, these locations and their operators need to be equipped with automatic weather stations. The GSM network coverage is adequate in nearly all regions to provide GPRS-based telemetry communication, which means that GPRS telemetry is a feasible and, compared to satellite telemetry, cheap option to communicate data from the weather stations to a central data management and forecasting location. The dense network of voluntary stations can furthermore be used to validate remotely sensed rainfall estimates, which can in turn be used in sparsely gauged or inaccessible areas.

5.3.2 Considerations for improvements of rainfall estimation

The gap analysis showed that currently available monitoring capabilities are in many cases not adequate to reach forecast requirements. Recommendations for improvements in rainfall estimation, which are given in Section 5.3.3, have been founded on a number of considerations, as presented below.

Short lead-time forecast requirements

Due to the high spatial and temporal variability of rainfall in the region, the station coverage requirements are very high in areas where daily forecasts are needed. If daily or decadal rainfall is needed in near-real time and estimates are to be delivered by ground measurements, the following arrangements need to be made:

- Replace existing manual gauges with automatic gauges, loggers and data transmission via GSM networks or satellite, and/or; and
- Supplement the existing network with new gauges.

To replace an existing station or to establish a new station, the following expenses and logistics should be expected:

- Purchase costs of station with communication equipment: given the fact that in most areas, GPRS coverage can be used for transmission, these costs will not be very high (about US$2 500 per unit which includes a full telemetry station with precipitation, temperature, relative humidity and wind speed sensors);
- Finding safe and accessible locations for placement;
- Finding a reliable local person to maintain the station; and
- Regular maintenance.

Given the above points, it is considered that a significant increase in the number of real-time stations is not realistic within a short time frame. However, the replacement of stations that are currently operated manually, with automatic weather stations with near real-time telemetry transmission, is a feasible option if funds are available to purchase and maintain them. In such cases, a secure and accessible location and a responsible person have already been established, which are besides funding the most relevant preconditions for a successful station.

Medium-range and seasonal forecast requirements

The analysis carried out in Section 2.7 shows that in most locations with a medium-range or seasonal lead time requirement, enough stations are currently available. For medium-range forecast locations, where decadal rainfall figures are required, rainfall data needs to be collected and transmitted automatically, since manual reading and transmission will result in too large a delay. Therefore, installation of automatic weather stations with a telemetry transmission system is also considered to be the most reliable at these locations. For forecast locations having a monthly or seasonal lead time requirement, in general, monthly rainfall is required for forecasting. At these forecast locations, rainfall does not necessarily have to be transmitted in real time. Instead data can be collected manually and transmitted by telephone. In order to ensure timely delivery of these data, a data collection protocol needs to be followed by the gauge reader.

Potential of remotely sensed rainfall

In Chapter 5 an investigation of the potential use of satellite rainfall estimates (SRE) in areas requiring a high density of stations or in areas that have unfavourable conditions for a high density operational rainfall station network was undertaken. All of the SRE products considered showed a reasonable comparison to the observed rainfall data over the catchments considered. The SRE were found to particularly good in determining whether a day was wet or dry, with GSMaP (one of the latest products) being slightly better than the other products. Most of the products, however, did show some bias, however this bias was found to be very consistent, which would allow for it to be easily corrected.

Given the short delay between satellite observations and the SRE products becoming available (e.g. GSMaP becomes available on hourly basis with a delay of 4 hours), it is considered that the evaluated satellite rainfall products, in particular the GSMaP NRT product, represent a promising opportunity for use in operational forecasting in the Zambezi River basin where ground-based measurement is deemed infeasible. The short delivery time of the product makes it particularly useful in fast responding forecast areas where considerable lead time is required. This is for example the case for flood prediction in the Luangwa catchment, which is so remote that extension of the rainfall network is not practical. However, as long as validation of GSMaP NRT has not been carried out, use of the TRMM 3B42RT product is recommended.

5.3.3 Recommendations on improving rainfall estimation per forecast location

Based on the results of the gap analysis, satellite rainfall investigations and the considerations, mentioned in the previous section, the following is recommended for the improvement of rainfall estimation per forecast location.

In general, it is recommended that rainfall station coverage issues are addressed wherever station coverage is close to that required for flow forecasting, and that satellite rainfall estimation is only used where it is unlikely that the needed station coverage will be achieved within the expected time frame for setting up an operational forecasting centre. Using ground records wherever deemed feasible ensures that data collection always remains under the control of the forecasting entity as much as possible. However, as the expected timeframe for implementation of SRE is likely to be a matter of months, while replacement of manual stations with real-time equipment may require a period of years, it is recommended that SRE is also used in areas with adequate gauge density until upgrading of ground based stations has been completed.

The resulting recommendations for short, medium and seasonal lead time forecast locations are summarised in the tables below. Wherever additional gauges are required, it is recommended that installation of only the minimum number of required gauges is initially undertaken. After one hydrological year, the station coverage can be revisited after an assessment of the quality of the forecasts, performed in that year.

Table 5.2. Recommendations for rainfall observations for short-term lead time forecast locations

Forecast area	Temporal scale needed	Recommended action
Zambezi between Katima Mulilo and Victoria Falls	Daily	Convert stations in the catchment area in between Katima Mulilo and Victoria falls into telemetry stations, no additional stations required
Chobe between Ngoma Bridge and Zambezi Confluence (~25.000 km^2)	Daily	Not enough rainfall stations available, remote area. Use remotely sensed rainfall estimates.
Lower reaches of Sanyati and Gwayi rivers	Sub-Daily	Convert primary stations and a selection of voluntary stations into telemetry stations, no additional station locations required. Given the high density of the rainfall network (including voluntary stations), use rainfall stations for annual validation of remotely sensed rainfall products.
Zambezi between Kariba Dam and Cahora Bassa Lake	Sub-Daily	Not enough rainfall stations available in the Zambian part of forecast area. Use remotely sensed rainfall estimates.
Luangwa Downstream of Great East Road Bridge to Zambezi confluence	Daily	Upstream area is highly remote and has poor station coverage. Use remotely sensed rainfall estimates over the full Luangwa catchment area.
Zambezi downstream Cahora Bassa to the Zambezi mouth	Sub-Daily (Flash-Floods)	Convert rainfall stations in Luenya catchment to telemetry stations. In Mozambique, use existing telemetry stations and convert manual gauges to telemetry.
Shire downstream of Kamuzu Barrage to confluence Zambezi	Sub-Daily (Flash-Floods)	Enough stations available. Convert primary full meteo and some of the subsidiary meteo stations to telemetry systems. Given the high density of the rainfall network (including subsidiary stations), use rainfall stations for annual validation of remotely sensed rainfall products.

Table 5.3. Recommendations for rainfall observations for medium lead time forecast locations

Forecast area	Temporal scale needed	Recommended action
Inflows to Lake Kariba	Decadal	Convert stations in the intermediate catchment between Barotse and Victoria Falls into telemetry stations, no additional stations required
Inflows to Itezhi-Tezhi and Kafue Gorge	Decadal	Convert stations in the Kafue catchment into telemetry stations, no additional stations required. Use the Kafue rainfall records for annual validation of remotely sensed rainfall products.
Inflows to Lusiwasi Reservoir[1]	Decadal	Install one gauge close to the inflow location of lake Lusiwasi
Inflows to Mulungushi Reservoir[1]	Decadal	Convert existing operational gauge at Kabwe to telemetry station.
Inflows to Lunsemfwa Reservoir[1]	Decadal	Install one telemetry gauge halfway upstream the reservoir
Inflows to Lake Cahora Bassa	Decadal/Monthly	Convert 5 stations (5) to telemetry stations. Select these so that a good spatial distribution of operational rainfall stations is established
Inflows/Outflows from Lake Malawi	Decadal/Monthly	No gauges can be placed on Lake Malawi. Use remotely sensed rainfall here. Downstream of the lake, a selection of about 5 existing telemetry gauges is needed.

Table 5.4. Recommendations for rainfall observations for seasonal lead time forecast locations

Forecast area	Temporal scale needed	Recommended action
Inflows to Lake Kariba	Monthly	Additional gauges are required in Angolan territory (not necessarily telemetry for long-term requirements). Reliable positions are unlikely to be found and maintenance cannot be guaranteed. Use remotely sensed rainfall.
Inflows to Itezhi-Tezhi and Kafue Gorge	Monthly	There are enough stations in place for long-term forecasting.
Inflows/Outflows from Lake Malawi	Monthly	No gauges can be placed on Lake Malawi. Use remotely sensed rainfall. Downstream of the lake, existing gauges may be used (see medium-range forecasts).

Tables 5.2 to 5.4 show that in many forecast areas (especially those with daily requirements), it is not feasible to extend the rainfall station network. This is either due to remoteness or due to the fact that protection or maintenance cannot be guaranteed (e.g. in Angola, where there is little or no recent experience with the maintenance of precipitation networks). ZMSD and MDCCMS have extensive and dense rainfall station networks consisting of both primary and voluntary/subsidiary stations. Because of the high network density in the Sanyati, Gwayi and Shire catchments, it is recommended that the stations in these areas (both official and voluntary/subsidiary) are used to perform an annual validation of remotely sensed rainfall. Such validations are necessary because as mentioned in Chapter 5, satellite rainfall algorithms are sometimes changed, which can result in anomalies in rainfall. At global scale, such changes generally lead to improvements in rainfall estimation, but regionally, the rainfall estimates may also deteriorate.

5.3.4 Recommendations for placement, instrumentation and transmission

Placement of weather stations

Tables 6.1, 6.2 and 6.3 show that only in the forecast areas of Lusiwasi and Lunsemfwa reservoirs, additional rain gauge locations are recommended. In all other forecast areas, either the use of satellite rainfall estimation is recommended or replacement of some or all of the existing manual gauge locations into automatic telemetry stations. In areas with high density rainfall networks (in particular forecast areas in Zimbabwe, Malawi and Mozambique), only a selection of gauges needs to be converted into telemetry systems. This is the case for the following areas:

- Gwayi and Sanyati catchment areas;
- Luenya catchment and most likely also the lower Zambezi area (dependent on the final rainfall station coverage in Mozambique which is as yet unknown to the Consultant); and
- Lower Shire catchment area.

In these areas it is recommended that a careful selection of suitable locations is made for placement of automatic weather stations. This should be performed in close consultation with the entity responsible for meteorological observations (e.g. Zambia Meteorological Department, ZRA, Zimbabwe Meteorological Services Department, Namibia Meteorological Service, Malawi Department of Climate Change and Meteorological Services, ARA Zambeze). The following aspects can be taken into consideration:

- Establishment of a measurement network that is evenly distributed in space. This is important in order to reach a reliable sampling of rainfall over the area of interest;
- Selection of locations that have been proven to be reliable in the past (in terms of data quality and local maintenance). This information will be known at the entity responsible for rainfall measurements; and
- Selection of protected and accessible locations. Protected locations are school premises, missions, police stations, hospitals and national parks.

Required and recommended instrumentation

For measuring rainfall, tipping bucket sensors are recommended. A tipping bucket records rainfall automatically in fixed quantities of mostly 0.1 or 0.2 mm, which is enough for the purpose of forecasting. Tipping bucket rainfall records are generally reported in 15 minute intervals, which can easily be converted to hourly or daily intervals if needed.

Besides measurements of rainfall, measurements of solar radiation, relative humidity, temperature and wind speed will also be required to estimate potential evaporation (as mentioned in Section 4.7.4). The spatial variability of these variables is much lower than for rainfall, thus these variables may be collected by far fewer stations than the amount needed for rainfall estimation. From the Consultant's experience, the estimated number of stations needed for estimation of potential evaporation is a factor of 5 lower than the number needed for rainfall estimation.

The major costs of a weather station however, will probably not be determined by the price of additional sensors for estimation of potential evaporation, since the remaining compulsory hardware on the station makes up the bulk of the price. Compulsory instruments on any automatic weather station are the following:

- Data logger (including connections with sensor equipment);
- Extension cables;
- Tripod and mounting materials;
- Power supply (preferably a solar panel); and
- Weather proof housing and radiation shield.

Besides this, there are installation costs, and costs for data transmission equipment and maintenance. Below, cost estimates for weather station components (including the compulsory hardware) are given. These cost estimates have been based on the price list of HOBO, a well-known brand, familiar to the Consultant[*].

Table 5.5. Weather station components including costs and whether required or optional

Sensor	Compulsory Yes/No	Cost estimate
Weather station data logger including connections	Yes	$ 500
Sensor connection extension cables	Yes	$ 100
Weather proof connection housing and sun light protection	Yes	$ 100
Tripod and mounting equipment	Yes	$ 200
Tipping bucket rain gauge sensor	Yes	$ 450
Telemetry (GSM)	Yes	$ 1000
Solar panel	Yes	$ 300
Anemometer inc. 10m. connection cable (wind speed)	No (needed for potential evaporation estimates)	$ 300
Temperature/Relative humidity sensor	No (needed for potential evaporation estimates)	$ 200
Pyranometer (incoming solar radiation)	No (needed for potential evaporation estimates). The lens of the pyranometer needs regular cleaning and recalibration. Alternatively, a satellite based estimate may be downloaded (see http://landsaf.meteo.pt/)	$ 250

A fully equipped weather station system, including sensors and data logging is powered for approximately one year using four AA batteries, but given the fact that data also need to be transmitted, it is recommended that stations are powered by a solar panel to reduce the need for power replacement.

[*] Information has been collected from http://www.microdaq.com/occ/hws/index.php, accessed on August 12, 2010

5.3.5 Implementation plan for precipitation monitoring network

A detailed implementation plan for upgrading and improvement of the precipitation monitoring network has not been prepared as part of this study. However, key details and actions have been identified and these are summarised under specific proposed recommendations or interventions in Chapter 10 (Recommendations). Further consultation with stakeholders and development of specific implementation details may be required before these interventions can be implemented.

6 Evaluation of model capabilities and recommendations

6.1 Introduction

As described in Section 2.2.1, the information required from the forecasting system consists primarily of levels and flows. For the shorter lead time forecasts, instantaneous levels and flows are the main variables of interest, whilst for medium and seasonal lead time forecasts, the primary variables of interest are flows and volumes.

To predict the evolution of levels and flows across the desired lead times, different types of hydrological and hydraulic routing models will be required. For each of the forecast requirements identified, a suitable strategy of models can be established. There are at present several models that have been developed by different organisations in the Zambezi River basin, some of which are used as operational models. These existing models can be assessed to determine whether they fulfil the model requirements established. In the following sections, an analysis is performed on which models are required. This analysis is based on the forecast requirements described in Section 2.2.

6.2 Model requirements and availability

In this analysis, there are several types of models that may be required to fulfil the forecast requirements.

- **Recession equations [Rec].** These models provide a simple relationship of the evolution in time of the variable of interest at the forecast location itself. These are primarily used for describing the recession part of the hydrograph during the dry season. Recession models are not applicable during the wet season;
- **Regression models [Regr].** These models are the simplest form of routing models, providing a simple relationship between levels/flows at an upstream location and the levels /flows at the forecast point. Regression models may also consider multiple upstream locations, as well as cumulated rainfall and other variables. As these models rely on the availability of observed data at the upstream location, the lead time provided is constrained by the lag times between the forecast point of interest and the closest upstream location used as an input;
- **Rainfall-runoff models [R-R].** These models describe the response of the catchment to rainfall. There are numerous rainfall-runoff models in use, with models from the conceptual catchment model family being the most commonly used in operational systems. The advantage of these models is that provided reliable inputs in the form of precipitation and evaporation are available, the models are robust. While observed data is useful in assessing model errors and correcting for these errors in real time, the models can be run without, and may even be applied to un-gauged basins;
- **Routing models [Route].** These models describe the propagation of the flood wave through the river network. There are again a wide range of models in use in operational systems. Where possible in operational systems the simplest model that is suitable is recommended, with simple hydrological routing models such as Muskingum or Kinematic wave approaches for reaches where backwater effects are negligible and where floodplains are insignificant, to more complex hydrodynamic models where these effects are non-negligible and/or there is significant floodplain flow;

- **Inundation models**. These models explicitly describe the inundation propagation of flow across the river and floodplain in two dimensions;
- **Reservoir simulation models.** These models allow for the simulation of reservoirs and their control. Simulation of flow within these models is typically quite simple, but these allow for implementing control rules for reservoirs to simulate the release from reservoirs, given the defined rule curves; and
- **Flash Flood Guidance models**. The last group of models considered are flash flood guidance models. These are often closely related to the rainfall-runoff models, but rather than the response of the basin to flooding, the typical approach is to provide an estimate of the amount and intensity of rainfall that would lead to flood thresholds being exceeded.

6.2.1 Short lead time forecasts

Model requirements for the forecast locations that require short lead time forecasts are detailed in Table 6.1. This table shows the types of model that would be suitable or may be required to fulfil the forecast requirement, as well an estimate of the required temporal resolution for these models. The table indicates whether there are models currently available that would be appropriate for this purpose. While these models may be available, it is clear that their true suitability can only be determined if these models are made available and tested.

Table 6.1: Forecast locations with model requirements for short lead time forecasts

Reach/Location	Basin	Discussion and Model Requirements
Zambezi between Katima Mulilo and Victoria Falls[1]	Upper Zambezi	**Inflow** Regression model **Levels in reach** Simple hydrological routing model for main reach. 1D and possibly 1D-2D hydrodynamic model round Chobe/Zambezi confluence **Resolution** Daily flows / Monthly Rainfall **Availability** • A recession model is used by ZRA to establish inflows for Lake Kariba during the dry season • A regression model is used by ZRA to establish inflows for Lake Kariba • Availability of any models around Chobe/Zambezi confluence unknown.
Kwando, Linyati and Chobe Rivers inside Namibia and Botswana[1]	Upper Zambezi	**Inflow** Regression model **Levels in reach** Simple hydrological routing model for main reach. 1D and possibly 1D-2D hydrodynamic model round Chobe/Zambezi confluence **Resolution** Daily flows / Monthly Rainfall **Availability** unknown.
Lower Reaches of Sanyati & Gwayi rivers	Middle Zambezi	**Inflow** Rainfall-Runoff model **Levels in reach** Simple hydrological routing model with rating curve to derive

Reach/Location	Basin	Discussion and Model Requirements
		levels. **Resolution** Sub-Daily to Daily **Availability** Unknown **Flash-flood Guidance modeling** Required
Zambezi between Kariba Dam and Cahora Bassa Lake[2]	Middle Zambezi	**Inflows** Reservoir model / Planned releases from Kariba Dam and Kafue Gorge Dam **Levels in reach** 1D Hydrodynamic model **Resolution** Sub-Daily **Availability** Kafriba model may be suitable to provide releases from Kafue Gorge Availability of other models unknown
Luangwa Downstream of Great East Road Bridge to Zambezi confluence	Middle Zambezi	**Inflow** Rainfall-Runoff model **Levels in reach** Simple hydrological routing model with rating curve to derive levels. **Resolution** Sub-Daily to Daily **Availability** • Research model (Winsemius, 2009) • Availability of other models unknown
Zambezi downstream Cahora Bassa to the Zambezi mouth[2]	Lower Zambezi	**Inflows** Reservoir model / Planned releases from Cahora Bassa Dam **Levels in reach** 1D Hydrodynamic model **Resolution** Sub-Daily **Availability** Mike11 Model of Lower Zambezi (ARA-Zambeze) **Flash-flood Guidance modelling** Required
Shire downstream of Kamuzu Barrage to confluence Zambezi	Lower Zambezi	**Inflows** Reservoir-Lake model / Regulation of Liwonde Weir **Levels in reach** 1D Hydrodynamic model Possibly Rainfall-Runoff models for small tributaries **Resolution** Sub-Daily **Availability** Unknown **Flash-flood Guidance modelling** Required and available: trigger based warning system on Shire and Ruo Rivers (Ministry of Water Development and Irrigation, Malawi)

Notes:

1 Flow patterns round the Chobe/Zambezi confluence can be very complicated, and depending on the levels in each of the dominant floodplain flow at the confluence may be either from the Chobe to the Zambezi or vice versa. To obtain accurate predictions of levels this will require at least 1D Hydrodynamic modelling;
2 In a number of catchments, flash flood guidance is needed. WMO is involved in the "Southern African Regional Flash Flood Guidance System" (SARFFG) project, which aims to implement a flash flood warning system for SADC, to be operated by RSMC Pretoria. RSMC Pretoria will provide flash flood guidance to NMC's. NMC's then issue local warnings to disaster management units as needed. The focus area includes the complete Zambezi basin. Therefore SARFFG can be integrated with the development of a central flow forecasting system for the Zambezi to provide short lead time warnings for flash floods (0 to 6 hours ahead); and
3 For releases from the large dams, reservoir models may be useful, but of greater importance is the availability of the planned releases from the dams.

6.2.2 Medium range lead time forecasts

Model requirements for the forecast locations that require medium range forecasts are detailed in Table 6.2. This table shows the types of model that would be suitable or may be required to fulfil the forecast requirement, as well as an estimate of the required temporal resolution of these models. The table indicates whether there are models currently available that would be appropriate for this purpose. While these models may be available, it is clear that their true suitability can only be determined if these models are made available and tested.

Table 6.2: Forecast locations with model requirements for medium range lead time forecasts

Reach/Location	Basin	Discussion and Model Requirements
Inflows to Lake Kariba	Upper /Middle Zambezi	**Inflows** Regression models & recession models Routing model (possibly inundation model for detailed propagation of flow on Barotse Plains) **Resolution** Decadal Flows/ Monthly Rainfall **Availability** • A recession model is used by ZRA to establish inflows for Lake Kariba during the dry season • A regression model is used by ZRA to establish inflows for Lake Kariba
Inflows to Itezhi-Tezhi and Kafue Gorge[1]	Middle Zambezi	**Inflows** Regression models & recession models Reservoir model for operation of Itezhi-Tezhi and Kafue Gorge Routing model (possibly inundation model for propagation of flow across Kafue flats. **Resolution** Decadal Flows/ Monthly Rainfall **Availability** • The Kafriba model simulates the propagation of flow across the Kafue flats. Rainfall-runoff processes are modelled within Kafriba by the WRSM2000 model.

Reach/Location	Basin	Discussion and Model Requirements
		• HEC-5 Model for operation of the dams (Beilfuss, unknown) • New InfoWorks model of the Kafue Flats (ZESCO, under development)
Inflows to Lusiwasi Reservoir	Middle Zambezi	**Inflow** Rainfall-Runoff model **Resolution** Decadal rainfall **Availability** Unknown
Inflows to Mulungushi Reservoir	Middle Zambezi	**Inflow** Rainfall-Runoff model **Resolution** Decadal rainfall **Availability** Unknown
Inflows to Lunsemfwa Reservoir	Middle Zambezi	**Inflow** Rainfall-Runoff model **Resolution** Decadal rainfall **Availability** Unknown
Inflows / Outflows to Lake Cahora Bassa	Lower Zambezi	**Inflows** Reservoir model for operation of Itezhi-Tezhi / Kafue Gorge and Kariba dams Reservoir model for operation of Cahora Bassa dams Simple hydrological routing **Resolution** Decadal-Monthly **Availability** • HEC-5 Model for operation of the large dams **Flash-flood Guidance modeling** Required
Inflows/Outflows from Lake Malawi	Lower Zambezi	**Inflows** Reservoir-Lake model / Regulation of Liwonde Weir **Resolution** Decadal **Availability** Unknown

Notes:

1 The Kafriba model has been developed based on the RIBASI code from DHV consultants in the Netherlands. While this may be suitable, it has been noted that this model is no longer supported by DHV and may be out of date. An alternative based on the Infoworks software program has been suggested but it is unknown if this has been developed; and

2 For releases from the large dams, reservoir models are important. The HEC-5 model reported in Beilfuss (2001) may be suitable. HEC-5 is, however, no longer supported and the more current HEC-ResSim model which replaced HEC-5 may be more suitable.

6.2.3 Seasonal forecasts

Model requirements for the forecast locations that require seasonal forecasts are detailed in Table 6.3. This table shows the types of model that would be suitable/may be required to fulfil the forecast requirement, as well as an estimate of the required temporal resolution of these models. The table indicates whether there are models currently available that would be appropriate for this purpose. As was stated for the other two time frames, the availability of a model does not necessarily imply its suitability, and it will have to be tested for suitability

Table 6.3: Forecast locations with model requirements for seasonal forecasts

Reach/Location	Basin	Discussion and Model Requirements
Inflows to Lake Kariba	Upper Zambezi	**Inflows** Rainfall-runoff (water balance) model **Resolution** Monthly Rainfall **Availability** • A regression model is used by ZRA to establish inflows for Lake Kariba
Inflows to Itezhi-Tezhi and Kafue Gorge	Middle Zambezi	**Inflows** Rainfall-runoff (water balance) model **Resolution** Monthly Rainfall **Availability** • Unknown
Inflows to Lake Cahora Bassa[1]	Middle Zambezi	**Inflow** Rainfall-Runoff model Reservoir models for Kariba Dam, Itezhi-Tezhi dam and Cahora Bassa dams **Resolution** Monthly **Availability** Unknown
Inflows/Outflows from Lake Malawi	Lower Zambezi	**Inflow** Rainfall-Runoff model Reservoir/Lake models for operation Kariba Dam, Itezhi-Tezhi dam **Resolution** Monthly **Availability** Unknown

6.3 Recommendations for improving model capabilities

The model requirements and current model capabilities in the Zambezi show that there are already quite some capabilities available that have the potential to form the simulation backbone of a flow forecasting system. It is recommended to use these capabilities wherever these prove suitable for the purpose of flow forecasting. Where other models are required, these should be set up and implemented as well. It is, however, recommended to set up such models in close collaboration with the responsible entities in the basin, and to use model codes that are commonly used in the basin, and are used by the research and consultancy community in the region. This ensures that models are owned, understood and maintained by basin entities, which safeguards their sustainability.

The following existing models are recommended for integration in a flow forecasting system:

- ZRA Regression and recession models for inflow forecast to Lake Kariba (SADC/ZRA);
- Mike-11 model upstream of Cahora Bassa to the Ocean (ARA Zambeze);
- WRSM2000 model (currently a component of Kafriba) for rainfall-runoff upstream of Itezhi-Tezhi and the Kafue Gorge (ZESCO);
- New InfoWorks model of the Kafue Flats (ZESCO, under development). This model will enable a much more accurate analysis of propagation of flow in the Kafue Flats than the conceptual Kafriba model;
- Trigger based warning system on Shire and Ruo Rivers (Ministry of Water Development and Irrigation, Malawi);

Existing models that are not officially accepted by basin entities, such as the Luangwa research model (Winsemius, 2009) are not recommended to be implemented as is, because these models are not widely known and cannot be maintained or improved using the capacity of basin stakeholders. Instead, a model could be built by basin entities, using the concepts of such research models.

A number of new models will be required to strengthen the existing model capabilities in the basin. In particular rainfall runoff models and reservoir/water balance models are still lacking in many parts of the basin and need to be set up. Any new model development needs to be accompanied by human capacity building to use the model. To this end, it is recommended that new models are established in close collaboration with the authority that will maintain it.

The following new models are required to meet the identified forecast requirements throughout the basin. The models are listed with the forecast lead time it should be used for:

- Routing models for the Gwayi, Sanyati, Luangwa, Hunyani, Luenya river (short lead time);
- Hydrodynamic routing model from Katima Mulilo to Victoria Falls (short lead time);
- Hydrodynamic routing model from the outlet of Kariba to Cahora Bassa (short lead time)
- Rainfall-runoff model for Sanyati and Gwayi (short lead time);
- Rainfall-runoff model for Luangwa, based on concepts of research model (Winsemius, 2009) (short lead time);
- Rainfall runoff model for Manyame and Luenya Rivers (short - medium lead time);
- Flash Flood Guidance procedures for the Gwayi/Sanyati, and Shire catchments linked to the Regional Flash-Flood Guidance System – Southern Africa project by WMO (short lead time);
- Reservoir models for operation of Itezhi-Tezhi and Kafue Gorge, Kariba and Cahora Bassa (medium lead time);
- Reservoir routing model for Lake Malawi including wind effects (medium lead time); and
- Water balance model for the complete Zambezi basin (seasonal lead time).

7 Evaluation of precipitation forecasting capabilities and recommendations

7.1 Introduction

The analysis of flow forecasting requirements for different stakeholders at short, medium and seasonal lead times has led to establishing forecast locations across both the Upper and Lower Zambezi basin. In Section 2.2.4., data requirements to fulfil these flow forecasting requirements are identified. At some forecast locations the need for forecast rainfall is indicated. Particularly in the case where the (natural) lag times upstream of a forecast location are shorter than the desired flow forecast lead time, a precipitation forecast will be required. This requirement is the most apparent for the flashier catchments such as the lower Sanyati, the Gwayi and the Shire.

In this section, the abovementioned data requirements are translated into requirements for precipitation forecasts. Based on available information, the current capabilities in precipitation forecasting relevant to the Zambezi basin will be assessed, and compared to the requirements posed. The resulting gap analysis is used to identify recommendations for improvements to the available precipitation forecasting capabilities.

7.2 Requirements for precipitation forecasting

As for the flow forecasting, the requirements for precipitation forecasting are divided into short, medium and seasonal requirements. In contrast to the flow forecast requirements, however, precipitation forecasts are generally made on a regional basis, and will need to cover the complete basin upstream of the forecasting point. Table 7.1 summarises the main differences in terminology between the meteorological and hydrological communities with respect to forecast timeframes.

Since weather forecasts are subject to increasing uncertainties as lead time increases, probabilistic information from ensemble prediction systems (EPS) are increasingly used above a single deterministic forecast to provide useful information on the prediction and the associated uncertainties from at least 3 days on to the seasonal time scale.

Table 7.1. Recommendations for rainfall observations for medium lead time forecast locations

Weather Forecasting		Flow Forecasting	
Terminology	**Time Period**	**Terminology**	**Time Period**
Short range	12 hours – 3 days	Short lead time	1 – 10 days
Medium range	3 – 10 days		
Extended range	11 – 30 days	Medium lead time	10 days – 3 months
Seasonal range	3 month periods	Seasonal lead time	3 months – 1 year

7.2.1 Short-range precipitation forecasts

Short range rainfall forecasts (12 hours to 3 days) are typically established through high resolution local area models. These typically cover an area greater in size than a 100km by 100 km block, obtaining boundary conditions on the edges of the domain from global forecasting models. Typically forecasts from these regional models have a lead time of 2-3 days, with a grid resolution in the order of 10 km. For example the COSMO-7 model operated by the

COSMO consortium (which included the German Weather Service, Meteo-Swiss and other partners), has a domain of about 2000 km by 2000 km, with a grid resolution of 7 km. This model is run twice daily (at 00 UTC and 12 UTC), though it is projected to increase frequency to four daily runs in the near future. Typical parameters provided by such forecasts include precipitation, temperature (both dry and wet bulb), cloud cover, etc. Integration of such high resolution models in operational flow forecasting is common in large basins such as the Rhine basin (Werner *et al.*, 2005), as well as in small flashy catchments (Roberts *et al.*, 2008).

Most of these models do not simulate convection explicitly but in a parameterised form, although more recently, very high resolution local area models are being linked to hydrological forecasting models that do have capabilities for simulating convection explicitly (Zappa *et al.*, 2009). The ability to provide reasonable skill in forecasting convective precipitation is an important asset, as rapid response floods and flashy floods in the Zambezi basin are typically a result of convective rain storms typical of tropical rainfall.

Table 7.2 provides an overview of the basins for which, based on the requirements for short term flow forecasts, precipitation forecasts were identified as being required. Given that regional models that could provide such forecasts cover a large domain, the requirements are aggregated to the catchment scale.

High resolution models will be able to provide input data for up to 2-3 days ahead, which will cater well for forecasting in flashier catchments. However, to achieve a lead time of up to 10 days, the precipitation forecast will have to be extended using for example coarser resolution data from the global models discussed in the next section. Additionally, for the Kwando, Linyati and Chobe, data from such global models will suffice, given the lead times in the area.

Table 7.2.Forecast locations with data requirements for short lead time forecasts

Catchment	Basin	Temporal Resolution	Remarks
Kwando, Linyati and Chobe inside Namibia and Botswana	Upper Zambezi	Daily	These basins are dominated by Wetlands, and although a rainfall forecast is required, it need not be at a high resolution
Sanyati and Gwayi	Middle Zambezi	Sub-daily	These basins have a flashy response, thus requiring high resolution forecasts at sub-daily scales (e.g. hourly time steps)
Luangwa	Middle Zambezi	Sub-daily	Although the Luangwa basin is relatively large, it is know for its fast response.
Lower Zambezi	Lower Zambezi	Sub-Daily (Flash Floods)	Flash floods (mainly in tributaries) will require high resolution forecasts
Shire (downstream of Liwonde Weir to Zambezi confluence)	Lower Zambezi	Sub-Daily (Flash Floods)	Flash floods (mainly in tributaries) will require high resolution forecasts

7.2.2 Medium -range precipitation forecasts

Medium range rainfall forecasts (3 days to 10 days) are typically available from global numerical weather prediction centres. These models have a relatively coarse spatial and temporal resolution, with grid cells in the order of 25-40 km. Temporal resolutions of the model output is typically in the order of 3-6 hours. There are several global meteorological forecasting centres that operate such models, including the European Centre for Medium Range Weather Forecasting (ECMWF), the National Centre for Environmental Prediction (NCEP-NOAA), the UK Met Office, the German Weather Service, and several other Meteorological Agencies around the world. These global models have been applied for medium range forecasts in several operational and pre-operational forecasting systems; see Cloke and Pappenberger (2009) for an overview. Some centres, like ECMWF, provide their information for a limited number of weather variables and at a lower resolution for users outside Europe.

In Section 2.2.4., precipitation forecasts are identified as relevant for all forecast locations with medium lead time flow forecast requirements. Forecasts should therefore be available to cover in any case the Upper Zambezi basin, the Kafue and Luangwa in the Middle Zambezi, and also the Lake Malawi/Shire basin. In effect the extent of global forecasts means that providing coverage for the full Zambezi basin would be obvious. Lead time of these global forecasts is generally in the order of up to 10-14 days, with data in the latter half typically being at a coarser resolution both spatially (GFS) and temporally (ECMWF). Additional to precipitation data being relevant, at the medium time scale information on variables required to determine evaporation (temperature, humidity, and wind speed) will be useful. These parameters are available in all such forecasts, though at lower resolutions in many cases.

7.2.3 Extended range forecasts

Given the generally long natural lag times of the Zambezi River basin (>1 month at some locations), extended range forecasts would generally be expressed relative to the precipitation that would normally be expected for that particular period of the year (i.e. more or less rainfall than normal). The method employed is similar to that used for seasonal forecasting, as described in Section 7.2.4.

Forecasting at this time-scale is not extensively studied or well understood at present. This is largely attributed to the fact that this type of forecasting is arguably the most complex part of Numerical Weather Prediction (NWP) since the physical basis for this time-scale is not as clear as for medium-range and seasonal forecasts. Theoretically, the underlying logic to exercise this type of prediction resides on the assumption that the time range 11 to 30 days is still short enough that the atmosphere retains some memory of its initial state. Further, it is, presumably, long enough that the slowly evolving boundary conditions have an impact on the atmospheric circulation. Notwithstanding the above, forecasting systems for this time scale have been set up, among others in the South African Weather Service providing weekly forecasts of the departure of climate values for the period for the SADC region.

7.2.4 Seasonal Forecasts

To forecast flows in the Zambezi basin at the seasonal time scales (defined as a 3-month period), any models used will, as in the medium range forecasts, require inputs of precipitation and temperature over the forecast period. At the seasonal scale, however, providing forecasts that are reliable and provide added value when compared to climatology is very difficult. These seasonal precipitation and temperature forecasts are usually described as a departure from climate values for that 3-month period. Four general methods can be identified in seasonal forecasting of water resources:

1. Rainfall and temperature forcing for the full lead time of the seasonal forecast is sampled from the basin climatology. The forecast is initiated based on the conditions within the basin. This means that for basins where there are very long lag times such as in the Barotse and Kafue Flats floodplain the persistence of the initial conditions results in a forecast that has some added value over climatology. The input climatology can also be adjusted to reflect expectations of "wetter" or "dryer" conditions. Referred to as Ensemble Flow Prediction (ESP), this approach is used widely in water resources forecasting by the National Weather Service in the United States (Day, 1995);

2. Rainfall in Southern Africa shows strong correlation to fluctuations in Sea Surface Temperatures (SST) in the equatorial Pacific and tropical Western Indian Ocean (Rautenbach and Smith, 2001). This means that statistical models for seasonal forecasting of rainfall at seasonal time scales, using for example the observed and predicted El-Nino Southern Oscillation (ENSO) index could be used as viable predictors of changes in seasonal precipitation. Sea surface temperature (SST) forecasts are undertaken in South Africa and elsewhere, and used in the SARCOF (Southern African Regional Climate Outlook Forum) process to predict empirically the rainfall deviation from climate using such correlations (Landman and Mason, 1999);

3. Rainfall and temperature forcing for the full lead time are derived from a seasonal Atmospheric Global Circulation Model (AGCM). This forcing should be suitably derived from the AGCM through the process of dynamical (Kgatuke, *et al.*, 2008) or empirical (Landman *et al.* 2009) downscaling. This extends the concept of the global models used in the medium range weather forecasting, and is presumably best done with fully coupled atmosphere-ocean models,. The latter is computationally expensive and run by a few centres globally in an operational domain in the seasonal time-scale (e.g., Stockdale *et al.* 1998; Palmer *et al.* 2004; Graham *et al.* 2005; Saha *et al.* 2006; Molteni *et al.*, 2007). However, conventional AGCMs with statistical downscaling providing computationally affordable alternatives and with comparable skills currently; and

4. A fourth approach which is increasingly used is based on a multi-model ensemble prediction system. These systems combine ensemble forecasts produced by various AGCM and/or coupled ocean-atmosphere models from different centres to produce one big ensemble of forecasts as the basis for deriving seasonal probabilistic information through statistical methods on deviation from climatology (Landman and Beraki, 2010). There are a few such systems in the international domain, including from the International Research Institute for Climate and Society (IRI) and Eurosip (a conglomerate of three European models managed by ECMWF). Such an approach is used in South Africa to predict precipitation and temperature for three consecutive rolling seasons operationally on a monthly basis for Southern Africa. The multi-model ensemble predication system should also include a similar downscaling procedure as in Item 3 above when it is applied to flow forecasts. It has been noted before that a multi-model ensemble is nearly always better than any of the individual model ensembles (e.g., Doblas-Reyes *et al.* 2000, Krishnamurti *et al.* 2000), and is definitely the preferred methodology of these four options.

In the Zambezi basin the outputs from such seasonal flow forecasts are primarily of interest to the operators of the large dams, such as Kariba and Cahora Bassa. This means that the domain that needs to be covered by these forecasts includes the complete catchments upstream of these dams. As the lead times of seasonal forecasts are well beyond the (natural) lag times in the basin, these forecasts will need to provide full coverage for the upstream basins, which in effect means full coverage of the Zambezi basin.

7.2.5 Requirements for probabilistic forecasting

As mentioned earlier, precipitation forecasting, in particular for longer lead times generally contains considerable uncertainties. To incorporate such uncertainties, state-of-the-art forecasting systems utilise probabilistic forecasts of precipitation, sometimes in tandem with deterministic forecasts. In particular for the longer lead times, such as medium range forecasts, extended range forecasts and seasonal forecasts, probabilistic forecasting of precipitation should be used. In these, the prime variable of interest is the volumetric forecast such as for reservoir inflows, and the operators of the reservoirs will have the greatest utility if the forecasts provide an estimate of not only the expected volume over the forecast period, but also the expected error in that forecast. This has been shown in several research applications and operational forecasting systems to be of greater value than the deterministic forecast (Roulin, 2007, Renner and Werner, 2009). The Ensemble Flow Prediction approach (Day, 1995) equally results in a probabilistic forecast of flows, and is actively used in for example the Colombia River Basin in the North-western USA for planning reservoir operations. Global weather prediction models applied in operational flow forecasting at the medium range are often also ensemble models, such as the ECMWF Ensemble Prediction System (see Cloke and Pappenberger, 2009).

For short range forecasts (12 hours to 3 days) in the Zambezi basin, both deterministic and probabilistic inputs could be considered. However, at these shorter timescales the availability of high resolution ensemble weather models will likely be a constraint. Such short range probabilistic forecasts are as yet only applied operationally in a limited number of forecasting systems such as in the Rhine basin (Renner and Werner, 2009) and in Switzerland (Zappa *et al.*, 2009).

In forecasting in the Zambezi, particularly as rainfall is convective in nature and therefore quite uncertain, the uncertainty in the rainfall forecast should be considered explicitly. This is particularly so for flash flood guidance approaches, where the probability of receiving a given amount of rainfall that is needed to trigger a flash flood is evaluated. As a deterministic downscaling of precipitation through a high resolution ensemble model is not available in the region, statistical approaches such as post-processing of the deterministic forecast (Krystofewicz, 1992), or quantile regression type approaches can be applied to derive an estimate of the uncertainty in the forecast precipitation.

7.3 Current Precipitation Forecasting Capabilities

Precipitation forecasting is generally undertaken in each country in the Southern African region by the National Meteorological Service (NMS) of each country. All NMSs in the region are members of the UN World Meteorological Organization (WMO). Additionally regional forecasting capabilities are also available at the Regional Specialized Meteorological Centre (RSMC Pretoria) hosted by the South African Weather Service for WMO. Forecasting at the global scale is generally undertaken at the global meteorological forecasting centres. Through the WMO system all NMSs have access to products of numerical weather prediction models (NWP) and ensemble prediction systems (EPS) from the regional centre (RSMC Pretoria) and global meteorological centres (mostly from ECMWF, NOAA and the UK Met Office) that they use to guide their country forecasting processes.

In this chapter a brief review is given of (known) precipitation forecasting capacity relevant to the requirements for precipitation forecasting in the Southern African region.

Botswana

Weather forecasting is undertaken by the Department of Meteorological Services (DMS, http://www.mewt.gov.bw) in Gaborone. These provide a 3-day weather forecast available to the general public using available NWP and EPS products from the regional and global centres. DMS has also implemented a 12 km HRM weather forecasting model of the German Weather Service (Deutsche Wetter Dienst) which runs operationally daily to 72 hours. Its domain also covers the Zambezi Basin completely.

The DMS also provide a seasonal climate outlook. This national outlook is produced after the regional outlook, which is established through the annual Southern Africa Climate Outlook Forum (SARCOF), organised by SADC.

Malawi

The Department of Climate Change and Meteorological Services provides weather forecasts in Malawi. These are provided for 1-5 days ahead, using available NWP and EPS products from the regional and global centres. A version of the WRF model of NCEP is also run once a day at a 14 km resolution covering the country and is used mainly for aviation forecasting. As in other countries, a national seasonal outlook is established following the regional SARCOF meeting.

Mozambique

In Mozambique the Instituto Nacional de Meteorologia (INAM) provides weather forecasts (http://www.inam.gov.mz) using available NWP and EPS products from the regional and global centres. Weather forecasts are established using a high resolution local area model. This is the BRAMS model, which is based on the Regional Atmospheric Modelling System (RAMS - Pielke *et al*., 1992). This has been specially adapted to forecasting in tropical regions by Brazilian research agencies. The resolution of this model is 40 km and its domain is from 5°S to 33.5°S and 23°E to 57°E, thus excluding the Upper Zambezi Basin. INM also employ guidance from global models, including ECMWF and GFS, and also operate a weather radar station, but this is located in Southern Mozambique.

Namibia

Namibia Meteorological Service (http://www.meteona.com) provides a detailed one day weather forecast, as well as a five day weather outlook using available NWP and EPS products from the regional and global centres. Seasonal outlooks are provided based on the SARCOF discussion.

Zambia

Weather Forecasting in Zambia is undertaken by the Zambia Meteorological Department (http://www.zmd.gov.zm). Rainfall forecasts are provided for 1 – 7 days. Daily forecasts, as well as 7 and 10 day outlooks are prepared using available NWP and EPS products from the regional and global centres. Seasonal outlooks are provided based on the SARCOF discussion

Zimbabwe

Weather Forecasting in Zimbabwe is undertaken by the Zimbabwe Meteorological Services Department (http://www.weather.co.zw). Forecasts for several lead times are available including daily, 10 daily, monthly and a 3-monthly (seasonal) outlook). Available NWP and EPS products from the regional and global centres are used Seasonal forecasts over three regions in Zimbabwe with a lead time of 2-3 months are provided. These are made in August, before the rainy season, and updated in December. These forecasts are based on similar techniques as SARCOF (model output statistics) and are given in the form of anomalies.

Angola

The Instituto Nacional de Hidrometeorologia e Geofisica is the National Meteorological Service of Angola. No information on meteorological forecasting undertaken in Angola was, however, found to be available.

South Africa as Regional Specialised Meteorological Centre

Although South Africa does not contribute to the Zambezi basin, meteorological forecasting in South Africa is the most developed in the region. The WMO Regional Specialised Meteorological Centre for Southern Africa, RSMC Pretoria is hosted by the South African Weather Service (SAWS) and provides forecasting services to the NMSs in the SADC region. The RSMC Pretoria, as part of the World Meteorological Organisation (WMO), has close cooperation with the NMSs in the region and with various global weather centres. It uses and distributes both deterministic NWP and probabilistic global EPS products from the global centres (ECMWF, NCEP, UKMO), and also runs high resolution limited area models. This is currently the 12km resolution Unified Model of the UKMO (UM SA12), which runs daily at SAWS (two versions, an early no data-assimilation, and a later data-assimilation version) and covers the entire Southern African region, including the full Zambezi basin (see Figure 8.1.). Products of the UM SA12 are available to, and used by all NMSs in SADC. RSMC Pretoria, through SAWS, also provide regularly updated extended range (updated weekly for the next 11-30 days period) and seasonal forecast (updated monthly for the next 3 months) products to NMSs from its own multi-model EPS system operating on these time ranges. SAWS run a 12-member ECHAM 4.5 AGCM ensemble system to produce seasonal forecasts with a 1, 2 and 3 month lead-time. The SAWS is a member of the WMO Global Producing Centres (GPC) of seasonal forecast products.

In 2006, WMO established the Severe Weather Forecasting Demonstration Project (SWFDP) in SADC in which global centres (ECMWF, NCEP, UKMO) provide NWP and EPS products to the RSMC Pretoria, which then makes these products available through a closed web portal to all NMSs in the SADC region, including all those in the Zambezi River basin. On a daily basis RSMC Pretoria also prepare severe weather guidance products for the next five days using the available NWP and EPS information and distribute it through the closed web portal to all the NMSs in the region. The NMSs use the NWP and EPS and the guidance products to issue warnings in their own countries. They also use the NWP and EPS products available for their daily forecasting activities on short- and medium range including precipitation forecasts.

WMO is currently involved in establishing a Southern African Regional Flash Flood Guidance (SARFFG) system that will cover Botswana, Namibia, Zambia, Zimbabwe, Malawi, Mozambique and South Africa. RSMC Pretoria will be the regional centre for this flash flood warning activity. The region is delineated in thousands of small river basins of 200 km^2 on average. NMSs will receive real-time guidance from the SARFFG hydrological modelling system on the amount of precipitation (mm) needed to cause bank-full discharge in these basins in the next 6 hours. They will then apply their own forecasting of rain in the next 6-hours to determine if and where flash flood warnings should be issued.

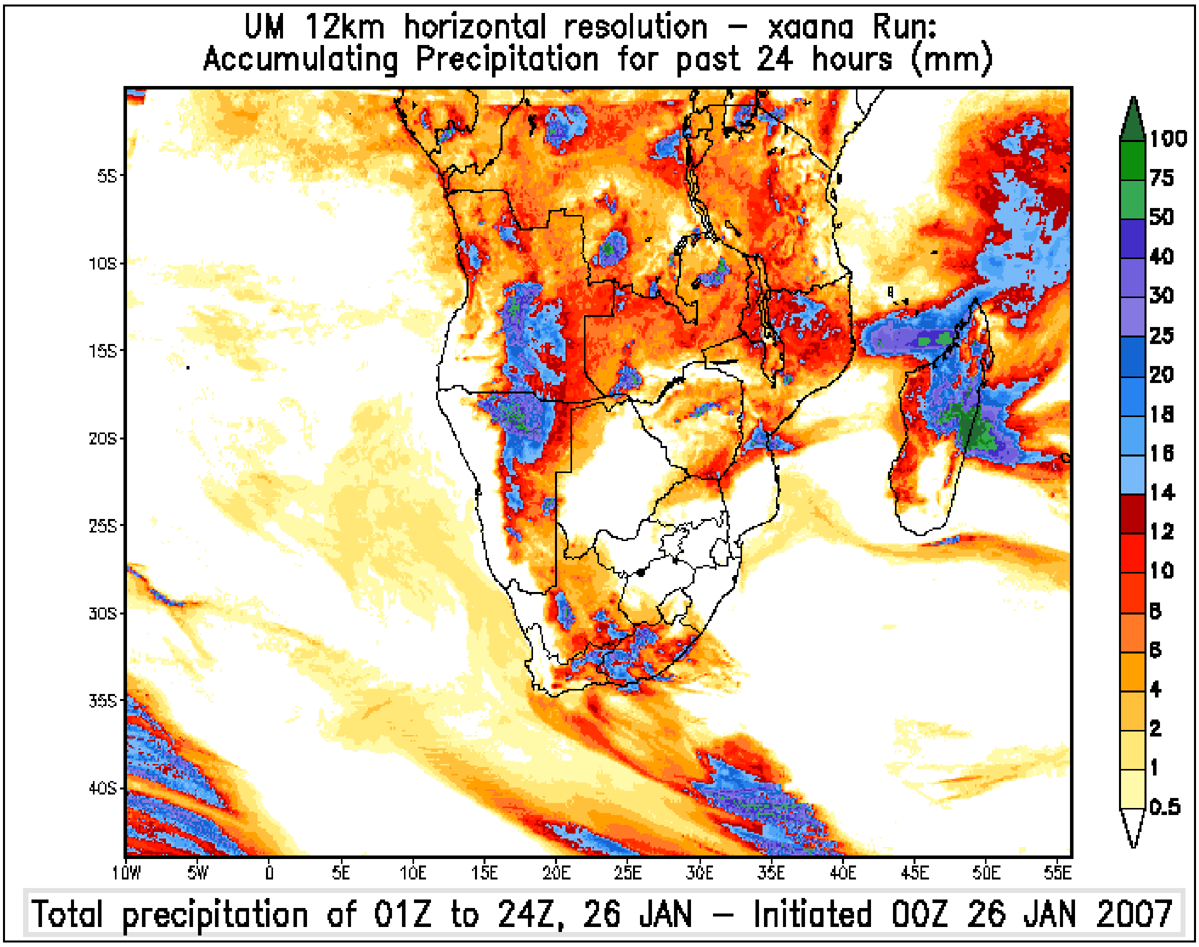


Figure 7.1. Snapshot of an accumulated 24h precipitation forecast from the regional meteorological model operated by RSMC

SADC Drought Monitoring Centre

This centre, which was previously in Harare, Zimbabwe was recently moved to Gaborone in Botswana. It provides seasonal outlooks for precipitation. One of the most important activities organised under the auspices of SADC, is the SARCOF meeting. At this meeting meteorologists and climate scientists from all SADC countries convene, and discuss the seasonal precipitation outlook. These outlooks are informed by (probabilistic) information from the global centres, as well as well as status and outlooks of SST anomalies. A subjective consensus forecast is produced as an official statement. The SARCOF forecasts are updated only once in the summer season, around December.

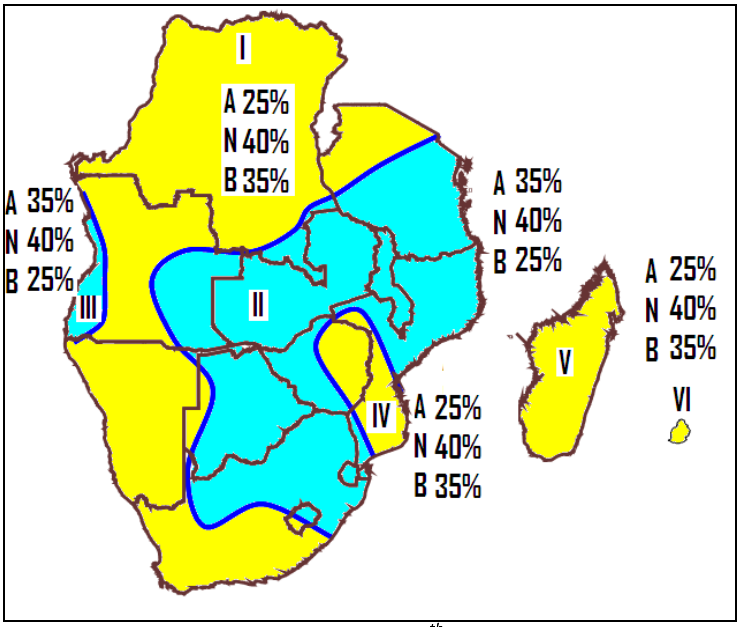


Figure 7.2. Example of the precipitation outlook in the 12th SARCOF meeting, showing the probability of precipitation being: above normal (A), normal (N), or below normal rainfall (B) for the January to March period of 2009.

Global Forecasting Centres

There are several operational forecasting centres that run global meteorological models operationally. Such models can provide useful inputs for medium range precipitation forecasting across the Zambezi basin. The resolution of such models is quite coarse (25-40km grid cells), with temporal resolutions in the order of 3-6 hours. Generally such models would not provide sufficient dynamics to represent rainfall at short lead times over smaller basins, but for larger basins and longer lead times these models can provide reliable forecasts (Renner & Werner, 2009). Many of the operational agencies provide both deterministic products, as well as probabilistic products (based on EPS) that can be used in operational (probabilistic) flow forecasting. Examples of such centres are the European Centre for Medium Range Weather Forecasting (ECMWF), the National Centers for Environmental Prediction (NCEP) in Washington DC, and the UK Met Office (UKMO) in Exeter in the UK. Forecast lead times are in the order of 10-16 days.

Availability of data for the area of interest depends on the institute, with an agreement being required for some. Such global forecasts are already actively used by the meteorological services across the region to establish forecast guidance (e.g. RSMC Pretoria, SARCOF), as well as providing boundary conditions for regional models (e.g. the UM SA12 model run at RSMC Pretoria).

7.4 Recommendations for improving precipitation forecasting

The discussion of the current capabilities shows that for most of the countries in the Zambezi basin the National Meteorological Services (NMS) have an established service in providing weather forecasts based on Numerical Weather Prediction (NWP) and Ensemble Prediction System (EPS) products of global and regional centres. The availability of local Numerical Weather Prediction products that can be used to derive inputs for hydrological models for flow forecasting is limited to that of RSMC Pretoria (using the UM SA12), INAM in Mozambique (using the low resolution BRAMS not completely covering the Zambezi Basin), and the HRM model of the Botswana Department of Meteorological Service (DMS, running at 12 km). Based on the discussion above, recommendations are established for the provision of precipitation forecasts to establish flow forecasts at the desired lead times across the Zambezi basin.

7.4.1 Short-range precipitation forecasts

Short range (12h – 3 days) precipitation forecasts to provide precipitation inputs for the short term flow forecasts will require high resolution local area models covering the areas for which these forecasts need to be provided. Clearly the UM SA12 model at RSMC Pretoria covers the full Zambezi basin, as does the HRM 12 km model in the Botswana DMS. The BRAMS model operated by INAM in Mozambique does not cover the Upper Zambezi Basin., and is currently also of comparatively low resolution. The establishing of regional precipitation forecasting capabilities for such high resolution forecasts requires significant investment in staff and hardware/infrastructure. It is therefore not recommended to establish independent regional precipitation capabilities in support of flow forecasting in the Zambezi. Rather it is recommended to strengthen existing capabilities.

As the UM SA12 model (RSMC Pretoria), the Botswana HRM (DMS) and the BRAMS model (INAM) appear to be the only operational regional models in the southern African region, these have all been assessed. The role of RSMC Pretoria as a regional forecasting centre, however, would mean that it would be closer to the mandate of the organisation to provide such forecasts as primary input to the flow forecasts. The reliability of the forecasts made at these three centres should, however, be carefully assessed to establish how well these perform over the Zambezi basin. It is recommended to use all three products in flow forecasting, where forecasts should be made using each of the products. Clearly a preferred model should be indentified based on an assessment of performance. However, the use of all three models in flow forecasting is highly beneficial and should be considered as it provides insight in the variability due to different models being used. Additionally, should one of the products not be available on a given day, and then the other can act as a backup.

Although all three products are recommended to be used, it would also be logical to pass the Botswana DMS and INAM forecasts through RSMC Pretoria. In this an additional quality check on the forecast can be made. For example, if the BRAMS model is consistently outperforming the UM model on tropical convection, the upgrading of the latter to be more applicable in the tropics could then be recommended.

7.4.2 Medium range precipitation forecasts

At the medium range (3-10 days), none of the meteorological services departments in the Southern African Region has the capabilities to provide any NWP model as inputs to the flow forecasts. (Probabilistic) NWP products should be obtained from the global centres (ECMWF, NCEP, etc). Again the reliability of these forecasts in the Zambezi basin will need to be assessed carefully to ensure these are not biased.

It is recommended to use probabilistic (ensemble) rainfall forecasts to ensure that the resulting flow forecast, which is used to calculate the inflow volume to the reservoirs, provides not only an estimate of the inflow, but also an indication of how uncertain that estimate is. Additionally global forecasts should be considered from multiple centres (e.g. ECMWF, NCEP).

It is recommended that the RSMC Pretoria has a central role in dissemination of these global forecasts, and it is recommended that the RSMC Pretoria is strengthened to fulfil the role of being a central agency for provision of precipitation inputs for hydrological forecasting in the region.

7.4.3 Seasonal precipitation forecasts

For precipitation forecasting at the seasonal time scale (both extended range 11-30 days and seasonal 3 months), the ECHAM 4.5 ensemble prediction system run at RSMC Pretoria could be used to provide inputs to the forecasts. This system runs once a month providing seasonal precipitation information with a 1, 2 and 3 month lead time, and once a week for 11-30 day precipitation anomalies.

To derive a seasonal water resources forecast, the hydrological models for the Zambezi basin will require quantitative precipitation inputs for the full period. The extended (11-30 days) and seasonal (1, 2, 3 months) lead time forecasts provide only the expected precipitation anomalies, with respect to the climatology.

A simple approach is recommended to derive the precipitation and temperature climatology in the basin. In the ESP approach (Day, 1995) available reference climate data are re-sampled to derive an ensemble of inputs over the forecast period of for the Zambezi basin. These can be used as inputs to the hydrological models, conditional on the catchment conditions and reservoir storage levels at the start of the forecast. Prior to running the models, the precipitation values representing the climatology are adjusted in accordance with the expected anomaly as predicted by the extended and seasonal meteorological forecast.
Currently the SARCOF outlook is established only once a year. It is recommended that the information used in the forecasting system for establishing the seasonal forecast is also available to the SARCOF, thus ensuring consistency between the two sources.

7.4.4 Summary of recommendations on improvements to precipitation forecasting

It is clear that there is an established climatology community in the Southern African region. The WMO Regional Specialised Meteorological Centre for Southern Africa, RSMC Pretoria, as well as the National Meteorological Centres (NMCs) in most countries within the Zambezi have an established cooperation, as well as sufficient forecasting capabilities to provide the required inputs for flow forecasting in the Zambezi basin at the Short, Medium, and Extended to Seasonal Range time scales. These centres are additionally actively pursuing the continued improvement of forecasting capabilities. RSMC Pretoria, as well as the NMCs additionally through WMO are in close collaboration with the established global centres.

To ensure precipitation inputs are available for flow forecasting in the Zambezi basin, the following recommendations are made:

- Precipitation forecasting capabilities should not be independently developed, but instead, close collaboration should be established with the RSMC Pretoria, which as the WMO regional forecasting centre, can provide the required information. This collaboration should include not only the transfer of forecast data, but also the ability for forecasters responsible for establishing a flow forecast in the Zambezi to actively discuss with meteorological forecasters at RSMC Pretoria;
- The link between the NMCs and flow forecasts made should be through the RSMC Pretoria. This will allow the established network to be utilised, as well as create a clear path through which precipitation inputs are obtained;
- A flexible approach to the use of precipitation data needs to be adopted. Both RSMC Pretoria and the NMC's are continuously improving forecast methods and skill, and these improvements should be available to the flow forecasting system as soon as these become operational; and

- It is recommended that the information used in the flow forecasting system for establishing seasonal forecast in the Zambezi basin, which if as recommended uses the forecast made at RSMC Pretoria with the most up-to-date meteorological forecast methods is also made available to the SARCOF. This will provide added insight to those partaking in the SARCOF process, as well as ensuring consistency between the SARCOF outlook and any seasonal forecasts emanating from the flow forecast system.

8 Requirements for establishment of a flow forecasting centre

8.1 Introduction

In order to achieve the goals of improving the management of the water resources in the Zambezi basin, the proposed flow forecasting system will provide key information in managing these resources to different stakeholders. The information provided will be used by these stakeholders to inform the operational process; for example, through reliable forecasting at the medium and seasonal time scales, Dam Operators will better anticipate future inflows, allowing them to optimise the use of hydropower generating capabilities, as well as possibly implementing environmental flow releases, based on a complete understanding of how this simultaneously impacts on other functions of the reservoir, such as hydropower production and flood control; disaster management units will obtain information from the forecasts on flood flows from reservoirs as well as from unregulated tributaries, allowing them to improve their response to flood events.

The above examples show that the basis of the improved management of the basin is the sharing of information between stakeholders. This information is provided through integration of hydrological and meteorological data from across the basin, through the integration of hydrological forecasting tools to predict future flows and water levels, and through integration of precipitation forecasts that provide information on expected rainfall, and allow reliable flow forecasts to be made at the required lead times to inform the operational processes of the stakeholders.

To attain the objective of improved management of the water resources of the Zambezi River basin, it is a prerequisite that all information be available in an integrated manner. However, this integration is a complex task, requiring significant investment in expertise and infrastructure. Concentrating these efforts in a centralised forecasting centre will allow for a natural integration and sharing of information. A dedicated team of experts at this central forecasting service will ensure efficient investment in human resources and reduce investments in forecasting, modelling and infrastructure.

The approach of establishing centralised forecasting has been taken in several other large (trans-boundary) river basins in the world. Two examples are provided in Box 1 and Box 2 below. The example of the Mekong River Commission (MRC) shows how a centralised forecasting service has been established in a large trans-boundary basin through cooperation of the riparian countries in the basin. As this centre has been established under the auspices of the MRC, it is recognised by all stakeholders across the basin. In another example, the Northwest River Forecast Center in the United States shows that through a centralised forecasting service, the community of stakeholders can interact and share information. This community includes stakeholders such as power companies and environmental groups.

The establishment of a central forecasting centre will allow information on current and future flows in the Zambezi basin to be shared to the benefit of the stakeholders. By establishing this as a subsidiary of ZAMCOM, with the objective of providing unbiased information openly to all stakeholders, the benefits of information sharing can be achieved. Additionally, a flow forecast centre can serve as a centre of excellence in operational management of the Zambezi basin, providing a facility that not only supports exchange of data, but also exchange of experts between stakeholders, and to facilitate research on improving water resource management in the basin.

Box 1: Operational Forecasting in the Mekong River Basin

The Mekong River Commission (http://www.mrcmekong.org/) was established as the River Basin Organisation for the Mekong River. The commission was formed in 1995 by an agreement between the governments of Cambodia, Lao PDR, Thailand and Viet Nam, with the four countries signing "The Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin", and agreeing on joint management of their shared water resources and development of the economic potential of the river. China and Myanmar, became dialogue partners in 1996, and now cooperate with the other riparian countries through a cooperation framework.

One of the key activities of the Mekong River Commission is the provision of operational forecasting across the Mekong River basin. This is provided by a central forecasting service, established at the Regional Flood Management and Mitigation Centre in Pnomh Phen, Cambodia. The aim is to inform the public and stakeholders about current and/or forecasted hydrological conditions in the Mekong basin and to convey this information in an understandable way. Information from the forecasting system is supplied as a service to the governments of the MRC Member States so that it may be used to inform existing national disaster forecast and warning systems.

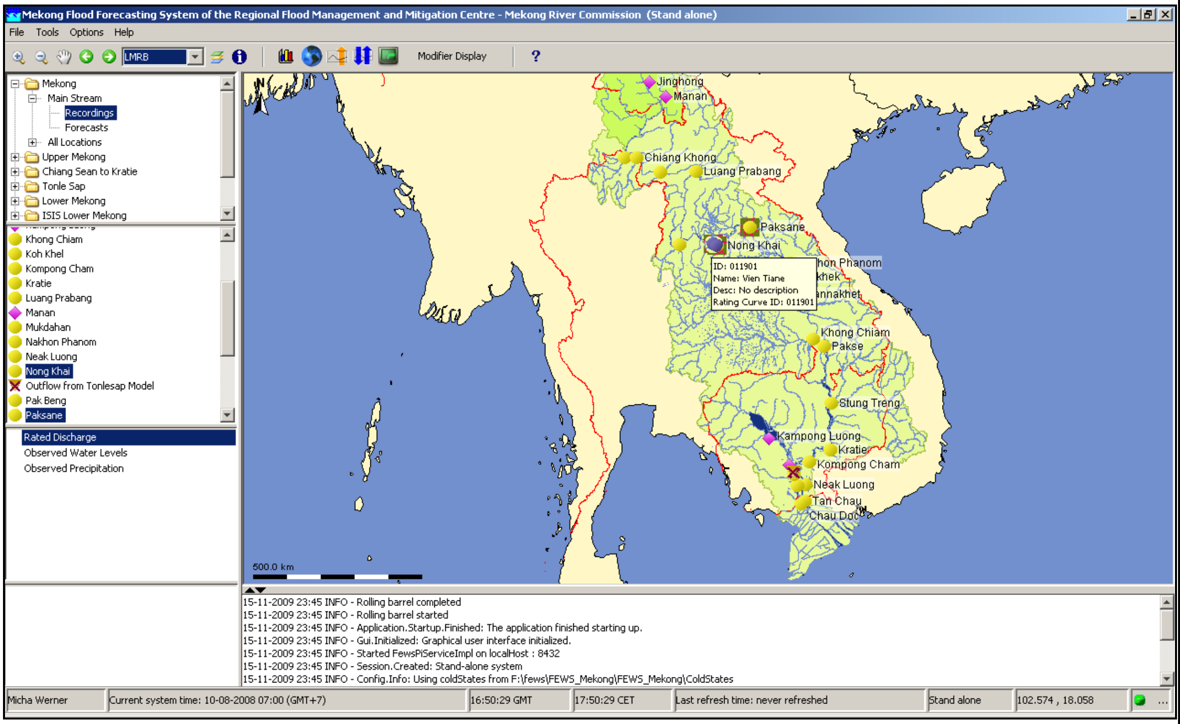


Figure 8.1 Main display of the Mekong River Commission Flood Forecasting System. This integrates models and observed hydro-meteorological data, as well as satellite rainfall estimates and precipitation forecasts across the basin in a single system, and provides outputs in the form of forecast data and bulletins to stakeholders. Forecasts reports and bulletins are published on a publicly accessible website (http://ffw.mrcmekong.org/overview.htm). The forecasting system has been implemented using the Delft

Box 2: Operational Forecasting in the Northwestern United States

Flow forecasting for all river basins in the United States is the mandate of the National Weather Service (NWS), a part of the National Oceanic and Atmospheric Administration (NOAA). The hydrological forecasting service is provided through thirteen regional offices. One of these, the Northwest River Forecast Center in Portland, Oregon (http://www.nwrfc.noaa.gov/), provides forecasts for the Columbia River Basin, as well as several other smaller basins in the North-western United States. The Columbia River Basin flows through Canada and the United States and is one of the most developed basins in the world in terms of hydropower potential. There are some 82 major hydropower reservoirs in the basin with an aggregate generation capacity of 33GW, as well as several smaller facilities. The management of the water resources in the basin requires close cooperation of the different stakeholders, including reservoir operators, power companies, environmental flows, and the Army Corps of Engineers.

The Northwest River Forecasting Center (NWRFC) caters to the needs of these stakeholders through a range of dedicated forecast products, including Flood Forecasts, Reservoir Inflow Forecasts, Recreational Forecasts, Forecasts for Commerce & Navigation, Water Supply Volumetric & Peak Flow Forecasts, Drought Bulletins, and Statistical and Probabilistic Products. Recently the NWS has adopted the Community Hydrological Prediction System (CHPS), which provides a platform through which the community of stakeholders can interact, thus enabling the forecasts to meet their needs. The open approach also allows a rapid integration of new forecasting methods and data and interaction with universities and research groups, greatly reducing the time from research to operations.

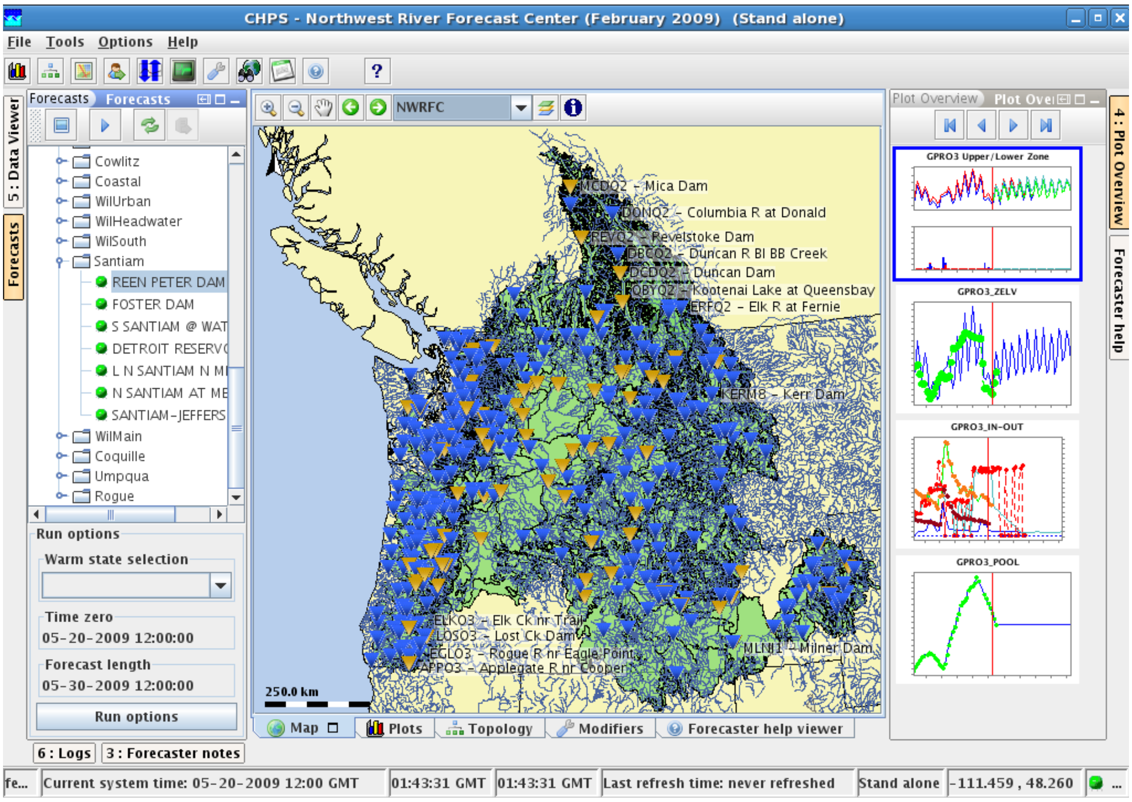


Figure 8.2 Main screen of the Community Hydrological Prediction System (CHPS) now operational at the Northwest River Forecast Center. This shows the extent of the river basin, as well as coverage of hydrological gauges. Each of the orange triangles represents the location of a major (hydropower)

8.2 Scoping options for location of forecasting centre

A key issue for the proposed establishment of a flow forecasting centre is the selection of a suitable host location. A number of important practical, political and capacity issues of a general and technical nature will need to be considered as part of the selection process. Some of the more important issues are listed below:

1) *Practical Issues:*

- Internet connectivity:- speed and reliability;
- Electricity power supply;
- Existing ICT infrastructure and staff;
- Ground and air transport connectivity; and
- Costs of operations.

2) *Political Issues:*

- Independence – the opportunity to operate as an independent institution without interference;
- Institutional mandate (recognition);
- Legal status / liability; and
- Political climate.

3) *Capacity Issues:*

- Human capacity; and
- Connections with knowledge institutes and universities.

In addition to the above, and particularly given that the purpose of the proposed flow forecasting centre will be closely linked to the mandate of ZAMCOM, the geographical and logistical relationship between the centre and ZAMCOM will require careful consideration. Two main options exist for selection of a location for the flow forecasting centre with respect to ZAMCOM: the centre could either be housed at the same location as the permanent ZAMCOM Secretariat, or at an entirely independent location. Each of these possible options would have certain advantages and disadvantages.

Locating the forecasting centre in the same building as the ZAMCOM Secretariat would greatly facilitate communication between these authorities and could also result in cost savings with respect to rent and ICT infrastructure. However, at the same time this arrangement could hinder the establishment of the flow forecasting centre as the ratification of the ZAMCOM Agreement by all basin states is a political process without any fixed timeframe, while selection of a location for the flow forecasting centre and the timeframe for establishment should ideally be based on technical issues. In addition, situating the flow forecasting centre and the ZAMCOM Secretariat at the same location would concentrate the risks of responsibilities of two significant entities in one country, while splitting them would spread these risks and responsibilities. Situating the forecasting centre at an independent location would therefore allow the establishment of the centre to proceed according at a timeframe dictated largely by technical and logistical requirements.

Although the technical criteria listed above should be used for selection of possible locations for the flow forecasting centre, the final decision on a location should be made by the basin states. It is therefore recommended that consultation with each of the basin states is first undertaken to identify possible locations for the centre. Following consultation with the basin states, an evaluation of each of the identified locations against the technical criteria listed above could be conducted resulting in a ranking of preferred locations. At the end of this process, the basin states could decide on the final location, giving due importance to the technical criteria.

8.3 Structure of the flow forecasting centre

The main objective of a fully fledged operational forecasting centre is to integrate information over the basin and distribute it to all stakeholders. It should therefore cater for sharing of information between stakeholders, and provision of operationally critical information to key stakeholders. This section proposes an overall structure for the forecasting centre that serves this objective. The presented structure includes a framework for data collection and archiving, the forecasting system itself, and staffing requirements. A consideration of potential locations for the flow forecasting centre is presented in Section 8.2.

Generally, a forecasting centre requires:

- A **flow forecasting system** that integrates all information and establishes new information, for instance by running hydrological and hydraulic models. Information is typically stored in an operational database as well as an accumulating historical digital archive;
- **Staff** to run the forecasting system on a 24/7 basis who would be capable of upgrading and improving it. Provision of a database and hardware maintenance of the systems; and
- **Dedicated staff** with the requisite experience and qualifications to run and maintain the forecasting centre.

In the following sections the essential components of the flow forecasting centre are described in more detail.

8.3.1 Structure of flow forecasting system

The forecasting system itself should contain three major components, which are schematised in Figure 9.3. It has been assumed here that the flow forecasting centre will be linked to the ZAMCOM Secretariat (see Section 8.2).

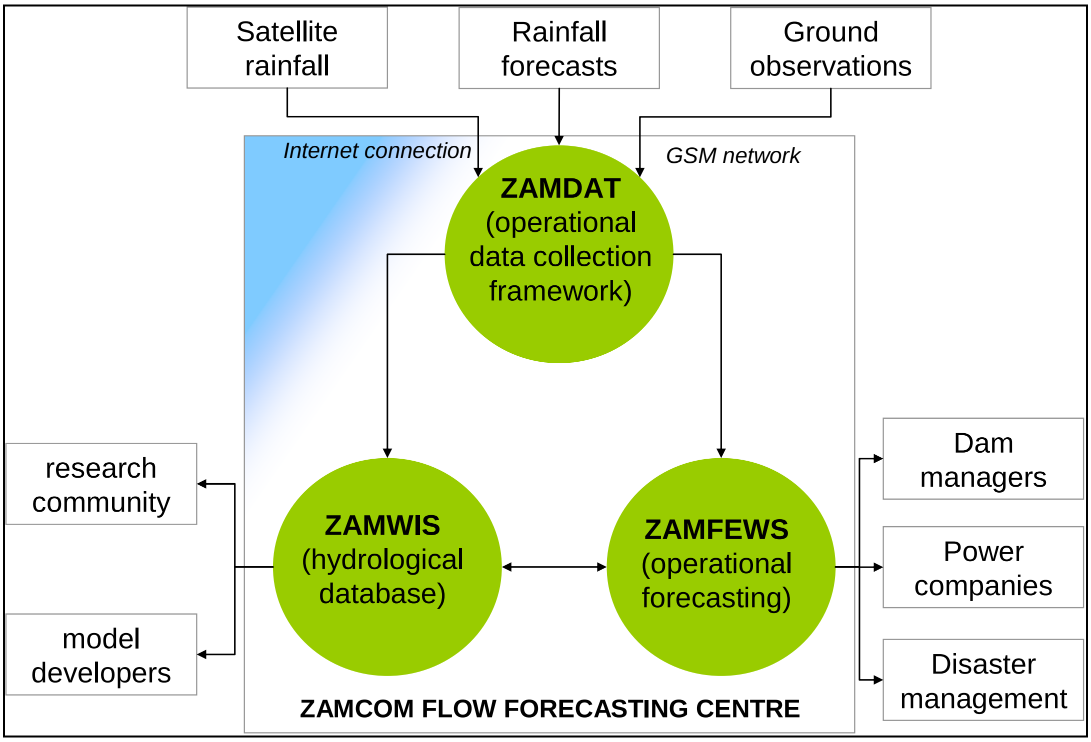


Figure 8.3. Recommended structure of the forecasting system.

ZAMDAT: ZAMDAT represents the near real-time data collection framework for operational collection of ground observations, satellite rainfall and rainfall forecasts. Technically, ZAMDAT consists of a dedicated connection with the GSM network for collection of ground observations as described in the recommendations on improvements to the precipitation and flow measurement networks, and a broadband internet connection to download real-time satellite rainfall and rainfall forecasts. For downloads of operational rainfall forecasts, about 100 MB of data needs to be transferred on a daily basis. For satellite rainfall, a maximum of about 25 MB per day needs to be downloaded. The internet download speed needs to be fast enough to ensure this download can be achieved within reasonable time. Details on data management are given in Section 9.4, hardware and network requirements for the data collection framework are outlined in Section 9.5.

To allow for real-time data collection, it is crucial that responsible entities of member states (i.e. National Hydrological Services (NHSs) and National Meteorological Centres (NMCs)) agree on procedures for real-time data collection. It is recommended that such procedures are established as an addendum under the ZAMCOM agreement. This addendum should include procedures for timely transmission of data and should underline the responsibility of NMCs and NHSs to collect and transmit data.

ZAMWIS: an operational hydrological archive for the Zambezi basin is required. This database should be continuously augmented by data from ZAMDAT as described above. The Flow Early Warning System (ZAMFEWS, described below), would use the latest records, stored in ZAMWIS to make forecasts and transmits model results back to ZAMWIS for archiving. Therefore, ZAMWIS would contain historical time series of observations, collected throughout the basin, as well as forecast data. This archive should be used for performance assessments of the system and to improve or (re)calibrate models. Furthermore, such an operational database would allow users to better comprehend the Zambezi basin water resources over long time scales and could be used to design new infrastructure. The current ZAMWIS was originally designed as a continually updated database for observed data in the Zambezi River basin and it is recommended that the current ZAMWIS is strengthened so that it can fulfil this role. This would require that ZAMWIS is operationally augmented with new records coming from both

ZAMDAT and ZAMFEWS. More details on data storage, acquisition and management are given in Section 9.4.

ZAMFEWS: ZAMFEWS would represent the forecasting shell of the flow forecasting system. This shell would integrate existing models that would be suitable for flow forecasting with the identified stakeholder requirements, as well as new models developed to fill the gaps in current model capabilities in the basin. Within ZAMFEWS, the latest information, collected by ZAMDAT and stored in ZAMWIS, would be used to run models and both observed and forecast data would be integrated into dedicated graphical displays, which could be viewed by accredited users in real-time.

ZAMFEWS should be based on an operational forecasting platform that allows for integration of many different existing or new models and data. The forecasting software should be flexible enough so that the staff of the forecasting centre can incorporate new model capabilities or data sources in the basin, as well as any new model developments or new data requirements. The software should provide capabilities that allow users to access forecast data interactively from their own (remote) offices.

8.3.2 Staffing requirements

A team of specialists would be needed at the flow forecasting centre to form the operational forecasting team. , presents a proposal on the staff complement for the forecasting centre, which would be needed to provide fully operational service 24 hours per day and 7 days per week. Although the requirements are described in some detail, they should be regarded as an approximate overview rather than a definitive staff composition.

Table 8.1. Staffing requirements for the flow forecasting centre

Staff	Number	Role in flow forecasting centre
Senior hydrologists	2/3	Senior hydrologists would know the forecasting system in detail. They would be aware of configuration options and would be able to change these. In the dry season, the senior hydrologists would coordinate system and database maintenance. Furthermore, they would assess the performance of the system each year to identify the potential for improvement of the data and models used. Therefore, they would follow up and implement new data sources, new models and other opportunities to improve the flow forecasting system.
Duty officers (not full time)	5/6	The pool of duty officers would consist of junior hydrologists. They would not be fully aware of details such as configuration options, but could work with the operational system in real time. The duty officers would operate the forecasting centre 24/7 during the wet season. And would be able to actively disseminate information from the system.
Hydrometeorologists	1/2	The hydrometeorologist would form the link between the meteorologists, who would provide weather forecast information, and the flow forecasting system. He/ she would ensure good communication between meteorological forecasts and hydrological forecasts. To this end, he/ she would keep in close contact with the Climate Services Centre, RSMC Pretoria, as well as National Meteorological Centres through which precipitation forecasts would be provided.
Database specialist	1	The forecasting centre would have an operational forecast database within ZAMFEWS and an operational archive (ZAMWIS). Both would need to be maintained. This work could also be outsourced to a specialised company.
ICT specialists	1/2	ICT specialists would be responsible for the hardware and data communication systems. The proper status of hardware is of crucial importance to guarantee 24/7 operational forecasting. Outsourcing this role would be a risk, which is not considered advisable.

Note that duty officers do not need to be on duty 24/7 during the dry season. In this period, the duty officers could work on maintenance, performance assessments, and training. Alternatively, the forecasting centre could be combined with other activities in the basin, which would provide more scope for allocating work in the dry season to other issues besides forecasting.

8.3.3 Establishing a centre of Excellence

To maintain and improve the capacity of the forecasting team and to establish ownership of the system with stakeholders in the basin, the establishment of a 'centre of excellence' within flow forecasting centre is recommended. Staff of all involved stakeholders could be seconded to this centre. This could be for short periods, in order to (re)establish their involvement and to identify arising needs of the forecasting system, or for a one-year term, wherein the stakeholder staff would be trained to use the forecasting system and would be made part of the duty forecasting team during the wet season. This would allow these staff to have a good understanding of the flow forecasting system and the benefits of the information that it would provide to the daily operations of the stakeholders that they represent. Such staff exchange should be financed by Member States. This would greatly enhance ownership of the system with the stakeholders in the basin and would improve each stakeholder's understanding of the objectives of other stakeholders. Furthermore, the centre of excellence could provide the backbone for research into new forecasting methods and their efficient implementation in the flow forecasting system, through close connections with universities, research centres and knowledge networks.

The centre of excellence could encompass the following facilities:

- Training facilities and programmes within the flow forecasting centre;
- Programmes to exchange staff between stakeholders and the forecasting centre; and
- Connections with universities and regional knowledge networks such as WaterNet.

8.4 Data storage, acquisition and management

As mentioned in Section 9.3, it is recommended that the forecasting system contains two separate database systems, one dedicated to the operational flow forecasting process itself and one to the archival storage of data collected from the recording stations in the basin collected data and forecasts. In this section the importance of these databases and a proposal for how the hydrological archive could be implemented are discussed.

Once an operational forecasting system is in place, a continuous flow of data and forecasts would become available. It would not be feasible to continuously augment the database, belonging to the operational forecasting system (ZAMFEWS) with these data streams. This would result in a continuous growth of the ZAMFEWS database, resulting in slow accessibility and eventually stalling of the forecasting process. In an operational forecasting database data are generally stored as a rolling archive with each dataset being stored for a specified period.

Together with this real time database, a permanent hydrological archive would be required. This integrated archive of data on water resources information and previous forecasts could serve several purposes such as:

- Performance assessments of the forecasting system based on hindcast information and historical validation data. Such performance assessments are important for identifying areas where system improvement is required;

- Performance assessments of (new emerging) satellite rainfall products, by ground-truthing with historical time series of ground rainfall data;
- Establishment of a comprehensive archive of observed data for the basin. This should be quality controlled and could be used for assessment of water resources in the basin, as well as (re)calibration of models; and
- Establishment of quality controlled long time series for research, strategic planning or design of new infrastructure.

The Zambezi Water Information System (ZAMWIS) was designed to fulfil in particular the third and fourth purpose, by providing a comprehensive online database of historical records of rainfall, water levels, flows and literature about the Zambezi and its water resources. ZAMWIS enables the legitimate sharing of information between member states of the Zambezi, which is the foundation for better management of the Zambezi's water resources and trust and cooperation between member states and stakeholders.

Although ZAMWIS is currently inaccessible through the internet and is not operationally augmented with newly collected records from the basin's member states, it provides a strong basis for an operational hydrological database. It is therefore recommended that ZAMWIS is upgraded into a fully operational hydrological database. The following requirements should be met to make this possible:

- Member states would need to agree on real-time sharing of flow and precipitation observations. This should include agreements on daily transmission, standardized data formats and permissions to share data. This agreement could be legitimised by including it as an addendum in the ZAMCOM agreement (see also Section 9.3.1);
- The current ZAMWIS would need to be extended to ensure that it would provide the necessary capabilities for archiving forecast data as made with ZAMFEWS;
- The current ZAMWIS would need to be extended to include rigorous quality control procedures that would ensure datasets collected from across the basin are consistent.
- The current ZAMWIS database would need to be converted into standardized and internationally accepted formats; and
- The upgraded ZAMWIS database would need to be established and operationalised at the flow forecasting centre as this is the location where the data from all member states could be collected centrally on a daily basis. The upgraded ZAMWIS could be established at the Interim ZAMCOM Secretariat as a first step towards the fully fledged flow forecasting centre.

8.5 Requirements for hardware infrastructure and communications

Establishing an operational forecasting centre will require appropriate infrastructure in terms of ICT Hardware and Software, as well as adequate communications systems. It should be noted that while the requirements provided are quite specific, these should be considered as an indication of the scope of investment, rather than a definitive list. It should also be noted that the requirements are based on recommended infrastructure. Prior to implementation, requirements on system availability and resilience, response speed and other operational considerations would need to be translated into detailed hardware specifications.

The requirements for hardware infrastructure are detailed in the tables below. These have been established using the system design of the Delft FEWS Forecasting system, although these can be considered typical of this scale of operational forecast system. It has been assumed that a fully operational system would be developed at a central forecasting location, where this system could also be used from remote locations (e.g. from the offices of stakeholders).

Table 8.2. Possible configuration of hardware at central forecasting location (includes hardware for remote access by stakeholders)

Item	Suggested configuration (vendor/model)	Number	Remarks
Central Server	HP ProLiant DL380 Server	1	Central server for operational system
Model Server	HP ProLiant DL360 Server	1	Server for running models (parallel)
Database Server	HP ProLiant DL360 Server	1	Server for controlling database (Note. This could be shared by other applications, such as an operational hydrological database)
Mass storage with redundant backup facilities	RAID Array (2 TB)	1	Server for controlling database (Note. This could be shared by other applications, such as an operational hydrological database)
Rack system		1	Rack for mounting hardware
Operator Terminals	Standard Desktop clients (include 21" Dual Screens)	3	Operator terminals at forecast centre
Backup/Remote Laptops	Standard laptops	3	Laptops for backup and remote operation
Operator Terminals	Standard Desktop clients	15	Operator terminals at stakeholder offices (assumed 15)
Printers, Plotters, Fax Machines, telephone lines			
Overhead projector	Standard projector	2	Used for facilitating forecast discussions and for training room
Training room clients	Standard Desktop clients	10	Equipment for training room
Backup generator	Standard backup generator facilities	1	Backup power supply for forecasting centre
UPS Systems	Standard UPS Systems	3	UPS Systems for central servers, RAID array and operator terminals

Table 8.3. Possible configuration of software additional to standard available office applications at central forecasting location

Item	Suggested configuration (vendor/model)	Number	Remarks
Application Server	JBoss	1	Free Standard Internet software
Web Server	Apache Tomcat	1	Free Used for hosting web sites
Database Software	Options Oracle MS SQL PostrgeSQL	1	Free (PostgresQL only) Database software (Note. This could be shared by other applications, such as an operational hydrological database)

Table 8.4. Possible configuration of communication equipment

Item	Suggested configuration (vendor/model)	Number	Remarks
Internet (Dedicated Broadband Lines)		1	
Satellite GSM receival stations and costs	TS2 Eutelsat W3A or NSS7	1	These would be required for backup at central location as well as at key data locations

8.6 Estimation of costs for forecasting centre

Approximate costs for establishment of a flow forecasting centre based on current, 2010, prices have been estimated as part of this project. These have been divided into capital costs and operating costs. The expected capital costs include office furniture and ICT hardware, while operating costs include staff salaries, building rental and other running costs. and below list the main expenditure items and the associated estimated costs.

Table 8.5. Flow Forecasting Centre Capital Investment Cost

Item	Number	Indicative Price (USD)	Amount (USD)
Office furniture	Lump Sum	$30,000	30,000
Central Server	1	$13,800	13,800
Model Server	1	$12,000	12,000
Database Server	1	$16,300	16,300
Mass storage with redundant backup facilities	1	$25,800	25,800
Rack system	1	$4,300	4,300
Operator Terminals	3	$2,600	7,800
Backup/Remote Laptops	3	$3,000	9,000
Operator Terminals	15	$1,800	27,000
Printers	2	$16,300	32,600
Plotter	1	$17,200	17,200
Fax machine	1	$1,200	1,200
Overhead projector	2	$2,600	5,200
Training room clients	10	$1,500	15,000
Backup generator	1	$20,000	20,000
UPS Systems	3	$12,900	38,700
Total Capital Investment Cost			**$275,900**

The major budget item for operating costs would be the staff salary bill. Another important item would be the lease of the office building. The location of the centre would have a major influence on this item. Rents in Angola are very high ($140/m^2), while they are relatively low in Zimbabwe ($4/m^2). However, this situation could change with the current improvement in the economic situation in Zimbabwe. In the six other riparian countries, rents are generally similar at around $15/m^2. For the operating cost budget estimate, the preceding average value has been used.

Table 8.6. Flow Forecasting Centre Operating Cost

Item	Number	Indicative Cost per Year (USD)	Remarks
Wages		$550,000 – $890,000	Bracket for minimum and maximum staffing. Excluding cost of 2-3 junior hydrologists coming from member states institutions
Office Building Lease	1	$12,000 – $60,000 Average*: $47,000	For a 250 m² office space. Extremely variable between different locations. *Rents in Angola are approx. ten times higher than the rest of the region and four times lower in Zimbabwe. Both countries are excluded from the average.
Power		$6,000	
Insurance		$13,000	Insurance for office content
Lease of photocopier, plotter, fax, telephone (+consumables)		$28,000	Possibility to buy instead of leasing
Cleaning materials and teas		$3,000	
Cell phones	5	$9,000	5 contract cellphone with 120 USD airtime
Telephone	4	$12,000	
Internet connection	1	$12,000	
Backup satellite internet connection	1	$12,000	
Real-time data access		$10,000	To precipitation forecast models
Postage and courier		$6,000	
Travel		$20,000	
Depreciation		$59,000	Based on 4 years for IT material, 10 years for office furniture.
Miscellaneous		$15,000	
Total operating cost		**798,000 – 1,138,000**	

8.7 Scoping of financing options

Financial resources will be required for the funding of the flow forecasting system and flow forecasting centre. This includes the establishment/ upgrading of the measurement and data collection network, as well as the operation of the flow forecasting centre. Various financing options were investigated and a range of donors was identified. One of the most common criteria considered by potential donors is the financial soundness of a project. It is therefore critical that financing be planned for the full project lifespan. In the long term, the most realistic option would be to seek financial assistance from funding organisations for the capital investment costs while the operating cost could be planned for and be financed by the member states and beneficiary stakeholders. Funding of operating costs by an external donor agency would be possible, provided such funding could be guaranteed in the long-term, thereby minimising the risk of a loss of sustainability.

The various possible donors include banks, development aid funds and organizations involved in issues related to flow forecasting. Donors could be involved in different ways: through grants, loans or by underwriting guarantees. The majority of the potential donors identified for this project are development aid funds operating in the region and having an interest in issues such as disaster management and forecasting, IWRM, measurement networks. The banks identified are the World Bank and the African Development Bank. lists the various donors and their particular interest and region of operation. Wherever possible, existing programs have been listed with their budget and period.

The operating costs cover operation and maintenance costs for the network and the operating costs of the flow forecasting centre. The operating cost should be budgeted from the main beneficiaries of the flow forecasting system. The Member States will benefit in many ways, including reduced flood damage, reduced costs for disaster management, poverty alleviation for riparian communities, improved dam operation, etc. A possible model for sharing of costs could see the main beneficiaries of the flow forecasting system contributing according to the extent of their likely benefits they receive. Dam Operators and Power Companies should for example see an improvement in their power generation and should contribute to the investment in relation to the extra revenue they will generate on the basis of improved forecasting. As part of a detailed study of this issue (which is beyond the scope of this project), a revenue analysis could be carried out to assess the potential for extra revenue generated by the operational forecasting system.

Table 8.7. Financing Options for the Flow Forecasting Centre

Organisation	Focus/Fund/ Existing programme or project	Objective of project / Criteria	Target area	Type of financing budget period
Danish International Development Agency (DANIDA)	ZACPRO 6.2	Achieve higher and sustainable socio-economic development through equitable and sustainable utilization of the shared water of the Zambezi.	Zambezi	SEK 30 million (SEK~ZAR)
UK Department for International Development (UK Aid)	Transboundary Support (through GTZ)	Help control floods, mitigate droughts and enable better use of water for agriculture, industry and power generation	SADC	£5 million
Directorate General for International Cooperation of the Netherlands (DGIS)	SADC HYCOS II	Consolidate and expand on the set-up of the regional information system on water resources	SADC	$2.1 million
European Investement Bank (IEB)	Environment	Promoting environmental sustainability	Sub-Saharan Africa	Loan – Up to 50% of project cost, guarantee
Fond Français pour l'Environment Mondial - Agence Française pour le	ORASECOM Action Plan, Pollution control and	International water emphasising collaboration between states, strengthening measurement	Transboundary water in Africa	€1-1.5 million

Organisation	Focus/Fund/ Existing programme or project	Objective of project / Criteria	Target area	Type of financing budget period
Dévelopement (FFEM - AFD)	management of the Zambezi	networks and monitoring systems		
Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ)	Transboundary Water Management in SADC	Strengthening RBO's, development of basin-wide IWRM,	SADC	€11 million
New Partnership for Africa's Development (NEPAD)	Short Term Action Plan - Water	Development of national integrated water resources management policies and strategies addressing effectively climate change - the effects of droughts and floods	Africa	-
Norwegian Agency for development Cooperation (NORAD)	ZAPRO 6.2 and ZAMCOM	Achieve a higher and sustainable socio-economic development through equitable and sustainable utilization of the shared water of the Zambezi	Zambezi	€0.8 million
Swedish International Development cooperation Agency (SIDA)	ZAPRO 6.2 and ZAMCOM	Achieve a higher and sustainable socio-economic development through equitable and sustainable utilization of the shared water of the Zambezi	Zambezi	€2.2 million
Swiss Agency for Development and cooperation (SDC)	SADC Water Resources Management	Establishment of RBOs for transboundary water resources	SADC	$0.86 million
United States Agency for International Development (USAID)	Water, Natural Disasters and Climate Change FEWS NET	Disaster Forecasting assisting developing nations with the installation and management of disaster monitoring and warning systems, USAID helps save lives, money and resources. Provision of timely and analytical early warning and vulnerability information based upon remotely sensed data, ground-based meteorological...	Global African countries	
World Bank (WB)	Mozambique Water Resources Development I	Supporting long-term strategic planning and management of the regional water authorities with specific emphasis on the Zambezi basin	Mozambique (including Mozambique)	$2.5 million

Organisation	Focus/Fund/ Existing programme or project	Objective of project / Criteria	Target area	Type of financing budget period
World Meteorological Organisation (WMO)	Flood Forecasting & Early Warning Strategy for the Zambezi River basin	Assess the capacity for flood forecasting and early warning in the countries of the Zambezi River basin	Zambezi	$0.59 million, 2009-2012
	Southern Africa Flash Flood Guidance System	Development and implementation of regional flash flood guidance and early warning systems. Development of infrastructure	Southern Africa	$1.2 million, 2009-2012
	SADC HYCOS III	Consolidate Phase I and II of HYCOS installations to achieve a fully functional and calibrated hydrological monitoring network	SADC	€3 million, 2010-2014

8.8 Institutional agreements and protocols

In order to establish the flow forecasting centre as a legal entity responsible for all of the functions related to real-time data collection and operational forecasting, a number of agreements and protocols would need to be established between the Member States. It is recommended that these agreements be established as addenda to the main ZAMCOM agreement, which enshrines the concept of cooperation and sharing in the basin between Member States. Some of the issues that would need to be addressed as part of this process include:

- Sharing of information from Member States/ Regional stakeholders with ZAMCOM;
- Sharing of benefits/costs;
- Develop procedures/protocols on what to do with forecast information (warning mitigation);
- Protocol on the type and detail of information to be received by each stakeholder;
- Agreement incentive that stakeholders should prepare and maintain protocols on how to act on forecast information;
- Agreement on the development of staff at the forecasting centre based on the concept of establishing the forecasting centre as a regional 'centre of excellence' for hydrology, modelling and flow forecasting;
- Agreement with RSMC and CSC to obtain access to precipitation forecast information; and
- Agreement on the use of SADC-HYCOS for forecasting and O&M of gauges.

8.9 Advantages and risks

An overview of the advantages of an established operational flow forecasting centre, as well as the potential risks or threats is presented below.

8.9.1 General advantages of a centralised operational flow forecasting system

The primary advantage of an operational flow forecasting centre is that information is integrated and shared amongst stakeholders. This information is provided through integration of hydrological and meteorological data from across the basin, through the integration of hydrological forecasting tools to predict future flows and water levels and through integration of precipitation forecasts that provide information on expected rainfall and allows reliable flow forecasts to be made at the lead times required to inform the operational processes of the stakeholders. The sharing of information will lead to improved management of the basin's water resources. Real-time flow forecasting enables better synchronized operation of reservoirs, enhanced hydropower production, environmental flow planning and timely flood warning.

As a result of this improved synchronisation, hydropower revenues and ecosystem services will increase and DMU's will be able to mobilize more effectively and timely during floods. Furthermore, through improved and synchronized operation using integrated and shared information as well as forecast information, the resilience of stakeholders against the large natural variability in river flows in the Zambezi River basin and against the effects of climatic change, will increase.

8.9.2 Specific advantages of the recommended flow forecasting centre

In the previous sections, an approach for the implementation of a centralized flow forecasting centre following examples of other basins, combined with the current context in the Zambezi River basin was outlined.

Key to attaining the advantages of the proposed flow forecasting system through the sharing of information amongst stakeholders across the basin is that it should be linked to ZAMCOM. ZAMCOM provides the opportunity to arrange agreements between member states and stakeholders to share information. The willingness of sharing information is a prerequisite to the success of a flow forecasting centre. Furthermore, establishing the flow forecasting centre as a subsidiary of ZAMCOM will strengthen the role of ZAMCOM.

The proposed forecasting system should where possible be based on existing model capabilities. Integration of existing models ensures that the knowledge and experience embodied in these models is sustained and that the value of the flow forecasting system is recognized by the entities that operate it.

The proposed 'Centre of Excellence' will ensure sustainability of the human capacity located in the forecasting centre. Furthermore, continuous training of stakeholders will lead to further recognition and acceptability amongst stakeholders.

It is proposed that a flexible and open operational forecasting platform that can be accessed both centrally as well as from the offices of stakeholders is adopted. The great advantage of this approach is that stakeholders can access any information produced by the forecasting system, whether they are at the flow forecasting centre, or at their own (remote) location.

8.9.3 Risks for the establishment of a flow forecasting centre

Sustainability is a prerequisite for operational forecasting and poses the largest risk to the establishment of a flow forecasting system that has real added value in the Zambezi River basin.

Below a number of risks related to the sustainability of the proposed forecasting centre are summarised:

- **Funding** - Measurement networks need to be operated and maintained. Without sufficient funding and commitment to operation and maintenance these networks will not provide the required input data for reliable flow forecasts to be established. Experience with the SADC-HYCOS Project indicates that it is important to recognize the need for operation and maintenance costs. To ensure a sustainable operational network, agreements should be set up on responsibilities and financing between member states. Such agreements should include responsibilities for maintaining stations, updating rating curves and replacing faulty stations. The benefit of having the centre as a subsidiary of ZAMCOM is that such agreements could be implemented as addenda to the main ZAMCOM agreement;

- **Willingness of NMSs to cooperate** -The proposed forecasting system would rely on real-time collection of data, with this data being made available in a timely fashion to the central forecast system. To achieve this, it is important that member states and responsible entities such as National Hydrological Services and National Meteorological Services are willing to cooperate in the real-time collection and transmission of precipitation and flow data. These entities need to follow agreed procedures, which again could be agreed upon in an addendum to the ZAMCOM agreement;

- **Adoption of Common Models** -To ensure the forecasting centre is accepted throughout the basin, existing model capabilities should be used where possible. There is a risk that stakeholders that own models will not be willing to cooperate and share their models for the benefit of the flow forecasting system. If this is the case and an alternative model is made use of in the forecasting system, there is an additional risk that the same stakeholders will not be willing to embrace the forecasting centre because their own models are not part of it. This risk can be reduced by ensuring that all stakeholders, in particular those that have developed data acquisition and modelling infrastructure, fully support the development of a centralized flow forecasting system. Again such commitment may be agreed upon in an addendum to the ZAMCOM agreement:

- **Adequate Staffing of Forecasting Centre with Competent Staff** -Sustainability greatly depends on available capacity in the region to use, maintain and improve the forecasting system. It is well known that human capacity is often lost to foreign countries because of job opportunities and potential to further develop capacity abroad. To avoid this from happening, the flow forecasting centre, along with the 'Centre of Excellence' should provide an attractive environment for both research and operational work. This can be reached by having strong links with research institutes and networks such as WaterNet; and

- **Guaranteed Funding by Member States** - Another key risk is the potential loss of funding. For this reason, it is proposed that operational and maintenance funding for the proposed forecasting centre be provided by the Member States. Reliance on donor agencies for funding could result in a loss of sustainability, as the priorities of donors do not necessarily follow the priorities of the Member States.

9 Development of a Pilot Forecasting System for the Zambezi

9.1 Goal

In order to more clearly establish recommendations and guidelines for the proposed flow forecasting system and to demonstrate how stakeholders could use forecast information to improve flood and water resources management, a demonstration pilot model of a portion of the Zambezi River basin was set up as part of this study. To illustrate some of the potential benefits, an historical flood event was simulated in the demonstration pilot system to show what information could have been provided by a forecasting system, and how this could have assisted with decisions on synchronised operation of the Kariba and Cahora Bassa Dams.

9.2 Description of ZAMFEWS pilot

Although it was beyond the scope of the demonstration pilot to develop a fully-fledged operational forecasting system, a pilot ZAMFEWS (Zambezi Flood Early Warning System) was setup (refer to Section 8.3.1). The main benefit of the pilot ZAMFEWS is that through simulation of an historical event, potential users can see first-hand what information a forecasting system could provide and how this information could be used for improved water resources management. It should be noted that the ZAMFEWS pilot has the ability to *demonstrate* this information, rather than to operationally forecast it. This means that the provided information is based as much as possible on actual historical data, collected or produced during the period simulated in the pilot system. It is therefore likely that the hydrological estimates provided by the system are physically meaningful and show how forecast information could have resulted in improved dam operation for the historical event concerned. However, the data used to run models and produce predictions is not always available operationally. For instance, in the case study event discussed in this chapter, a forecast is demonstrated using a rainfall-runoff model based on remotely sensed rainfall estimates as input. In an operational context, remotely sensed rainfall estimates would not be available *ahead* of time and *predicted* rainfall from weather forecasting would be needed.

In addition, in setting up the ZAMFEWS pilot, a selection of prediction models that were readily available for demonstration purposes were used. As explained in Chapter 6, in an operational context a number of additional models would be needed for a fully operational basin-wide forecasting system.

9.2.1 An open modelling shell for forecasting: Delft-FEWS

The pilot system was configured using the state-of-the-art forecasting shell, Delft-FEWS (Werner *et al.*, 2004). Delft-FEWS (Figure 10.1) is a highly configurable forecasting shell that can be used to manage the forecasting process. It incorporates a wide range of general data handling utilities, while providing an open interface to any external calculation model (for instance a hydrological or hydraulic model). The modular and highly configurable nature of Delft-FEWS allows it to be used effectively in both simple and highly complex systems. Delft-FEWS can be deployed in either a stand-alone environment, a manually driven environment, or a fully automated distributed client-server environment. In this pilot system, only a stand-alone operating system was setup. Although the completed pilot system contains components that may be used operationally, the system as such is not suitable for operational forecasting.

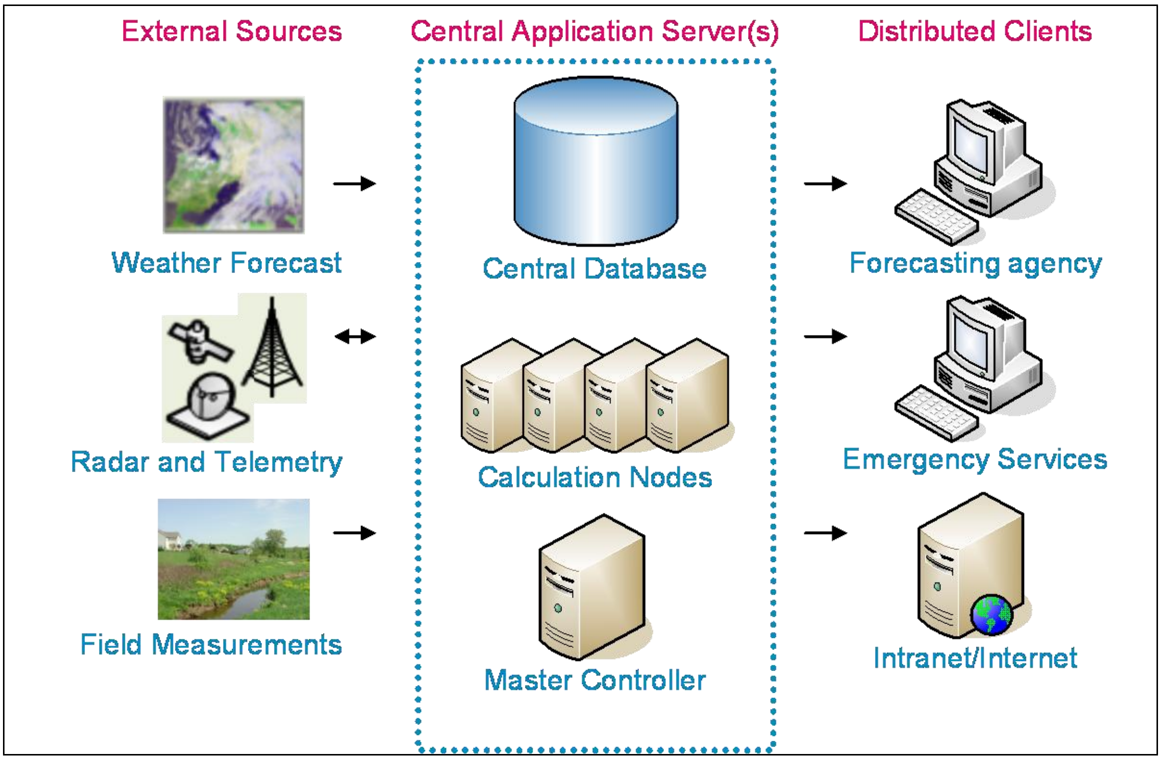


Figure 9.1. Components of Delft-FEWS in an operational setup

9.2.2 Targeted stakeholders

The focus of the ZAMFEWS pilot forecasting system was primarily on the operation of Kariba and Cahora Bassa Dams and therefore the system will be of greatest interest to the operators of these dams. The system, as set up, would allow these dam operators to see the following information:

- Current and predicted (10 days ahead) inflows at relevant upstream locations. For Kariba, this would include flows from the upper Zambezi, the Gwayi and the Sanyati rivers, while for Cahora Bassa, this would include the Luangwa, which is known for unexpected high inflows, and the middle Zambezi Rivers, the latter being predominantly influenced by releases from Kariba and the Kafue;
- In addition, it would be of value to know the planned release strategy of the upstream dam operators. For this reason, the system allows both Kariba and Cahora Bassa operators to see each other's current and predicted reservoir releases. In this pilot system, the operation strategy was determined by an optimized real time control (RTC) model, using the actual operating rules as input; and
- The previous, current and predicted water levels in both reservoirs.

By allowing operators of Kariba and Cahora Bassa to see information from each other's reservoirs, coordinated releases could be planned and timely warnings of forthcoming floods could be issued. In addition, the system could be used by disaster management units for improved disaster response and mobilisation. The system could therefore be used to provide information at short, medium and seasonal lead times.

9.2.3 Available data and models in ZAMFEWS pilot

As mentioned earlier, the ZAMFEWS system focused on improved reservoir operation of Lakes Kariba and Cahora Bassa, as the main benefits of the proposed forecasting system can best be demonstrated through the improved operation of these reservoirs. Figure 9.3 below shows in schematic form the main features of the demonstration pilot system. All introduced features can be implemented and used in a fully fledged operational forecasting system.

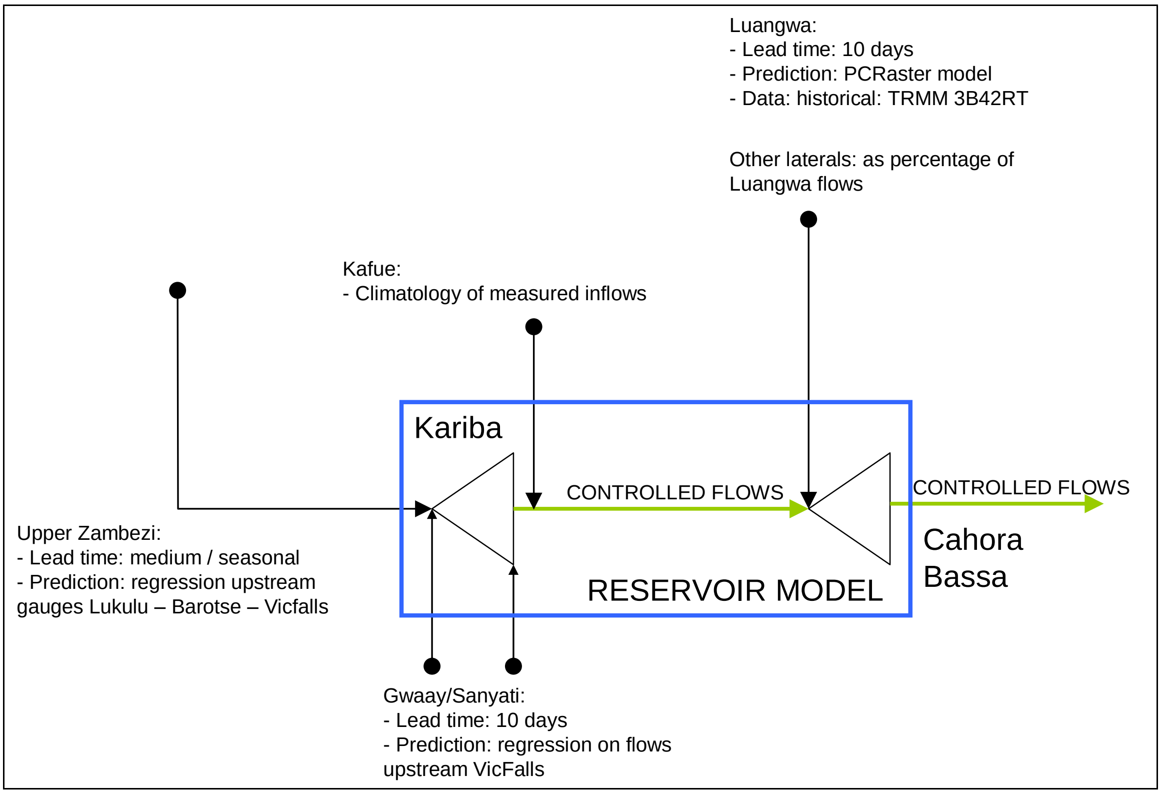


Figure 9.2. Schematic overview of the pilot forecasting system

As shown in this figure, to provide the required information components, models are needed. Section 6.2 describes the models that would be needed for a fully operational system. In the pilot system, the required information was partly provided by available models (some of which comply with the requirements discussed in Section 6.2) and partly using other techniques (e.g. by regression). gives a short description of the approach that was used to estimate each variable where model output was not available.

Table 9.1. Description of components of the ZAMFEWS pilot system.

Component description	Approach to estimate component
Daily inflows at Kariba	No model was used. Instead, past observations at Big Tree station were used as if they were forecasted values. Contributions to Lake Kariba in between Big Tree and Kariba Dam were estimated by a contributing area approach, based on the Big Tree flow records. ZRA currently uses a regression model. In an operational system, this regression model could be implemented.
Daily outflows from Kariba	A Real Time Control reservoir model, mimicking planned releases (turbined and spilled) from Kariba was used, based on

Component description	Approach to estimate component
	operating rules and calibrated using available time series of water levels.
Daily outflows from Kafue	A climatology of observed values at Ceres was used as a proxy.
Routed daily flows from Middle Zambezi to Cahora Bassa	The outflows from Kariba and Kafue are lagged and attenuated within the Zambezi River channel and in particular at Mana Pools. A Muskingum routing model was implemented to simulate the lag and attenuation between Kariba and Cahora Bassa
Daily outflows from Luangwa river	A PCRaster rainfall runoff model, based on PhD research (Winsemius, 2009) was implemented to estimate flows from this tributary. The model is forced by satellite rainfall estimates. For the case study, TRMM 3B42 rainfall estimates were used (see also Chapter 4 of this report)
Daily inflows into Cahora Bassa	Besides the Middle Zambezi and Luangwa River, other tributaries contribute to Cahora Bassa inflows such as the Manyame River. The contribution from the remaining contributing areas was estimated by means of a contributing area approach, based on predicted flows from the Luangwa catchment.
Daily outflows from Cahora Bassa	A Real Time Control reservoir model, mimicking planned releases (turbined and spilled) from Cahora Bassa was implemented, based on operating rules and calibrated on available monthly reservoir outflows. This model provides outflows, as well as reservoir water levels. Unfortunately no water level time series were available for calibration. Instead, it was assumed that turbine capacity would be used when water levels were more than 2 metres below the flood rule curve and that spillage could also be used when the water level was less than 2 metres below the flood rule curve. This ensured that the flood rule curve could be followed.

9.2.4 Visualisation of results

A fully-fledged forecasting system for the Zambezi River Basin would provide a range of information to a range of users. A valuable tool for making forecast data readily comprehensible to users is the use of visual displays or visualisations that allow specific users the ability to find the information they need. For the ZAMFEWS pilot system, a number of time series visualisations that provide forecast information at specific forecast locations were configured. In particular, time series displays were generated for the Luangwa River (at Mfuwe and at its confluence with the Zambezi), Lake Kariba and Lake Cahora Bassa. Examples of these time series displays are presented in Figure 10.3 and Figure 10.4.

In Figure 10.3, the top panel shows historically simulated inflows (blue line), simulated outflows (red line) and spillage (purple line), while the bottom panel shows simulated or (if available) observed water levels (blue shaded area). In this example, observed water levels were available at Lake Kariba. A similar display is available for Cahora Bassa. In Figure 10.4, the top panel shows remotely sensed rainfall estimates (blue bars) and actual evaporation (red line), both averaged over the Luangwa basin (blue bars). The lower panel shows the simulated daily flows at Mfuwe (black line) and at the Great East Road Bridge (blue line), which close to the confluence with the main stem of the Zambezi.

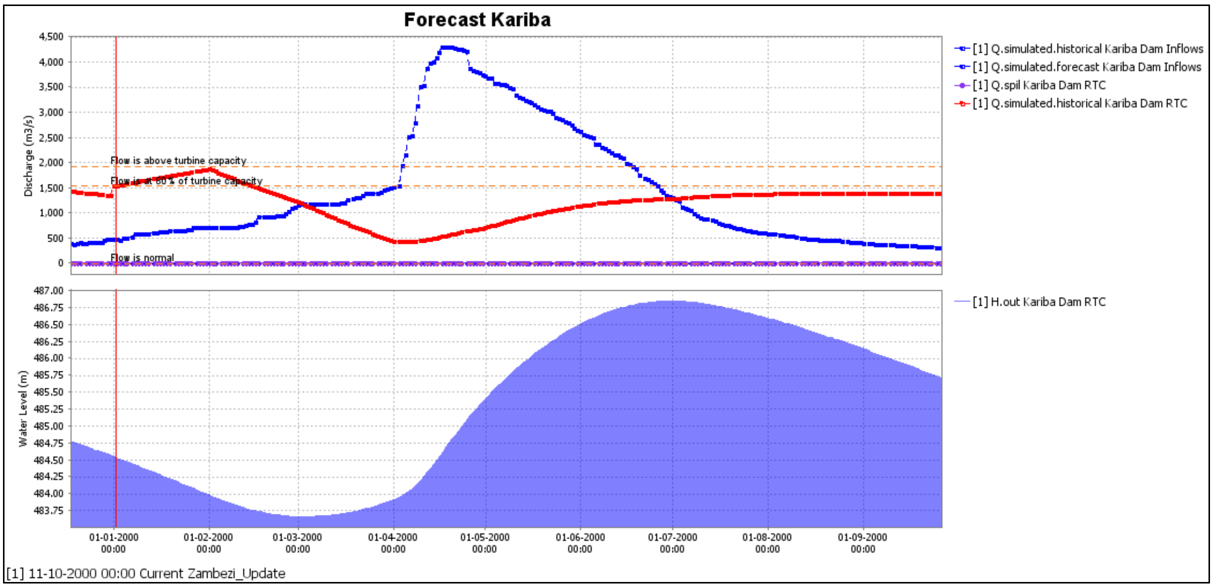


Figure 9.3. Time series display of forecast information at Lake Kariba.

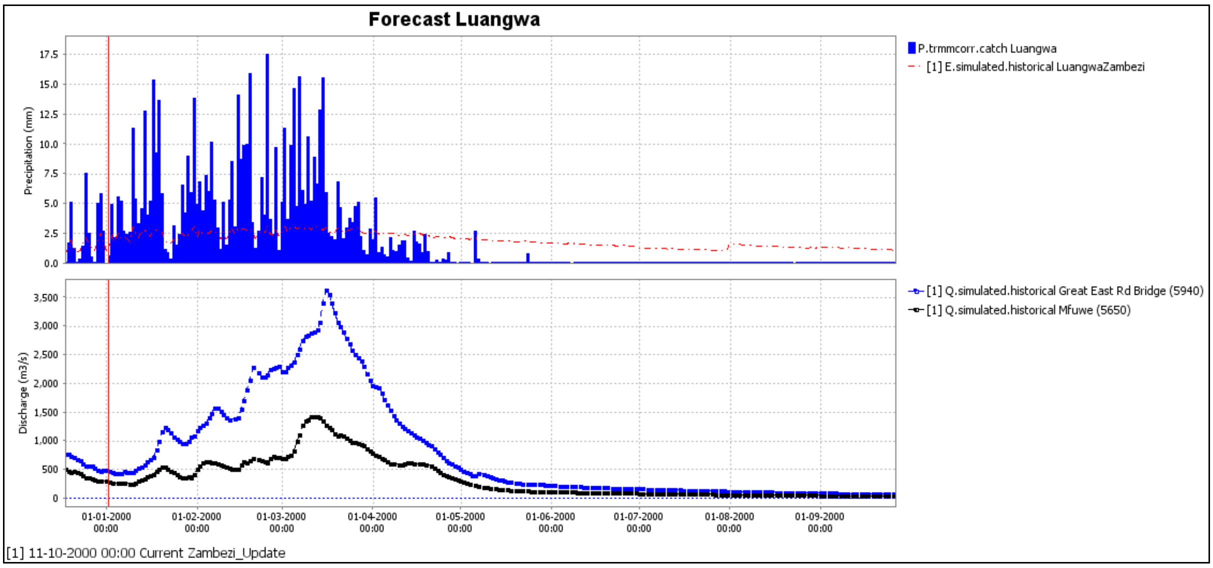


Figure 9.4. Time series display of forecast information in the Luangwa catchment.

FEWS can also be configured to display information in a user-friendly manner through the use of so-called SCADA[7] displays. In the ZAMFEWS pilot system, three SCADA displays were implemented. The first of these shows the basin and all relevant associated information (Figure 10.5), including current flows at important locations. The display also shows whether inflows over the coming 10 day period will exceed the maximum turbine release capacity of the Kariba and Cahora Bassa dams. This can be seen from coloured bars next to the reservoirs.

[7] SCADA stands for Supervisory Control And Data Acquisition. A SCADA display within Delft-FEWS primarily presents information in a highly condensed and user-friendly way to the user. In this pilot system, the user cannot influence data or control models.

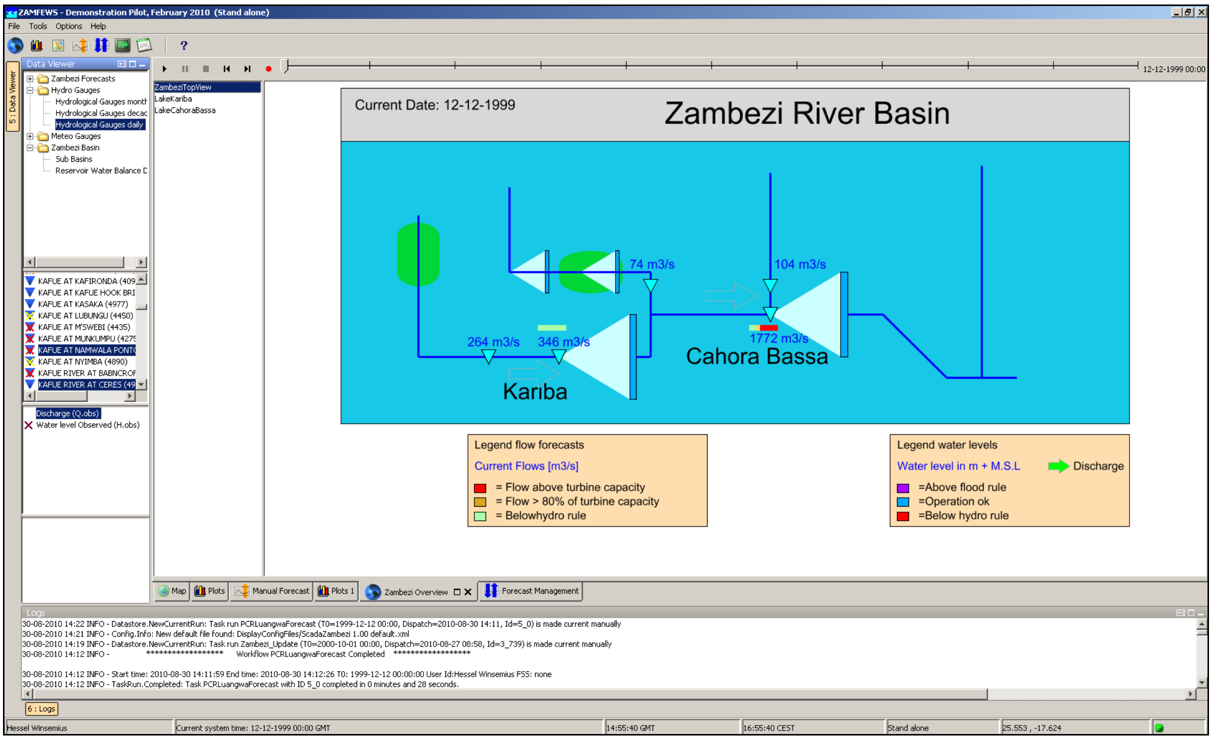


Figure 9.5. SCADA top-view of the Zambezi basin, as presented in ZAMFEWS.

In addition, both Kariba and Cahora Bassa can be seen in more detail in two separate SCADA views. The user can show these by clicking on the reservoir of interest within the top-view SCADA (see Figure 10.6). The reservoir views have the following features:

- **Reservoir water level**: The water level within the reservoir is equal to the current water level, as simulated by the RTC model. In the event that observations of water levels are available, the latest observed level is given. The current water level is also displayed above the reservoir;
- **Changing colours of water level**: the water behind the dam will change to red as soon as the water level drops below the Minimum Operating Level (MOL) and to purple when the water level exceeds the Full Supply Level (FSL). When the level is in between MOL and FSL, it will be shaded blue; and
- **Animations of water levels and colours:** the user can click on the ‘Play’ button on top of the SCADA view of the reservoir which will trigger an animation. The animation shows how water levels will evolve over the next 10 days, given the inflows and planned releases for the same period.

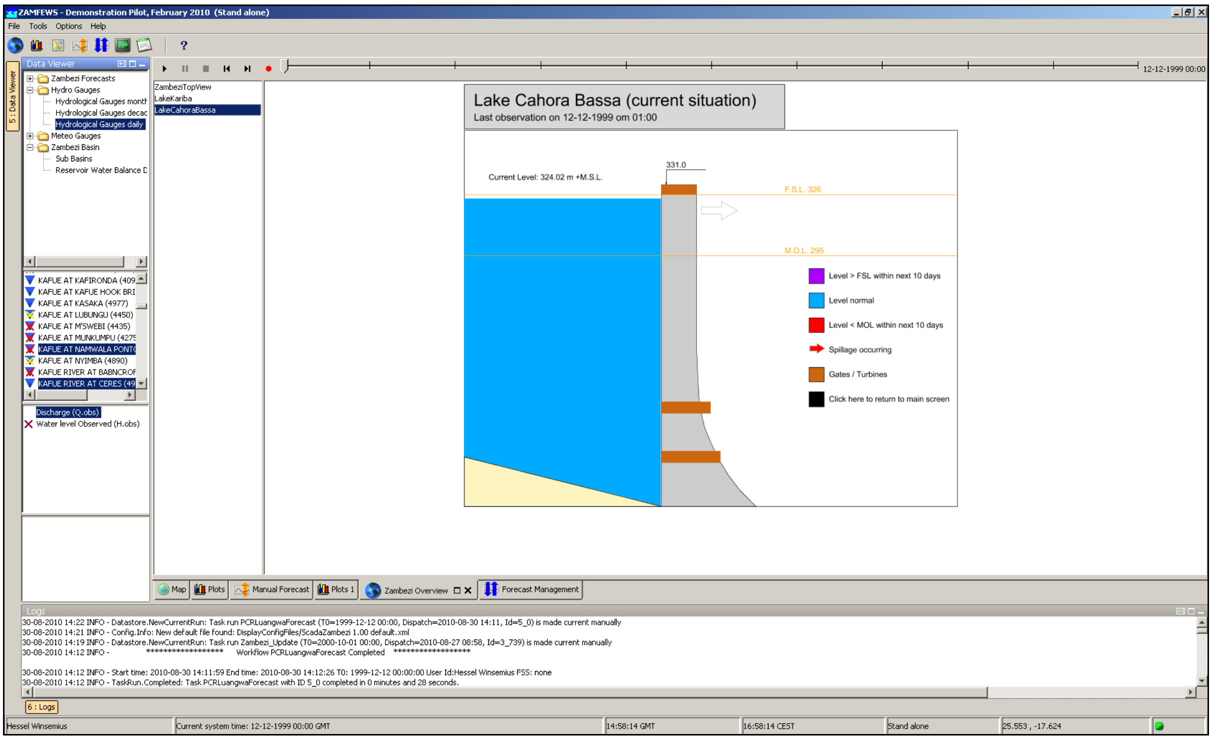


Figure 9.6. SCADA view of Cahora Bassa Reservoir.

9.3 Case study

A case study was built around the wet season of 1999-2000. From 1998, inflows into Lake Kariba increased (a significant period of drought occurred prior to this 1998). When Cyclone 'Eline' arrived in January/February 2000, the water level in Lake Kariba was already high, necessitating the opening of 4 flood gates at a certain stage. The gates were kept open until 12 August 2000 and a total of 13.1 million cubic meters of water was spilled during the period 26 February 2000 to 12 August 2000 (Tumbare, 2000). In Mozambique, 700 people were killed as a consequence of flooding.

The above event was simulated in the pilot system. To this end, the observed releases at Kariba were imposed on the reservoir model. The control of Cahora Bassa was determined from the RTC model using the observed storage level on 1 October 1999 as an initial condition. Below, the critical periods within the simulation period are briefly described, as if they had been forecasted. It should be noted that the simulated behaviour of water levels and releases is not equal to what happened in reality but a reflection of what could have happened if the information provided in ZAMFEWS had been available to the operator.

Date	Current situation description
12 December 1999	Flows in the Luangwa River basin are predicted to increase in the next few days, which will cause a corresponding increase in inflows into Cahora Bassa. These flows will exceed the turbine capacity of the reservoir, meaning that without spillage, the water level will rise. The reservoir level is already above the flood rule curve.
15 January 2000	Operators need to open flood gates at Cahora Bassa in order to remain within the flood rule curve.
1 February 2000	Cahora Bassa progressively increases spillage up to 2000 m^3/s.
1 April 2000	Cahora Bassa closes a few spill gates and spillage continues at a reduced flow.
7 April 2000	Cahora Bassa is within the flood rule curve and spillage therefore stops.

Figure 9.7 shows a ZAMFEWS overview of how the event at Kariba was simulated within the ZAMFEWS pilot, while Figure 9.8 shows the same for Cahora Bassa. Major spillage occurs at both reservoirs according to the RTC model. Crucial to the flood management of Cahora Bassa is the rapidly changing inflow, which is mostly due the ungauged Luangwa River inflow.

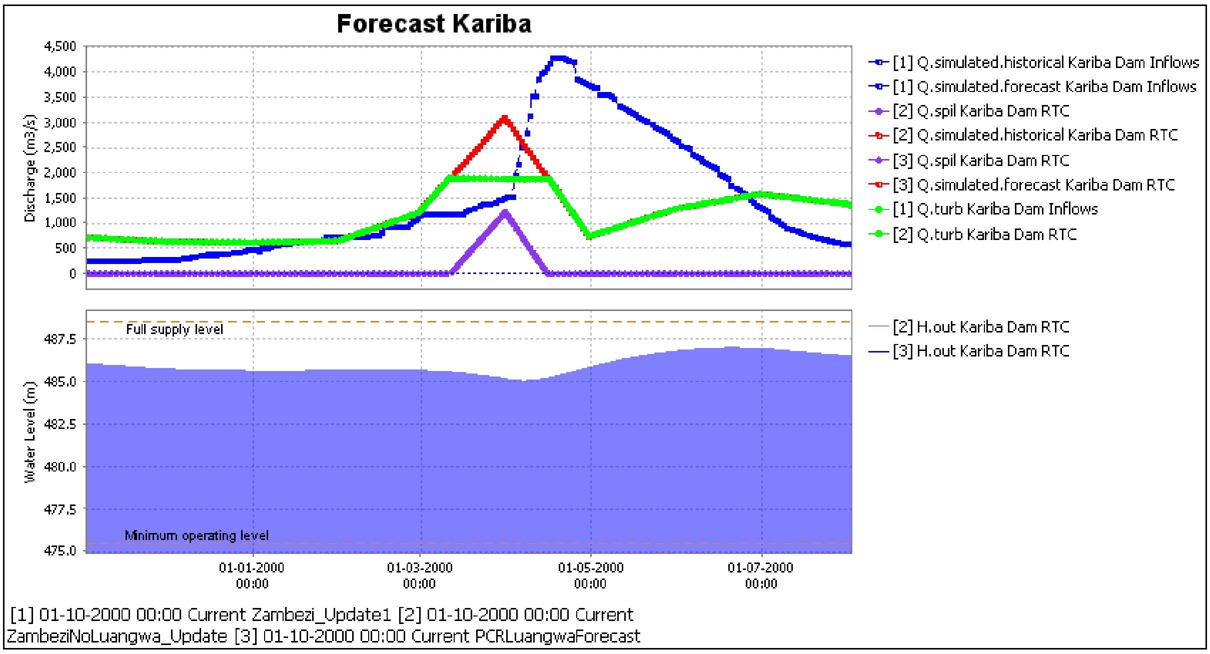


Figure 9.7. Time series view of 1999-2000 event at Kariba (blue line: inflows, green line: turbine flow, purple line: spillage, red line: total outflow).

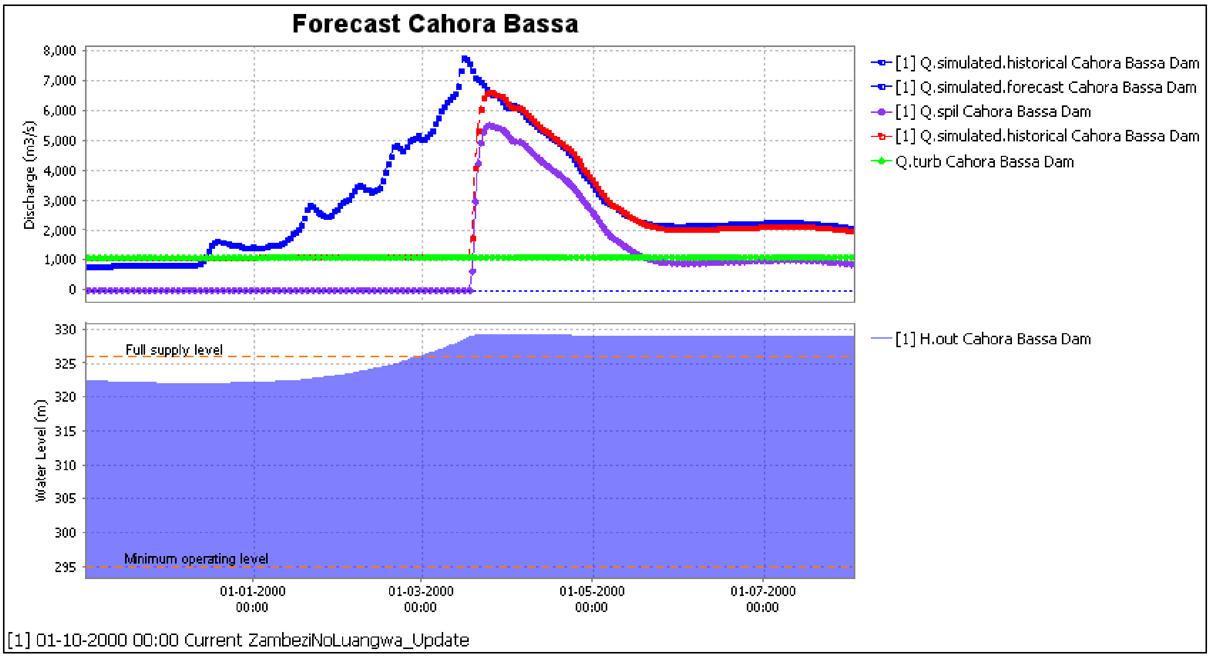


Figure 9.8 Same as above, but for Cahora Bassa

To investigate how forecast information could have resulted in improved operation of both Kariba and Cahora Bassa under Cyclone Eline, an alternative scenario to the one described above was imposed on the ZAMFEWS pilot system, with modified operation at both reservoirs. It has been assumed that Kariba performed a pre-release starting around 1 February 2000, as a response to the approaching flood wave. In this way, a storage deficit would have been created to capture the forecasted flood wave. Given the long lead times provided by the forecasting system, this would have been feasible in reality. Figure 10.9 shows the resulting operating scenario. It is clear that the operators at Kariba would not have needed to spill any flow if the reservoir had been operated using forecasted information and had performed a pre-release. This would have increased the turbine flow at Kariba by up to about 5% of the total amount during the wet season, which in turn would have generated additional revenue.

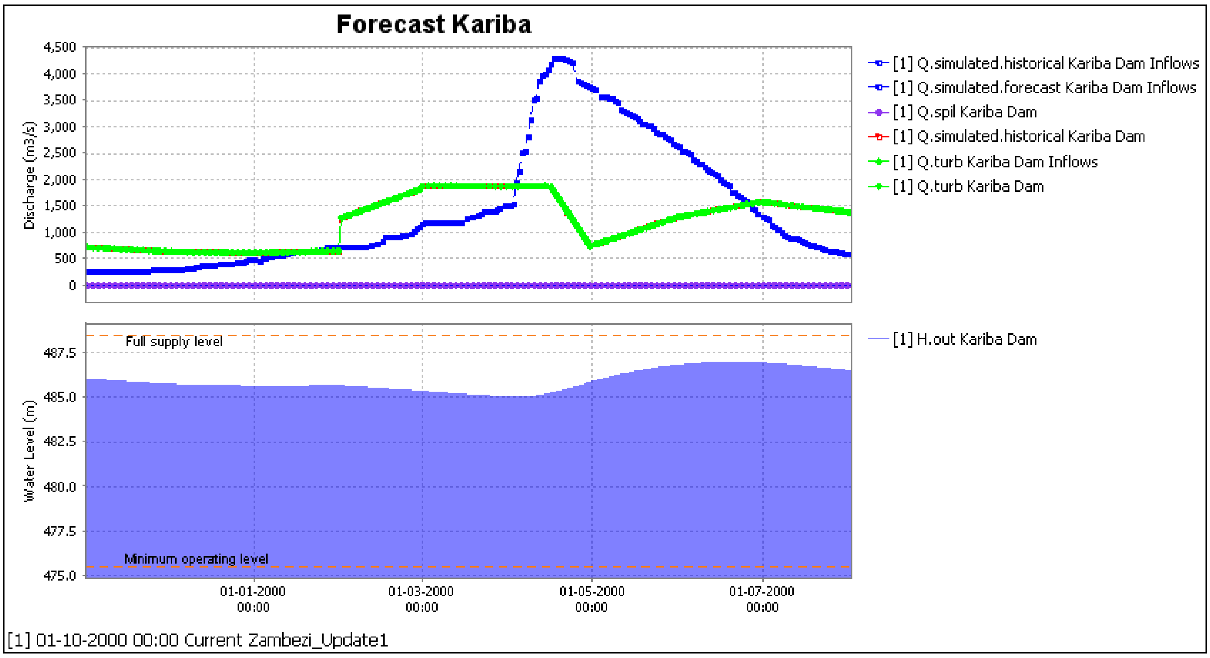


Figure 9.9: Scenario operation of Kariba

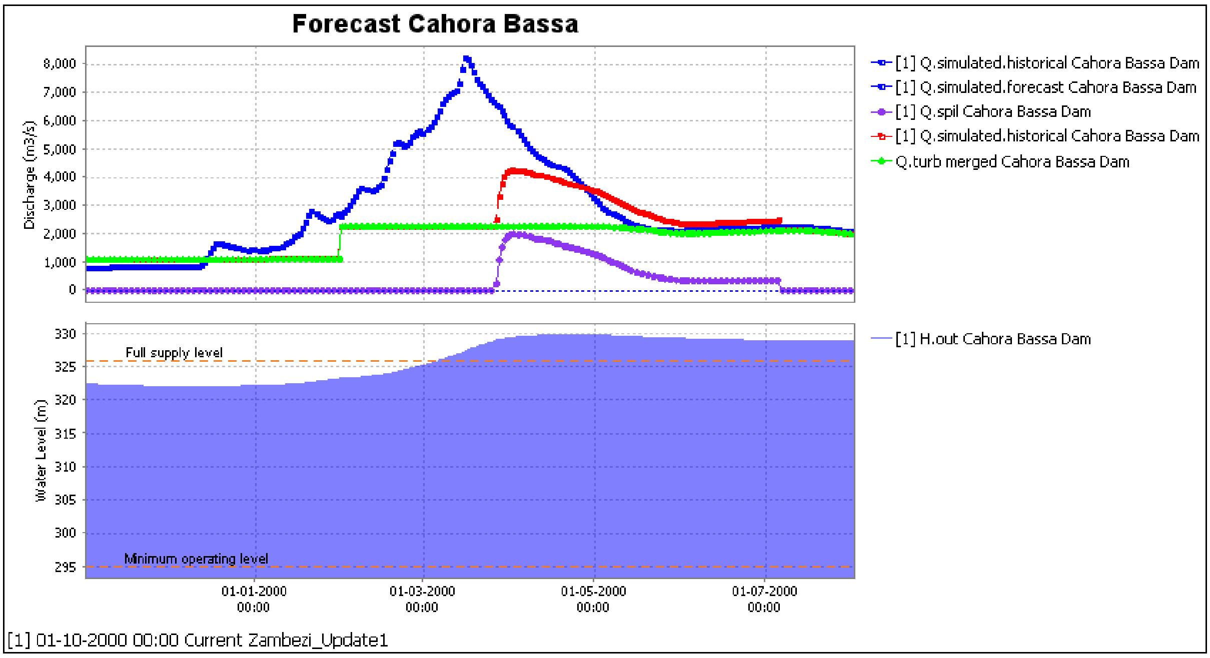


Figure 9.10. Scenario for Cahora Bassa (note that the RTC model of Cahora Bassa is influenced by the new scenario release strategy at Kariba).

Figure 10.10 shows the scenario for Cahora Bassa. Around 1 February 2000, operators at Cahora Bassa would have responded to the early release from Kariba by increasing turbine outflow, resulting in increased revenue from power generation. The high inflows from the Luangwa River would still have necessitated some spillage, but significantly reduced from what was needed in the initial scenario.

9.4 Conclusions

The results of the two case study scenarios demonstrate some of the key benefits that could arise from implementation of a basin-wide operational forecasting system. In particular, if the existing reservoirs in the basin are operated using forecast information and operators share information on planned releases, then power generation at both Kariba and Cahora Bassa could be optimised, resulting in less spillage and improved flood management.

10 Recommendations

This chapter provides summary recommendation or intervention sheets for establishment of a basin-wide flow forecasting system in the Zambezi River basin. The interventions are based on the findings and recommendations presented in Chapters 1-9 of this report and have been prepared to facilitate the implementation of proposed actions. These intervention sheets are not project proposal sheets. They are based on the findings of the Technical Study "Dam Synchronisation and Flood Releases in the Zambezi River Basin". Before implementation, further consultation with stakeholders and establishment of specific project details may be required.

In preparing these sheets, it should be noted that a key assumption has been the future ratification of the ZAMCOM agreement by all basin states. As management of the Zambezi River basin is currently limited to piecemeal management by the 8 basin states, implementation of basin-wide strategies is unlikely to be successful until the full ratification of the ZAMCOM agreement has been achieved. Other specific assumptions have been listed for each recommendation or intervention.

Figure 10.1 on the following page is a schematic summary of the structure and relationship between the concepts and recommendations for precipitation and flow forecasting, as developed in this project. It is important to recognise that implementation of the recommendations listed will have greatest value, if implemented as part of an overall concept. For example, while the development of new flow forecasting models will offer a significant improvement in flow forecasting capability, this development will not add significant value if the coverage, reliability, data transmission and sustainability of the flow and rainfall monitoring networks is not sufficiently upgraded to deliver the required data to the forecasting models.

The recommendation/ intervention sheets included in this chapter include a number of standardised fields. A brief description of these fields is provided below:

Intervention sheet # - the number of the recommendation/ intervention linked to specific focus areas. Interventions starting with "3" are linked to Concepts and "Recommendations for Precipitation and Flow Forecasting".

Timeframe – the timeframes presented here are approximate and are limited to short term (0-2 years), medium term (2-5 years) and long term (>5 years).

Budget range – to facilitate implementation of the proposed interventions, a budget range has been included to assist with obtaining funding. Four budget ranges have been considered, as follows: < US$ 0.5 million, US$ 0.5-2 million, US$ 2-5 million and > US$ 5 million. It should be noted that the costs presented in this field are rough order cost estimates prepared in most cases from an educated assessment of the likely cost for implementation of each respective intervention.

Linkages – this field details the locations within the report where further information on each recommendation/ intervention can be obtained.

Concept – this field outlines the overall concept to which the proposed intervention is expected to contribute.

Justification – this field explains the rationale behind the proposed recommendation/ intervention.

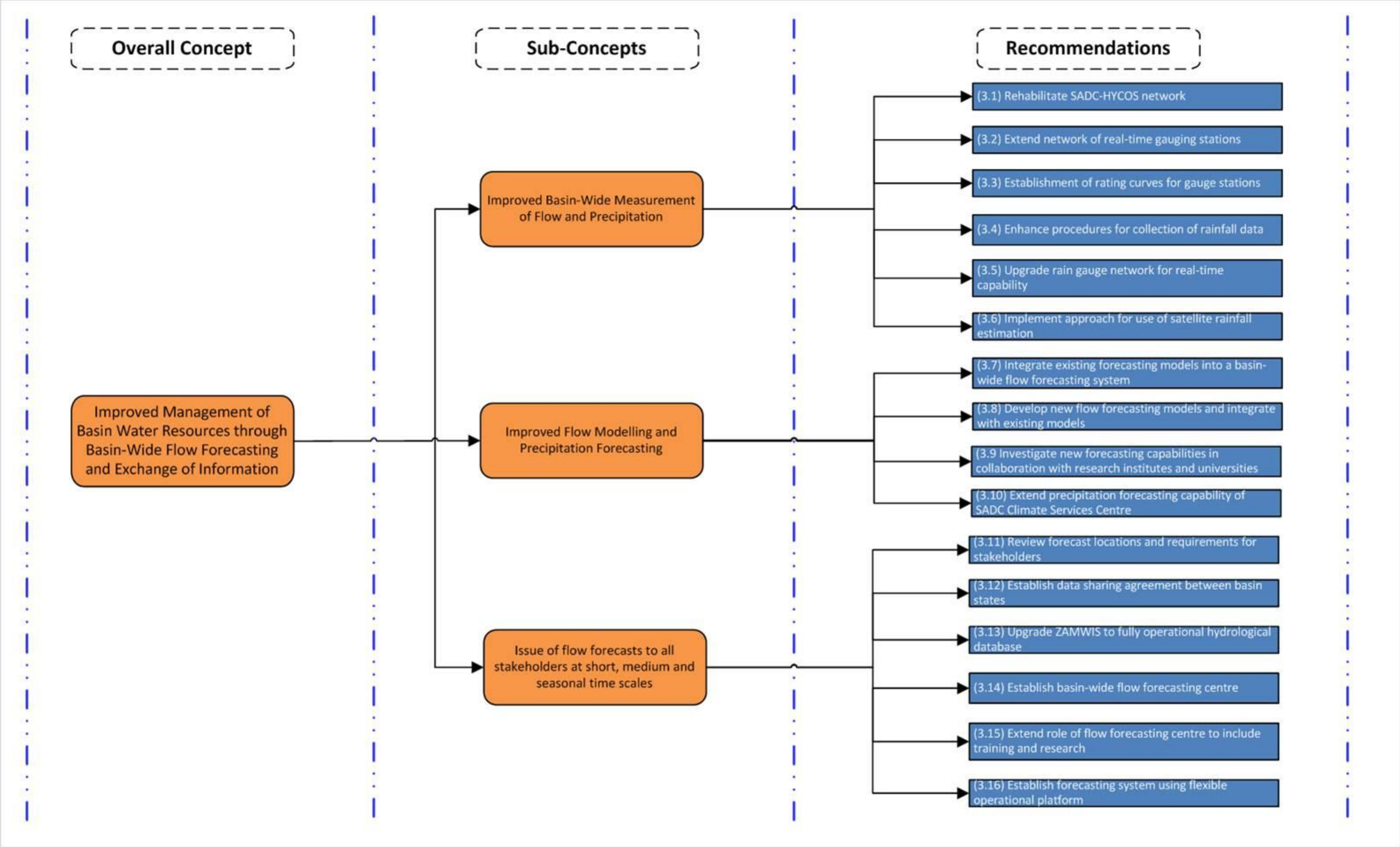
Actions/ responsibilities – this field lists the specific actions that are required for achievement of the proposed recommendation/ intervention and the responsibility for implementation. Although the SADC Secretariat and the basin states are generally listed as the responsible parties for implementation, the appointment of either consultants, equipment suppliers or contractors will be required as part of the implementation procedure for each recommendation/ intervention.

Benefits/ beneficiaries – this field was included to demonstrate the expected benefits arising from implementation, as well as the likely beneficiaries. Particular attention was given to specifying whether the beneficiaries would be limited to a single country or multiple countries.

Means of implementation – this field briefly describes the expected process for implementing the proposed recommendation/ intervention, such as the expected implementing parties and the actions to be implemented.

Specific assumptions/ risks – this field includes any specific assumptions or risks associated with this specific recommendation.

Comments – any remaining comments or issues not covered by the other standard fields are captured in this field.



TRANSBOUNDARY WATER MANAGEMENT IN SADC: DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT

ANNEX 3 FIG 10-1 CONCEPTS AND RECOMMENDATIONS FOR PRECIPITATION AND FLOW FORECASTING

Figure 10.1: Structure of Concepts and Recommendations related to Precipitation and Flow Forecasting

<table>
<tr><th colspan="6">REHABILITATE SADC-HYCOS NETWORK</th></tr>
<tr><td>Intervention Sheet #</td><td>3.1</td><td>Timeframe:</td><td>Short term (0 - 2 years)</td><td>Budget range:</td><td>0.5 – 2 million USD</td></tr>
<tr><td>Linkages:</td><td colspan="5">Annex 3, Sections 3.5 and 5.2</td></tr>
<tr><td>Concept:</td><td colspan="5">A comprehensive flow and precipitation monitoring network is required to provide real-time data for the proposed flow forecasting system.</td></tr>
<tr><td>Purpose:</td><td colspan="5">Rehabilitation of the real-time SADC-HYCOS network within the Zambezi River basin.</td></tr>
<tr><td>Justification:</td><td colspan="5">The SADC-HYCOS network is the only basin-wide, real-time flow gauging network in the Zambezi River basin. While some gauges are no longer operational due to breakdown or theft of equipment, a considerable investment in the identification of suitable sites and establishment of gauge infrastructure (civil works and gauge equipment) has already been made. By applying important lessons and experience from SADC-HYCOS Phase I and II, the risk of future theft, vandalism and damage will be minimised.</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="4">Obtain information on existing status of identified SADC-HYCOS stations and where necessary conduct condition assessments.
Procure spare parts and new equipment giving preference to equipment that can be serviced and supported by local suppliers (share regional experience, such as spare parts locally produced by Namibia DWAF).
Repair/ upgrade stations which are currently not functional
Install and utilise GSM as primary communication, with satellite communication as a back-up for all SADC-HYCOS stations in the Zambezi (GSM transmission units have already been successfully installed at some SADC-HYCOS stations in Swaziland), as the risk of vandalism for satellite equipment is high.</td><td>SADC-HYCOS Project/
Basin States</td></tr>
<tr><td>Benefits/ beneficiaries:</td><td colspan="4">Significantly reduced investment costs for establishment of the real-time flow gauging network.
SADC-HYCOS stations were selected by the respective National Hydrological Services in each country and therefore ownership and responsibility for these gauges has already been established.
Some countries already have costs for maintenance of SADC-HYCOS gauges included in their national budgets.
All SADC-HYCOS gauges are registered with the WMO and therefore are not subject to charges for data transmission via METEOSAT through EUMETSAT.</td><td>National Hydrological Services and other agencies requiring hydrological data in all Basin States.</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">Implementation of this project would best be undertaken through the SADC-HYCOS Project office, as they have necessary contacts and information on equipment that would be needed for successful implementation. Alternatively, the project could be coordinated by the Interim ZAMCOM Secretariat through the NHSs. Procurement of equipment would best be undertaken for the entire basin through the SADC-HYCOS office or Interim ZAMCOM Secretariat, so that equipment is standardised and bulk purchase discounts can be obtained</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="5">It has been assumed that the SADC-HYCOS project office in Pretoria will be re-opened in the near future (1-2 years) to facilitate implementation of this recommendation.
Funding will be required not only for the rehabilitation and upgrading of stations, but also for on-going maintenance and future replacement.</td></tr>
<tr><td>Comments:</td><td colspan="5">This intervention is linked to Intervention 3.2 (Extension of real-time flow gauging network). Together, Interventions 3.1 and 3.2 will result in establishment of a real-time flow gauging network that includes the 51 flow gauges identified in this project for basin-wide flow forecasting. Intervention 3.3 (upgrading of rating curves) will also be required to render the network suitable for the development of forecast models and flow forecasting.</td></tr>
</table>

<table>
<tr><th colspan="6">EXTEND NETWORK OF REAL-TIME GAUGING STATIONS</th></tr>
<tr><td>Intervention Sheet #</td><td>3.2</td><td>Timeframe:</td><td>Short/ medium term</td><td>Budget range:</td><td>> 5 million USD</td></tr>
<tr><td>Linkages:</td><td colspan="5">Annex 3, Sections 3.5 and 5.2</td></tr>
<tr><td>Concept:</td><td colspan="5">A comprehensive flow and precipitation monitoring network is required to provide real-time data for the proposed flow forecasting system.</td></tr>
<tr><td>Purpose:</td><td colspan="5">Extend network of real-time gauging stations to provide sufficient coverage for basin-wide flow forecasting.</td></tr>
<tr><td>Justification:</td><td colspan="5">Although the SADC-HYCOS network provides good coverage in most key areas of the Zambezi River Basin, approximately 23 additional flow gauges, which do not currently have real-time equipment, were identified in the network design for establishment of a basin-wide flow gauging network. This includes existing manual and real-time (non-SADC-HYCOS) gauges used by basin based forecasting authorities such as ZRA, ZESCO, Namibia DWAF and ARA Zambeze, as well as other locations where additional coverage is considered necessary. Changes to the forecasting locations and requirements (Recommendation 3.11) could require changes to the network design, necessitating consideration of additional gauges.</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="4">• Identify any non-SADC-HYCOS real-time stations not considered in this project and evaluate suitability with respect to location and equipment for inclusion in the network design;
• Review and confirm additional non-SADC-HYCOS manual gauges included in the network design that require upgrading to real-time capability;
• Implement study to determine appropriate measurement and transmission technology for each gauge within the network;
• Install and utilise GSM transmission as primary method of communication;
• For manual measurements – establish procedure for data retrieval and transmission.
• Procure equipment supported by local suppliers (upgrade or replace equipment at existing real-time stations, as required).</td><td>Basin states/
SADC Secretariat / Interim ZAMCOM Secretariat</td></tr>
<tr><td>Benefits:</td><td colspan="4">Additional gauges will provide improved basin-wide monitoring capability at the required coverage for accurate flow forecasting.</td><td>National Hydrological Services and other agencies requiring hydrological data in all Basin States.</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">The work proposed under this Intervention Sheet (IS) has been kept separate from IS 3.1, as it will require a considerably larger investment (civil works and procurement of equipment) for upgrading of gauges not currently part of the SADC-HYCOS network. However, implementation could be conducted in association with the SADC-HYCOS project office, as this would build on the success of previous initiatives and would be more likely to receive the support of the Basin States. However, given the amount of work required, it is likely that a specialist consultant will be required to manage the process with the SADC-HYCOS project office and the interim ZAMCOM Secretariat.</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="5">The work proposed in this Intervention Sheet forms part of a broader recommendation for the establishment of a basin-wide flow forecasting system. It has therefore been assumed that this intervention would be conducted as part of a series of recommendations leading to the establishment of the flow forecasting system. However, in the event that this intervention is implemented alone, it would still lead to considerable benefit in terms of improved real-time flow data to assist informal forecasting.</td></tr>
<tr><td>Comments:</td><td colspan="5">• Manual communication may be acceptable where natural response times are sufficiently long for daily flow measurements to be adequate for forecasting.
• Use of gauges not owned or operated by the national hydrological services will require the consent and approval of the relevant authority for incorporation into the flow gauging network.</td></tr>
</table>

<table>
<tr><th colspan="6">ESTABLISHMENT OF RATING CURVES FOR KEY GAUGES</th></tr>
<tr><td>Intervention Sheet #</td><td>3.3</td><td>Timeframe:</td><td>Medium term</td><td>Budget range:</td><td>2-5 million USD</td></tr>
<tr><td>Linkages:</td><td colspan="5">Annex 3, Section 3.4, 3.5, 5.2</td></tr>
<tr><td>Concept:</td><td colspan="5">A comprehensive flow and precipitation monitoring network is required to provide real-time data for the proposed flow forecasting system.</td></tr>
<tr><td>Purpose:</td><td colspan="5">Development and implementation of programme for updating and maintaining of flow rating curves (relationships for calculation of flow from water level measurements).</td></tr>
<tr><td>Justification:</td><td colspan="5">In addition to functioning flow measurement and data transmission equipment, an essential aspect of managing a flow-gauging network is the establishment and regular updating of rating curves for the conversion of water level readings into flows. This has been an on-going issue with some SADC-HYCOS stations, for which accurate rating curves have never been established. Most stations within the Zambezi River basin are located at natural control sections, which often change with each flood season, necessitating that rating curves are updated after significant floods and at least annually. The value of a flow gauging network is dependent, to a large degree, on the accuracy of rating curves; otherwise only stage hydrographs can be reliably used. While NHSs are responsible for establishing and maintaining rating curves, throughout the basin there is generally a lack of both human capacity and equipment for undertaking this task. It is therefore important that as part of a programme for establishment of rating curves, capacity and equipment within the NHSs are strengthened.</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="3">Coordination for this intervention should be undertaken by the SADC Secretariat:
• Appoint a consultant to coordinate this programme in conjunction with the SADC Secretariat, as well as provide medium term assistance and training to NHSs.
• Plans for the establishment and regular updating of rating curves should be prepared in each country by the respective NHS. These plans should include: existing staff capacity and equipment, any additional personnel and equipment needs, training requirements and the proposed methodology and timeframe for establishment of rating curves.
• Conduct a review of plans prepared by NHSs with further feedback and discussion with NHSs where required. This review should include standardisation of methods, equipment needs, training requirements and overall capacity.
• Obtain funding for required equipment, procure equipment and implement basin wide programme for establishment of rating curves through the various NHSs, including training and support where required and as established in the steps listed above.</td><td colspan="2">Basin States/ SADC Secretariat</td></tr>
<tr><td>Benefits/ beneficiaries:</td><td colspan="3">The primary benefit of this recommendation is that accurate flow measurements can be obtained from the flow gauging network, which is essential for the development of an accurate flow forecasting system. Without accurate rating curves, only approximate flow forecasting will be possible. In addition, accurate rating curves will assist other potential uses such as water resources analysis.</td><td colspan="2">National Hydrological Services and other agencies requiring hydrological data in all Basin States.</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">Given the considerable amount of work required to establish rating curves over a wide range of flows and the high cost for purchase of the necessary equipment to carry out this work, it seems likely that specific assistance and support to the Member States will be necessary. It is therefore recommended that this intervention is coordinated by the SADC Secretariat with assistance from a consultant.</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="5">• The cooperation of Member States and existing forecasting agencies will be essential for this task to be successful.
• It may not be possible to define accurate rating curves at all locations, due to issues such as very wide floodplains during floods, dangerous conditions, etc.. These issues will have to be assessed during the project.
•
• Training and additional equipment will be needed in some countries to assist NHSs with undertaking the required field work. This training may delay full establishment of rating curves in these countries.</td></tr>
</table>

Comments:	To be useful for accurate flow forecasting, flow rating curves should ideally be established over a wide range of flows from low-flows during the dry season to flood flows during particularly wet years. Although initial establishment of rating curves is considered to be a medium term initiative, this intervention should be considered a continuous or long term initiative in the sense that continuous updating of rating curves will be required.

<table>
<tr><th colspan="6">ENHANCE PROCEDURES FOR COLLECTION OF RAINFALL DATA</th></tr>
<tr><td>Intervention Sheet #</td><td>3.4</td><td>Timeframe:</td><td>Short/ medium term</td><td>Budget range:</td><td>< 0.5 million USD</td></tr>
<tr><td>Linkages:</td><td colspan="5">Annex 3 report, Section 8.9</td></tr>
<tr><td>Concept:</td><td colspan="5">A comprehensive flow and precipitation monitoring network is required to provide real-time data for the proposed flow forecasting system.</td></tr>
<tr><td>Purpose:</td><td colspan="5">Enhance procedures for collecting data from the existing rain gauge networks by the National Meteorological Services (NMSs).</td></tr>
<tr><td>Justification:</td><td colspan="5">Currently, most precipitation measurement stations, which are owned by the respective NMSs in the basin, are read manually. Most measurements are transmitted by phone or sent by post on a monthly basis to the central NMS office in each country. For real time forecasting, measurements should arrive at the central forecast location as soon as possible after the measurement has been taken. To this end, a procedure needs to be agreed upon between SADC and the responsible National Meteorological Services (NMS's) to ensure timely delivery of data to the proposed flow forecasting centre.</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="4">Set up an addendum under the ZAMCOM agreement with the NMSs to ensure procedures are followed for real time transmission of precipitation measurements to the proposed flow forecasting centre. Arranging this as part of the ZAMCOM agreement will ensure that it becomes part of ZAMCOM's mandate and will give ZAMCOM control over data collection.

(1) Undertake a review of existing procedures (if any) in the basin for the exchange of data between NMSs.

• (2) Based on the results of the above review, develop recommendations for improvement of existing procedures, or establishment of new procedures that take into account the following (development of these procedures should be undertaken in consultation with the relevant NMSs): Timely transmission of data from rainfall gauges in the existing rainfall network to the forecasting centre. For real-time gauges the transmission should be direct from the gauge to the centre. For manual gauges, data from manual measurements could be transmitted to the forecasting centre via the NMSs.
• Rainfall measurements need to be communicated on a daily basis.</td><td>ZAMCOM Secretariat</td></tr>
<tr><td>Benefits / Beneficiaries:</td><td colspan="4">• The procedure will ensure timely provision of rainfall estimates to allow for flow forecasting without unnecessary loss of lead time. This is important, especially in the areas with short response times such as the Gwayi/Sanyati and Luangwa basins.
• The collected archive of rainfall data can be used to validate SRE and to establish new models, or (re)calibrate existing rainfall-runoff models.</td><td>• Basin-wide Disaster Management Units, Dam Operators with a fast responding upstream river system.
• Operators of the flow forecasting system</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">The addendum could be drafted by a consultant, but ratification of the agreement should be obtained by the ZAMCOM Secretariat</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="5">The assistance of the NMSs will be needed to develop the required procedures and their commitment will be required to ensure that the procedures are followed.</td></tr>
<tr><td>Comments:</td><td colspan="5">Interim measures to build stronger links between NMSs would be beneficial, but a formal agreement is needed for the proposed flow forecasting centre.

There is currently an existing Southern Africa NMS member organisation (under the auspices of the WMO) that coordinates activities between the NMSs in Southern Africa, including training and sharing of experience. This organisation should be included in the consultation for the development of procedures for the exchange of data as proposed in this intervention.</td></tr>
</table>

<table>
<tr><th colspan="6">UPGRADE RAIN GAUGE NETWORK FOR REAL-TIME CAPABILITY</th></tr>
<tr><td>Intervention Sheet #</td><td>3.5</td><td>Timeframe:</td><td>Medium/ long term</td><td>Budget range:</td><td>0.5 – 2 million USD</td></tr>
<tr><td>Linkages:</td><td colspan="5">Annex 3 report, Section 3.7 for the analysis and section 5.3 for recommendations</td></tr>
<tr><td>Concept:</td><td colspan="5">A comprehensive flow and precipitation monitoring network is required to provide real-time data for the proposed flow forecasting system.</td></tr>
<tr><td>Purpose:</td><td colspan="5">Upgrade and extend rain gauge network for real time capability.</td></tr>
<tr><td>Justification:</td><td colspan="5">Upgrading of the precipitation gauge coverage will result in sufficiently accurate rainfall estimates over basins where rainfall-runoff models need to be run in order to establish flow forecasts. This intervention will require close cooperation with NMSs, as well as their broad support.</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="4">Establish close cooperation with the NMSs in the basin to obtain their support and willingness for this intervention. Work with the NMSs to develop plans for the gradual upgrading of important manual stations to real-time. These plans should address the following key outcomes:
• Convert manually gauged stations to automatic by replacement of instrumentation. Besides an automatic tipping bucket rain gauge, a data logger, extension cables, a tripod, solar panel, weather proof housing and radiation shield are required.
• Convert manually transmitted readings to real time using GSM transmission.
• Establish sites for new gauges at protected locations such as police stations, schools, missions, hospitals & national parks. Investigate whether existing sites of wildlife authorities can be used.
• Equip approximately 1 in 5 new stations with sensors for temperature, humidity, and wind speed. Due to the relatively low spatial variability of radiation, global radiation estimates can be collected from existing synoptic stations at meteorological offices and airports. The global radiation estimates can be augmented with satellite estimates.</td><td>• Coordinated by SADC Secretariat / network upgraded by NMSs</td></tr>
<tr><td>Benefits / Beneficiaries:</td><td colspan="4">• Extending the network and upgrading to automatic measurements and transmission improves the quality of gauged rainfall over catchments to meet the requirements for the identified forecast locations.
• Improved catchment averaged rainfall improves capabilities for validation and bias correction of SRE.</td><td>• Dam Operators
• Power companies
• Disaster Management Units
• Water authorities
• NMSs</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">Implementation of this intervention shold be coordinated by the SADC Secretariat in association with the Interim ZAMCOM Secretariat. The following steps are proposed:
• Appointment of a consultant to investigate feasible siting options and to establish required number of rainfall stations according to the recommendations of this study (see Annex 3, section 6.3).
• Provide assistance to NMSs for the funding, procurement and installation of meteorological measurement equipment, including the purchase of new equipment and spare parts and the training of NMS staff.</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="5">• The extension and upgrading of the gauging network requires financing.
• The network requires maintenance and financing for operation and maintenance</td></tr>
<tr><td>Comments:</td><td colspan="5">Although updrading of manual stations to real-time status is recommended as a long-term measure for improvement of the precipitation monitoring network, Satellite Rainfall Estimation (SRE) is recommended in the short to medium term for the improvement of rainfall monitoring.</td></tr>
</table>

<table>
<tr><th colspan="6">IMPLEMENT APPROACH FOR USE OF SATELLITE RAINFALL ESTIMATIONS (SRE)</th></tr>
<tr><td>Intervention Sheet #</td><td>3.6</td><td>Timeframe:</td><td>Short term</td><td>Budget range:</td><td>< 0.5 million USD</td></tr>
<tr><td>Linkages:</td><td colspan="5">Annex 3 report, Chapter 5: validation analysis, Section 5.3 for recommendations</td></tr>
<tr><td>Concept:</td><td colspan="5">A comprehensive flow and precipitation monitoring network is required to provide real-time data for the proposed flow forecasting system.</td></tr>
<tr><td>Purpose:</td><td colspan="5">Implement approach for collection of Satellite Rainfall Estimation Data (TRMM 3B42 RT)</td></tr>
<tr><td>Justification:</td><td colspan="5">Analysis undertaken for this project indicates that SRE is accurate enough for operational flow forecasting in the Zambezi River Basin (see validation in Annex 3, Chapter 4) as an alternative to ground based measurement. SRE could be used to provide valuable rainfall observations, both in remote areas where operation and maintenance of an extensive rain gauge network is not feasible, and as an interim measure in areas where upgrading of manual gauges to real-time capability is required for operational forecasting. Furthermore selected SRE products have operational status and are made available with little delay between acquiring satellite information and availability of the product on the internet. This intervention could be implemented as a short term measure through the SADC Climate Services Centre, which would allow basin states to start receiving and benefitting from SRE data prior to the full establishment of ZAMCOM.</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="4">Develop procedures and software to download process and archive SRE products. At the time of writing, the TRMM 3B42 Real Time product is the most attractive for operational use.
Collect and archive alternative SRE products as well, in case TRMM 3B42RT is temporarily unavailable.
Establish procedure to regularly investigate change of quality and bias of existing products, and the emergence of new SRE products.
Consult with relevant NMSs to obtain their input and support for establishment of an approach for SRE in the basin, as well as the WMO Regional Specialised Meteorological Centre in Pretoria, South Africa.</td><td>Coordinated by SADC Secretariat, to be performed by water resources consultant, with expertise in remote sensing.</td></tr>
<tr><td>Benefits / Beneficiaries:</td><td colspan="4">Rainfall estimates could be provided by SRE for the entire basin, but would be most important in areas which are generally ungauged or sparsely gauged.
The rainfall estimates by SRE could be used to drive rainfall-runoff models in sparsely gauged basins (for recommended areas, see Annex 3, Section 5.3) and in other required areas with adequate gauges where upgrading of manual gauges to real-time will require some time and investment.</td><td>Users of the flow forecasting system in remote areas, Angola, Zambia, Luangwa basin. Particularly Disaster Management Units</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">SADC Secretariat to appoint consultant to undertake study and develop the required software.</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="5">SRE needs regular validation by ground truthing and bias corrections.</td></tr>
<tr><td>Comments:</td><td colspan="5">Note that this intervention should be undertaken in the context of a larger coordinated effort in establishing a comprehensive and consistent operational flow forecasting system.</td></tr>
</table>

<table>
<tr><th colspan="6">INTEGRATE EXISTING FLOW FORECASTING MODELS INTO A BASIN-WIDE FLOW FORECASTING SYSTEM</th></tr>
<tr><td>Intervention #</td><td>3.7</td><td>Timeframe:</td><td>Medium term</td><td>Budget range:</td><td>0.5-2 million USD</td></tr>
<tr><td>Linkages:</td><td colspan="5">Annex 3 report, Section 5.2 for recommendations</td></tr>
<tr><td>Concept:</td><td colspan="5">An integrated set of models is required to provide stakeholders with targeted forecast information.</td></tr>
<tr><td>Purpose:</td><td colspan="5">Integrate existing models in the Zambezi region into a flow forecasting system.</td></tr>
<tr><td>Justification:</td><td colspan="5">There are currently a number of flow routing or forecasting models available for the Zambezi Basin, which are likely to be suitable for use in a basin-wide flow forecasting system. These models contain local knowledge and are known to the authorities that own and use them. By integrating these existing models into a flow forecasting system, these authorities will recognize and understand the functionality of such a system. As a result, the sustainability of the forecasting system will increase, as it will be easier for the authorities to operate and enhance the underlying models. Furthermore, by integration, models can be connected together.

Ideally, an open (free) flow forecasting shell such as Delft-FEWS is used for integration of models. This highly configurable forecasting shell software imports and converts data for input to models, runs models in sequence and presents the model results operationally. It also provides warnings and HTML reports for use on web-sites (examples can be found in Annex 3, Section 8.1, Box 1 and 2). Security and access is controlled according to the needs and requirements of each stakeholder. The ownership of models would be retained by the original authority responsible for their development. The centralised forecasting centre would work closely with these authorities for the on-going improvement/ updating of these models.</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="4">(1) Evaluate available software options for integration of different types of models into a single flow forecasting system (such as Delft FEWS) and identify a preferred option. As part of this evaluation, criteria for the software to be used for the flow forecasting system will be developed.

(2) Undertake consultation with existing model owners to obtain feedback on proposed approach and secure buy-in for integrated forecasting model approach.

(3) Collect existing models and evaluate each model with respect to its suitability for flow forecasting as part of a basin-wide flow forecasting system.

(2) Integrate existing models into the proposed flow forecasting system. Suitable existing models are listed below with the authority that owns and operates the model (taken from Annex 3 section 7.2):
• ZRA Regression and recession models for forecasting of inflows at Lake Kariba (SADC/ZRA)
• Mike-11 model upstream of Cahora Bassa to the river mouth (ARA Zambezi)
• WRSM2000 model (currently component of KAFRIBA) for rainfall-runoff upstream of Itezhi-Tezhi and the Kafue Gorge (ZESCO)
• New InfoWorks model of the Kafue Flats (ZESCO, under development)
• Trigger based warning system on Shire and Ruo Rivers (Ministry of Water Development and Irrigation, Malawi)</td><td>• Coordinated by SADC Secretariat, model integration to be performed by consultancy services</td></tr>
<tr><td>Benefits / Beneficiaries:</td><td colspan="4">• Knowledge, encapsulated in existing models is preserved.
• Integration of models will lead to recognition of the flow forecasting system by the authorities that operate the models.</td><td>• Owners of the existing models will benefit from each other’s models by integration.
• Basin-wide users of the flood forecasting system</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">This intervention would coordinated by the SADC Secretariat, but consultancy services would be needed for most of the required actions.
• Appoint a consultant to evaluate software options, undertake consultation with model</td></tr>
</table>

	owners in conjunction with the SADC Secretariat and collect existing available models. • • The Consultatnt would be required to integrate models into the flow forecasting system. Note that this should be undertaken in the context of a larger coordinated effort in establishing a comprehensive and consistent operational flow forecasting system
Specific assumptions/ risks:	• The model owners need to be willing to make their models available for use in the flow forecasting system.
Comments:	This intervention would require the approval of stakeholders and therefore is considered to be a medium term intervention.

DEVELOP NEW FLOW FORECAST MODELS AND INTEGRATE WITH EXISTING MODELS

Intervention Sheet #	Timeframe:	Budget range:
3.8	Medium - long term	2 – 5 million USD

Linkages:	Annex 3, Section 6.3 for recommendations	
Concept:	An integrated set of models is required to provide stakeholders with targeted forecast information	
Purpose:	Develop new models and integrate them with the existing models in the flow forecasting system (e.g. based on Delft-FEWS, see intervention 3.7)	
Justification:	Strengthening of existing model capabilities in the proposed flow forecasting system will ensure that the forecast requirements of Dam Operators, energy companies and disaster management units are met. The required new models serve forecasts with different lead times. These models include rainfall-runoff models, flash flood guidance, hydrodynamic and river routing models for short lead times; reservoir models for medium-range and seasonal lead times; and water balance models for seasonal lead times. The new models need to be coupled with the existing models in the flow forecasting shell (such as Delft-FEWS, see also intervention 3.7). The result should be a system wherein a sequence of models can be run operationally, feeding each other with input (e.g. a hydrological model, providing input to a hydraulic model, providing input to a 2D inundation model).	
Actions/ Responsibilities:	Develop the following new models to meet the forecast requirements of the involved stakeholders. The models are listed with the forecast lead time for which it is required (taken from Annex 3 Section 6.3): • Routing models for the Gwayi, Sanyati, Luangwa, Manyame, Luenya river (short term) • Hydrodynamic routing model from Katima Mulilo to Victoria Falls (short lead time) • Hydrodynamic routing model from the outlet of Kariba to Cahora Bassa (short lead time) • Rainfall-runoff model for Sanyati and Gwayi (short term) • Rainfall-runoff model for Luangwa, e.g. based on concepts of research model (Winsemius, 2009) (short lead time) • Rainfall runoff model for Manyame and Luenya Rivers (short - medium lead time) • Flash Flood Guidance procedures for the Gwayi/Sanyati catchments linked to the Regional Flash-Flood Guidance System – Southern Africa project by WMO (short lead time) • Reservoir models for operation of Itezhi-Tezhi and Kafue Gorge, Kariba and Cahora Bassa (medium lead time) • Reservoir routing model for Lake Malawi including wind effects (medium lead time) • Water balance model for the complete Zambezi basin (seasonal)	SADC Secretariat to coordinate; basin states to contract water resources specialists to establish new models and to integrate them in the flow forecasting shell
Benefits / Beneficiaries:	Improved capabilities of the proposed flow forecasting system to serve the requirements of all stakeholders.	Basin-wide users of the flood forecasting system
Means of implementation:	Consultancy services (coordinated by the SADC Secretariat). Note that this should be undertaken in the context of a larger coordinated effort in establishing a comprehensive and consistent operational flow forecasting system.	
Specific assumptions/ risks:	Any new model development needs to be accompanied by human capacity building to use the model in the flow forecasting system (see also Recommendation 3.15)	
Comments:	Development of capacity within the existing research institutions/ universities would help to ensure the long-term sustainability of the forecasting system. However, it is recommended that modelling work is tendered out to consultants so that existing centres of excellence that undertake consultancy services, as well as other consultants, would have the opportunity to submit tenders, either together or separately.	

<table>
<tr><th colspan="6">INVESTIGATE NEW FORECASTING CAPABILITIES IN COLLABORATION WITH RESEARCH INSTITUTES AND UNIVERSITIES</th></tr>
<tr><td>Intervention Sheet #</td><td>3.9</td><td>Timeframe:</td><td>Long term</td><td>Budget range:</td><td>< 0.5 million USD annual costs</td></tr>
<tr><td>Linkages:</td><td colspan="5">Annex 3 report, Section 8.3.3</td></tr>
<tr><td>Concept:</td><td colspan="5">An integrated set of models is required to provide stakeholders with targeted forecast information.</td></tr>
<tr><td>Purpose:</td><td colspan="5">Investigate new forecasting capabilities in collaboration with research institutes and universities</td></tr>
<tr><td>Justification:</td><td colspan="5">Hydrological and hydraulic models, precipitation forecasting and satellite information are rapidly evolving. New developments can improve the accuracy and versatility of the proposed flow forecasting system. To keep track of such new developments and ensure implementation in the flow forecasting system, strong links with research institutes and universities are needed. In particular WaterNet (regional network of universities and research institutes in Southern Africa) can offer a strong link with universities and positions for MSc and PhD research. MSc and PhD researchers can investigate potential improvements of the flow forecasting system using new models, new techniques, and new satellite information. The link with research institutes and universities could also be applied to other key areas in this project, such as dam management.</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="4">• Establish link with WaterNet. Amongst its activities, WaterNet offers financing options for PhD research and MSc programmes throughout the region, organizes short courses and annual symposia.
• Establish links with universities in the region</td><td>ZAMCOM Secretariat</td></tr>
<tr><td>Benefits:</td><td colspan="4">• The flow forecasting system will benefit from new technology, which improves accuracy and versatility.
• By continuous improvement, the flow forecasting system will be recognized as being state of the art, also after its establishment.</td><td>• Basin-wide users of the flood forecasting system.
• ZAMCOM and operators of the flow forecasting system.</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">Establish research collaboration with research institutes and universities, with regular MSc studies and PhD studies being implemented (coordination by SADC Secretariat until ZAMCOM fully established)</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="5">Developed human capacity is often lost to foreign countries because of job opportunities and potential to further capacity development. Therefore, the flow forecasting centre needs to provide an attractive environment for both research and operational work.</td></tr>
<tr><td>Comments:</td><td colspan="5">• Note that the budget mentioned above is considered as an annual investment.
• At present, it is likely that development of new models and improvements to forecasting techniques will require a blend of international and regional skills. However, by establishing strong links with universities and by creating opportunities for MSc and PhD students, it is likely that regional expertise in this area will grow over time.</td></tr>
</table>

<table>
<tr><th colspan="6">EXPAND PRECIPITATION FORECASTING CAPABILITY OF SADC CLIMATE SERVICES CENTRE</th></tr>
<tr><td>Intervention Sheet #</td><td>3.10</td><td>Timeframe:</td><td>Medium Term</td><td>Budget range:</td><td>0.5 – 2 million USD</td></tr>
<tr><td>Linkages:</td><td colspan="5">Annex 3 report, Section 7.4.4</td></tr>
<tr><td>Concept:</td><td colspan="5">Precipitation forecasts are required to meet the flow forecast requirements at the short, medium and seasonal time scales.</td></tr>
<tr><td>Purpose:</td><td colspan="5">Integrate existing capabilities in precipitation forecasting through SADC Climate Services Centre (former Drought Monitoring Centre) in collaboration with RSMC Pretoria (or other regional centres with similar capabilities), and National Meteorological Services.</td></tr>
<tr><td>Justification:</td><td colspan="5">Current capabilities in precipitation forecasting are well established in the Southern African region. The National Meteorological Services in the region, and in particular the WMO Regional Specialised Meteorological Centre in Pretoria has well developed precipitation forecasting capabilities. Within SADC the annual SARCOF has an acknowledged role in establishing seasonal forecasts, with the Climate Services Centre (former Drought Monitoring Centre) updating and disseminating the seasonal outlooks made by SARCOF on a regular basis.</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="4">• Extend the role of the SADC Climate Services Centre (former Drought Monitoring Centre) in the coordination of short term, medium range and seasonal precipitation forecasting in SADC region, including the Zambezi basin.
• Establish close collaboration between the SADC Climate Services Centre and the RSMC in Pretoria to use precipitation forecasts at short, medium and seasonal time scales run at RSMC Pretoria to serve as inputs for flow forecasting.
• Strengthen collaboration with NMSs to utilise precipitation forecasts where available and to integrate knowledge from forecasters at the national centres.</td><td>• SADC Secretariat and Climate Services Centre
• SADC Climate Services Centre
• SADC Climate Services Centre</td></tr>
<tr><td>Benefits / Beneficiaries:</td><td colspan="4">• Through integrating existing capacities within the region in precipitation forecasting, flow forecasting can benefit from existing investments and knowledge.
• Linking to the National Meteorological Services, as well as the RSMC Pretoria will ensure that ongoing advances in precipitation forecasting at local, regional and global scale are introduced to the flow forecasting system.
• Strengthening the role of the SADC Climate Services Centre will further its acknowledged role in coordinating meteorological forecasts in the region.</td><td>• Basin-wide users of flow forecasting system
• Basin-wide users of flow forecasting system
• SADC Climate Services Centre</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">Implementation to be coordinated by SADC Secretariat, as follows
• Establish agreements and protocols to exchange data
• Establish a protocol that allows for fast implementation of new improved forecasting methods
• Establish a dedicated internet connection for data exchange</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="5">• The network infrastructure (i.e. internet connections) between organisations will need to be sufficient to allow exchange of the expected significant amount of data involved.
• Although duplication of efforts is avoided, this approach does create dependencies on external institutions for providing critical inputs in the forecast process.</td></tr>
<tr><td>Comments:</td><td colspan="5">Note that this should be undertaken in the context of a larger coordinated effort in establishing a comprehensive and consistent operational flow forecasting system.</td></tr>
</table>

<table>
<tr><th colspan="6">REVIEW FORECAST LOCATIONS AND REQUIREMENTS FOR STAKEHOLDERS</th></tr>
<tr><td>Intervention Sheet #</td><td>3.11</td><td>Timeframe:</td><td>Medium Term</td><td>Budget range:</td><td>< 0.5 Million USD</td></tr>
<tr><td>Linkages:</td><td colspan="5">Annex 3 report, Section 2.2</td></tr>
<tr><td>Concept:</td><td colspan="5">Basin-wide flow forecasting and exchange of information between stakeholders results in improved management of the water resources of the Zambezi River basin.</td></tr>
<tr><td>Purpose:</td><td colspan="5">To review and refine forecast locations and requirements for stakeholders and develop procedures for use of forecasts.</td></tr>
<tr><td>Justification:</td><td colspan="5">A basin-wide flow forecasting system will provide key information to stakeholders across the Zambezi River basin. Each stakeholder requires information tailored to meet specific needs. To utilitse these forecasts in such a way that they provide maximum benefit to the stakeholder, the information provided by the forecast system should be fine-tuned to meet the requirements. Procedures need to be developed with regard to when critical information is conveyed from the forecast system to the stakeholders, as well as how these stakeholders will use the information to guide and improve their operational process..</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="4">• Review and refine stakeholders and forecast requirements
• Develop procedures for use of forecasts</td><td>• Basin states / SADC Secretariat
• Basin states / SADC Secretariat</td></tr>
<tr><td>Benefits / Beneficiaries</td><td colspan="4">• Forecasts provided by forecasting system cater to the full needs of all stakeholders
• Procedures developed detail how forecast information is used by each stakeholder, leading to improvements in the operational process.</td><td>• Users of forecast information, including Dam operators and Disaster Management Units.</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">Requirements to be identified through stakeholder consultation. It is recommended that stakeholders are closely involved during the development of operational forecasting capabilities, thus ensuring an interactive process through which stakeholder needs are piloted, discussed and refined.</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="5">Full commitment of stakeholders to the development of a centralised forecasting system that will meet their needs.</td></tr>
<tr><td>Comments:</td><td colspan="5">This intervention involves fine-tuning of forecast requirements and forecast locations, which could have some impact on the scope of Interventions 3.1 to 3.8. It is therefore important that this implemented as a short-term measure.</td></tr>
</table>

<table>
<tr><th colspan="6">ESTABLISH DATA SHARING AGREEMENT BETWEEN DAM OPERATORS AND OTHER STAKEHOLDERS</th></tr>
<tr><td>Intervention Sheet #</td><td>3.12</td><td>Timeframe:</td><td>Long Term</td><td>Budget range:</td><td>< 0.5 million USD</td></tr>
<tr><td>Linkages:</td><td colspan="5">Annex 3, Sections 3.5.4, 5.2.3</td></tr>
<tr><td>Concept:</td><td colspan="5">A comprehensive flow and precipitation monitoring network is required to provide real-time data for the proposed flow forecasting system.</td></tr>
<tr><td>Purpose:</td><td colspan="5">Establish an agreement and protocol between Member States for the sharing of hydrological and meteorological data.</td></tr>
<tr><td>Justification:</td><td colspan="5">Establishment of a basin-wide flow forecasting system will require the sharing of real-time hydrological and meteorological data and information between National Hydrological Services (NHSs), National Meteorological Services, forecasting agencies, Dam Operators and the permanent ZAMCOM Secretariat, once established. At present, there are no formal agreements for the sharing of data between these parties, except between the Namibia DWA and ZRA. This situation is currently of greatest concern for downstream countries which need information on upstream rainfall and flows for their forecasting. The agreement should include a protocol on how the data will be shared and in what format and any agreed charges for the data or agreed contributions to the collection of this data and any agreed charges for the data or agreed contributions to the collection of this data, etc.</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="4">Establishment of a data and information sharing agreement between NMSs, NHSs, Dam Operators and forecasting agencies. The agreement should include details of:
• the data and information to be shared;
• the format of the data and whether the data is in its raw form or otherwise aggregated or interpreted;
• the means and manner in which the data will be collected;
• the means of transmission, the frequency of transmission and the timing of transmission after observation (if not real-time);
• any applicable data quality assurance procedures;
• the cost for data (if any);
• the organisations and departments responsible for the sharing of data;
• the staff members responsible within each organisation, updated at least annually.
• any other important issues, such as ownership of data, integrity of data and intellectual property rights.</td><td>SADC Secretariat</td></tr>
<tr><td>Benefits/ beneficiaries:</td><td colspan="4">The benefits of data sharing would be many. Even without establishment of a basin-wide forecasting system, establishment of a basin-wide data sharing agreement would provide information on rainfall and flows that could be used in existing forecasting systems, both formal and informal. The benefits would therefore include optimised power generation and improved disaster management among others.</td><td>All Member States</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">Drafting of a basin-wide data sharing agreement and protocol could be prepared by an external specialist, but the project would have to be led and undertaken by the SADC Secretariat. While establishing such an agreement would be significantly easier following ratification of the ZAMCOM agreement, it is recommended that establishment of this agreement proceed irrespective of progress on the ratification of the ZAMCOM Agreement by all basin states.</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="5">A critical assumption for the establishment of a basin-wide data sharing agreement is that all member states agree on the importance and value of data sharing and make a commitment to uphold the agreement for the benefit of all.</td></tr>
<tr><td>Comments:</td><td colspan="5"></td></tr>
</table>

<table>
<tr><th colspan="7">UPGRADE ZAMWIS TO A FULLY OPERATIONAL HYDROLOGICAL DATABASE</th></tr>
<tr><td>Intervention Sheet #</td><td>3.13</td><td>Time frame:</td><td>Short term</td><td>Budget range:</td><td colspan="2">0.5 - 2 million USD</td></tr>
<tr><td>Linkages:</td><td colspan="6">Annex 3 report, Section 8.4</td></tr>
<tr><td>Concept:</td><td colspan="6">A comprehensive flow and precipitation monitoring network is required to provide real-time data for the proposed flow forecasting system.</td></tr>
<tr><td>Purpose:</td><td colspan="6">Upgrade ZAMWIS to be a fully operational hydrological database for the Zambezi Basin</td></tr>
<tr><td>Justification:</td><td colspan="6">Real-time sharing of information between stakeholders will provide a strong foundation for operational flow forecasting. An operational hydrological database will provide real-time information about the state of the Zambezi basin. This will assist in improved decision making and will form the foundation for flow forecasting.</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="5">Establish agreements with member states on real-time sharing of flow and precipitation observation data (as an addendum to the ZAMCOM Agreement, see also intervention 3.12).
Convert ZAMWIS database into agreed standardized formats
Establish the database at the flow forecasting centre. If ZAMCOM is selected as the location, the operational hydrological database could be established at the office of the Interim ZAMCOM Secretariat.
Obtain on-going feedback and support from relevant stakeholders, such as the NMSs, NHSs, and dam operators.</td><td>SADC / ZAMCOM Secretariat
ZAMCOM Secretariat, with consultancy from specialists</td></tr>
<tr><td>Benefits / Beneficiaries:</td><td colspan="5">Sharing of information in real-time will lead to improved management of the water resources of the Zambezi</td><td>Basin-wide Dam Operators, energy companies, Disaster Management Units</td></tr>
<tr><td>Means of implementation:</td><td colspan="6">The draft addendum could be drafted by a consultant for implementation by the Interim ZAMCOM Secretariat (see intervention 3.12)
Standardization of data and establishment of an operational database through consultancy services.</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="6">The owners need to be willing to make their data available for use in the operational hydrological database
Sustainable receipt of real time data for input into ZAMWIS depends on commitments by national hydrological and meteorological services to maintain and operate rainfall and flow gauges.</td></tr>
<tr><td>Comments:</td><td colspan="6">In addition to flow forecasting, upgrading of ZAMWIS is also required for other applications such as dam management. The actions presented here should therefore be combined with the actions proposed in other areas of this study.</td></tr>
</table>

<table>
<tr><th colspan="7">ESTABLISH BASIN-WIDE FLOW FORECASTING CENTRE</th></tr>
<tr><td>Intervention Sheet #</td><td>3.14</td><td>Timeframe:</td><td>Long Term</td><td>Budget range:</td><td colspan="2">< 0.5 million USD capital investment
0.5 – 2 million USD annual costs</td></tr>
<tr><td>Linkages:</td><td colspan="6">Annex 3 report, Chapter 8</td></tr>
<tr><td>Concept:</td><td colspan="6">A basin-wide flow forecasting centre provides and disseminates forecasts to all stakeholders for the Zambezi at the short, medium and seasonal time scales.</td></tr>
<tr><td>Purpose:</td><td colspan="6">Establish a basin-wide flow forecasting centre to provide flow forecasts across the Zambezi basin</td></tr>
<tr><td>Justification:</td><td colspan="6">To allow sustainable operation of a basin wide foresting system providing information to all stakeholders in the Zambezi basin, an operational forecasting centre is required. This centre should have adequate capabilities in terms of human resources and infrastructure to ensure that high quality forecasts can be produced. The flow forecasting centre for the Zambezi basin should be a key activity of the permanent ZAMCOM Secretariat as per the provisions of the ZAMCOM Agreement, Articles 6 and 15.</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="5">While the role and functions of the flow forecasting centre would be directly linked to the permanent ZAMCOM Secretariat, the flow forecasting centre would not necessarily need to be situated at the same location as ZAMCOM.
• Undertake consultation with each of the basin states to determine preferences for the location of the flow forecasting centre.
• Conduct an evaluation of the locations proposed by the basin statesagainst the important technical criteria identified in Section 8.3 of the Annex 3 Report (i.e the technical advantages and disadvantages of each potential location).
• Identify the most suitable location and arrangement for the flow forecasting centre (situated at the same location as ZAMCOM or at a different location), including selection of a suitable building or premises.
• Establish under the permanent ZAMCOM Secretariat (if established) a team of specialists to form the operational forecasting team. The team of experts is detailed in Annex 3, Section 8.3.2.
• Establish internal forecasting and hydrologist training programmes to ensure the capacities for the forecasting team are sustained.
• Establish dedicated hardware infrastructure for operation of the forecasting system. These requirements are detailed in Annex 3, Section 8.5.
• Establish network infrastructure to meet the requirements of the forecasting system. These requirements are detailed in Annex 3, Section 8.5.</td><td>• SADC Secretariat in conjunction with Interm ZAMCOM Secretariat or alternatively the permanent ZAMCOM Secretariat, if established.</td></tr>
<tr><td>Benefits / Beneficiaries:</td><td colspan="5">• A well equipped forecasting centre, with the required human capabilities and infrastructure will ensure that reliable forecasting can be made sustainably. The forecasting centre will provide additional strength to ZAMCOM’s mandate.</td><td>• ZAMCOM Secretariat
• Basin-wide users of forecasting system</td></tr>
<tr><td>Means of implementation:</td><td colspan="6">Coordination for the implementation of this intervention could be undertaken by the permanent ZAMCOM Secretariat (if established) or the SADC Secretariat in conjunction with the interim ZAMCOM Secretariat.
• Establish ZAMWIS at the Interim ZAMCOM Secretariat (see intervention 3.13) as a basis for the flow forecasting system.
• Identify a suitable location and premises for the flow forecasting centre.
• Establish a team of specialists to run and configure the flow forecasting system
• Establish required hardware and network connections
• Implement the flow forecasting system, along with interventions 3.7 until 3.13 and 3.16. This will require consultancy services (sheet 3.16) which should be performed in close collaboration with the team of experts. In this way, the experts will learn how to (re)configure the forecasting system and how to add or change features.</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="6">Requires continued commitment and due to annual costs, continued financial support to ensure sustainable operation.</td></tr>
</table>

<table>
<tr><th colspan="6">EXTEND ROLE OF FLOW FORECASTING CENTRE TO INCLUDE TRAINING AND RESEARCH</th></tr>
<tr><td>Intervention Sheet #</td><td>3.15</td><td>Time frame:</td><td>Long Term</td><td>Budget range:</td><td>< 0.5 million USD</td></tr>
<tr><td>Linkages:</td><td colspan="5">Annex 3 report, Section 8.3.3</td></tr>
<tr><td>Concept:</td><td colspan="5">A basin-wide flow forecasting centre provides and disseminates forecasts to all stakeholders for the Zambezi at the short, medium and seasonal time scales.</td></tr>
<tr><td>Purpose:</td><td colspan="5">Extend the role of the flow forecasting centre to include research and education to attract and retain regional talent in precipitation and flow forecasting.</td></tr>
<tr><td>Justification:</td><td colspan="5">The operation of the flow forecasting centre, as well as the continued development of the forecasting methods used can be sustained by extending the role of the flow forecasting centre to establish it as a centre of excellence for this field. Staff from different stakeholders (Dam Operators, Disaster Management Units) can be seconded to the centre for short periods of time to ensure the involvement of stakeholders and the recognition of their needs, as well as facilitating the incorporation of new forecasting methods into the operational domain. The centre of excellence should also provide training of staff from stakeholders across the basin, so that the anticipated benefits of the use of forecasts are sustained.</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="4">• Develop training facilities and programmes within the flow forecasting centre.
• Implement programmes to allow exchange of staff between the forecasting centre and stakeholders.
• Establish connections with universities/WaterNet (research on new developments to be implemented in the flow forecasting system)
• Establish links with national and international forecasting institutions to assist with research, training and the on-going development of staff members at the flow forecasting centre.</td><td>• ZAMCOM Secretariat
• ZAMCOM Secretariat (performed by specialists)
• ZAMCOM Secretariat</td></tr>
<tr><td>Benefits / Beneficiaries</td><td colspan="4">• As a recognised centre of excellence within the Zambezi basin, the forecasting centre will attract skilled staff and ensure that developments in forecasting methods are efficiently brought into operations. This will also allow for collaboration with other forecast centres.
• Exchange of staff between the centre and stakeholders will ensure that stakeholders obtain extensive knowledge of the service provided by the system, as well as providing a mechanism through which their requirements for continued improvements to the service are incorporated.</td><td>• Basin wide forecasting centre
• Universities and Research institutes</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">• ZAMCOM to appoint consultants to assist with establishing training programmes
• ZAMCOM to facilitate connection with WaterNet education programmes and universities</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="5"></td></tr>
<tr><td>Comments:</td><td colspan="5"></td></tr>
</table>

<table>
<tr><th colspan="6">ESTABLISH FORECASTING SYSTEM USING FLEXIBLE OPERATIONAL PLATFORM</th></tr>
<tr><td>Intervention Sheet #</td><td>3.16</td><td>Time frame:</td><td>Long Term</td><td>Budget range:</td><td>0.5 – 2 million USD</td></tr>
<tr><td>Linkages:</td><td colspan="5">Annex 3 report, Section 8.9</td></tr>
<tr><td>Concept:</td><td colspan="5">A basin-wide flow forecasting centre provides and disseminates forecasts to all stakeholders for the Zambezi at the short, medium and seasonal time scales.</td></tr>
<tr><td>Purpose:</td><td colspan="5">Implement an operational forecasting system based on a flexible and open operational forecasting platform.</td></tr>
<tr><td>Justification:</td><td colspan="5">Requirements for operational forecasting by the stakeholders will change over time. Additionally the models and methods available for precipitation forecasting are a subject of continued research and development. The software that is used for the operational forecasting system should be flexible enough to allow for incorporation of these changes by the staff at the flow forecasting centre.

It is recommended that a flexible software platform, such as Delft-FEWS is used as the open flow forecasting shell (see also interventions 3.8 and 3.9)</td></tr>
<tr><td>Actions/ Responsibilities:</td><td colspan="4">• Implement forecasting system software that is flexible for integration of a wide range of (hydrological) models
• Implement forecasting system software that is flexible for integration of data from different external sources, including observed levels and flows and meteorological data.
• Implement forecasting system software that has extensive capabilities for visualisation and dissemination of information to users.
• Implement forecasting system software that allows access to data and results both at the central forecasting location and at the offices of the stakeholders.</td><td>All listed actions are the responsibility of the ZAMCOM Secretariat but are to be implemented by specialists.</td></tr>
<tr><td>Benefits: / Beneficiaries</td><td colspan="4">• Existing models used in operational forecasting systems across the Zambezi Basin can be integrated, ensuring that the extensive knowledge and experience vested in those models is sustained.
• New developments in models and data can be easily incorporated to answer to the changing needs of the stakeholders.
• A distributed approach whereby the system can be accessed both centrally and remotely will allow all stakeholders to be involved in the forecast process.</td><td>• Owners of the existing model can benefit from the integration of each other's models.
• ZAMCOM secretariat
• Basin-wide users of the flood forecasting system</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">Consultancy services in close collaboration with the team of specialists at the permanent ZAMCOM Secretariat (see intervention 3.14). Note that this should be undertaken in the context of a larger coordinated effort in establishing a comprehensive and consistent operational flow forecasting system.</td></tr>
<tr><td>Specific assumptions/ risks:</td><td colspan="5"></td></tr>
<tr><td>Comments:</td><td colspan="5">• Flexible and open forecasting platforms have been developed and implemented at several operational forecasting centres across the world, and these can be adapted to the requirements in the Zambezi basin.</td></tr>
</table>

References

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. (1998). FAO Irrigation and Drainage Paper No. 56 - Crop Evapotranspiration, Food and Agriculture Organization.

Beilfuss, R. (2001). Prescribed flooding and restoration potential in the Zambezi Delta, Working Paper #3, Program for the Sustainable Management of Cahora Bassa Dam and the Lower Zambezi Valley.

Beilfuss R, dos Santos D. (2001). "Patterns of Hydrological Change in the Zambezi Delta, Mozambique".

Burrough, P. and McDonnell, R. A. (1988): Principle of Geographical Information Systems, Oxford University Press, New York.

Carsell, K. M., Pingel, N. D. and Ford, D. T. (2004). Quantifying the benefit of a flood warning system. *Natural Hazards Review*, 5, 131-140.

Cloke H.L, and Pappenberger F. (2009). Ensemble flood forecasting: A review, *Journal of Hydrology* 375: 613-626.

Day, G.N. (1985). Extended Streamflow Forecasting Using NWSRFS, *Journal of Water Resources Planning and Management*. ASCE, 111(2), 157-170.

Namibia Department of Water Affairs, Namibia, Hydrology Division. (2004). Draft Report on the 2004 Floods in the Upper Zambezi River.

DHI Water Environment Health, CONSULTEC Consultores Associados Lda. (2008). *Modelo de Aviso e Controlo de Cheias na Bacia do Rio Zambeze em Moçambique (Early Warning and Flood Control Model for Zambezi River Basin in Mozambique)*. Final Report for ARA Zambezi, Mozambique.

Doblas-Reyes, F. J., M. Déqué, and J. P. Piedelièvre. (2000). *Multi-model spread and probabilistic seasonal forecasts in PROVOST*. Quart. J. Roy. Meteor. Soc., **126**, 2069–2088.

Graham, R. J., M. Gordon, P. J. McLean, S. Ineson, M. R. Huddleston, M. K. Davey, A. Brookshaw, and R. T. H. Barnes. (2005). *A performance comparison of coupled and uncoupled versions of the Met Office seasonal prediction general circulation model*. Tellus, **57A**, 320–319.

IRD and BRL Ingénierie. (2004). *Pollution Monitoring and Management on the Zambezi River - Description of Completed Hydrological Gauging Stations with Special Reference to the Instrumentation Supplied*. Technical Report No 2 prepared for the French Fund for the Global Environment (FFEM)/ French Development Agency (AFD).

Kagan, R. (1972) Planning the spatial distribution of hydrometeorological stations to meet an error criterion, in Casebook on Hydrological Network design practice, Geneva.

Kgatuke, M.-J., W. A. Landman, A.F. Beraki**,** M. P. Mbedzi. (2008). Internal variability of the RegCM3 over South Africa, *Int., J. Climato.,* **28**, 504-526.

Krishnamurti, T. N., C. M. Kishtawal, Z. Zang, T. LaRow, D. Bachiochi, E. Williford, S. Gadgil, and S. Surendran. (2000). Multimodel ensemble forecasts for weather and seasonal climate. *Journal of Climate*, **13**, 4196-4216.

Landman, W. and A. Beraki. (2010). Multi-model forecast skill for mid-summer rainfall over southern Africa, *International Journal of Climatology,* n/a. doi: 10.1002/joc.2273.

Landman, W. A., M.-J. Kgatuke, M. Mbedzi, A. Beraki**,** A. Bartman & du Piesanie A. (2009). Performance comparison of some dynamical and empirical downscaling methods for South Africa from a seasonal climate modelling perspective *Int. J. Climat.,* **29**, 1535-1549.

Landman, W.A., and S.J. Mason. (1999). *Operational long-lead prediction of South African rainfall using canonical correlation analysis. Int., J. Climato.*, **19**, 1073-1090.

Malawi Ministry of Irrigation and Water Development. (2005). *Flood Warning System for the Lower Shire Valley for 2005/2006 Flood Season.*

Molteni, F., *et al.* (2007). ECMWF Seasonal Forecast System 3, CLIVAR Exch., **43**, 7–9.

Murwira, A., Mazvimavi, D. (not dated). *Strategic and Optimum Network Design for the SADC-HYCOS Phase II Project.* Final Report.

NVE (Norwegian Water Resources and Energy Directorate). (2003). *Quality Check - Historical Hydrological Data in Angola*. Report prepared for Angolan National Directorate of Water, DNA.

Oldenborgh GJ van Balmaseda MA. Ferranti L. Stockdale TN. Anderson DLT. (2005). Did the ECMWF seasonal forecast model outperform statistical ENSO forecast models over the last 15 years? J. Climate. **18.** 3240-3249.

Palmer, T. N., A. Alessandri, U. Anderson, P. Cantelaube, M. Davey, P. Délécluse, M. Déqué, E. Díez, F. J. Doblas-Reyes, H. Feddersen, R. Graham, S. Gualdi, J. -F. Guérémy, R. Hagedorn, M. Hoshen, N. Keenlyside, M. Latif, A. Lazar, E. Maisonnave, V. Marletto, A. P. Morse, B. Orfila, P. Rogel, J. -M. Terres, and M. C. Thomson. (2004). Development of a European ensemble system for seasonal to inter-annual prediction (DEMETER). *Bulletin of the American Meteorological Society*, **85**, 853–872.

Rautenbach C. J deW., Smith I. N. (2001). Teleconnections between global sea-surface temperatures and the interannual variability of observed and model simulated rainfall over southern Africa, *Journal of Hydrology*, 254: 1-15.

Roberts N.M., Cole S.J., Forbes R.M., Moore R.J., Boswell D. (2008). Use of high-resolution NWP rainfall and river flow forecasts for advance warning of the Carlisle flood, north-west England, *Meteorological Applications*.

Renner M., Werner M.G.F., Rademacher S., Sprokkereef. E., Verification of ensemble flow forecasts for the River Rhine. (2009). *Journal of Hydrology*, 376:463-475.

Roulin, E. (2007). Skill and relative economic value of medium-range hydrological ensemble predictions, *Hydrol. Earth Syst. Sci.*, 11, 725–737.

Rutashobya, D.G. and Mensah, J.W. (2002). *SADC-HYCOS Evaluation Mission Report.* Report prepared for SADC and the European Union.

SADC Water Sector Coordinating Unit. (2002). *Consolidation and Expansion of the Hydrological Cycle Observing System in the SADC Sub-Regiion (SADC-HYCOS).* Implementation Document.

Saha, S., S. Nadiga, C. Thiaw, J. Wang, W. Wang, Q. Zhang, H.M. van den Dool, H, L. Pan, S. Moorthi, D., Behringer, D. Stokes, G. White, S. Lord, W. Ebisuzaki, P. Peng and P. Xie. (2005). *The NCEP Climate Forecast System*. J. Climate, **19**, 3483-3517.

Shawinigan Engineering (1994). Wet Season Flow Forecasting for Victoria Falls and Kariba. Draft Report for SADC AAA.3.4, Hydroelectric Hydrological Assistance Project – Phase 2.

Shukla, J. (1981) Dynamical predictability of monthly means. J. Atmos.Sci. 38: 2547–2572.

Stockdale, T. N., D. L. T. Anderson, J. O. S. Alves, and M. Balmaseda, (1998): Global seasonal rainfall forecasts using a coupled ocean-atmosphere model. Nature, 392, 370–373.

Tumbare, M. J.: Mitigating floods in Southern Africa, in 1st WARFSA/WaterNet Symposium: sustainable use of water resources, pp. 1-8, Maputo, Mozambique., (2000).

Werner, M., van Dijk, M. and Schellekens, J.: DELFT-FEWS: an open shell flood forecasting system, in Proceedings of the 6th International Conference on Hydroinformatics, pp. 1205-1212., (2004).

Werner MGF. Schellekens J. Kwadijk JC. Flood Early Warning Systems for Hydrological (sub) Catchments, Encyclopedia of Hydrological Sciences, Volume 1, Chapter 23, 349-364, John Wiley & Sons, ISBN: 0-471-49103-9. (2005).

Winsemius, H. C.: Satellite data as complementary information for hydrological modelling, PhD thesis, Delft, University of Technology., (2009).

World Bank, (2010). The Zambezi River Basin - A Multi-Sector Investment Opportunities Analysis, Volume 1 to 5.

World Meteorological Association. Presentations given during the Regional consultation meeting on Zambezi river basin flood forecasting and early warning strategy. http://www.wmo.int/pages/prog/hwrp/Zambezipresentations.html. 10 March, 2010.

World Meteorological Association (WMO). (2008). Guide to Hydrological Practices, Volume I, Hydrology - From Measurement to Hydrological Information, WMO-No. 168, Sixth Edition.

World Meteorological Association (WMO). (2008). Guide to Hydrological Practices, Volume II Management of Water Resources and Application of Hydrological Practice, WMO-No. 168, Sixth edition.

WWF and ZESCO. (2004): Decision Making system for Improved Water Resources Management for the Kafue Flats, Republic of Zambia : Ministry of Energy and Water Development

Zappa M., Rotach M., Arpagaus M., Dorninger et al. (2008). MAP D-PHASE: real-time demonstration of hydrological ensemble prediction systems. Atmos. Sci. Let. 9: 80–87.

Appendix A
Summary of Stakeholder Questionnaire Survey Consultation

Institution	Country	Response Received	Comments
State Secretariat of Water Affairs - Hydrological Resources	Angola	No	Telephone and email follow-up attempted; no response received.
Department of Water Affairs	Botswana	No	Telephone and email follow-up undertaken; contact person not available after several attempts.
Ministry of Irrigation and Water Development (Malawi)	**Malawi**	**Yes**	
Ministry of Water - Hydraulic Infrastructure Office	Mozambique	No	Telephone and email follow-up attempted, meeting requested.
Ministry of Agriculture, Water and Forestry	**Namibia**	**Yes**	
Ministry of Water Development	Tanzania	No	Telephone and email follow-up attempted, but unsuccessful (no answer when telephoned).
Department of Water Affairs	Zambia	No	Meeting held; questionnaire issues largely addressed.
Ministry of Water Resources Development and Management	Zimbabwe	No	Email follow-up used; new request sent 27/06/2010 – response awaited.
Directror of Planning (Energy)	Angola	No	Telephone and email follow-up attempted, but unsuccessful.
Department of Energy Affairs	Botswana	No	Telephone and email follow-up attempted, but unsuccessful (message left with secretary).
Department of Energy	**Malawi**	**Yes**	
Ministerio da Energia	Mozambique	No	Telephone and email follow-up attempted, but unsuccessful.
Energy Directorate	Namibia	No	Telephone and email follow-up attempted, but unsuccessful. Directed to Dr Tjipangandjara (email forwarded), but not available when telephoned.
Ministry of Energy and Minerals	Tanzania	No	Telephone and email follow-up attempted, but unsuccessful (telephone calls not answered).
Ministry of Energy	**Zambia**	**Yes**	
Ministry of Energy and Power Development	Zimbabwe	No	Telephone and email follow-up attempted, but unsuccessful. Directed to Mr Frederic Maziveyi, but not available when telephoned.
Director of Disaster Management	Angola	No	Telephone and email follow-up attempted, but unsuccessful.
Disaster Management	**Botswana**	**Yes**	
Department of Disaster Management Affairs	**Malawi**	**Yes**	
Nacional Center for Emergency Operations	**Mozambique**	**Yes**	

Institution	Country	Response Received	Comments
(CENOE)/ INGC			
Directorate Disaster Risk Management	**Namibia**	**Yes**	
Disaster Management Department	Tanzania	No	Telephone and email follow-up attempted, but unsuccessful (telephone calls not answered).
Disaster Management & Mitigation Unit / OVP	**Zambia**	**Yes**	
Civil Protection	**Zimbabwe**	**Yes**	
The Electricity Supply Corporation of Malawi Limited (ESCOM)	**Malawi**	**Yes**	
Hidroeléctrica de Cahora Bassa	Moçambique	No	Questionnaire emailed 30 June & 6 July 2010 – response currently awaited.
Zambezi River Authority	Zambia	No	Questionnaire emailed 28 June 2010 – response currently awaited.
Zimbabwe Electricity Supply Authority (ZESA)	**Zimbabwe**	**Yes**	
World Wide Fund for Nature (WWF)	Zambia	No	Telephone and email follow-up used; confirmation received. Questionnaire re-emailed 28 June 2010 – response awaited.
ARA-Zambeze	Mozambique	No	Telephone and email follow-up attempted, but unsuccessful.

Appendix B
List of Questions used in Stakeholder Questionnaire Survey

Stakeholder Questionnaire – Disaster Management

1. What is your legal responsibility with respect to flooding emergencies in the Zambezi River basin?

2. Do you have your own system for flood forecasting? If so, please could you give an outline of how this system works?

3. Do you receive forecasts / warnings / notifications of flood disasters from other authorities? Who are these authorities and how are these forecasts / warnings / notifications communicated to you (fax, email, telephone, etc)?

4. What information is given to you when you receive a forecast / warning / notification of a flood event? Please indicate in as much detail as possible what sort of information is received (i.e. flow, water depth or water level, flood arrival time, area of inundation, duration of inundation, accuracy of forecast, etc.).

5. How accurate have the forecasts / warnings / notifications you have received in the past been?

6. How does the information you receive influence your decision-making process? For example, do you normally act as soon as you receive a warning, or do you wait for additional confirmation of a potential emergency situation before acting?

7. How much lead time (time prior to arrival of a flood event) are you usually given between receiving a forecast or notification of a flood warning (from forecasting authorities) and the arrival of a flood event?

8. What is the minimum lead time you generally require in order to provide an effective response (protection of people and property) in keeping with your legal mandate?

9. Could you give an indication of which areas along the river are prone to flooding and therefore in which areas flood forecasts are required?

10. Do you currently have any information sharing agreements with corresponding departments in other countries within the Zambezi River basin?

11. Do you have any recommendations for improvements to the current system? Please indicate how these improvements would help you?

12. Please could you provide us with your full name, job title and contact details in the event that we need further information or to allow us to arrange a meeting with you.

Stakeholder Questionnaire – National Energy Ministries

13. Do you have a legal mandate with respect to management of hydro power production (HPP) in the Zambezi River basin in your country? If so, please could you give an outline of this mandate?

14. How are you involved in the decision making process with respect to hydro power production in your country?

15. How is potential energy production for the coming season determined / estimated?

16. Do you have any recommendations on how flow forecasting processes could be improved to provide better management of river flows and dam storage for optimization of power production?

17. Do you currently liaise with or have any information sharing agreements with corresponding departments in other riparian countries of the Zambezi River basin?

18. Do you have any other recommendations for actions or issues that should be taken into consideration in this project?

Stakeholder Questionnaire – National Water Ministries

19. What is your legal mandate with respect to the Zambezi River basin in your country? For example, are you required to manage a hydrological monitoring system and issue flood forecasts or warnings?

20. Do you have your own system for flood forecasting? If so, please could you give an outline of how this system works?

21. How accurate and reliable is your forecasting system?

22. When you issue a forecast or flood warning, what information do your provide? For example, do you indicate the area that will be flooded, the depth of flooding, the duration of flooding and the time at which flooding will commence?

23. How much advance warning of a flood event (lead time) are you generally able to provide to affected stakeholders (e.g. disaster management authorities)?

24. Could you give a description of the hydrological monitoring network (rainfall, river flows, levels, etc.) you currently manage in the Zambezi River basin?

25. How are measurements taken (automatically, manually) and how is this data transferred to you (telemetry, phone, email, etc.)?

26. How accurate and reliable is your monitoring network?

27. Do you have any comments on the flow gauge map included with this questionnaire (the data in this map was extracted from the ZAMWIS database)? Is the information included in this map accurate?

28. To assist us with an assessment of the Zambezi River basin hydrological monitoring network, would it be possible for you to provide us with a list of all of the hydrological gauges you manage (including location coordinates), as well as the historical data for these gauges? If so, how could permission for this be arranged?

29. Do you receive flood forecasts from other authorities (e.g. Hidroeléctrica de Cahora Bassa - HCB)? Who are these authorities and how are these forecasts communicated to you (fax, email, telephone, etc)? What information is provided with these forecasts?

30. Could you give an indication of which areas in the basin are subject to flooding and therefore in which areas flood forecasts are required?

31. Do you currently have any information sharing agreements with corresponding departments in other countries within the Zambezi River basin?

32. Do you have any recommendations for improvements to the current system – both the monitoring network and the forecasting system? Please indicate how these improvements would help you?

33. Please could you provide us with your full name, job title and contact details in the event that we need further information or to allow us to arrange a meeting with you.

Stakeholder Questionnaire – Dam Operators

A – General Questions

34. Please could you provide us with your name, job title and contact details in the event that we need further information or to allow us to arrange a meeting with you.

35. What is the legal mandate of your organisation with respect to the Zambezi River basin or the dam(s) that you operate?

B – Flow Forecasting

B1. Do you have your own system for flow forecasting? If so, please could you give a description of this system? If you use a forecasting model, could you briefly describe this model?

B2. How accurate is your forecasting system?

B3. Do you issue forecasts or flood warnings to other stakeholders? If so, please indicate which stakeholders.

B4. When you issue a forecast or flood warning, what information do you provide? For example, do you indicate the area that will be flooded, the depth of flooding, the duration of flooding and the time at which flooding will commence?

B5. How much advance warning of a flood event (lead time) are you generally able to provide to affected stakeholders (e.g. disaster management authorities)?

B6. If you manage a hydrological monitoring network (rainfall, river flows, levels, etc.), could you provide a description of this network?

B7. How are measurements taken (automatically, manually) and how is this data transferred to you (satellite, GSM, GPRS, phone, email, etc.)?

B8. How reliable is your monitoring network?

B9. The SADC-HYCOS flow gauging network is currently the only real-time gauging network that operates across the entire Zambezi River basin. Do you have any suggestions on how this system could be improved?

B10. To assist us with assessing the existing Zambezi River basin flow monitoring network, would it be possible for you to provide us with a list of the gauges you manage, their locations (lat, long) and the length of record available for each gauge?

B11. Do you receive flood forecasts or warnings from other Dam Operators or national authorities in the Zambezi River basin? Who are these authorities and how are these forecasts communicated to you (fax, email, telephone, etc)? What information is provided with these forecasts?

B12. Do you currently have any information sharing agreements with other authorities either in the country where you are based or other countries within the Zambezi River basin?

B13. Do you have any suggestions on the criteria that should be used for the selection of potential locations for a regional forecasting centre for the entire Zambezi River basin?

B14. What are the main problems with your existing forecasting system that could be addressed by a basin-wide real-time flow forecasting system?

B15. To assist us with understanding the system you have used to issue flood warnings in the past, we would be grateful if you could provide us with as much of the data/ information listed below, as possible, for the last 25 years. This will allow us to obtain a better understanding of the issues that must be addressed in designing a forecasting system for the entire Zambezi River basin.

- Date when gates were opened;
- Number of gates opened;
- Dam level on the date when gates were opened;
- Date when warning was issued;
- Dam level on the date when warning was issued;
- A description of how the warning was issued and a list of stakeholders informed;
- Date when gates where closed; and
- Dam level on the date when gates were closed.

B16. If you have any other suggestions or recommendations that should be taken into consideration in the design of a basin-wide flow forecasting system, please could you outline these below. We would also be grateful to receive any reports or other information that you think would be of assistance to us.

Appendix C
Method for Determining the Required Spatial Coverage of Rainfall Stations

In section 3.2.1.1, it was determined how many stations are required in a given forecast area. To this end Kagan's equation has been used (Kagan, 1972), given below:

$$Z_{areal} = C_v \sqrt{\frac{1}{N}\left(1 - r_0 + \frac{0.23}{d_0}\sqrt{\frac{S}{N}}\right)}$$

Where

Z_{areal}: the relative root mean square error of the area averaged rainfall estimate in the forecast area of interest
C_v: the coefficient of variation of the station rainfall
N: the number of stations in the forecast area
r_0: the correlation that station values would have if stations would be placed exactly next to each other e.g. due to instrumental errors and randomness of rainfall.
d_0: the correlation length, which is defined above for each station.
S: the surface area of the forecast area

This equation shows that if the temporal variability in rainfall time series (i.e. a high C_v) or the spatial variability (i.e. a low d_0) is high, a higher error can be expected from areal estimates. The factor N/S is a measure for the station coverage, i.e. the amount of stations per unit area. If this number increases, the error will reduce. This equation was applied as follows:

For each forecast area of interest, it has been assumed that a relative error (Z_{areal}) of 15% is required and that the assumption of the average of C_v and d_0 over the stations that lie within the forecast area is reasonable and valid.

r_0 was estimated to be 0.9 for daily values and 0.95 for decadal and monthly values.

d_0 shows how rapidly the correlation between station values declines with distance. It is the distance from a station at which the variability in the rainfall at that station cannot be explained by the observed rainfall at another station.
The estimation of d_0 has been performed for each station separately. For each station, its time series has been compared with all the other time series in the surrounding stations. This has been done by computing the semivariogram for the compared time series. The experimental semivariogram function is given below (Burrough and McDonnell, 1988):

$$\gamma(h) = \frac{1}{2N}\sum_{t=0}^{N}\left[x_t(0) - x_t(h)\right]^2,$$

where $\gamma(h)$ is the semivariance at distance h. Distance h is the distance between the station investigated and the station against which the time series are compared. $x_t(0)$ is the rainfall value at the investigated station (located in h=0) and $x_t(h)$ is the value at a station a distance h from $x(0)$.

γ is computed pair-wise between stations which yields a relation between distance and γ. A variogram function is fitted through this relation. An example is given in Figure 11.1.

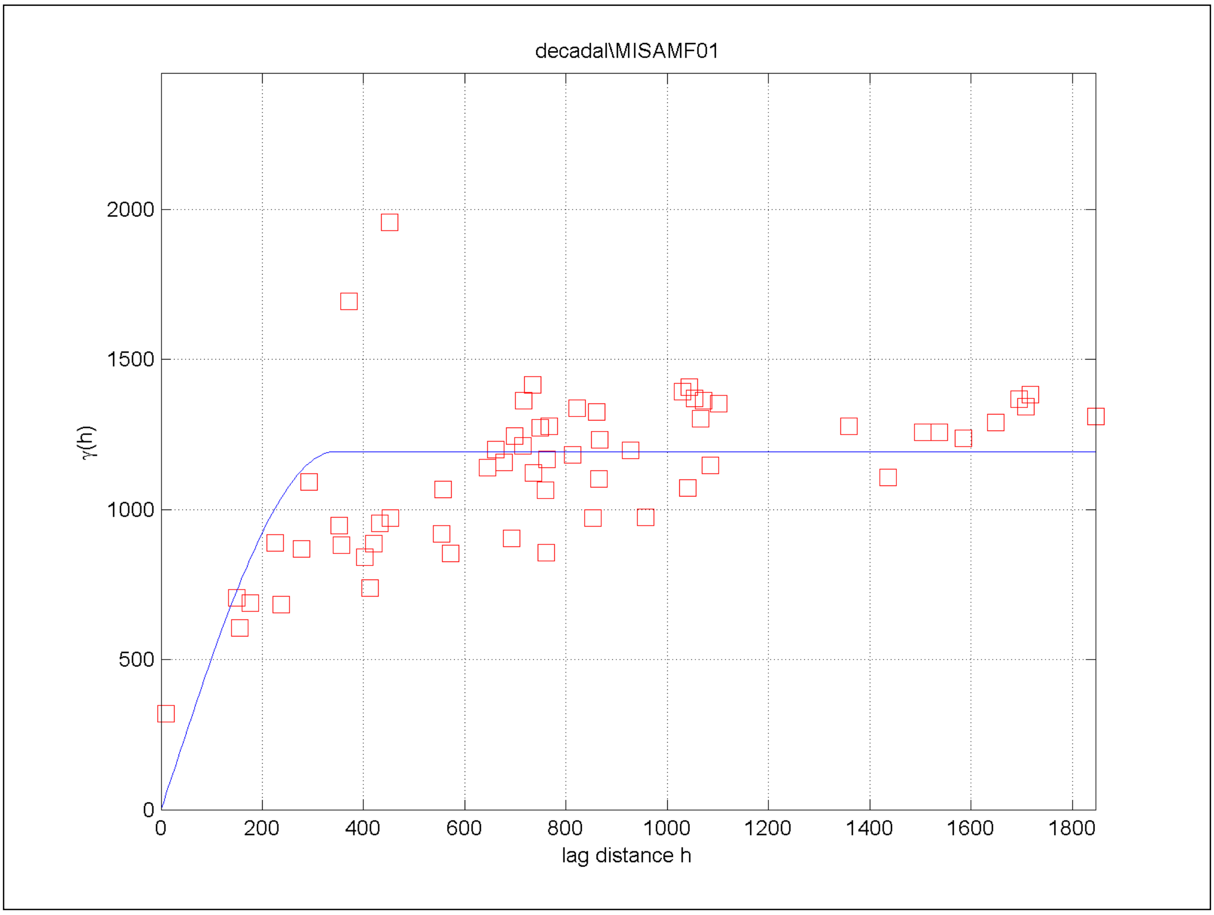


Figure A3.0.1: Example of distance - variance relation for the station 'MISAMF01'. The blue line gives the variogram fit

Typical variogram fitting functions have been searched that seem to follow the empirical semivariogram, computed. The so-called *spherical function* gave the best results. The equation of the spherical function is given below:

$$\gamma(h) = \frac{3h}{2a} - \frac{1}{2}\left(\frac{h}{a}\right)^3,$$

where a is a distance parameter reflecting the point where the blue line becomes horizontal. It was assumed that this distance parameter is equal to the correlation distance d_0.

References

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M.: FAO Irrigation and Drainage Paper No. 56 - Crop Evapotranspiration, Food and Agriculture Organization., (1998).

Burrough, P. and McDonnell, R. A.: Principle of Geographical Information Systems, Oxford University Press, New York., (1988).

Kagan, R.: Planning the spatial distribution of hydrometeorological stations to meet an error criterion, in Casebook on Hydrological Network design practice, Geneva., (1972).

Tumbare, M. J.: Mitigating floods in Southern Africa, in 1st WARFSA/WaterNet Symposium: sustainable use of water resources, pp. 1-8, Maputo, Mozambique., (2000).

Werner, M., van Dijk, M. and Schellekens, J.: DELFT-FEWS: an open shell flood forecasting system, in Proceedings of the 6th International Conference on Hydroinformatics, pp. 1205-1212., (2004).

Winsemius, H. C.: Satellite data as complementary information for hydrological modelling, PhD thesis, Delft, University of Technology., (2009).

Appendix D
Technical Aspects of the SADC-HYCOS (SADC-HYCOS Project)

Gauge Equipment

Six of the Zambezi River Authority's flow gauging stations, namely Chavuma, Kalabo, Matongo, Senanga, Gwayi and Sanyati Bridge were equipped with the AURORE equipment from SERPE-IESM, Guidel, France in the mid 1990s, whilst the 19 SADCHYCOS Phase 1 stations were also equipped with the same type of equipment between 1998 and 2001.

The instrumentation needed to equip one station for real-time data collection and transmission equipment is collectively referred to as a Data Collection Platform (DCP) and consists of:

- Electronics for data acquisition and storage (logging unit);
- Meteosat radio transmitter and directional antenna;
- Power supply device with battery and solar panel;
- 2 water level sensors;
- Tipping bucket rain gauge;
- 1 water temperature and 1 conductivity sensor;
- Air temperature sensor; and
- Waterproof housing and connectors.

The above is a basic configuration for a typical DCP and more sensors can be added if required.

However, for the SADC- HYCOS stations, it was not possible to install downstream water level and conductivity sensors at all the stations due to terrain constraints and sensor cable lengths. The measurement interval of the parameters is 15 minutes and the data is transmitted every 3 hours.

Figure A4.1: A typical DCP shelter with air temperature/ humidity sensor, rain gauge and antenna on roof.

Figure A4.2: A typical AURORE logging unit with the transmitter on the right hand side.

For SADC-HYCOS Phase II stations, civil works on the DCP shelters are now almost complete in all the member states and the remaining task is the installation of the equipment. As of June 2010, Malawi and Mozambique had completed the required civil works, but some stations were still not complete in Zimbabwe and Zambia. Zambia and Malawi had taken receipt of their respective gauge equipment, whilst for Zimbabwe and Mozambique the equipment had not yet been delivered.

The member states are facing numerous challenges with the maintenance of the AURORE equipment mainly due to the unavailability of spare parts. In order to solve the issue of spare parts and provision of back up service the Phase II equipment was sourced from a company which has agencies in a number of countries in the region. For sustainability, a number of training sessions for technicians were conducted, both on site and at centralised locations.

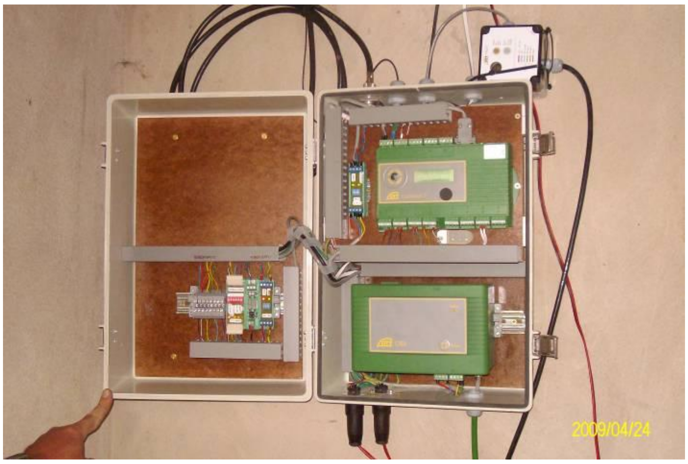


Figure A4.3: The OTT LOGOSENS equipment procured for SADC-HYCOS Phase II stations.

In general, the real time data collection system installed under the SADC-HYCOS project has improved the data collection techniques in all of the member states. The system utilises modern technology for transferring data from the field to the Pretoria Regional Centre for archiving in the RDB and dissemination to participating countries. Threats to the performance of the instrumentation may be classified into instrument failure, natural hazards such as floods and lightning, and vandalism or theft of equipment. So far the instrumentation has proved to be reliable but it has to be realised that the instrumentation is fragile and does not tolerate errors in installation or electrical coupling easily.

The most common problem has been the short life span of the water level sensors. On most of the stations the average life span was three years only. It is thus advisable to look at alternative ways of capturing stage height of rivers, preferably keeping electronic devices well clear of the water due to lightning surges. One sensor, which now addresses this problem, is the compact bubble-in sensor. It requires very little power and has its own compressor for air supply. It is coupled to the river water level via a plastic, (non-conductive) pipe, thereby eliminating power surges. In the installation program of SADC-HYCOS Phase II it has been agreed to install two sensors one being the bubble-in sensor.

Theft and vandalism unfortunately have played the dominant role in damage to or loss of instrumentation and data. A number of measures are being implemented in the member states to mitigate or combat vandalism. Some of the measures being undertaken are;

Local observers being housed at some of the SADC-HYCOS field installations to take regular manual readings and to protect the installations. This has been applied with great success in Zimbabwe and the example is being followed to a lesser extent in Botswana, Malawi and Lesotho. Some countries which have carried out awareness campaigns on the local community have registered a decline in vandalism.

Most countries have now extensive cell phone coverage which will allow the use of GSM/GPRS enabled data loggers which only relies on a small battery for power. The CELLO data loggers shown below were installed in Swaziland, a country which experienced a high rate of vandalism, in 2008 and up to now none of the installed six data loggers have been vandalised.

Figure A4.4: Typical CELLO data logger at a station in Swaziland

Most stations only measure water levels which is insufficient for flood management and development of hydrological products. For stations with rating curves most of them are now outdated. There is now a general awareness in the region on the need to strategically improve the data collection system. There are a number of initiatives currently taking place in the region to improve the quality of data collected especially on updating the rating curves. The Okavango Basin Commission made up of Botswana, Namibia and Angola have been carrying out joint flow gaugings on a number of stations using Acoustic Dopplers. Namibia and Angola have also managed to procure their own Acoustic Dopplers. ZRA has also procured a Doppler and carries out joint gaugings with personal from the Ministry of Water, Zambia. The Department of Water Affairs, South Africa, hosts gauging excursions on a yearly basis and personnel from Mozambique, Namibia and Zimbabwe attended some of the events.

Some of the challenges being encountered are:

- Poor station maintenance by some countries which greatly compromises the quality of data collected
- In most instances training is conducted too early and thus forgotten when needed.
- A number of stations have been damaged or washed away by floods. Most of the stations washed away were located in the flood basins because of the restrictions in the water level cable length then, which had a maximum length of 30 meters. Now the maximum cable length is 200 metres which will permit the location of stations outside the flood plains.
- High staff turnover in the member states which has adversely affected the operation and maintenance of stations.
- Most of the equipment is sourced from Europe is not suitable for the harsh African environment; this has resulted in regular replacement of outside instruments and cables.
- The maintenance of the stations has been greatly compromised during the crucial rainy season period because of poor access.

Data transmission techniques

The ZRA and the SADC-HYCOS DCPs use the same data transmission system. The data flow is shown in elementary form below.

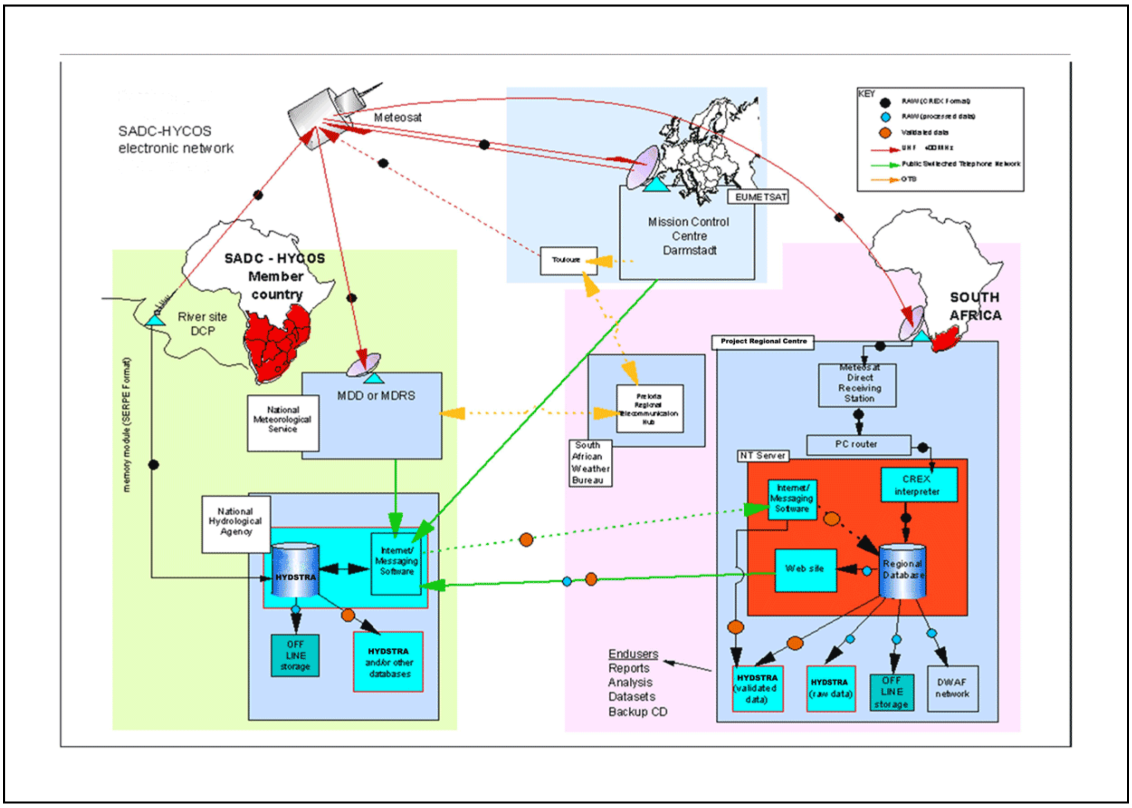


Figure A4.5: The flow of hydrological data and information within a HYCOS regional project.

Each data collection platform is equipped with a UHF transmitter which automatically sends the hydro meteorological data collected at the site (on an hourly basis, although the Phase 1 gauges are yet to be reprogrammed from 3 hours) to the Eumetsat mission control centre at Darmstadt in Germany. Eumetsat is the operator of the METEOSAT system. Transmissions are in a format (CREX) which is specified by WMO and transmission from each site occurs at times and frequencies allocated by Eumetsat. The data are retransmitted via METEOSAT to the regional centre in Pretoria where it is received on a METEOSAT Direct Receiving Station. From the direct receiving station, the data are routed to the computer server hosting the regional database, where the CREX files are automatically interpreted and loaded onto the database, from where the data can be viewed via the Website. Each national agency is able to manually download data from the stations in its country from the Website, and load the data into their local database, where it can be checked and quality-controlled. Should there be any errors in the raw data, these can be corrected and the validated data returned to the PRC in Pretoria for loading onto the regional database. ZRA directly downloads its data from the Eumetsat website.

The major challenge faced so far on this aspect is the poor internet facilities in most member states. Most of the countries are facing difficulties in accessing data from the regional database and this has greatly impacted data validation and data exchange.

Data Storage

The regional database is a relational database, with the data stored in indexed tables. Views allow tables to be linked together, and stored algorithmic procedures allow various operations to be carried out on the data either automatically or on demand. The database design follows standard procedures for relational databases and, as such, should be independent of any particular relational database product. In this case, the database has been implemented using Microsoft SQL Server software running under Windows NT4 Server.

The data loaded onto the regional database can be divided into three main categories: real-time data, historical data and metadata. The real-time data consist of data received in CREX format via METEOSAT. To avoid complications arising from the time differences across the region, all data are stored at GMT. Some basic automatic checking occurs as data are loaded (e.g. against minimum/maximum limits), which filters out grossly incorrect values. However, the main validation of data is performed by the national agencies. Data values on the database (and Website) are flagged indicating either raw values or validated data. Within the database, various operations are carried out automatically on a daily basis e.g. sub-daily values are converted to mean or total daily values, as appropriate, and water levels are converted to flows or reservoir/lake storages using stored rating equation coefficients. At any time, the database contains the most recent sub-daily data, weekly, monthly and the primary datasets (i.e. the raw data).

The historical data provide a longer-term context in which to view the real-time data. The main historical data sets available for the region consist of daily mean flows, and some daily rainfall totals. Due primarily to economic constraints, other meteorological data and water quality data are not generally available. Within Southern Africa, there are also several other data sets which include data for some of the sites at which data collection platforms are installed and, where available, these are being loaded onto the regional database. One of these is the Southern African FRIEND (Flow Regimes from International Experimental and Network Data) database of river flow data, which is currently held by the project co-ordinating centre at the University of Dar Es Salaam in Tanzania. This database contains data for some 800 stations across the region up to about 1990 (UNESCO, 1997). Another data set is the ZAMWIS database on the Zambezi River, which is currently held by the interim ZAMCOM office in Lusaka in Zambia. The data were obtained from a network of manual observation sites and some 20 radio-based data collection platforms.

The metadata (or static data) consist of all information which is fixed in time or only changes infrequently. This includes details of the data collection platforms (such as location, equipment, operator, history, photos, site maps, rating equations), project reports (such as titles, authors, contact details, summary), security information for the database (such as operator and client contact details, user-ids and passwords), data transmission settings (such as data collection platform codes, internet addresses) and data quality control information (such as minimum/maximum values allowed), amongst other information. The majority of this information is being provided by the national agencies for loading onto the regional database.

The main route for dissemination of the data collected from the data collection platform network is through the SADC-HYCOS Website with address http://www-sadchycos.dwaf.gov.za/sadc.

In addition to the hydrometeorological data, the SADC-HYCOS Website includes descriptions of the WHYCOS and SADC-HYCOS projects, contact details and descriptions of the participating organisations and latest news on the project, as well as links to related sites. Users can select a station by locating the station on a map, by choosing the station from a list or by searching according to user-defined criteria. Plots can be obtained of all the data types measured at each station, and of the derived data types, such as flow or potential evaporation. The various housekeeping parameters, such as solar panel current and battery voltage, can also be viewed. Data are displayed at daily intervals. Raw data that can be downloaded is available at sub-daily intervals ranging between 12minutes to hourly values.

Local Databases in Participating Countries

Within each country, the main requirement is for purpose-made databases, which can be used off-line for the validation, analysis and long-term, archiving of the data collected during the project. With the exception of the PRC and Namibia, prior to Phase II, all countries were using the Centre for Ecology and Hydrology's HYDATA v4.1 hydrological database software (IH, 1999) for the initial storage and validation of data from their data collection platforms. At present a new database HYDSTRA has been installed in all the countries in the region except Zimbabwe and Tanzania.

HYDSTRA is a Windows-based database and analysis system for storing and processing the types of data most commonly required in water resources studies, including river levels and flows, reservoir/lake levels and storages, rainfall and other meteorological data. It also includes facilities for developing rating curves, and routines for hydrological analyses, such as the derivation of flow duration curves and calculation of low flow statistics.

The local HYDSTRA databases are designed to store all of the available data for each country which has been collected and downloaded from the regional database at the PRC. The data stored on the database are automatically interpreted, and major errors deleted, upon loading. However, the data is still essentially raw requiring validation by hydrologists in each country. To help in this work, HYDSTRA includes a number of facilities for checking, quality controlling and editing data. These include time series comparison plots of different data types at the same station, or of the same data types at different stations, and double mass plots and validation plots where data can be reviewed in the context of the long-term historical extremes. During the project, additional training has been provided on data validation techniques, particularly for data types (e.g. water quality and some meteorological data) which have not previously been measured in real-time in some parts of the region.

At many sites, manual observations of river levels will continue to be made two or three times a day by observers, and/or chart recorders will be kept. Observer records can be manually typed into HYDSTRA, and chart records can be digitised and loaded into HYDSTRA using standard file import routines. In addition, at each site, data are archived locally in data loggers, which can be downloaded by portable memory modules every few weeks for reading at head office. For some variables, the logger data are at 12 or 15-minute intervals rather than the coarser 1-hour or 3-hour intervals used in the METEOSAT transmissions, so there is the option to use these values as the primary data source for computing long-term flow statistics and meteorological conditions. However, these alternative data sources all provide an independent check on the data from the data collection platform, as well as essential backup in case of transmission problems.

Appendix E
Analysis of Zambezi River Basin Flow Gauge Data

Note: daily streamflow data was taken from ZAMWIS/Time Series/1105.txt (for example)

Legend:

OK: Values for all days in the year
Missing days: Odd days missing from months
Missing April only: Only April missing, all other values are OK
Missing months: 2 or more months missing entirely
M: Entire year missing

Table E. Analysis of Zambezi River Basin Flow Gauge Data

Year	1105 Chavuma	1650 Kabompo	2250	2030 Lukulu	2400 Senanga	2700	330090 Vic Falls	6135 James Camp	6624 Kasane	4350 Chilenga	4435 Mswebi	4560 Chifumpa	4669 Kafue Hook	4977 Kasaka	4710 Itezhi-tezhi	5800 Luangwa	5940	C75	E375 Mepanda Uncua	E348	E299	1B1	1C12	E288	E285
	Upper Zambezi									Middle Zambezi									Lower Zambezi						
1924							Missing Oct only																		
1925							OK																		
1926							OK																		
1927							OK																		
1928							OK																		
1929							OK																		
1930							OK																		
1931							OK																		
1932							OK																		
1393							OK																		
1934							OK																		
1935							OK																		
1936							OK																		
1937							OK																		
1938							OK																		
1939							OK																		
1940							OK																		
1941							OK																		
1942							OK																		
1943							OK																		
1944							OK																		
1945							OK																		
1946							OK																		
1947					Missing months		OK																		
1948					Missing months		OK																		
1949					Missing days		OK																		
1950					OK		OK																		
1951					OK		OK																		
1952					OK		OK																		
1953					OK		OK				OK														
1954					OK		OK				OK														
1955					OK		OK				OK														
1956					OK		OK				OK														

Year	1105 Chavuma	1650 Kabompo	2250	2030 Lukulu	2400 Senanga	2700	330090 Vic Falls	6135 James Camp	6624 Kasane	4350 Chilenga	4435 Mswebi	4560 Chifumpa	4669 Kafue Hook	4977 Kasaka	4710 Itezhi-tezhi	5800 Luangwa	5940	C75	E375 Mepanda Uncua	E348	E299	1B1	1C12	E288	E285
	Upper Zambezi									Middle Zambezi									Lower Zambezi						
1957					OK		OK				OK														
1958	Missing months				OK		OK				OK														
1959	Missing months				OK		OK				OK	OK			M										
1960	M				OK		OK				OK	OK			OK										
1961	M				OK		OK			Missing years	OK	Missing days			OK										
1962	M				OK		OK			OK	OK	Missing days			OK										
1963	M				OK		OK			OK	OK	OK		OK	OK										
1964	M				OK		OK			OK	OK	OK		OK	OK										
1965	M				OK		OK			OK	OK	OK		OK	OK										
1966	M				OK		OK			OK	OK	OK		OK	OK										
1967	M				OK		OK			OK	OK	OK		OK	OK										
1968	M				OK		OK			OK	OK	Missing days		OK	OK										
1969	M				OK		OK			OK	OK	OK		OK	OK										
1970	OK				OK		OK			OK	OK	OK		OK	OK										
1971	OK				OK		OK			OK	OK	OK		OK	OK										
1972	OK				OK		OK			OK	OK	OK	Missing months	OK	OK										
1973	Missing days				OK		OK			OK	OK	OK	Ok	OK	OK										
1974	OK				OK		OK			OK	OK	OK	OK	OK	OK										
1975	OK				OK		OK			OK	OK	OK	OK	OK	OK										
1976	OK				OK		OK			OK	OK	OK	OK	OK	OK										
1977	OK				OK		OK			Missing days	Missing months	Missing days	Missing days	OK	OK										
1978	Missing months				Missing months		OK			OK	Missing March only	Missing months	OK	OK	OK										
1979	M				Missing months		OK			OK	OK	Missing months	OK	OK	OK										
1980	OK				Missing June only		OK			OK	Missing months	Missing days	OK	OK	OK	OK									
1981	Missing October only				Missing months		OK			Missing days	Missing July only	Missing months	OK	OK	OK	Missing Oct only									
1982	Ok				Missing days		OK			OK	Missing months	Missing August only	OK	OK	OK	OK									

Year	1105 Chavuma	1650 Kabompo	2250	2030 Lukulu	2400 Senanga	2700	330090 Vic Falls	6135 James Camp	6624 Kasane	4350 Chilenga	4435 Mswebi	4560 Chifumpa	4669 Kafue Hook	4977 Kasaka	4710 Itezhi-tezhi	5800 Luangwa	5940	C75	E375 Mepanda Uncua	E348	E299	1B1	1C12	E288	E285
	Upper Zambezi									Middle Zambezi									Lower Zambezi						
1983	OK				OK		OK			Missing days	Missing months	Missing months	OK	OK	OK	OK									
1984	Missing days				Missing October only		OK			Mising June	Missing months	Missing months	OK	OK	OK	Missing Sept only									
1985	OK				OK		OK			OK	Missing months	Missing months	OK	Missing September only	OK	OK									
1986	Missing days				OK		OK	Missing months		Missing months	Missing months	Missing months	OK	OK	OK	OK									
1987	Missing months				Missing days		OK	Missing August		Missing months	Missing months	Missing days	OK	OK	OK	OK									
1988	OK				OK		OK	Missing months		Missing months	Missing months	Missing months	Missing months	OK	OK	Missing months									
1989	OK	Missing months		Missing months	OK		OK	Missing months		Missing days	Missing days	Missing days	OK	OK	OK	M									
1990	Missing Oct only	Missing months		Missing months	Missing days		OK	Missing months		OK	Missing days	Missing days	OK	OK	OK	M									
1991	Missing Sep only	Missing months		Missing month	Missing Sept		OK	Missing months		Missing months	Missing months	OK	OK	OK	Missing September only	M									
1992	Missing months	Missing months		Missing months	Missing years		OK	Missing March		M	Missing months	Missing Sept only	OK	OK		M									
1993	Missing months	M		Missing month	Missing years		Missing days	Missing months		M	M	Missing months	Missing months	OK		M									
1994	Missing months	M		Missing months	OK		OK			Missing months	M	Missing months	OK	OK		M									
1995	Missing Sep only	Missing months		Missing month	Missing January only		OK			M	M	Missing months	OK	OK		M									
1996	Missing days	Missing September only		OK	OK		OK			M	M	Missing months	OK	OK		M									
1997	Missing months	M		OK	OK		OK			M	M	Missing months	OK	OK		M									
1998	Missing months	M		Missing month	OK		OK			M	M	Missing months	OK	OK		M									
1999	Missing months	M			OK					M	M	Missing months	OK	OK		M									

Year	1105 Chavuma	1650 Kabompo	2250	2030 Lukulu	2400 Senanga	2700	330090 Vic Falls	6135 James Camp	6624 Kasane	4350 Chilenga	4435 Mswebi	4560 Chifumpa	4669 Kafue Hook	4977 Kasaka	4710 Itezhi-tezhi	5800 Luangwa	5940	C75	E375 Mepanda Uncua	E348	E299	1B1	1C12	E288	E285
	Upper Zambezi									Middle Zambezi									Lower Zambezi						
2000	Missing months	M			OK					M	M	Missing months	OK	OK		M									
2001	Missing months	M			Missing days					M	M	Missing Nov only	OK	OK		M									
2002	Missing months	M			M					M	M	OK	OK	Missing Sept only		M									
2003	Missing months	Missing month			M					M	M	Missing months	Missing July only	M		M									
2004	Missing months	Missing month			M					M	M	M	M	M		M									
2005	Missing months	M			M					M	M			M											