Water Allocation Models for the Incomati River Basin, Mozambique

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Contents

Tables

Figures

1 Introduction

1.1 ARA-Sul

The Administração Regional de Aguas (ARA) Sul is one of the five ARAs in Mozambique. ARA-Sul is the water agency responsible for the river basins in southern Mozambique, including the trans-boundary flood prone rivers Incomati, Limpopo and Maputo. ARA-Sul and Mozambican partners have started a process to improve the management of their water resources in relation to the current and future water demands.

To cope with the competing claims of the water resources of the Incomati impartial analyses tools are needed. To develop and implement accurate policies, a clear understanding of the behavior of river basins in relation to the variability of water availability is necessary. The policy information can be made available through a Water Allocation Model (WAM). The model should increase the understanding of the behavior of Incomati river basin under different circumstances that can be worked out in scenarios. Climate change and socio-economic developments are important components that will influence the future availability of water. For operational reasons ARA-Sul also needs the WAM for scenario's assessments and short term planning and licensing.

In 2015 two Water Allocation Models, a strategic and an operational one, for the Umbeluzi river basin have been developed using the WEAP framework. Also training has been provided to relevant staff members of ARA-Sul. Based on this project a similar approach for the Incomati Basin was followed.

The two WAMs described in this report will serve two purposes. First, the WAM-Strategic (WAM-S) 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. Secondly, WAM-Operational (WAM-O) was built to manage the Corumana reservoir on a daily and weekly base.

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

2 Incomati

2.1.1 Overview

The Incomati[1] River Basin is located in the eastern region of southern Africa and is shared by Swaziland, Mozambique, and South Africa. The catchment area is 46,800 km^{2}(2). In the north-east of South Africa its headwaters lie in the western Transvaal plateau area of Mpumalanga province at some 2000 m above sea level. The Komati River, as it is known in that region, then flows into northern-western Swaziland where it descends rapidly down from the Great Escarpment through to the middle-field (above 600 m.asl) and into the low-field and re-enters South-Africa in the south-east of Mpumalanga at Swaziland's northern border at some 200 m above sea level.

Figure 1. Overview of the Incomati Basin.
Source: http://www.ecologyandsociety.org/vol15/iss1/art1/

Thereafter the Komati is joined by a significant tributary, the Lomati at which point it is still known as the Komati and flows in a north-easterly direction. Adjacent to the town of Komatipoort the Komati is fed by a major tributary from the west, the Crocodile River, becoming the Inkomati before flowing across the Lebombo mountains and into Mozambique where it is joined by the Sabie River from the north and is thereafter known as the Incomati River. The Incomati River then follows a "horse-shoe" course across the coastal plain and flows into the Indian Ocean a short distance north of Maputo.

The Incomati also contains three significant ephemeral tributaries, i.e. the Massintonto and Uanetze that rise in the semi-arid plains of the Kruger National Park, and the Mazimechope, all of which join the main stem as the river flows through southern Mozambique. Respective catchment areas for the three countries within the Incomati are 61.4%, 33.2% and 5.4% for South Africa, Mozambique[3] and Swaziland.

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[1] Incomati is used for the entire river, while Inkomati refers to the South African part only.

[2] This is approximately 15 times the area of the province of Friesland.

[3] The Incomati catchment area within Mozambique is approximately 5 times the area of the province of Friesland.

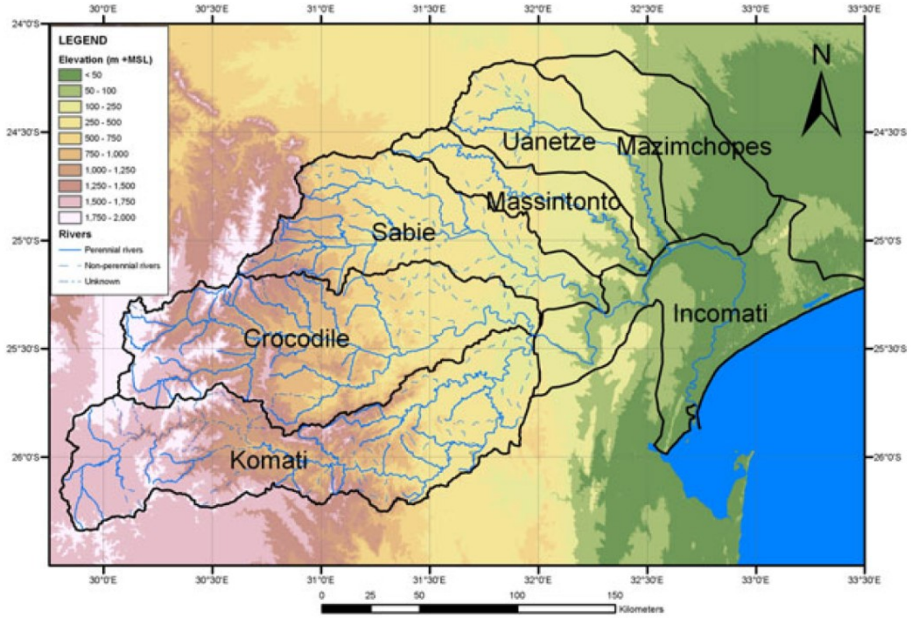

Figure 2. Subbasins in the Incomati River Basin.
Source: Hellegers, 2012. An interactive water indicator assessment tool to support land use planning.

2.1.2 Climate

The Incomati catchment is situated within the sub-tropics and lies within the summer rainfall region of southern Africa (October-March). The Incomati basin as a whole has an average rainfall of 740 mm/y and is characterized by rainfalls in the high altitude western region with a Mean Annual Precipitation between 800 and 1000 mm/y. Along the escarpment area this can reach up to 1400 and 1800 mm/y and then drops rapidly as one moves further east away from the escarpment down to as little as 300-400 mm on the western side of the Lebombo range. Tropical cyclones emanating from the Mozambique channel frequently cause flooding in the Incomati basin between January and March.

Catchment average potential evaporation is some 1900 mm/y and decreases from east to west, which results in an increase in the water deficit from west to east and consequent irrigation demand in that direction also.

2.1.3 Water Resources

The estimated total net runoff in the basin is 3587 MCM/y, of which 82% is generated in South Africa, 13% in Swaziland and 5% in Mozambique[4]. About 80% of all runoff in a hydrological year is generated during the months November–April. Variations of discharge from year to year are significant with floods and droughts occurring regularly. Economic developments resulting in increased water use in the basin have been tremendous since the 1970s. By the year 2002 total net consumptive water use was estimated at 1810 MCM/y. Water is used by forest plantations and for domestic and industrial use, while irrigation is the major water user (48% of total water use). Interbasin transfers amount to 10% of water use. From the late 1960s major dams have been commissioned that allowed increased water withdrawals at increasing levels of assurance.

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[4] For comparison: the total net runoff of the Province of Friesland in the Netherlands is 1200-1500 MCM/year.

All these developments have boosted the economies of the three riparian countries, but have also impacted on the environment. In the Tripartite Interim Agreement (TIA), the three riparian countries agreed to permit water withdrawals and use to increase to about 2340 MCM/y by the year 2010. This represents 65% of the Mean Annual Runoff (MAR) and will obviously further impact on the flow regime. The same agreement also made an allowance for environmental flows, in order to mitigate environmental degradation. Although environmental flows are considered in the agreement, the allowed increase in water withdrawal still raises many issues, one of which is what the downstream impacts may be, in particular on the estuary.

Table 1. Some key data according to http://www.thewaterpage.com/WWW-domino2.PDF.

Adm. origin of the area	area (km^2)(%),	population (%),	population density
Incomati Catchment (Mozambique)	14.900(32.3%)	258.122(11.2%)	17 p/km^2
Komati Catchment (Swaziland)	2.600(5.6%)	151 900(6.6%)	58.4 p/km^2
N'Komati catchment (South Africa[1])	28.700(62.1%)	1 884 520(82%)	65.6 p/km^2
Total Incomati Basin	46.200(100 %)	2.294.542 (100 %)	49.6 p/km^2

	Irrigated Area (ha)	MAR (*m^3/a),	pop,	wateravailability m^3p/a[2]
Incomati Catchment (Mozambique)	>20.000(17%)	630	258.122	2440
Komati Catchment (Swaziland)	14.060(12%)	509	151 900	3350
N'Komati catchment (South Africa[3])	83.382(71%)	2.943	1 884 520	1561
Total in Incomati Basin	117.442(100 %)	4.082	2.294.542	1779

2.1.4 Catchment Infrastructure

The Incomati basin has a large variety of water related infrastructure developments including over 90 dams with a supply capacity greater than 50,000 m^3. The main dams being: Maguga dam (in Swaziland), Driekoppies, Nooitgedacht, Vygeboom in the Komati sub-basin; Kwena dam in the Crocodile sub-basin; and Inyaka dam.

The most important reservoir is the Corumana Dam. It is an embankment dam (inclined core rock fill dam with a 45 m height and 3,050 m crest length) constructed between 1983 and 1989. The dam is located on the Sabie River immediately downstream of the border with the South Africa and approximately 90 km north-west of Mozambique‘s capital Maputo in the Moamba District of Maputo Province. The dam was not completed in 1989 due to lack of funding and the civil war. The dam was originally constructed for improving flood control, regulation for downstream irrigation abstractions and hydropower production.

It is planned to complete the dam and increasing the full supply level (FSL) of the reservoir from the current 111 meter above sea level (MASL) to 117 MASL, with a flood surcharge water level of approximately 120 MASL. Increasing the FSL of the reservoir‘s originally intended capacity will increase the dam‘s current storage from 720 MCM (million m^3) at present to an estimated 1,240 MCM

Completion of the Corumana Dam involves civil and hydromechanical works, consulting services for design and supervision and technical assistance. These activities will be completed by the Direcção Nacional de Águas, DNA (National Directorate of Water) who owns the dam through the Government Ministry of Public Works and Housing.The Administração Regional de Águas do Sul, ARA-Sul (Southern Regional Water Administration) manages and operates the dam.

Moreover, construction of a new reservoir, Moamba-Major, has been started in 2014. The project, which will be built on the Incomati River, will have the capacity to store 760 MCM of water, to be partly used for irrigation in the river valley of and produce 15 megawatts of electricity to add to the national energy grid. The Moamba-Major dam is also designed to help solve the drinking water deficit in Maputo, Matola, Boane and Marracuene as well as along the route of the main pipe. The cost of the work is estimated at US$466 million to be financed with a loan to Mozambique from Brazil.

3 Water Allocation Models Development

3.1 WEAP backgound

The WAM (Water Allocation Model) developed under this project are based on the WEAP framework. WEAP is selected as most suitable tool for this specific project for various reasons. 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 3). 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 in Mozambique revealed also that the WEAP model outperformed others (Juizo, 2008). The analysis compared the WRYM, WAFLEX and WEAP models. The WRYM model was considered to be very complex, has limited transparency, and far from user-friendly. The WAFLEX model is spreadsheet based and was originally built by Savenije in 1995. WAFLEX uses the same reservoir operational concepts as WEAP, but is lacking a user-friendly interface and GIS environment. Moreover, WAFLEX can become somewhat less transparent and error-prone since advanced macros should be introduced if the model has to be expanded or altered. Also, WAFLEX is focused towards reservoir operations and is therefore less suitable as a generic WAM. WEAP is also freely available for organization in developing countries.

Finally, using WEAP has the advantage that ARA-Sul is familiar with the model in previous projects including the Umbeluzi models. Moreover, WEAP has been applied for the Pungwe in ARA-Centro. Important is also that Nuffic has supported training in WEAP for the three Northern ARAs (Centro, Norte and Centro-Norte).

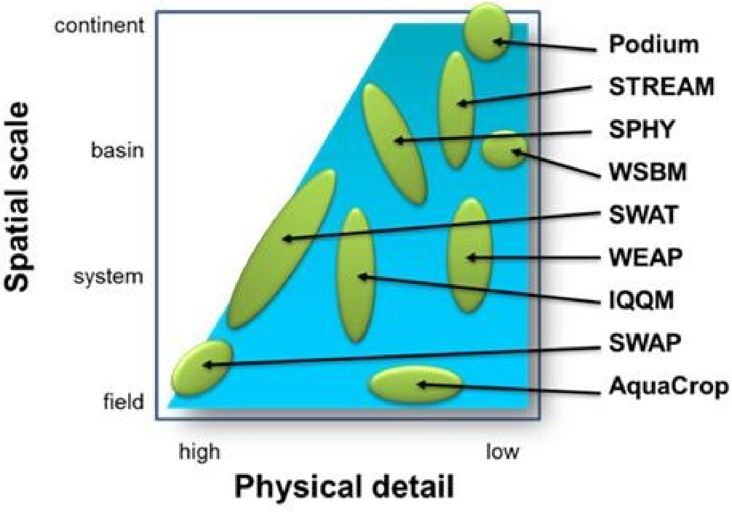

Figure 3: Relation between spatial scale and physical detail in water allocation tools. The green ellipses show the key strength of some well-known models. (Source: Droogers and Bouma, 2014)

A detailed discussion on WEAP can be found in the WEAP manual which can be freely downloaded from the WEAP website (http://www.weap21.org/). In summary WEAP out performs 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, SPHY, SWAP, Mike11, HEC-HMS, HEC-RAS and Geo-SFM.

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 Incomati basin
- Scenario based
- Setup for 1981-2010 (reference) and 2010-2050 (scenarios).

3.2.2 Data

3.2.2.1 Schematization

A well-accepted schematization in terms of catchment areas does not exist. Some previous studies use seven catchments as shown in Figure 2. However, the diversity within these seven catchments is quite large and therefore a more refined schematization is needed. Based on the HydroSHEDS DEM subcatchments can be created using QGIS. The procedure used is:

> Processing Toolbox > GRASS > Raster > r.watershed

By setting the “minimum size of exterior watershed basin” different levels of details can be created. For a value of 10,000 cells a total of 11 watersheds is defined. Using a value of 5,000 cells the number of watersheds defined becomes 25. To ensure that country borders are followed as well, these were included in the catchment delineation process. Also some smaller watersheds were combined with neighboring bigger ones.

The final number of catchments considered in WAM-S is 24. These are shown in Figure 5; the representation in WEAP is shown in Figure 6.

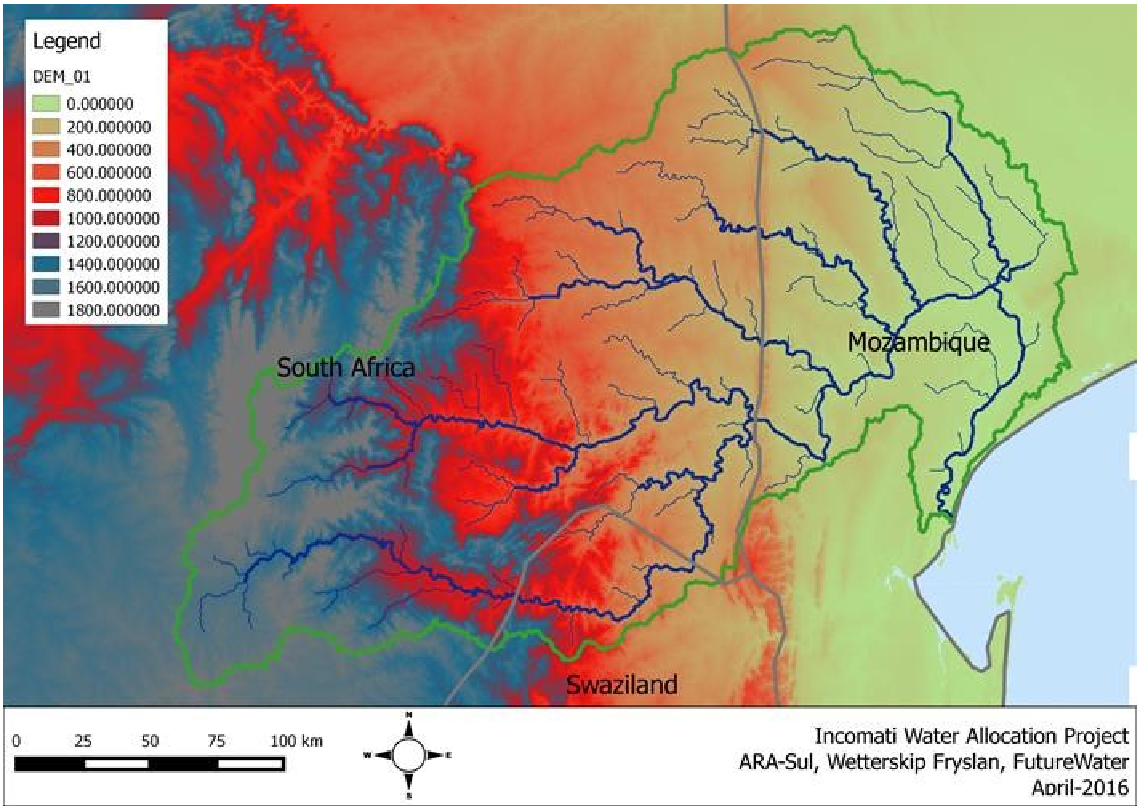

Figure 4: Elevation (in meters) based on HydroSHEDS

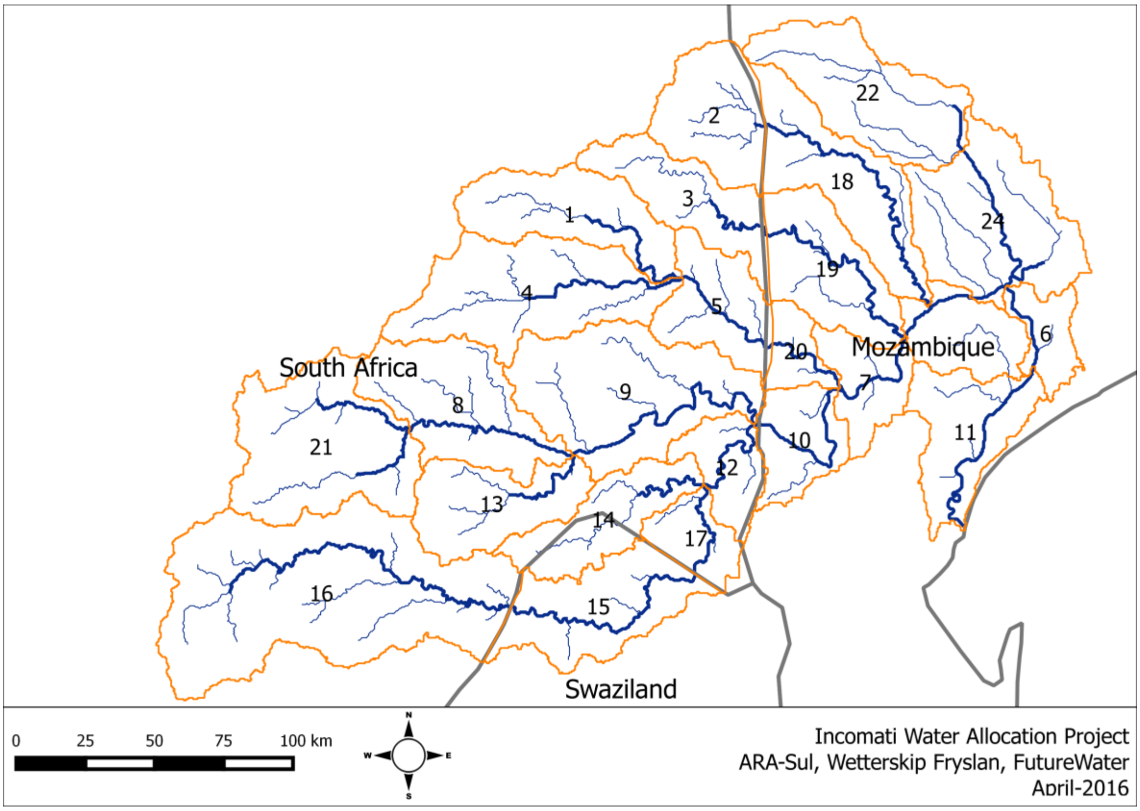

Figure 5: Watersheds delineation based on DEM and country borders.

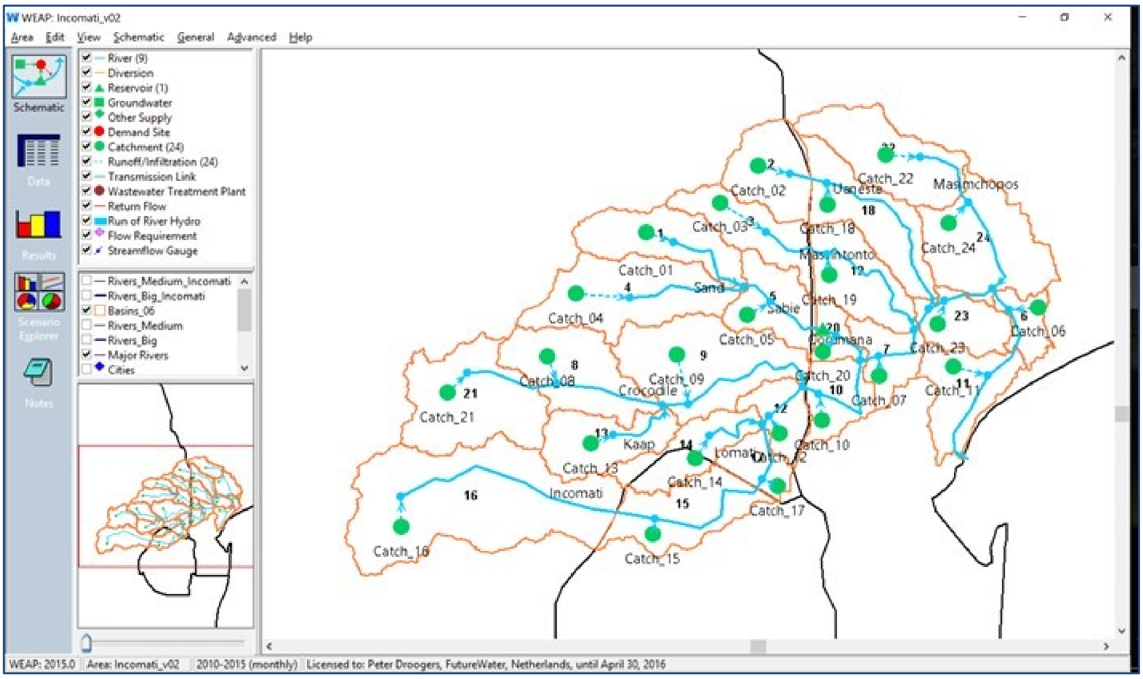

Figure 6: Schematization of Catchments in WAM-S as implemented in WEAP.

The schematization for the Incomati as implemented in WEAP has the following characteristics:

- Number of Catchments: 24

Catchments are characterized by the following properties (see APPENDIX I: WEAP Land Use Parameters for detailed explanation):

- Area
    - Derived from GIS analysis
- Kc
    - A fixed value of 1.0 is used. Can be updated for each individual catchment if detailed information is available.
- Soil Water Capacity
    - Value of 400 mm is used[5]. Is adjusted by the calibration process.
- Deep Water Capacity
    - Value of 500 mm is used. Can be updated if better soils data are available, although this parameter has limited influence on model performance.
- Runoff Resistance Factor:
    - Value of 5 (no unit) is used. Can be updated if better soils data are available.
- Root Zone Conductivity
    - Value of 25 mm per month is used. Is adjusted by the calibration process.
- Deep Conductivity
    - Value of 50 mm per month is used. Can be updated if better soils data are available, although this parameter has limited influence on model performance.
- Preferred Flow Direction
    - Value of 0.15 is used.
- Initial Z1 and Z2
    - Set to 30%. Is less sensitive as 10 years of initialization has been used.

3.2.2.2 Reservoirs

Reservoirs having a storage capacity higher than 100 MCM have been included in the model. Reservoirs smaller than this capacity are captured by Catchment and Demand Nodes of WEAP. In other words, storage capacity of these smaller reservoirs is mimicked by the storage capacity of the soil, and the abstraction out of these reservoirs is realized by the three demands (domestic, irrigation, industry).

The following reservoirs have been included (Source Incomti Basin, UNESCO[6]):

Dam	Country	Tributary	Year	Capacity (MCM)	Dam height (m)
Maguga	Swaziland	Komati	2002	332	115
Driekoppies	South Africa	Lomati	1998	251	50
Kwena	South Africa	Crocodile	1984	155	52
Injaka	South Africa	Sabie	2001	120	53
Corumana	Mozambique	Sabie	1988	879	110

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[5] Water holding capacity of a soil can be given in two ways: (i) mm water per m of soil depth, or (ii) total mm of water available for plants. In WEAP the soil depth is not explicitly given and therefore the Soil Water Capacity (in mm) represents total water holding capacity.

[6] http://webworld.unesco.org/water/wwap/pccp/zaragoza/basins/incomati/incomati.pdf

3.2.2.3 Domestic water demands

Population living in the area is derived from www.worldpop.org (Figure 7). This dataset is the most up-to-date global population product. It provides estimates of numbers of people residing in each 100x100m grid cell for every low and middle income country. Through integrating census, survey, satellite and GIS datasets in a flexible machine-learning framework, high resolution maps of population counts and densities for 2000-2020 are produced, along with accompanying metadata. For WAM-S we used the data for the year 2010.

Population data was summarized by the 24 Catchments Figure 8. Water use rate is defined as 125 liter per person per day, and actual consumption set as 70%.

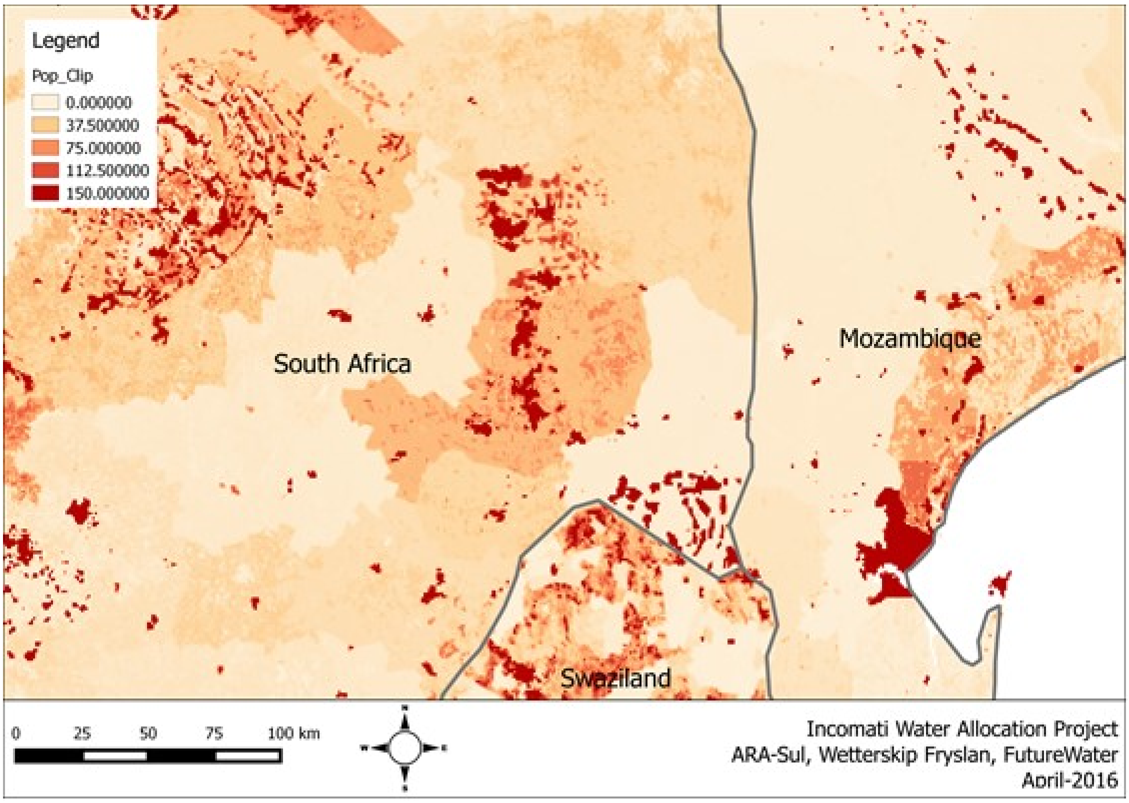
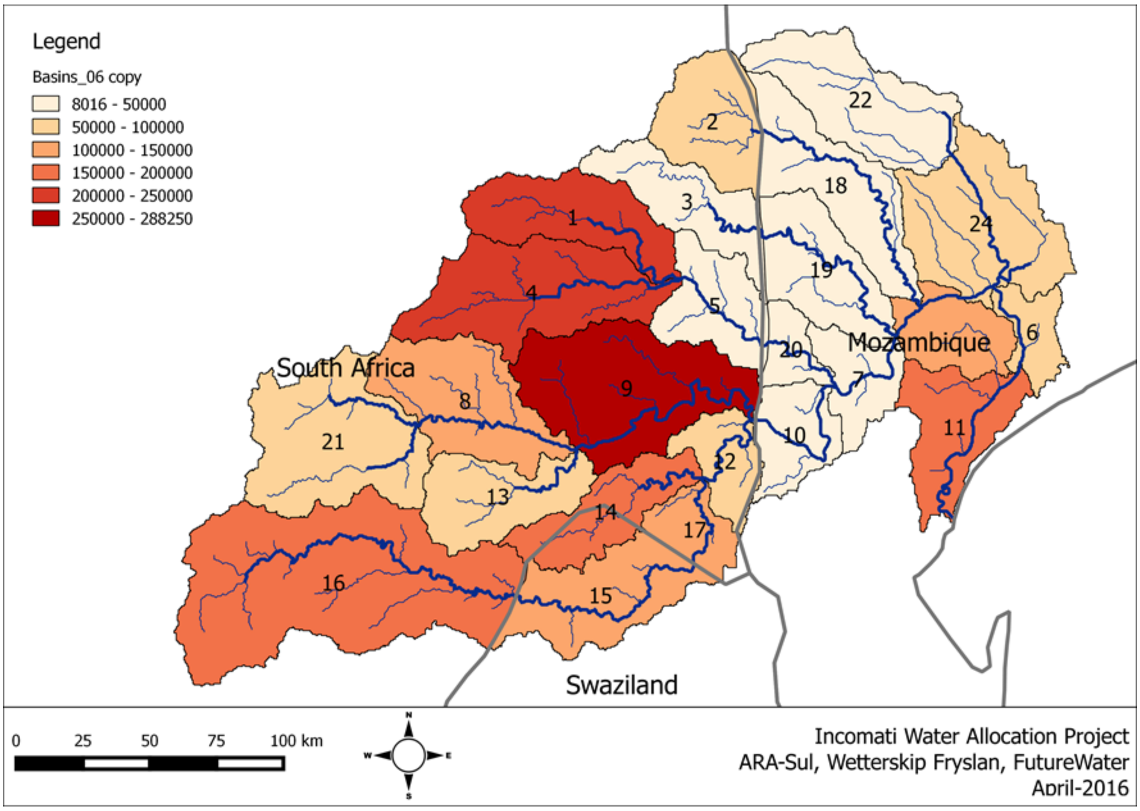


Figure 7: Population density in cap / km^2 (Source: www.worldpop.org.uk).



Incomati Water Allocation Project
ARA-Sul, Wetterskip Fryslan, FutureWater
April-2016

Figure 8: Total population for each of the 24 sub-basins.

3.2.2.4 Irrigation water demands

To ensure that formal and informal irrigation water demands are captured irrigated areas have been derived from the population. A non-linear relationship between population and irrigated area has been used to ensure that more rural areas will have higher irrigated areas compared to urban areas (Figure 9):

Irrigation (ha) = (population / 5) ^ 0.86

The water use rate was defined as 10,000 m^3 per irrigated hectare per year (=1000 mm per year), and return flows as 30% (consumption 70%).

3.2.2.5 Industrial water demands

No detailed information on industrial water demands was available. Therefore, a non-linear relationship between population and industrial units has been used to ensure that more rural areas will have relatively lower industrial water demands compared to urban areas (Figure 9).

Industrial Units = (population / 1000) ^ 1.6

Water use rate was defined as 10 m^3 per industrial unit per day and return flows as 30% (consumption 70%).

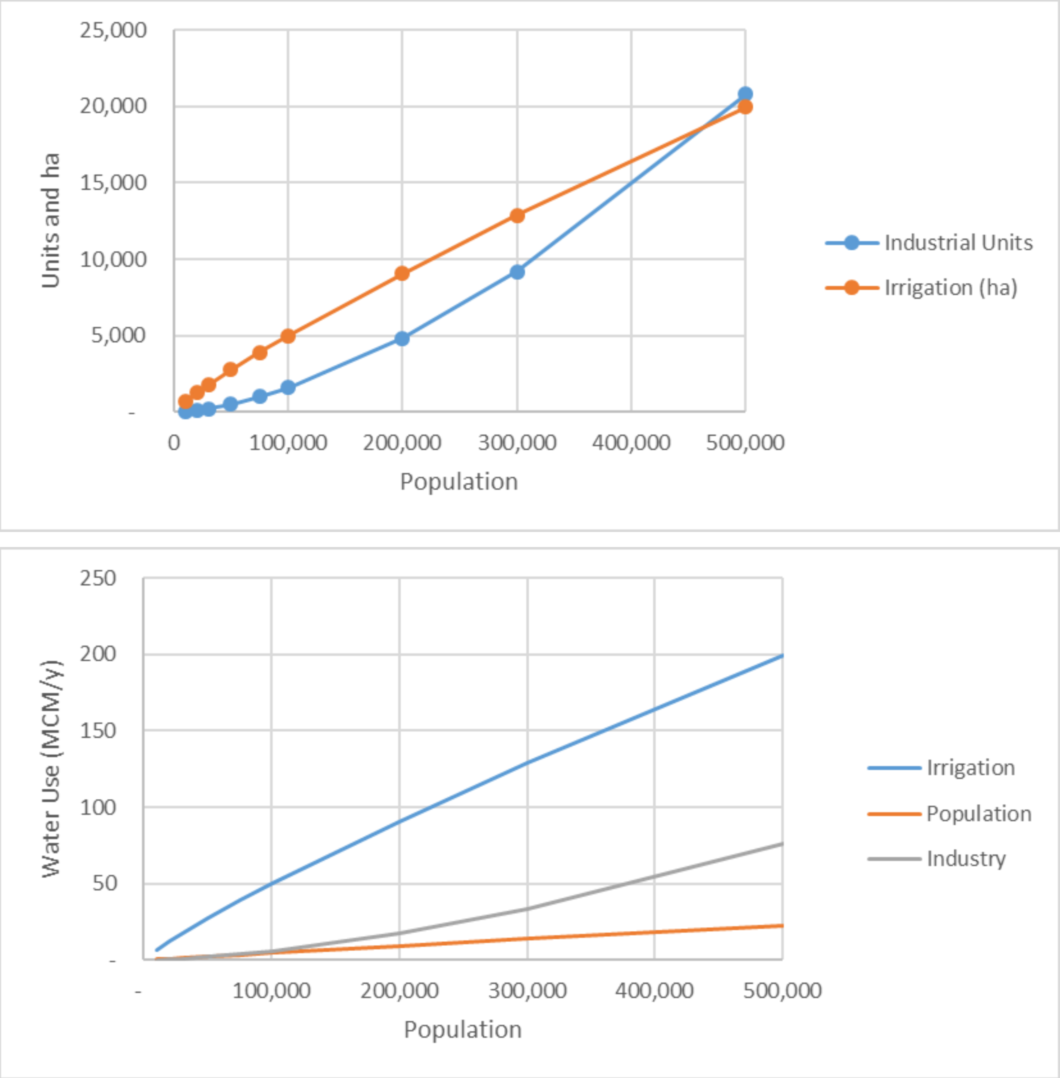


Figure 9. Relationship between population per catchment and industrial units and irrigation area (top) and resulting water demand (bottom).

3.2.2.6 Precipitation and temperature

Precipitation originated from the CHIRPS dataset.

Some other less relevant climate data were set at fixed values, but can be adjusted if better data might become available:

- Humidity: 60%
- Wind: 2 m/s
- Cloudiness: 0.75
- Latitude: -26 (decimal degrees south of the equator)

3.2.2.7 Water quality

A first order water quality analysis has been included in the model using the Total Dissolved Solids (TDS) as quantity. TDS is a measure of the combined content of all inorganic and organic substances contained in suspended form. The principal application of TDS is in the study of water quality for streams, rivers and lakes and represents an aggregate indicator of the presence of a broad array of chemical contaminants.

The unit of TDS can be expressed and measured as gravimetric values (mg/liter) or as electrical conductivity (mS/cm). The relationship between these two is can be approximated by the following equation:

$$TDS = k_e \times EC$$

where TDS is expressed in mg/L and EC is the electrical conductivity in microsiemens per centimeter at 25 °C. The correlation factor k_e varies between 0.55 and 0.8 depending on the composition of the dissolved material. In general a value of 0.64 can be used.

Specific data on point and nonpoint source solution over the entire Incomati Basin is lacking. It was therefore decided to use some standard values as defined by the Inkomati River Basin Plan (all numbers related to TDS):.

- Typical composition of untreated domestic sewage:
  - 200 mg/L (weak), 500 mg/L (medium), 1000 mg/L (strong)
- Typical loading of 250 g/d/cap[7]. Most is from wash-water and about 25% from sanitation.
- Drinking water rating:
  - United States water quality standard of 500 mg/l
  - DWAF[8]: 1000 mg/l
- Irrigation water quality standards:
  - < 450 mg/L no restriction to use
  - > 2000 mg/L severe restrictions to use

Based on these data the following data have been used in WAM-S:

- Domestic TDS loading: 100 g/d/cap
- Industrial TDS loading: 2000 g/d/unit
- Irrigation TDS loading: 1000 g/d/ha
- Catchments TDS loading: 20,000 kg/y/ha

The source of the domestic TDS is untreated domestic sewage. The source of industrial TDS is the effluent of water used for processing and cooling. For irrigation the source of TDS is fertilizer and herbicides in the return flows and for the Catchments the TDS source is soil particles due to erosion.

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[9]:
  - $R^2 >= 0.8$
  - Bias < 10%

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[7] http://www.eolss.net/eolsssamplechapters/c06/e6-13-04-05/e6-13-04-05-txt-04.aspx

[8] Department of Water Affairs and Forestry, South Africa

[9] The criteria for R^2 and bias are the same as for the Umbeluzi models.

3.2.3.1 Number of nodes

The number of realized nodes for WAM-S is in accordance to the number as agreed in the proposal. (Table 2). For most node types the actual number is higher compared to the agreed ones, indicating a more inclusive model has been delivered. The only exception is that the number of flow requirement is one less compared to the agreed once. Reasoning is that the number of demand nodes is much higher so less need for additional flow requirement nodes.

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

Node Type	Agreed	Realized
Demand Nodes	10	24
Catchment Nodes	20	24
River Nodes	3	9
Flow Requirements Nodes	2	1
Reservoirs	5	5

3.2.3.2 Schematic Setup

The schematic setup was discussed and approved during the meeting in Wageningen with the project leader from ARA-Sul on March 24th, 2016.

3.2.3.3 Observed versus Simulated flows

For 13 locations flow data were available that could be used for the FAT (Table 3 and Figure 10). Based on this table, it was decided to use the following measurements for the Factory Acceptance Test:

- (i) Flow Crocodile and Incomati entering Mozambique
- (ii) Inflow in Corumana Reservoir
- (iii) Flow at Xinavane

Table 3. Flow gauging stations.

Station	Average (m3/s)	Average (MCM/y)	Min (m3/s)	Max (m3/s)	Available (%)
E-0022H	33	1,044	0	564	78
E-0023H	51	1,617	0	1,821	91
E-0024H	26	813	0	741	76
E-0025H	N/A	N/A	0	0	0
E-0026H	36	1,125	0	550	37
E-0027H	39	1,241	0	584	42
E-0029H	0	4	0	1	27
E-0030H	11	333	0	109	25
E-0043H	63	1,973	0	1,193	95
E-0044H	91	2,867	3	1,144	79
E-0176H	0	6	0	6	13
E-0396H	2	65	2	2	0
Inflow Corumana	25	796	1	725	100

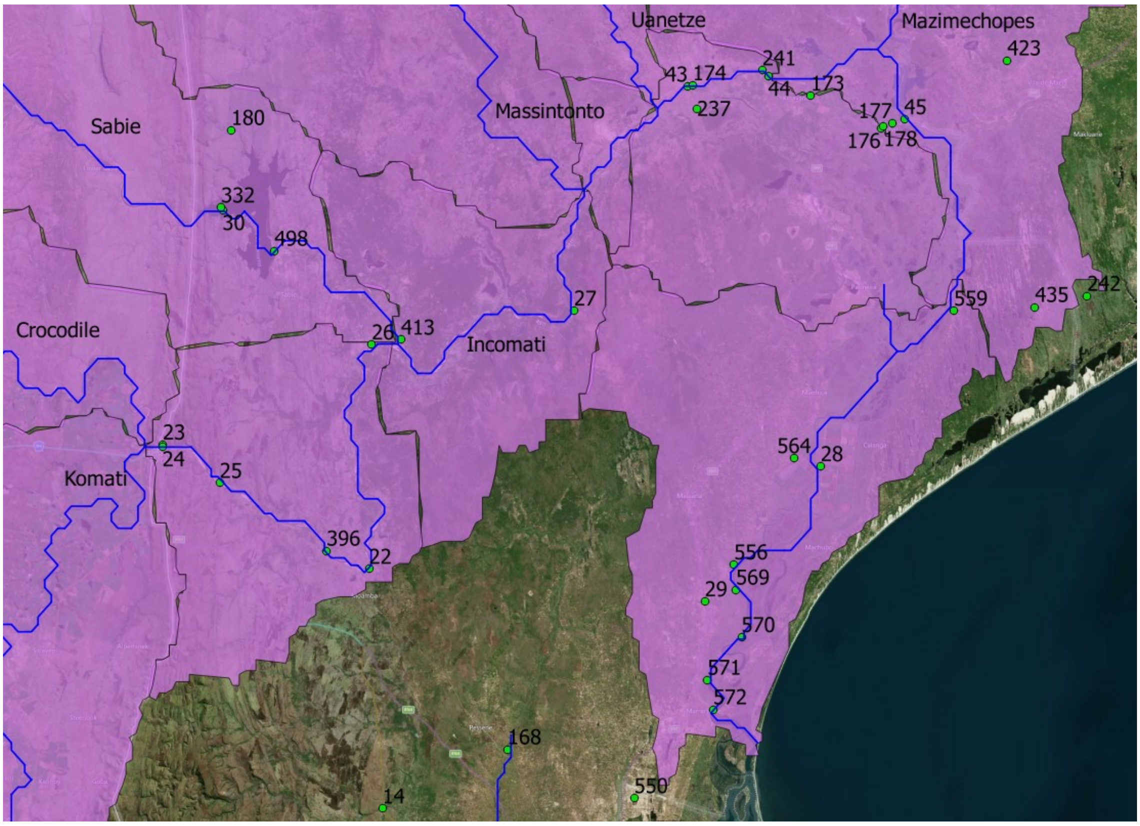

Figure 10. Flow gauging stations in Mozambique.

(i) Inflow Crocodile and Incomati entering Mozambique

For the combined inflow of Crocodile and Incomati entering Mozambique, the following stations are available (in downstream direction): 23, 24, 25 and 22. For the period 1981-2010 the following monthly data are available for these stations (for station 25 no records were found):

	E-0022H	E-0023H	E-0024H
Average (m3/s)	33	51	26
Average (MCM/m)	87	135	68
Max (m3/s)	564	1821	741
Min (m3/s)	0	0	0
Availability (%)	79	92	77

Station 23 and 24 are very near to each other, while station 22 is about 35 km downstream of the other two. Although station 23 and 24 and close to each other, recorded streamflows are quite different; also the streamflow of station 22 is quite different. Main reasons are difficulty in getting correct rating curves and irregularity in number of observations and missing observations.

Results of the comparison between observed and simulated flows are shown in Figure 11 and Table 4[10]. From Figure 11 it can be seen that during most years with high observed annual flow (except 2006) WAM-S is underestimating the annual flow. For most years with a low observed annual flow WAM-S gives an overestimation of the annual flow. Overall the bias of the simulated flow is low (< 4%), which means that the simulated flows are not structurally higher or structurally lower than the observed flows. Furthermore, the R^2 is high (≥ 0.8), which means that

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[10] In APPENDIX IV: Glossary, the calculation procedures for the Bias and R^2 are given.

the difference between the simulated flows and the observed flows is small. Therefore, it can be concluded that the FAT can be considered as passed.

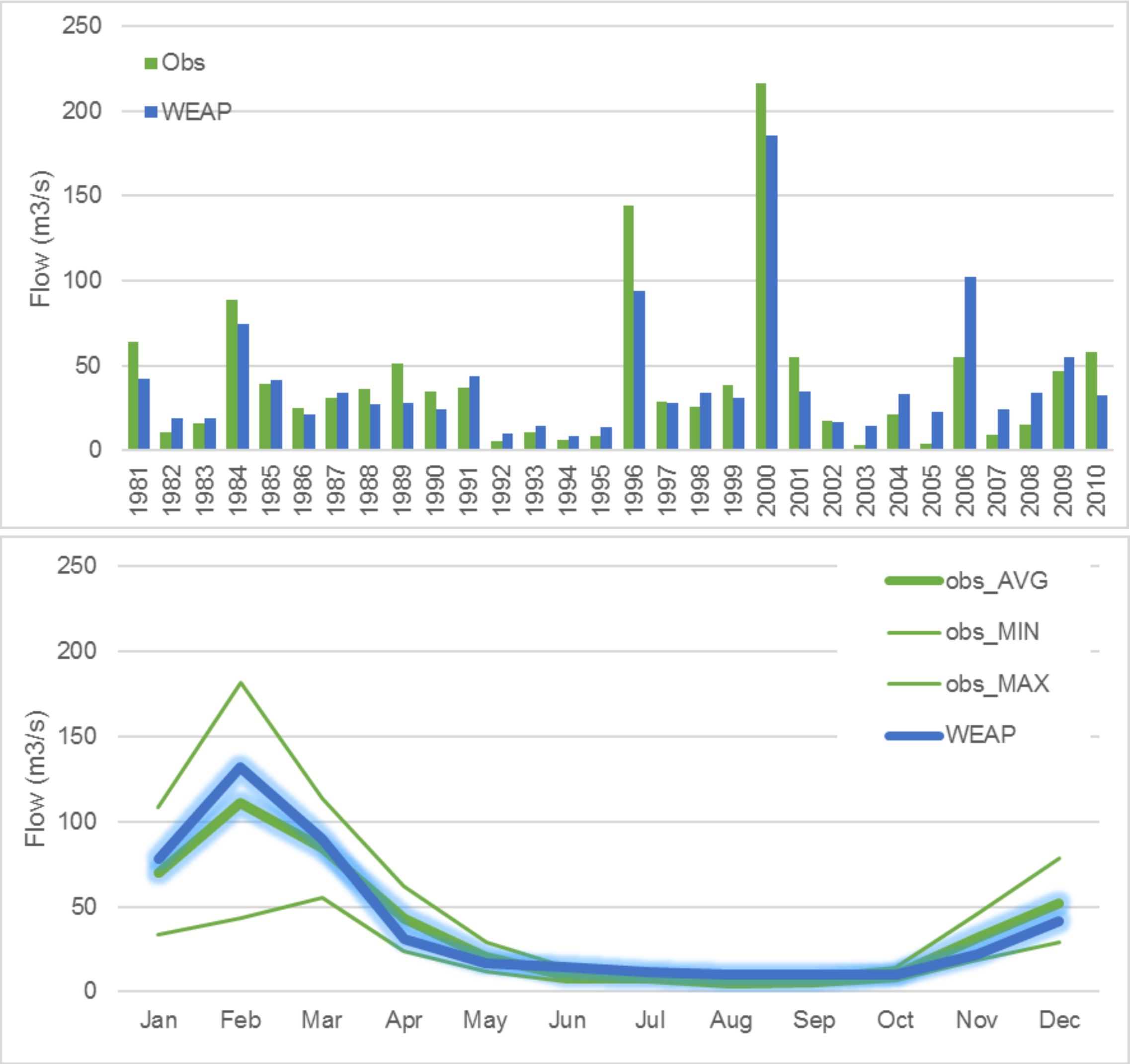

Figure 11. Observed and simulated flow for the Incomati entering Mozambique.

Table 4. Factory Acceptance Test (FAT) for the flow at the Incomati entering Mozambique (1981-2010).

	Average (m3/s)	Bias (%)	R^2	Pearson R
Individual months				
Observed	38.2			
Simulated	38.8	1.7	0.77	0.88
Annual				
Observed	40.1			
Simulated	38.8	-3.1	0.84	0.92
Average monthly				
Observed	37.8			
Simulated	38.8	2.7	0.96	0.98

Note: differences in observed average flows is caused by missing values.

(ii) Inflow in Corumana Reservoir

For the observed flow into the Corumana reservoir the inflow data from the water balance of the reservoir was used. Since the inflow into the reservoir is not measured but is calculated from the water balance, it can become less than zero. When this was the case, the measured streamflows from the gauging station X3H015 at Lower Sabie (in South Africa) were used.

Results of the comparison between observed and simulated flows are shown in Figure 12 and Table 5. From Figure 12 it can be seen that during most years with high observed annual inflow WAM-S is underestimating the annual flow. For years with a low observed annual flow WAM-S gives an overestimation of the annual flow. Overall the bias of the simulated flow is low (< 4%), and the R^2 is high (≥ 0.8). Therefore, it can be concluded that the FAT has passed.

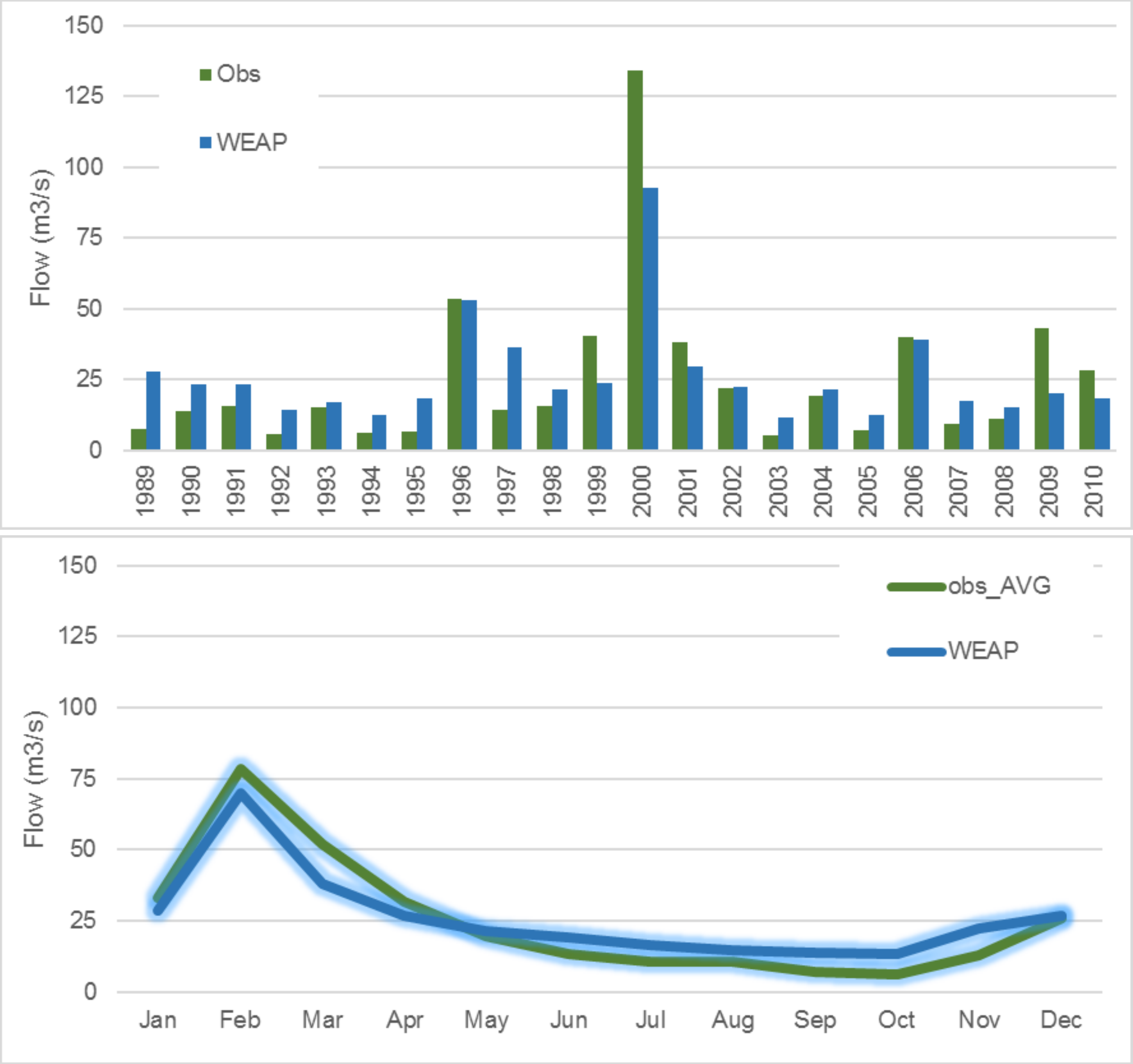

Figure 12. Observed and simulated flow for the inflow into Corumana.

Table 5. Factory Acceptance Test (FAT) for the inflow at Corumana (1989-2010).

	Average (m3/s)	Bias (%)	R2	Pearson R
Individual months				
Observed	25.2			
Simulated	26.0	3.1	0.85	0.92
Annual				
Observed	25.2			
Simulated	26.0	3.1	0.83	0.91
Average monthly				
Observed	25.2			
Simulated	26.0	3.1	0.95	0.97

(iii) Flow at Xinavane

For the flow at Xinavane, the following two stations are available: 43 (near Magude) and 44 (near Xinavane; Figure 13). Although these station are near to each other recorded streamflows is for some of the overlapping periods quite different. It was therefore decided to use the average values during overlapping data, and otherwise use the station for which data are available. Main reasons are difficulty in getting correct rating curves and irregularity in number of observations and missing observations.

Resulting comparison between observed and simulated flows are shown in Figure 14 and Table 6. From Figure 14 it can be seen that for most years WAM-S is underestimating the annual flow. However, for the flood year 2000 and for the years with the lowest observed annual flows WAM-S gives an overestimation of the annual flow. Overall the bias of the simulated flow is low (< 10%), and the R^2 is high (≥ 0.8), except for the comparison of the individual months ($R^2 \approx 0.6$). Conclusion is that the FAT has passed.

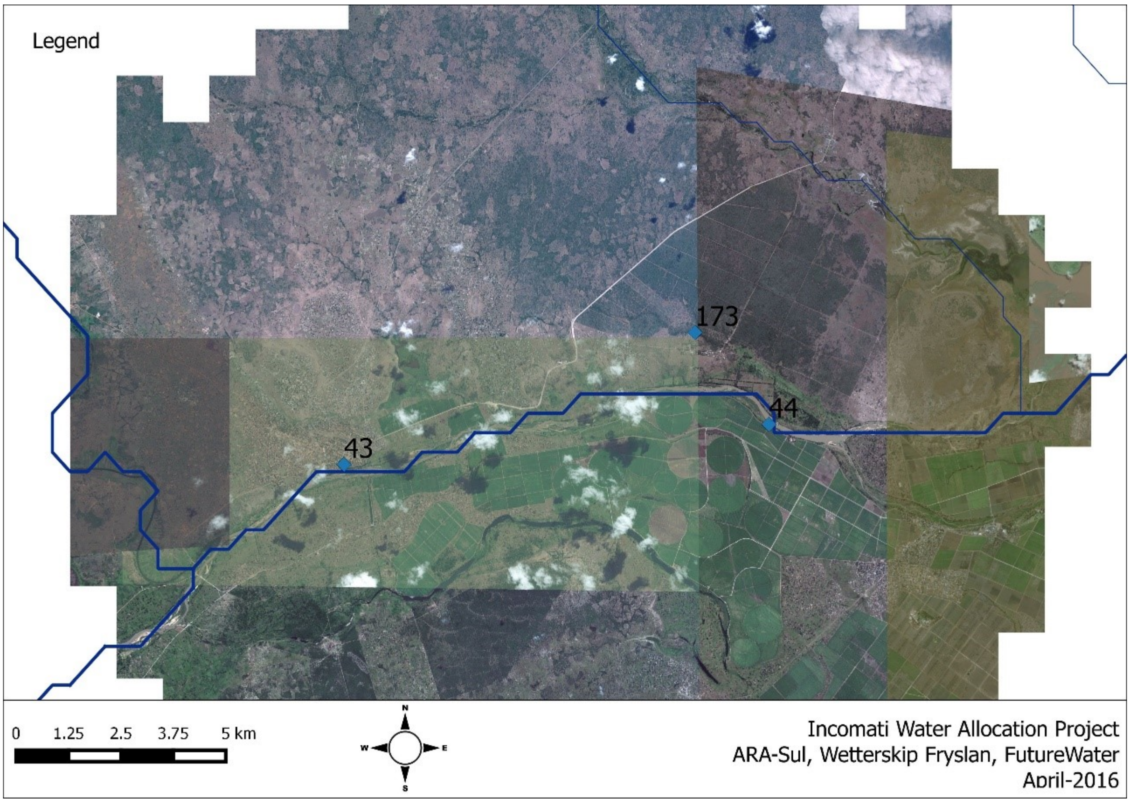

Figure 13. Location of streamflow gauging stations 43 and 44.

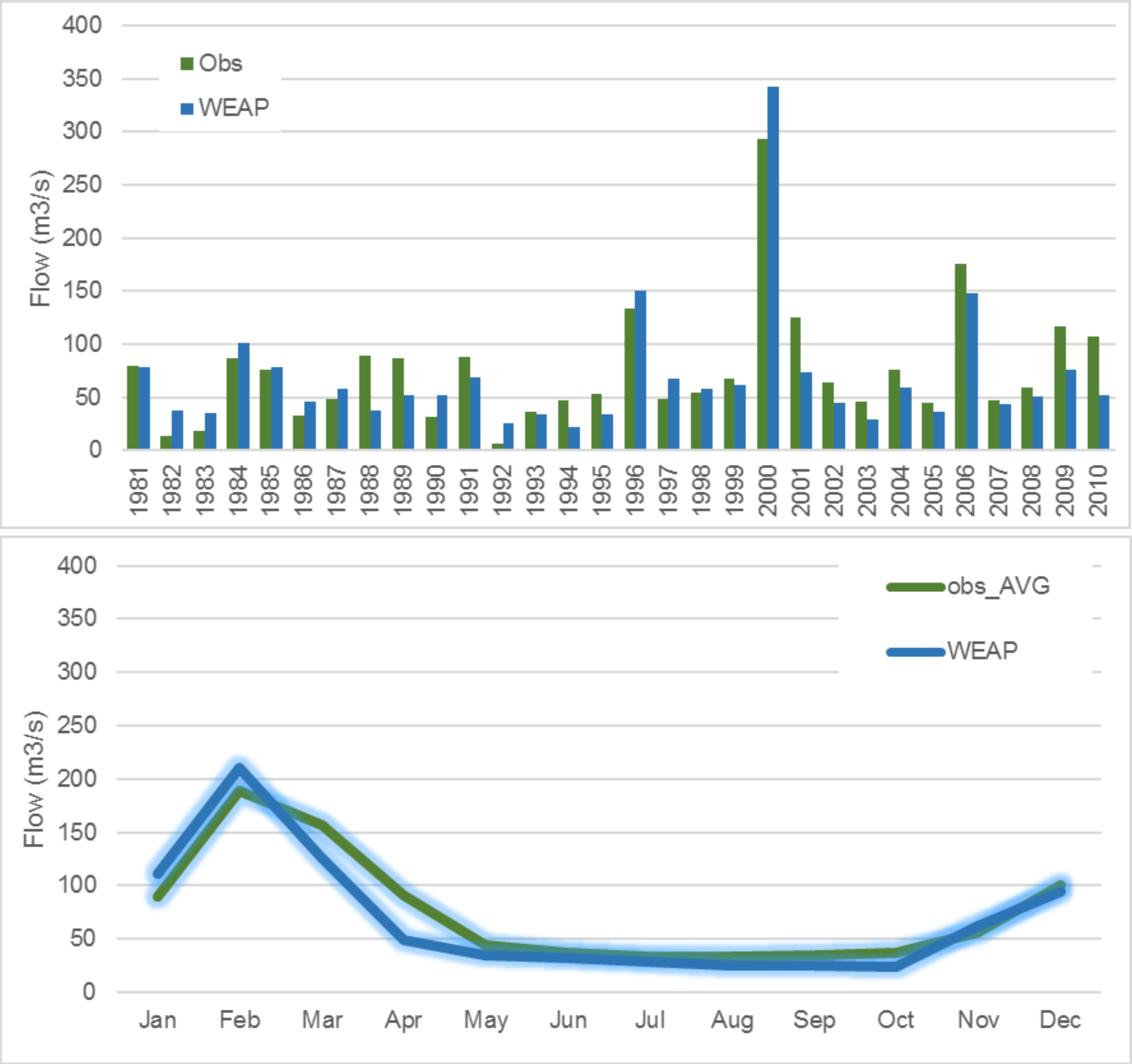

Figure 14. Observed and simulated flow for the flow at Magude.

Table 6. Factory Acceptance Test (FAT) for the flow at Magude (1981-2010).

	Average (m3/s)	Bias (%)	R^2	Pearson R
Individual months				
Observed	75.2			
Simulated	68.4	-9.0	0.57	0.75
Annual				
Observed	75.2			
Simulated	68.4	-9.0	0.82	0.91
Average monthly				
Observed	75.2			
Simulated	68.4	-9.0	0.90	0.95

3.2.4 Site Acceptance Test

A Site Acceptance Test was described in the project proposal document and consists out of the following five 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 12 scenarios have been explored using WAM-S
- At least 8 scenarios have been explored using WAM-S

The result of the SAT is further described under WAM-O.

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 15 and Figure 16):

- Total available water is equal to total rainfall and is 36,141 million m^3/year
- Most water is consumed by vegetation (=evapotranspiration) and is 32,813 million m^3/year (~90% of rainfall)
- Consumption by irrigation, domestic use and industry is 947 million m^3/year
- Average annual outflow is 2,289 million m^3/year (~73 m^3/s), and varies substantial per year and per month.

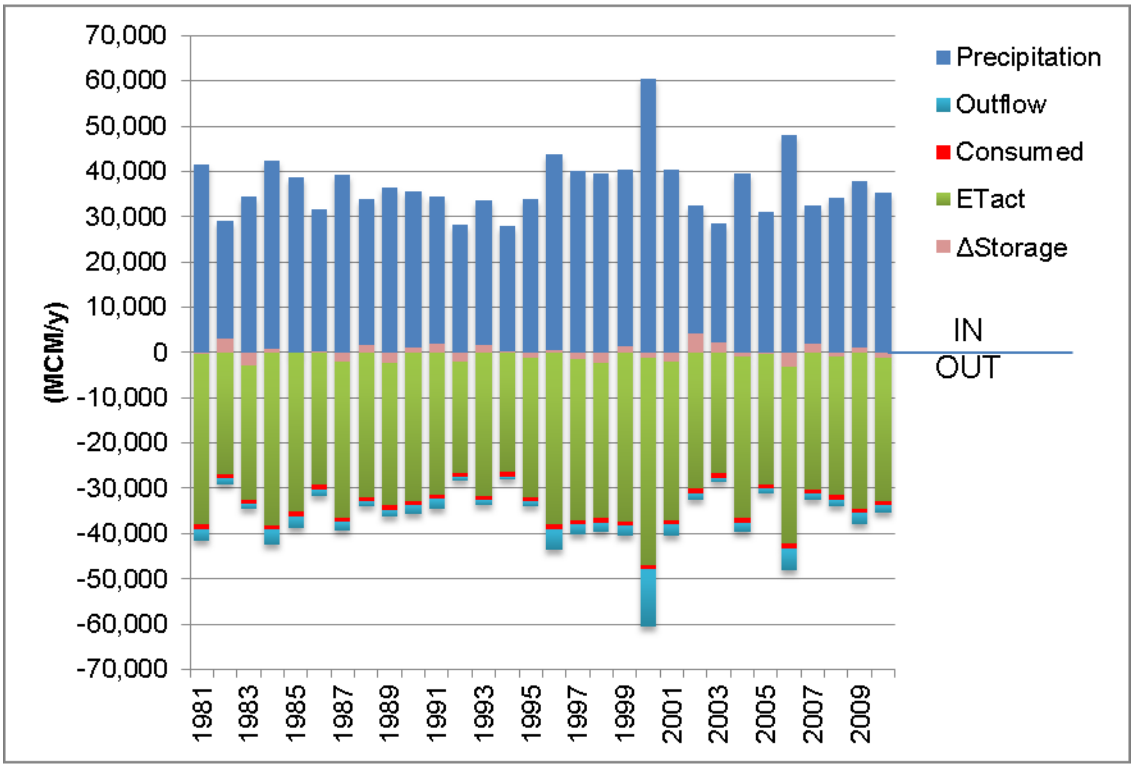

Figure 15. Annual water balance for the entire Incomati Basin.

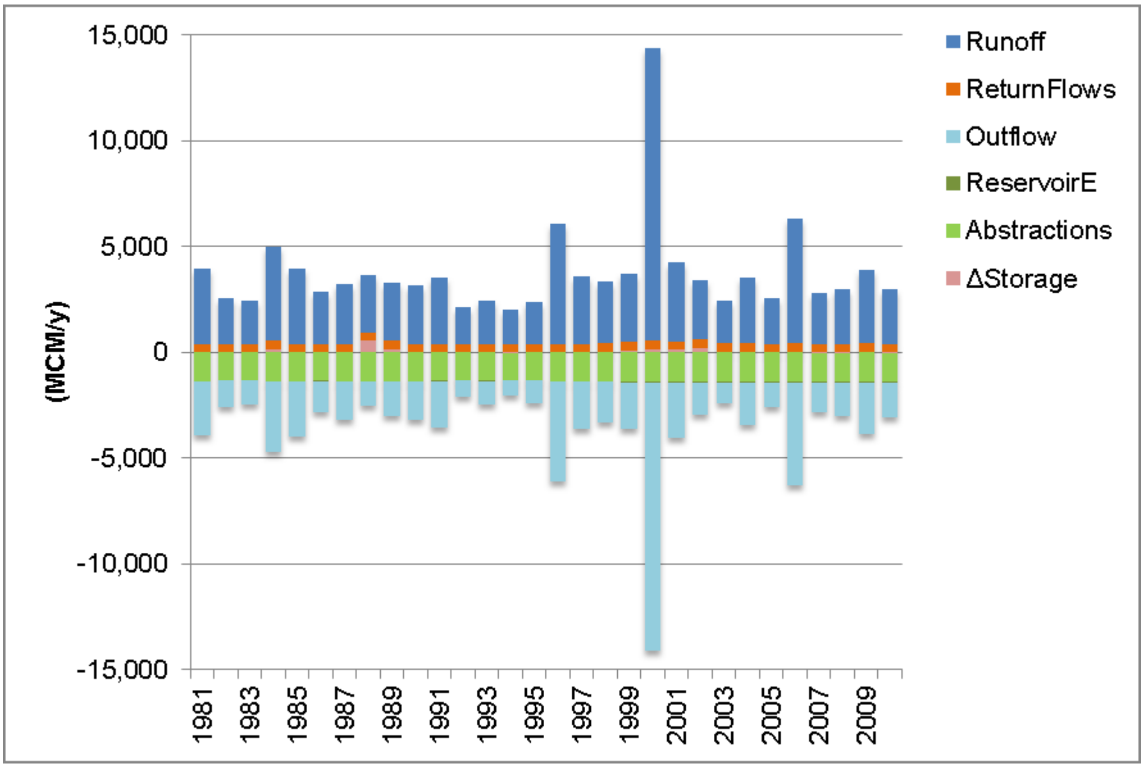

Figure 16. Annual water balance for the entire Incomati Basin, showing only water in the river (Runoff, Return Flows) and abstractions from the river (Outflow, Abstractions) and reservoirs (ReservoirE, Δ Storage).

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 Corumana reservoir and other water users.

The main characteristics of WAM-O are:

- Daily time-step
- Corumana reservoir and downstream area
- Decision based
- Setup for 2005-2014 (calibration/validation) and 1-24 months forecasts

3.3.2 Data

3.3.2.1 Schematization

For WAM-O only the part of the Incomati River that flows in Mozambique is schematized. The most upstream point is at Ressano Garcia, which is the border between South Africa and Mozambique. Here the headflow of the Incomati is represented by measurements of gauging station X2H036 (see Figure 17), which is located in South Africa just upstream of the border. The Sabie River is schematized from the point where it flows into the Corumana reservoir. The

headflow of the Sabie is represented by the inflow into the reservoir as calculated from the water balance of the reservoir. Since the inflow into the reservoir is calculated from the water balance, it can become less than zero. When this was the case, the measured streamflows from the gauging station X3H015 at Lower Sabie (in South Africa, see Figure 17) were used.
The Massintonto, Uanetze and Mazimechopes catchments are schematized from their most upstream points. The schematization of WAM-O is shown in Figure 18. In the upper panel the schematization of the total area included in WAM-O is shown. For better visibility the demand sites are not shown. In the lower panel the detailed schematization of the Incomati and Sabie River in WAM-O is shown.

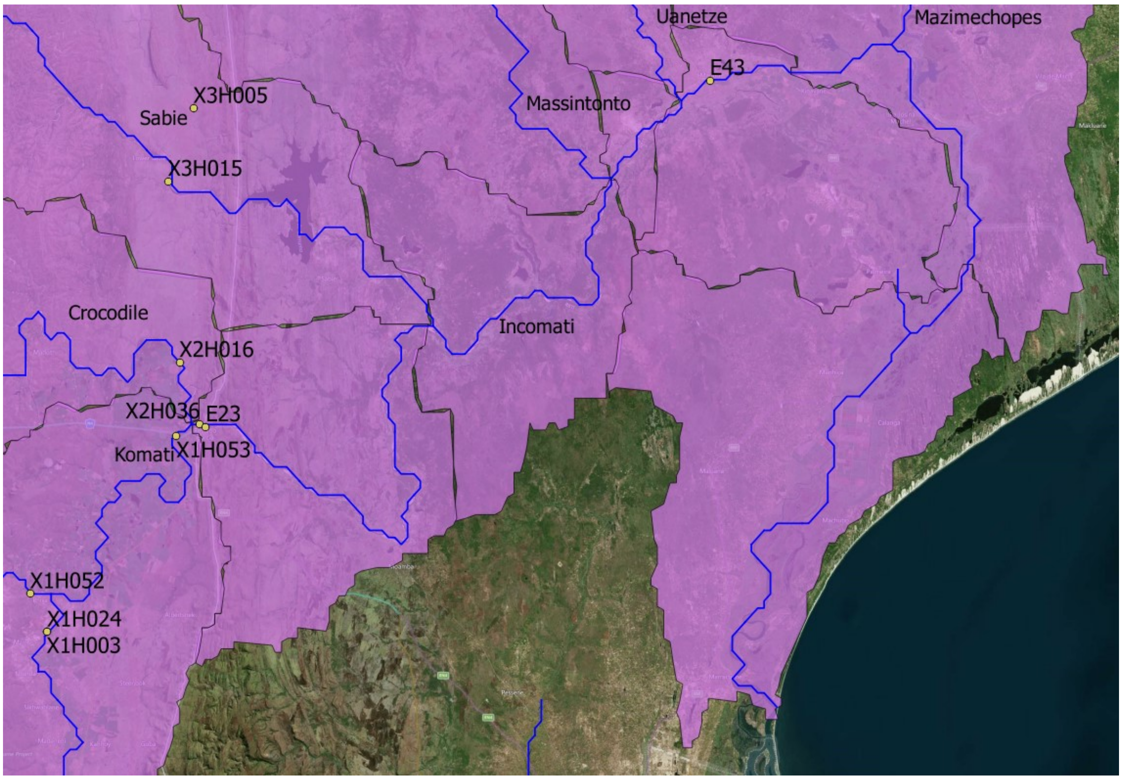

Figure 17. Flow gauging stations in South-Africa and Mozambique (only E23 and E43).

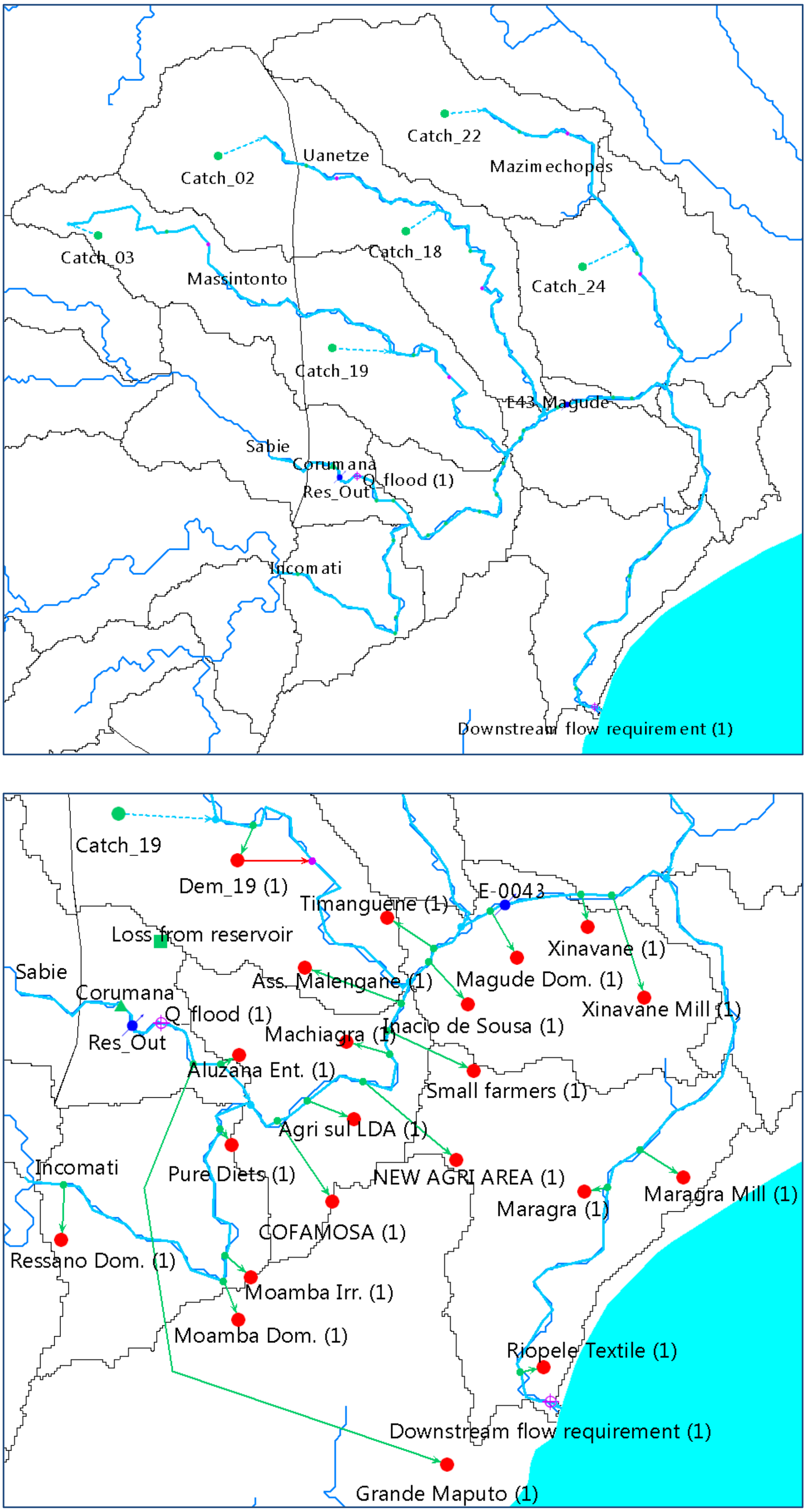

Figure 18. Schematization of WAM-O.

The WAM-O consist of the following elements:

- Demand notes: 26 (of which 2 are only active in the scenarios)
- Catchments nodes: 6
- Rivers nodes: 5
- Flow Requirements nodes: 2
- Reservoir nodes: 1
- Gauging stations: 2

The catchments in WAM-O (02, 03, 18, 19, 22 and 24) have the same schematization as in WAM-S (see Chapter 3.2.2.1).

Catchments are characterized by the following properties (see APPENDIX I: WEAP Land Use Parameters for detailed explanation):

- Area
    - Derived from GIS analysis
- Kc
    - A fixed value of 0.9 is used. Can be updated if detailed information is available.
- Soil Water Capacity
    - Value of 500 mm per month used.
- Deep Water Capacity
    - Value of 500 mm per month used. Can be updated if better soil data is available, although this parameter has limited influence on model performance.
- Runoff Resistance Factor:
    - Value of 5 (no unit) is used. Can be updated if better soil data is available.
- Root Zone Conductivity
    - Value of 1.67 mm per month is used.
- Deep Conductivity
    - Value of 1.67 mm per month is used. Can be updated if better soil data is available, although this parameter has limited influence on model performance.
- Preferred Flow Direction
    - Value of 0.15 is used.
- Initial Z1 and Z2
    - Set to 30%.

3.3.2.2 Corumana reservoir

The characteristics of the Corumana reservoir that were implemented in WAM-O were derived from ARA-Sul (2010) and are given in Table 7.

Table 7. Characteristics of the Corumana reservoir.

Physical			
Storage capacity:	Initial storage at 01-01-2005:	Net evaporation (mm/d):	Loss to groundwater (in MCM/d):
1616 MCM	531 MCM	Values calculated from reservoir water balance	$1.57055 * 10^{-4} * (h_{res} - 94.51)^{3.388977}$

Operation

Top of inactive (volume in reservoir not available for allocation):

137 MCM (corresponding to a reservoir elevation of 95 m)

Hydropower

Max. turbine flow:	Tailwater elevation:	Hydropower priority:	Energy demand (in 10^3 Gigajoule):
47.8 m^3/s[11]	77 m	2	If $H_{res} > 105$: $((1.99 * H_{res}) - 197.1) * 3600 * 24 * (H_{res} - 77) * 9.806 / 10^9$

H_{res} is the reservoir elevation of the previous time step. Next to these characteristics a Volume-Elevation curve was specified. The equation used to calculate the reservoir volume (V, in million m^3) from reservoir elevation (h, in m) is as follows:

If $h > 80$

$V(h) = (1.0519322 * 10^4) – (2.42625 * 10^2 * h) + (1.4035714 * h^2)$

If $h > 108$

$V(h) = (1.36617 * 10^4) – (2.99814 * 10^2 * h) + (1.67143 * h)$.

The maximum hydraulic outflow (maximum reservoir outflow due to hydraulic constraints), top of buffer (below this level, reservoir releases are constrained), buffer coefficient (fraction of water in buffer zone available each day for release), top of conservation (the maximum volume of water in reservoir), plant factor (percentage of each day that hydropower plant is running) and generating efficiency were not specified.

Note that the total storage capacity is schematized differently than in WAM-S. This is because the Corumana reservoir has been modeled in more detail for WAM-O (see Chapter 3.3.2.5).

3.3.2.3 Domestic water demands

For every catchment a domestic water demand was specified. These domestic water demands were specified in the same way as for WAM-S (see Chapter 3.2.2.3). Furthermore the domestic water demands of the cities shown in Table 8 were included in WAM-O. These cities take 20% of their total water demand from Incomati River (Government of Mozambique, 2003).

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[11] This is the required flow to produce the maximum potential (15 MW) at a reservoir elevation of 111 m. When the reservoir elevation is lower, the discharge must be higher to reach the maximum potential. The maximum measured outflow through the hydropower turbines was 107.11 m^3/s.

Table 8. Domestic water demand of cities included in WAM-O

Demand site	Population	Water abstracted from the river for domestic use (m^3/person/year)
Ressano Garcia	8,977[12]	7.48 (= 20 L/person/day)
Moamba	11,120	4.28 (= 12 L/person/day)
Magude	24,473	1.3 (= 3 L/person/day)

3.3.2.4 Irrigation water demands

The irrigation water demands that are included in WAM-O are shown in Table 9.

Table 9. Irrigation water demand included in WAM-O

Name	Location	Area (in ha)	Water use (m^3/ha/year)
Maragra	25°26’56’’S; 32°46’48’’E[13]	6440[13]	7,500[13]
Xinavane	25°2’34.76”S; 32°47’4.49”E[13]	12,000 (2005) 14,000 (2009)[14] 16,161 (2015)[15] 17,959 (2016)[13]	10,000[13]
Aluzana Ent.	25°15’18.7’’S; 32°15’59.6’’E[13]	60[13]	10,000[13]
Pure Diets	25°21’57.3’’S; 32°14’36.6’’E[13]	147.5[13]	10,000[13]
Small farmers	Incomati between Sabie and Massintonto (random choice)	2,500[13]	10,000[13]
Inacio de Sousa	Incomati between Massintonto and Uanetze (random choice)	181.6[13]	7,550[13]
Agri-sul LDA	Incomati between Sabie and Massintonto (random choice)	105[13]	10,000[13]
Machiagra	Incomati between Sabie and Massintonto (random choice)	171.8[15]	10,000[15]
COFAMOSA	Incomati between Sabie and Massintonto (random choice)	20,000 (2005) 29,000 (2007)	10,000[14]
Moamba irrigation	Moamba (Incomati before Sabie)	500[16]	18,000[16]

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[12] http://knoema.com/MNSORS2012Nov/regional-statistics-of-mozambique-2015?region=1005770-ressano-garcia

[13] ARA-Sul, 2016. ‘Key water users.xls’

[14] Aurecon, 2010. ‘System Operating Rules: Status Report First Draft’

[15] ARA-Sul, 2016. ‘Facturaçao.xls’

[16] ARA-Sul, 2010. Informação para a operação da barragem de Corumana.

Timanguene	Incomati between Massintonto and Uanetze (random choice)	1500[14]	10,000[14]
Ass. Malengane	Incomati between Sabie and Massintonto (random choice)	1500[14]	10,000[14]

The total irrigated area in the basin in WAM-O is approximately 60 thousand hectares.

Table 10. Daily water requirements (m^3/s) of Xinavane and Maragra (source: ARA-Sul)

Month	Xinavane	Maragra
Jan	8.3	1.1
Feb	9.6	0.0
Mar	10.2	0.0
Apr	6.2	1.5
May	5.4	1.3
Jun	5.4	1.2
Jul	5.1	1.3
Aug	6.2	0.9
Sep	7.1	0.9
Oct	7.9	1.1
Nov	9.2	1.3
Dec	9.3	1.1
Annual	**89.8**	**11.61**

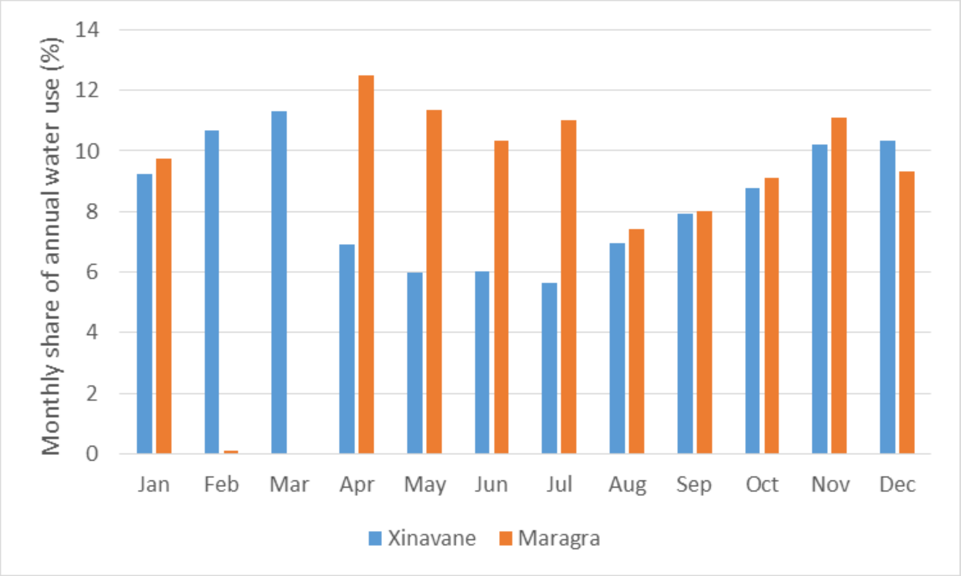
Monthly shares of water use for Xinavane and Maragra (Table 11) were calculated by dividing the average monthly water use given in Table 10 by the annual water use. To get the daily shares the monthly shares should be divided by the number of days in a month.
As can be seen from Table 10 and Table 11 the water use of Maragra is zero in February and March, whereas in those months the water use of Xinavane is relatively high (see Figure 19). According to ARA-Sul staff this is not realistic and the water use variation of Maragra should be more equal to the pattern of Xinavane.

Table 11. Monthly shares of water use for Xinavane and Maragra

Month	Xinavane (in %)	Maragra (in %)
Jan	9	10
Feb	11	0
Mar	11	0
Apr	7	12
May	6	11
Jun	6	10
Jul	6	11
Aug	7	7
Sep	8	8
Oct	9	9

Nov	10	11
Dec	10	9
Annual	**100**	**100**

Figure 19. Monthly shares of annual water use for Xinavane and Maragra



3.3.2.5 Industrial water demands

The industrial water users that were included in WAM-O are given in Table 12. For the water use of Xinavane and Maragra sugar mills different numbers could be found. The numbers from the PRIMA study (Aurecon, 2010) were used, since this was the most recent study.

Table 12. Industrial water users included in WAM-O

Name	**Production units**	**Water use per production unit (10^6 m^3/year)**
Xinavane Sugar Mill	1	5
Maragra Sugar Mill	1	5
Riopele Textile	1	0.6

Both Xinavane and Maragra sugar mills only operate between May and October (Government of Mozambique, 2003). Therefore, their daily variation was 0.543% between 1 May and 31 October and 0% for the other part of the year.

3.3.2.6 Environmental flow requirement

Two flow requirement nodes were included in the model. One downstream flow requirement at the outlet of the Incomati to the Indian Ocean with a minimum flow of 5 m^3/s was included mainly to prevent saltwater intrusion (Government of Mozambique, 2003).

Currently, the effective storage capacity of the Corumana reservoir is 880 million m^3, which corresponds to a reservoir level of 111 m. However, in reality the reservoir level can become higher during flood peaks, since the water is dammed up by the pillars that were originally constructed to hold sluice doors (Figure 20). Therefore, in WAM-O the storage capacity in the model is set to 1,616 million m^3, which is the maximum flood level and corresponds to a water level in the reservoir of 120 m. Since there are no sluice doors yet, the surplus of water that flows into the reservoir cannot be stored when the reservoir level is 111 m. However, during floods the inflow into the reservoir can be higher than the outflow capacity of the sluice openings and as a result the water level will keep increasing. When this happens water is flowing out of the reservoir with a known flow rate (Q, in m^3/s), which depends on the reservoir elevation of the previous time step (h, in m):

$$Q(h) = ((0.00778 * h) – 0.4606) * 480.2 * (h – 111)^{1.5}$$

A flow requirement node with a required flow equal to Q (if h > 111) is used to simulate this flood peak outflow. The flow requirement node is located on the Sabie just downstream of the reservoir.

Figure 20. The sluices of Corumana reservoir (http://www.panoramio.com/photo/96326009)

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 realized nodes for WAM-O is in accordance to the number as agreed in the proposal (Table 13). For most node types the realized number is higher than was agreed, indicating a more inclusive model has been delivered.

Table 13. Number of agreed and realized nodes in WAM-O

Node Type	Proposed	Realized
Demand Nodes	3	24 (+ 2 for scenarios)
Catchment Nodes	4	6
River Nodes	2	5
Flow Requirements Nodes	2	2
Reservoirs	1	1

3.3.3.2 Schematic Setup

The schematic setup was discussed and approved during the meeting in Wageningen with the project leader from ARA-Sul on March 17th, 2016.

3.3.3.3 Observed versus Simulated flows

For 13 locations flow data were available that could be used for the FAT (Table 3). Based on location and data availability the gauging station at Magude (E-0043, see Figure 17) was chosen as reference for the Factory Acceptance Test. Furthermore the measured outflow and the observed volume of the Corumana reservoir were used.

- (i) Observed volume Corumana Reservoir
- (ii) Outflow from the Corumana reservoir
- (iii) Flow of Incomati at Magude (station E-0043)

The period used for validation was 2005-2014.

(i) Observed volume Corumana Reservoir
After calibration of the model the simulated reservoir volume (blue line in Figure 21) corresponded to the observed reservoir volume (red line in Figure 21) very well. During 2010 the simulated storage volume is lower than the observed storage volume of the reservoir[17]. The statistics of model performance can be read from Table 14. The bias of the simulated reservoir volume is low (≤ 2%), and the R^2 is very high (> 0.9). Therefore the conclusion is that the FAT has passed.

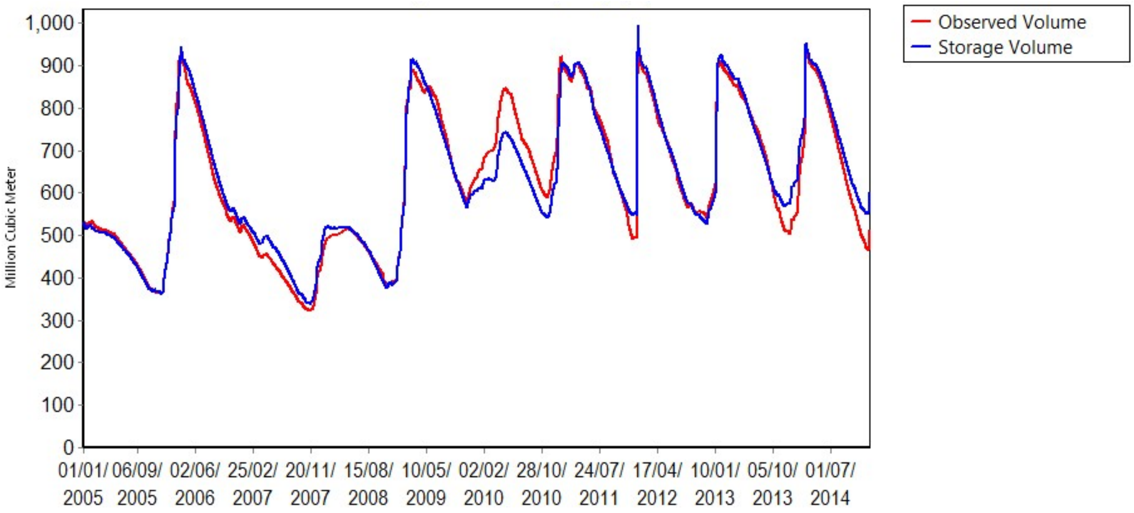


Figure 21. Observed and simulated daily reservoir volumes of the Corumana reservoir.

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[17] In 2010 the inflow from Sabie into the reservoir was normal.

Table 14. Factory Acceptance Test (FAT) for the Corumana reservoir volume (2005-2014).

	Average Reservoir Volume (Million m³)	Bias (%)	R²	Pearson R
Individual days				
Observed	629			
Simulated	617	-2.0	0.95	0.97
Monthly				
Observed	630			
Simulated	618	-2.0	0.95	0.97
Average Monthly				
Observed	630			
Simulated	618	-2.0	1.00	1.00

(ii) Outflow from the Corumana Reservoir

For the Corumana reservoir measured outflows were available. These measured outflows were compared to the simulated flow just downstream of the reservoir.

Results of the comparison between observed and simulated flows are shown in Figure 22, Figure 23 and Table 15. The bias of the simulated flow is very low (≤ 1%) and the R² is high (≥ 0.8). Only the R² of the comparison of the daily flows is somewhat lower (R² ≈ 0.7).

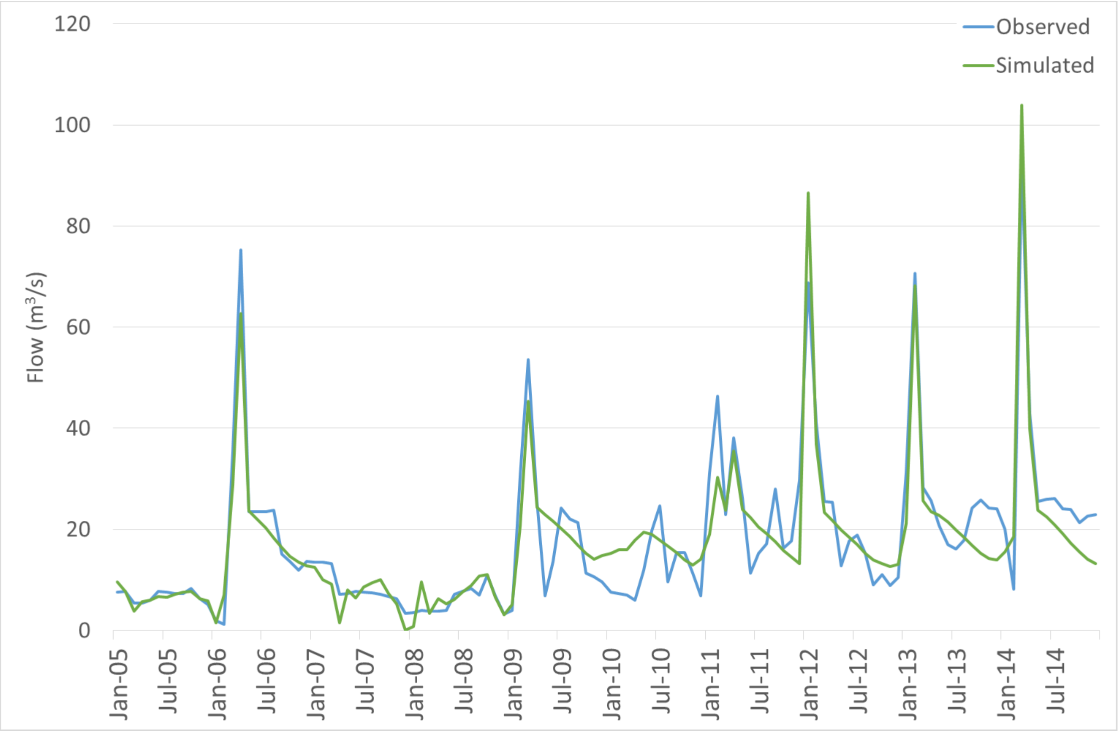

Figure 22. Observed and simulated averaged monthly outflows of the Corumana Reservoir between 2005 and 2014.

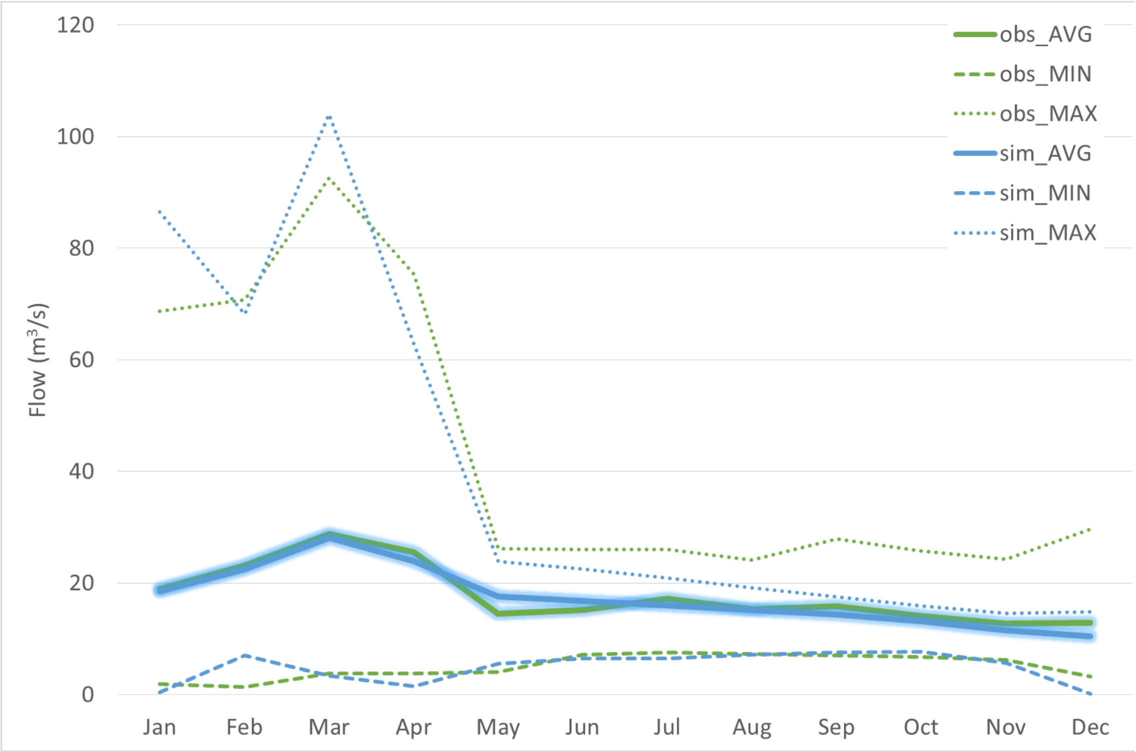

Figure 23. Observed and simulated monthly averaged outflows of the Corumana reservoir over 2005-2014.

Table 15. Factory Acceptance Test (FAT) for the outflow of the Corumana reservoir (2005-2014).

	Average (m3/s)	Bias (%)	R^2	Pearson R
Individual days				
Observed	17.8			
Simulated	17.7	-0.5	0.68	0.82
Monthly				
Observed	17.8			
Simulated	17.7	-0.5	0.80	0.89
Average monthly				
Observed	17.8			
Simulated	17.7	-0.5	0.89	0.94

The fact that the R^2 of the comparison of the daily flows is somewhat lower can be explained by the fact that no strict rules seem to be followed for reservoir management. For example between 2005 and 2010 the outflow from the reservoir is often lower on Mondays (see Figure 24). Sometimes the outflow is reduced to 2.5 m^3/s and sometimes even to zero. Furthermore the outflow is not gradually changing but sudden changes from one constant outflow level to another level occur (from 17 m^3/s to 8 m^3/s to 3.8 m^3/s see Figure 24 and Figure 25).
The unpredictable reservoir outflow can be explained by the importance of hydropower production. From Table 16 (third, yellow column) it can be seen that the total outflow through the hydropower turbine is not only depending on total downstream demand (green column), but also on energy production. The outflow of 10.17 MCM per month for agricultural use that is mentioned in Table 16 corresponds to an outflow of 3.8 m^3/s, which is one of the outflow levels we can recognize in Figure 24 and Figure 25.

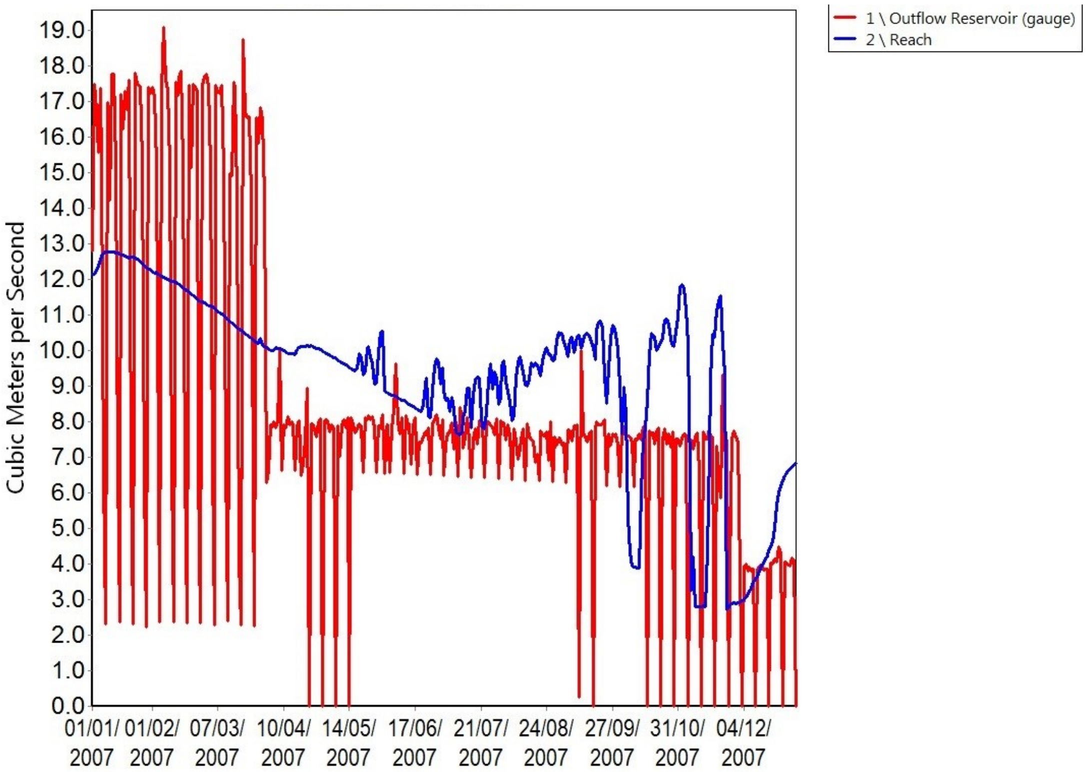

Figure 24. Daily observed outflow (red line) and simulated outflow (blue line) of Corumana Reservoir in 2007.

Table 16. Summary of Corumana reservoir outflow in 2007 (source: ARA-Sul)

		E D M	Agricultura				
Meses	Cota	Central Hidroeléctrica Volume	Xinavane	Maragra	Pequenos Agricultores	Total	Outros Consumos
	(m)	(Mm^3)	(Mm^3)	(Mm^3)	(Mm^3)	(Mm^3)	(Mm^3)
Jan	105.01	36.06	5.95	4.05	0.17	10.17	25.89
Fev	104.61	32.62	5.95	4.05	0.17	10.17	22.45
Mar	104.01	35.44	5.95	4.05	0.17	10.17	25.27
Abr	103.69	16.95	5.95	4.05	0.17	10.17	8.53
Mai	103.62	18.42	5.95	4.05	0.17	10.17	9.41
Jun	103.12	17.59	5.95	4.05	0.17	10.17	9.67
Jul	102.65	17.52	5.95	4.05	0.17	10.17	10.13
Ago	102.12	17.56	5.95	4.05	0.17	10.17	9.60
Set	101.57	17.27	5.95	4.05	0.17	10.17	8.72
Out	101.10	17.08	5.95	4.05	0.17	10.17	7.98
Nov	100.82	16.42	5.95	4.05	0.17	10.17	6.25
Dez	101.81	9.24	5.95	4.05	0.17	10.17	-
Média	102.84	**21.01**	**5.95**	**4.05**	**0.17**	**10.17**	**11.99**
Total		**252.17**	**71.40**	**48.60**	**2.04**	**122.04**	**143.90**

Since hydropower production is not the main goal of the Corumana reservoir, extra water for hydropower production is released only when high inflows into the reservoir are expected and when the reservoir volume is higher than 100 m (according to ARA-Sul staff). However, when we look at the data, there is no clear relation between inflow into the reservoir and outflow through the hydropower turbines or between the reservoir elevation and the outflow through the hydropower turbines (Figure 25). No rules on this topic can be found in the reservoir manual either. In the model there is an assumed relationship between reservoir level and hydropower production (see Table 7) but as can be seen from Figure 25 (upper panel) the correlation is low. However, from Figure 24 it can be seen that the general outflow trend is captured by the model and the results for averaged monthly flows are good (Table 15). Therefore, it can be concluded that the FAT has passed.

Figure 25. Hydropower turbine outflow versus reservoir elevation (upper panel) and versus reservoir inflow (lower panel).

(iii) Flow of Incomati at Magude (station E-0043)

For the flow of Incomati at Magude, gauging station E-0043 was available (Figure 17). The station has missing data in January 2007 and between 27 and 31 August 2008 (in total 1% of time). As can be seen from Figure 27 (upper panel) there was one major flood peak observed between February and June 2006. The observed mean monthly discharge of March 2006 (1200 m^3/s) is extremely high compared to the average monthly discharge of March for the years 1953 – 2013 (160 m³/s). Therefore the observed flows during this flood peak are probably not realistic, possibly due to the lack of a good rating curve for high discharges[18]. Furthermore the WEAP model has to perform well especially on low flows and is not a flood forecasting model. Therefore the high flow period between 31 January 2006 and 15 May 2006 was not taken into account for calculating model performance at Magude.

Results of the comparison between observed and simulated flows are shown in Figure 26, Figure 27 and Table 17. The bias of the simulated flow is low (≤ 5%) and the R^2 is high (≥ 0.9). Only the R^2 of the comparison of the daily flows is somewhat lower (R^2 ≈ 0.7). This is probably mainly caused because in reality there's a delay in flood peaks between two locations, whereas in the model there is no delay between flood peaks coming from Incomati at Ressano Garcia and the resulting flood peaks at Magude. The river length between Ressano Garcia and Magude is approximately 150 km. From Figure 28 it can be seen that the delay is approximately 5-7 days. Since the general flow patterns are captured well by the model and the results for averaged monthly flows are good (see Table 17) the conclusion is that the FAT has passed.

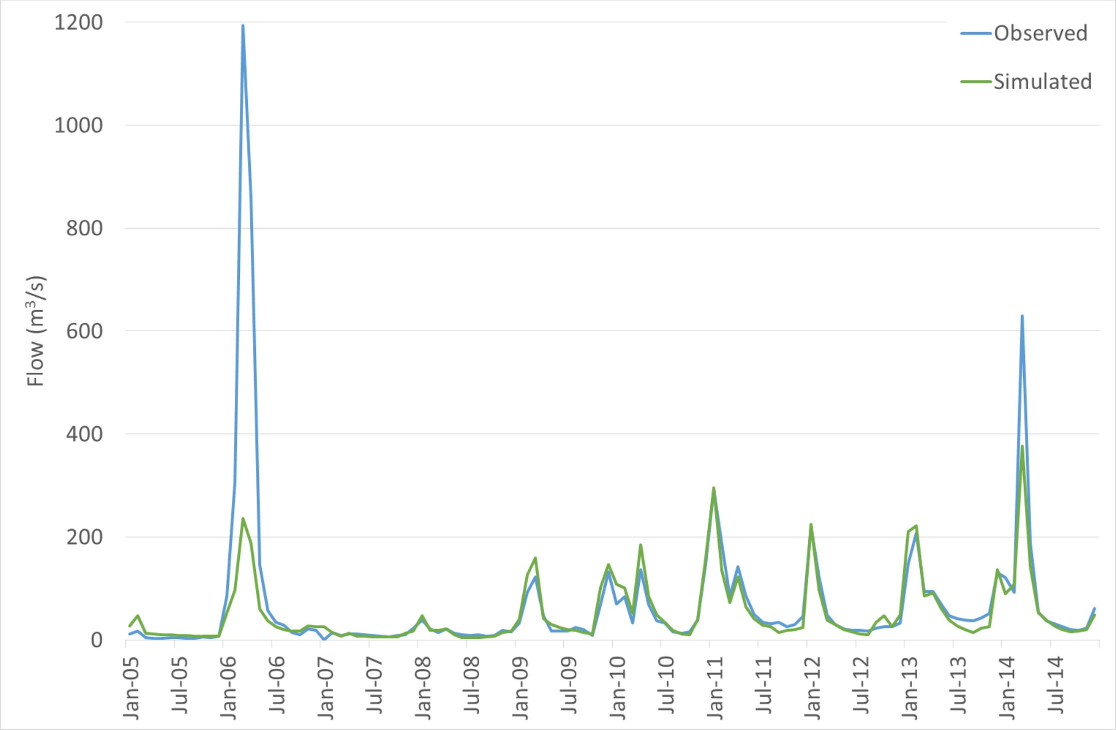

Figure 26. Observed and simulated averaged monthly flows at Magude between 2005 and 2014.

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[18] This was confirmed by ARA-Sul staff during the training from 9-13 May 2016 in Corumana, Mozambique.

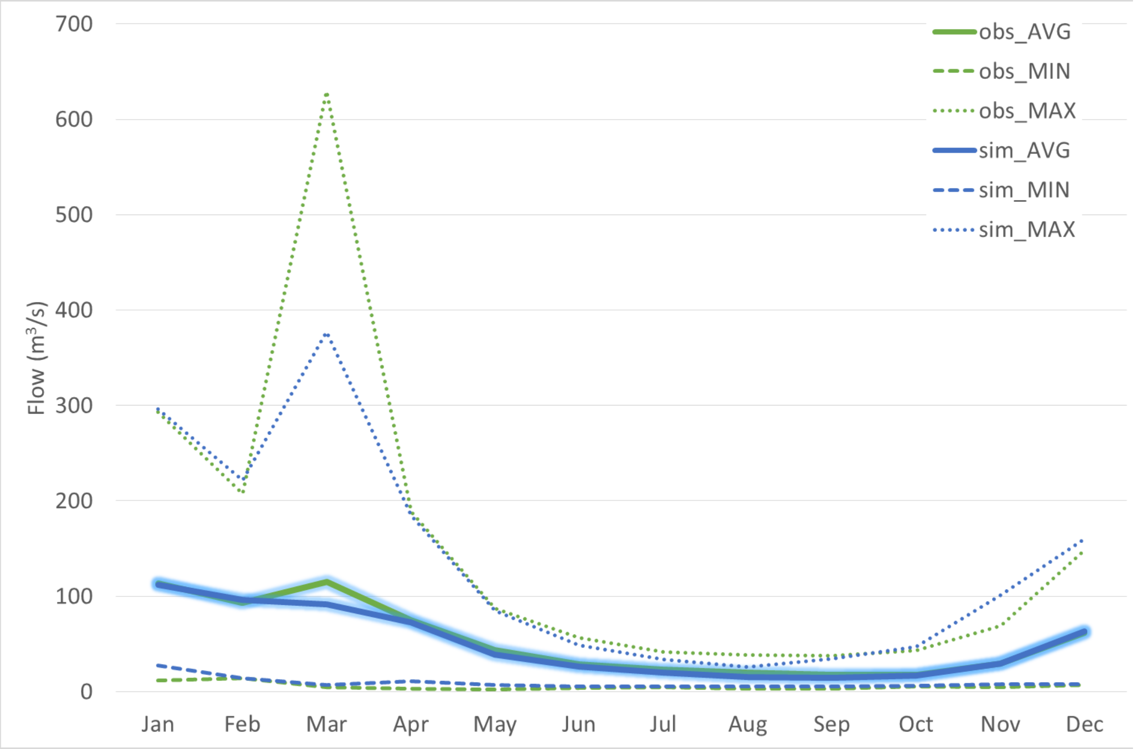

Figure 27. Observed and simulated monthly averaged outflows of the Corumana reservoir over 2005-2014.

Table 17. Factory Acceptance Test (FAT) for the flow of Incomati at Magude (2005-2014).

	Average (m3/s)	Bias (%)	R^2	Pearson R
Individual days				
Observed	51.0			
Simulated	49.2	-3.7	0.69	0.83
Monthly				
Observed	51.3			
Simulated	49.4	-3.8	0.87	0.93
Average monthly				
Observed	52.8			
Simulated	50.3	-5.0	0.96	0.98

Note: differences in average flows is caused by missing values.

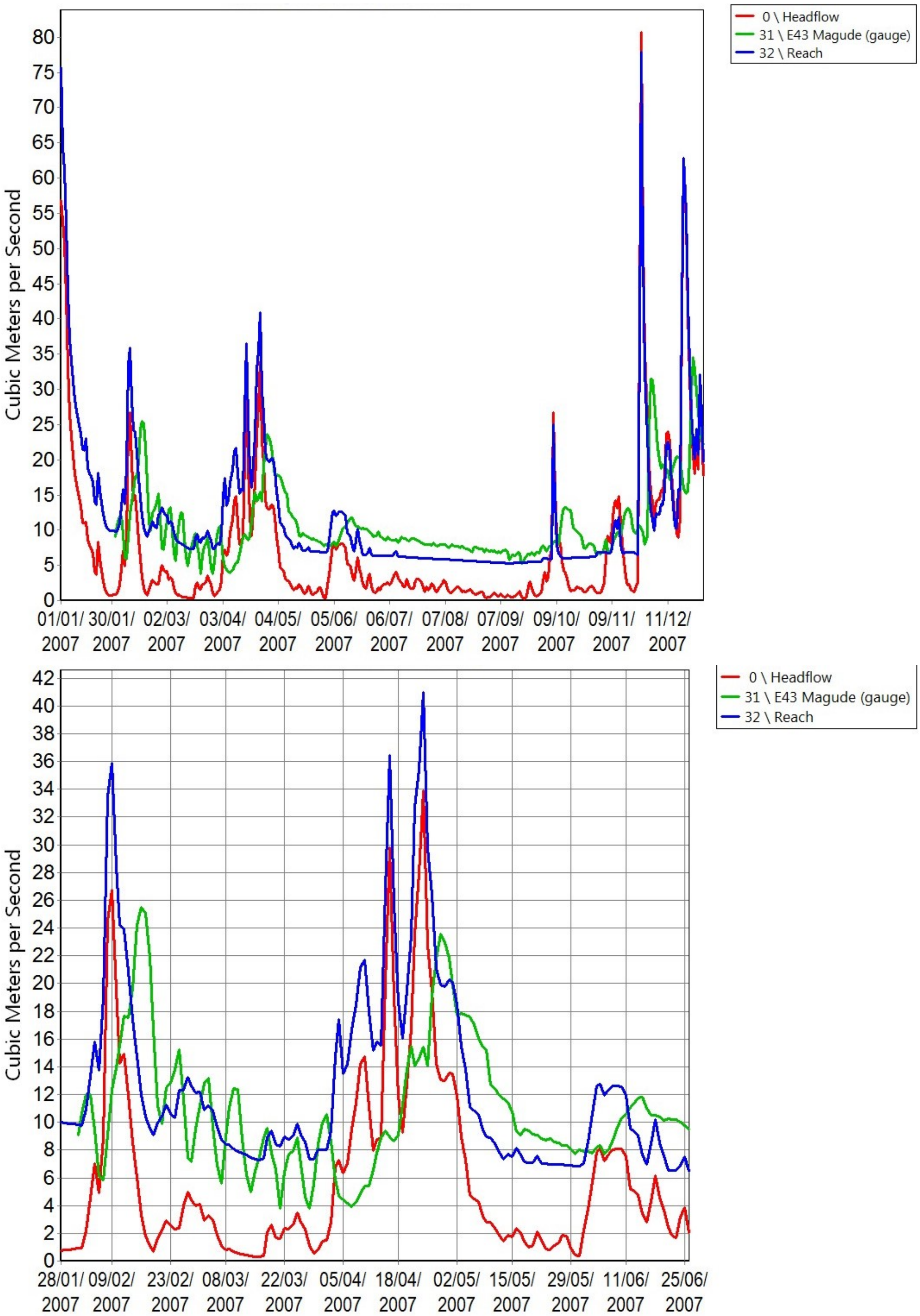

Figure 28. Observed streamflow of Incomati at Ressano Garcia (red line), at Magude (green line) and simulated streamflow at Magude (blue line) for 2007 (upper panel) and from 28-01-2007 to 25-06-2007 (lower panel).

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 five 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 12 scenarios have been explored using WAM-S
- At least 8 scenarios have been explored using WAM-O

At the beginning of March and at the beginning of May a distance training was given by Skype. These training moments were attended by six ARA-Sul staff members (see APPENDIX VI: Participants of Distance Training and Intensive Training Week). During these training moments presentations were given on the background and relevance of the project and the WEAP model. Furthermore the participants did some exercises to get to know WEAP and installed WAM-O and WAM-S on the local computer to test if the model was running.

The week after the second distance training a one week intensive training course was given in Corumana, Mozambique. At the start of this week the WAMs were installed on the PCs of the present ARA-Sul staff members (see APPENDIX VI: Participants of Distance Training and Intensive Training Week). The WAMs, tutorials and training manual were also provided through Dropbox prior to the intensive training week. Five ARA-Sul staff members joined the training and successfully finished the program.
Next to the training mission in Mozambique Mr. G. Macaringue from ARA-Sul followed a personal traineeship of two weeks in The Netherlands at the beginning of March. Seven days were spend at the office of FutureWater and two days were spend in the field and at the office of Wetterskip Fryslân. During the traineeship the scenarios to be implemented in the WAMs were discussed. That resulted in 11 scenarios for WAM-O of which the results are presented in Chapter 5. Results of 12 scenarios for WAM-S are described in Chapter 4. The evaluation of this traineeship can be found in APPENDIX VII: Evaluation traineeship G. Macaringue.

4 Strategic Water Allocation using WAM-S

4.1 Scenario Development

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: Maputo transfer: water transfer to Maputo area of 72 million m^3 per year from 2019 onwards.
- (02a) Impact: Population growth[19] (2.45% per year from 2011 onwards). Since the extent of the irrigated area and amount of industrial units are related to the population (see Chapter 3.2.2.4 and Chapter 3.2.2.5) the irrigated area increases by 2.1% and the industrial units increase by 4.0% per year simultaneously.
- (02b) Impact: Population growth only (2.45% per year from 2011 onwards). The irrigated area and industrial units are kept constant.
    - (03) Adaptation: Prevent tap water leakage losses. As a result the Annual Water Use Rate of the population decreases by 25%.
- (04) Impact: Increase in irrigated areas (2% per year from 2011 onwards).
    - (05) Adaptation: Increased reservoir capacity. From 2019 onwards the Moamba Major reservoir on the Incomati River is active with a Storage Capacity of 760 MCM. The Storage Capacity of the Corumana reservoir is increased from 879 to 1345 MCM from 2019 onwards.
    - (06) Adaptation: Reduce conveyance losses in irrigation systems. As a result the Annual Water Use Rate of the irrigated areas decreases by 25%.
- (07) Impact: Climate change (precipitation -10%[20], temperature +3 °C[21] from 2014 onwards)
- (08) Impact: Likely Future (impact 01, 02a, 04 and 07 as defined above)
    - (09) Adaptation: Increased reservoir capacity (adaptation 05).
    - (10) Adaptation: Improved systems (adaptations 03 and 06).
    - (11) Adaptation: Full adaptation (adaptations 03, 05 and 06).
- (12) Water Quality: Improved Land Management. The Catchment TDS load is decreased by 25%.

The above 12 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 Incomati basin, the precipitation trend for the past 40 years (1975-2014) was analyzed for all sub-basins. Since the year 2000 was an extremely wet year, this year was excluded from the analysis. The total annual precipitation over the past 40 years showed an upward trend for more than half of the catchments and a downward trend for the remaining catchments. According to Okello et al. (2015) statistical analysis of 20 rainfall stations within the Incomati catchment did not reveal any significant trends. However, RCP6.0 from the IPCC projections shows a projected increase in temperature of 3 °C and a projected decrease in rainfall of approximately 10% in 2100 for Southern Africa. This projection was used in the climate change scenario (04) and the likely future scenarios (05,

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

[20] Appendix III: Climate change projection; Figure 46; Representative Concentration Pathway 6.0 (RCP6.0)

[21] Appendix III: Climate change projection; Figure 47; RCP6.0.

06 and 07). Climate change projections for temperature and precipitation made by the IPCC can be found in Appendix III: Climate change projection.

Table 18. Precipitation trend of 1975-2014 for the catchments in the Incomati River Basin

	Positive trend	**No trend**	**Negative trend**
Number of catchments	13	1	10
Average trend	+ 1.0 mm/year	-	-1.13 mm/year

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

a) Water shortage in all Mozambican demand sites (06, 07, 10, 11, 18, 19, 20, 22, 23, 24 and Maputo transfer) and water shortage in demand sites downstream of Corumana reservoir (demand Sites 06, 07, 11, 20, 23 and Maputo transfer).
b) Reservoir volume of Corumana.
c) Outflow of Icnomati to Indian Ocean.

The above indicators were calculated for the current situation (2011-2015) and periods around the year 2025 (2021-2030), and 2045 (2041-2050). 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 1975-2013 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 two wettest years in the historic period were excluded from this random year selection.

4.2 Results

4.2.1 Water shortage

In Figure 29 the annual total water demand for all Mozambican demand sites between 2010 and 2050 is shown for different Impact Scenarios. From this figure it can be seen that the water demand will have risen approximately by 15% in 2050 for the Population growth scenario, by 25% for the Maputo transfer scenario and even by 100% and 200% for the Irrigated area growth scenario and the Likely future scenario respectively. The water demand for the Climate change scenario does not increase. This scenario only affects the streamflow.

In Figure 30 the annual total unmet demand for all Mozambican demand sites is shown. For the Reference scenario, the Maputo transfer scenario and the population growth scenario no unmet demand is projected until 2050. Also the influence of climate change on unmet demand is relatively small. However, a steady increase in irrigated area will result in water shortages from 2030 onwards. The combination of all impacts (Likely future scenario) has a large influence on unmet demand: already around 2020 there will be significant water shortages.

The same analysis of unmet demand for the demand sites downstream of the reservoir (these are demand sites 06, 07, 11, 20, 23 and Maputo transfer) shows that unmet demand projected in the future is negligible.

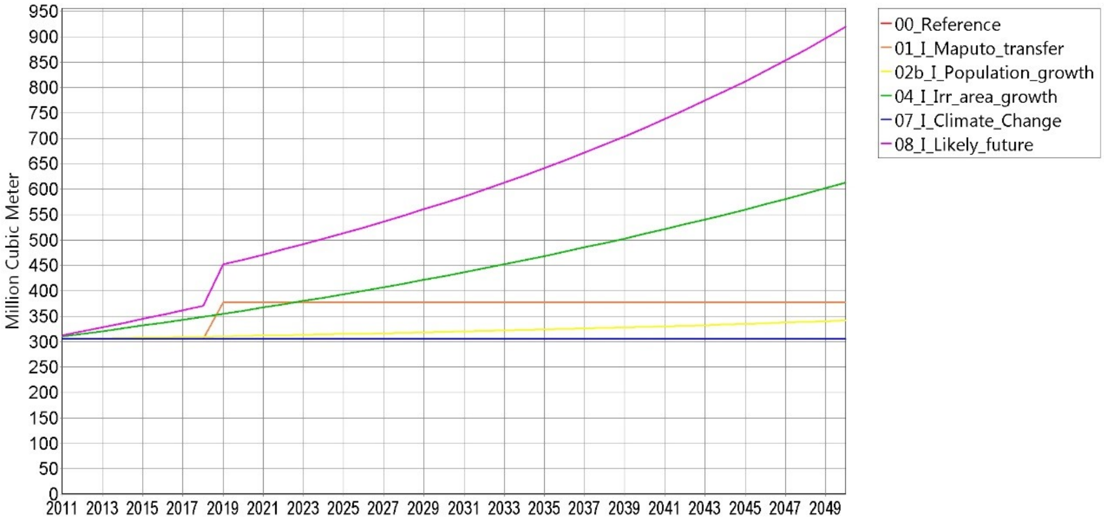

Figure 29. Annual total water demand for the Mozambican demand sites (2011-2050).

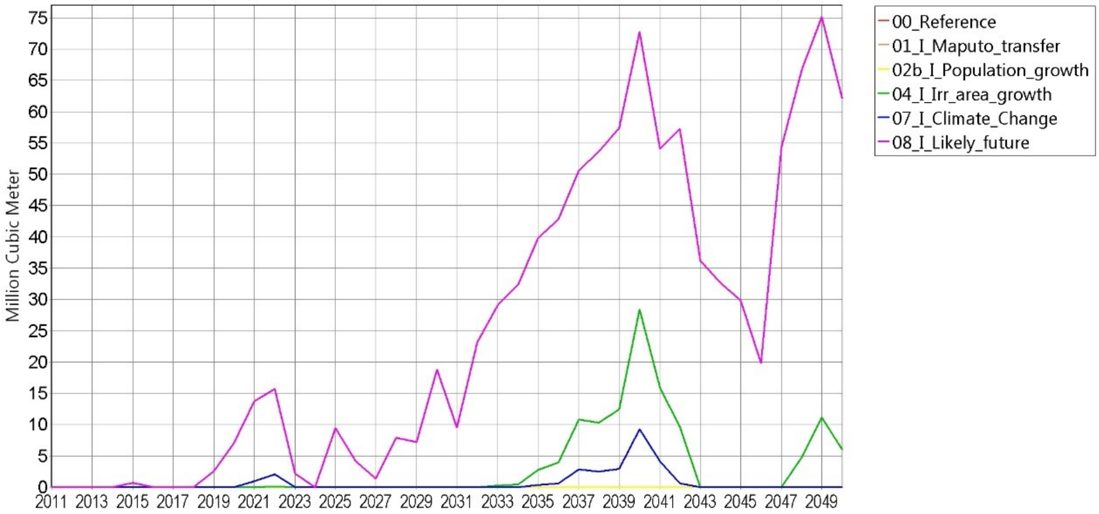

Figure 30. Annual total unmet demand for al Mozambican demand sites (2010-2050) for different Impact scenarios.

4.2.2 Reservoir volume

In Figure 31 the monthly reservoir volume of Corumana is presented for the impact scenarios. The water transfer to Maputo does not significantly influence the reservoir volume. For all scenarios the reservoir volume is projected to stay above 650 million m^3, except for the Likely future scenario. For the likely future scenario the reservoir volume is projected to decrease to very low levels after 2040.

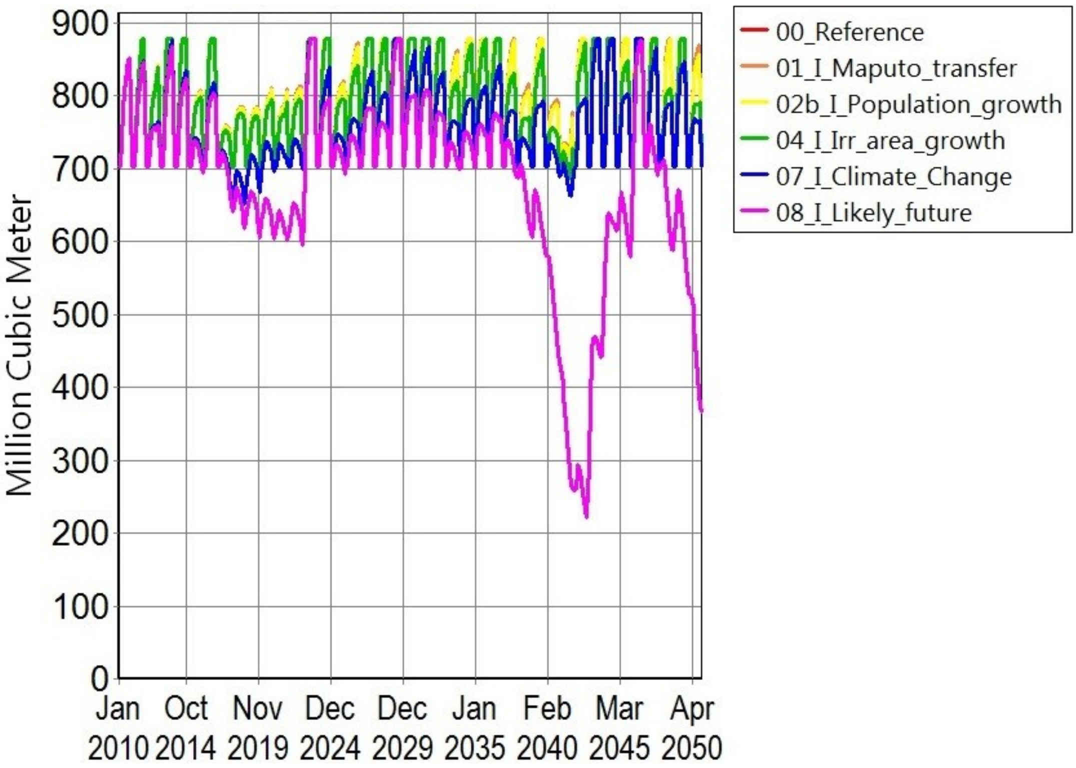

Figure 31. Reservoir volumes under the various Impact Scenarios.

4.2.3 Outflow of Incomati into the Indian Ocean

In Figure 32 the annual outflow of Incomato into the Indian Ocean is shown for the impact scenarios. From the upper panel it can be seen that the annual average outflow is projected to stay above 10 m^3/s until 2050 for all scenarios, except the Likely future scenario. For this scenario the average annual streamflow will structurally be below 10 m^3/s around 2030 and around 5 m^3/s from 2040 onwards. Climate change has the largest impact on the projected streamflow, followed by the increase in irrigated agriculture. In the lower panel of Figure 32 and in Table 19 the exceedance probabilities of the annual outflow between 2011 and 2050 are given for the impact scenarios.

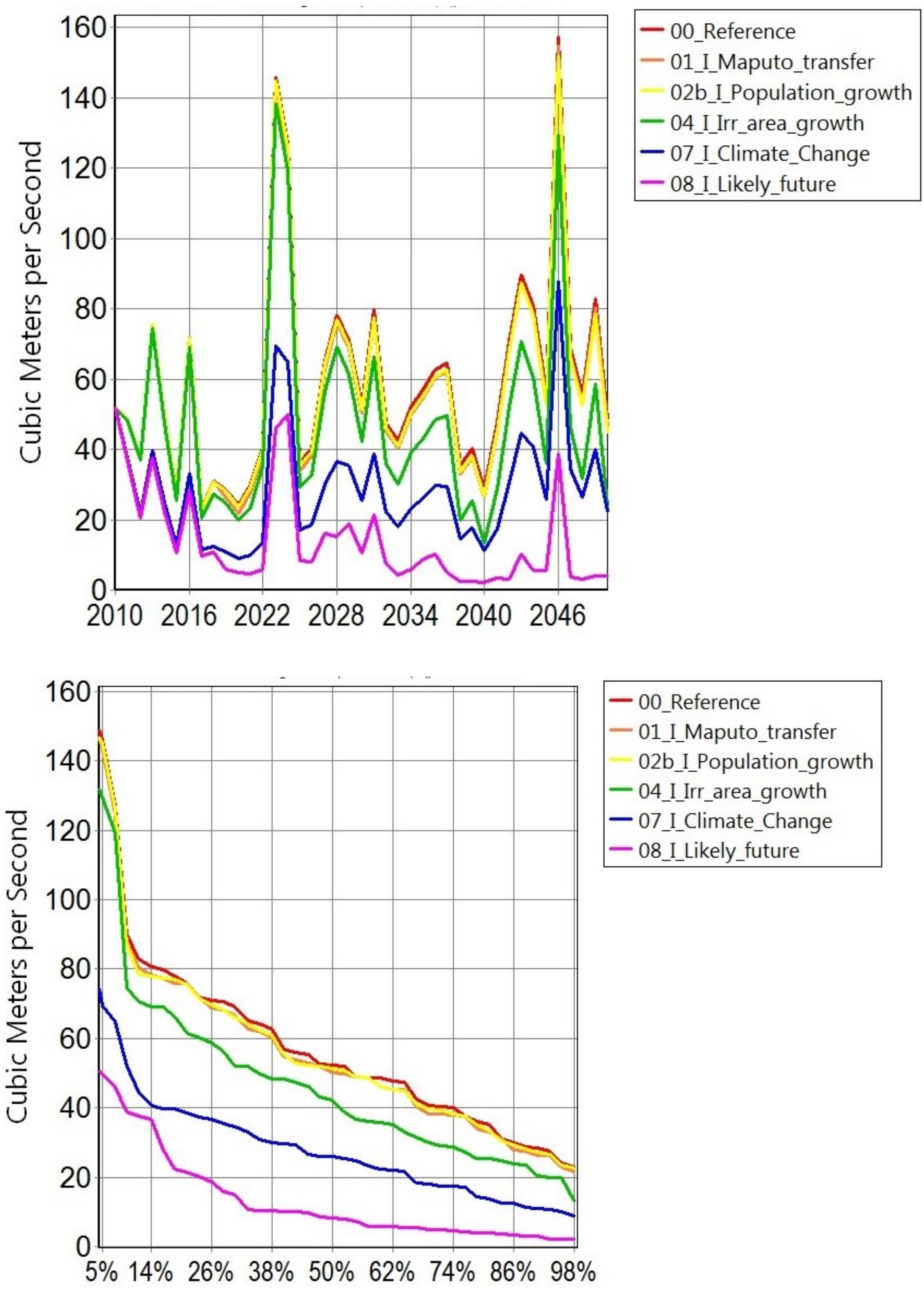

Figure 32. Annual total outflow of Incomati to the Indian Ocean. In the upper panel the outflow in m^3/s between 2010 and 2050 is given. In the lower panel the exceedance probability of the annual outflow between 2011 and 2050 is shown.

Table 19. Exceedance probability of annual outflow of Incomati between 2011 and 2050

	95%	90%	80%	70%	60%	50%	40%	30%	20%	10%	5%
Reference scenario (m^3/s)	24.2	28.6	34.5	40.5	47.6	55.3	62.7	70.3	80.1	119.4	150.9
Scenario 01 (m^3/s)	23.3	26.4	32.6	38.2	45.4	53.1	60.4	68.0	77.8	117.1	148.6
Scenario 02b (m^3/s)	23.6	27.3	32.9	39.7	45.3	52.3	60.9	67.8	77.7	118.2	148.1
Scenario 04 (m^3/s)	19.8	20.6	25.3	29.0	32.7	39.0	46.2	55.5	63.4	109.6	133.4
Scenario 07 (m^3/s)	10.1	11.1	13.6	17.4	21.5	25.9	29.3	33.8	39.2	60.8	77.7
Scenario 08 (m^3/s)	2.3	3.1	4.0	4.7	5.6	6.0	8.3	10.3	15.5	35.3	47.7

4.2.4 Adaptation scenarios

In Figure 33 the influence of the adaptation scenarios on the unmet demand for the Mozambican demand sites is presented. Somewhat surprisingly, increasing the reservoir capacity does not have influence on the unmet demand. The reason is that for the Likely future scenario only the demand sites that are not influenced by reservoir management have an unmet demand. This is also the reason that the Full adaptation scenario has the same effect on unmet demand as the Improved systems scenario. With improved systems water shortages will occur approximately from 2030 onwards, whereas for the Likely future scenario without adaptations this will be around 2020.

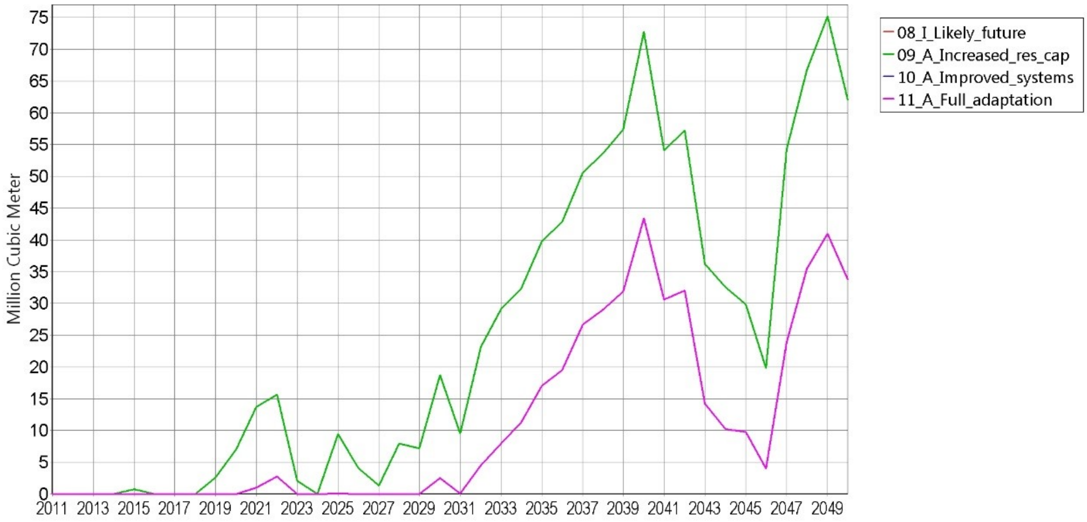

Figure 33. Annual total unmet demand for al Mozambican demand sites (2011-2050) for different Adaptation scenarios.

In Figure 34 the total reservoir volume of the Corumana reservoir (enlarged from 2019 onwards) and Moamba Major (from 2019 onwards) for different adaptation scenarios is presented. From this figure it can be seen that for all adaptation scenarios the total reservoir volume is projected to stay above 550 MCM. For the full adaptation scenario the total reservoir volume will even stay above 700 MCM.

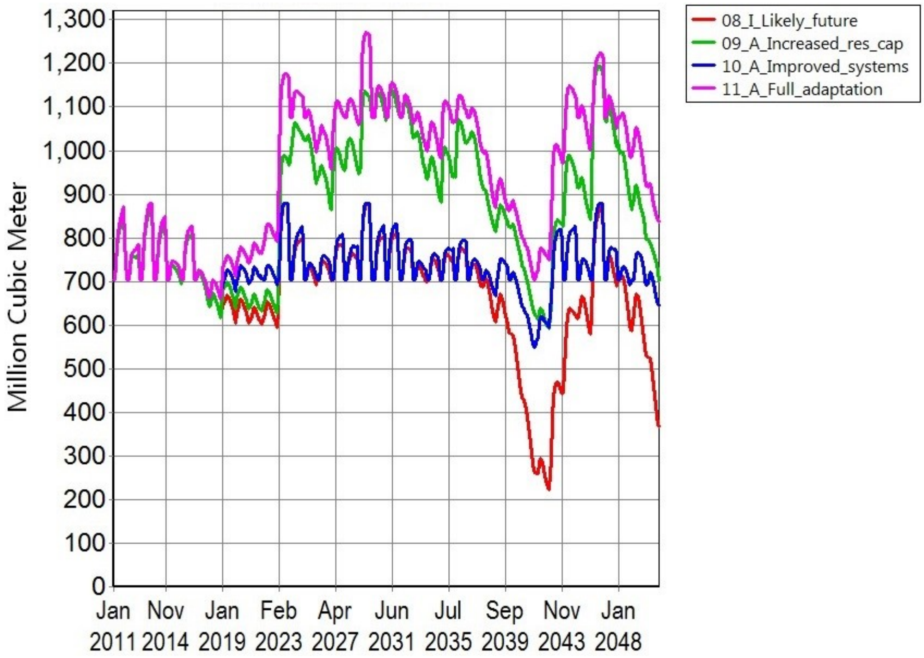

Figure 34. Total reservoir volume of Corumana (enlarged from 2019 onwards) and Moamba major (from 2019 onwards) for different adaptation scenarios.

In Figure 35 the annual total outflow of Incomati to the Indian Ocean is given for different adaptation scenarios. For the Increased reservoir capacity scenario the outflow to the Indian Ocean will be lower than for the Likely future scenario, because more water will be stored in the reservoirs and no minimum flow requirement is specified downstream. However the average yearly flow is projected to stay above 2 m^3/s. For the Improved systems scenario the average yearly outflow will be higher than for the Likely future scenario and in most years the outflow for the Full adaptation scenario will also be higher compared to the Likely future scenario. However, the average yearly flow for these adaptation scenarios is also projected to become lower than 5 m^3/s after 2040.

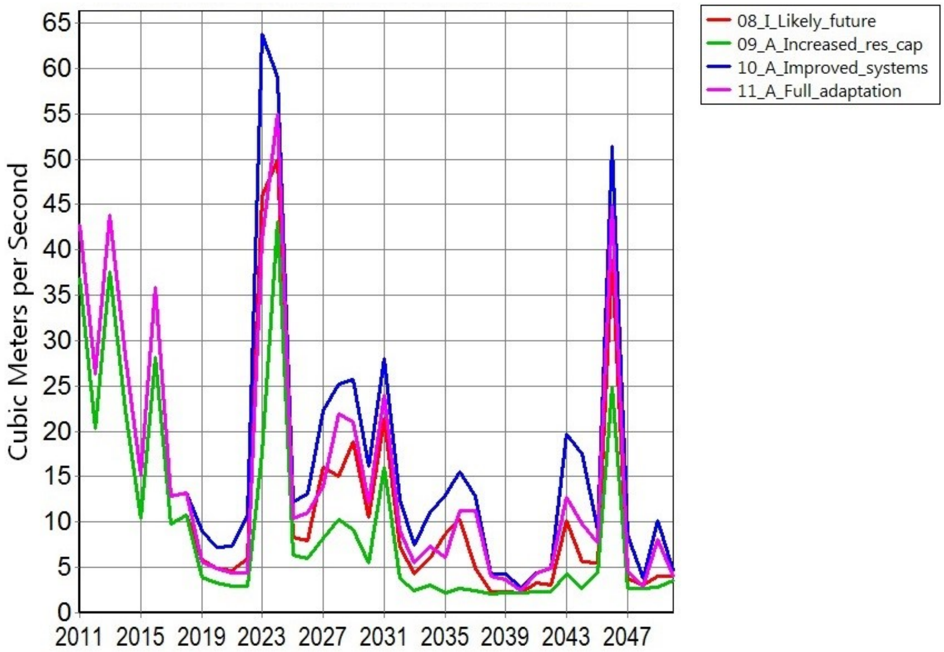

Figure 35. Annual total outflow (in m^3/s) of Incomati to the Indian Ocean for different adaptation scenarios.

4.2.5 Water quality

In Figure 36 a map of the water quality (TDS in g/L) for all streams in the Incomati River Basin can be seen for the Reference scenario for two different moments. The upper map shows the water quality in September 1995, whereas the lower map shows the water quality in March 2001. Because in September 1995 it was a relatively dry situation, the TDS in the streams is higher than for March 2001, which was a relatively wet situation. The TDS values are not only given as numbers, but are also visualized: when the TDS is higher the blue lines that represent the streams are bigger.

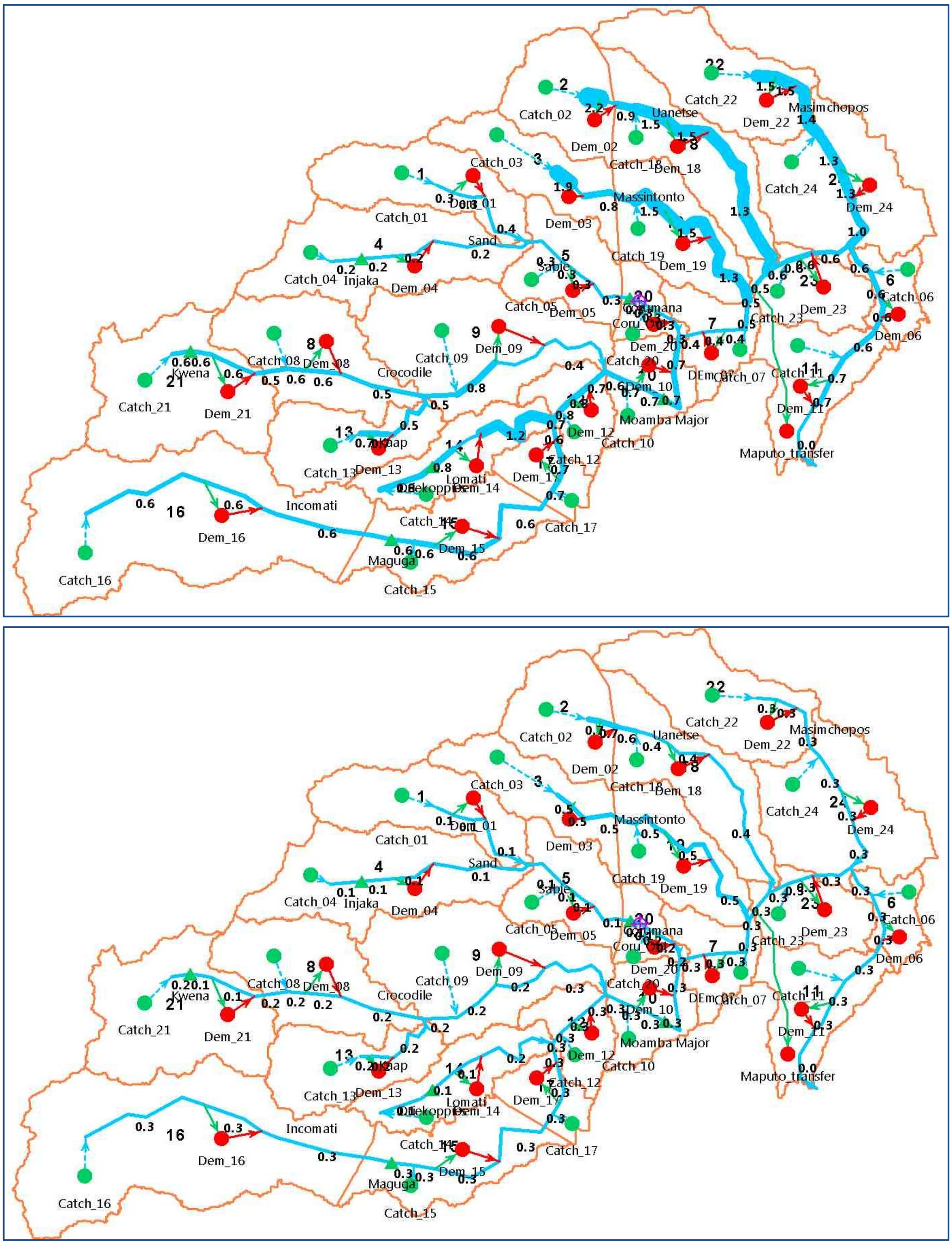

Figure 36. Water quality (TDS) in all streams for a relatively dry (top) and wet (bottom) situation. All values in g/L. September 1995 (top) and March 2001 (bottom).

From Figure 37 it can be seen that from 1981-2010 the catchments have the highest contribution to TDS loads (see Chapter 3.2.2.7 for an explanation of the sources of TDS). Therefore a scenario was made in which the TDS loads of the catchments was reduced by 25%. From Figure 38 and Figure 39 it can be seen that the TDS load is reduced most (in absolute terms) during the months with a high TDS load (May-October).

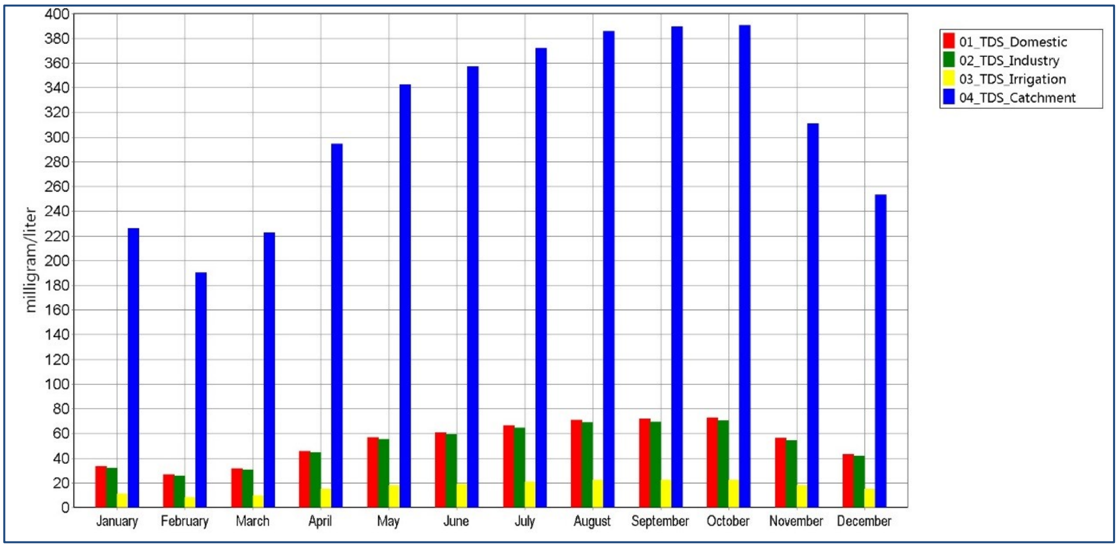

Figure 37. Water quality (TDS) at the outlet point of Incomati into the Indian Ocean, specified per source. Monthly averages over 1981-2010 in mg/L.

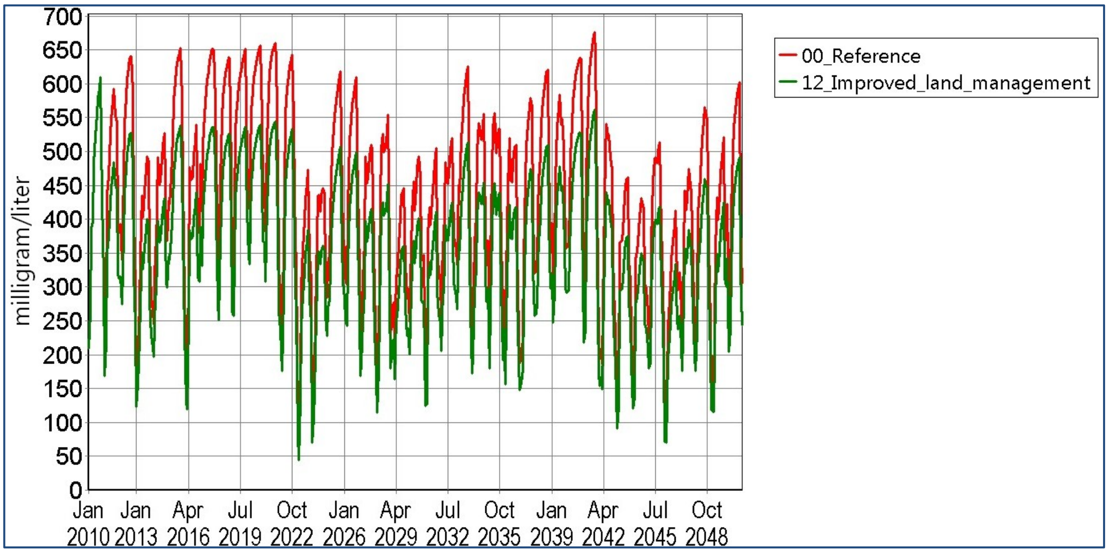

Figure 38. Water quality (TDS) at the outlet point of Incomati into the Indian Ocean for the Reference scenario and the Improved land management scenario. All values in mg/L.

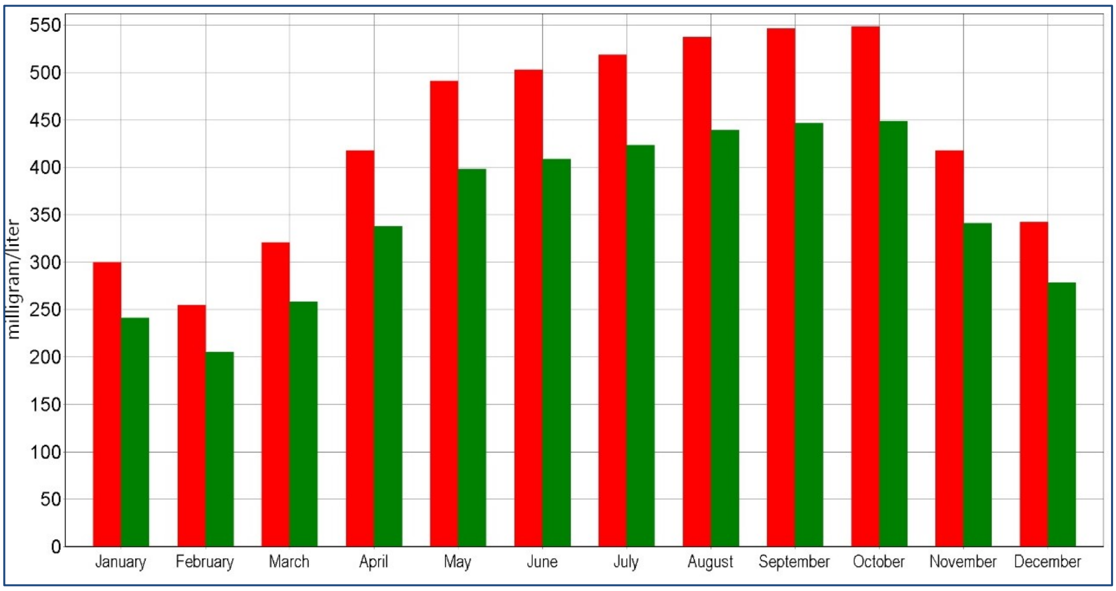

Figure 39. Water quality (TDS) at the outlet point of Incomati into the Indian Ocean for the Reference scenario (red bars) and the Improved_land_management scenario (green bars). Monthly averages over 2011-2050 in mg/L.

5 Water Licensing Scenarios using WAM-O

5.1 Scenario Development

Currently there are plans to establish a new irrigated area in the Mozambican part of the Incomati River Basin. There is already a commitment to one new user for an area of 10,000 ha of agriculture. However, it is not yet clear which effect this will have on the water availability for other users. Furthermore, Mozambique is currently in a severe drought situation. As a result of El Ninõ there has been little rain during the rainy season of 2014-2015 and 2015-2016 and the reservoir level is low.

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

- (00) Reference
  For the reference scenario the precipitation for the year 2015 and 2016 is equal to the year with the minimum precipitation between 1971 and 2014 (the year 2002). Also the net evaporation from the reservoir for the year 2016 is equal to the year 2002.
  The inflow of Incomati for 2016 is equal to the minimum observed yearly inflow of Incomati between 1983-2015 (the year 1994). The inflow of Sabie for 2016 is equal to the minimum observed yearly inflow of Sabie between 1989-2015 (the year 2003).
  - (01) Irrigated area 75%
    This scenario is based on the Reference scenario, but from 2016 onwards the water user per hectare is reduced by 25%.
  - (02) Irrigated area 50%
    This scenario is based on the Reference scenario, but from 2016 onwards the water user per hectare is reduced by 50%.
  - (03) Irrigated area + 5,000 ha
    This scenario is based on the reference scenario, but an extra demand side is added (between Agri sul and Machiagra) which is active from 2006 onwards, has an irrigated area of 5,000 ha and a water use rate of 10,000 m3/ha/year.
  - (04) Irrigated area + 10,000 ha
    This scenario is based on the reference scenario, but an extra demand side is added (between Agri sul and Machiagra) which is active from 2006 onwards, has an irrigated area of 10,000 ha and a water use rate of 10,000 m3/ha/year.
  - (05) Water transfer Maputo
    This scenario is based on the reference scenario, but an extra demand side is added directly downstream of the reservoir which is active from 2006 onwards and represents a water transfer to Grande Maputo with a monthly water use rate of 2.19 hm^3 (26.3 million m^3/year).
- (06) Median inflow
  This scenario is based on the reference scenario, but for 2016 the inflow of Incomati is equal to the median observed yearly inflow of Incomati between 1983-2015 (the year 1997). The inflow of Sabie is equal to the median observed yearly inflow of Sabie between 1989-2015 (the year 1998).
  - (07) Irrigated area 75%
    This scenario is based on the Median inflow scenario, but from 2016 onwards the water use per hectare is reduced by 25%.

    - (08) Irrigated area 50%
      This scenario is based on the Median inflow scenario, but from 2016 onwards the water use per hectare is reduced by 50%.
- (09) Zero inflow
  This scenario is based on the reference scenario, but for 2016 the inflow of Sabie and Incomati is zero.
    - (10) Irrigated area 75%
      This scenario is based on the Zero inflow scenario, but from 2016 onwards the water use per hectare is reduced by 25%.
    - (11) Irrigated area 50%
      This scenario is based on the Zero inflow scenario, but from 2016 onwards the water use per hectare is reduced by 50%.

Results of the water licensing scenarios were evaluated using some illustrative graphs and the following indicators (for the period 2015-2016):

- Water shortage (average and number of days)
- Percentage of time the reservoir volume is below 95 m.
  The minimum storage level of the reservoir is 95 m. When the reservoir volume becomes lower still some water can be released but this will cause problems with water quality and abrasion due to soil particles. The lowest gate level is 78 m.
- Outflow to Indian Ocean (percentage of days that flow requirement is met)

5.2 Result

5.2.1 Water shortage

In 2015 an annual total water shortage is negligible for all scenarios. Some minor water shortage is experienced by the demand sites that abstract their water from Incomati upstream of the confluence with Sabie and are thus not influenced by reservoir management (Ressano Garcia Domestic, Moamba Domestic, Moamba Irrigation and Pure Diets).

In 2016 the projected annual total water shortage ranges between 342 MCM for the Zero inflow scenario and 1 MCM for the Median inflow scenarios (Table 20). From Table 20 and Figure 42 it can be seen that the annual total water shortage is reduced significantly when the water use per hectare for the irrigated areas is reduced by 25 or 50%. However, the number of days on which water shortage is experienced by one or more demand sites, does not decrease much. In Figure 40 the projected daily water shortage for different development scenarios can be seen. In Figure 41 the projected daily water shortage for different inflow scenarios is shown.

Table 20. Projected annual water shortage and percentage of days with water shortage in 2016 for different scenarios

	Annual water shortage in 2016 (in MCM)	Percentage of days
00_Reference	216	87
01_Irr_area_75%	91	84
02_Irr_area_50%	3	80
03_Irr._Area_+5000	278	87
04_Irr._Area_+10000	344	88
05_Water_transfer	248	87
06_Median_inflow	1	45
07_Med_inflow-Irr_area_75%	1	45
08_Med_inflow-Irr_area_50%	1	45
09_Zero_inflow	342	100
10_Zero_inflow-Irr_area_75%	211	100
11_Zero_inflow-Irr_area_50%	90	100

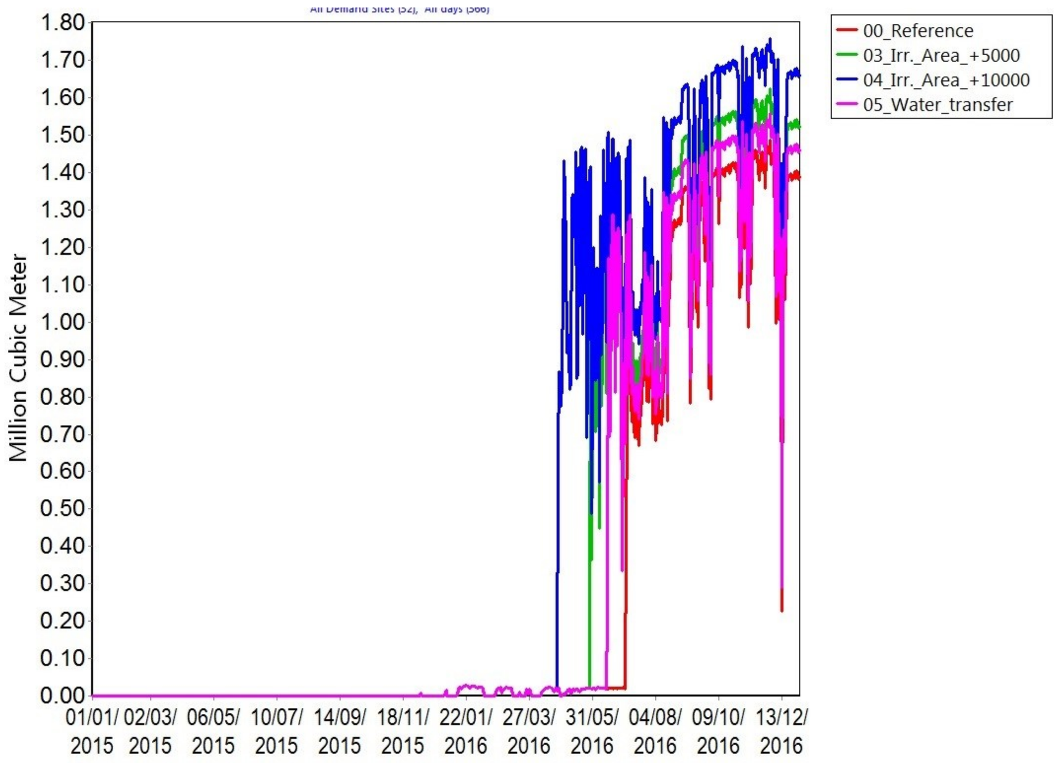

Figure 40. Projected daily water shortage in 2015 and 2016 for different development scenarios.

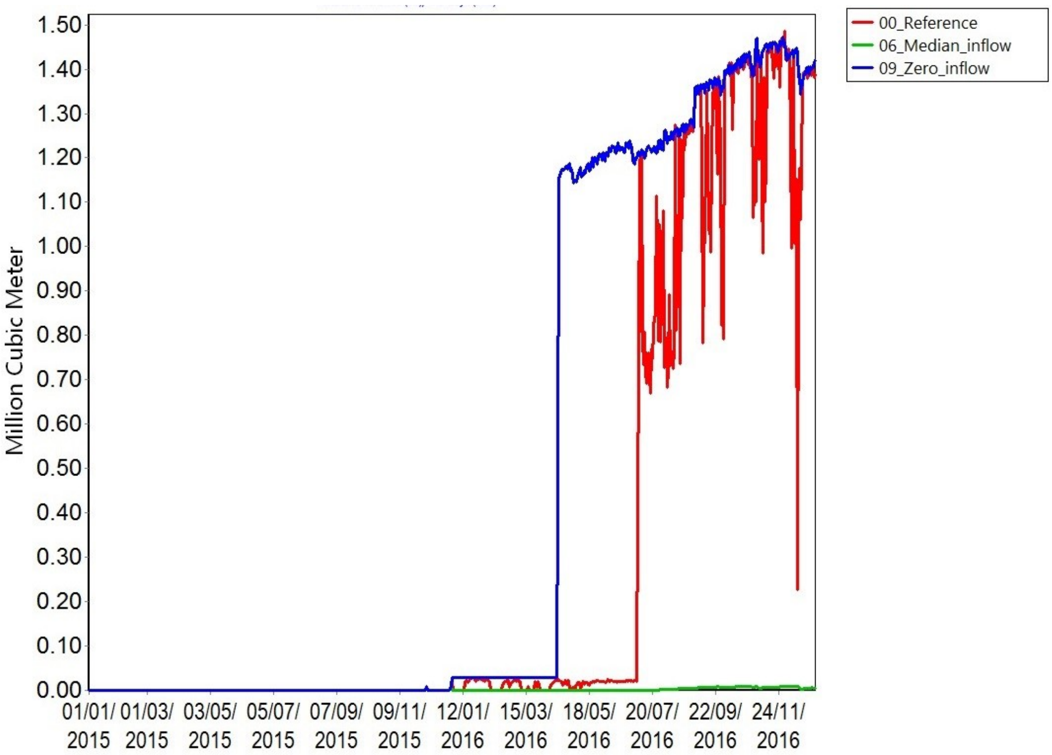

Figure 41. Projected daily water shortage in 2015 and 2016 for different inflow scenarios.

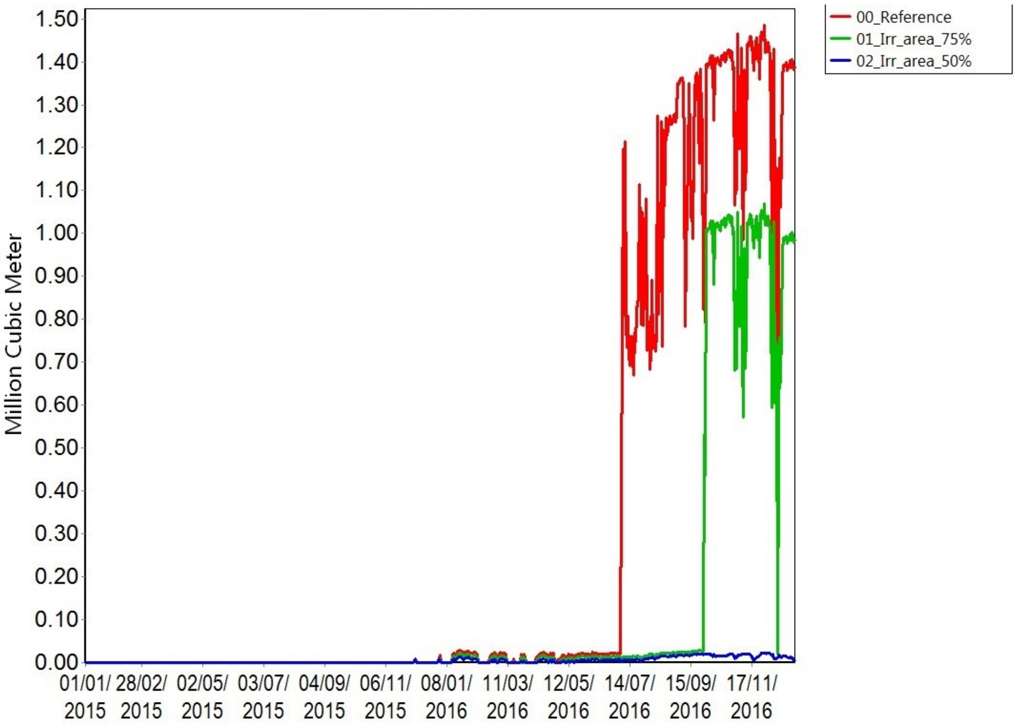

Figure 42. Projected water shortage in 2015 and 2016 for different water saving scenarios.

5.2.2 Reservoir volume

For most scenarios the reservoir volume is projected to become lower than 137 MCM (corresponding to a reservoir elevation of 95 m) during 2016 (see Figure 43, Figure 44 and Table 21, Table 22). Only for the median inflow scenarios and for scenario 02 (reference with 50% less water use for irrigation) the reservoir volume is projected to stay higher than 137 MCM.

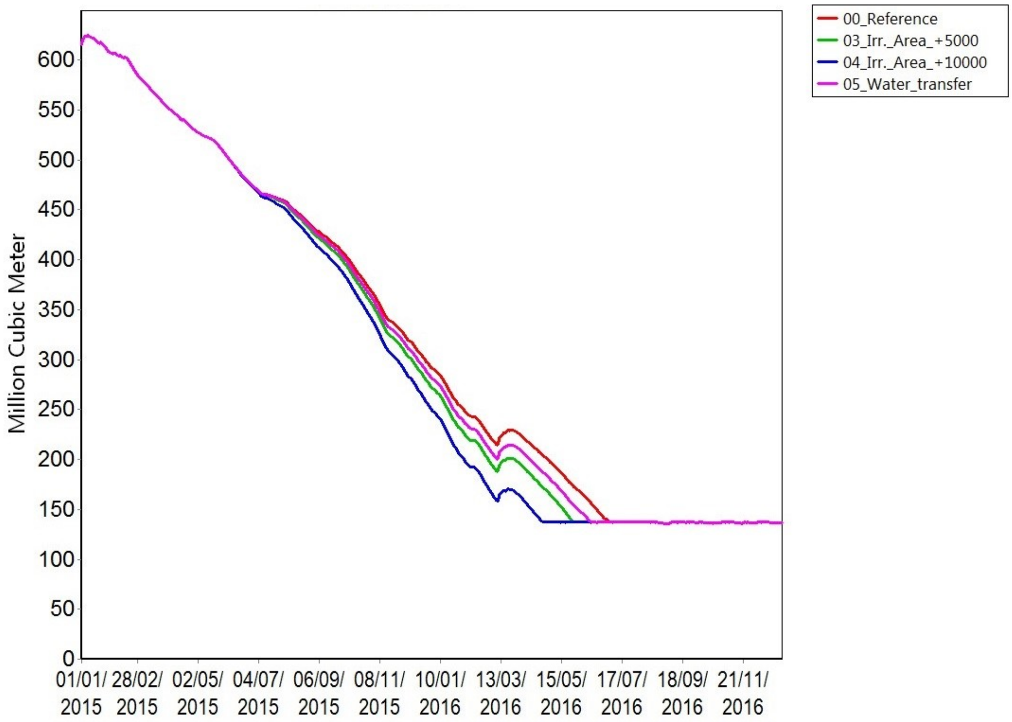

Figure 43. Projected reservoir volume for different development scenarios (2015-2016).

Table 21. Projected moment of the year the reservoir elevation will become lower than 95 m for different development scenarios

Scenario	Reservoir elevation < 95 m
00_Reference	July 2016
03_Irr area +5000	June 2016
04_Irr area +10000	May 2016
05_Water transfer	June 2016

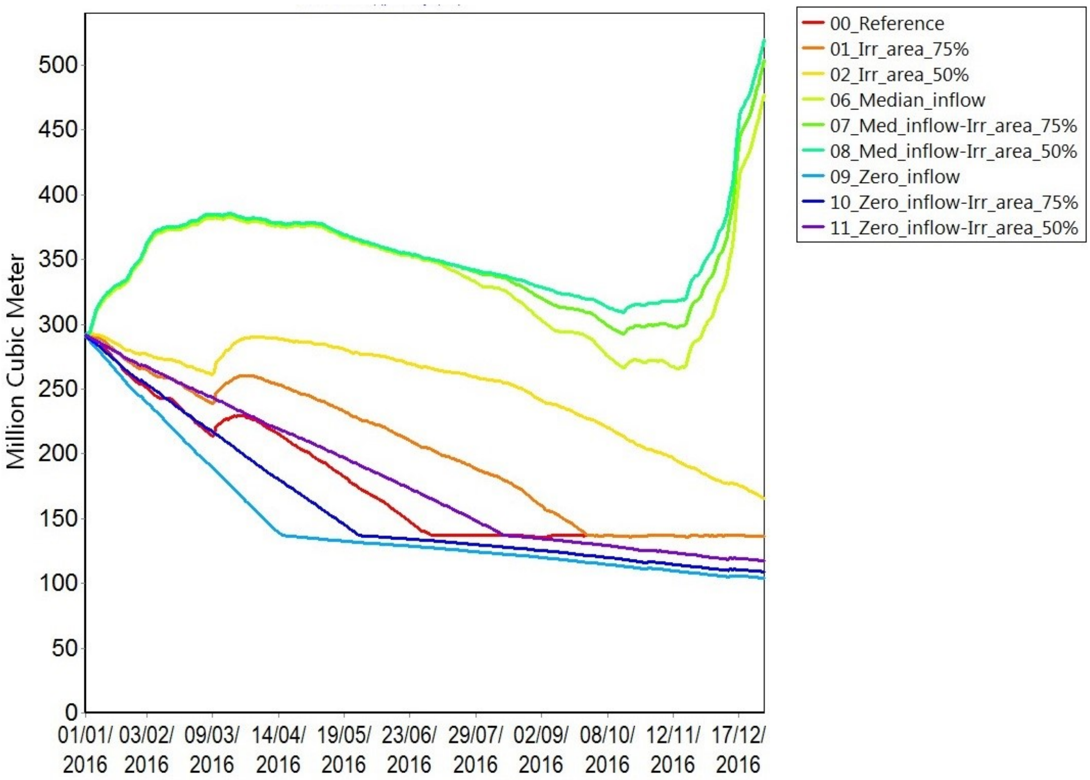

Figure 44. Projected reservoir volume for different inflow and water saving scenarios (2016).

Table 22. Projected moment of the year the reservoir elevation will become lower than 95 m for different inflow and water saving scenarios

Scenario	Reservoir elevation < 95 m
00_Reference	July 2016
01_Irr area 75%	October 2016
02_Irr area 50%	-
06_Median inflow	-
07_Irr area 75%	-
08_Irr area 50%	-
09_Zero inflow	April 2016
10_Irr area 75%	June 2016
11_Irr area 50%	August 2016

5.2.3 Outflow of Incomati into the Indian Ocean

The outflow of Incomati into the Indian Ocean is projected to become lower than the minimum flow requirement of 5 m^3/s during 2016 for most scenarios (see Table 23 and Table 24). For the reference scenario the outflow is projected to be lower than 5 m^3/s during approximately 50% of the days in 2016 (see Table 23). However, the streamflow will not become lower than 2.7 m^3/s.

Table 23. Projected percentage of the year 2016 during which the outflow of Incomati to the Indian Ocean will be lower than 5 m^3/s for different development scenarios

Scenario	< 5 m^3/s (in 2016)	Minimum streamflow (m^3/s)
Reference	49%	2.7
Irr area +5000	59%	2.7
Irr area +10000	68%	2.7
Water transfer	55%	2.7

Table 24. Projected percentage of the year 2016 during which the outflow of Incomati to the Indian Ocean will be lower than 5 m^3/s for different inflow and water saving scenarios

Scenario	< 5 m3/s (in 2016)	Minimum streamflow
Reference	49%	2.7
Irr area 75%	26%	3.1
Irr area 50%	0%	5.0
Median inflow	0%	5.0
Irr area 75%	0%	5.0
Irr area 50%	0%	5.0
Zero inflow	71%	2.7
Irr area 75%	60%	3.1
Irr area 50%	38%	3.6

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 45 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.

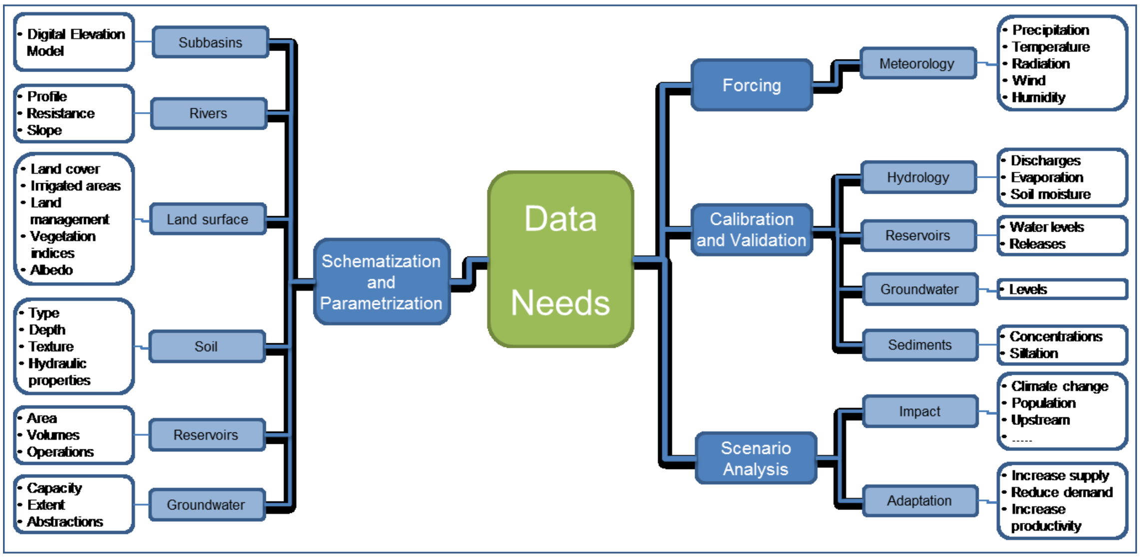

Figure 45. Overview of data needs to build water allocation models.

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 → A shapefile with subbasins was available, however another (similar) shapefile was created. The subbasins in this shapefile are based on a previous WIBIS study and include also the country borders.
    - Rivers → a shapefile with rivers was available.
    - Land surface → No land cover and/or land use maps were available. Therefore an estimation of the irrigated area was made based on the population number.
    - Soil → No soil map was available. Therefore more generic soil data was used. In case more detailed data is needed one could use the African Soil Grids 250m Database if local soil maps are lacking.

    - Reservoirs → Detailed information on the Corumana reservoir in Mozambique was available. For Swaziland and South Africa no detailed data was available and information was used from the UNESCO study.
    - Groundwater → Groundwater was considered to be less relevant for the WAM-O and WAM-S. However, based on the overall basins characteristics (a dry season 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 CHIRPS dataset.
- Calibration and Validation
    - Hydrology → Quite some streamflow data was available for South Africa and Mozambique. However, a lot of data was outdated and/or stage-discharge relationships somewhat outdated. For the most important streams data was available and was used.
    - 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 → Water quality data was available for South Africa and very sparse water quality data was available for Mozambique. Since only a first order water quality analysis has been included in the model, this data was not used for calibration and validation.

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 not clear regarding to the volumes that are released for hydropower production. In order to decrease the uncertainty of the future scenarios the predictability of the reservoir operations should be improved. It is therefore advised to establish and document clear rules on volumes that can be used for hydropower production based on the inflow of the reservoir, the reservoir levels and the energy demand.
- Some errors were detected in the calculation spreadsheet of the Corumana reservoir. Although these errors are not major, it would be advised to correct those. The errors are summarized in APPENDIX V: Errors in Water Balance Calculations.
- Many streamflow gauging stations exist in the Incomati Basin; a selection of these stations is provided in Table 3. Many of the 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 May 2016, 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. Furthermore, the data that is stored by different staff members is not always consistent. 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 the results described in this report and additional experiences and discussion with ARA-Sul staff involved in the current project the following conclusions can be drawn:

- Current operational management of the Corumana reservoir is not based on clear rules. A certain amount of water is released to meet downstream demands, but a large amount of extra water is released for hydropower production. However, clear rules are specified for the restriction of releases when the reservoir volume is below a certain level during a certain moment of the year. The establishment of clear rules for hydropower releases is recommended to decrease the uncertainty of future projections of reservoir storage and downstream water availability.
- The reservoir level of Corumana reservoir is expected to drop below 95 m during 2016. Only when the water use for irrigated agriculture is reduced by around 50% the reservoir level will stay above 95 m. When water will be released up to reservoir levels of 85 m the water use for agriculture can be reduced less. It is expected that from 2019 onwards extra storage capacity will be available. With this extra storage capacity severe water shortages are only projected for demand sites that are not influenced by reservoir management.
- 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 the characteristics of the hydropower production could be improved in case clear operational rules will be established. Furthermore, rules for restricting releases in case of low reservoir levels could be specified. Both WAM-O and WAM-S could be improved by adding more detailed water user information and including more detailed information on downstream flow requirements. Now the location, water use and return flows of most users are estimated or based on global numbers. Furthermore, the variation of water use within the year is not known for most users. Once the water user data has been improved the result of WAM-S can be improved further by making the reservoir characteristics in WAM-S more specific (see ARA-Sul, 2010 or WAM-O). 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. Currently a one week internal ARA-Sul training on working with the WAMs is planned and will be supervised by ARA-Sul staff that has already more experience. 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.
- The developed models for the Incomati, as described in this report, follow the same approach as the models developed previously for the Umbeluzi. For both basins a WAM-Operational — focusing on reservoir management — and a WAM-Strategic for water allocation policy have been developed. The approach for WAM-O for Incomati was similar as the approach for Umbeluzi. The only difference is that some of the catchments in WAM-S were also included in WAM-O for the Incomati model. The reason that this was not done for the Umbeluzi is that this basin is much smaller. The approach for WAM-S for Incomati is similar as the approach for Umbeluzi with the exception that more nodes were used and that water quality was included as well.
- 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. Limpopo). 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: WEAP Land Use Parameters

Kc
The crop coefficient, relative to the reference crop, for a land class type.

Root Zone Water Capacity
The effective water holding capacity of the top layer of soil, represented in mm (top "bucket").

Deep Water Capacity
Effective water holding capacity of lower, deep soil layer (bottom "bucket"), represented in mm. This is given as a single value for the catchment and does not vary by land class type. This is ignored if the demand site has a return flow link to a groundwater node.

Deep Conductivity
Conductivity rate (length/time) of the deep layer (bottom "bucket") at full saturation (when relative storage z2 = 1.0), which controls transmission of baseflow. This is given as a single value for the catchment and does not vary by land class type. Baseflow will increase as this parameter increases. This is ignored if the demand site has a return flow link to a groundwater node.

Runoff Resistance Factor
Used to control surface runoff response. Related to factors such as leaf area index and land slope. Runoff will tend to decrease with higher values (range 0.1 to 10). This parameter can vary among the land class types.

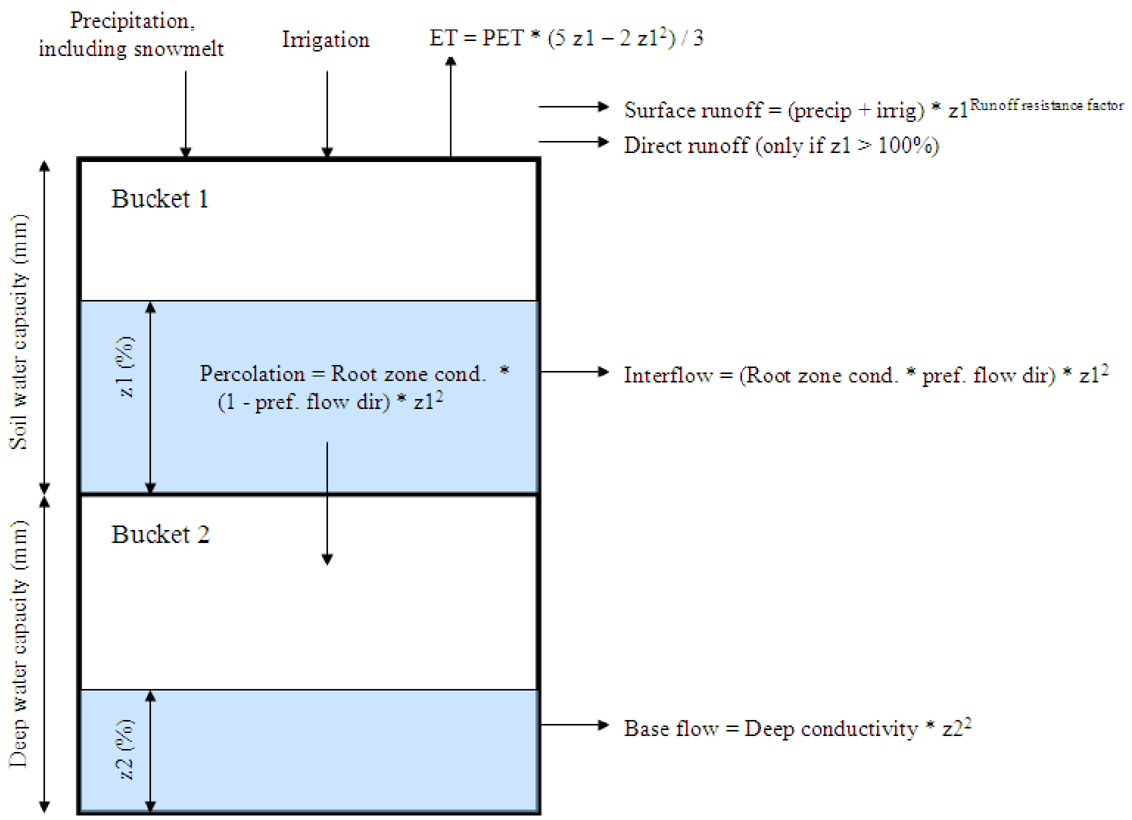
Root Zone Conductivity
Root zone (top "bucket") conductivity rate at full saturation (when relative storage z1 = 1.0), which will be partitioned, according to Preferred Flow Direction, between interflow and flow to the lower soil layer. This rate can vary among the land class types.

Preferred Flow Direction
Preferred Flow Direction: 1.0 = 100% horizontal, 0 = 100% vertical flow. Used to partition the flow out of the root zone layer (top "bucket") between interflow and flow to the lower soil layer (bottom "bucket") or groundwater. This value can vary among the land class types.

Initial Z1
Initial value of Z1 at the beginning of a simulation. Z1 is the relative storage given as a percentage of the total effective storage of the root zone water capacity.

Initial Z2
Initial value of Z2 at the beginning of a simulation. Z2 is the relative storage given as a percentage of the total effective storage of the lower soil bucket (deep water capacity). This parameter is ignored if the demand site has a runoff/infiltration link to a groundwater node. This rate cannot vary among the land class types.
Conceptual diagram and equations incorporated in the Two-bucket model

Conceptual Diagram And Equations Incorporated In The Two-Bucket Model



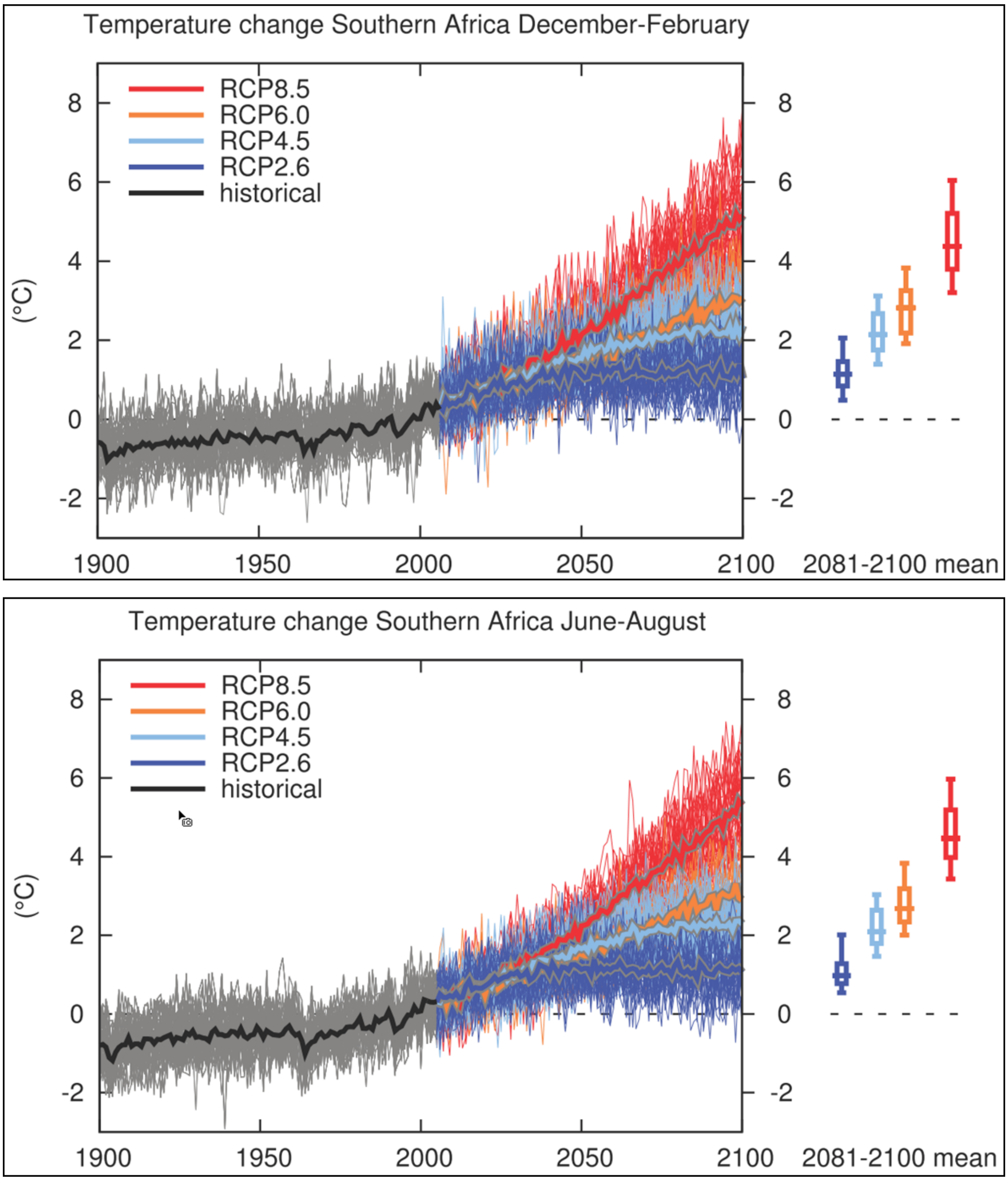


Figure 46. Changes in temperature for Southern Africa. Source: IPCC Fifth Assessment Report, 2013

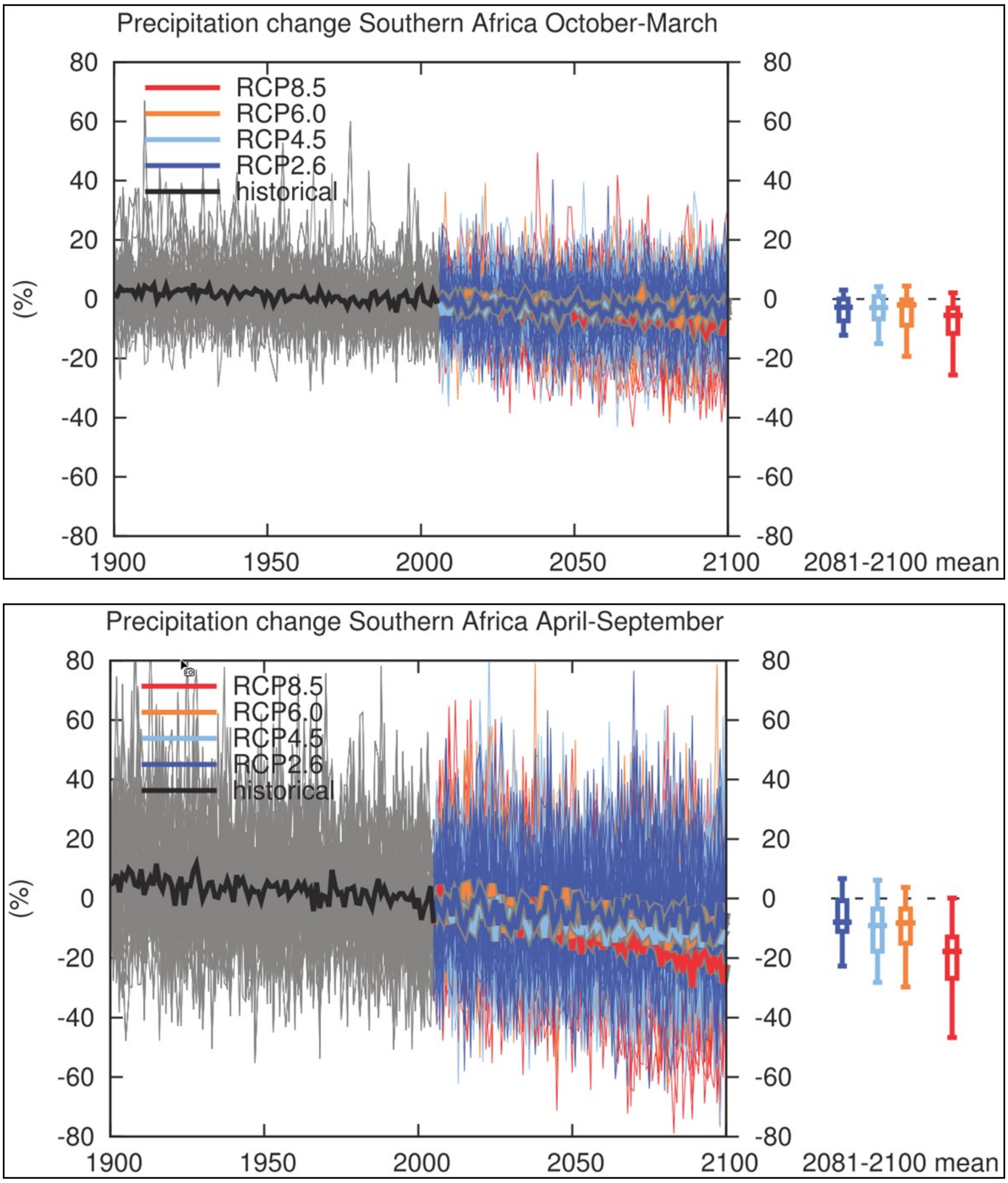


Figure 47. Changes in precipitation for Southern Africa. Source: IPCC Fifth Assessment Report, 2013

APPENDIX III: Implementation of Scenarios

- (01) Impact: Maputo transfer
  - Demand Sites and Catchments > Maputo_transfer > Startup Year > 2019
  - Demand Sites and Catchments > Maputo_transfer > Water Use > Annual Activity Level > 1 Prod.
  - Demand Sites and Catchments > Maputo_transfer > Water Use > Annual Water Use Rate > 12*6 MCM/production unit

- (02a) Impact: Population growth[22] (2.45% per year from 2011 onwards)
  - Key Assumptions > Demand_Pop > If(Year>2010,Growth(2%),0.125*365)
  - Demand Sites and Catchments > All Demand Sites > Population > Annual Activity Level > If(Year>2010,Growth(2.45%),201606[23])

- (02b) Impact: Population growth only (2.45% per year from 2011 onwards)
  - Demand Sites and Catchments > All Demand Sites > Population > Annual Activity Level > If(Year>2010,Growth(2.45%),201606[23])
  - Demand Sites and Catchments > All Demand Sites > Irrigation > Annual Activity Level > 9136.1[24]
  - Demand Sites and Catchments > All Demand Sites > Industry > Annual Activity Level > 4866.4[25]

- (03) Adaptation: Prevent tap water leakage losses
  - Key Assumptions > Demand_Pop > If(Year>2010,0.75*0.125*365,0.125*365)

- (04) Impact: Increase in irrigated areas (2% per year from 2011 onwards)
  - Demand Sites and Catchments > All Demand Sites > Annual Activity Level > Irrigation > If(Year>2010,Growth(2%),(Population[cap] / 5) ^ 0.86)

- (05) Adaptation: Increased reservoir capacity (from 2019 onwards)
  - Supply and Resources > River > Incomati > Reservoirs > Moamba Major:
    - Startup Year > 2019
    - Physical > Storage Capacity > 760 MCM
    - Physical > Volume Elevation Curve > Volume: 760, Elevation: 40
    - Water Quality > Supply and Resources\River\Incomati\Reaches\Below Dem_10 Withdrawal:TDS Concentration[mg/l]
  - Supply and Resources > River > Sabie > Reservoirs > Corumana > Physical > Storage Capacity > If(Year <2019,879,1345)
  - Supply and Resources > River > Sabie > Reservoirs > Corumana > Physical > Volume Elevation Curve > Volume: 1345, Elevation: 117

- (06) Adaptation: Reduce conveyance losses in irrigation systems
  - Key Assumptions > Demand_Irri > If(Year>2010,0.75*10000,10000)

- (07) Impact: Climate change (precipitation -10%, temperature +3°C)
  - Key Assumptions > Precip_Corr > If(Year>2010,0.9,1)
  - Demand Sites and Catchments > All Catchments > Climate > Temperature > If(Year>2010,ReadFromFile(UserData\Temperature.txt,1)+3,ReadFromFile(UserData\Temperature.txt, 1))

- (08) Impact: Likely Future (impact 01, 02a, 04 and 07 as defined above)
  - Demand Sites and Catchments > Maputo_transfer > Startup Year > 2019
  - Demand Sites and Catchments > Maputo_transfer > Water Use > Annual Activity Level > 1 Prod.
  - Demand Sites and Catchments > Maputo_transfer > Water Use > Annual Water Use Rate > 12*6 MCM/production unit
  - Key Assumptions > Demand_Pop > If(Year>2010,Growth(2%),0.125*365)
  - Demand Sites and Catchments > All Demand Sites > Population > Annual Activity Level > If(Year>2010,Growth(2.45%),201606[26])

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

[23] Give for each Demand Site the Population of the Current Accounts Year.

[24] Give for each Demand Site the Irrigated Area of the Current Accounts Year.

[25] Give for each Demand Site the number of Industrial Units of the Current Accounts Year.

[26] Give for each Demand Site the Population of the Current Accounts Year.

    - Key Assumptions > Precip_Corr > If(Year>2010,0.9,1)
    - Demand Sites and Catchments > All Catchments > Climate > Temperature > If(Year>2010,ReadFromFile(UserData\Temperature.txt,1)+3,ReadFromFile(UserData\Temperature.txt, 1))

- (09) Adaptation: Increased reservoir capacity (adaptation 05)
    - Supply and Resources > River > Incomati > Reservoirs > Moamba Major:
        - Startup Year > 2019
        - Physical > Storage Capacity > 760 MCM
        - Physical > Volume Elevation Curve > Volume: 760, Elevation: 40
        - Water Quality > Supply and Resources\River\Incomati\Reaches\Below Dem_10 Withdrawal:TDS Concentration[mg/l]
    - Supply and Resources > River > Sabie > Reservoirs > Corumana > Physical > Storage Capacity > If(Year <2019,879,1345)
    - Supply and Resources > River > Sabie > Reservoirs > Corumana > Physical > Volume Elevation Curve > Volume: 1345, Elevation: 117

- (10) Adaptation: Improved system (adaptations 03 and 06)
    - Key Assumptions > Demand_Pop > If(Year>2010,0.75*0.125*365,0.125*365)
    - Key Assumptions > Demand_Irri > If(Year>2010,0.75*10000,10000)

- (11) Adaptation: Full adaptation (adaptations 03, 05 and 06)
    - Key Assumptions > Demand_Pop > If(Year>2010,0.75*0.125*365,0.125*365)
    - Supply and Resources > River > Incomati > Reservoirs > Moamba Major:
        - Startup Year > 2019
        - Physical > Storage Capacity > 760 MCM
        - Physical > Volume Elevation Curve > Volume: 760, Elevation: 40
        - Water Quality > Supply and Resources\River\Incomati\Reaches\Below Dem_10 Withdrawal:TDS Concentration[mg/l]
    - Supply and Resources > River > Sabie > Reservoirs > Corumana > Physical > Storage Capacity > If(Year <2019,879,1345)
    - Supply and Resources > River > Sabie > Reservoirs > Corumana > Physical > Volume Elevation Curve > Volume: 1345, Elevation: 117

- (12) Water Quality: Improved treatment.
    - Key Assumptions > TDS_loads > Catchments > If(Year>2010,0.75*20000,20000)

APPENDIX IV: Glossary

ARA = Administração Regional de Água
CMS = cubic meter per second = m^3/s
CHIRPS = Climate Hazards group InfraRed Precipitation with Station data
DWAF = Department of Water Affairs and Forestry
FAT = Factory Acceptance Test
FSL = Full Supply Level
MASL = Meters Above Sea Level
MAR = Mean Annual Runoff
MCM = million cubic meter = 10^6 m^3
RCP = Representative Concentration Pathway
SAT = Site Acceptance Test
TDS = Total Dissolved Solids
Unmet Demand = Water Shortage
WAM = Water Allocation Model

Statistic variables

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

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

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

APPENDIX V: Errors in Water Balance Calculations

In the water balance from 2004 to 2008 precipitation was not taken into account in the water balance to calculate the inflow into the reservoir. Precipitation should be included as a minus term.

YYYY	MM	DD	Improvement
1989	01	03	The elevation at 12:00 should be around 87.8 instead of 87.0
	01	23	The elevation at 12:00 should be 89.04 instead of 88.04 and the value of 17:00 should be 89.05 instead of 88.05.
	01	24	The elevation at 12:00 should be 89.07 instead of 88.07.
	04	22	The elevation at 12:00 should be around 91.67 instead of 91.97.
	06	22	The elevation at 07:00 should be 93.29 instead of 92.29.
1990	01	22	The elevation at 17:00 should be 97.8 instead of 92.8.
	01	27	The elevation at 12:00 should be 97.9 instead of 98.9.
	02	18	The elevation at 12:00 should be 99.24 instead of 98.24 and the value of 17:00 should be 99.26 instead of 98.26.
1991	01	27	The elevation at 12:00 should be 103.75 instead of 102.75.
	07	15	The elevation at 17:00 should be 104.73 instead of 107.73.
1992	01	16	The elevation at 07:00, 09:00 and 12:00 should be 103.39 instead of 103.49.
	04	30	The elevation at 17:00 should be 102.53 instead of 102.23.
	05	14	The elevation at 07:00 and 09:00 should be 102.39 instead of 103.39.
	05	16	The elevation at 12:00 should be 102.34 instead of 103.34.
	09	30	The elevation at 12:00 and 17:00 should be 99.81 instead of 99.91 and 99.41 respectively.
1993	01	30	The elevation at 07:00 and 09:00 should be 102.21 instead of 101.21.
	01	31	The elevation at 07:00 and 09:00 should be 102.23 instead of 101.23.
	06	16	The elevation at 12:00 should be 105.87 instead of 108.87.
	10	10	The elevation at 17:00 should be 105.03 instead of 103.03.
	10	11	The elevation at 07:00, 09:00, 12:00 and 17:00 should be 105.03 instead of 103.03.
1994	01	25	The elevation at 17:00 should be 104.98 instead of 105.98.
1996	01	28	The elevation at 09:00 should be 103.02 instead of 102.02.
	05	01	The elevation at 17:00 should be 110.43 instead of 101.43.

	08	28	The elevation at 07:00 and 09:00 should be 106.92 instead of 109.92.
1998	02	14	The elevation at 07:00 should be 103.23 instead of 102.23.
1999	11	14	The elevation at 12:00 should be 105.9 instead of 109.9.
2000	01	20	The elevation at 12:00 should be 109.24 instead of 108.24.
	01	29	The elevation at 12:00 should be 109.78 instead of 108.78.
	03	08	The elevation at 12:00 should be 108.78 instead of 109.78.
2009	04	14	Formula for calculating volume from elevation in cell G26 should be: =IF(F26>**108**,1.35617*10^4-2.99814*10^2*F26+1.67143*F26^2,IF(F26>80,1.0519322*10^4+-2.42625*10^2*F26+1.4035714*F26^2,NA())) This changes also the inflow of 15 April.
2010	04	14	Formula for calculating volume from elevation in cell G26 should be: =IF(F26>**108**,1.35617*10^4-2.99814*10^2*F26+1.67143*F26^2,IF(F26>80,1.0519322*10^4+-2.42625*10^2*F26+1.4035714*F26^2,NA())) This changes also the inflow of 15 April.
	12	09	Typing error in elevation at 17:00. Should be 106.77 instead of 103.77 (in cell D63). This changes also the inflow of 10 December.
2011	01	01	Elevation at 31 December 2010 (in cell C5) is not 107.15, but 108.00.
	04	14	Formula for calculating volume from elevation in cell G26 should be: =IF(F26>**108**,1.35617*10^4-2.99814*10^2*F26+1.67143*F26^2,IF(F26>80,1.0519322*10^4+-2.42625*10^2*F26+1.4035714*F26^2,NA())) This changes also the inflow of 15 April.
	07	19	Typing error in elevation at 09:00. Should be 109.52 instead of 10.952 (in cell B73). Changes also inflow of 20 July.
	09	06	Typo in Cell C59 should be 108.46 instead of ‘108.46.
	01-11 to 01-12		All references to the elevation refer to the wrong row, e.g. the reference to A56 should be to A55, B56 to B55, etc. As a result the values for 30 November were missing and the elevation difference for 1 December was missing.
	11	22-30	Missing values at 09:00, 12:00 and 17:00 were replaced by the value at 07:00.
	12	06	Typo in Cell A60 should be 105.38 instead of 106.38. Changes also inflow of 7 December.

2012	29-02 to 01-03		The row for the elevation reference to the value of 29 February is missing. Also the reference for the elevation value of the previous day in the sheet of March (cell C5) is wrong.
	04	14	Formula for calculating volume from elevation in cell G26 should be: =IF(F26>**108**,1.35617*10^4-2.99814*10^2*F26+1.67143*F26^2,IF(F26>80,1.0519322*10^4+-2.42625*10^2*F26+1.4035714*F26^2,NA())) This changes also the inflow of 15 April.
	05	10	Typo in cell A64 and B64. Should be 109.07 instead of 109.97. Changes also inflow of 11 May.
	08	01	Typo in cell B55 should be 106.86 instead of 108.86. Also changes inflow of 2 August.
	09	24	Typo in cell C76 and D76 should be 106.00 instead of 160.00. Also changes inflow of 25 September.
2013	01	01	Elevation at 31 December 2012 was not 104.52, but 106.44 (in cell C5).
	04	14	Formula for calculating volume from elevation in cell G26 should be: =IF(F26>**108**,1.35617*10^4-2.99814*10^2*F26+1.67143*F26^2,IF(F26>80,1.0519322*10^4+-2.42625*10^2*F26+1.4035714*F26^2,NA())) This changes also the inflow of 15 April.
	08	01	Typo in cell C55. Should be 108.91 instead of 109.91. Changes also inflow of 2 August.
	09	10	Typo in cell A62 and B62. Should be 107.88 instead of 107.98. Changes also inflow of 11 September.
	11	06	Typo in cell B60 should be 105.82 instead of 108.82. Changes also inflow of 7 November.
2014	01	01	Elevation at 31 December 2013 was not 104.52, but 104.89 (in cell C5).
	01	31	Typo in cell C85 should be 105.81 instead of 108.81. Changes also inflow of 1 February.
	02	28	Missing values at 12:00 and 17:00 replaced by value at 09:00. Changes also inflow of 1 March.
	04	14	Formula for calculating volume from elevation in cell G26 should be: =IF(F26>**108**,1.35617*10^4-2.99814*10^2*F26+1.67143*F26^2,IF(F26>80,1.0519322*10^4+-2.42625*10^2*F26+1.4035714*F26^2,NA())) This changes also the inflow of 15 April.

	06	30	Missing values replaced by of previous day. Changes also inflow of 1 July.
	08	28	From 12:00 onwards the elevation cell does not contain a reference anymore, but just a value. They should refer to table.
	08	29-31	The elevation cells do not contain a reference anymore, but just a value. They should refer to table. Changes also inflow of 1 September.
	10	13	Typo in Cell C67 and D67 should be 106.04 and 106.03 instead of 105.04 and 105.03. Changes also inflow of 14 October.
	10	17	Typo in Cell A71 should be 105.93 instead of 105.393. Changes also inflow of 18 October.
	10	22	Typo in Cell C76 should be 105.82 instead of 102.82. Changes also inflow of 23 October.
	11	01-30	Elevations, Evaporation and Outflow from the reservoir do not refer to table at bottom of sheet. The precipitation, time and ‘cota jusante’ columns refer to the wrong row, e.g. to F56 instead of F55. The time in cell H55 was not 24h (wrong format).
	12	01	The sheet of December is Titled October in the header of Cell T7. The Elevation of the previous day refers to 30/09 instead of 30/11 in Cell C7 and Cell E7 refers to ='Setembro '!H44 instead of =Novembro!F42.
	12	29-31	Missing Reservoir Elevation values are interpolated between 29 December 09:00 (104.00) and 1 January 2015 (105.12). For Evaporation and Outflow from the reservoir the average over the month is used. Precipitation is kept at zero.
2015	01	01	Average Elevation at 31 December 2014 was not 105.02, but 104.87 (in cell C5) → see improvements 29-31 December 2014.
	05	31	The cells did not refer to the table at the bottom.
	11	01	The Elevation of the previous day in cell C5 refers to the sheet of September instead of October.
	12	31	Typo in Cell D87 should be 98.85 instead of 99.85.
2016	01	01	Elevation of previous day in cell C5 should be 98.85 instead of 98.84.

APPENDIX VI: Participants of Distance Training and Intensive Training Week

Table 25. Participants of the distance training

I. Technical Department
Mr. Gimo Macaringue
Mrs. Adalgisa Tinga
Mr. Teodomiro Cabral
Mr. João Neto da Costa
II. Incomati Basin
Mr. Simião Sumbana
Mr. Abu Jamal

Table 26. Final participants for intensive training week in Mozambique:

Name	**Department**
Mr. Gimo Macaringue (1 day)	ARA-Sul/Technical Department
Mr. Teodomiro Cabral	ARA-Sul/Technical Department
Mr. Simião Sumbana	Incomati/UGBI
Mr. Abu Jamal	Incomati/UGBI
Mr. Edson Guambe	Limpopo/UGBI
Mr. Carlitos Samo Fulana	Umbeluzi/UGBI

APPENDIX VII: Evaluation traineeship G. Macaringue

Departure date _13//_03_//_2016
Return Date _27//_03_//_2016

Objective

To attend the training course in water allocation model of the Incomati Basin

Destination

The Netherlands – Wageningen in Future Water

Activities

- Practical exercises for construction of the water allocation models using the WEAP program - Basic Tutorial WEAP;
- Training in the operating model for the basin Incomáti;
- Conducting practical exercises on future scenarios of water allocation in Incomati basin;
- Inspection and visualization of data used for construction of the strategic model ;
- Field trip and quick visit to Wetterskip Fryslân

Findings

The training course surpassed the expectations of the technician. The training was very interactive lessons which enabled the range of results positive and is ready to use this tool and share the experience with other colleagues involved in modeling;

Models are at in advanced stage of construction however the prevailing challenges to obtain hydrological data from the RSA and water demands in the national section of the Incomati basin, particularly necessary for the strategic and operation model;

It was noted some inconsistencies of the data flow in the Ressano Garcia and Magude stations as well as estimated flow in the water balance of Corumana dam;

It was recommended whenever possible using the hydrological data available on the web- site in the Department of Water in South African to use in models. Tributaries flow to the country can also be found in located immediately upstream stations of South African side.

As subsequent steps, it was scheduled another training session at distance. It was also agreed the completion of the training course for about 7 technical ARA-Sul staff to use this model, from 9 to 13 May.