The ZAMBEZI
Guidelines in modelling hydrology and hydropower based on case studies

Prepared for the EU ACEWATER2 research program

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Contents

1 Introduction

According to the Southern African Power Pool (SAPP), only three out of 12 SADC countries (South Africa, Mozambique and Zambia) currently have excess power generation capacity, with the others having a shortfall (www.sapp.co.zw). Hydropower is considered a key solution for minimising greenhouse gas emissions in energy production. In 2016, hydropower accounted for 21% of SADC's power generation (SAPP, 2016). However, pressure on water resources from population growth, agricultural growth, urbanisation and resultant pollution, limits the potential energy generation that hydropower could offer (IHA, 2017; Opperman et al., 2017).

It is of critical importance that hydropower plants are planned carefully and that an understanding of its potential impact on the entire basin is well understood before approval and implementation (Larentis et al., 2010; Opperman et al., 2017). This is particularly important in developing countries: energy is a much-needed resource with many people still being without access to electricity, but the same people are heavily reliant on the rivers as water resource for their livelihood and food production. For instance, any change to the river's flow, caused by incorrect planning of dams or hydropower plants upstream, could have devastating effects on biodiversity and ecology of the river (Magilligan & Nislow, 2005; Ronco et al., 2010). Different species of invertebrates and fishes respond differently to increases and decreases in flow and sedimentation, which makes planning for damming or other alterations to the river, difficult (Magilligan & Nislow, 2005).

Hydrological modelling has become an important tool for hydropower project design and impact assessment, in an attempt to better understand the potential impacts of damming and alteration of the river flow could have on sedimentation, biodiversity and ecology. Basin-scale hydrological modelling has also been used, particularly in the developing world, to inform national development and prevent transboundary conflicts over a shared resource (Johnston & Smakhtin, 2014), although this is relatively new due to the complexity of the exercise (Ronco et al., 2010).

Modelling at a basin scale is complex and subject to high uncertainty, mainly due to the large volumes of data that are required – soils, topography, land-use types, weather etc. over vast areas. As put by Grayson and Blöschl (2000, p55):

> *"Models of catchment hydrology must represent complex systems made up of interactions between many components, most of which vary in space and time. There is little point in representing one component in great detail while greatly simplifying another on which it depends. "*

Data should be of good enough quality to ensure a good resolution, so a good understanding could be gained of the balance between water requirements of the hydropower station and of downstream user and ecological demand (Andersson et al., 2015; Grayson & Blöschl, 2000; Kusre et al., 2010; Pechlivanidis et al., 2011). However, at a basin-scale, information cannot be so complex and detailed that it makes the model unusable (Grayson & Blöschl, 2000). Researchers have worked on the issue of scale in basin-wide hydrology for over two decades (e.g. Blöschl & Sivapalan, 1995). A lot of knowledge has been generated in the field of basin-wide hydrology, such as types of models and the pitfalls thereof. This document will present case studies to illustrate the options available for basin-wide hydrological modelling with respect to large hydropower projects.

This document has been developed in the framework of the ACEWATER2 project (EU-projects) to support the WACOZA (Water and Cooperation within the Zambezi River Basin) project.

2 Overview of this manual

This document strives to provide direction in regard to the access to IWRM information, providing access to the available data and data resources that are needed for regional water assessments. The document further strives to indicate the state of hydrological modelling already performed within this catchment and the main, currently available models and resources that should form the basis for future work.

The document outlines the hydrological concepts related to flows and hydropower generation, potential downstream impacts that could impact on flows and electricity supply, case studies and the direction they provide for modelling for management. We also took a look at other large catchments of the world where hydropower generation occur and what we can learn and could influence management and operation of the Zambezi catchment water resource. All this information could be of particular use to update the ZAMCOM approach with recent and applicable modelling techniques (ZAMCOM, 2016).

An important aspect of this planning and data accumulation is to be able to substantiate planned changes and uncertainties in terms of a cost-benefit approach. The reality we face in terms of climate change necessitates that we optimise water use, but to do that we need to reflect on the impacts of change. A study in this regard was conducted by the Economic Commission for Africa in 2010. This is still indicated as the guideline document for SADC regarding cost-benefit analysis in the water and power sectors and can be found here:

https://www.uneca.org/sites/default/files/PublicationFiles/cost-benefit-analysis-for-regional-infrastructure-in-water-and-power-sectors_0.pdf

This document should be read with this manual. The manual contains a lot of information presented as links to websites where the text, data or models can be found.[1]

Lastly, this document was developed to be used as a reference for modellers and to provide access to data.

3 Data requirements

The physical measurement and modelling of the total Zambezi water resource is currently possible, but the context and the purpose for which this is conducted and presented is equally important. The water resource supports more than the basic needs of people and the added uses, with its constraints, have to

[1] Last date of access of all links in this document: 28 October 2018

be dealt with on the same footing, so that the integration of all impacts, all uses and future needs be balanced in a single management approach. This section will therefore provide baseline information for hydrological modelling only, as a good understanding of the hydrology provides the key to management of the water resource.

3.1 Baseline data

The baseline data required for hydrological modelling consist of the following categories:

- Topography
- Geology
- Surface flows
- Groundwater data
- Soils information
- Land use
- Climate
- Reservoir volume and level
- Reservoir discharge
- Water abstraction
- Trans catchment distribution/transfer of water

3.2 Sources of information

Internet searches were focused around the following key words:

- Zambezi hydrology
- Hydropower case studies
- Large catchment hydrology
- The pitfalls in modelling large catchment hydrology

The results are summarised in Table 1. The table also confirms the centres in Africa and elsewhere in the world that does hydrological research in the Zambezi catchment. These centres also provides the best clues around data used and the data availability.

Table 1: Known general resources of information related to Zambezi

Publisher	**Resource**	**Access**
ZAMWIS	Zambezi Hydrological data	http://zamwis.zambezicommission.org/
Delft University	SWAT model	https://www.tudelft.nl/en/ceg/research/stories-of-science/a-better-understanding-of-the-zambesi-river/
Stellenbosch University	NEPAD SANWATCHE	http://nepadwatercoe.org/centres-of-excellence/
Rhodes University	SPATSIM	https://www.ru.ac.za/iwr/research/software/
University of Zimbabwe	WEAP model and application	https://www.weap21.org/ , http://www.erc.uct.ac.za/sites/default/files/image_tool/images/119/Hydro-Zambezi/HZ-Water_Supply_and_Demand_Scenarios_Report.pdf

University of Zambia	Data	http://dspace.unza.zm:8080/xmlui/handle/123456789/1287
University of KwaZulu-Natal	ACRU Model	http://cwrr.ukzn.ac.za/resources/acru
CSIR	Climate data	https://www.csir.co.za/developing-african-based-earth-system-model
World Bank	Reports	http://siteresources.worldbank.org/INTAFRICA/Resources/Zambezi_MSIOA_-_Vol_1_-_Summary_Report.pdf https://openknowledge.worldbank.org/handle/10986/2958
ZAMCOM	Data and publications	http://www.zambezicommission.org/
Global Water Partnership	Reports case studies	https://www.gwp.org/en/learn/KNOWLEDGE_RESOURCES/Case_Studies/Africa/Zambia-Integrated-Water-Resources-Management-and-Water-Efficiency-planning-process-332/
Republic of Mozambique, National Institute of Disaster Management	Management modelling techniques, catchment information	https://hydro-at.poyry.com/zambezi/index.php
GRID-Arendal, UNEP	Catchment information	http://www.grida.no/publications/189
International Journal on Hydropower & Dams, Water storage and Hydropower development for Africa	African Dams Project online water resources database	https://infoscience.epfl.ch/record/209347 https://infoscience.epfl.ch/record/209347 https://lch.epfl.ch/page-7708-en.html
International Journal of River Basin Management	1-D hydro-morphodynamic model	https://www.scopus.com/record/display.uri?eid=2-s2.0-84882243902&origin=resultslist&sort=plf-f&src=s&sid=c3144c513b00cb8f20721d5d4546a0db&sot=autdocs&sdt=autdocs&sl=18&s=AU-ID%2826031638500%29&relpos=7&citeCnt=8&searchTerm=

Table 2 provides examples of secondary resources where information exists that contributes to the information source providing maps, tools and software with general relevance. These sources are often key in our understanding of modelled data and remotely sensed data derivations.

Table 2: Examples of data resources often used for modelling in SADC, containing data, tools and software of general relevance.

Publisher	Resource	Access
WATERBASE	World grid data	http://www.waterbase.org/download_data.html
GISGeography	Maps, software, data, especially bathometry	https://gisgeography.com/category/data-sources/

Jena	JAMS model	http://jams.uni-jena.de/

4 Information resources

Dealing with water in the ACEWATER2-WACOZA programme implies that a comprehensive or all-inclusive approach is necessary. Therefore, in this section a link is made to the specific information needed and where it can be sourced. The information or IT realm refers to place, type of measurement, tools/equipment and manuals to guide the project. This section will therefore look at devices for measurement, as well as elevation, climate, geology, soils, land use and dams as items impacting on flow.

4.1 Water and Cooperation within the Zambezi River Basin project (WACOZA)

An online platform has been created to allow all members of the ACEWATER project to share data and documents. The platform is facilitated by the NEPAD Centres of Excellence of Southern Africa (SANWATCE). Just under 100 databases have been uploaded to the site. These include, amongst many others: Hydrogeological and hydro-chemical maps for the Zambezi River Basin, historical irrigation dataset, dam indices, population and GDP data, harmonised soil water databases with various variables, as well as different groundwater, land cover and meteorological data. The data is available at https://aquaknow.jrc.ec.europa.eu/nepad-sanwatce [2]. .

4.2 Surface and groundwater measurement and recording devices

Various information sources are needed for successful modelling. Most of the temporal information relies on well-calibrated equipment. Water measurement related to flows and dam water depths are nowadays also done through remote sensing. We are dependent on information or data that are generated with measurement instruments. Measurement instruments for hydrology include the following, examples and further details being available on internet:

- Weirs
- Flumes
- Submerged orifices
- Current meters
- Acoustic flow meters
- Other open-channel devices
- Other closed conduit devices
- Divers for depth, temperature, electrical conductivity and ion specific

The suppliers for surface and groundwater measuring equipment we are used to, include the following:

- Eijkelkamp (http://www.eijkelkamp.com/)
- Decagon, now known as METER Environment (https://www.metergroup.com/environment/)
- Solinst (http://www.solinst.com/)
- Ott (http://www.ott.com/web/ott_de.nsf/id/pa_home_e.html)

[2] Access can be requested from cesar.carmona-moreno@ec.europa.eu

- HOBO (http://www.onsetcomp.com/)
- HERON (http://www.heroninstruments.com/)

4.3 Topography

The best resource to use for elevation information is the following:

https://earthexplorer.usgs.gov/

Be aware that ASTER data is mostly flawed and is not representing true soil surface.

The SRTM 30 and 90m, that can be downloaded using Earth-Explorer, is the preferred source for hydrology. Based on the SRTM products, the USGS also provides corrected and DEM derived products in their HYDROSHEDS online facility found at:

https://hydrosheds.cr.usgs.gov/dataavail.php

4.4 Geology

To be able to model the hydrology taking groundwater movement into account, it is important to build a conceptual geological model. This is especially important for models like SWAT, J200, PRMS and ACRU as geology helps to define hydrological response units. The best online geological information available can be found at:

http://www.brgm.eu/project/new-edition-of-110000000-geological-map-of-africa, which leads to a download portal: http://portal.onegeology.org/OnegeologyGlobal/

4.5 Soils

The following sources are available to obtain soils data for modelling:

- The soils database of the FAO http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/en/
- The ISRIC soils database: http://www.isric.org/explore/isric-soil-data-hub and https://soilgrids.org/#!/?layer=TAXNWRB_250m&vector=1
- Digital soil mapping from Stellenbosch University. The Soil Science department will generate digital soil maps on request (wpdc@sun.ac.za) [3].
- The soil survey manual of the USDA as a source of information (Soil Survey Division Staff, 1993).
- The Agricultural Research Council – Institute for Soil, Climate and Water (ARC – ISCW) procedure for describing soil profiles (Turner, 1991). This unit was also key in the construction of the Soter data base (https://esdac.jrc.ec.europa.eu/projects/sotersoil-terrain-database , https://www.isric.online/projects/soil-and-terrain-soter-database-programme)
- The procedure for soil survey and mapping by Le Roux et al. (1999)
- The methods of soil analyses monography series of the Soil Science Society of America (https://dl.sciencesocieties.org/publications/books/tocs/sssabookseries/methodsofsoilan3)
- The relationship between soil water regime and morphology: a proposal for continued research (Van Huyssteen et al, 2007).

[3] Please check the WACOZA-AquaKnow database for updates.

- The South African soil classification proposed by the Soil Classification Working Group (1991) (http://www.soils.org.za/)
- The revised classification of South African soils proposed by Fey (2010).
- The World Bank: https://datacatalog.worldbank.org/dataset/zambezi-river-basin-land-use-land-use-change-and-soil-erosion

4.6 Land use

There are various sources of land-use data but not all are detailed related to agricultural use. Agricultural land-use needs more ground-truthing. The general resources are provided below.

- Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images
- United States Geological Survey database (http://glovis.usgs.gov/).
- European Space Agency (http://due.esrin.esa.int/page_globcover.php)
- http://www.waterbase.org/download_data.html
- Overview of benefits and drawbacks of aerial photography, satellite imagery, and ground observations (Wentz et al., 2004).
- The World Bank: https://datacatalog.worldbank.org/dataset/zambezi-river-basin-land-use-land-use-change-and-soil-erosion
- GISGeography is a GIS data hub generated by GIS experts providing a large array of GIS solutions, https://gisgeography.com/category/data-sources/

4.7 Climate

The Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) – a research project by 5 southern African countries and Germany – has made great strides in providing free access to climate information for modelling (http://www.sasscal.org/). SASSCAL Weathernet offers free access to weather information from numerous weather stations across the region. A book on SASSCAL research results is available at http://www.biodiversity-plants.de/biodivers_ecol/vol6.php.

The Council for Scientific and Industrial Research (CSIR) has a High Performance Computing facility and have partnered with other countries to combine expertise and infrastructure to create fine-scale (1-10km) climate modelling for Africa and the Southern Ocean (CSIR, 2016).

Climate data sets are available as modelled data and are publicly available from the following, for example:

Area covered	**Source**
Africa	https://climate.copernicus.eu/data-evaluation-climate-models
World, Africa, local	http://apps.ecmwf.int/datasets/
Local and Africa	http://cip.csag.uct.ac.za/webclient2/datasets/africa-merged-cmip5/
Africa	http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisCCode=ZAF
World	https://www.ecad.eu/
Africa	https://www.dwd.de/EN/climate_environment/cdc/cdc_node.html
Local	https://www.csir.co.za/developing-african-based-earth-system-model

World	https://globalweather.tamu.edu/
World. Africa and local	https://gisgeography.com/category/data-sources/
World	http://www.worldclim.org/
World	http://www.ipcc-data.org/,
World	http://www.climatus.com/index.php
World and local	http://www.ncdc.noaa.gov/sotc/global/2012/10
World and local	http://ipcc.ch/publications_and_data/publications_and_data_reports.shtml#.US9h5Dfoixk
World and local	www.lapig.iesa.ufg.br
World	http://ageconsearch.umn.edu/
World and local	http://glovis.usgs.gov/
Africa	http://www.fao.org/climatechange/climatesmart/en/
Africa	ftp://ftp-anon.dwd.de/pub/data/gpcc/html/download_gate.html
Africa and local	http://www.climatic-maps.org/daily-data
World and local	http://www.ipcc-nggip.iges.or.jp/software/index.html

Weather generator software for modelling can also be found online. The software is mainly used to test models within specific scenarios and it is commonly also used for scaling data. As examples the following:

https://www.ars.usda.gov/midwest-area/west-lafayette-in/national-soil-erosion-research/docs/wepp/cligen/

https://crudata.uea.ac.uk/cru/projects/betwixt/cruwg_hourly/

https://www.tandfonline.com/doi/abs/10.1080/02571862.2003.10634936

https://github.com/metno/wxgen

https://ccafs.cgiar.org/marksimgcm-weather-generating-tool

https://www.ncl.ac.uk/ceser/research/software/weather-generator/

The current accessible and preferred data sources for the Zambezi regarding the WACOZA project, are indicated as follows:

- WACOZA datasets, including SASSCAL hourly and daily meteorological data, daily and monthly CHIRPS precipitation datasets and global surface summary (GSOD).

https://aquaknow.jrc.ec.europa.eu/nepad-sanwatce

- WATCH WFDEI data, which is daily at 0.5 deg. It's a reanalysis dataset, i.e. it is based on climate model simulations, but it is the only one that would have internal consistency between all variables.

ftp://rfdata:forceDATA@ftp.iiasa.ac.at/

- CRU data - it's an observational, gridded data product that includes monthly rainfall and temperature, but also calculated PET.

http://www.cru.uea.ac.uk/data

- Other similar data sources

https://climexp.knmi.nl

- Particularly relevant to SWAT modelling:

http://www.waterbase.org/download_data.html

The spectrum of climate measuring and recording devices used in SADC is actually very narrow. A full list of climate stations and data is provided on the CSAG website of the University of Cape Town (http://cip.csag.uct.ac.za/webclient2/datasets/africa-merged-cmip5/). Furthermore, SASSCAL has established Weathernet (www.sasscalweathernet.org/), which provides real-time data online.

The three types of climate stations that generates more than 90% of the climate data of this region are the following:

1. MCS (https://www.mcsystems.co.za/)
2. Campbell (https://www.campbellsci.co.za/)
3. Ott, or ADCON (http://www.ott.com/about-us/)

4.8 Dams and Reservoirs

The Zambezi as a transboundary river, relevant for a number of economic sectors namely, domestic water supply, agricultural and fishing, tourism, recreation and power generation. Since the water in the Zambezi is important to all the countries of the region, potential impacts that electricity generation (and thereby changes on flow-pattern) will have on users in all of these countries need to be considered.

The variability in rainfall patterns that is expected to increase because of climate change, necessitates the development of alternative sources than water for power generation. As land development to the north in Zambezi became a priority in terms of employment and development, the building of large dams in them main river stream as well as in the tributaries of the Zambezi will impact on the WEFE resources downstream, including the alteration of the river morphology and delta (Ronco et al., 2010, Nones et al., 2013).

Data on dams and reservoirs are important, as they delay or reduce flow within catchments. For the larger dams in the Zambezi, the reservoir level is directly proportional to the capacity to generate power. Modelling the effects of changes in flow and sedimentation rates is important for planning and management of the reservoir/dam and the hydropower plant – not only to ensure adequate water levels for power generation, but also to reduce flood risk (Okumura & Sumi, 2012). The effect that climate change can have on sedimentation rates should also be considered in such modelling exercises (Scleiss et al., 2016).

For modelling purposes it is important to know the reservoir capacities and their levels over time. These measurements are mostly logged electronically but with smaller dams, the use of stages are still quite common. As for the data reported as provided by ZAMCOM, the data is hosted in the ZAMWIS database. For this project a MoU was signed and with that Non-Disclosure Agreements (NDA) with partners using the data. A NDA is required to have access to ZAMWIS.

- Level recorders (data provided by ZAMCOM)
- Satellite data (Bathymetry) (https://www.usgs.gov/faqs/where-can-i-find-bathymetric-data-0?qt-news_science_products=0#qt-news_science_products) and (http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/info/zambezi_modelling) and https://gisgeography.com/category/data-sources/
- Stage levels (data provided by ZAMCOM)

Relevant research on sedimentation management and modelling include:

- Merritt et al. (2003), providing a detailed overview of erosion and sediment transport models, many of which are relevant to reservoirs.
- Ronco et al. (2010), providing a robust 1D model at river basin scale on sediment/erosion morphodynamics accounting for the changes on discharges pattern due to large reservoirs of the Lower Zambezi;
- Bronstert et al. (2014), who developed modelling techniques for erosion, sediment transport and reservoir siltation in semi-arid catchments.
- Okumura & Sumi (2012), proposed management measures for reservoir sedimentation

5 Hydrology

In this section, an overview is provided regarding hydrology in general, with a specific focus on the Zambezi. It is important to keep in mind that hydrology and human interventions, especially hydropower generation from a river system, has positive and negative impacts on a huge number of sectors that benefit from the river and its water. Therefore the following benefits need to be considered:

1. Electricity trade
2. Emission benefits
3. Externalities like social impacts
4. Loss of land, changes in river morphology
5. Lower environmental costs, less pollution
6. Landscape, tourism
7. Downstream hydrological effects
8. Cross border policies of water and energy sharing
9. Employment

Based on bibliographic information, the seasonality of flow in the Zambezi seems to be cushioned by the capacity of the dams in the system, to such an extent that power generation until now was not compromised by seasons. With the concerns expressed related to climate change impact, population growth and economic growth and more people moving to the cities, the Zambezi hydropower system needs to be optimised so that the river system is not compromised and alternative energy sources be found elsewhere.

5.1 Hydrology instructing cost-benefit analysis

A cost-benefit analysis (CBA) related to a development may differ according to the needs of the different stakeholder groupings. Some of these stakeholder groupings can be indicated as follows:

1. Single Government
2. The SADC region
3. Agriculture
4. Municipalities
5. Social groupings
6. Religious groupings
7. Fishing community
8. Investors
9. Other

According to ECA (2010), a CBA should include the following procedures:

1. Determination of costs and benefits;
2. Conversion of market prices to accounting prices/ shadow prices;
3. Monetisation or quantifying non-market impacts (e.g. externalities);
4. Inclusion of any indirect effects (when relevant and also not already captured by shadow prices);
5. Social discounting (costs and benefits are discounted with a real social discount rate); and
6. Calculation of economic performance indicators i.e. economic net present value (ENPV), economic rate of return (ERR) and the benefit-cost (B/C) ratio.

ECA (2010) indicated the Economic Net Percent Value (ENPV) as the most reliable social CBA indicator and proposed that this be used as the main indicator for project appraisal. It is defined as follows:

- Economic Net Present Value (ENPV) - the difference between the discounted total social benefits and costs;

$$ENPV = \sum_{t=0}^{n} a_t s_t = \frac{S_0}{(1+i)^0} + \frac{S_1}{(1+i)^1} + \dots + \frac{S_n}{(1+i)^n} \quad ENPV = \sum_{t=0}^{n} a_t s_t = \frac{S_0}{(1+i)^0} + \frac{S_1}{(1+i)^1}$$

St = balance of cash flows at time t, *ai* = discount factor, n=number of years, t= time

- Economic Internal Rate of Return (ERR) - the rate that produces a zero value for the ENPV;

$$ENPV ENPV = \sum s_t \sum s_t / (1 + ERR)^t (1 + ERR)^t = 0$$

- Benefit -Cost ratio, i.e. the ratio between discounted economic benefits and costs.

$$B/C B/C = PV(B)/PV(C) PV(B)/PV(C)$$

PV = present value, B= total benefits, C=total costs

This approach, however, relies on approximations, working hypotheses and shortcuts, because of a lack of data or constraints on the resources of evaluators. This approach is distant from hydrological modelling but could instruct hydrological interventions and hydropower developments. A further requirement is that this type of study be carried out by an unbiased group.

5.2 CBA for regional cooperation in joint infrastructure on transboundary basins

The 1997 UN Convention on shared water courses was followed by the SADC Revised Protocol on Shared Water courses, adopted in 2000. ECA (2010) proposes a different and more direct CBA approach to regional infrastructure projects. The steps proposed relates to the following:

1. Identify the constraints
2. Determine the stakeholders to be considered
3. Assess the costs and benefits
    a. Direct costs
    b. Quantity and quality of goods to be supplied
    c. Efficiency of competition (in supplying the same service)
4. Output
    a. Define the primary project aim
    b. Provide the main options to be considered
    c. Provide a statement regarding the CBA of the options indicated

The complexity of calculating CBA, can be seen in Appendix D of ECA (2010). The costs related to infrastructure and water supply are well imbedded in these calculations. It is therefore necessary that hydrological modelling be conducted in such a manner as to generate the springboard for these analysis. The dynamics in terms of water availability in the river system, as may also be compromised by various factors, are key to long term planning and sustainability for regional growth.

Relevant literature on CBA can be found here:

https://www.uneca.org/sites/default/files/PublicationFiles/cost-benefit-analysis-for-regional-infrastructure-in-water-and-power-sectors_0.pdf

Other examples:

(http://www.qca.org.au/getattachment/1b69ab51-79d4-498e-904f-836924cf9a82/MJ-CBA-Report-2.aspx)

https://enviroincentives.com/wp-content/uploads/2017/12/CBA_Document_Version_0.9_Fact_Sheet.pdf

http://www2.ulpgc.es/hege/almacen/download/7073/7073892/johansson_y_kristrom_021109.pdf

5.3 Water supply and (WEFE) demand scenarios

Fecher (2014) researched the climate change and upstream development impacts on new hydropower projects in the Zambezi. The objective of the research was to make a “first pass” assessment of how upstream changes in climate and irrigation demand would affect water availability for major downstream Zambezi River Basin hydropower plants. They indicated that with an increase of 6% in irrigation consumption, the energy output at Cahora-Bassa will be reduced by 20%.

Kling et al., 2014 studied the impact of water resources development and climate scenarios on the Zambezi discharge. They indicated that discharge is highly sensitive to small precipitation changes. In this study they also provide a summary of the studies until 2014 on supply and demand for the Zambezi. They also carefully presented the sources of their data and problems converting the data to usable formats. The sources are as follows:

1. Precipitation: Global Precipitation Climatology Centre (GPCC, version 5, published 2011), Deutscher Wetterdienst, Germany;
2. Air temperature: Climate Research Unit (CRU, version TS 3.1, published 2011), University of East Anglia, UK;
3. Long-term mean monthly potential evapotranspiration (mPET) data were obtained from the CLIMWAT data set of FAO for 30 stations in the region;
4. The Penman–Monteith method (Monteith, 1965) was used in the CROPWAT model of FAO to calculate the sensitivity of mPET to changes in temperature;
5. Climate scenario data about future precipitation and temperature were obtained from the recently finished EU WATCH project (WATer and global CHange, published 2011, http://www.eu-watch.org)

The River Basin Model, related to the PITMAN model, addresses water balance and water allocation issues. The model is available for use should anyone need this for further studies. This study also refers to the Pitman model and the work done by the group of Prof Denis Hughes from the Rhodes University in South Africa. It also refers to the Delft group with Prof Savenije.

Gumindoga et al. (2016) estimated runoff from ungauged catchments for reservoir water balance in the Lower Middle Zambezi Basin. This study applied a rainfall-runoff model (HEC-HMS) and GIS techniques to estimate both the gauged and ungauged runoff contribution to the water balance of Cahora-Bassa. This is an important study as results from this study are also applied in the current SPATSIM model of Prof Denis Hughes (Tirivarongo, 2012).

5.4 Models

A general saying about models is that your efforts with an unknown model is as good as your access to the model developer. It is therefore better to use models for which the capacity of using the tool already exist in the region where it is applied. Many authors have raised this point; that creating models for the same catchment wastes resources that could have been directed towards implementation (e.g. Johnston & Smakhtin, 2013). Urbonas (2007) highlights the need to find a balance between "accuracy" and "precision" when it comes to large-scale modelling, or modelling without having enough data readily available for proper calibration. According to Urbonas (2007, p2), the following are the most important elements in modelling:

- *The modeller's skill is most important.*
- *Selecting the appropriate model is next.*
  - *Some models are best for urban areas dealing with small sub-catchments.*
  - *Others are best for large non-urban catchments.*
  - *What happens when we have a large urban catchment or mixed catchment?*

- *Next in importance is the math engine of model, provided,*
  - *It has no significant bugs*
  - *It represents the equations it uses accurately*
  - *It provides for user input to override defaults built into the code*

The following groups have been attempting to improve basin hydrological modelling, particularly where input data is scarce. Through this work a lot of progress has been made to improve model uncertainties (taken from Pechlivanidis et al., 2011, p204):

- *Prediction in ungauged basins (PUBs)*: Developed by the International Association of Hydrological Science, this is a programme that has been focusing on examining and improving existing models' predictive ability in ungauged basins, and developing new models to reduce predictive uncertainty.

- *Model Parameter Estimation Experiment (MOPEX)*: The project aims at improving and developing datasets in ungauged basins, validate parameter estimation methodologies, as well as improve models through calibration.

The hydrological models that could be useful in the Zambezi catchment can generally be grouped as three types:

a. Watershed models, mainly physically based
b. Deterministic models
   i. Lumped (with parameters that do not vary spatially, not accounting for sub-basins)
   ii. Semi distributed (parameters that may vary in space, and with sub-basins like SWAT)
   iii. Distributed (with full variation in space based on user resolution selection)
c. Physically based models, based on overland flow making use of response equations (like SPATSIM and PITMAN)

5.5 Hydropower and the basics

The International Finance Corporation (IFC), World Bank Group, published a guideline for developers of hydroelectric power plants in 2015 (IFC, 2015). Two chapters are relevant here: design options and hydrology and energy calculations.

In terms of design, Figure 1 is indicated as an example of knowledge needed to optimise sustainable hydropower generation where the headwater and flow rates required per turbine typology, may impact on the best conditions to generate power between 0,1 MW and 1000 MW. Here, the selection of the turbine among different typologies is based on the ratio between water head and water flow, according to the power generation capacity that can be, reasonably, obtained from that configuration. This is also indicated as an example where the cost of selected equipment and infrastructure linked to electricity demand design, must be matched with a benefit analysis. Should the water that reaches the Zambezi be impacted through climate change and developments elsewhere, the selected turbines may lose their efficiency as they will operate outside their design specifications.

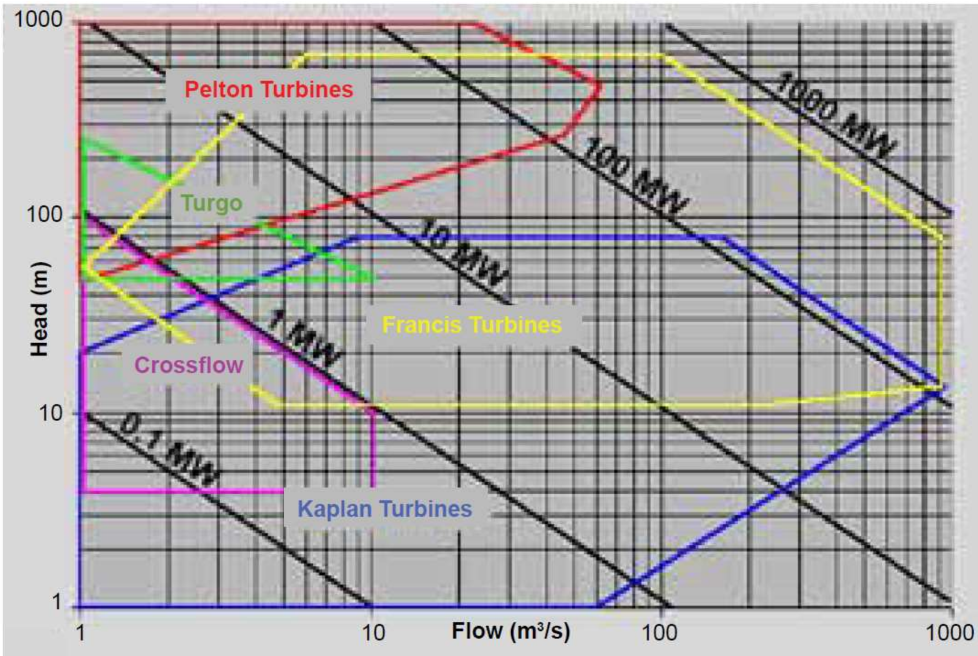


Figure 1. Head-flow ranges of hydro turbines (IFC 99392, 2015)

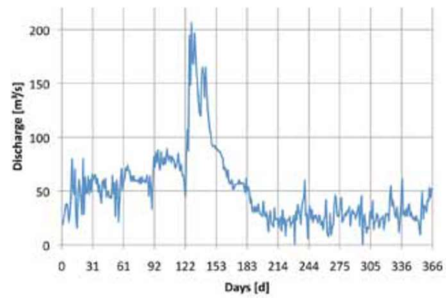
Chapter seven of the guideline deals with calculations and a summary of factors to consider with the associated methodologies, will be summarised here.

- **Hydrology calculations used in models (**IFC 99392, 2015**):**

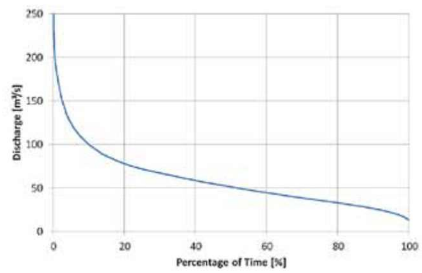
PARAMETERS	HOW TO CALCULATE
River discharge	
Require at least 15 years data to determine discharge	The three most common methods to determine intake discharges: • *Simultaneous flow measurements*: Temporary gauging station installed upstream from existing point, take simultaneous measurements. Transpose historical hydrological data from the existing gauging station to the proposed intake. • *Relationship between specific runoff and altitude*: Empirically derive a relationship between specific runoff [l/s/km2] and average catchment area altitude. Use data from multiple gauging stations and control profiles to generate the regional curve. • *Catchment area method*: Assumes that in a specific gauging station catchment area the same quantity of runoff is generated on each km², independent of elevation. Intake discharge is calculated as a function of the catchment area: $Q_{Intake} = Q_{Gauginstation} \cdot \left(\frac{Area_{Intake}}{Area_{Gauginstation}} \right)$
Flow duration curve	
Temporal variations in precipitation and	There are two ways to express variation in river flow:

<table>
<tr>
<td>temperature causes a variance in water discharge. Discharge has to be measured at different times of the day to achieve daily, as well as yearly averages.</td>
<td>

- Annual hydrograph:



- Flow duration curve:



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- **Power and energy calculations (**IFC 99392, 2015**)**:

The following basic calculation applies:

$$E = P * t$$

• E is the generated energy [MWh]
• P is the power produced [MW],
• t is the period of time [h]
(1 MWh is equal to 3,600,000,000 joules)

- **Power production from hydropower plants**, where available power is proportional to the product of head and flow rate:

$$P = \frac{n * p * g * Q * H}{10^6}$$

• P is the power produced at the transformer [MW]
• η is the overall efficiency of power plant [-]
• ρ is the density of water [1000 kg/m³]
• g is the acceleration due to gravity [9.81 m/s²]
• Q is the volume flow rate passing through the turbine [m³/s]
• H is the net head [m]

- **Efficiency (**IFC 99392, 2015**)**:

For 87% typical overall plant efficiency:

$$P(kW) = 8.5 * Q * H$$

When considering the efficiency of the turbine, transformer and other parts one can calculate overall turbine efficiency:

$\eta_{overall} = \eta_{Turbine} * \eta_{Generator} * \eta_{Transformer}$

The following figure provides an overview of turbine efficiencies:

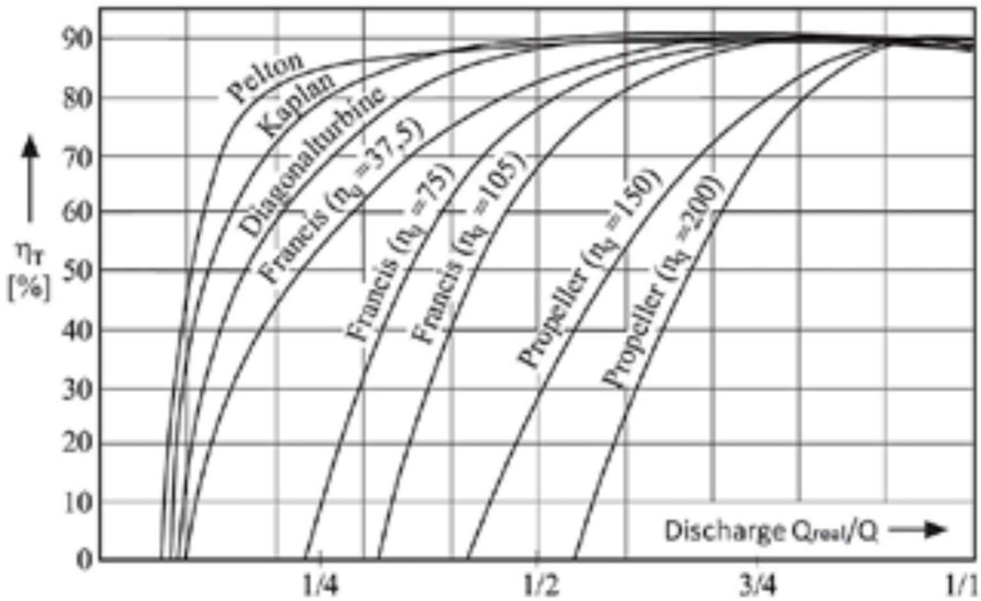

Figure 2. Efficiency of turbines types, Qreal/QD is the relative discharge related to the design discharge and ηT is the efficiency (IFC 99392, 2015)

- **Design discharge (**IFC 99392, 2015**):**

Discharge available for energy production depends on:

1. Hydrology
2. Ecological flow
3. Irrigation requirements
4. Leakage
5. Evaporation
6. Other water consumption

The design of the hydropower plant should be based on the hydrology of the catchment and take the above factors, as well as geological and topographical factors, into account. Optimised design can be calculated by comparing project expenditures and income for each design discharge scenario. The following graph provides an example, using Internal Rate of Return as the financial indicator:

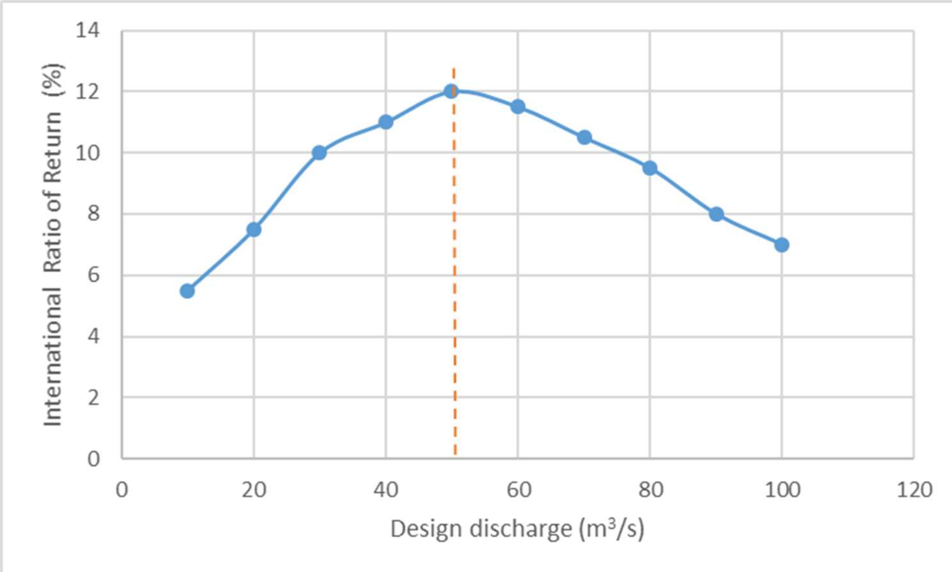

Figure 3. Internal Rate of Return as the financial indicator (IFC 99392, 2015)

The discharge design concept also needs to be influenced by a cost to benefit analysis.

- **Hydraulic Head (**IFC 99392, 2015**):**

This is a key parameter to determine the hydropower potential. Gross Head is the difference in altitude available for energy generation (and dependent on the type of turbine), and Net Head is Gross Head minus the hydraulic losses in the waterways. Such losses are dependent on the square of flow velocity.

5.6 Risks, impacts and vulnerabilities

The term risk is used to indicate negative impacts that could severely compromise the costs and benefits foreseen in hydropower projects. These risks to hydropower projects are outlined by the IFC report of 2015. The wide range of these risks all depend on a sound hydrological database and modelling to be able to mitigate and work with these issues. The summary in the addendum of the IFC report can be outlined as follows.

Table 3: Risks that could impact on the success of hydropower production (IPC, 2015).

Political risks	Political change Corruption Licensing Transboundary issues
Economic and financial risks	Cost escalation Foreign exchange Electricity market Financing package Performance of contractors
Technical risks	Hydrological Geotechnical and seismic Electro-mechanical and equipment performance Construction

	Operation and maintenance
Social risks	Land and water use conflicts Resettlement and social conflicts Public health and safety International objection on social, environmental or cultural grounds Cultural heritage issues
Environmental risks	Water quality Sedimentation Upstream/downstream flow regime Wetland protection Biodiversity Fish habitat
Added risks	Climate change Mining activity Increased irrigation agriculture Population increase

5.7 Climate change

Researchers have paid a lot of attention in using hydrological modelling to predict the impact of climate change on water availability. The use of global atmospheric general-circulation models (GCMs) is one such approach to incorporate the complexity of climate change in models (Pechlivanidis et al., 2011). However, there are still accuracy challenges in the parameters used in these hydrological models, such as land-use changes and moisture fluxes, which undermines its efficiency as part of global climate models (Pechlivanidis et al., 2011; https://openknowledge.worldbank.org/handle/10986/21875).

Hydropower generation will likely be affected by climate change in various ways – both on the demand and supply side. Changes in rain and rainfall pattern may affect river flows, which could impact on power generation capacity, just as general climate and temperature changes may affect the demand for electricity (Cervigni et al., 2015, Gaudard & Romerio, 2014, Vicuna et al., 2008). Climate change therefore poses a real threat to hydropower (Gaudard & Romerio, 2014). If authorities do not properly consider climate change scenarios at the present, the power plants could suffer revenue losses in the future (Cervigni et al., 2015).

Climate change is, according to various authors, the single factor that may impact flows in the Zambezi the most. It has been estimated that, if planners of hydropower in the Zambezi ignore climate change, it could soon lead to 18% losses, while wrong adaptation measures could lead to about 30% losses in the future (Cervigni et al., 2015).

For the above-mentioned reasons, it is imperative to focus in scenario development as was done by various authors mentioned in this document.

6 Modelling the Zambezi

This section will pay attention to the model set-ups that were done in the past and reported on internationally. In this search, it was only a couple of models that stood out as the preferred models, but they were also the models with high scalability in terms of the resolution of input data. The preferred models that are also available for this study, are the SWAT model set up by the Delft group with Prof H Savenije, SPATSIM set up by the Rhodes University group with Prof D Hughes, and WAFLEX set up by the University of Zimbabwe group, and currently used by the NUST group in Windhoek.

6.1 SWAT

The Zambezi received a lot of attention in the past but the most current major modelling attempts was found to be SWAT as done by Prof Savenije's group at Delft IHE. There was also attempts to model the dams and related hydropower generation by the same group, using WEAP. The group of Liechi et al. (2014), (Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne, Switzerland) worked extensively with the SWAT model researching various aspects of the Zambezi hydrology. Liechti et al., (2011) modelled the Zambezi successfully and also presented an online version of their Zambezi SWAT model at http://zambezi.epfl.ch/, which was however recently removed. The information generated by this group is however available at https://search.epfl.ch/?q=zambezi.They recently applied the SWAT model to the Zambezi catchment, testing a number of questions regarding the Zambezi flows.

The SWAT model and reference data can be downloaded from https://swat.tamu.edu/ . The model embeds in a GIS, which can be ESRI, MapWindows or QGIS. For those that does not have access to ESRI software, the QGIS option is the best to use. The latter is called QSwat. The SWAT model is presented online with instructional videos also supporting a tutorial. A full SWAT training course is also available.

From the TUDELFT group, most publications were with HC Winsemius, with Prof Savenije as project leader (Winsemius et al., 2005). This group was contacted and are quite willing to share the model with the WACOZA group. The results of both groups are well published and can be accessed online. This also means that large capacity exists in terms of SWAT modelling for the Zambezi.

Steps in securing a working SWAT model is still underway and will be possibly made available through the WACOZA database.[4]

6.2 ZAMWIS DSS:

The ZAMCOM Water Information System (ZAMWIS) is an interactive web-based data and information system, based on contemporary and historical spatial data, hydrological time series, earth observation information, knowledge products and other related information. It was established recently to inform the management of such a transboundary river system. ZAMWIS allows sharing of information and urges the partner states to routinely share data and information on the system. Consequently a basin-wide Decision Support System (DSS) is being developed. The DSS will support planning and operational management also supporting the balance between water usage and electricity demand. This is possibly the most significant innovation for the Zambezi Catchment modelling to date and should be supported. Though this information base is still being developed, access to this information needs to be arranged with the proper authorities.

6.3 SCADA:

In 2011 the DELTARES project investigated the dam synchronisation and flood releases in the Zambezi River Basin. In this project the focus was on a basin-wide flow forecasting system and expert inputs.

[4] Please check the WACOZA-AquaKnow database for updates.

“The project is an example of an excellent collaboration between European and African experts, with concentration of the work on the ground in Africa” (Deltares, 2011). The project made use of SCADA software and the reservoir balances could be modelled and forecasts could be done. This model was not available at the time this document was prepared.

6.4 SPATSIM/PITMAN:

There is also a large interest and investment made in the Zambezi modelling from the Rhodes University Integrated Water Resource Management group under Prof Denis Hughes. This group modelled sub-catchments of the Zambezi using the SPATSIM (PITMAN based) model. The group also tested the modelling on ungauged basins. SPATSIM (SPAtial and Time Series Information Modelling) software package has been developed by the Institute for Water Research (IWR) of Rhodes University in South Africa over a period of 1999-2018.

The package has been developed using ESRI Map Objects as a tool for managing and modelling the data that are typically associated with water resource assessment studies. It contains an integrated database management system that uses GIS Shape files as the main form of data access. It also has a number of built-in data analysis and processing tools (such as for generating catchment average rainfall data from gauged station data or generating monthly and annual frequency tables from time series data), as well as a wide range of external models that can be setup and integrated seamlessly with the database (i.e. the models access their data requirements from the SPATSIM database and store their results in the database without any intermediate data transformation). The models include Design Flood, Spatial Interpolation of Observed Flow Records, Monthly Rainfall-Runoff Simulation Model, Desktop Model for Environmental Flow Assessment, etc. Detailed SPATSIM description and Help options are available with the installation package, which in turn is available from IWR (https://www.cbd.int/doc/case-studies/tttc/tttc-00153-en.pdf and courtesy of Prof Denis Hughes).

A running SPATSIM model for the Zambezi catchment (Figure 5) was made available for this study. For the ACEWATER2 research, all the SPATSIM Zambezi modelling of the past was combined into a single model for the whole of the Zambezi catchment and is available for use. The current setup makes use of monthly time steps in modelling. Current results shows acceptable responses. Figure 5 shows the model interphase with the Zambezi model elements.

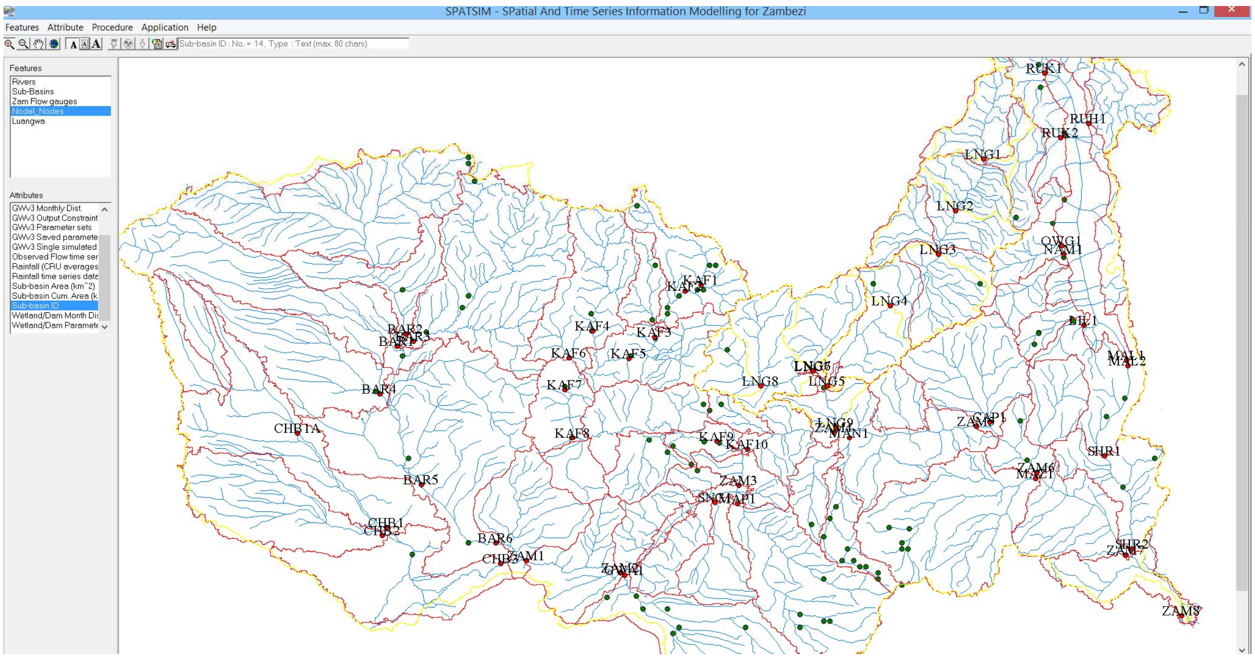

Figure 5. The Zambezi hydrological model setup in SPATSIM.

The SPATSIM and Pitman models basically share the same approach. The conceptual approach is given in figure 6.

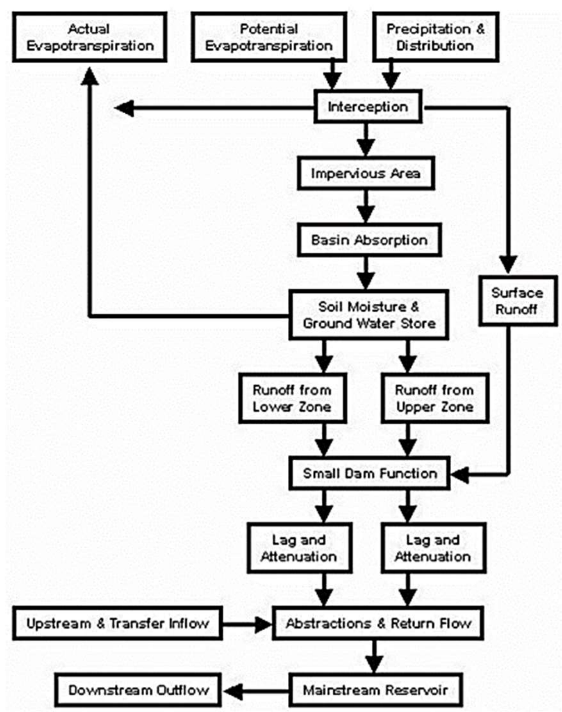

Figure 6. The model structure and conceptual flow used by the Pitman and SPATSIM models (Hughes, 2014).

6.5 WAFLEX:

The Water Allocation and Flow Model in Excel (WAFLEX) is a spreadsheet-based model that can be used to model interactions between up- and downstream (Siwale, 2008). WAFLEX is one of the early models used to reflect on reservoir volume in relation to hydropower production. The first reporting about this was done by Savenije (1995). It has been applied widely in southern Africa (Juízo & Lidén, 2010). The model uses a comparison between demand and availability to produce water allocation strategies (Juízo & Lidén, 2010). Because of its relative simplicity, it has potential to be used as practical guideline for catchment managers (Symphorian et al., 2002, in Siwale, 2008). The Namibia University of Science and Technology (NUST) is in the process of applying the WAFLEX model to the Zambezi River.[5]

For examples on its application, see:

- Siwale, 2008 (Zambia)
- Juízo & Lidén, 2010 (Swaziland and Mozambique)

7 Further examples

Examples of modelling tools for management of water resources can be found on the websites of basin management agencies, similar to ZAMCOM. Some examples include:

- Colorado: University of Colorado Center for Advanced Decision Support for Water and Environmental Systems, US Bureau of Reclamation and Tennessee Valley Authority. https://www.colorado.edu/cadswes/creative-works/riverware; http://www.riverware.org/riverware/RW_Can_Do.html).
- Nile Basin Initiative (NBI): http://www.nilebasin.org/index.php/documents-publications.
- Mekong River Commission (MRC): http://www.mrcmekong.org/publications/reports/technical-paper-series/.
- Orange-Senqu River Commission (ORASECOM): www.orasecom.org.
- Limpopo Watercourse Commission (LIMCOM): http://www.limpopo.riverawarenesskit.org/LIMPOPORAK_COM/EN/GOVERNANCE/WATER_GOVERNANCE_IN_THE_LIMPOPO/LIMCOM.HTM.
- Amazon Waters: http://amazonwaters.org/readings/.

8 Conclusion

A good insight into the current status of water resource management for the Zambezi was provided in this document. The work done to date was included and links were provided to the literature, the models and the modellers. The document also eluded on data availability both from SADC-based resources as well as international resources. The resources indicated are repositories of raw data, modelled data and satellite derived products. The main source of raw data resides with ZAMCOM and is partly available on the ZAMWIS online information system.

[5] For more information about WAFLEX and the application thereof for the Zambezi, please contact Andrea Vuche, avushe@nust.na

The document also presents a review on matters linked to water resource management and matters that may impact on water availability and may impact on hydropower generation. In this regard two leading documents namely a cost benefit analysis (ECA, 2010) and risk and vulnerabilities analysis by the IFC (2015) provided a perspective of what to take into account to generate stability and sustainability in access to water and power in the future. The latter two concepts to date have not found their way into the Zambezi management protocol, mainly as a result of the lack of acceptable water resource management tools. What is further also lacking, is an economic model or economic analysis for the Zambezi, indicating the impact of water demand and hydropower demand on the sustainability of the total system.

The tools for water and power management is currently being developed by ZAMCOM as a priority and made available online through the ZAMWIS facility. This is however not yet a system that could reflect on different scenarios and early warning. This document therefore reflected on centres where expertise was developed in water resource management since 1995. The modelling done to data by these centres are not all accessible. The accessible models and modelling environments are, the SWAT model by the Delft group, the SPATSIM model by the Rhodes University group in South Africa and the WAFLEX model at NUST in Namibia.

The main features of SWAT is that it is a globally recognised model that has the ability to simulate flows in the system and the dams and it can be sensitised around the dam water levels in hydropower generation. SWAT is also taking land-use, soils information and topography into account in its set-up. This implies that climate and land-use change will impact on modelling of flows, and scenarios in this regard could be studied. The SWAT model makes use of hydrological response units, in which regions and responses are lumped. This can be done to a very high resolution, depending on the quality of land-use data, climate data, geology and soils information available. This implies that SWAT has the largest sensitivity and degrees of freedom in terms of modelling compared to any of the other models used in the Zambezi. Another advantage of SWAT is that the groundwater response is also defined and can be dealt with.

SPATSIM is very successful in terms of water planning and once set up and calibrated, can simulate runoff very well. It can also accommodate the responses in the dams as a result of hydropower generation. SPATSIM has the advantage that it is fairly fast to set up once the typical flow responses for all the sub-catchments were defined. With SPATSIM the surface to groundwater reaction is defined in terms of a total runoff response to the point of measurement.

WAFLEX is a spreadsheet model, where the model operates around a comparison between demand and availability, to produce water allocation strategies. This makes the model very useful to reflect on the demands of hydropower generation, and is possibly the biggest advantage of the model, but less useful in terms of scenario development and impact.

Many publications and a large amount of information exist on Zambezi catchment modelling, mainly based on SWAT and SPATSIM. The authors are generally keen to share their information. As reported in this manual, most of the available information is not provided in standardised formats for modelling. There are different temporal scales, different geo-referencing systems, different resolutions and different levels of quality used by the different groups. The calibration of flow measurement equipment also seems to be not standardised over the whole catchment. It is therefore difficult to start a new modelling approach, without tapping into the experience of modellers that have been in the region and involved over a long period.

The way forward in modelling is to set SWAT, WAFLEX and SPATSIM up using the same climate database. SWAT will be sensitive to changes in the landscape and generate flow responses that should feed into WAFLEX and SPATSIM. WAFLEX will reflect the maximum amount of hydropower possible related to water availability. SPATSIM will be set up as a tool to be used for general water planning and could replace SWAT.

It is also very important to develop the tools and sensitivity in modelling to such an extent that it can be imbedded in the ZAMWIS information system. The aim should be to increase the automation of modelling results from ZAMWIS, to also act as an early warning system. The data for ZAMWIS will also have to include defined in-field measurement and supported with remote sensed information.

The Zambezi is an international river system and the need for a regional information system like ZAMWIS may prevent future conflict and uneven and patchy development in this region.

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