Water Allocation Models for the Umbeluzi River Basin, Mozambique

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1 Introduction

Sustainable management of Umbeluzi water resources is one of the responsibilities of ARA-Sul. An improved understanding of the behavior of the basin in relation to water demand, supply and availability is therefore needed. Some typical water related issues the basin is experiencing are increased water demand by Maputo, expansion of irrigation, inter-basin transfer treaties with Swaziland, environmental flow requirements, salt intrusion, and changing climate, amongst others. Since 1987 the reservoir “Pequenos Libombos” is operational. The reservoir was specifically built to supply drinking water for Maputo. A small part of the available water is allocated to irrigation and industries. Since the construction of the reservoir the demand of water increased through population growth and the development of irrigation. Climate change is influencing the variability of the annual rainfall-runoff into the water reservoir, which directly affects the water availability to the downstream users.

ARA-Sul, in collaboration with Wetterskip Fryslân and FutureWater and with financial support from the Netherlands Embassy in Maputo, has therefore developed Water Allocation Models (WAM). The two WAMs described in this report will serve two purposes. First, the WAM-Strategic will support to evaluate policies and their impact on water demands, supply and shortages. To this end a flexible tool was built that captures the main water issues in a model. Second, an operational WAM was built to evaluate the impact of permits and licenses on Pequenos Libombos reservoir and other water users.

The developed WAMs as described in this report, together with the associated training and educational activities, will serve as pilot for other basins managed by ARA-Sul.

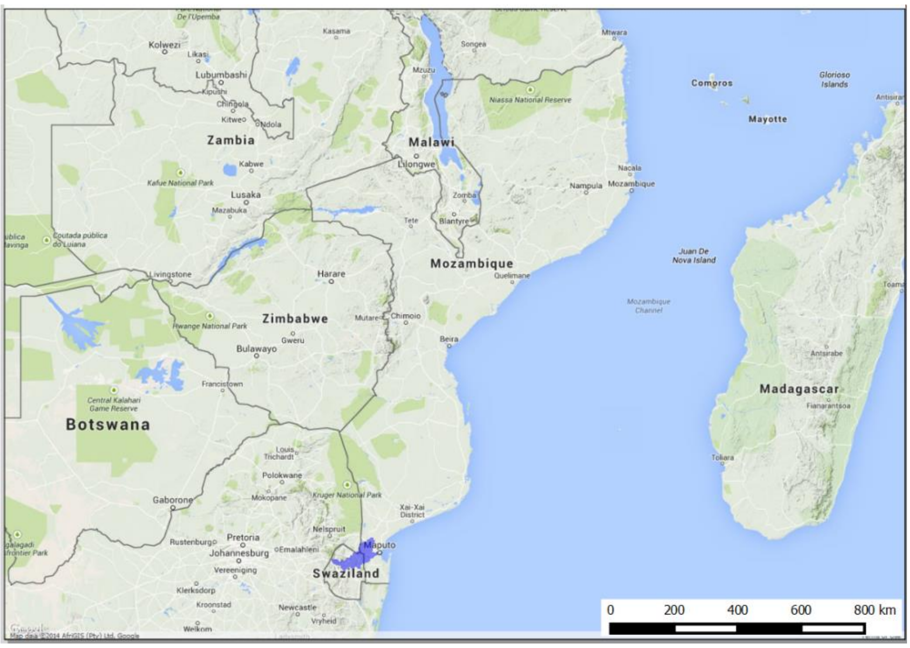


Figure 1. Location of Umbeluzi river basin in Southern Mozambique and Swaziland.

2 Umbeluzi

[1]The Umbeluzi River Basin is shared with Mozambique, South Africa and Swaziland and is an important source of water supply for Maputo (Figure 2). The headwater of the Umbeluzi River is located in Swaziland close to its western border with South Africa. The river flows in an easterly direction and discharges into the Indian Ocean via the Espirito Santos estuary south of Maputo. The total catchment area of the Umbeluzi River basin is about 5400 km^2. 40% Of the area is in Mozambique, 58% in Swaziland and only 2% in South Africa. Two major tributaries join the main Umbeluzi river, the White Umbeluzi in Swaziland and the Movene in Mozambique. The altitude increases from sea level to almost 2000 MASL in the western part. Rainfall varies from 500 mm/year in the lower parts to 1500 mm/year in the mountainous part. The basin experiences two distinct seasons; the rainy season from November to April and the dry season between May and October.

The Umbeluzi River has two major dams located in the basin. The Mnjoli Dam, with a total capacity of 152 million m^3 (MCM), was built in 1978 to secure water for the sugar cane estates in eastern Swaziland. The Pequenos Libombos Dam in Mozambique, with a total capacity of 392 million m^3, was constructed in 1987 mainly to secure the urban water supply for Maputo City. A small part of the available water is allocated to irrigation (Figure 3) and industries. The intake and water treatment plant for Maputo City is located some kilometers downstream of the Pequenos Libombos reservoir and the dam is therefore constantly releasing a minimum flow to allow for water supply. Additionally, a small dam in the upper basin in Swaziland, the Hawane (2.75 million m^3), supplies the capital Mbabane with fresh water.

The largest water user in the entire Umbeluzi basin is irrigation. The total estimated present water demand for surface water is 350 million m^3/year but is forecasted to increase by 67% to 586 million m^3/year by the year 2025 (Juizo and Liden, 2008). Under natural conditions the available water is estimated to be 535 million m^3/year. The two countries have a number of small-scale users distributed in the catchment and because of the water scarcity many proposals exist to build storage infrastructure.

The Administração Regional de Água (ARA) Sul is one of the five ARA in Mozambique. ARA-Sul is the water agency responsible for the river basins in southern Mozambique, including the trans-boundary flood prone rivers Limpopo and Maputo. The Umbeluzi basin is of key importance for Maputo domestic water supply. ARA-Sul is strongly involved in the hydrological modelling including water availability, dam operation and flood forecasting.

Some previous water allocation modeling projects have been undertaken for the Umbeluzi. The most relevant are the SWECO studies as reported in 2005 and the work of Juizo and Liden around 2008. Both studies are somewhat outdated and were hampered by “hydrological data uncertainty and lack of adequate modelling tools and insufficient institutional capacity”. In the current project as much as possible data, methods and results from these studies were used. Moreover, the current study uses the most suitable modeling framework currently available (WEAP) and overcomes data shortages by using state-of-the-art data from public domain and satellite information.

[1] This section is based on various sources. Most important ones: SWECO 2005 study, Juizo 2008, Droogers 2014.

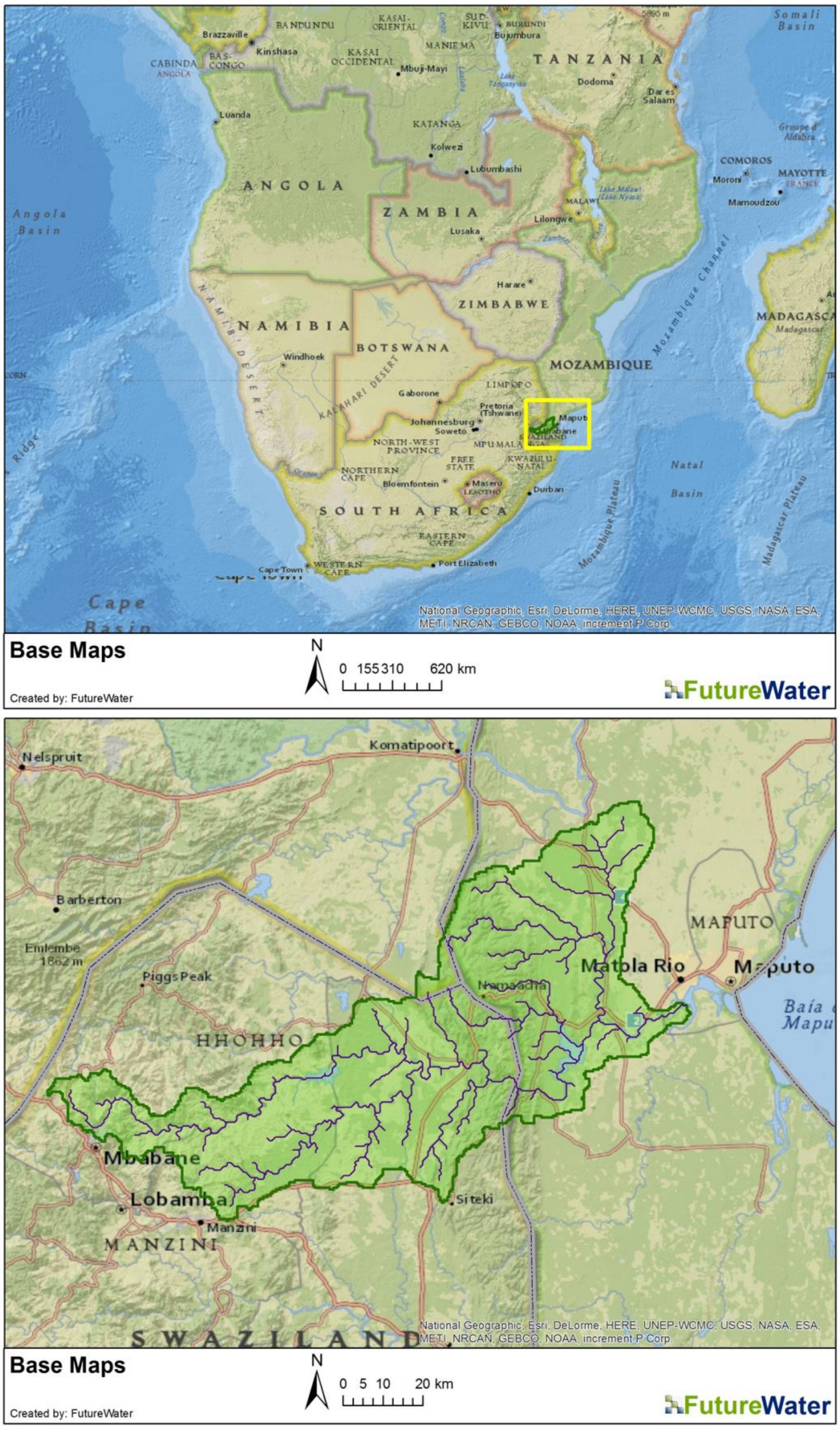


Figure 2. Location of Umbeluzi River Basin (top) and detailed overview of main rivers (bottom).

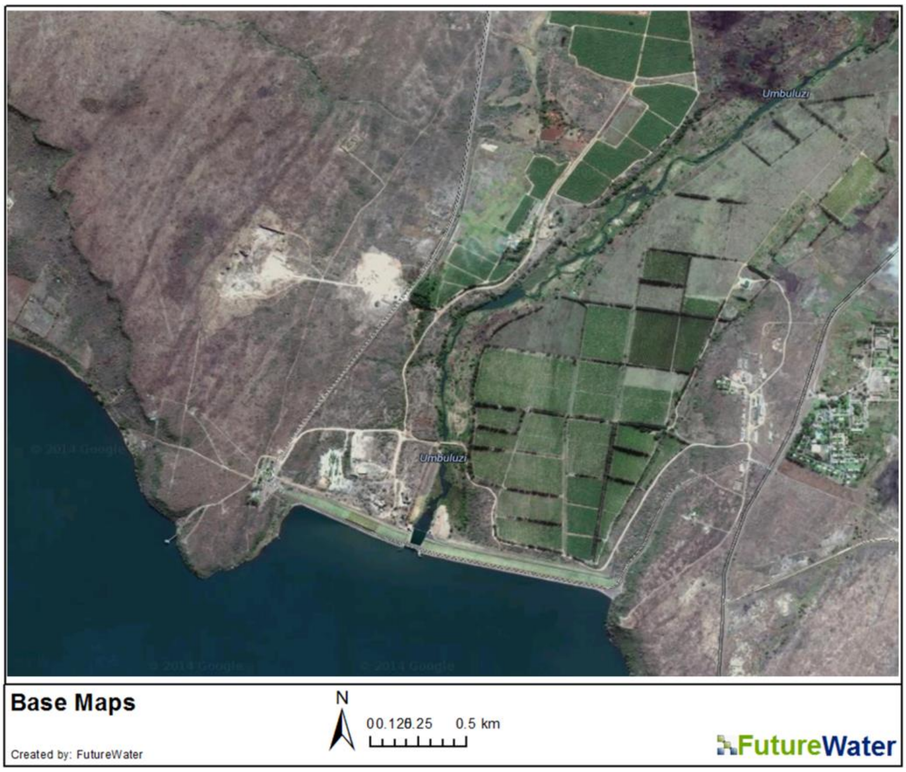


Figure 3. Details of irrigation downstream Pequenos Libombos dam.

3 Water Allocation Models Development

3.1 Overview

Sustainable management of Umbeluzi water resources is one of the responsibilities of ARA-Sul. An improved understanding of the behavior of the basin in relation to water demand, supply and availability is therefore needed. It is expected that competition for water will increase in the basin. ARA-Sul wants to anticipate on the expected changes by improving their existing decision making procedures. Hence ARA-Sul is looking for a Water Allocation Model that will serve to evaluate policies and support the operational management of the Pequenos Libombos reservoir

The WAM (Water Allocation Model) that was developed is based on the WEAP framework. WEAP was selected for various reasons. First of all, it is well accepted that the best model does not exist, but is a function of the questions to be answered. A common approach of model selection is to look at the spatial scale to cover and the amount of physical detail to be included (Figure 4). Obviously, other factors such as resource (time and money) availability, access to data, knowledge level, support, amongst others, should be considered as well.

An analysis on similar models that have been applied to the Umbeluzi revealed also that the WEAP model outperformed others (Juizo and Liden, 2008). The analysis compared the WRYM, WAFLEX and WEAP model as developed for the Umbeluzi. WEAP is freely available for organizations in developing countries. Finally, using WEAP has the advantage that ARA-Sul has some past expertise in the use of the model. ARA-Centro is in the process of developing and using WEAP for the Pungwe basin.

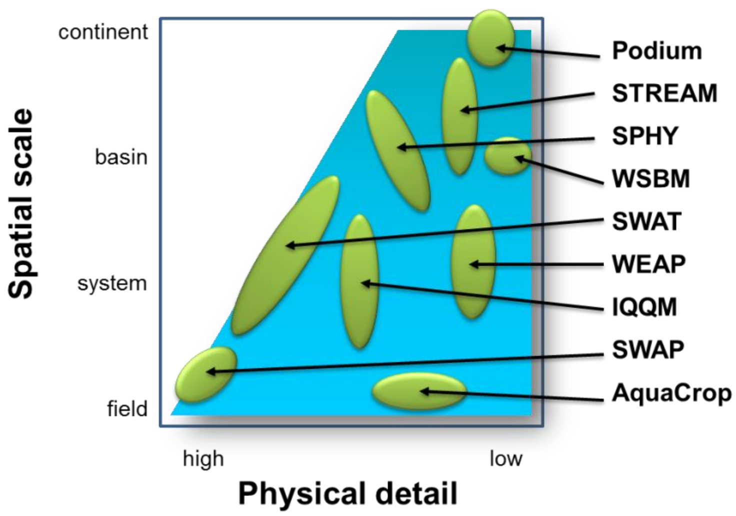


Figure 4: Relation between spatial scale and physical detail in water allocation tools. The green ellipses show the key strength of some well-known models. (Source: Droogers and Bouma, 2014)

A detailed discussion on WEAP can be found in the WEAP manual which can be freely downloaded from the WEAP website (www.weap21.org). In summary WEAP outperforms many other water allocation models as:

- Integrated Approach: Unique approach for conducting integrated water resources planning assessments.
- Stakeholder Process: Transparent structure facilitates engagement of diverse stakeholders in an open process.
- Water Balance: A database maintains water demand and supply information to drive mass balance model on a link-node architecture.
- Simulation Based: Calculates water demand, supply, runoff, infiltration, crop requirements, flows, and storage, and pollution generation, treatment, discharge and in-stream water quality under varying hydrologic and policy scenarios.
- Policy Scenarios: Evaluates a full range of water development and management options, and takes account of multiple and competing uses of water systems.
- User-friendly Interface: Graphical drag-and-drop GIS-based interface with flexible model output as maps, charts and tables.
- Model Integration: Dynamic links to other models and software, such as QUAL2K, MODFLOW, MODPATH, PEST, Excel and GAMS. Links to all other models can be developed quite easily since WEAP can read and write plain text files similar as SWAT, SWAP, Mike11, HEC-HMS, HEC-RAS and Geo-SFM.

The two WAMs as developed do not replace the existing operation rules for releasing water from Pequenos Libombos as described in the Operational Manual and implemented in the SIGA Microsoft Access Tool. An overview of the three main supporting tools and their applications is shown in Figure 5.

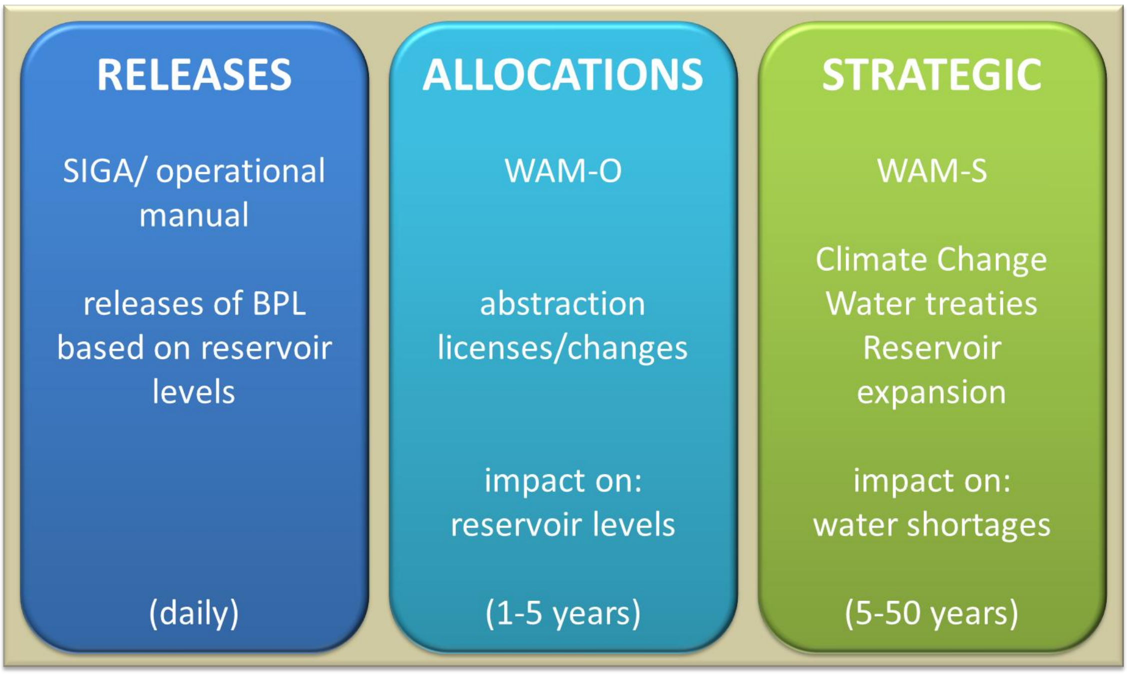


Figure 5. The three tools to support decision making for the Umbeluzi basin.

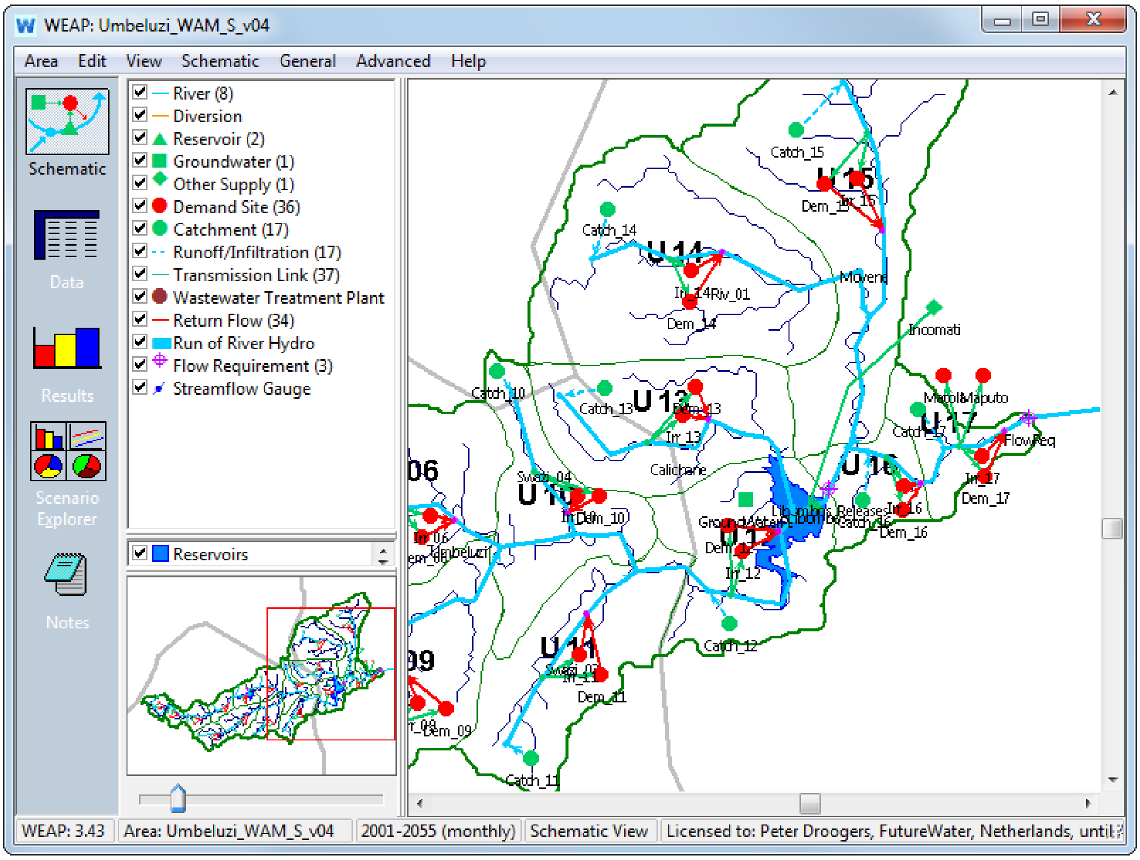


Figure 6. Screenshot of WEAP: GIS interface to develop the schematization.

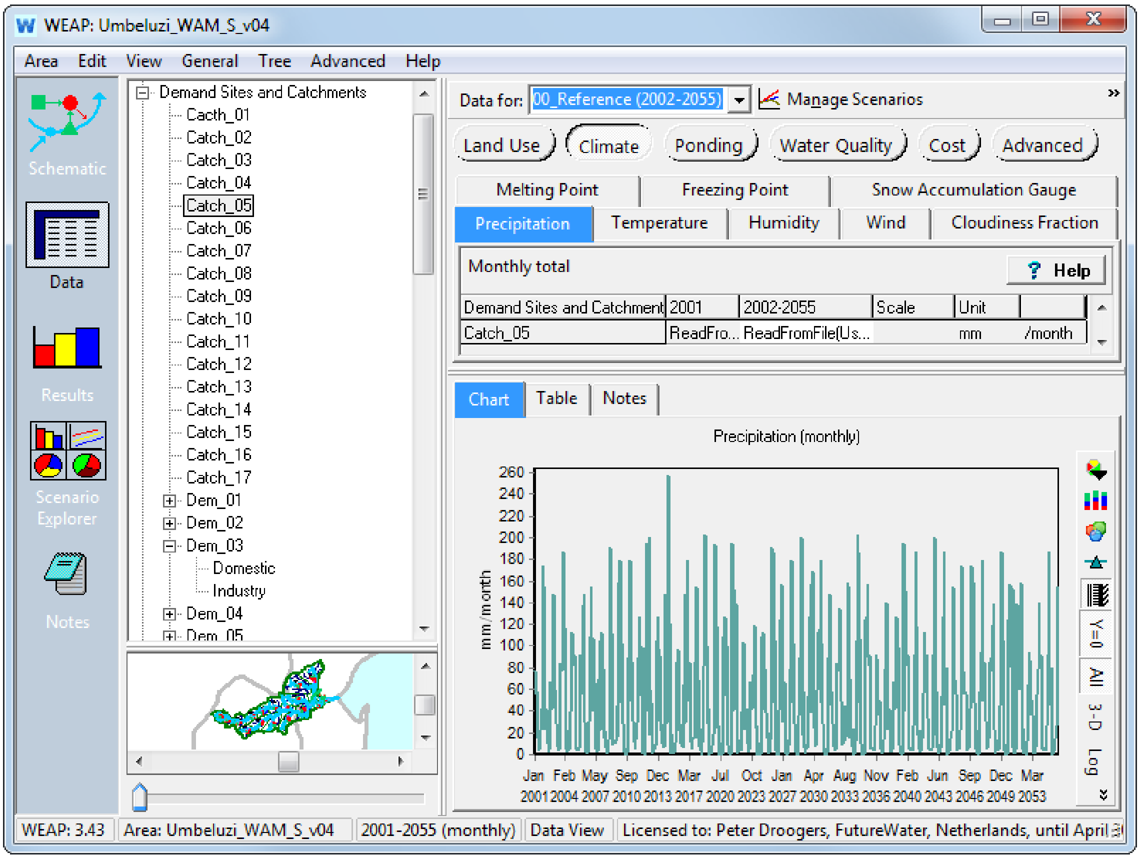


Figure 7. Screenshot of WEAP: data input page. Data can be entered manually or read from files.

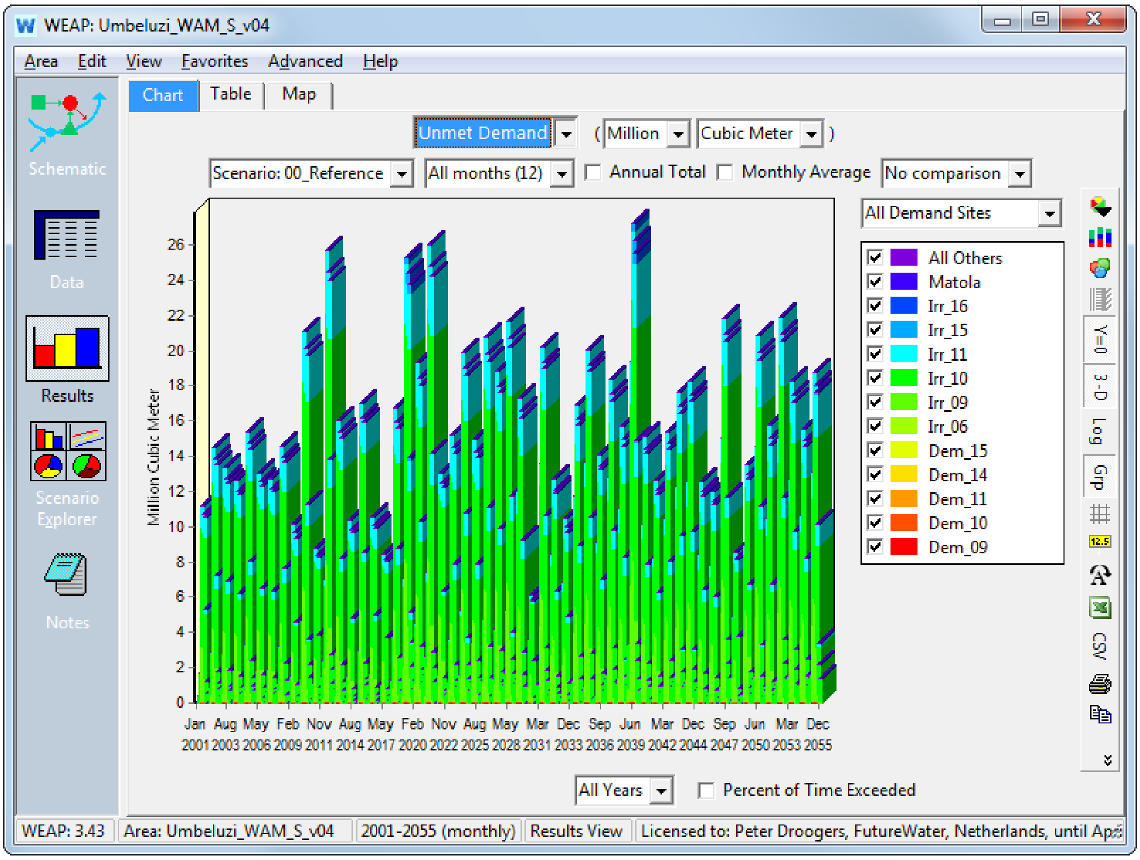


Figure 8. Screenshot of WEAP: results presentation. Results can be shown as graphs, as numbers or can be exported to files and/or Excel.

3.2 WAM-Strategic

3.2.1 Introduction

The Water Allocation Model – Strategic (WAM-S) should be suited to support strategic decision making processes and reveal the impact of decisions on water demands, supply and shortages. To this end a flexible tool is required that captures the main water issues. From the existing modeling frameworks it was decided to use the WEAP approach.

The main characteristics of WAM-S development are:

- Monthly time-step
- Entire Umbeluzi basin
- Scenario based
- Setup for 1981-2010 (reference) and 2001-2100 (scenarios).

3.2.2 Data

3.2.2.1 Schematization

The schematization is similar to previous studies (SWECO, 2005; Juizo and Liden, 2008) and consists out of 17 subbasins (Figure 9, Table 1).

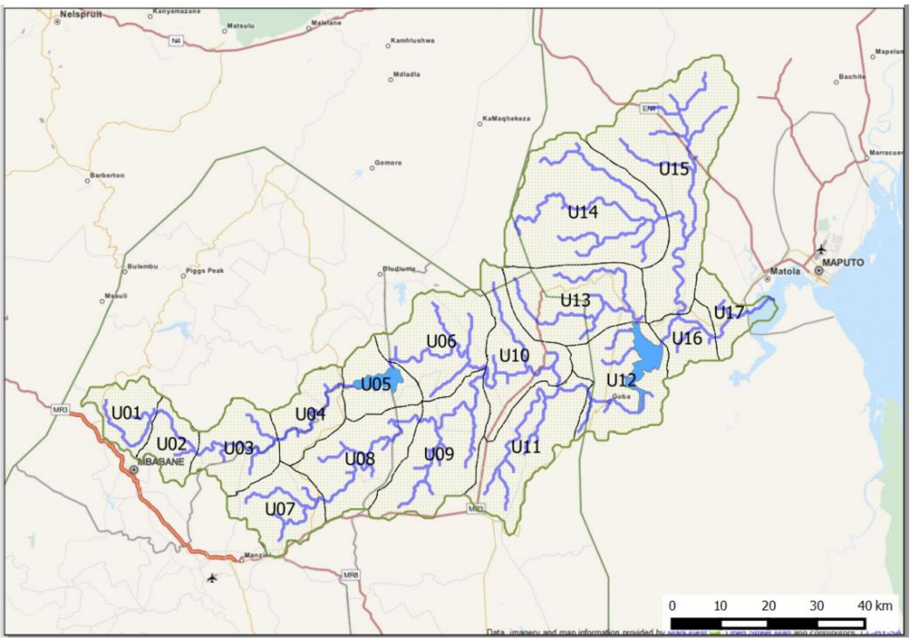


Figure 9. Subbasins in the Umbeluzi as used in this study.

3.2.2.2 Land cover and land use

The distribution of land cover for each of the 17 subbasins was assessed using two global data sources. The first one is GlobCover. GlobCover is an ESA initiative which began in 2005 with the aim to develop a service capable of delivering global composites and land cover maps using observations from the 300m MERIS sensor on board the ENVISAT satellite mission as input. The latest product is based on information of the year 2009. The map was produced using 12 months of data from Envisat's Medium Resolution Imaging Spectrometer at a resolution of 300 m (size of one pixel is 300 x 300 m).

Since GlobCover is not very accurate on the irrigated area, the Global Map of Irrigated Areas (GMIA) was used as overlay. The map shows the extent of area for irrigation around the year 2005 as percentage of the total area on a raster with a resolution of 5 arc-minutes. The two datasets were combined and aggregated into one land cover map (APPENDIX I: Land cover map based on GlobCover; Figure 27 and Table 11). For each subbasin the data was extracted, providing land cover per subbasin. Based on this the so-called Kc factor was calculated. This factor is used to convert reference evaporation to potential evapotranspiration.

Table 1. Subbasin information for the Umbeluzi setup. Source: Government of the Republic of Mozambique. 2003. National water resources development Plan for the Umbeluzi river basin. NDF 197-5. Chapter 6: Surface Water Hydrology

Code	Name	km2 Area	km2 Acc. Area	mm MAP	mm MAE
U01	W60A	172	172	1,156	1,400
U02	W60B	143	315	1,201	1,400
U03	W60C	233	548	1,161	1,400
U04	W60D	187	735	937	1,400
U05	W60E / Mnjoli Dam	134	869	806	1,400
U06	W60F	418	2,321	801	1,450
U07	W60G	222	222	912	1,400
U08	W60H	365	587	796	1,450
U09	W60J	447	1,034	819	1,450
U10	GS32	315	2,636	825	1,500
U11	Moz/Swazi border	350	2,986	800	1,500
U12	Pequenos Libombos Dam	263	3,735	700	1,600
U13	Calichane	486	486	820	1,600
U14	Movene dam site	709	709	760	1,600
U15	Movene	720	1,429	670	1,600
U16	Maputo water intake	140	5,304	660	1,600
U17	River mouth	96	5,400	610	1,600

MAP = Mean Annual Precipitation (mm). MAE = Mean Annual Evaporation (mm).

3.2.2.3 Population

No local data on population for each subbasin were available. Therefore the Gridded Population of the World (GPW) dataset was used. GPW provides globally consistent and spatially explicit human population information and data for use in research, policy making, and communications. The gridded data set is constructed from national or subnational input units (usually administrative units) of varying resolutions. The native grid cell resolution is 2.5 arc-minutes, or ~5km at the equator. The GPW will convert into the Global Rural-Urban Mapping Project (GRUMP) which provides data at a higher resolution and will make a distinction between rural and urban population.

3.2.2.4 Precipitation and temperature

Limited local data on precipitation and temperature were available. Moreover, for Swaziland no data could be accessed at all. Therefore precipitation and temperature data were used from the CRU TS series (CRU TS = Climatic Research Unit Time Series). CRU contains monthly time series of precipitation, daily maximum and minimum temperatures, cloud cover, and other variables, covering Earth's land areas for 1901-2012. The data set is gridded to 0.5x0.5 degree resolution, based on analysis of over 4000 individual weather station records (APPENDIX II: Example CRU rainfall, Figure 28).

3.2.3 Factory Acceptance Test

A Factory Acceptance Test was described in the project proposal document and consists out of the following three components:

- Number of nodes is same as agreed with ARA-Sul
- Schematic setup is same as agreed with ARA-Sul
- Simulated flow compared to observed flow:
    - R^2 >= 0.8
    - Bias < 10%

3.2.3.1 Number of nodes

The number of realized nodes for WAM-S is as agreed during the wrap-up meeting in Maputo (ARA-Sul) on 26 September 2014 and is given in Table 2.

Table 2. Number of agreed and realized nodes in WAM-S

Node Type	Agreed	Realized
Demand Nodes	17	36
Catchment Nodes	17	17
River Nodes	5	8
Flow Requirements Nodes	1	3
Reservoirs	2	2

3.2.3.2 Schematic Setup

The schematic setup was discussed and approved during the wrap-up meeting in Maputo (ARA-Sul) on 26 September 2014.

3.2.3.3 Observed versus Simulated flows

The WAM-S is developed to analyze long-term trends and scenarios. The model performance is tested by comparing modelled inflow, outflow and reservoir volume of Pequenos Libombos to long-term monthly average observed flows and reservoir volumes (Figure 10). Given data availability, for this a period of 10 years was used (2004-2013). As can be seen in Table 3 the criteria of the FAT were met.

Table 3. Statistics of simulated flows compared to observed flows for WAM-S (2004-2013)

	Bias (%)	R^2	Pearson R
Inflow into Pequenos Libombos	-2.4	0.93	0.96
Outflow from Pequenos Libombos	0.2	0.85	0.92
Reservoir volume Pequenos Libombos	6.8	0.90	0.95

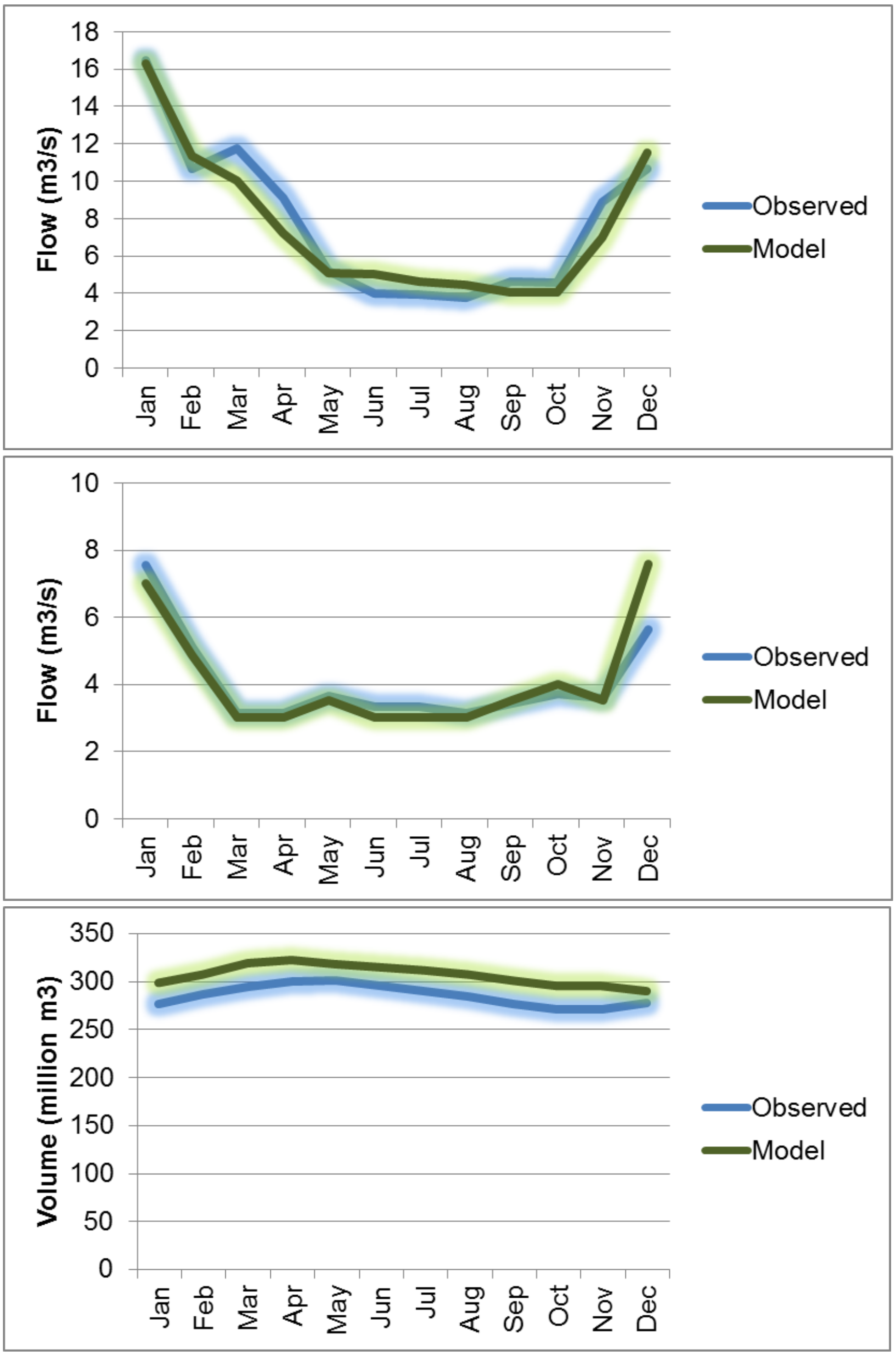


Figure 10. Observed and modelled inflow into Pequenos Libombos (top), outflow from Pequenos Libombos (middle), and volume of Pequenos Libombos (bottom).

3.2.4 Site Acceptance Test

A Site Acceptance Test was described in the project proposal document and consists out of the following four components:

- WAM runs on PCs from ARA-Sul
- At least three ARA-Sul staff members can use and modify the two WAMs
- At least two ARA-Sul staff members can use the WAM-O
- At least 10 scenarios have been explored using WAM-S

In September a first training and educational mission was undertaken. In November 2014 a second training mission was undertaken. The WAMs were installed on the PCs of the present ARA-Sul staff members at the start of the second training. The WAMs, user guide, tutorials and training manual were also provided through Dropbox prior to the second training mission. Four ARA-Sul staff members joined the training and successfully finished the program. During the training mission the scenarios to be implemented in the WAMs were discussed. That resulted in 11 scenarios for WAM-S of which the results are presented in chapter 4. Results of 3 scenarios for WAM-O are described in chapter 5.

3.2.5 Current situation

The calibrated and validated model was used to evaluate water demand, supply and shortages over the historic period of 30 years (1981-2010). For this, it is important to make a distinction between the entire water balance of the basin (sometimes referred to as “Green Water”) and the water balance of only water that ends up in the river and is abstracted (sometimes referred to as “Blue Water”).

The total water balance can be summarized as (for annual variation see Figure 11 and Figure 12):

- Total available water is equal to total rainfall and is 4,077 million m^3/year
- Most water is consumed by vegetation (=evapotranspiration) and is 3,628 million m^3/year (~89% of rainfall)
- Runoff into the river is 558 million m^3/year (~11% of rainfall)
    - Consumption by irrigation, domestic use and industry is 211 million m^3/year
    - Average annual outflow is 241 million m^3/year (~10 m^3/s), and varies substantial per year and per month.

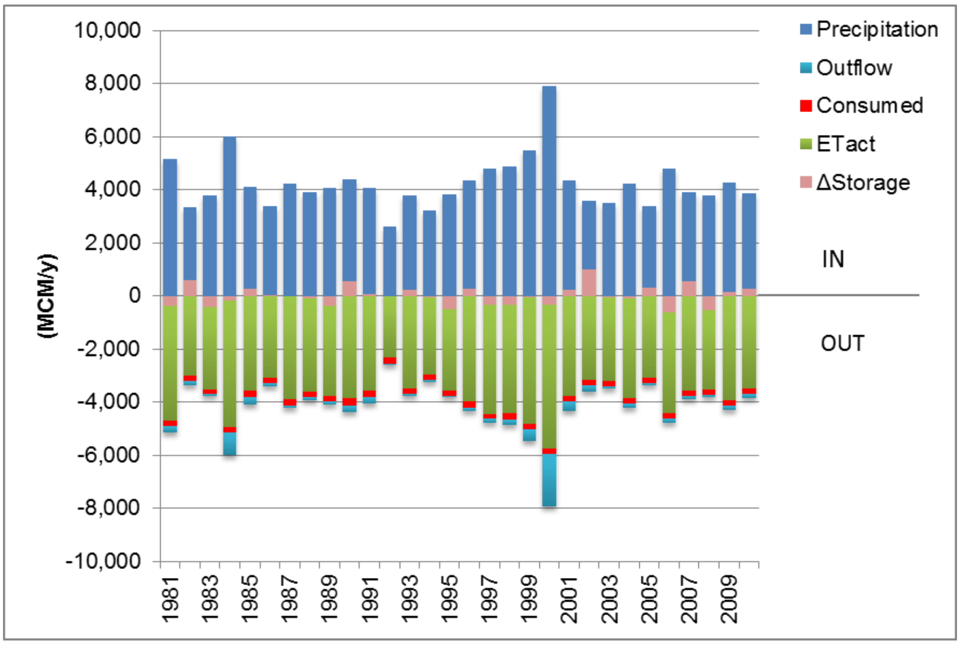


Figure 11. Annual water balance for the entire Umbeluzi Basin.

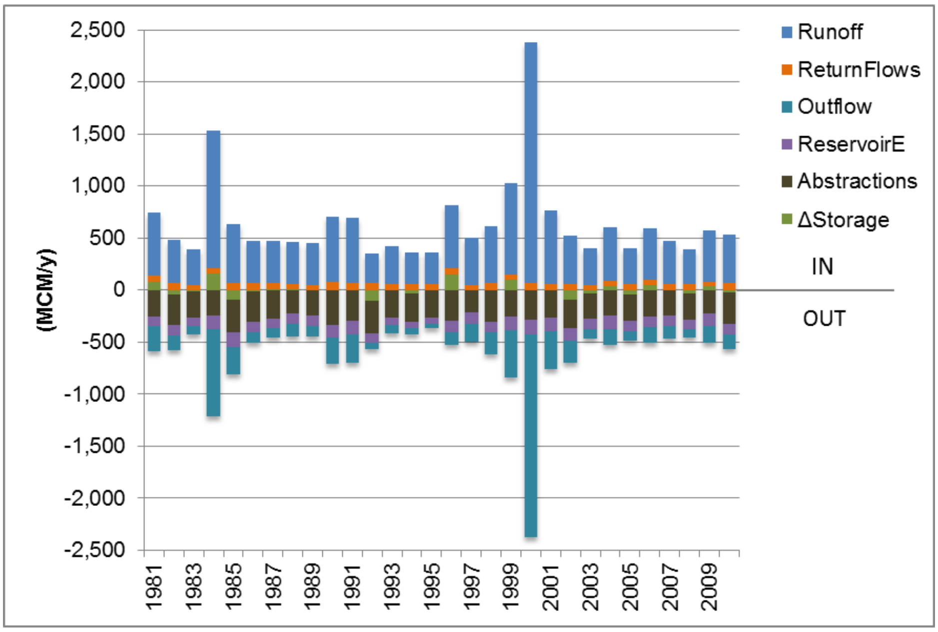


Figure 12. Annual water balance for the entire Umbeluzi Basin showing only water in the river and abstractions from the river and reservoirs.

3.3 WAM-Operational

3.3.1 Introduction

The Water Allocation Model – Operational (WAM-O) will serve as a tool to evaluate the impact of granting new permits and licenses on the Pequenos Libombos reservoir and other water users.

The main characteristics of WAM-O are:

- Daily time-step
- Pequenos Libombos reservoir and downstream area
- Decision based
- Setup for 2004-2013 (reference) and 2014-2023 (scenarios)

3.3.2 Data

3.3.2.1 Schematization

The Pequenos Libombos reservoir is schematized by one reservoir node (green triangle in Figure 13) and one groundwater node (green square in Figure 13). The tributaries of Pequenos Libombos are schematized by four inflow nodes (cyan lines and dots in Figure 13) which are described in more detail in the next paragraph (3.3.2.2). The demand sites are schematized by fifteen demand nodes and transmission links (red dots and green arrows in Figure 13 respectively) and will be discussed in paragraph 3.3.2.3. Furthermore one flow requirement node is schematized (paragraph 3.3.2.5).

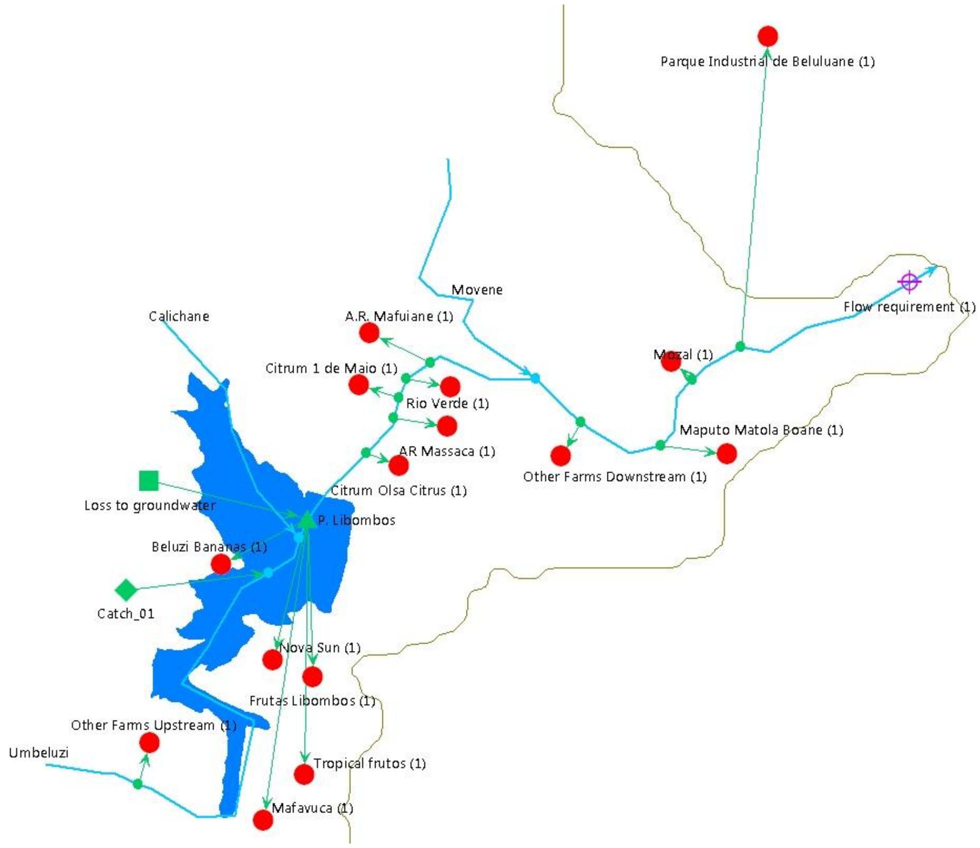


Figure 13. Schematization of Pequenos Libombos, tributaries and demand sites.

3.3.2.2 Inflow Nodes

WAM-O is defined by four inflow nodes:

- Umbeluzi upstream Pequenos Libombos
- Calichane
- Small streams directly flowing into Pequenos Libombos
- Movene

Insufficient streamflow data was available for any of the rivers and streams mentioned above. Therefore streamflow data for Umbeluzi and Calichane was derived from the inflow data of Pequenos Libombos reservoir. The process of deriving streamflow data for Umbeluzi and Calichane is described in more detail in Appendix IV: .

3.3.2.3 Demand sites

Fifteen demand sites were specified in WAM-O. The annual water use rate of Parque Industrial de Beluluane is unknown. The annual water use rate of the other demand sites remained constant between 2004 and 2013. The total annual water demand per demand site is given in Table 4. Urban water demand is 70% of the total water demand, irrigation demand is 29% of total water demand and industrial demand is only 0.5% of total water demand. The monthly environmental flow requirement at the outlet of the Umbeluzi is not a demand site and is therefore not included in Table 4 but shown separately in Paragraph 3.3.2.5, Table 5.

Table 4. Water use rate and total annual water demand per demand site. Source: ARA-Sul.

Demand site characteristics	Demand site	Annual water use rate (m^3/ha/year)	Annual water demand (million m^3/year)
Agricultural demand sites upstream Pequenos Libombos	Beluzi Bananas	8714	4.36
	Tropical frutos	8714	3.05
	Frutas Libombos	8714	6.10
	Nova Sun	8714	4.36
	Mafavuca Entreprise,Lda	11619	1.74
	Other farms upstream Pequenos Libombos	13071	2.61
Agriculture demand sites downstream	Citrum Olsa Citrus	8714	1.31
	Citrum 1 de Maio	8714	1.31
	Rio Verde, Bloco 3 e 4	8714	2.61
	A. R. Mafuiane	8714	1.41
	A.R.Massaca	8714	1.24
	Other Farms Downstream Pequenos Libombos	8714	2.18
Industrial demand sites downstream	Mozal	-	0.60
	Parque Industrial de Beluluane	-	-
Urban demand site downstream	Maputo/Matola/Boane	-	78

All upstream agricultural water users abstract their water directly from the reservoir, except for “Other farms upstream Pequenos Libombos” of which the exact location is not specified. ‘Other farms upstream Pequenos Libombos’ abstract their water from Umbeluzi somewhere upstream of Pequenos Libombos in Mozambique. All downstream demand sites abstract their water directly from Umbeluzi River.

3.3.2.4 Characteristics of Pequenos Libombos reservoir

The total storage capacity of Pequenos Libombos (including inactive storage) is 391.5 million m^3, corresponding to a reservoir elevation of 47 m. The initial storage on 1-1-2004 was 213.2 million m^3. The top of inactive (or dead) storage corresponds to a volume of 10.2 million m^3 and a reservoir elevation of 25 m. The volume elevation curve was calculated for every meter between 25 meter (top of inactive storage) and 47 meter (full storage level). The equation used to calculate the reservoir volume (V) from reservoir elevation (h) is as follows (ARA-Sul, 2010):

$$V(h) = 0.018787\, h^3 – 1.17037\, h^2 + 26.284\, h – 209.$$

To leave space for flood control, from November 2010 onwards the top of conservation was lowered every year from 47 meter on the 15th of November (corresponding to a volume of 391.52 million m^3) to 44.5 meter on the 15th of December (corresponding to a volume of 298.54 million m^3). The top of conservation remained 44.5 meter between 15 December and 15 February. From 16 February onwards it increased again to 47 meter on the 15th of March.

A maximum hydraulic outflow (Q_{max}) depending on reservoir elevation (h) was defined in accordance with ARA-Sul, 2010:

$Q_{max} = 4.6\ (h - 15.25)^{0.5}$.

Seepage loss (Q_{loss}) from the reservoir to the groundwater was calculated when the reservoir level was higher than 41.5 m with the following equation (ARA-Sul, 2010):

if $h \geq 41.5$ m $\qquad Q_{loss} = 0.0595 * (h - 41.5)^{0.596}$

in which h is the reservoir elevation.

3.3.2.5 Environmental flow requirement

In accordance with the operational manual of the reservoir (ARA-Sul, 2010) an environmental flow requirement at the outlet of the Umbeluzi was implemented in WAM-O from 2010 onwards. The environmental flow requirement is 15% of the average monthly inflow to Pequenos Libombos for the years 2004-2009. This resulted in the following minimum outflow requirement per month (Table 5):

Table 5. Minimum outflow requirement (Source: ARA-Sul, 2010)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
m^3/s	1.06	0.87	1.68	0.86	0.49	0.45	0.46	0.48	0.38	0.35	1.04	1.04
MCM/month	2.8	2.1	4.5	2.2	1.3	1.2	1.2	1.3	1.0	0.9	2.7	2.8

3.3.3 Factory Acceptance Test

The model performance criteria that were described in paragraph 3.2.3 (Factory Acceptance Test) also have to be met by the WAM-O. The model performance criteria apply to the number of nodes, the schematic setup and the observed flows of the model and will be described in the next paragraphs.

3.3.3.1 Number of nodes

The number of agreed and realized nodes of the WAM-O are given in Table 6.

Table 6. Number of agreed and realized nodes in WAM-O

Node Type	Agreed	Realized
Demand Nodes	11	15
Inflow Nodes	4	4
River Nodes	3	3
Flow Requirements Nodes	1	1
Reservoirs	1	1

3.3.3.2 *Schematic Setup*

The schematic setup was discussed and approved during the wrap-up meeting in Maputo (ARA-Sul) on 26 September 2014.

3.3.3.3 *Observed versus Simulated flows*

The calibration of WAM-O is described in more detail in Appendix V: Calibration of WAM-O. After calibration of the model the simulated reservoir volume (blue line in Figure 14) corresponded to the observed reservoir volume (red line in Figure 14) very well. Statistics of model performance can be read from Table 7.

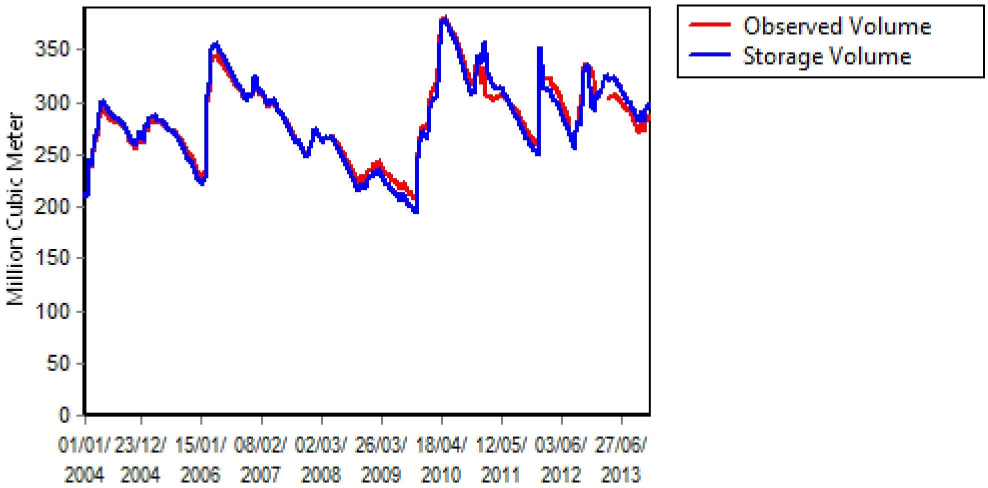


Figure 14. Observed and simulated reservoir volume from 2004 to 2013.

The simulated outflow of Pequenos Libombos was compared to the observed outflow of Pequenos Libombos. From Figure 15 and Figure 16 it can be seen that WEAP simulates observed flows well. As can be seen from Table 7 the criteria of the FAT for simulated flows (R^2 >= 0.8, Bias < 10%) were also met for WAM-O.

Table 7. Statistics of simulated variables compared to observed variables

	Bias (%)	R^2	Pearson R
Daily reservoir levels	-0.09	0.96	0.98
Daily reservoir volumes	-0.25	0.96	0.98
Monthly reservoir outflow	0.54	0.81	0.90

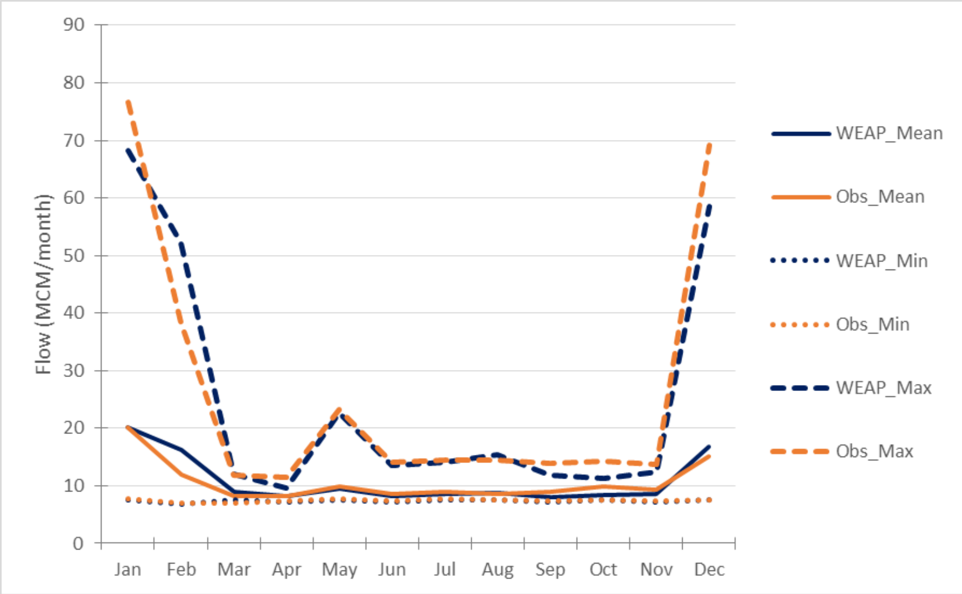


Figure 15. Observed and simulated outflow of the Pequenos Libombos reservoir.

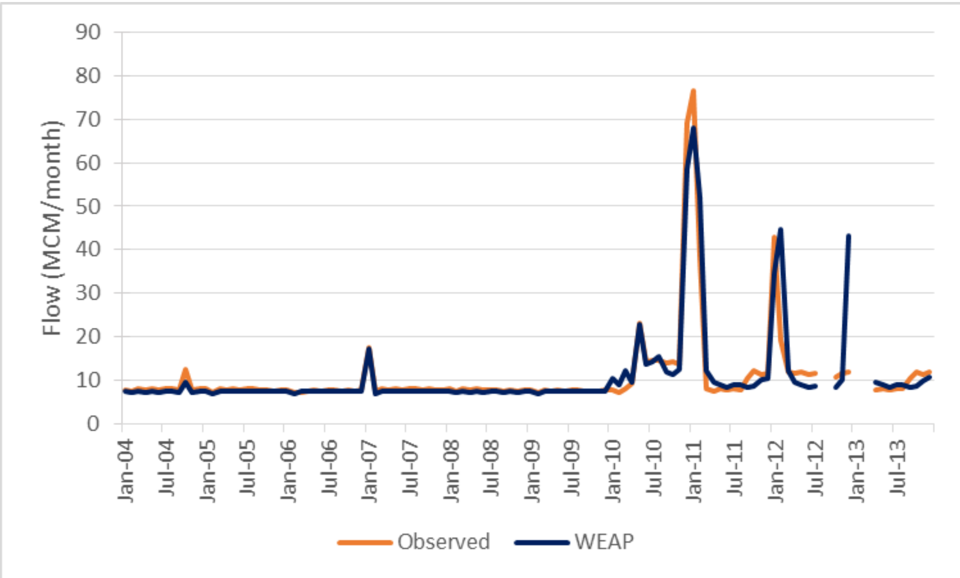


Figure 16. Observed and simulated monthly outflow of the Pequenos Libombos reservoir.

3.3.4 Site Acceptance Test

Criteria of a Site Acceptance Test, that is similar to that of WAM-S, have to be met by WAM-O. The Site Acceptant Test consists out of the following four components:

- WAM runs on PCs from ARA-Sul
- At least three ARA-Sul staff members can use and modify the two WAMs
- At least two ARA-Sul staff members can use the WAM-O
- At least 10 scenarios have been explored using WAM-S

In September a first training and educational mission was undertaken. In November 2014 a second training mission was undertaken. The WAMs were installed on the PCs of the present ARA-Sul staff members at the start of the second training. The WAMs, user guide, tutorials and training manual were also provided through Dropbox prior to the second training mission. Four ARA-Sul staff members joined the training and successfully finished the program. During the training mission the scenarios to be implemented in the WAMs were discussed. That resulted in 11 scenarios for WAM-S of which the results are presented in chapter 4. Results of 3 scenarios for WAM-O are described in chapter 5.

4 Strategic Water Allocation Scenarios

4.1 Scenario Development

The WAM-S was developed to support decision making at a strategic level. During a brain-storming session at the capacity building workshop in the week of 17-Nov-2014 the following scenarios were mentioned by participants:

- Impact scenarios (stressors):
  - Climate change (frequencies of droughts)
  - Population growth (urban)
  - Expansion irrigated area
  - Increase Industrial activity
  - Development Swaziland
  - Water quality (Swaziland; irrigation, industry)
- Adaptation scenarios (responses):
  - Controlling wildfires (queimadas descontroladas) caused by slash and burn
  - Reservoir Incomati (760 million m^3)
  - Water treatment plants
  - Swaziland-Mozambique water treaties
  - Reduce conveyance losses
  - Prevent tap leakages
  - Water pricing

Some of the above scenarios are beyond the scope of the current study (e.g. water quality) or the developed models are not appropriate to undertake the analysis (e.g. controlling wildfires caused by slash and burn). Moreover, these scenarios contain a mixture of so-called Impact (not directly under control of ARA-Sul) and Adaptation (can be influenced by ARA-Sul). Impact scenarios are sometimes referred to as “external” or “stressors”, while adaptation scenarios are sometimes called “responses”.

Based on these initial ideas, combined with knowledge from similar studies, the following set of impact scenarios and adaptation response scenarios were analyzed using WAM-S:

- (01) Impact: Population growth[2] (2% per year)
  - (02) Adaptation: Water transfer from Incomati (2 m^3/s)
  - (03) Adaptation: Prevent tap water leakage losses so that urban water supply can be reduced (by 25%)
- (04) Impact: Increase in irrigated areas (2% per year)
  - (05) Adaptation: Increased reservoir capacity in Umbeluzi basin (by 100%)
  - (06) Adaptation: Reduce conveyance losses in irrigation systems so that water suplly to irrigated areas can be reduced (by 25%)
- (07) Impact: Climate change (precipitation -10%[3], temperature +3^{o}C[4])
- (08) Impact: Likely Future (impacts 01, 04 and 07 as defined above)
  - (09) Adaptation: Infrastructure (= 02 and 05)
  - (10) Adaptation: Improved system (= 03 and 06)
  - (11) Adaptation: Full (adaptations 02, 03, 05 and 06 as defined above)

[2] This scenario includes also a growth in water use per person by 2% per year.

[3] Appendix III: Climate change projection; Figure 30; Representative Concentration Pathway 6.0 (RCP6.0)

[4] Appendix III: Climate change projection; Figure 29; RCP6.0. Temperature increase influences irrigation demand automatically. For impact on urban water demand an increase of 10% has been assumed.

The above 11 scenarios were evaluated using WAM-S. Details on how these scenarios were implemented in WAM-S can be found in Appendix VI. More scenarios with other values, e.g. another growth percentage for water use per person, can easily be implemented in WAM-S.

In order to assess the climate change process in the Umbeluzi basin, the precipitation trend for the past 30 years for subbasin U17 was analyzed. Since the year 2000 was an extremely wet year, this year was excluded from the analysis. The total annual precipitation over the past 30 years showed a clear downward trend of 2.2 mm/y (Figure 17). It is not known whether this trend is similar for the whole Umbeluzi basin. However, a full climate change analysis is out of the scope of this study. If the downward precipitation trend is similar for the whole Umbeluzi basin and if this trend will continue, significantly dryer conditions can be expected in future in the Umbeluzi basin. Climate change projections for temperature and precipitation made by the IPCC can be found in Appendix III: Climate change projection. From the IPCC projections RCP6.0, with a projected increase in temperature of 3ºC and a projected decrease in rainfall of approximately 10% in 2100, was used in the climate change scenario (07).

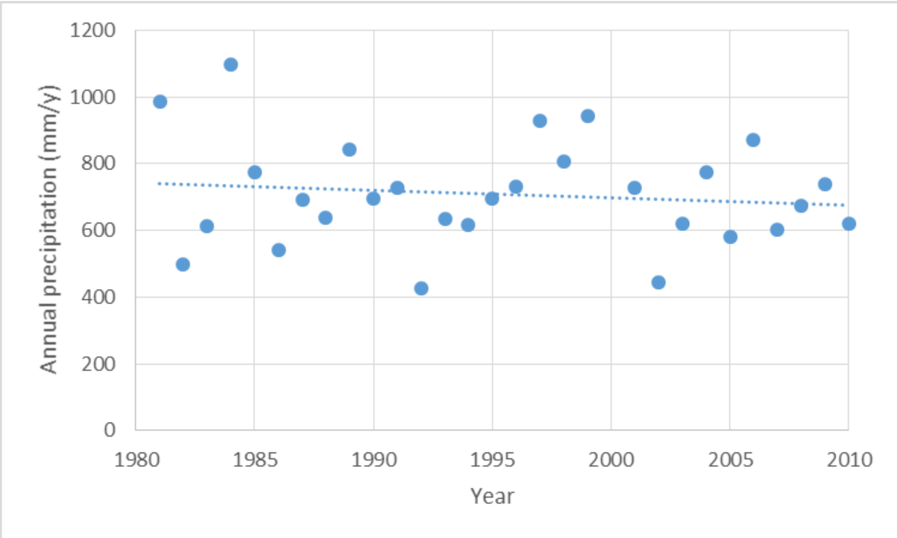


Figure 17. Precipitation trend for 1981-2010.

The following indicators were selected to quantify and summarize the scenarios:

a) Water shortage in Maputo
b) Reservoir volumes [5]
c) Outflow of Umbeluzi[6].

The above indicators were calculated for the current situation (2001-2010) and periods around the year 2030 (2026-2035), and 2050 (2046-2055). Both annual averages as well as percentage of months in which shortages occur were calculated. In order to undertake these analyses future weather conditions were needed. For this the observed weather conditions from 1981-2013 were used for the future by selecting for each year in the future a random year in the past. To ensure that this random year selection will not generate potential unrealistic positive future conditions, the five wettest years in the historic period were excluded from this random year selection.

[5] Somewhat arbitrary a reservoir volume of 50 million m^3 was chosen as threshold value to evaluate the water availability situation. Other values can be used according to the user's interest.
[6] The Environmental flow requirement at the outlet of the Umbeluzi is different for every month. The average over the year is 1 m^3/s. This was chosen as threshold value to evaluate the magnitude of the outflow of the Umbeluzi.

4.2 Results

WAM-S is able to provide results of many output variables (demands, shortages, streamflow, reservoir levels, etc) and has a wide-range of displaying options (figures, maps, tables). In this section some typical outputs will be presented as examples while at the end a summary will be presented.

Figure 18 shows the demand and unmet demand for Maputo for the impact scenarios (01, 04, 07, 08). It is clear that population growth (scenario 01) and the likely future (scenario 08 = population growth, increase in irrigation, climate change) will lead to vast water shortages. For the population growth scenario (01) water shortage can be expected around 2030, while for the likely future water shortage can be expected already around 2020. Obviously, future weather conditions might change this.

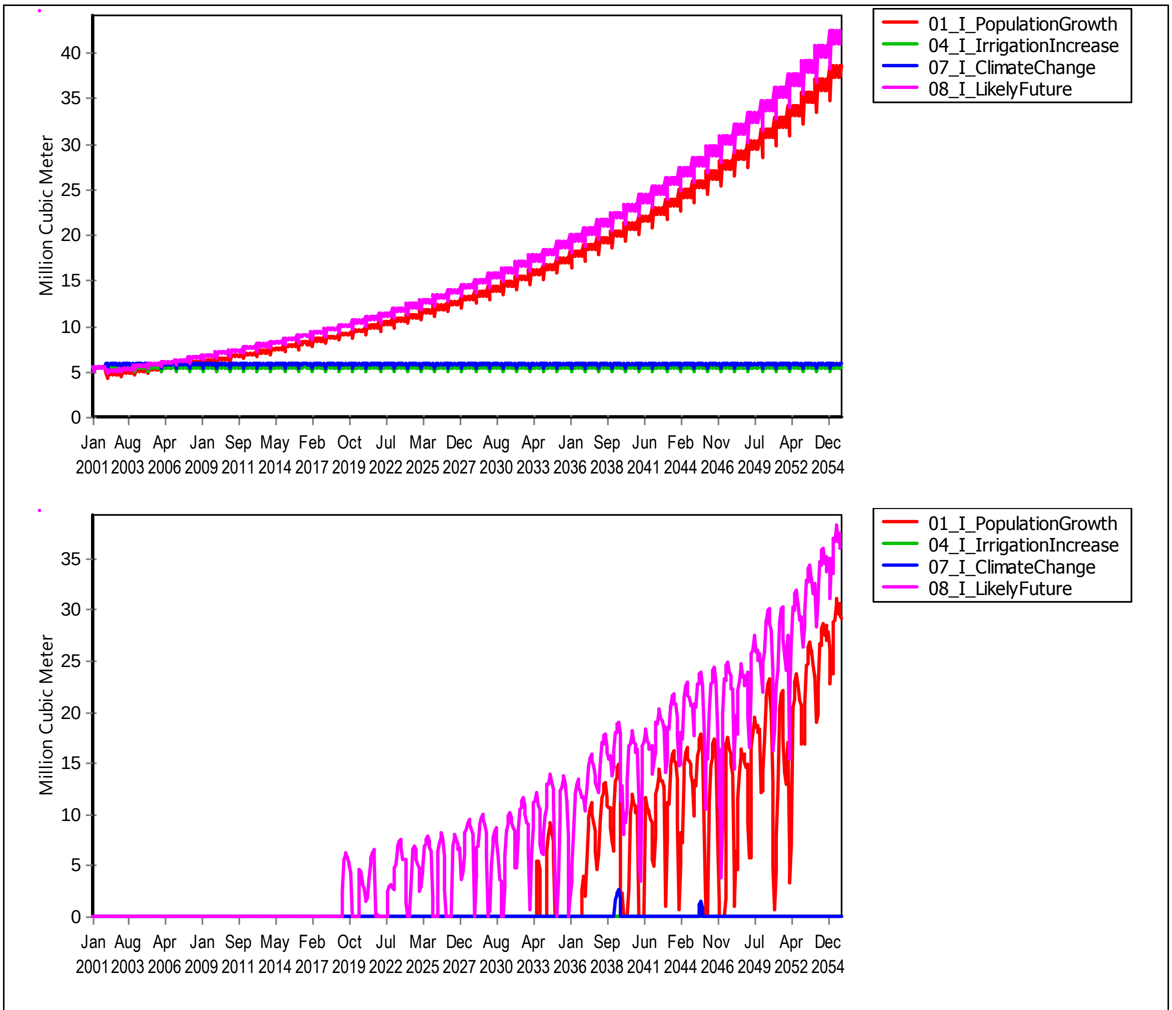


Figure 18. Annual water demand (top) and unmet demand (bottom) for Maputo under the various Impact Scenarios.

Figure 19 presents the average monthly reservoir levels of Pequenos Libombos for the four impact scenarios. For all scenarios, except the increase in irrigation scenario, reservoir levels are projected to decrease to very low levels after 2020 to 2030.

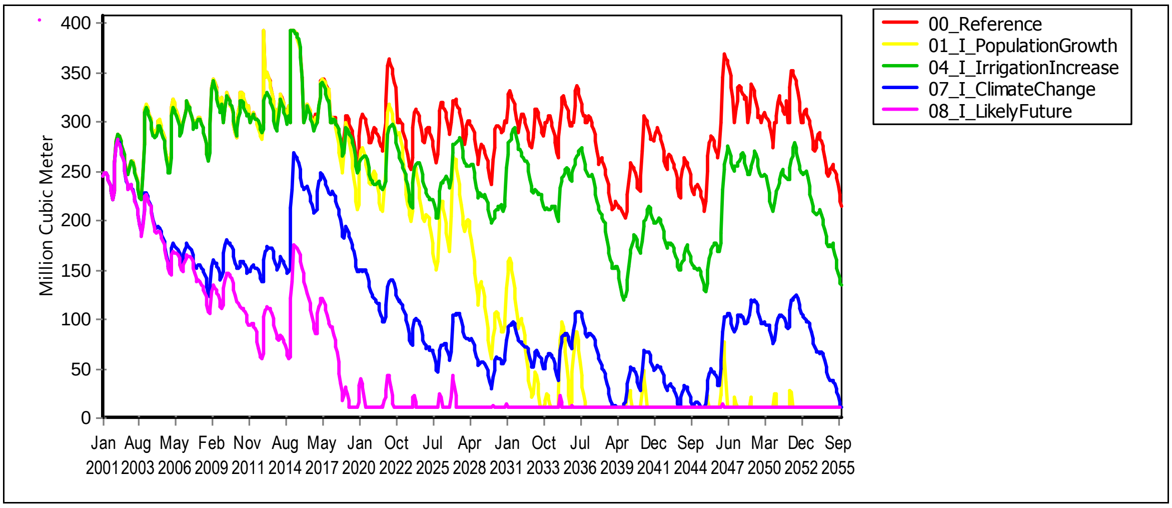
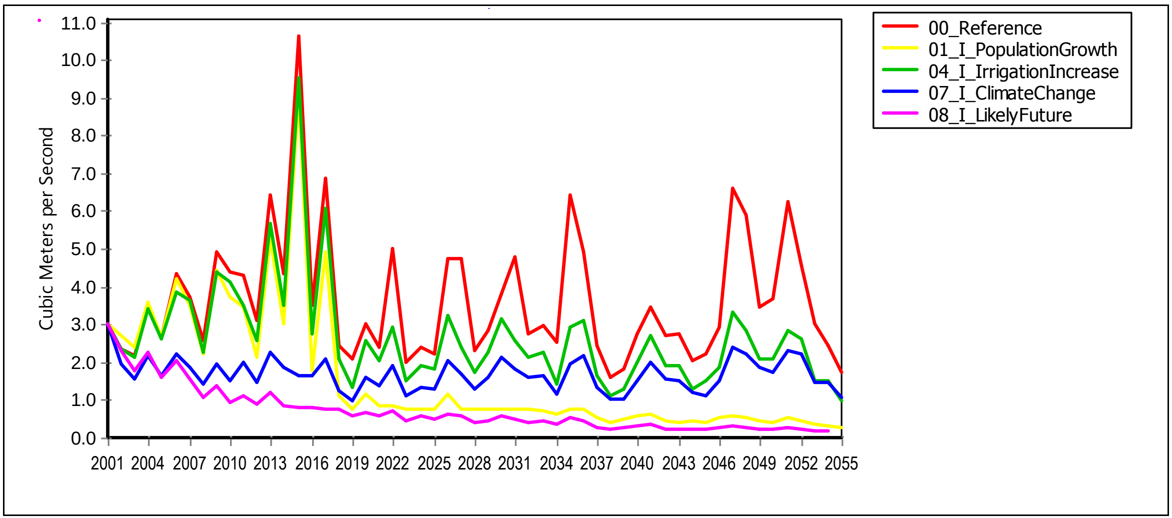


Figure 19. Reservoir volumes under the various Impact Scenarios. Note that reservoir volume is never below 10 MCM (inactive storage).

Figure 20 shows the flow at the outlet point of the Umbeluzi. For the population growth and the likely future scenarios, projected flows will be very low. For those two scenarios the chances of flows being below 1 m^3/s are 57% and 75% of the time respectively. The non-exceedance probability of Umbeluzi streamflow at the outlet point into the Indian Ocean for the Impact Scenarios is given in Table 8. Far more analysis can be undertaken with the model, e.g. on cumulative drought periods, i.e. subsequent months for which the flow at the outlet point of Umbeluzi is under a certain threshold level.



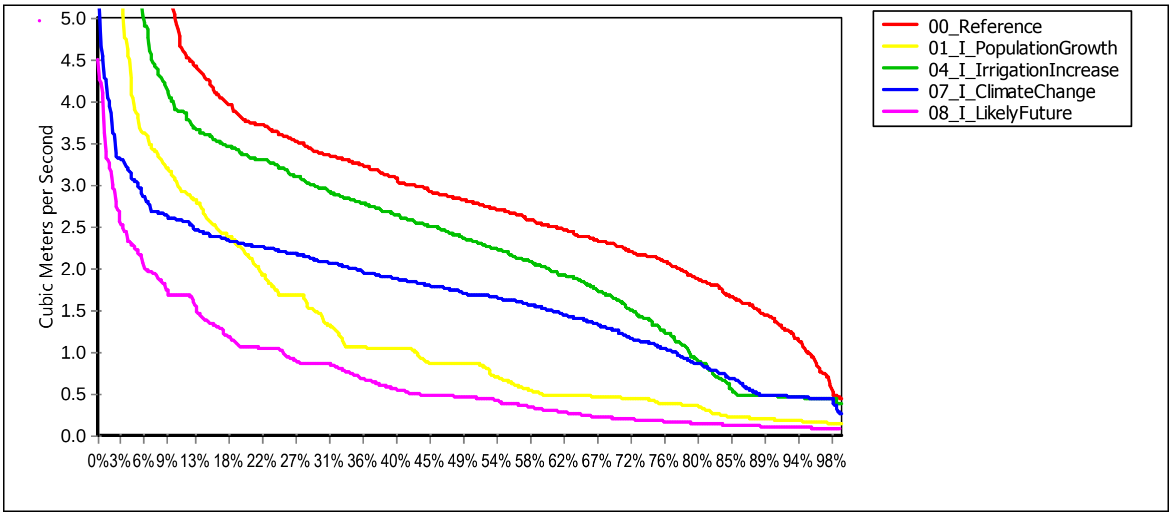


Figure 20. Annual Umbeluzi streamflow at outlet point into Indian Ocean (top) and exceedance probability of Umbeluzi streamflow at outlet (bottom), expressed as % of months, for the Impact Scenarios.

Table 8. Non-exceedance probability of Umbeluzi streamflow at outlet point for Impact Scenarios

	1%	**5%**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**95%**	**99%**
Reference scenario (m^3/s)	0.48	1.0	1.4	1.9	2.3	2.5	2.8	3.1	3.4	3.8	5.2	9.8	23.7
Scenario 01 (m^3/s)	0.14	0.17	0.20	0.35	0.45	0.49	0.86	1.0	1.5	2.18	3.16	3.92	18.7
Scenario 04 (m^3/s)	0.45	0.45	0.48	0.93	1.6	2.0	2.3	2.6	3.0	3.4	4.0	5.5	16.7
Scenario 07 (m^3/s)	0.36	0.46	0.48	0.87	1.2	1.5	1.7	1.9	2.1	2.3	2.6	3.1	4.3
Scenario 08 (m^3/s)	0.08	0.09	0.11	0.15	0.20	0.30	0.46	0.55	0.86	1.1	1.7	2.3	3.6

Figure 21 indicates the effectiveness of the adaptation scenarios can be presented. It is clear that under the impact scenario likely future the four adaptations are still not sufficient to overcome water shortages.

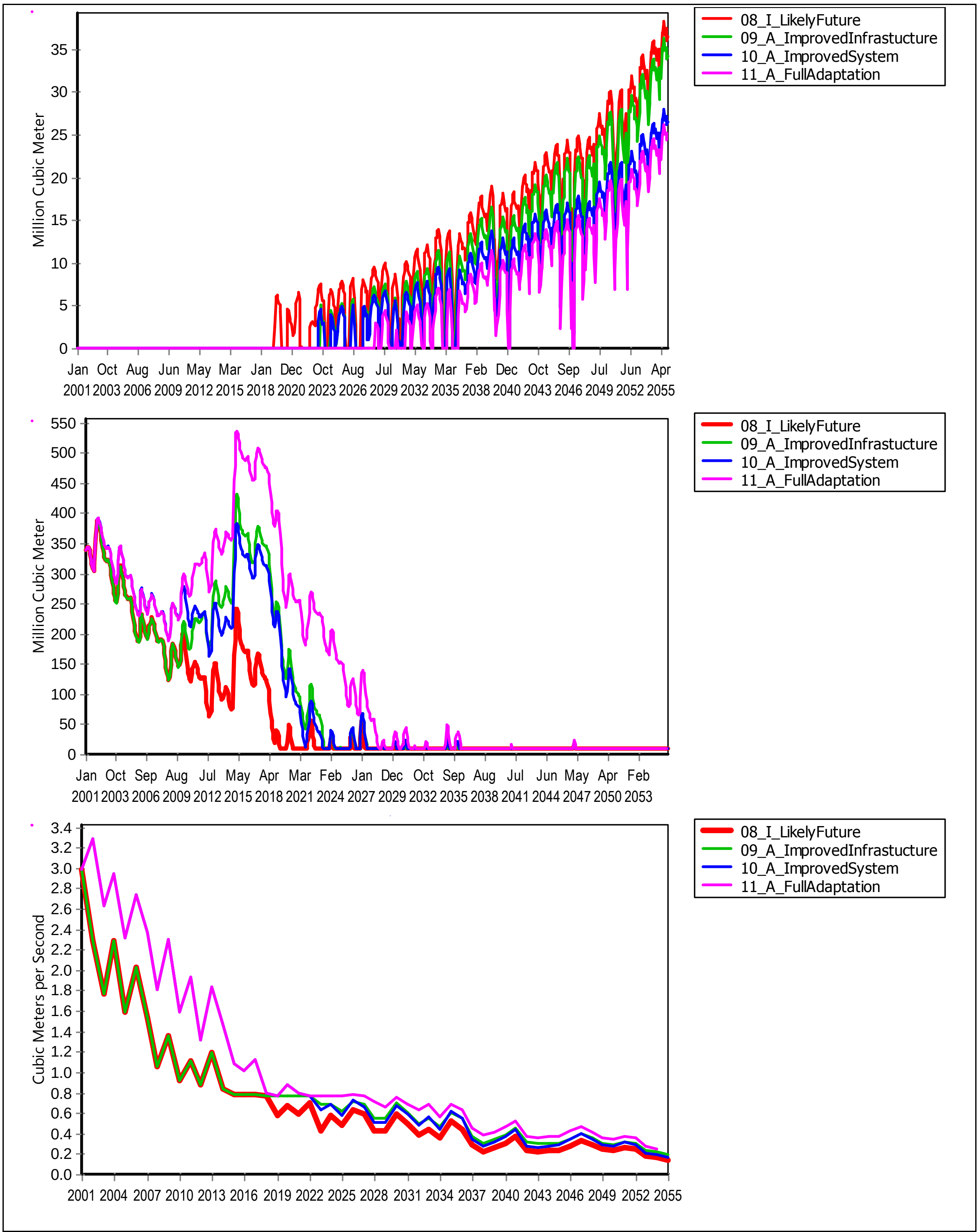


Figure 21. Effectiveness of adaptation scenarios on unmet demand (top), reservoir volumes of P. Libombos (middle) and streamflow at outlet point of Umbeluzi (bottom).

A summary of the impact scenarios and the adaptation scenarios is presented in two tables; one for the near future (2030) and one for the distant future (2050). Table 9 shows that water shortage in Maputo around the year 2030 is expected to be not severe. However, in 2050 the situation might change completely (Table 10). Especially under the population growth scenario and the likely future scenario shortages can be very high. Also reservoir volumes and outflow of Umbeluzi are projected to decrease substantially. The defined adaptation scenarios are not sufficient to overcome the water shortages related to the given impact scenarios and therefore more measures should be taken.

Table 9. Summary of the impact and adaptation scenarios on water shortage in Maputo, reservoir volume of Pequenos Libombos and outflow of Umbeluzi around 2030

	Shortage Maputo[(a)]		Reservoir volume [(b)]		Outflow[(c)]	
	MCM/y	% of month	MCM	% of month	CMS	% of month
Reference	**0**	**0%**	**295**	**0%**	**3.8**	**3%**
(01) Impact: Population growth	**7**	**8%**	**109**	**28%**	**0.8**	**67%**
(02) Adaptation: Water transfer from Incomati	0	0%	227	0%	1.0	66%
(03) Adaptation: Prevent tap water leakage losses	0	0%	203	0%	1.0	66%
(04) Impact: Increase in irrigated areas	**0**	**0%**	**240**	**0%**	**2.4**	**24%**
(05) Adaptation: Increased reservoir capacity	0	0%	242	0%	2.4	24%
(06) Adaptation: Reduce conveyance losses	0	0%	273	0%	2.9	12%
(07) Impact: Climate change	**0**	**0%**	**69**	**11%**	**1.7**	**25%**
(08) Impact: Likely Future	**85**	**83%**	**11**	**100%**	**0.5**	**88%**
(09) Adaptation: Infrastructure	56	71%	13	98%	0.6	81%
(10) Adaptation: Improved system	46	70%	14	98%	0.6	80%
(11) Adaptation: Full	20	40%	29	80%	0.7	74%

% of month is set for: (a) shortage Maputo ≥ 10% of demand; (b) reservoir volume ≤ 50 million m^3, (c) outflow ≤ 1 m^3/s. Green indicates the positive magnitude of impacts. Red indicates the negative magnitude of impacts.

Table 10. Summary of the impact and adaptation scenarios on water shortage in Maputo, reservoir volumes of Pequenos Libombos and outflow of Umbeluzi around 2050

	Shortage Maputo[(a)]		Reservoir volume [(b)]		Outflow[(c)]	
	MCM/y	% of month	MCM	% of month	CMS	% of month
Reference	**0**	**0%**	**300**	**0%**	**4.0**	**3%**
(01) Impact: Population growth	**204**	**90%**	**13**	**98%**	**0.4**	**92%**
(02) Adaptation: Water transfer from Incomati	176	86%	14	97%	0.5	90%
(03) Adaptation: Prevent tap water leakage losses	132	80%	14	97%	0.5	88%
(04) Impact: Increase in irrigated areas	**0**	**0%**	**225**	**0%**	**2.2**	**33%**
(05) Adaptation: Increased reservoir capacity	0	0%	226	0%	2.2	33%
(06) Adaptation: Reduce conveyance losses	0	0%	252	0%	2.4	24%
(07) Impact: Climate change	**0**	**0%**	**82**	**22%**	**1.8**	**19%**
(08) Impact: Likely Future	**318**	**100%**	**10**	**100%**	**0.2**	**99%**
(09) Adaptation: Infrastructure	291	100%	10	100%	0.3	98%
(10) Adaptation: Improved system	222	98%	10	100%	0.3	98%
(11) Adaptation: Full	198	98%	10	100%	0.4	98%

% of month is set for: (a) shortage Maputo ≥ 10% of demand; (b) reservoir volume ≤ 50 million m^3, (c) outflow ≤ 1 m^3/s. Green indicates the positive magnitude of impacts. Red indicates the negative magnitude of impacts.

5 Water Licensing Scenarios

5.1 Scenario Development

According to information obtained during the training mission in November 2014, ARA-Sul currently provides licenses to water users mainly based on evaluating the number of users (for urban extractions), the level of industrial activity (for industrial demands), or the area and crop types (for irrigation requests). These requests are subsequently discussed in a broader committee in which the impact on potential water shortages and reservoir levels are assessed. So far, this assessment is rather qualitative, based on expert knowledge rather than on quantitative evaluations. The WAM-O is especially meant to close this information gap.

To demonstrate in which way WAM-O can be used to support licensing requests to ARA-Sul the following scenarios were implemented and analyzed:

- Scenario A: An additional demand of 0.5 m^3/s downstream Pequenos Libombos
- Scenario B: An additional demand of 1.0 m^3/s downstream Pequenos Libombos
- Scenario C: An additional demand of 2.5 m^3/s downstream Pequenos Libombos

In order to undertake these analyses, future weather conditions were needed. For this the observed streamflows from 2004-2013 were used for the future (2014-2023). To ensure that this would not generate potential unrealistic wet future conditions, the five years with high flows (2009-2013) in the historic period were excluded. Therefore, the years 2004 to 2008 were used for 2014-2018 and for 2019-2023 as well.

Results of the water licensing scenarios were evaluated using some illustrative graphs and the following indicators (for the period 2014-2023):

- Water shortage (average and number of days)
- Reservoir volume below 50% and below 25% of the total available storage volume (number of days)
- Outflow to Indian Ocean (number of days that flow requirement is met)

Water shortage experienced by the users that abstract their water from Umbeluzi upstream of Pequenos Libombos is not influenced by reservoir management or different license scenarios. Therefore this demand site (“Other Farms Upstream”) is not taken into account in the scenario analysis.

5.2 Results

5.2.1 Water shortage

Before 2018 no water shortages are expected (Figure 22). From 2018 onwards there are serious water shortages for scenario C in which an additional amount of 2.5 m^3/s of water is released from the reservoir to meet downstream demand (Figure 22). The average yearly water shortage between 2018 and 2023 for scenario C is 33 million m^3 for all demand sites together. For this scenario water shortage is expected on 30% of the days between 2018 and 2023. For the reference scenario and for scenario A and B, with an additional downstream demand of 0.5 m^3/s and 1.0 m^3/s respectively, there are no projected water shortages up to 2023.

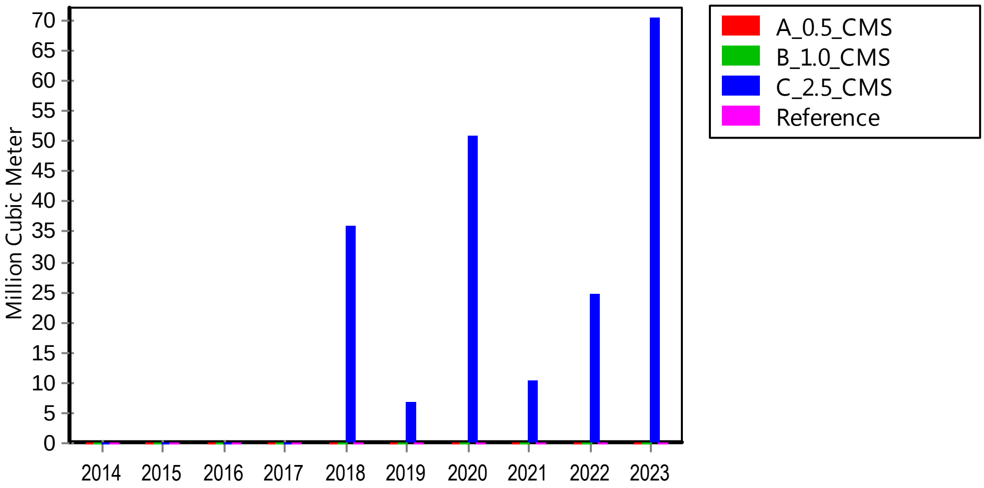


Figure 22. Sum of annual water shortage for all demand sites (in million m³) for different scenarios.

Since all demand sites have the same demand priority in the model, the water shortage per demand site is proportional to the water demand (Figure 23).

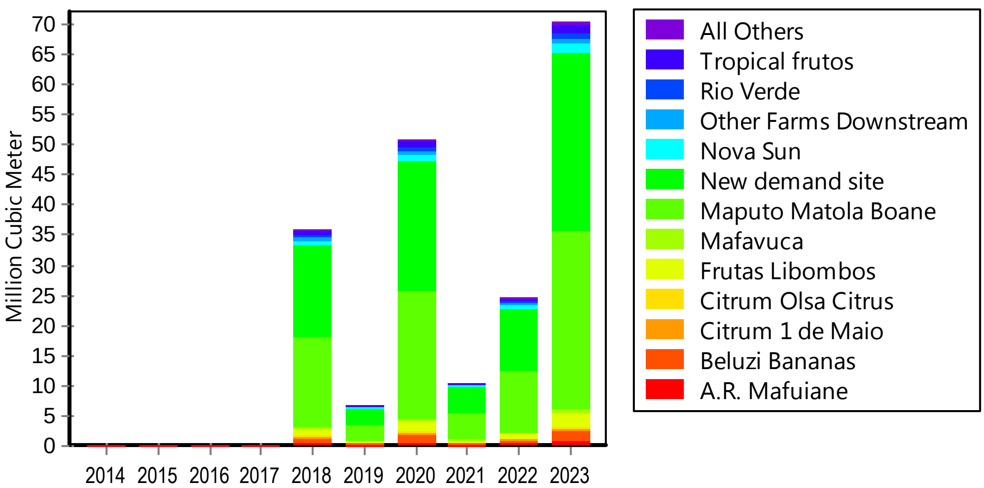


Figure 23. Annual water shortage per demand site (in million m³) for Scenario C.

5.2.2 Reservoir volume

Between 2004 and 2023 the reservoir volume decreases to less than 190 million m³ (50% of the total available reservoir volume) a couple of times for all scenarios, including the reference scenario (Figure 24). The available reservoir volume is below 95 million m³ (25% of the total available storage volume) on 2.8% of the days for scenario B and on 31% of the days for scenario C. For the reference scenario and scenario A the reservoir volume stays always above 105 million m³. Only for scenario C the reservoir volume reaches minimum reservoir level (Figure 24). For the other scenarios reservoir volume stays above 70 million m³.

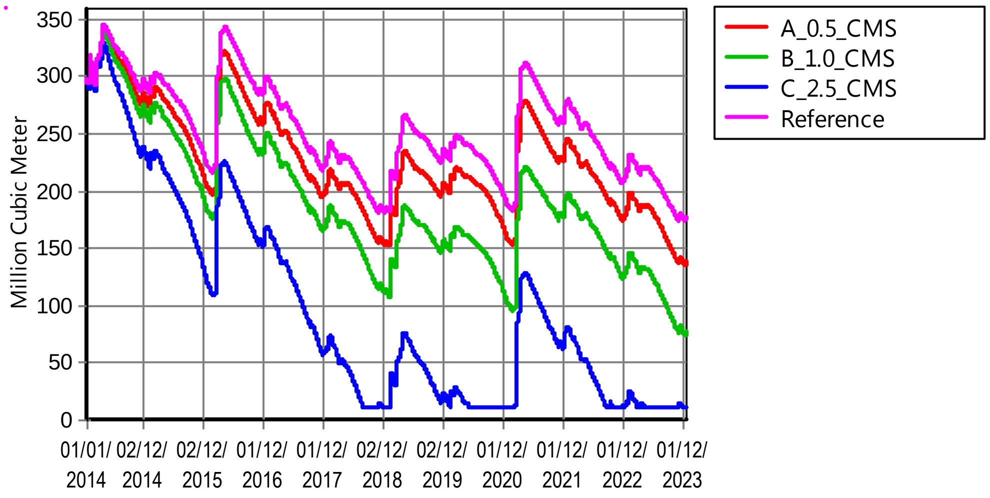


Figure 24. Daily reservoir volume (in million m^3) for different scenarios.

5.2.3 Outflow to Indian Ocean

The annual flow requirement of Umbeluzi to the Indian Ocean is approximately 24 million m^3. For scenario A and B the flow requirement is met during all years. For scenario C the flow requirement is not met from 2018 onwards (Figure 25). In 2023 the outflow of Umbeluzi to the Indian Ocean is only 50% of the flow requirement for scenario C. For the other years between 2018 and 2023 the coverage of the flow requirement is 57 to 93 percent.

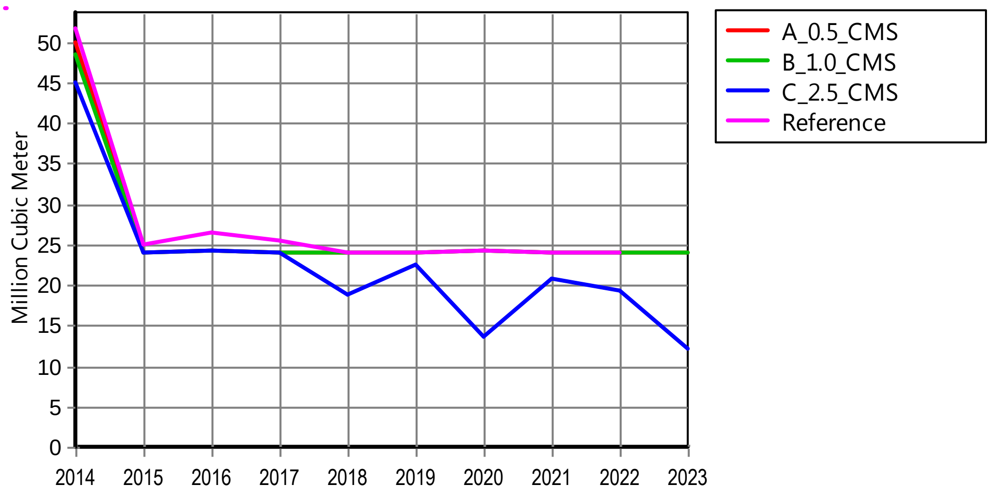


Figure 25. Annual outflow of Umbeluzi to Indian Ocean (in million m^3) for different scenarios.

6 Monitoring and Data Management

6.1 Data Needs

The quality and usefulness of the Water Allocation Models (WAMs) depends to a large extent on the available data. In Figure 26 an overview of data needs to build WAMs is shown. Important to note in this Figure is that some elements are more relevant for specific applications and locations than others. A typical example is that for the WAM-O the division in subbasins is less relevant, while for the WAM-S this is very important. A second important comment is that some components are essential to build the model (“schematization and parameterization” and “forcing”), while “calibration and validation” are used to assess the quality of the model.

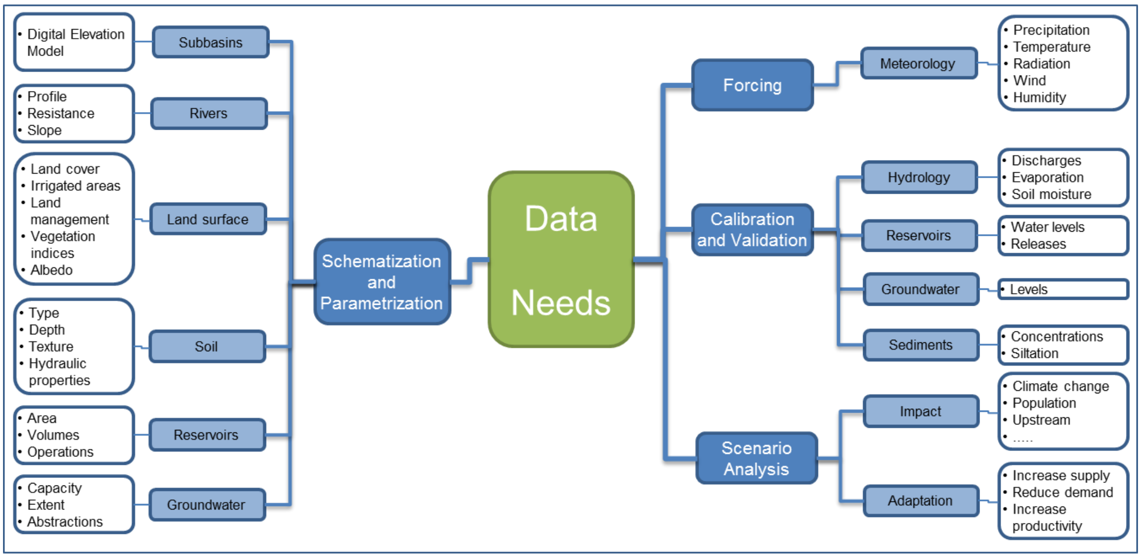


Figure 26. Overview of data needs to build water allocation models.

6.2 Data Availability

Based on this diagram relevant datasets to build the Water Allocation Models (WAMs) were obtained from ARA-Sul. Datasets were evaluated on availability, quality and accuracy. Based on the above scheme of data requirements and data that have been obtained the following conclusions can be drawn.

- Schematization and Parameterization
  - Subbasins → No information on subbasins was available as these were not used by ARA-Sul. For the WAM-S this information was required and subbasins were used based on previous SWECO studies. Since no shape files were available, these were digitized and can be included in the ARA-Sul GIS dataset. In case other basins will be modelled where no subbasin delineation has been performed the SRTM DEM can be used.
  - Rivers → A shapefile with rivers was available.
  - Land surface → No land cover and/or land use maps were available. Therefore the well-known GlobCover was used which was updated with the Global Map of Irrigated Areas.

    - Soil → No soil map was available. For the WAM-O this was not required. For the WAM-S more generic soil data were used. In case more detailed data is needed one could use the Harmonized World Soil Database if local soil maps are lacking
    - Reservoirs → Detailed information on the Pequenos Libombos was available. For Swaziland no data were available and information was used from the SWECO study. However, operational rules of Mnjoli Dam were lacking and were derived from observed flows.
    - Groundwater → Groundwater was considered to be less relevant for the WAM-O and WAM-S. However, based on the overall basins characteristics (a dry seasons after a relatively wet season) one would expect substantial groundwater use.
- Forcing
    - Meteorology → Local meteorological data were patchy and of low quality. Moreover, data for Swaziland was completely missing. It was therefore decided to use the CRU dataset (see Appendix II)
- Calibration and Validation
    - Hydrology → Quite some streamflow data were available. However, a lot of data were outdated and/or stage-discharge relationships somewhat outdated. For the most important streams data were available and were used. A detailed analysis is presented in Appendix IV.
    - Reservoirs → Sufficient data to undertake the FAT and SAT
    - Groundwater → Groundwater consumption was not considered in the WAMs and therefore no groundwater levels were needed for calibration and validation
    - Sediments → Not relevant for the current study.

A more detailed overview of the amount and quality of data is provided in Appendix IV.

6.3 Recommendations on Monitoring and Data Management

ARA-Sul has various monitoring and data management components with respect to water allocation. During the project these components have been used and evaluated. The following conclusions and recommendations emerged:

- The operational rules of the reservoir are very clear and are followed by the reservoir operators. The use of the Operational Manual as implemented in the SIGA Access Database system is effective and does not require any changes.
- Some errors were detected in the calculation spreadsheet of the Pequenos Libombos reservoir. Although these errors are not major, it would be advised to correct those. The errors are summarized in Appendix VIII.
- Many streamflow gauging stations exist in the Umbeluzi Basin; an overview is provided in Appendix IV. Many of these stations have incomplete datasets. It is advised to undertake a critical review of these stations in order to select some key stations. A firm decision should be taken on which stations to include in the future and which stations to abandon. Based on this selection all efforts can be put on these selected stations, including deriving reliable stage-discharge curves.
- Data from Swaziland are not available. It is strongly advised to ensure that agreements with Swaziland will be materialized. Such an agreement should go beyond sharing

measured data on rainfall and flows, but should include planning on additional water use by Swaziland as well.

- Providing licenses to potential water users requires some additional steps. According to information obtained during the training mission in November 2014, ARA-Sul currently provides licenses to water users mainly based on evaluating the number of users (for urban extractions), the level of industrial activity (for industrial demands), or the area and crop types (for irrigation requests). These requests are subsequently discussed in a broader committee in which the impact on potential water shortages and reservoir levels are assessed. So far, this assessment is rather qualitative, based on expert knowledge rather than on quantitative evaluations. It is strongly advised that this qualitative assessment will be replaced by a rigorous quantitative analysis using the WAM-O.
- Most data are currently stored in HEC-DSS (Hydrological Engineering Center-Data Storage System). Data is often only stored at individual PCs or laptops of ARA-Sul staff, making loss of data a serious risk. It is advised that ARA-Sul will explore a system to setup a structured data approach and that data will be stored in one central location. Such a system requires substantial investments and, very importantly, regular and continuous maintenance efforts.

7 Conclusions and Recommendations

7.1 Conclusions Current Project

Based on experiences and discussion with ARA-Sul staff involved in the current project the following conclusions were drawn:

- Current operational management of Pequenos Libombos reservoir is based on well-established operational rules. No specific changes are required.
- In the very near future (three years) no specific water shortages are expected. After this problems can arise when (i) a few prolonged low rainfall years will occur and/or (ii) demand for water will increase beyond current projections.
- Requests for permits for additional water allocations are not sufficiently embedded in the impact on the entire water availability on the longer time-frame. The use of WAM-O is highly recommended to support decision making on water allocation permits.
- Strategic water allocation decisions, such as new reservoirs, climate change, inter-basin transfer, amongst others, are hardly supported by quantitative analysis tools. The developed WAM-S can be used for this.
- The two developed WAMs might benefit from some additional improvements. For WAM-O data on the main tributaries could be improved in case more accurate flow records will become available. WAM-S would greatly benefit from including local data from Swaziland to replace the global public domain data as used now.
- Training and capacity building remains key to the success of the applications of the WAMs. The current capacity building material is sufficient for additional development of staff from ARA-Sul. In addition a one-day seminar for a broader audience might be organized to show the benefits of using WAMs.

7.2 Future Outlook

During the various meetings and capacity building the following advice on how to proceed can be summarized as:

- The use of the developed Water Allocation Models (WAM-Operational and WAM-Strategic) should be streamlined in the decision process of ARA-Sul. This requires some changes in the permit procedures.
- In the long-run ARA-Sul should aim at developing a “modeling-center” where all data and models will be brought together. Such a modeling center would require 4-5 full-time staff completely dedicated to developing and maintaining data and models. This modeling center should support decision makers at operational and strategic level. Such a modeling center could be established independently by ARA-Sul or this might be done in collaboration with other ARA and/or DNA.
- Data and monitoring should get more attention. It is clear that only undertaking more measurements is not sufficient. Only by working with the data and information the weak points are revealed. In Chapter 6 clear recommendations are provided and could be integrated in the proposed “modeling-center”

- To keep the momentum of the current project it is strongly advised to develop similar WAMs for another basin (e.g. Incomati). In this way, capacity building and embedding the WAMs into decision making will get the required long-term attention.

8 Selected References

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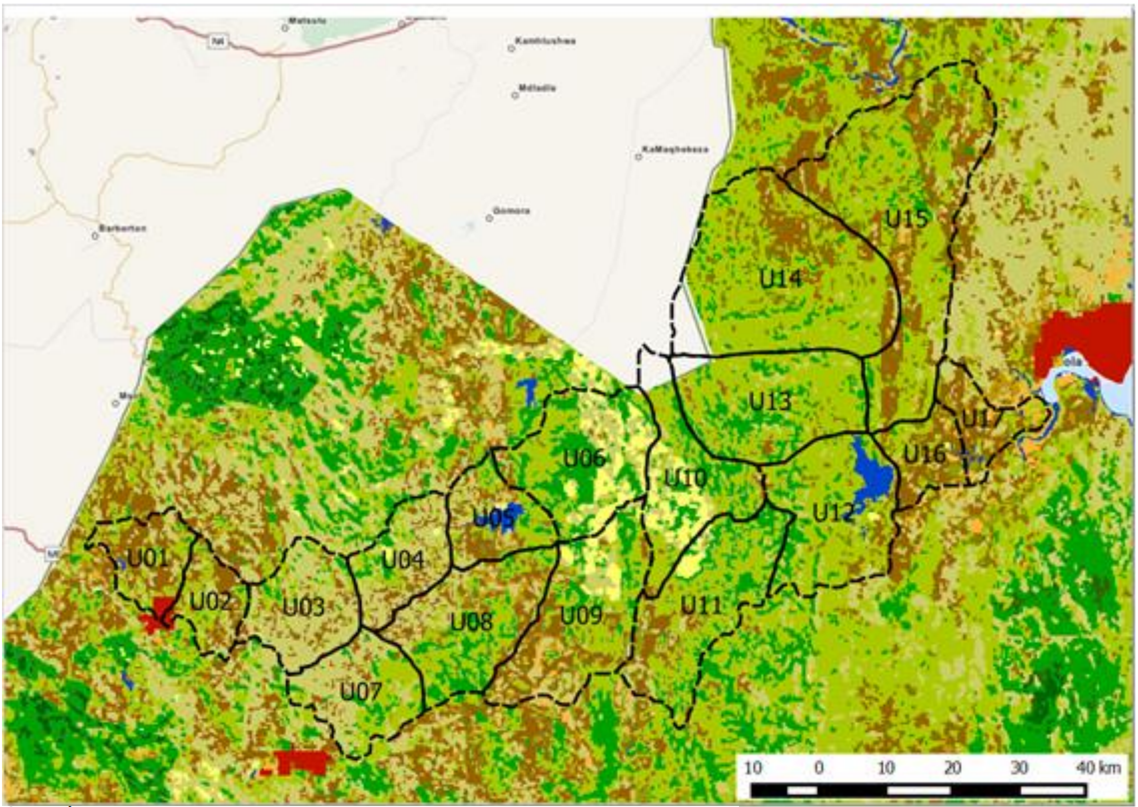
APPENDIX I: Land cover map based on GlobCover



Legend

moz_gc_adg

- Rainfed croplands
- Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)
- Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)
- Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)
- Closed (>40%) broadleaved evergreen and/or semi-deciduous forest (>5m)
- Closed (>40%) broadleaved deciduous forest (>5m)
- Open (15-40%) broadleaved deciduous forest/woodland (>5m)
- Open (15-40%) needleleaved deciduous or evergreen forest (>5m)
- Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)
- Mosaic forest or shrubland (50-70%) / grassland (20-50%)
- Mosaic grassland (50-70%) / forest or shrubland (20-50%)
- Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (max 5m)
- Closed to open (>15%) broadleaved deciduous shrubland (max 5m)
- Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)
- Closed (>40%) grassland
- Open Herbaceous Vegetation
- Sparse (max 15%) vegetation
- Sparse (max 15%) grassland
- Closed to open broadleaved forest on temporarily flooded land - Fresh water
- Closed (>40%) broadleaved forest or shrubland permanently flooded - Saline or brackish water
- Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water
- Artificial surfaces and associated areas (Urban areas >50%)
- Bare areas
- Consolidated bare areas (hardpans, gravels, bare rock, stones, boulders)
- Salt hardpans
- Water bodies

Figure 27. Land cover map based on GlobCover.

Table 11. Percentage share of different land cover types for Swaziland and Mozambique, based on GlobCover

Landuse	**Swaziland (U1-U11)**	**Mozambique (U12-U17)**
Rainfed croplands	2	0
Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)	28	0
Closed (>40%) broadleaved deciduous forest (>5m)	7	13
Open (15-40%) broadleaved deciduous forest/woodland (>5m)	46	1
Open (15-40%) needleleaved deciduous or evergreen forest (>5m)	0	81
Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)	0.3	0
Mosaic forest or shrubland (50-70%) / grassland (20-50%)	0.2	0.4
Mosaic grassland (50-70%) / forest or shrubland (20-50%)	0.2	0.1
Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)	14	0.2
Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	0.1	4
Open Herbaceous Vegetation	0	0.1
Artificial surfaces and associated areas (Urban areas >50%)	1	0
Salt hardpans	0	0
Water bodies	0.1	0
Irrigated areas	1	0.1
Total	100	100

APPENDIX II: Example CRU rainfall

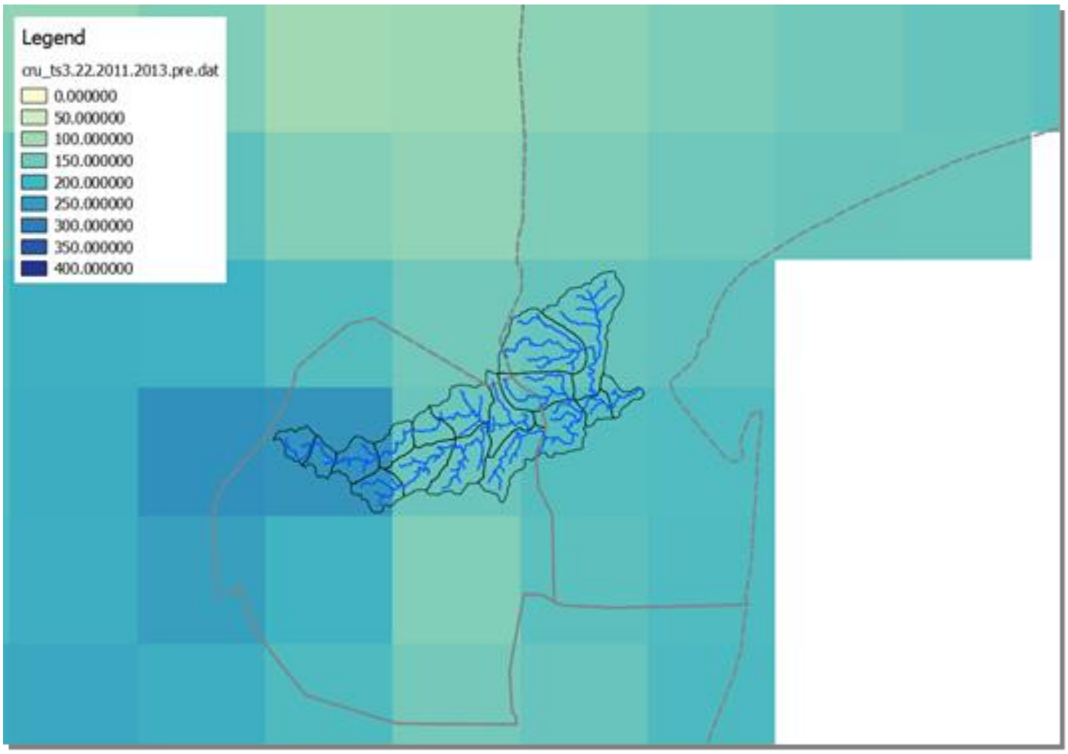


Figure 28. Example of CRU rainfall data set (Jan-2011). Grid size is 55x55 km.

Appendix III: Climate change projection

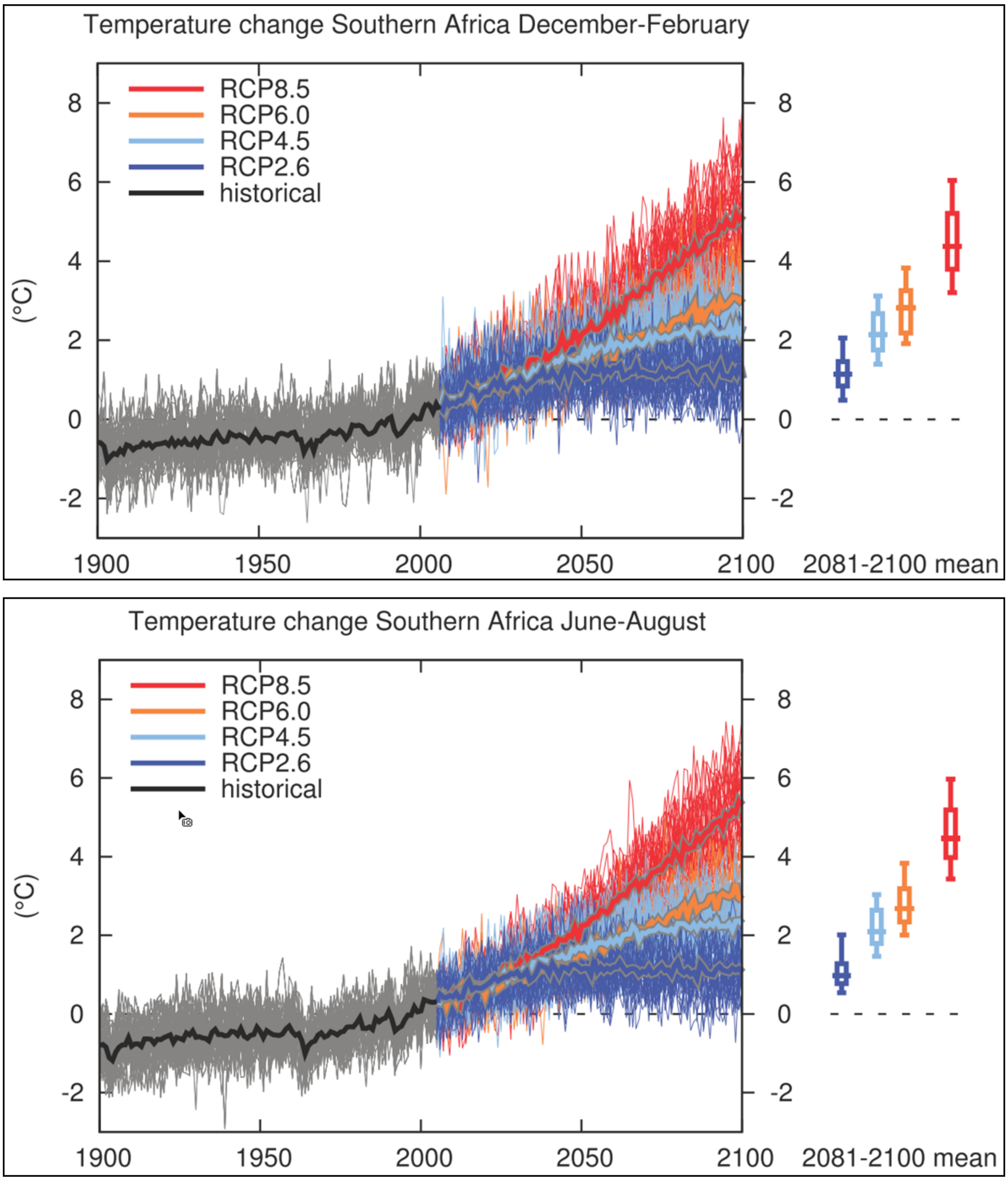


Figure 29. Changes in temperature for Southern Africa. Source: IPCC Fifth Assessment Report, 2013

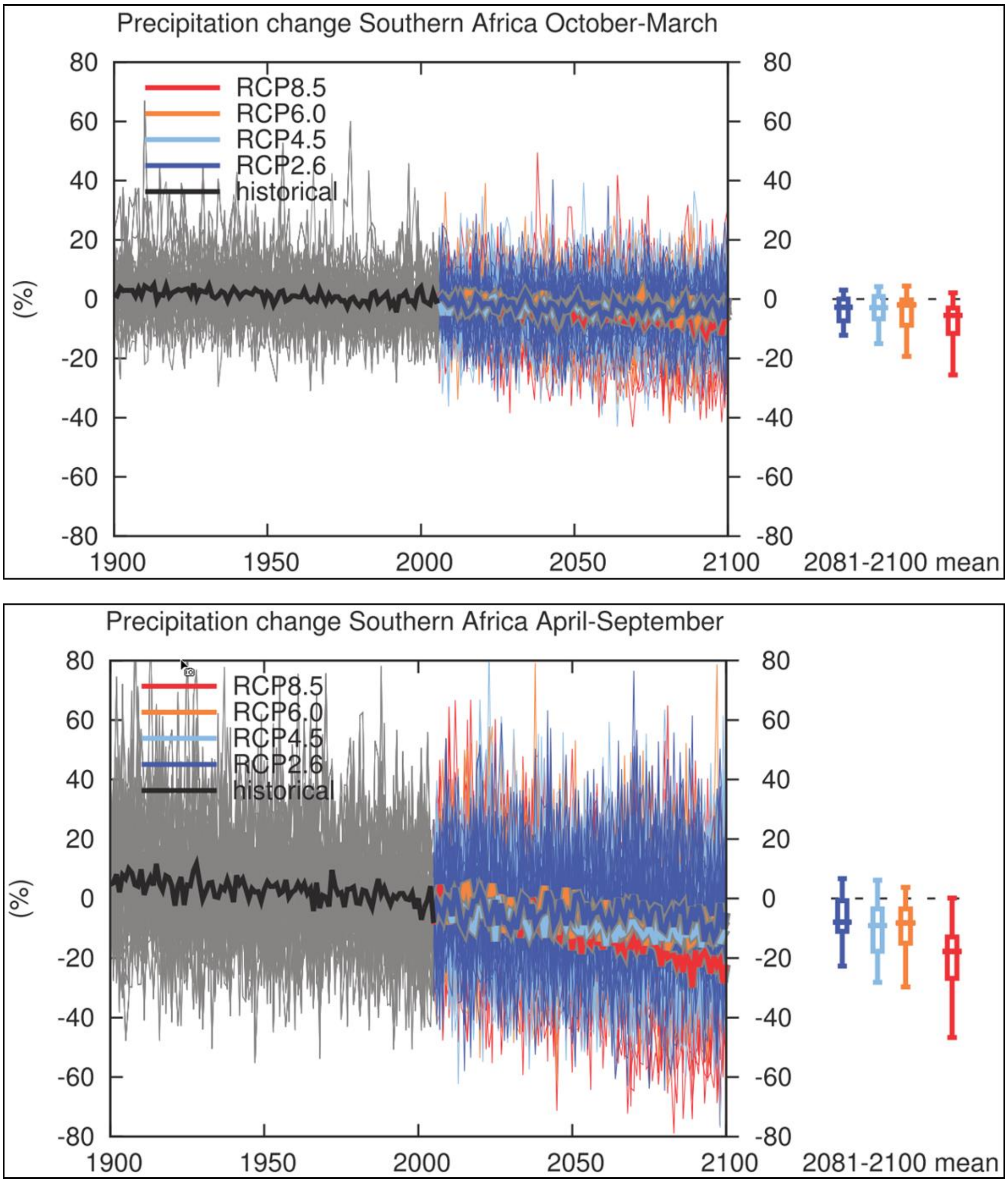


Figure 30. Changes in precipitation for Southern Africa. Source: IPCC Fifth Assessment Report, 2013

Appendix IV: Quality of Existing Datasets

WAM-O is defined by four inflow nodes:

- Umbeluzi upstream Pequenos Libombos
  - Four gauging stations are known. Of those only E-0010H has sufficient data and will be used (Figure 31, Figure 32, Table 12).
- Calichane
  - Five gauging stations are known. Of those only E-0019H has sufficient data and will be used (Figure 31, Figure 33, Table 12).
- Small streams directly flowing into Pequeno Libombos
  - No gauging stations are known.
- Movene
  - Only gauging station E-0012H is known (Figure 31, Figure 34). Approximately 70 percent of the data for this station is missing (Table 12).

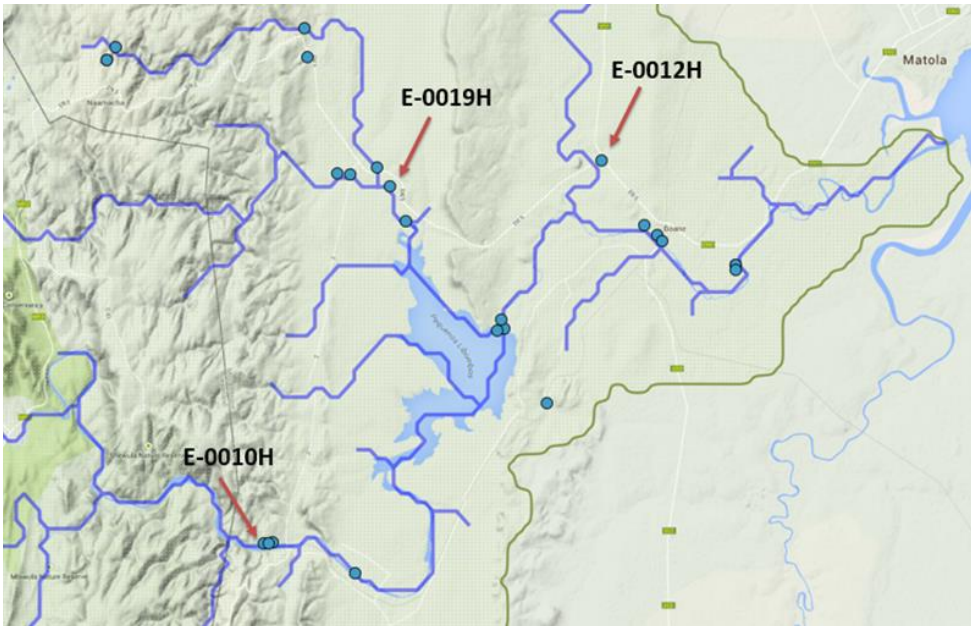


Figure 31. Gauging stations in the Umbeluzi basin as used for WAM-O.

For the Umbeluzi upstream Pequenos Libombos four gauging stations are known. Of those four only E-0010H has sufficient data and will be used (Table 12). The percentage of missing data is different for every year (Table 13). Missing data was filled with monthly average flows of the period 1981-2014. From Figure 32 it can be seen that total yearly streamflow for Umbeluzi measured at gauging station E010 varies roughly between 50 million m^3/year and 550 million m^3/year, with a peak of 1700 million m^3/year in the year 2000.

Table 12. Overview gauging stations

Station	Location	FirstDate	LastDate	Missing (%) 1981-2013	Missing (%) 2004-2013	Missing (%) 1981-2010	Average Flow (MCM) 1981-2013	Average Flow (MCM) 2004-2013	Average Flow (MCM) 1981-2010
E-0010H	Umbeluzi upstream	24/Apr/1943	30/Apr/2014	15	6	17	263	214	262
E-0011H	Umbeluzi upstream	1/Jul/1951	30/Sep/2003	64	100	60	96	96	96
E-0377H	Umbeluzi upstream	1/Jun/2007	30/Sep/2010	94	79	93	100	100	100
E-0338H	Umbeluzi upstream	NO DATA							
E-0530H	Calichane	NO DATA							
E-0019H	Calichane	12/Nov/1954	30/Sep/2011	58	25	56	13	7	13
E-0170H	Calichane	NO DATA							
E-0331H	Calichane	NO DATA							
E-0020H	Calichane	NO DATA							
E-0012H	Movene	14/Nov/1947	30/Sep/2006	73	74	70	72	65	72
E-0009H	Downstream dam	12/May/1959	30/Sep/1967	100	100	100			
E-0629H	Downstream dam	1/May/1987	30/Sep/1997	68	100	65	157	157	157
E-0395H	Downstream dam	2/Aug/1967	30/Jun/1999	88	100	86	321	322	321
E-0240H	Downstream	NO DATA							
E-0008H	Downstream	1/Oct/1954	30/Sep/2006	36	73	29	211	203	211
E-0239H	Downstream	NO DATA							
E-0631H	Downstream	NO DATA							
E-0330H	Downstream	NO DATA							
E-0167H	Downstream	27/Sep/1951	31/Jul/2006	72	78	69	2,348	2,134	2,348

Table 13. Percentage of missing data for gauging stations E-0010H, E-0019H and E-0012H

	Umb. E-010	Cal. E-019	Mov. E-012		Umb. E-010	Cal. E-019	Mov. E-012		Umb. E-010	Cal. E-019	Mov. E-012
1981	0	100	100	**1992**	29	100	100	**2003**	0	12	16
1982	0	100	100	**1993**	43	100	95	**2004**	17	2	0
1983	0	100	100	**1994**	77	100	100	**2005**	0	0	8
1984	0	100	100	**1995**	77	45	100	**2006**	8	1	27
1985	0	100	100	**1996**	1	55	100	**2007**	0	21	100
1986	0	100	92	**1997**	3	35	99	**2008**	8	0	100
1987	25	100	70	**1998**	4	5	45	**2009**	0	0	100
1988	40	100	30	**1999**	0	25	5	**2010**	17	0	100
1989	25	100	92	**2000**	0	76	25	**2011**	0	25	100
1990	100	100	100	**2001**	0	8	9	**2012**	0	100	100
1991	25	100	100	**2002**	3	0	0	**2013**	8	100	100

For the Calichane five gauging stations are known. Of those five only E-0019H has sufficient data and will be used (Table 12). The years without missing data are 2002, 2005 and 2008-2010 (Table 13). Total yearly streamflow from 1995 to 2011 varies roughly between 0.15 million m3/year and 40 million m^3/year (Figure 33). From Figure 33 it can be seen that total yearly streamflow is constant from 1981 to 1994 and in 2012 and 2013. This is caused by the gap-filling that was necessary due to missing data and thus represents the average flow.

For the Movene only gauging station E-0012H is known (Table 12). Approximately 70 percent of the data for this station is missing. The only years without missing data are 2002 and 2004 (Table 13). As can be seen from Figure 34 total yearly streamflow between 1981 and 1985, between 1990 and 1992, between 1994 and 1996 and between 2007 and 2013 is constant and equal to the average flow due to missing data. The streamflow for the remaining years varies approximately between 2 million m^3/year and 135 million m^3/year, with a peak of 410 million m^3/year in the extremely wet year 2000 (Figure 34). The average measured flow is 2.3 m^3/s, but the distribution over the year is very skew. Since no reliable measurements were available for the Movene the flow was assumed to be zero.

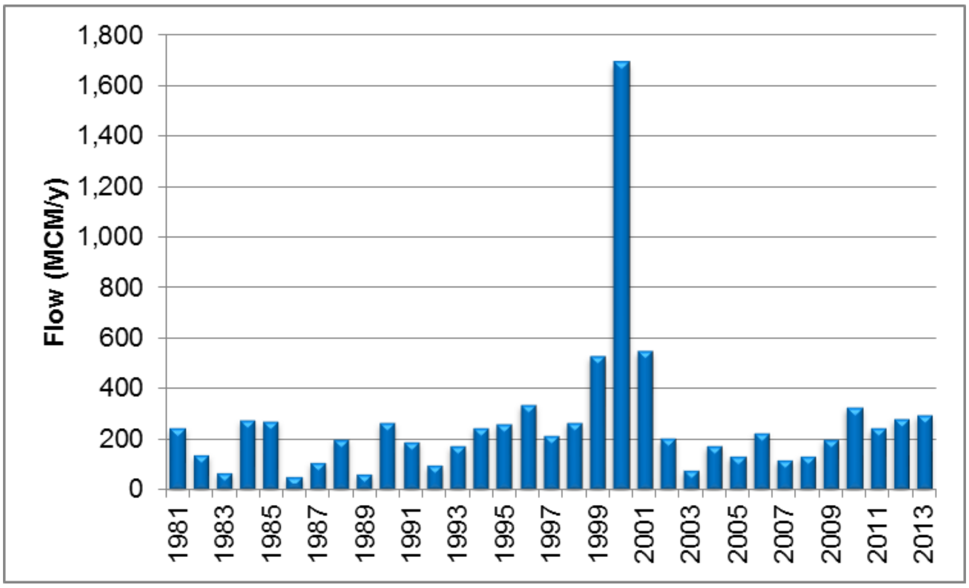


Figure 32. Total yearly streamflow for Umbeluzi from 1981-2013 measured at gauging station E-0010H.

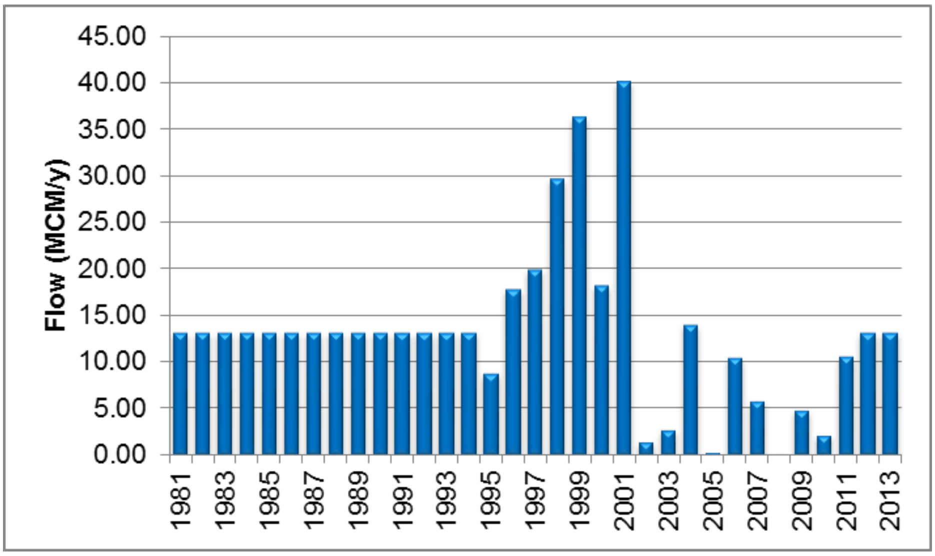


Figure 33. Total yearly streamflow for Calichane from 1981-2013 measured at gauging station E-0019H.

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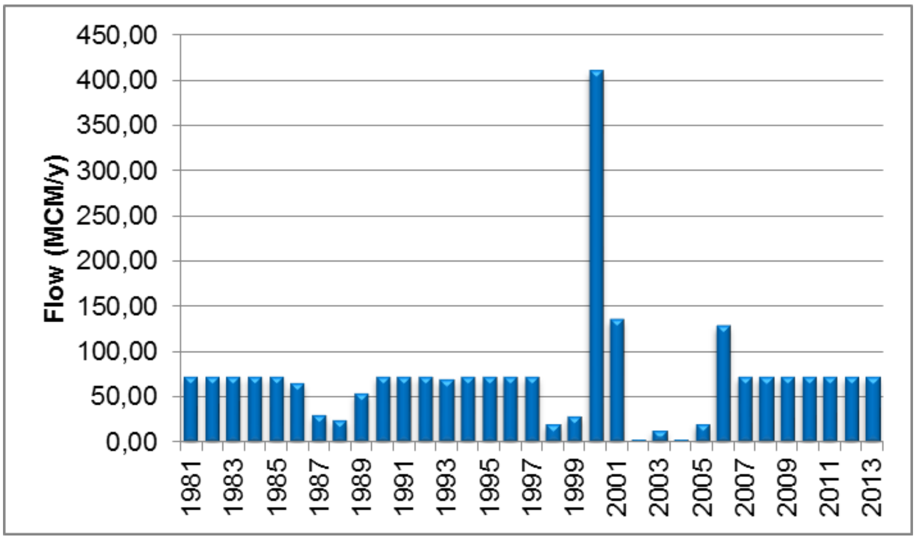


Figure 34. Total yearly streamflow for Movene from 1981-2013 measured at gauging station E-0012H.

The inflow into the Pequenos Libombos reservoir was calculated from the water balance of the reservoir. The inflow was compared to the sum of measured streamflow of Umbeluzi and Calichane, which both discharge to Pequenos Libombos. The comparison was done for the years 2005 and 2009, because daily streamflow data for both tributaries contained no missing values for these years (Table 13).

The correlation coefficient (Pearson R) between daily inflow into Pequenos Libombos and the daily sum of measured streamflow from Umbeluzi and Calichane was 0.65 for 2005 and 0.85 for 2009. Inflow into Pequenos Libombos and the sum of measured streamflow of Umbeluzi and Calichane for the years 2005 and 2009 are shown in Figure 35 and Figure 36 respectively. Umbeluzi is the major river supplying the Pequenos Libombos reservoir. The percentage of total yearly streamflow of Umbeluzi compared to the inflow into Pequenos Libombos was 104.6% for the year 2005. For Calichane it was 0.3%. When the streamflows of Umbeluzi and Calichane are defined as percentages that add up to 100% (of the inflow into Pequenos Libombos), Umbeluzi would account for 99.7% and Calichane for 0.3%. For 2009 total yearly streamflow of Umbeluzi was 12% higher than the flow into Pequenos Libombos. Total yearly streamflow of Calichane was only 2.7% of the inflow into Pequenos Libombos. Defined as percentages that add up to 100%, Umbeluzi would account for 97.6% and Calichane for 2.4% of inflow into Pequenos Libombos.

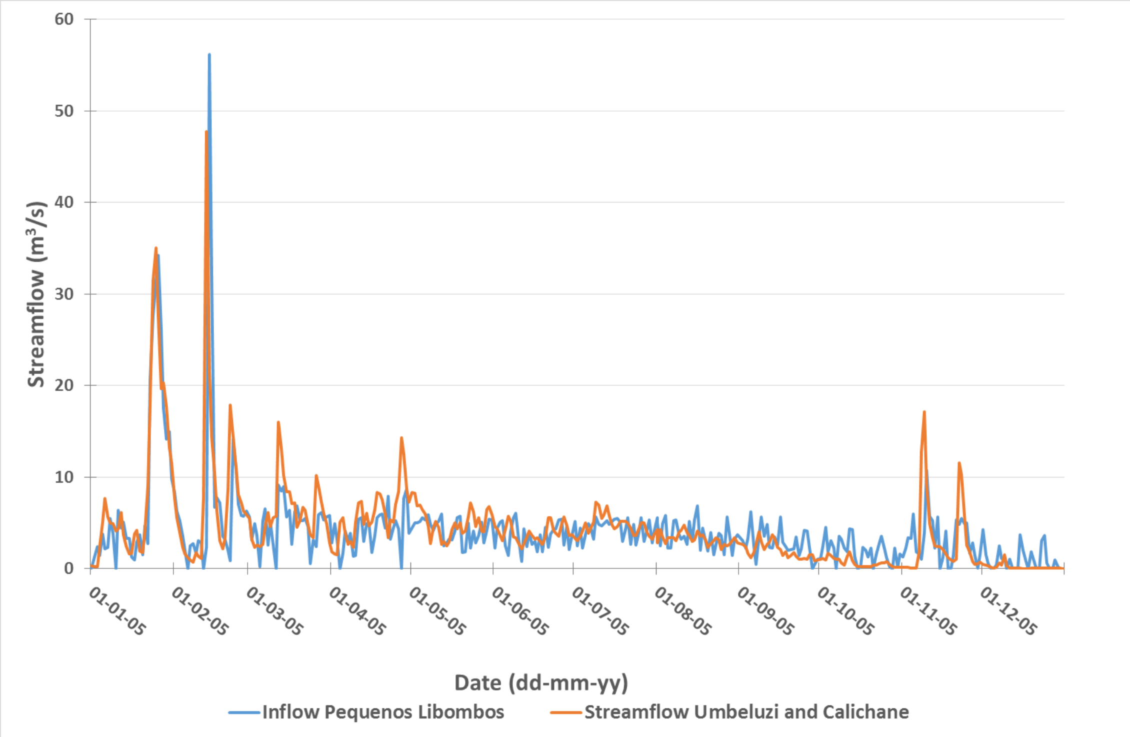


Figure 35. Comparison of inflow into Pequenos Libombos and streamflow of Umbeluzi and Calichane for 2005.

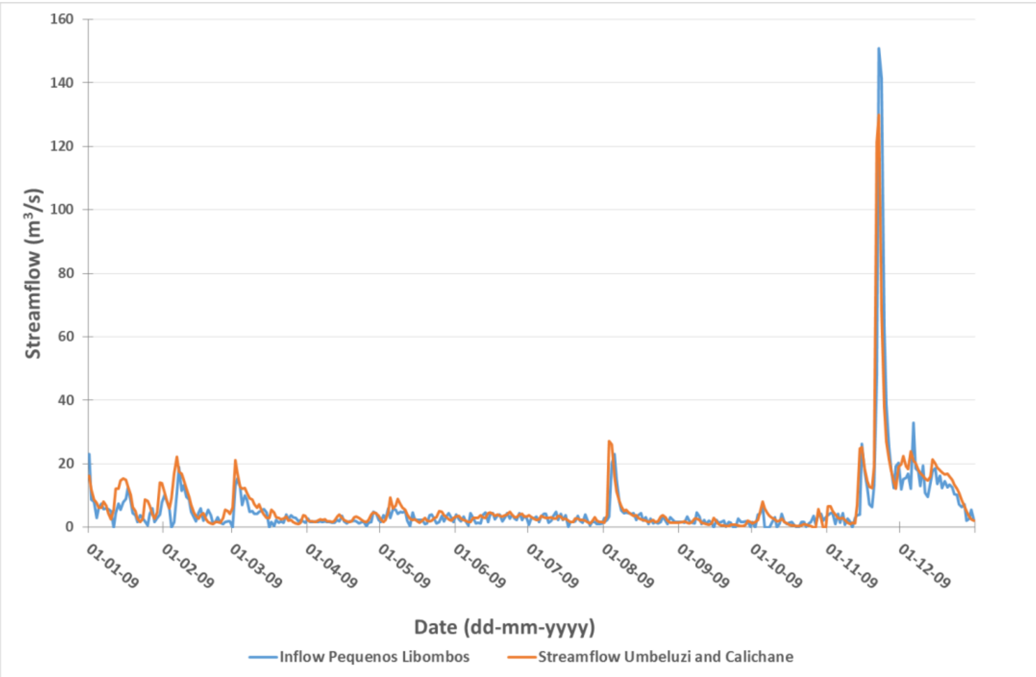


Figure 36. Comparison of inflow into Pequenos Libombos and streamflow of Umbeluzi and Calichane for 2009.

Since streamflow time series of Umbeluzi and Calichane contained too much missing data, the inflow into Pequenos Libombos was divided over these two rivers for the years 2004-2013. The inflow into Pequenos Libombos coincides better with the streamflow of Umbeluzi and Calichane for the year 2009 than for the year 2005. Therefore in WAM-O, streamflow for Umbeluzi was

98% of the inflow into Pequenos Libombos and streamflow for Calichane was 2% of the inflow. Inflow from other small streams could not be derived from the difference between the inflow into Pequenos Libombos and the summed streamflow of Umbeluzi and Calichane, because the summed streamflow was higher than the calculated inflow into Pequenos Libombos. Therefore the inflow from other small streams was schematized in WAM-O with a flow of zero. When more data will become available in future, this can be adjusted. Also for Movene no sufficient data was present and therefore this river was schematized in WAM-O with a flow of zero.

Since the inflow to Pequenos Libombos was calculated from the water balance, it contained negative values. Negative inflows to Pequenos Libombos were set to zero. Furthermore the original calculation of the difference in reservoir volume between two subsequent days contained errors and therefore the difference was recalculated. The improved results were used to recalculate the inflow to Pequenos Libombos from the waterbalance.

In the original dataset the reservoir volume made a jump from 206.17 million m^3 on 30-09-2009 to 212.31 million m^3 on 01-10-2009. This jump could not be attributed to a (high) rainfall event and was caused by a change in how the reservoir volume was calculated from the reservoir elevation. The jump in reservoir volume caused an unrealistic peak inflow to the reservoir. Therefore the reservoir volume between 01-01-2004 and 30-09-2009 was recalculated with the latest formula to keep consistency.
The same was done for the period between 01-10-2012 and 01-10-2013. Furthermore the reservoir elevation made a jump of 1 meter between 29-09-2013 and 1-10-2013 (data of 30-09-2013 was missing). This jump could not be attributed to a (high) rainfall event and was probably caused by a typing error (due to a change of data arrangement). Therefore reservoir elevation was lowered by one meter from 1-10-2013 onwards.

Appendix V: Calibration of WAM-O

The simulated reservoir volume of the uncalibrated model (red line in Figure 37) is lower than the observed reservoir volume (blue line in Figure 37) between 1-1-2004 and 31-12-2013. R^2 of the simulated and observed reservoir volume was 0.93.

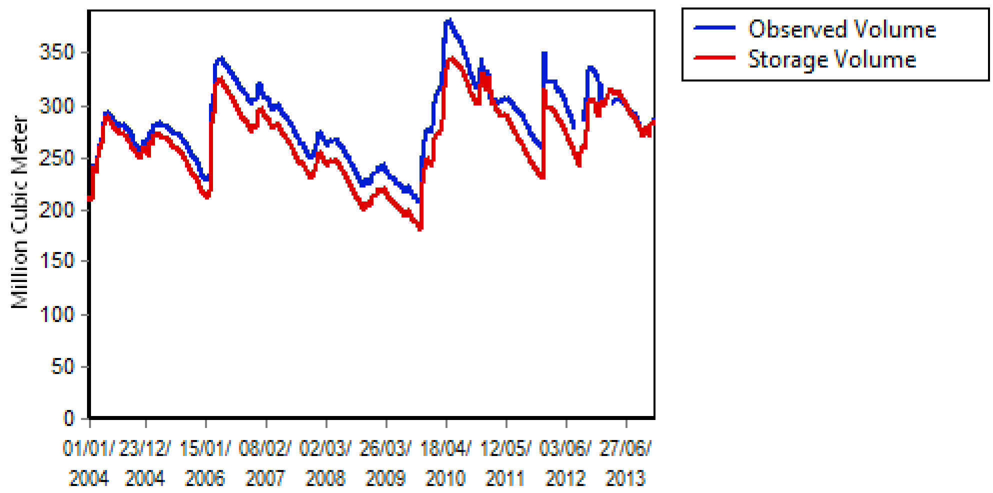


Figure 37. Observed reservoir volume (blue line) and simulated reservoir volume of the uncalibrated model (red line) from 2004 to 2013.

The underestimation of reservoir volume was probably due to an underestimation of inflow to P.Libombos. The observed inflow of Umbeluzi alone for the years 2005, 2007, 2009, and 2011-2012 was on average 4.3% higher than the inflow calculated from the water balance of the reservoir, which was used in the model. Next to the higher inflow of Umbeluzi there is inflow of Calichane and other small tributaries as well.
To take the higher inflow into account, the inflow of the tributary catchment, which was set to zero previously, was set to 15% of the daily inflow of Umbeluzi and Calichane for months with a normal flow. For months with a relatively high flow (inflow of Umbeluzi and Calichane more than 1.5 times the average inflow for the corresponding month) the inflow of the tributary catchment was set to 20% of the daily inflow of Umbeluzi and Calichane.
Extra releases from the reservoir were done during some periods in which the reservoir volume was high. Not all extra releases were captured by the uncalibrated model. Therefore extra releases were added to the model on 8-10-2004, in January 2007 and from May to November 2010.
After this calibration procedure the simulated volume corresponded better to the observed volume (Paragraph 3.3.3.3).

APPENDIX VI: Implementation of Scenarios

- (01) Impact: Population growth[7] (2% per year)
  - KeyAssumptions > DemandDomestic > GrowthFrom(2%,2010,125*365/1000)
  - KeyAssumptions > Demand_Industry > GrowthFrom (2%,2010,10*365)
  - All Demand Sites > Domestic > Annual Activity Level > Growth(2%)

- (02) Adaptation: Water transfer from Incomati (2 $m^3\ s^{-1}$)
  - Supply and Resources > Other Supply > Incomati > Inflows and Outflows > 2 CMS

- (03) Adaptation: Prevent tap water leakage losses (by 25%)
  - All Demand Sites > Urban > Annual Water Use Rate > *0.75

- (04) Impact: Increase in irrigated areas (2% per year)
  - KeyAssumptions > DemandIrrigation > Growth(2%)

- (05) Adaptation: Increased reservoir capacity (by 100%)
  - Supply and Resources > River > Umbeluzi > Reservoirs > Storage Capacity > *2
  - Supply and Resources > River > Umbeluzi > Reservoirs > Top of Conservation > *2

- (06) Adaptation: Reduce conveyance losses in irrigation systems (by 25%)
  - All Demand Sites > Irrigation> Annual Water Use Rate > *0.75

- (07) Impact: Climate change (precipitation -10%, temperature +3ºC[8])
  - KeyAssumptions > PrecipFactor > 0.9
  - KeyAssumptions > Demand_Domestic > *1.1
  - KeyAssumptions > Demand_Industry > *1.1
  - Demand Sites and Catchments > Climate > Temperature > +3

- (08) Impact: Likely Future (three impacts as defined above)
  - KeyAssumptions > DemandDomestic > GrowthFrom(2%,2010,125*365/1000 * 1.1)
  - KeyAssumptions > Demand_Industry > GrowthFrom(2%,2010,10*365* 1.1)
  - KeyAssumptions > DemandIrrigation > Growth(2%)
  - KeyAssumptions > PrecipFactor > 0.9
  - All Demand Sites > Domestic > Annual Activity Level > Growth(2%)
  - Demand Sites and Catchments > Climate > Temperature > +3

- (09) Adaptation: Infrastructure (= 02 and 05)
  - Supply and Resources > Other Supply > Incomati > Inflows and Outflows > 2 CMS
  - Supply and Resources > River > Umbeluzi > Reservoirs > Storage Capacity > *2
  - Supply and Resources > River > Umbeluzi > Reservoirs > Top of Conservation > *2

- (10) Adaptation: Improved system (= 03 and 06)
  - All Demand Sites > Urban > Annual Water Use Rate > *0.75
  - All Demand Sites > Irrigation > Annual Water Use Rate > *0.75

- (11) Adaptation: Full (=all above)
  - Supply and Resources > Other Supply > Incomati > Inflows and Outflows > 2 CMS
  - Supply and Resources > River > Umbeluzi > Reservoirs > Storage Capacity > *2
  - Supply and Resources > River > Umbeluzi > Reservoirs > Top of Conservation > *2
  - All Demand Sites > Urban > Annual Water Use Rate > *0.75
  - All Demand Sites > Irrigation > Annual Water Use Rate > *0.75

[7] This scenario includes also a growth in water use per person by 2% per year.
[8] Temperature increase influences irrigation demand automatically. For impact on urban increase of 10% has been assumed.

ARA = Administração Regional de Água
CMS = cubic meter per second = m^3/s
CRU TS = Climatic Research Unit Time Series
FAT = Factory Acceptance Test
MASL = Meters Above Sea Level
MCM = million cubic meter = 10^6 m^3
RCP = Representative Concentration Pathway
SAT = Site Acceptance Test
Unmet Demand = Water Shortage
WAM = Water Allocation Model

Reservoir characteristics

Inactive Storage = Volume in reservoir not available for allocation, also called "dead storage" (Inactive Zone in Figure 38; Equal to 10.2 MCM for P. Libombos)
Full Storage level = Total Storage level (Figure 38; Equal to 391.5 MCM for P. Libombos)
Top of Conservation = Maximum volume of water in reservoir when leaving space for flood control (Figure 38; Between Full Storage level and 298.5 MCM depending on time of the year)

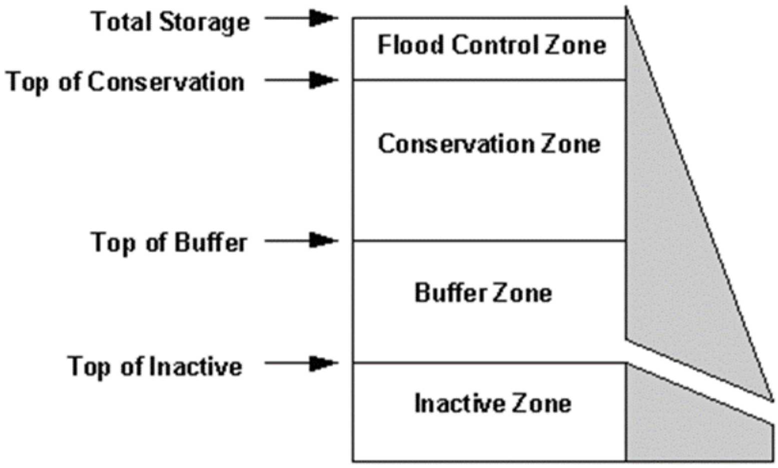


Figure 38. Reservoir storage zones.

Statistic variables

R^2 = Square of Pearson R
Bias (%) = (Average Simulated – Average Observed)/Average simulated *100

Pearson R $= \dfrac{\sum (x-\overline{x})(y-\overline{y})}{\sqrt{\sum (x-\overline{x})^2 \sum (y-\overline{y})^2}}$

In which:
x = observed value, $\bar{x}$ = average of observed values
y = simulated value, $\bar{y}$ = average of simulated values

APPENDIX VIII: Errors in Water Balance Calculations

During the data analysis some errors in the water balance spreadsheets (“Balancos da Barragem dos PLibombos”) were discovered. Since correct input data is crucial in model development, it is important that as much as possible improvements are made to the input data.

- First of all the water abstraction from the reservoir should be taken into account in the water balance that is used for calculating the inflow into the reservoir (column R: “Volume afluente”).
- Some minor improvements that can be made to the water balance spreadsheets that were composed before October 2009 are:
    - All cell references in the formula located in cell G5, in which the reservoir volume of the last day of the previous month is calculated, should refer to cell B12 and not to cell F12.
    - The calculation of the difference in reservoir volume on 28 and 29 February 2004 is incorrect. Instead of referring to one day prior to the ‘current’ day, the formula refers to two days prior of the ‘current’ day.

APPENDIX IX: Summary Training Sep-2014

WRAP UP SESSION:

Water Allocation Models
for the
Umbeluzi River Basin, Mozambique

26-Sep-2014

Peter Droogers

ARA-Sul
Administração Regional de Águas do Sul

WETTERSKIP FRYSLÂN

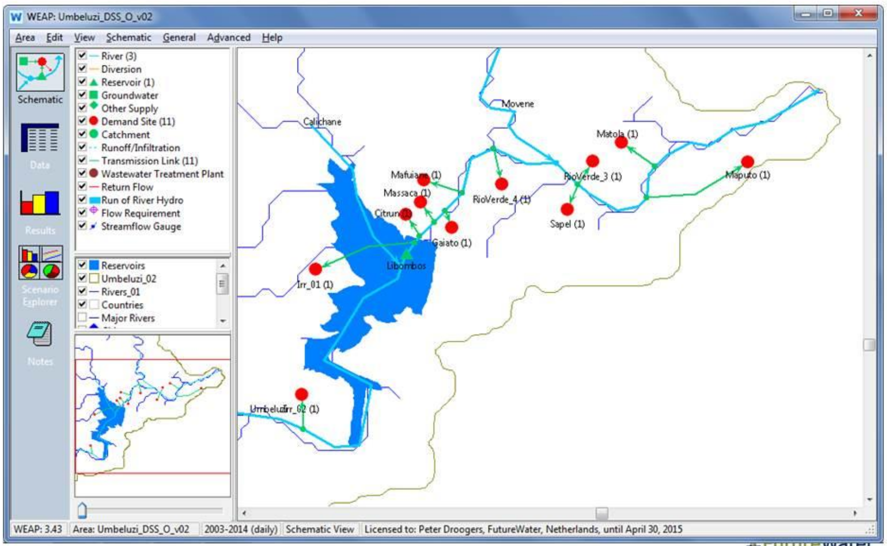
FutureWater

Activities Undertaken

- Project initiation
- Discussion WEAP schematizations
- Collection of data
- Training
- Field visit
- NL Embassy visit

FutureWater

WAM-Operational Schematisation



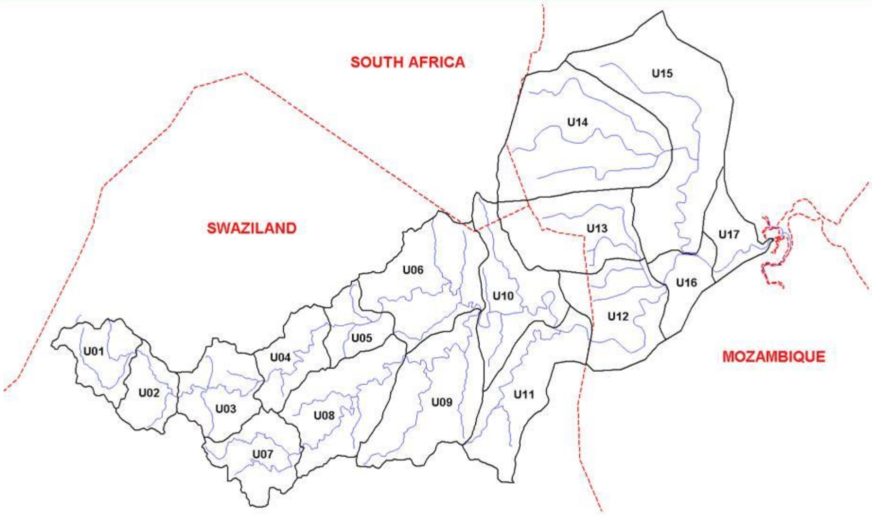
FutureWater

Water Allocation Model - Operational

- Demand Nodes [11]:
  - Urban (Maputo)
  - Industrial (Matola)
  - Irrigation (9)
- Inflow Nodes [4]
  - Goba
  - Calichane
  - Movene
  - Smaller
- River Nodes [3]
- Flow Requirements Nodes [1]
- *Hydrological or "human" year?*

FutureWater

WAM-Strategic Schematisation



FutureWater

Water Allocation Model - Strategic

- Demand Nodes [17]:
  - Urban
  - Industrial
  - Irrigation
- Catchment Nodes [17]
- River Nodes [5]
- Flow Requirements Nodes [1]
- Reservoirs [2]

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Data

- Collected
  - Rainfall
  - Flows
  - GIS
- Next step: cleaning, checking, gap filling
- Missing
  - Swaziland
  - Abstraction data is missing

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Training

- Training manual distributed
- Gimo, João, Zimba, Nercia
- Prepare updated training manual
- Next mission Nov-2014 (dates?)
  - 17-21 Nov or 24-28 Nov 2014

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Acceptance Tests

- FAT (Factory Acceptance Test)
  - Number of nodes is same as agreed with ARA-Sul
  - Schematic setup is same as agreed with ARA-Sul
  - Simulated flow compared to observed ones:
    - $R^2 >= 0.8$
    - Bias < 10%
    - if data quality permits

- SAT (Site Acceptance Test)
  - WAM runs on PCs from ARA-Sul
  - At least three ARA-Sul staff can use and modify the two WAMs
  - At least two ARA-Sul staff can use the WAM-O
  - At least 10 scenarios have been explored using WAM-P

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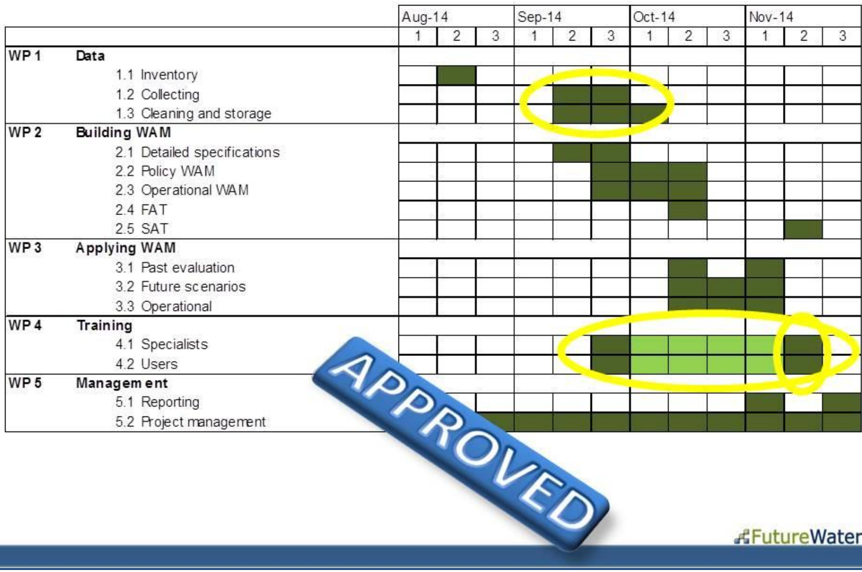
Updated Planning



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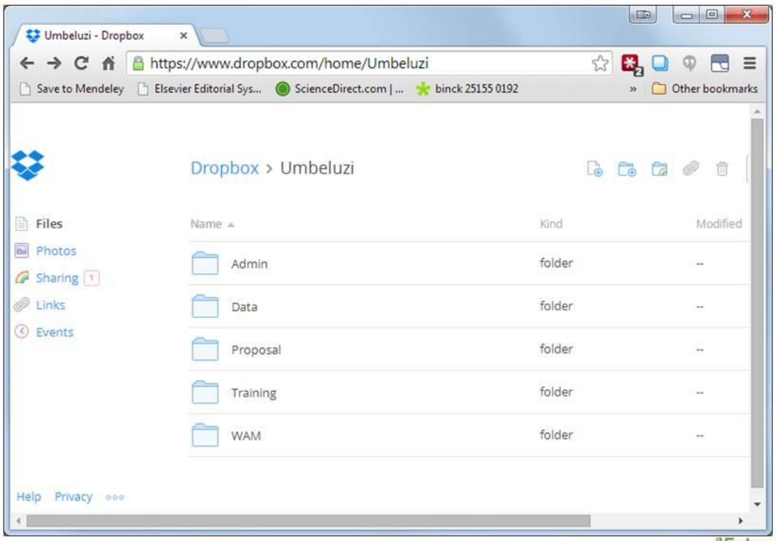
Project Website



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Shared Actions

- Mission Report → Peter
- Training
  - Updated training manual → Peter
  - Learn WEAP → Gimo, João, Zimba, Nercia
- Data
  - Abstractions → Gimo
  - Sub catchments → Gimo, João
  - Swaziland → Lizette (REMCO conference)
- Next mission → 17-21 or 24-28 Nov 2014
- ....

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et al.,

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APPENDIX IX: Summary Training Nov-2014

WRAP-UP
Water Allocation Models
for the
Umbeluzi River Basin, Mozambique

Nov-2014
Peter Droogers
Froukje de Boer
Wilco Terink

ARA-Sul
Administração Regional de Águas do Sul
WETTERSKIP FRYSLÂN
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Decision Support Systems (DSS)

Strategic DSS

- What happens if….
- Investment decisions
- Impact and adaptation scenarios

Operational DSS

- What to do now
- Managerial decisions
- License scenarios

Same tool but different level of

- input data
- physical detail
- time steps

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Water Allocation Models

WAM-Strategic	WAM-Operational
Monthly time-step	Daily time-step
Entire Umbeluzi	Pequenos Libombos and downstream
Scenario based	Decision based
Setup for 1981-2010 (reference) and 2010-2100 (scenarios)	Setup for 2004-2013 (calibration/validation) and 3-6 months forecasts

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Decision Support Tools

RELEASES

SIGA/ operational manual

releases of BPL based on reservoir levels

(daily)

ALLOCATIONS

WAM-O

abstraction licenses/changes

impact on: reservoir levels

(1-5 years)

STRATEGIC

WAM-S

Climate Change
Water treaties
Reservoir expansion

impact on: water shortages

(5-50 years)

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FOLLOW UP ACTIONS

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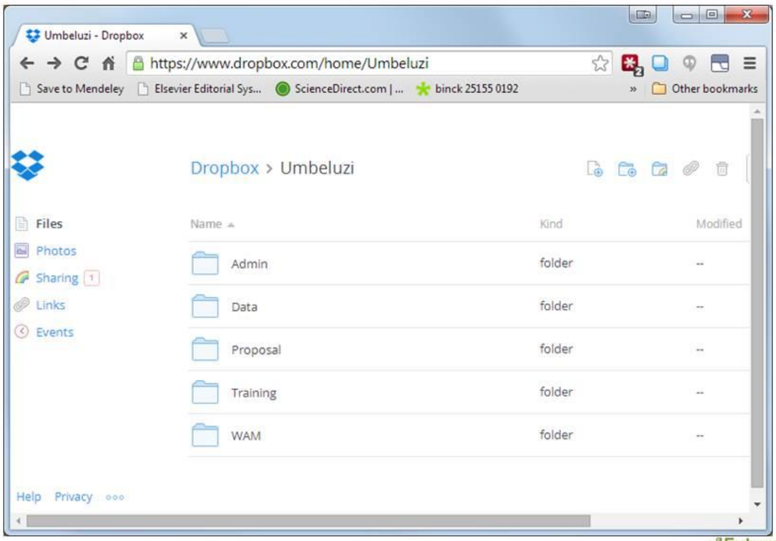
Project Website



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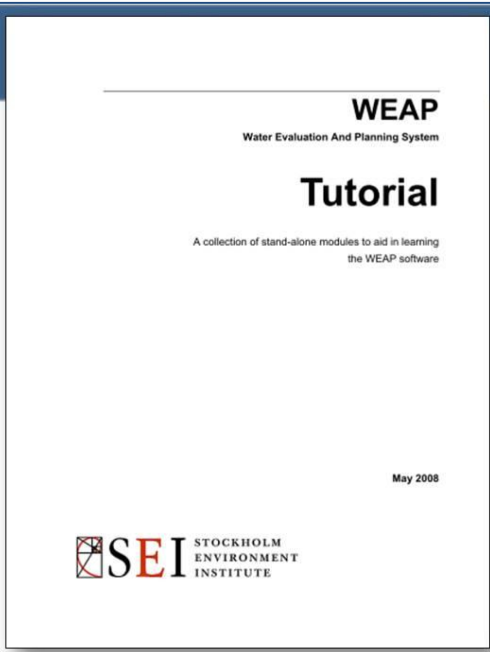

WEAP

Water Evaluation And Planning System

Tutorial

A collection of stand-alone modules to aid in learning
the WEAP software

May 2008

SEI STOCKHOLM ENVIRONMENT INSTITUTE

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Scenario Analysis

- Impact
  - Additional abstractions
  - Population
  - Climate Change
  - Upstream development
  - ....
- Adaptation
  - Reduce demands
    - less water to sectors
    - avoid losses
  - Increase productivity
    - cropping patterns
    - from agriculture to industry
  - Increase supply
    - groundwater
    - basin transfer
    - reservoirs

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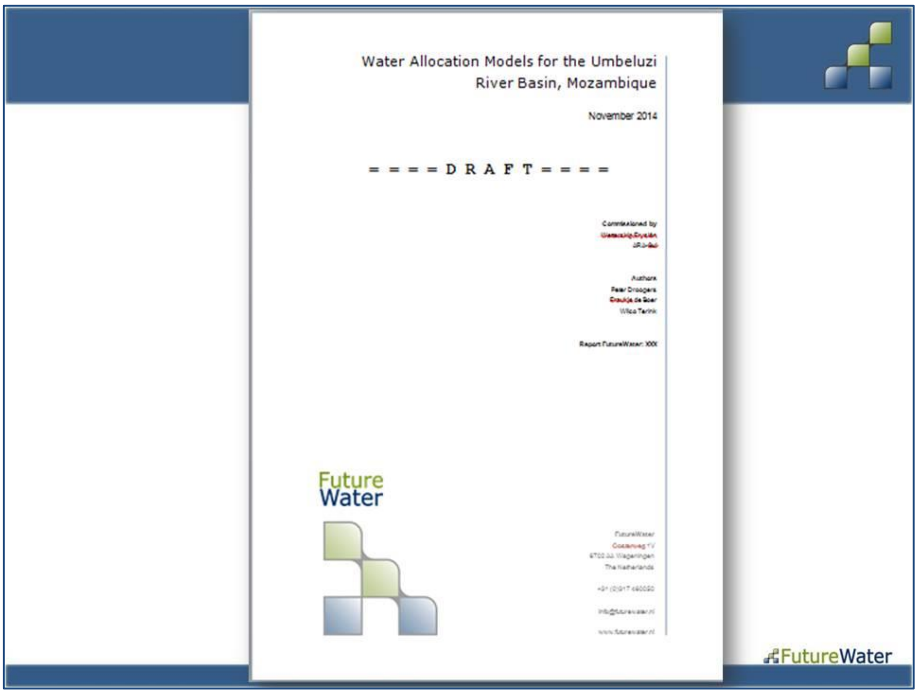
Idea	Impact	Adaptation
1 WAM-S	Population growth (urban)	Re-use of waste water
2 WAM-S	Expansion irrigated area Increase Industrial activity	
3 WAM-S	Development Swaziland	
4 WAM-S	Water quality (Swaziland)	Reservoir 760 MCM Movene Barragem de Moamba Major
5 WAM-O	Water quality (irrigation/industry)	
6 WAM-S	Climat Change	Prevent controlling slash&burn // Queimadas descontroladas Prediction of drought circumstances????
7 WAM-O / WAM-S	Les rainfall	Optimizing agricultural use
8 WAM-O / WAM-S		Reduce demands • Avoid losses, reduction of conveying losses • Tapwater (200-300MZ/month/household) (18-50MT/m3) • Delivery to domestic 0,454 MT/m3 • Delivery for agriculture 0,136/0,227 MT/m3 • Delivery for industry 0,227 MT/m3 • Less water to sectors
9 WAM-O / WAM-S		Increase productivity • Cropping patterns • From agr. To industry
10 WAM-O		Increase supply • Groundwater • Basin transfer • reservoir



SWOT analysis of project

- SAT and FAT of WAMs (S)
- Time for learning (W)
- WEAP as tool (S)
- Expansion to other basins (O)
- Number of staff trained (T)
- …

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