Water Allocation Planning in Pungwe Basin Mozambique

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Commissioned by

Partners for Water

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Preface

The Netherlands' "Partners for Water" initiative has the objective to support the Dutch water sector to capitalize on its technologies and expertise internationally, while simultaneously ensure that Dutch technologies and knowledge contribute to solving world water challenges.

A call for proposal was announced by "Partners for Water" 2013. A consortium of three Netherlands' partners developed a proposal on request of Administração Regional de Águas do Centro (ARA-Centro), Beira-Mozambique, under the name "Water Planning Tools to Support Water Governance". The project was granted on 16-May-2013 and will run from March 2013 to September 2014.

The contract number is PVWS13001.

The project partners are:

- Administração Regional de Águas do Centro (ARA-Centro), Beira-Mozambique *(beneficiary)*
- FutureWater, Wageningen, Netherlands *(lead)*
- Waterschap Hunze en Aa's, Veendam, Netherlands *(consortium partner)*
- UNESCO-IHE, Delft Netherlands *(consortium partner)*
- WE-Consult, Maputo, Mozambique *(support partner)*

1 Introduction

1.1 Relevance

Mozambique is experiencing a steady economic growth of 5 to 10% a year. Much of this economic growth is related to capital-intensive international projects that are high water demanding (aluminum smelter, hydropower, transportation, irrigation). Also the water use by the drinking water companies grows as the cities develop, and several new irrigation schemes are planned to increase the Mozambican food production. On the long term 190,000 ha of irrigated agriculture will be developed in the Beira region. A substantial part of this irrigation will be developed in the management area of ARA-Centro. Also an increase in water use by FIPAG (Water Supply Investments and Assets Fund) Beira and the sugar estate Mafambisse is expected along the river Pungwe. All these developments result in an increase in water demand of 10-20% per year and this trend is expected to continue the coming decades.

Large water shortages are projected if no mitigation measures will be taken over the coming years. In general improved water governance is needed to guarantee the ecological and economic use of water, now and on the long term in Mozambique. ARA-Centro has to advise on the water availability and the required measures that are needed to make this development possible. For this advisory role hydrological models and water allocation tools are needed that can be used to quantify the available water resources and the present and future water demand. Only by state-of-the-art models and tools, and better trained staff, based on the Netherlands water governance principles, ARA-Centro is able to take-up these challenges. Moreover, ARA-Centro has expressed their ambition to become the front-runner to actually develop and implement these water governance principles.

This report is part of the **'Water Planning Tools to Support Water Governance'** project, which main objective is: *"Demonstrate the Netherlands water governance system to one water management organization (ARA) in Mozambique"*.

The specific objective of the hydrological component of the entire study is to perform a water resources and demand assessment of the Pungwe River Basin in order to:

- Strengthen ARA-Centro's knowledge on the current hydrological state of the Pungwe River Basin;
- Provide ARA-Centro with knowledge on the data and tools that are available to undertake a hydrological assessment study;
- Provide ARA-Centro with a roadmap (guideline) that can be followed to undertake hydrological assessment studies for other river basins within Mozambique.

One of the activities of this project is to introduce, refine and demonstrate the application of two water planning tools (SWAT and WEAP) to a pilot area in the ARA-Centro management area. This report describes the water demand and unmet demand of the water resources within the Pungwe basin using the WEAP modeling framework.

1.2 Pungwe Basin[1]

The Pungwe river is shared by Zimbabwe and Mozambique. The length of the river is nearly 400 km of which 340 km is in Mozambican territory. The Pungwe river drains an area of 31,000 km^2. Only 5% of the basin is situated in Zimbabwe.

The Pungwe river rises from the foothills of Mount Inyangani in eastern Zimbabwe, flows into Honde Valley where it crosses into Mozambique (Figure 1). This part is considered the middle Pungwe, up to the point at Bué Maria where it reaches the plains, referred to as the lower part of the basin. Downstream of Bué Maria the river divides in several streams, of which the Dingue is the most important, because through it the main discharge in the dry period is transported. The streams join near the bridge over the Pungwe river on the EN6, which is situated some 100 km from the estuary mouth, in the zone under tidal influence. At the estuary the Pungwe waters enter the Indian Ocean. This is some 20 kilometers north-west of the City of Beira.

The discharge at Bué Maria plays an important role in pushing back the salt sea water intrusion through the estuary, which is crucial for the City of Beira's water supply intake. The 10% low flow (i.e. the flow with a return period of 10 years) at Bué Maria has been established at 8.8 m^3/s (Zanting et al., 1994). A flow of 10 m^3/s is considered the minimum flow to safeguard the intake of fresh water for Beira (Chamuço, 1997).

More details of the Pungwe Basin can be found in various other sources including the SWAT report (Terink et al., 2014).

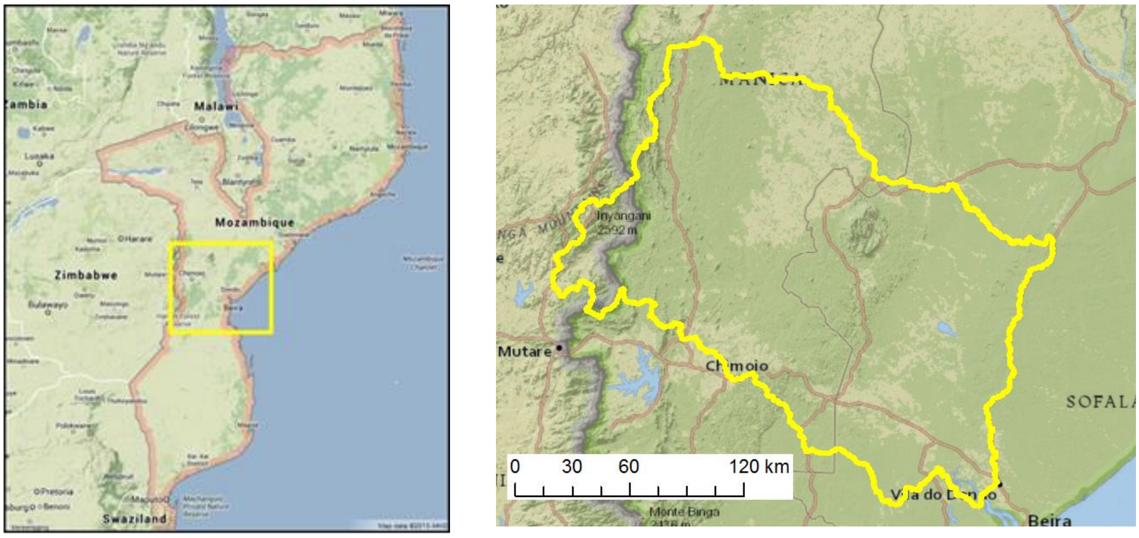


Figure 1: Location of the Pungwe River basin in central Mozambique.

[1] This section is based on Van der Zaag, 2000

2 Methods and Tools

2.1 Relevance

Previous analysis and modeling activities in the Pungwe Basin revealed that water shortage might hamper further economic development in the region. However, these analysis and modeling studies were quite outdated using obsolete modeling frameworks, old data sets and do not focus on the most recent strategic plans. It was therefore decided to develop two new modeling frameworks for the Pungwe basin, using state-of-the-art models, data mining techniques (including satellite remote sensing ones) and latest strategic plans. The Soil Water and Assessment Tool (SWAT) model was developed to capture all physical processes at the highest level of detail to understand processes in the basin. These analyses are described in a report by Terink et al (2014). That report discusses also data sources, including advanced data mining processes, used in the current water allocation analysis. This report describes the second modeling approach, using WEAP, focusing on water demand, supply and shortages for the current situation as well as under some development scenarios.

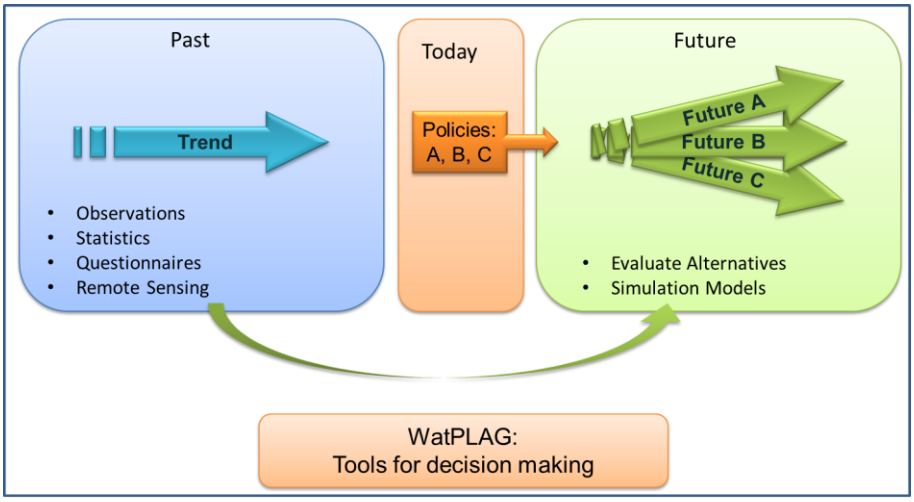


Figure 2: Application of models to evaluate future water resources developments based on today's policies.

2.2 WEAP

The model used for the Pungwe basin is built using the WEAP framework. WEAP is selected as it is designed to work at basin scales and the amount of physical detail needed for this project (Figure 3). 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/). A summary of WEAP's capabilities is provided here.

An easy-to-use tool is needed to match water supplies and competing demands, and to assess the upstream–downstream links for different management options in terms of their resulting water sufficiency or un-met demands, costs, and benefits. The Water Evaluation and Planning tool (WEAP) has been developed to meet this need. It uses the basic principle of water balance accounting: total inflows equal total outflows, net of any change in storage (in reservoirs, aquifers and soil). WEAP represents a particular water system, with its main supply and demand nodes and the links between them, both numerically and graphically. Delphi Studio programming language and MapObjects software are employed to spatially reference catchment attributes such as river and groundwater systems, demand sites, wastewater treatment plants, catchment and administrative political boundaries (Yates *et al.* 2005).

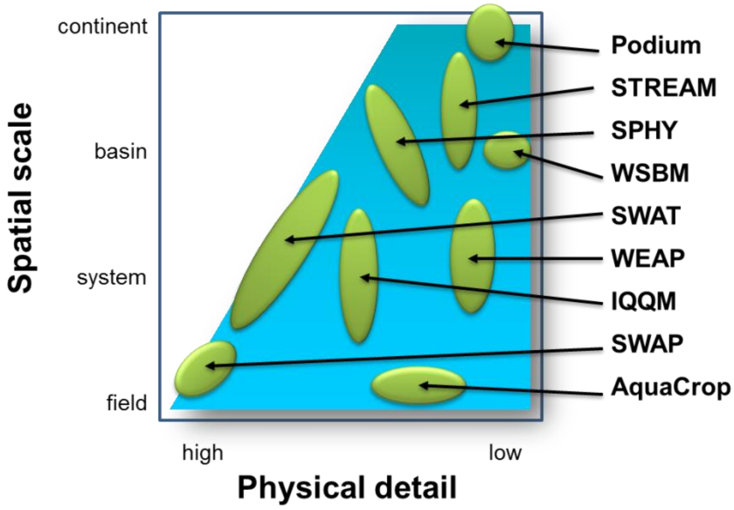


Figure 3: Relation between spatial scale and physical detail in water allocation tools. The green ellipses show the key strength of some well-known models. (Source: Droogers and Bouma, 2014)

Users specify allocation rules by assigning priorities and supply preferences for each node; these preferences are mutable, both in space and time. WEAP then employs a priority-based optimisation algorithm and the concept of "equity groups" to allocate water in times of shortage.

In order to undertake these water resources assessments the following operational steps can be distinguished:

- The study definition sets up the time frame, spatial boundary, system components and configuration. The model can be run over any time span where routing is not a consideration, a monthly period is used quite commonly.
- System management is represented in terms of supply sources (surface water, groundwater, inter-basin transfer, and water re-use elements); withdrawal, transmission and wastewater treatment facilities; water demands; and pollution generated by these activities. The baseline dataset summarises actual water demand, pollution loads, resources and supplies for the system during the current year, or for another baseline year.
- Scenarios are developed, based on assumptions about climate change, demography, development policies, costs and other factors that affect demand, supply and hydrology. The drivers may change at varying rates over the planning horizon. The time horizon for these scenarios can be set by the user.
- Scenarios are then evaluated in respect of desired outcomes such as water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables.

Water supply: Using the hydrological function within WEAP, the water supply from rainfall is depleted according to the water demands of the vegetation, or transmitted as runoff and infiltration to soil water reserves, the river network and aquifers, following a semi-distributed, parsimonious hydrologic model. These elements are linked by the user-defined water allocation components inserted into the model through the WEAP interface.

Water allocation: The challenge is to distribute the supply remaining after satisfaction of catchment demand the objective of maximizing water delivered to various demand elements, and in-stream flow requirements - according to their ranked priority. This is accomplished using an iterative, linear programming algorithm. The demands of the same priority are referred to as “equity groups”. These equity groups are indicated in the interface by a number in parentheses (from 1, having the highest priority, to 99, the lowest). WEAP is formulated to allocate equal percentages of water to the members of the same equity group when the system is supply-limited.

The concept-based representation of WEAP means that different scenarios can be quickly set up and compared, and it can be operated after a brief training period. WEAP is being developed as a standard tool in strategic planning and scenario assessment and has been applied in many regions around the world.

3 Building WEAP for Pungwe Basin

3.1 Introduction

Building the WEAP model for Pungwe requires various sets of data. Data can be divided into the following main categories:

- Model building
    - Static data[2]
        - Soils
        - Land use, land cover
        - Population
        - Reservoir operational rules
    - Dynamic data
        - Climate (rainfall, temperature, reference evapotranspiration)
        - Water demands
        - Reservoir releases (if present)
        - Flow requirements
- Model validation/calibration
    - Streamflow

Data were obtained from various sources and combined into a consistent set of input for WEAP. The following sections will summarize the building of the model, details can be found in the model input data itself.

3.2 Model Components

3.2.1 Boundary, area extent and background layers

Within WEAP various background layers were added to support the development of the model. These layers were created using a GIS tool such as for example ArcMap or QGIS. The most relelvant layers that were added are (Figure 4):

- Geographic based on the National Geographic World Map
- Digital elevation models based on SRTM (Shuttle Radar Topography Mission)
- River flow network based on the of topographic analysis using the SWAT model.
- Subbasins as defined during the SWECO 2006 project.

[2] Nota that static data can still vary over longer time frames, but are fairly constant over days/weeks

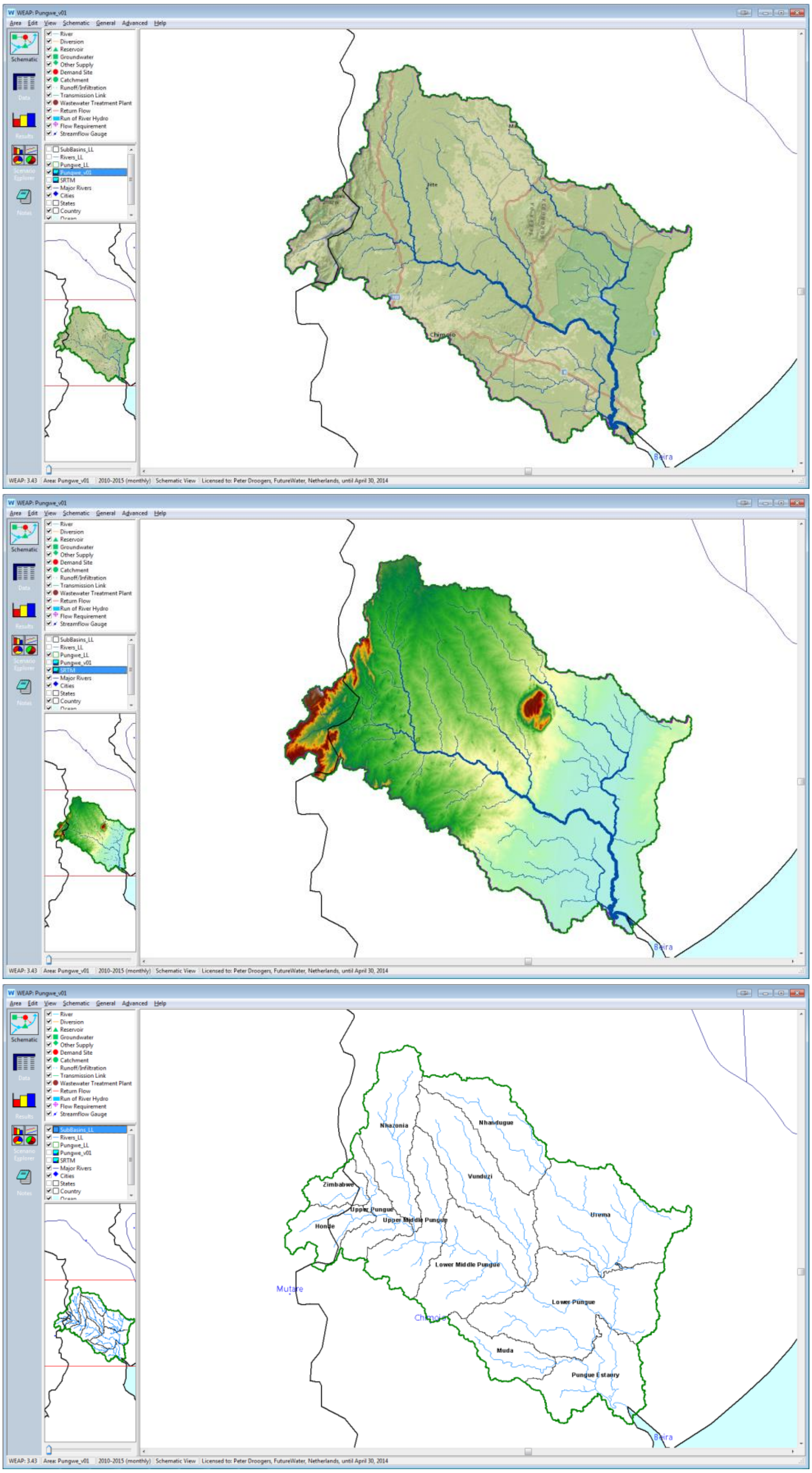


Figure 4. Various background layers used to support model building in WEAP. National Geographic Base map (top), SRTM-DEM (middle), main rivers and subbasins (bottom)

3.2.2 Sub-catchments

Based on the SWECO 2006 study a total of 12 subbasins have been identified (Table 1).

Table 1. Areas of the 12 sub-basins as applied in WEAP.

NAME	Area km2
Nhazonia	2,846
Zimbabwe	687
Honde	1,245
Vunduzi	3,439
Upper Pungue	1,360
Nhandugue	2,830
Urema	5,572
Upper Middle Pungue	2,400
Lower Middle Pungue	2,990
Lower Pungue	3,512
Muda	1,336
Pungue Estaury	2,933

3.2.3 Climate

Various sets of rainfall products are available for the Pungwe basis. The most relevant ones are:

- Observations from ARA-Centro
- Observations from GSOD (Global Summary Of the Day)
- FEWS-RFE (Food Early Warning System – RainFall Estimates) data from NOAA climate prediction center
- TRMM (Tropical Rainfall Measuring Mission) data from satellite

A detailed analysis of these various data products is described in the SWAT report (Terink et al., 2014). From their detailed analysis it was concluded that the FEWS RFE 2.0 rainfall product is the most reliable one with some small corrections for the most upstream parts of the basin in Zimbabwe.

For reference evapotranspiration the following procedure was used:

- Calculated by WEAP based on the Penman-Monteith equation
- Temperature was based on the seven GSOD station in the basin
- Relative Humidity was scaled using the precipitation
- Windspeed and cloudiness fraction were set at default values (2 m/s)

This climate data was converted from Excel into text files. These text files can be read by WEAP. In this way, changing climate information requires only a change in text file and not in the entire WEAP model.

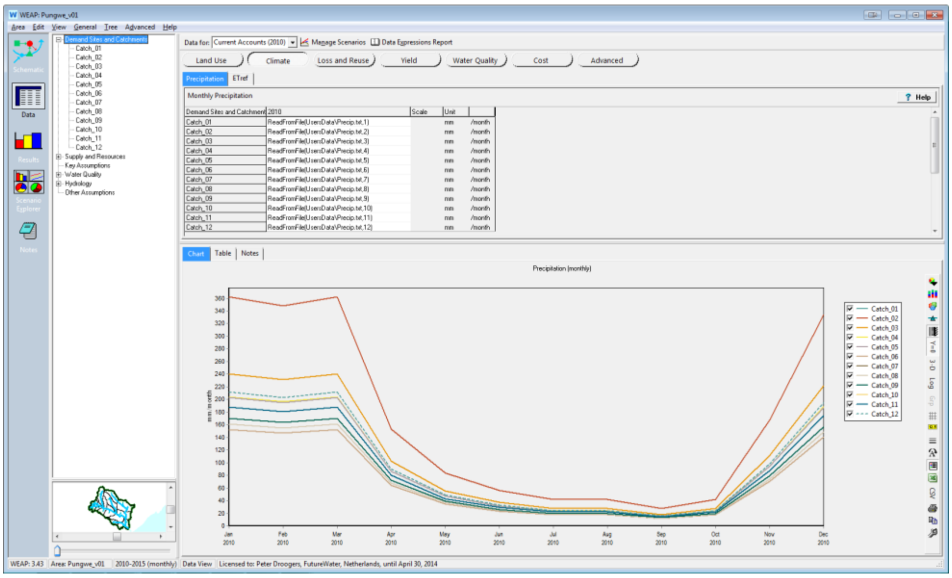


Figure 5. Example of input data: precipitation read from a text file.

3.2.4 Urban and industrial demand

Based on data combined from local expertise of ARA-Centro the population for each sub-basin was obtained.

NR	NAME	Population
1	Nhazonia	44,000
2	Zimbabwe	4,000
3	Honde	5,000
4	Vunduzi	32,000
5	Upper Pungue	11,000
6	Nhandugue	4,000
7	Urema	35,000
8	Upper Middle Pungue	14,000
9	Lower Middle Pungue	32,000
10	Lower Pungue	115,000
11	Muda	36,000
12	Pungue Estaury	75,000

3.2.5 Minimum outflow requirement

In order to ensure that salt intrusion will not hamper intake of water for Mafambisse and Beira a minimum outflow requirement of 10 $m^3 s^{-1}$ is imposed.

3.2.6 Land cover

A land cover coverage for each catchment has been made (Table 2). Further refinement in terms of area as well as number of land classes can be implemented rather easily within WEAP in case more detailed information will become available.

The Kc factor (referred to as crop factor) is used to convert the ETref (reference evapotranspiration) to the ETpot (potential evapotranspiration). This ETpot is subsequently used by WEAP to calculate the ETact (actual evapotranspiration) based on the availability of water. So as equation:

$$ETact = Ks \cdot ETpot$$
$$ETpot = Kc \cdot ETref$$

with

ETact : actual evapotranspiration (mm/d)
ETpot : potential evapotranspiration (mm/d)
ETref : reference evapotranspiration (mm/d)
Ks : reduction by water deficit (-)
Kc : crop factor (-)

Table 2. Aggregated land classes of the 12 catchments as applied in WEAP.

		Area (km2)	Area (%)					
NR	NAME		Rainfed	Irrigated	Plantation	Bare	Shrubs	Forest
1	Nhazonia	2,846	9	1	0	20	20	50
2	Zimbabwe	687	29	1	0	20	20	30
3	Honde	1,245	9	1	0	20	20	50
4	Vunduzi	3,439	9	1	0	20	30	40
5	Upper Pungue	1,360	9	1	0	20	30	40
6	Nhandugue	2,830	10	0	0	20	30	40
7	Urema	5,572	10	0	0	20	50	20
8	Upper Middle Pungue	2,400	19	1	0	20	50	10
9	Lower Middle Pungue	2,990	20	0	5	20	50	5
10	Lower Pungue	3,512	20	2	5	20	50	3
11	Muda	1,336	20	1	5	20	50	4
12	Pungue Estaury	2,933	20	5	5	20	50	0

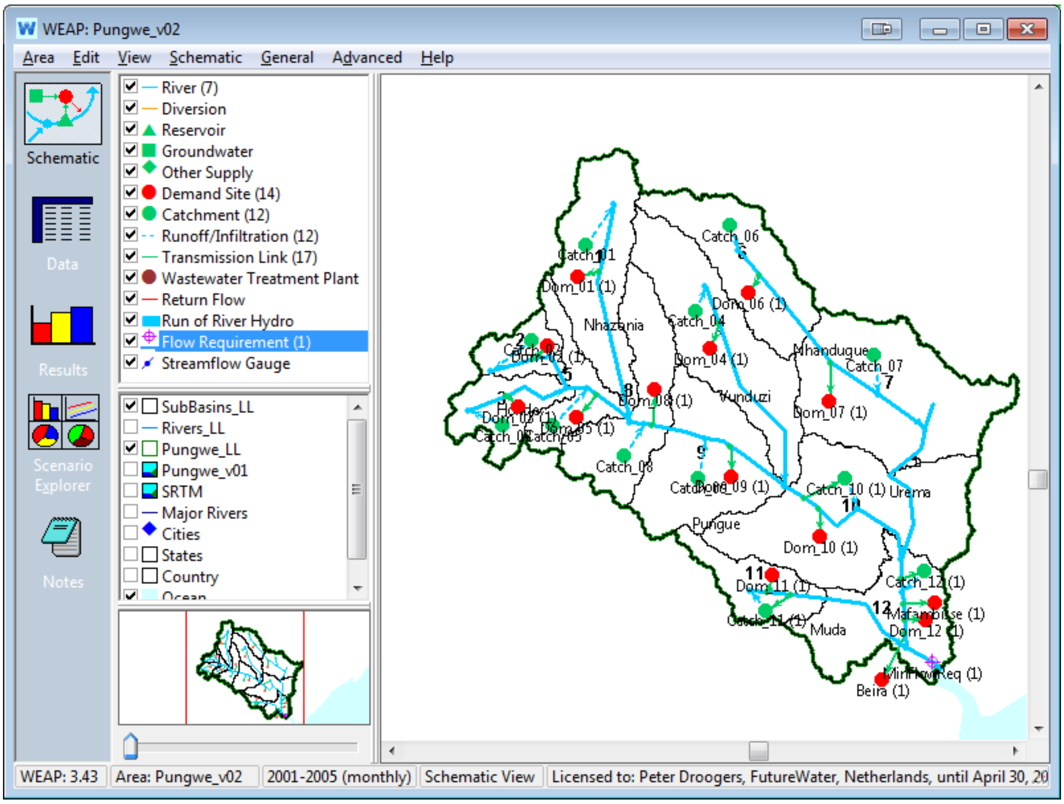


Figure 6. Final WEAP model of Pungwe Basin.

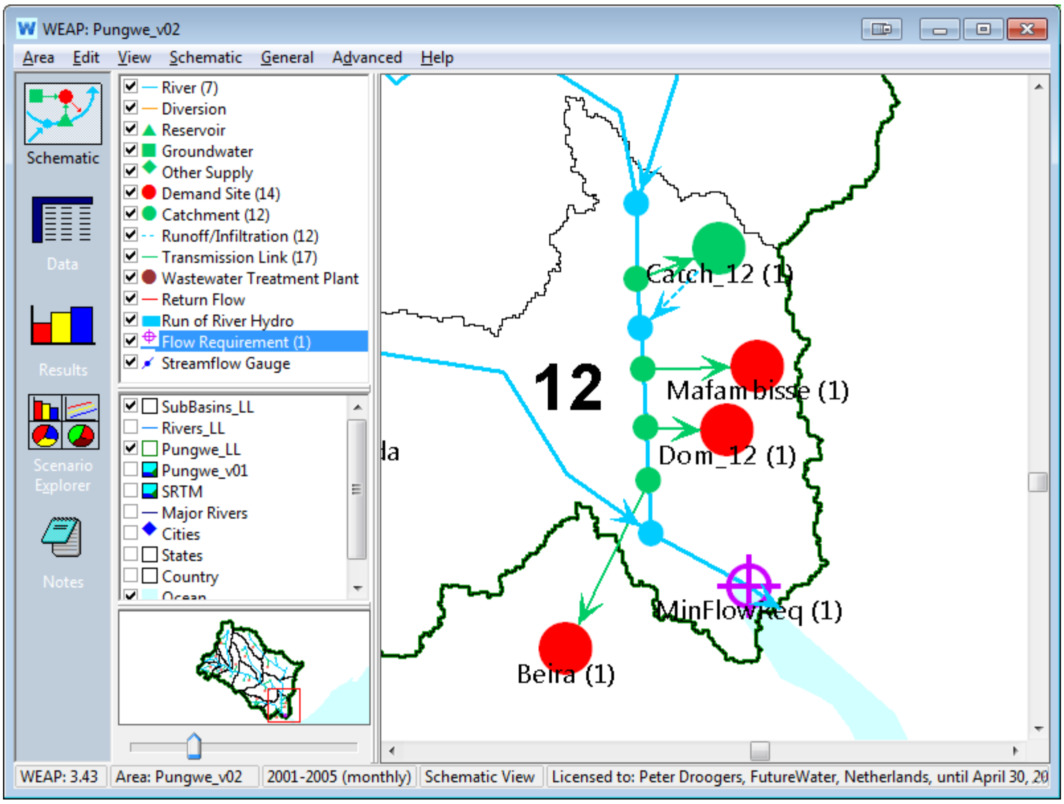


Figure 7. Details of downstream area of the WEAP model for the Pungwe Basin.

3.3 Validation and calibration

A full validation and calibration of the hydrological SWAT model is described elsewhere (Terink, et al., 2014). This validation/calibration of SWAT resulted in the conclusion that the model performed well when comparing observed and simulated streamflow. To ensure that the WEAP model, which is based on the data as used in SWAT, is also reliable, a first order validation has been undertaken. For this the observed outflow data from the most downstream station have been used. Since WEAP is not a fully distributed hydrological model the WEAP validation is done on observed and simulated minimum, average and maximum monthly flows.

The overall validation of WEAP is shown in Figure 10. It is clear that WEAP is also able to simulated observed flows. Since WEAP is a water resources model it would be desirable to undertake another level of validation comparing observed and simulated demands and water shortages. For this pilot project limited resources and data were available and it was therefore not possible to undertake this second order of validation and calibration.

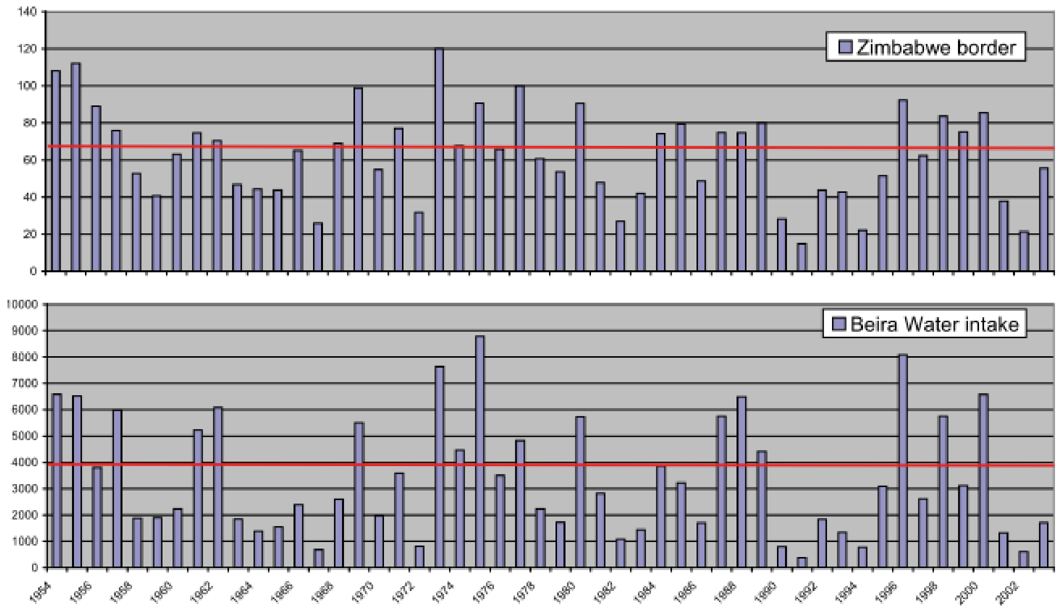


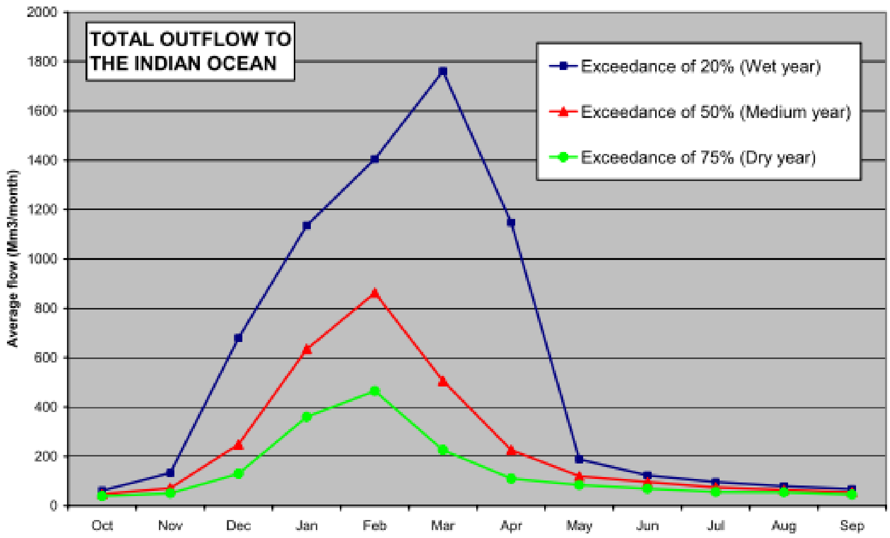
Figure 8. The figure shows the mean annual runoff for the last 50 years (Mm 3 /year). The red line denotes the average annual river flow. The large inter-annual variation in water resources in the Pungwe River Basin causes large demands on water management. Dry spells, e.g. 1991-1995, create large stress on the water users. (Source: GRM, GRZ, 2006).

Table 3. Distribution of surface water availability in Mozambique and Zimbabwe for the Pungwe River basin based on the hydrological years 1960-80. The long-term available water resources are judged to be 5-15% lower than the values given in the table. (Source: SWECO, 2004).

Point	Area (km^2)	Natural MAR (Mm^3/year)	Natural MAR (mm/year)	Percentage of total
Zimbabwe	1 463	1 191	814	28%
Mozambique	29 687	3 004	101	72%
Total	31 150	4 195	135	-

Table 4. Estimated natural runoff (MAR) for the Pungwe subbasins for the period Oct 1960 to Sep 1981. The runoff coefficient is the ratio between MAR and MAP. The coefficient of variation is the ratio between the standard deviation on of annual flows and the MAR. The long-term available water resources are judged to be 5-15% lower than the values given in the table. (Source: SWECO, 2004).

Subbasin	Local area (km^2)	Local MAR (Mm^3/year)	Local MAR (mm/year)	Runoff coeff. (%)	CV (%)
Pungwe Zimbabwe	687	821	1 195	60	0.35
Honde	1 245	594	477	36	0.53
Upper Pungwe	1 360	446	328	29	0.70
Nhazonia	2 846	471	166	15	0.73
Upper Middle	2 400	211	88	10	1.05
Vunduzi	3 439	441	128	11	1.20
Lower Middle	2 990	231	77	8	1.28
Nhandugue	2 830	169	60	7	0.85
Urema	5 572	329	59	7	1.09
Lower Pungwe	3 512	206	59	6	1.79
Muda	1 336	88	66	6	2.13
Pungwe Estuary	2 933	188	64	5	1.91



	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
20%	61	133	680	1135	1405	1761	1147	188	123	96	79	67
50%	47	71	249	635	863	508	226	120	96	74	64	54
75%	39	51	130	360	465	226	110	84	69	56	54	45

Figure 9. Monthly distributions of natural runoff at the river mouth. (Source: GRM, GRZ, 2006).

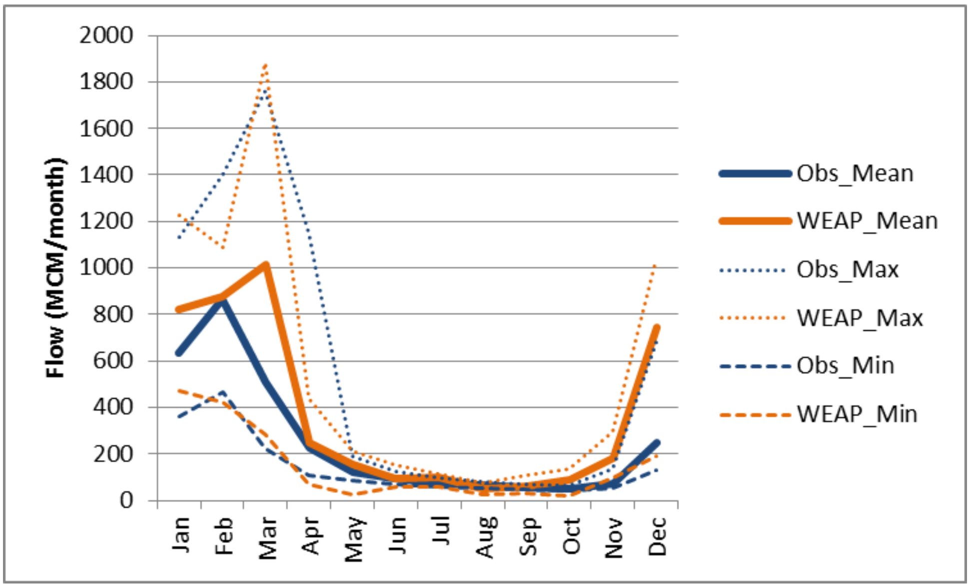


Figure 10. Validation of the WEAP model: outflow observed and modeled to Indian Ocean.

4.1 Current situation

The WEAP model as described in the previous sections is used to assess current water demands and shortages. As reference the period 2001-2010 was used and analyses were undertaken at monthly time scales. Industrial and domestic demands were considered to be constant over each year, while demands for irrigation are scaled towards the actual needs based on climate data and crop characteristics.

Results of the WEAP runs reflecting the current situation will be mainly presented in figures and tables. A summary of these outputs is provided here.

- Total annual average demand for water withdrawals in the basin is about 550 MCM. Some year-to-year variation exist and during wet years demand can go down to about 520 MCM, while under dry years this demand can be almost 600 MCM. (Figure 11)
- A large monthly variation in water demands exist where during the month April to November demands are much higher compared to the period December to March. (Figure 12)
- Annual average water shortage (unmet demand) is about 15 MCM. Comparing this to the total demand means a shortage of only a few percentages. This shortage is not the same for every year and varies substantially from zero in some years up to about 40 MCM in dry years. Monthly unmet demand is highest for August, September and October. (Figure 13 and Figure 14)
- Outflow from the basin is highly variable. Large variation exists with flows down to 7 $m^3 s^{-1}$ and during some months flow can go up to 1000 $m^3 s^{-1}$. Note that these numbers are monthly averages and daily flows can be substantially lower and higher. Recalculating these cubic meters per second to millimeters shows that average long-term outflow from the basin is 140 mm per year. (Figure 15)

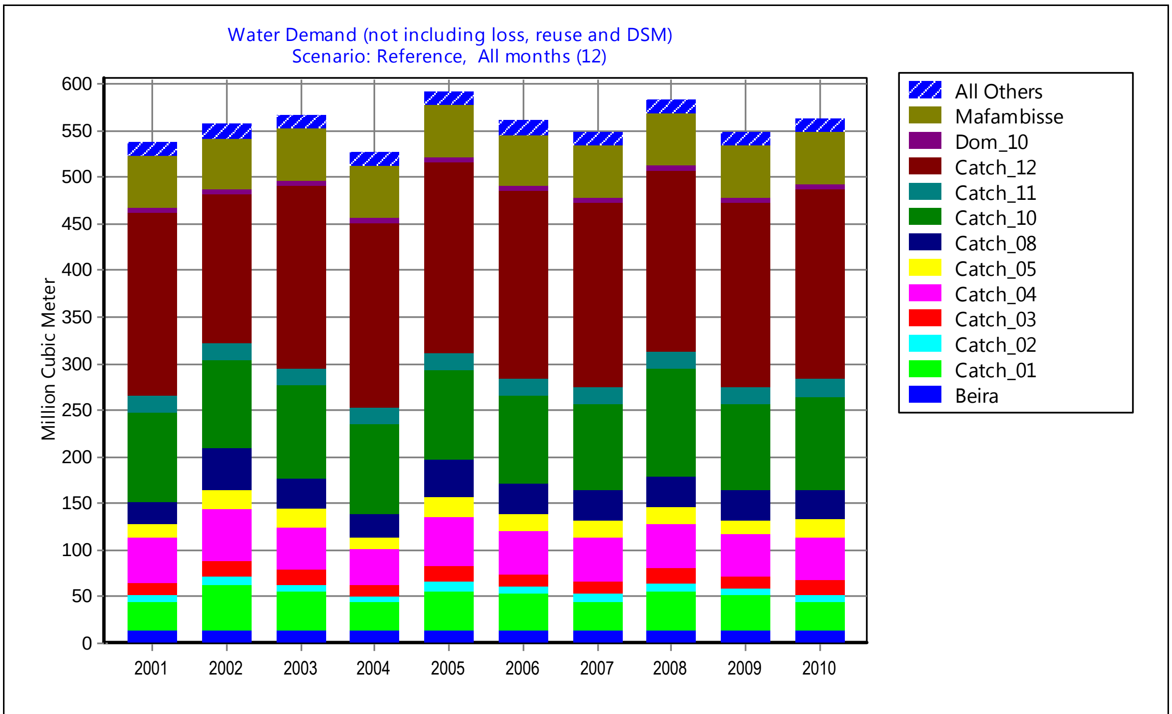


Figure 11. Annual total water demand.

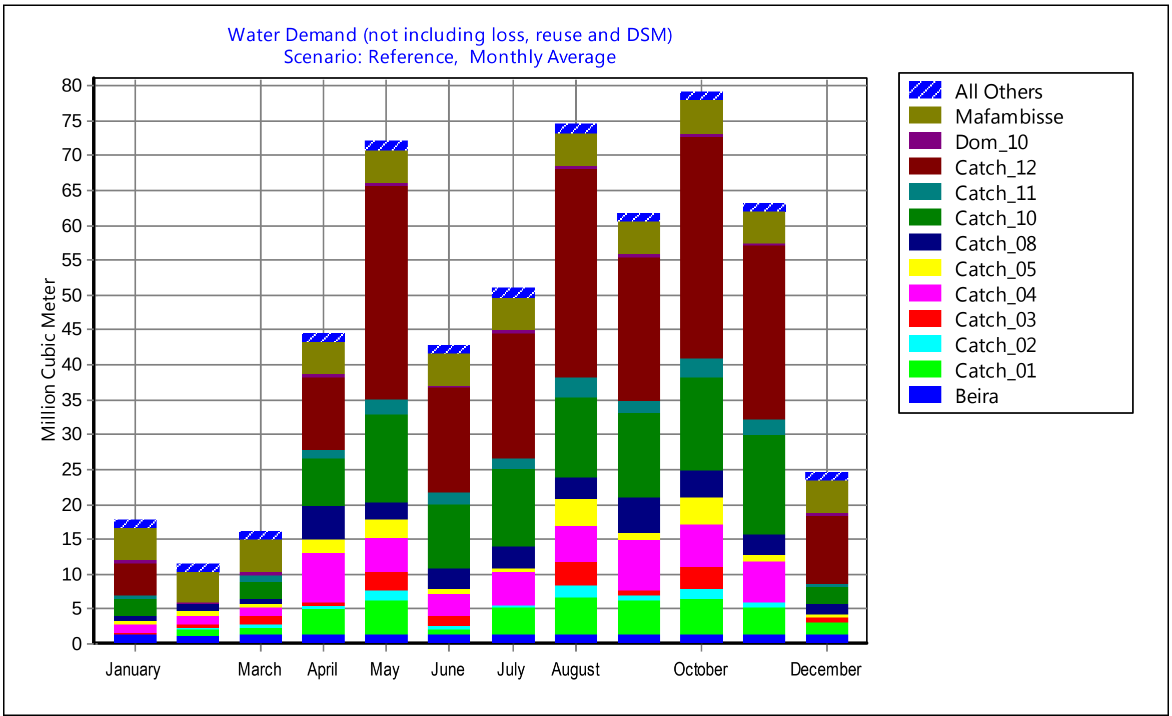


Figure 12. Monthly average water demand for the period 2001-2010.

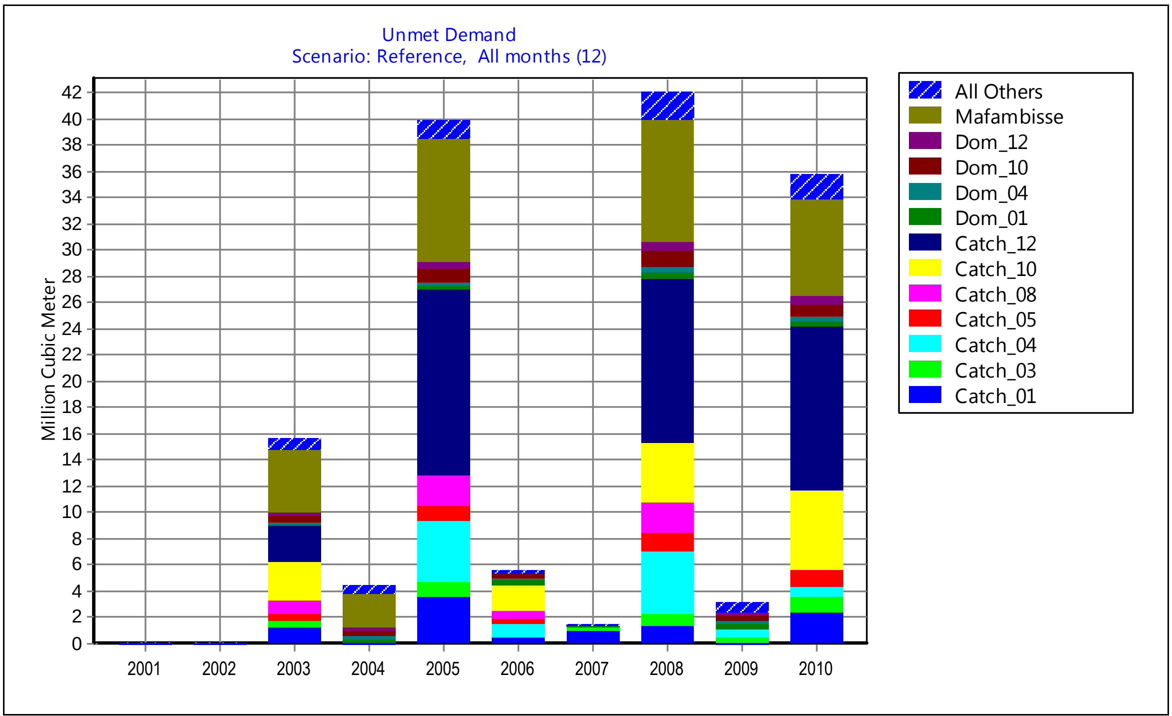


Figure 13. Annual total unmet demand (water shortage).

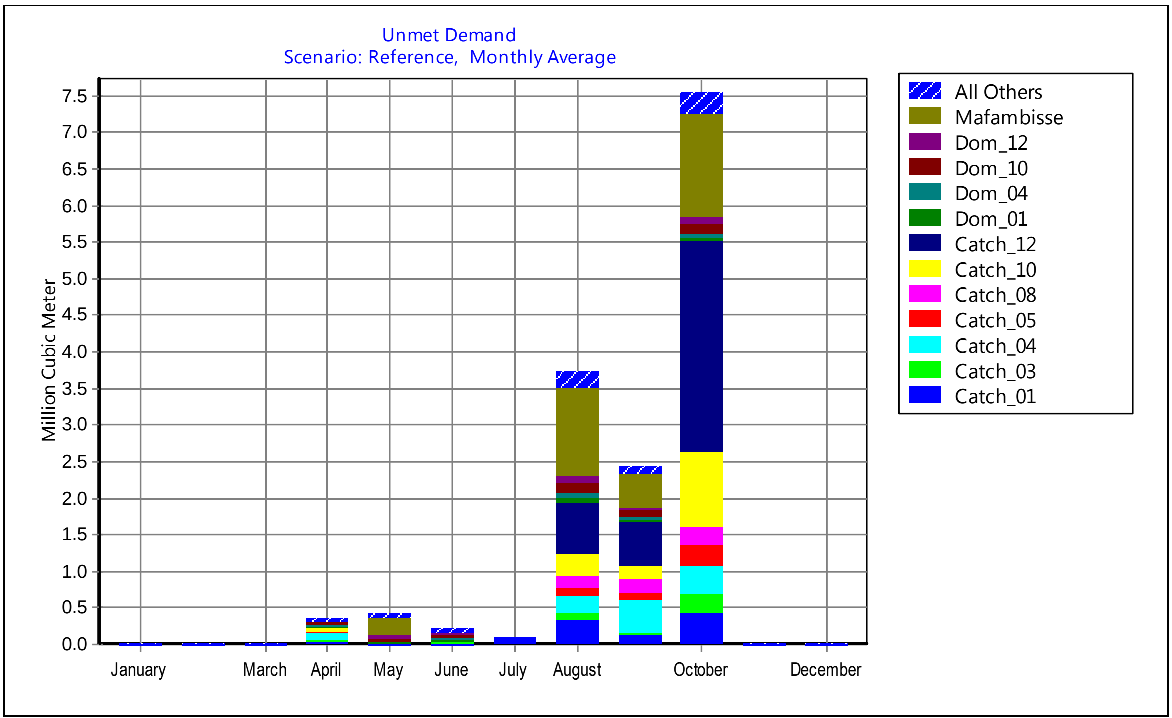


Figure 14. Monthly average unmet demand (water shortage) for the period 2001-2010.

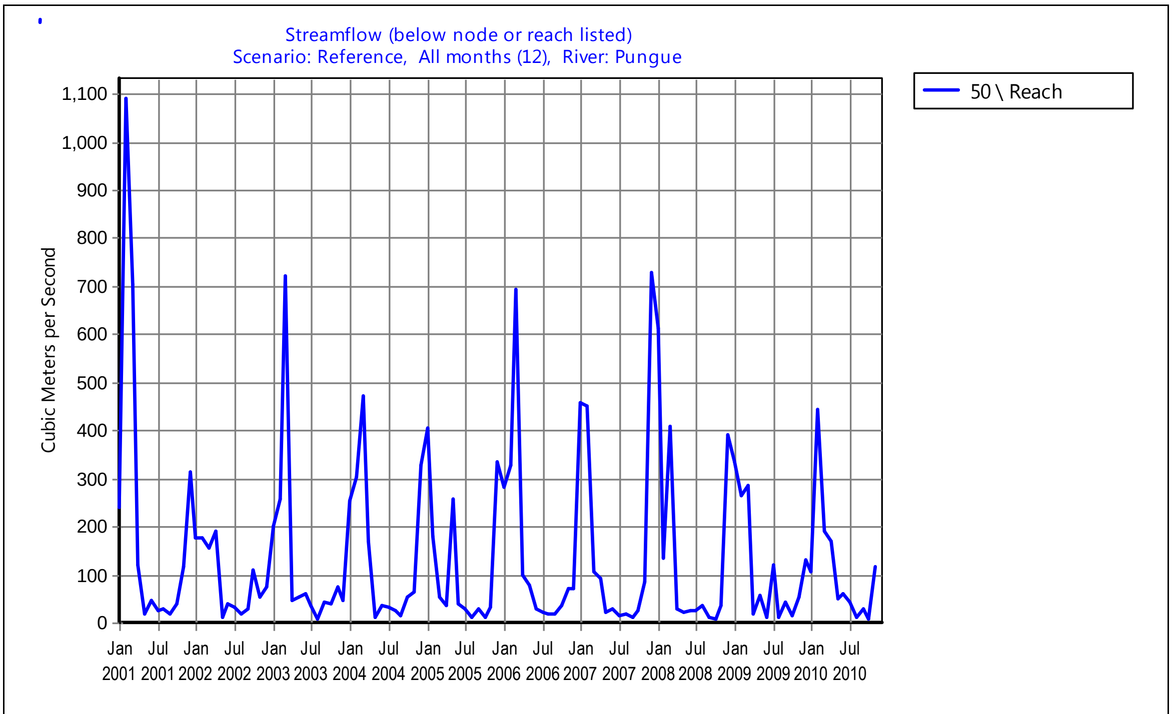


Figure 15. Monthly outflow of the basin into the ocean.

4.2 Future Developments

Several new irrigation schemes are planned to increase the Mozambican food production. For this purpose the so called Beira Agricultural Growth Corridor project (BAGC) is developed. On the long term this project will develop 190,000 ha of irrigated agriculture.

The[3] Beira Agricultural Growth Corridor (BAGC) initiative is a partnership between the Government of Mozambique, private investors, farmer organisations and international agencies. It was launched in 2010 and aims at promoting increased investments in commercial agriculture and agribusiness within the Beira Corridor (Tete, Sofala and Manica Provinces).

The Beira Agricultural Growth Corridor aims to boost agricultural productivity and competitiveness in the region through:

- Ensuring public and private sector investments along agriculture value chains are properly coordinated;
- Leveraging existing “anchor” investments (e.g. in the mining sector and railways) to benefit agriculture;
- Developing new infrastructure and agriculture projects as commercially-viable business opportunities that drive growth and benefit local communities;
- Supporting the development of sustainable agriculture support services with a special focus on production inputs, financial services and extension services; and
- Supporting investment and help to provide a suitable business environment for agricultural investors who will engage with small and medium sized farming interests in the corridor.

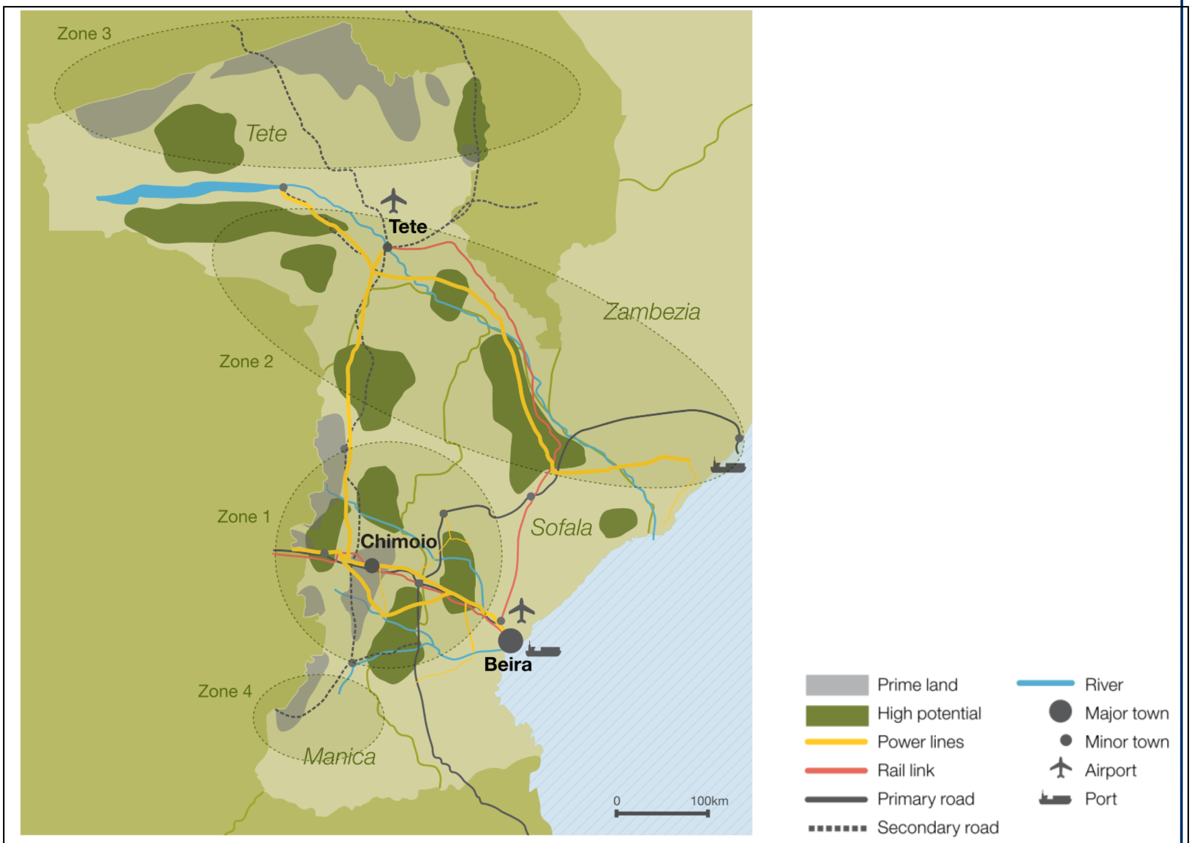


Figure 16. Beira Agricultural Growth Corridor: high potential agricultural areas.

[3] http://www.beiracorridor.com/

In this modeling pilot study a full analysis of water demands, supply and shortages as a result of the BAGC irrigation component is not foreseen. However, a first order estimate of the potential water related challenges the BAGC will face, has been made using the WEAP model. For this it was assumed that irrigated agriculture will be developed around Chimoio. Water for this irrigation is assumed to originate from both the main Pungwe as well as from the Vunduzi. Three scenarios are analyzed here to explore the impact of an extension of irrigation:

- #1: Extent of 5,000 ha
- #2: Extent of 10,000 ha
- #3: Extent of 25,000 ha

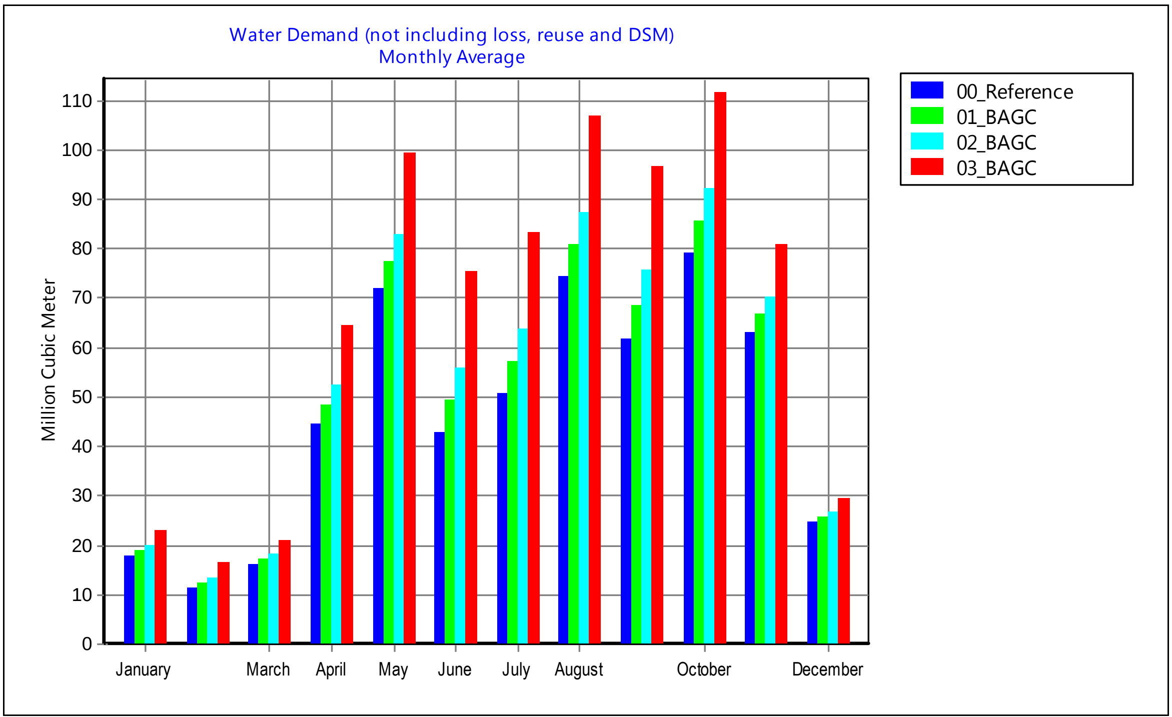


Figure 17. Monthly average water demand under the three scenarios.

A summary of these findings is presented here, while the various Figures provide more detail:

- Total annual average water demand will increase from 550 MCM (currently) to 600 MCM (#1), 650 MCM (#2), and 800 MCM (#3). This increase in water demand is well distributed over the year. (Figure 17)
- The water shortage (unmet demand) used to be small with about 15 MCM/yr currently. The expansion of irrigation will lead to an average annual water shortage of about 25 MCM (#1), 35 MCM (#2), and 100 MCM (#3). (Figure 18)
- Combining this demand with the unmet demand provides the coverage of water. Focusing on the new BACG irrigated areas this coverage varies per month and for the driest month (August) this can be as low as 50% for the largest expansion (#3). Figure 19 provides averages over 10 years. Considering the individual 120 months in those ten years during quite some months even a coverage of 50% cannot be met:
    - #1: 9 months (out of 120)
    - #2: 16 months (out of 120)
    - #3: 23 months (out of 120)
- The impact of these new irrigation developments on outflow from Pungwe River into the Indian Ocean is also analyzed. Especially during the low flow periods (May-Nov) decreases

in flows of 10 $m^3 s^{-1}$ can be expected for the scenario #3. Actual flows will therefore fall below the critical level of 10 $m^3 s^{-1}$ frequently. For the other two scenarios decreases in flows are relatively small.

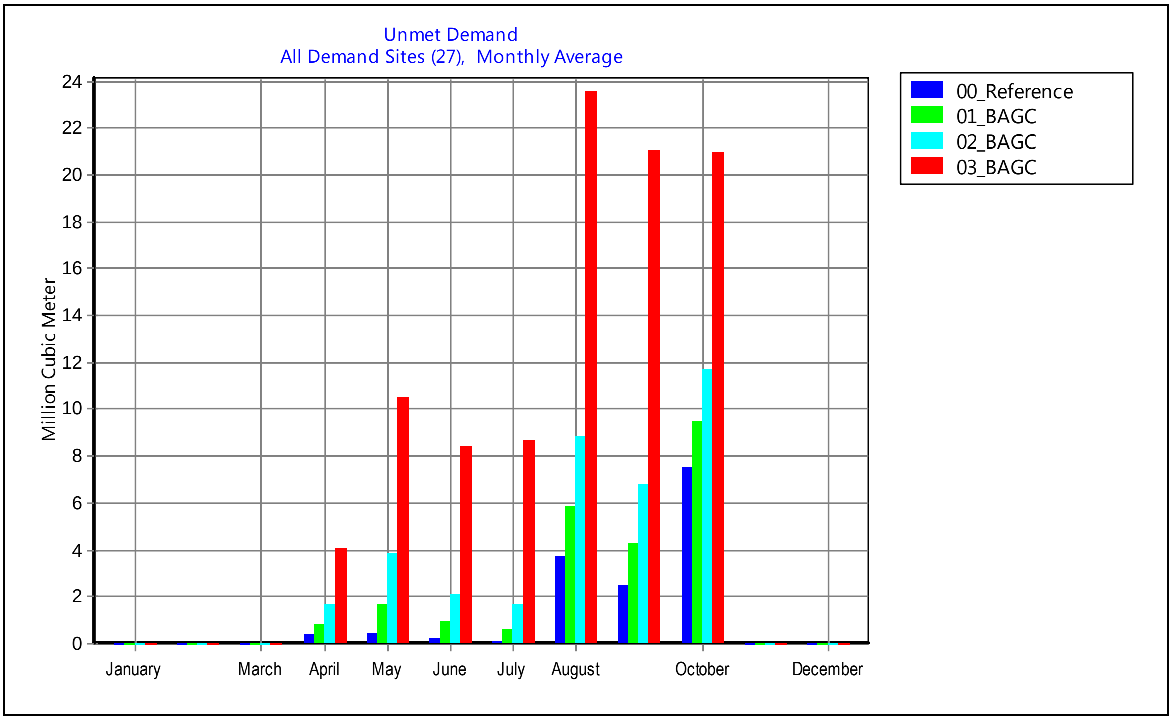


Figure 18. Monthly average water shortage (unmet demand) under the three scenarios.

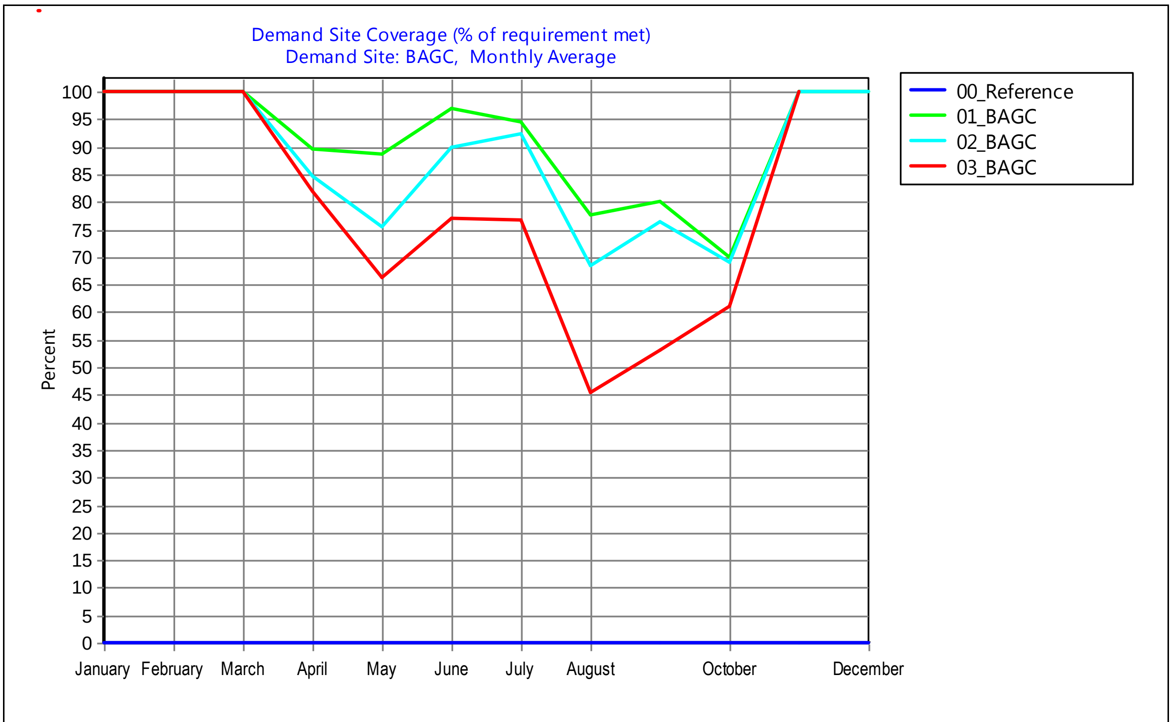


Figure 19. Coverage of water demand under the three scenarios.

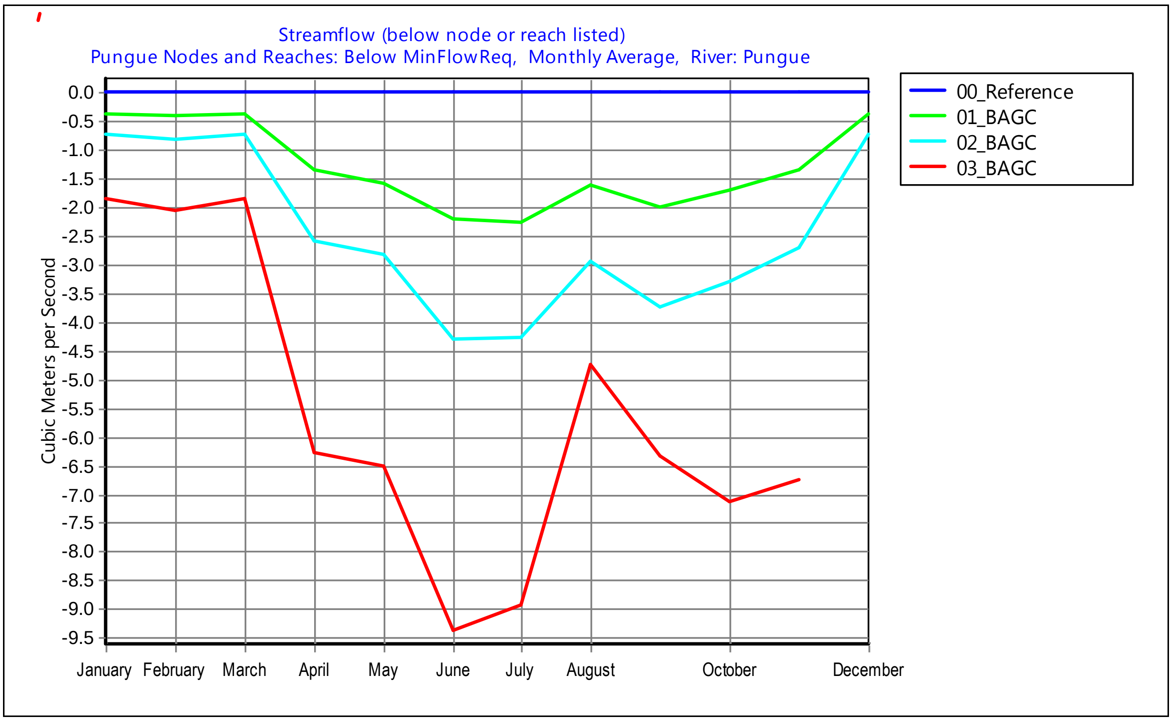


Figure 20. Impact of the three BAGC scenarios on outflows of the Pungwe. The Graph shows the reduction in flows compared to the reference condition.

4.3 Water Infrastructure Developments

It is clear that development of new irrigation schemes without any other developments will increase water shortages in the basin to undesirable levels. If irrigation expansion is limited to 10,000 ha no severe problems can be expected. Larger expansions can only be justified if additional measures are taken. Typical examples of measures are: changes in agricultural water management practices, changes in cropping patters, additional water sources (e.g. groundwater, interbasin transfer), water savings in other sectors, amongst others. For this pilot project the option to develop small scale reservoirs have been analyzed.

The effectiveness of these small scale reservoirs is analyzed for the scenario of an extent of irrigated area by 25,000 ha. Three options of reservoir capacity are explored:

- Res_01: storage capacity of 25 Million Cubic Meters
- Res_02: storage capacity of 50 Million Cubic Meters
- Res_03: storage capacity of 100 Million Cubic Meters

Translating this in practical terms, using the 25 MCM as example, means that for every hectare irrigation 1000 m^3 storage should be created. If a reservoirs is on average 5 m deep, 2% of the area should be covered by reservoirs (= 200 m^2 per hectare). It might be interesting to explore whether a combination with some medium-scale or large-scale reservoirs is feasible. Also, combining reservoirs with groundwater storage, by enhancing surface infiltration, might be an option.

The results of implementing one of these three storage capacities can be summarized as follows:

- Annual unmet demand (water shortage) will reduce from 100 MCM to 65 MCM (Res_01), 45 MCM (Res_02), and 25 MCM (Res_03). The effectiveness of the Res_03 (100 MCM storage capacity) is that in about half of the years no water shortage will occur. (Figure 21)
- Monthly water shortages will reduce substantially if storage capacity will be developed. Only during the driest months (Aug-Oct) water shortage can occur. Obviously, a better balanced reservoir operation could be considered to distribute water shortage over the months. (Figure 22)
- The coverage of water demand shows that using the largest reservoir capacity most months coverage is 100%. Only during September and October coverage can fall below 75%. Again, improved reservoir operations might flatten this out. (Figure 23)

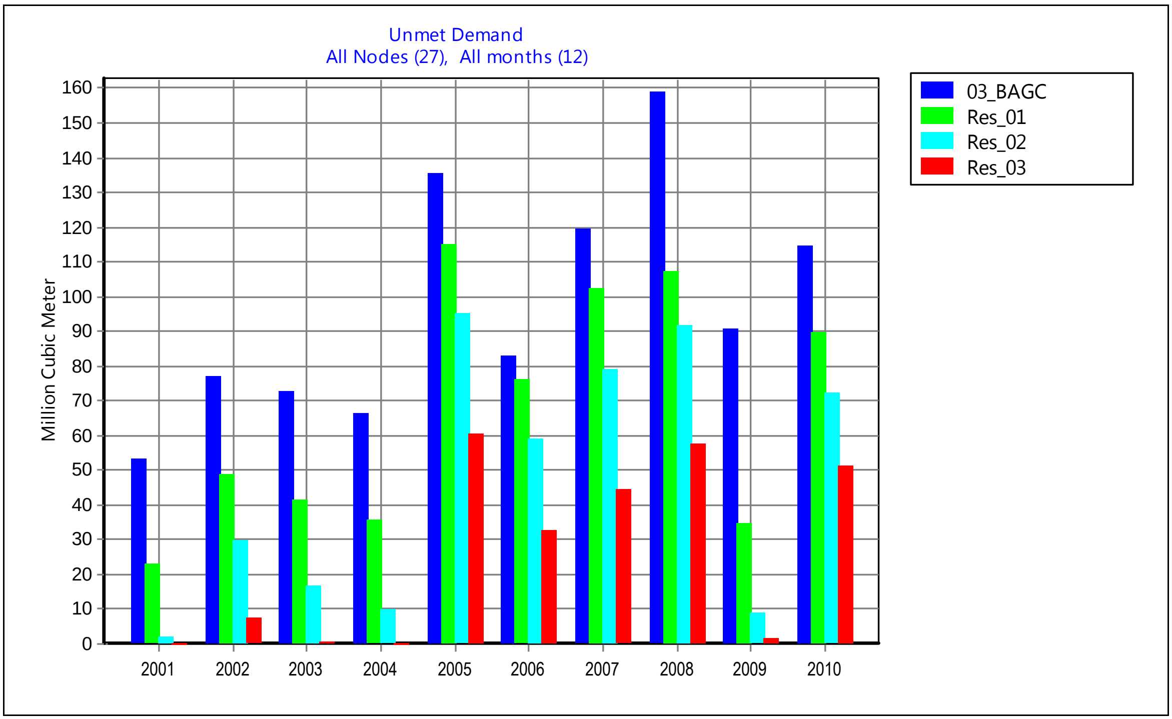


Figure 21. Effectiveness of developing storage capacity (Res_01 to Res_03) under the BAGC irrigation expansion. The Graph shows the annual unmet demand.

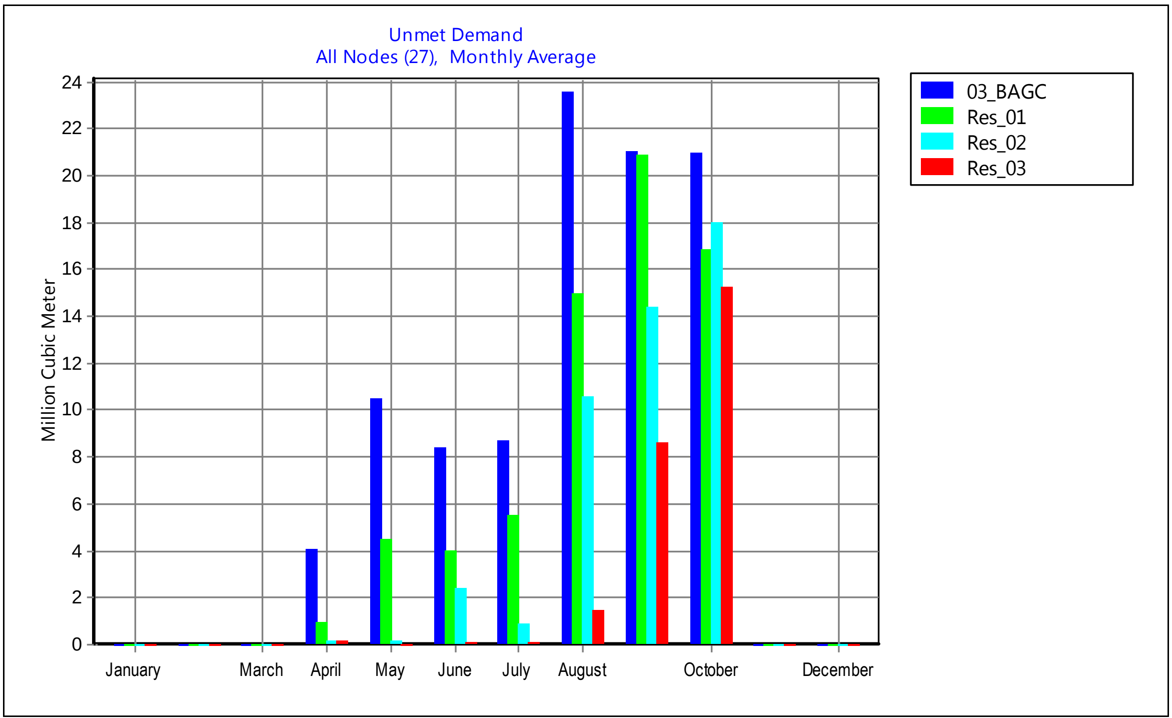


Figure 22. Effectiveness of developing storage capacity (Res_01 to Res_03) under the BAGC irrigation expansion. The Graph shows the average annual unmet demand over a period of 10 years.

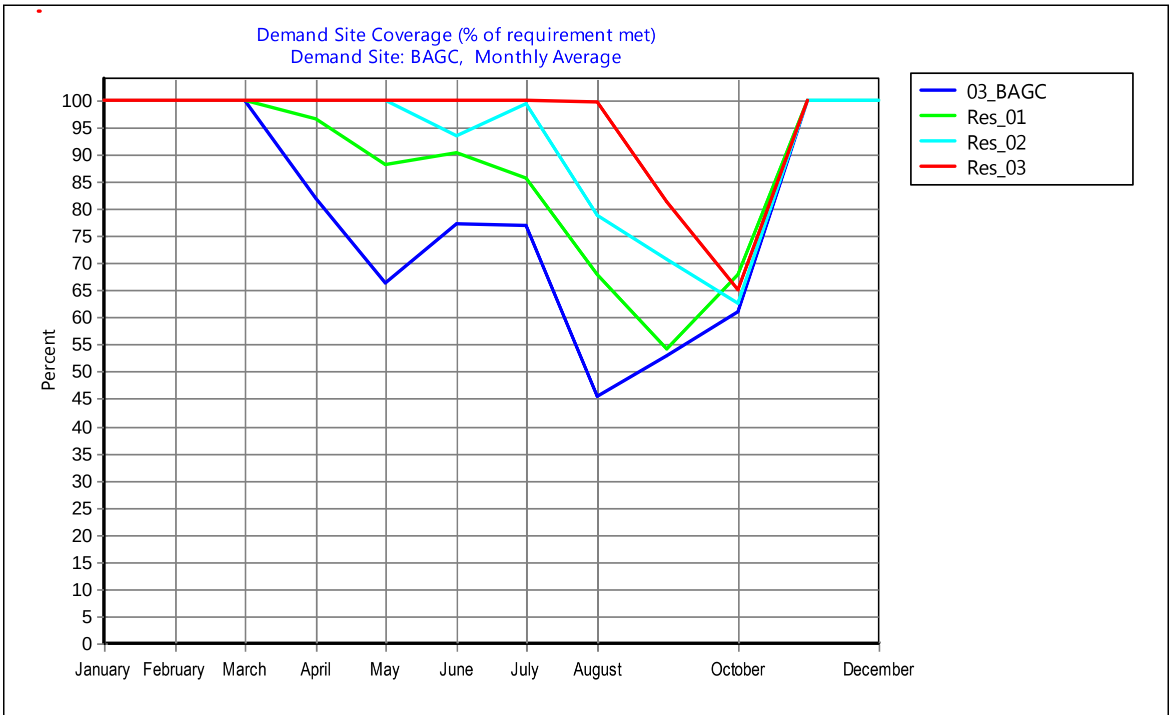


Figure 23. Effectiveness of developing storage capacity (Res_01 to Res_03) under the BAGC irrigation expansion. The Graph shows the coverage of water demand.

4.4 Daily Reservoir Operations

WEAP was originally developed as a strategic decision support system (S-DSS). Over the last years, WEAP has been further developed to be used as an operational decision support system (O-DSS) for water managers. WEAP does not include the full hydraulic processes as other O-DSS such as SOBEK, HEC-RAS, MIKE-11, amongst others, but has particular strengths in operational management of water allocation. Since WEAP is based on a simplified hydraulic representation and not on the full hydraulic processes, data requirements are much lower and usability is relatively easy.

Within WEAP a diverse set of operational rules for reservoir management exists. WEAP can therefore function as an operational decision support system (O-DSS) to explore decisions on the impact on water delivery, shortages and reservoir status. From the existing options the following two reservoir operational rules were explored here:

- **Top of Buffer**: A reservoir releases water from the conservation pool to fully meet withdrawal and other downstream requirements, and demand for energy from hydropower. Once the storage level drops into the buffer pool, the release will be restricted according to the buffer coefficient, to conserve the reservoir's dwindling supplies.
- **Buffer Coefficient**: The buffer coefficient is the fraction of the water in the buffer zone available each day for release. Thus, a coefficient close to 1.0 will cause demands to be met more fully while rapidly emptying the buffer zone, while a coefficient close to 0 will leave demands unmet while preserving the storage in the buffer zone.

To demonstrate the use of WEAP in an operational mode, the proposed option to construct a reservoir about 150 km upstream from Beira, is explored. The existing WEAP model as described in the previous sections has been changed. The most important changes are:

- Streamflow is not assessed using the catchment approach, but observed streamflow from station E651 has been used
- The model was setup at a daily time-step
- Only the water demand downstream of the proposed reservoir has been evaluated.

A screenshot of the model developed can be seen in Figure 24. The model was setup using streamflow data from station E651. In reality observed streamflow data does not exist for the future, but can be projected using WEAP by including forecasted weather data. At the beginning of the dry period water managers are then confronted with decisions on when and how much water from the reservoir should be released on a particular day. This is a repetitive decision process, either daily or weekly, in which WEAP can play a supportive role.

In this particular example we assume that it is the start of the dry season (July) and water managers make their first round of decisions on the operation of the reservoir. It is assumed that water managers consider a set of water conservation operations and would like to know the impact on releases and reservoir storage over the dry period. In Table 5 a total of five possible operations are shown, but other ones can be easily evaluated as well.

The resulting reservoir volumes and inflows and outflows are shown in Figure 25 and Figure 26. It is clear that if no conservation would be applied, the reservoir will be emptied quickly and during prolonged periods no water can be released. Obviously, this will result in undesirable situations by leaving the city of Beira without a single drop of water. The conservation options can resolve this problem and for a relatively wet year medium conservation is sufficient, while for a dry year substantial conservation is needed.

The above example shows that reservoir operations can benefit from using WEAP as an operational decision support system (O-DSS). Water managers will be able to undertake these analyses on a regular base (daily and/or weekly) to support their decision making.

Table 5. Reservoir operational rules as explored using WEAP as an O-DSS (Operational Decision Support System).

	Top of Buffer	Buffer Coefficient
Reference: no conservation	0%	
A: late and low conservation	50%	0.10
B: late and medium conservation	50%	0.05
C: late and strong conservation	50%	0.01
D: early conservation	80%	0.01

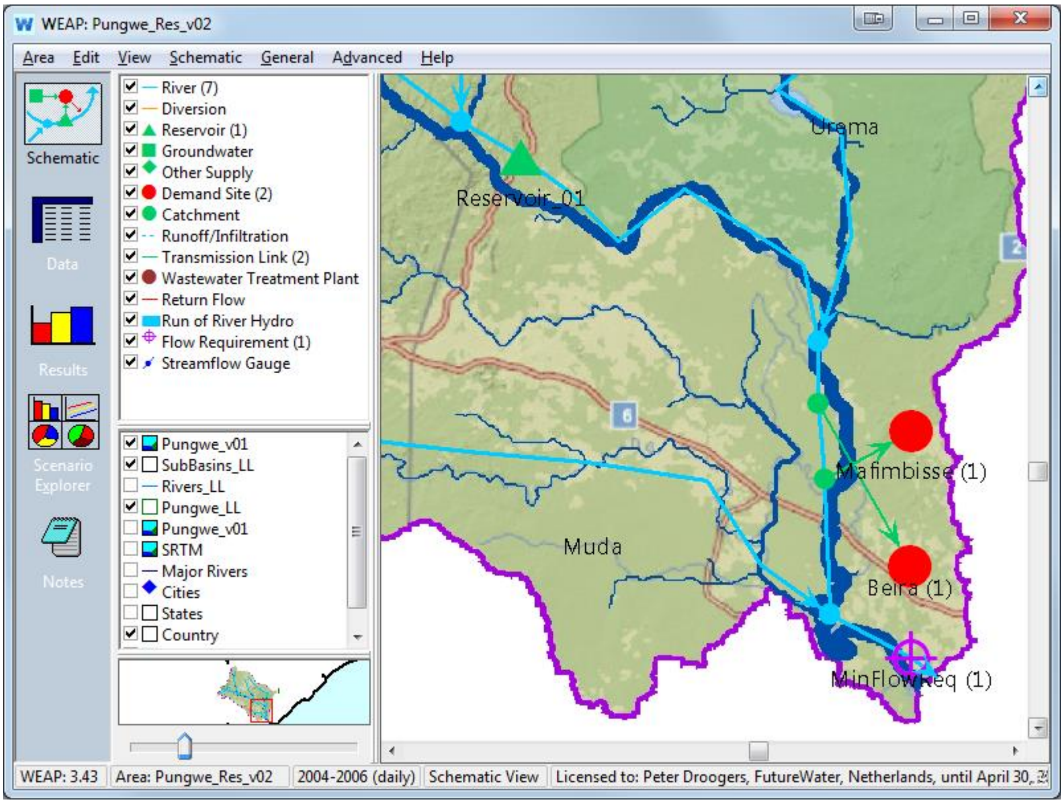
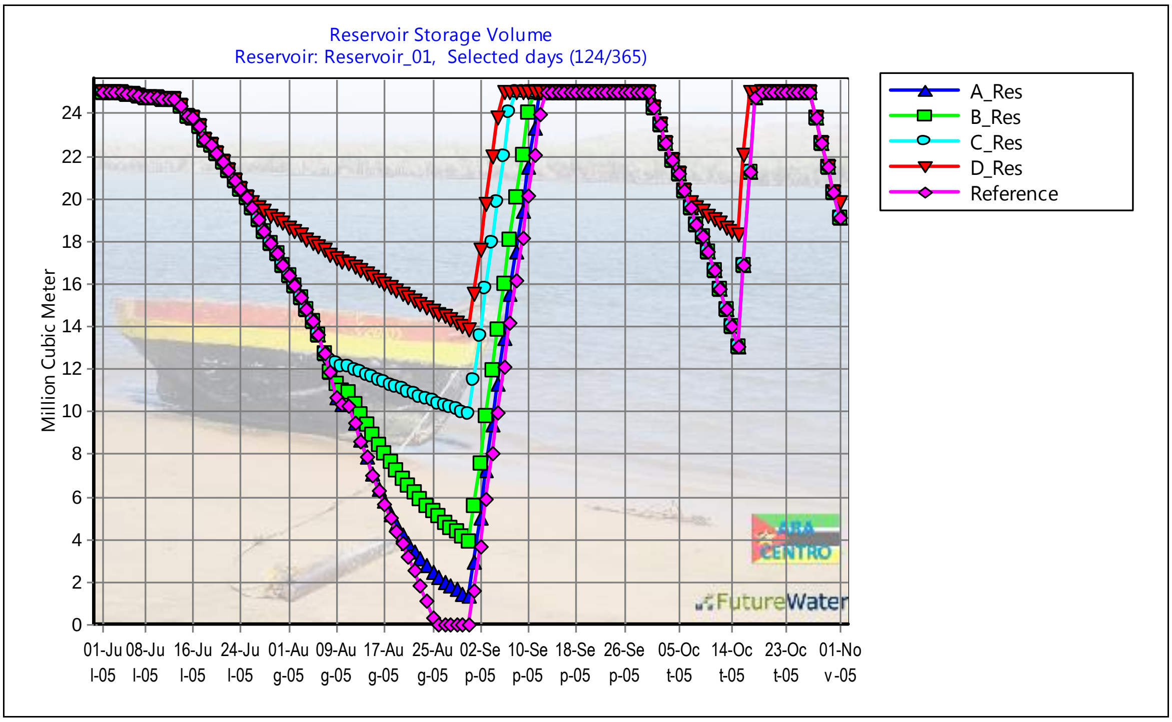


Figure 24. The WEAP model used as an O-DSS (Operational Decision Support System) to explore operational rules for a proposed reservoir.



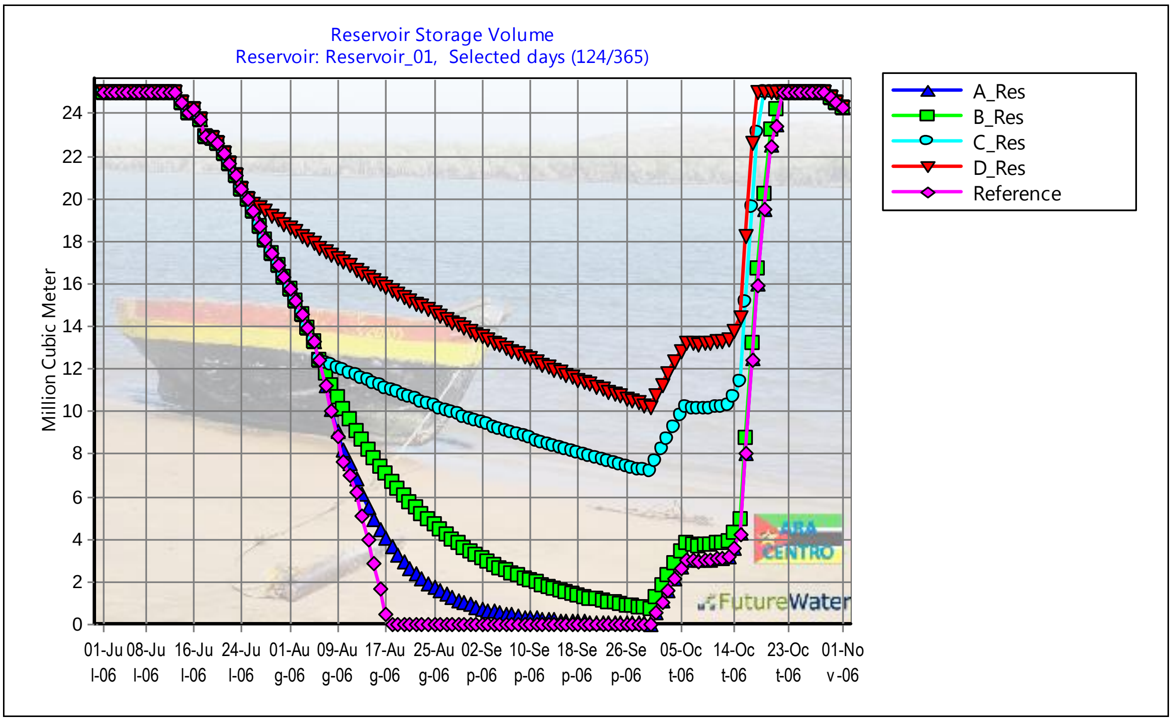


Figure 25. Different operations of the reservoir and its impact on reservoir volume as explored using WEAP as an O-DSS (Operational Decision Support System). Data used for two historic years 2005 (top) and 2006 (bottom) as demonstration.

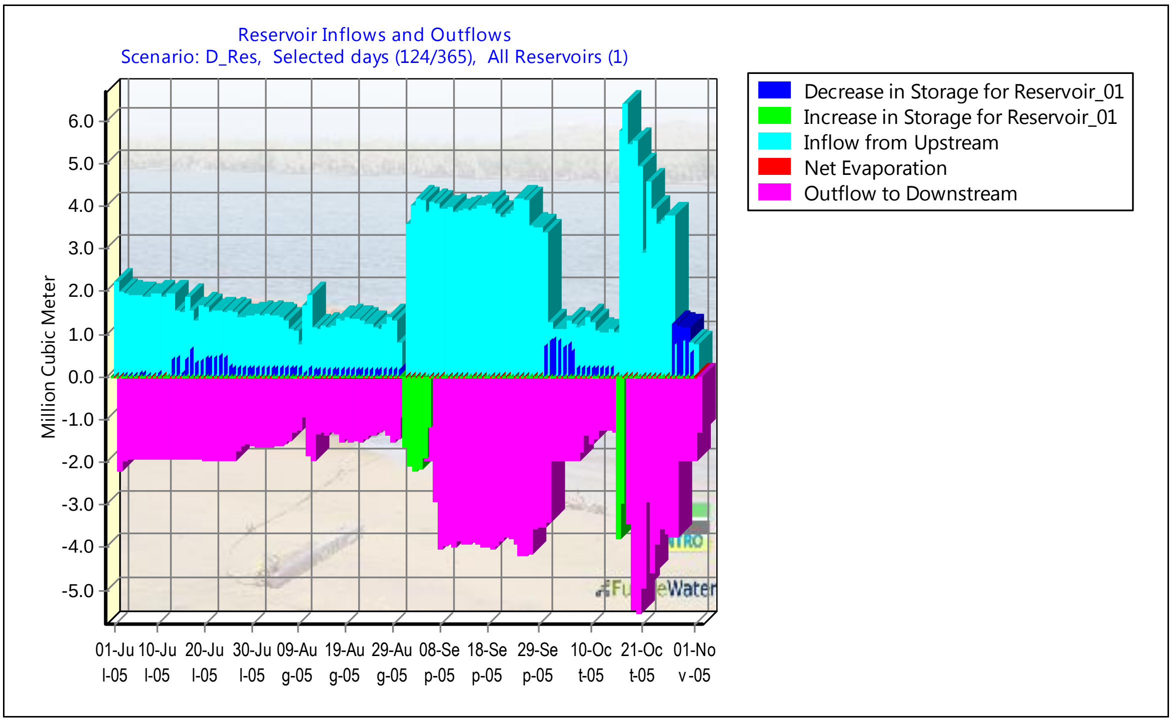


Figure 26. Reservoir inflows and outflows for the management scenario "early conservation" as explored using WEAP as an O-DSS (Operational Decision Support System). Data used from a historic year (2005) as demonstration.

5 Conclusions and Recommendations

Mozambique's development pathways require a proper water governance system. An important aspect in this regard is knowledge on current and future water challenges. In the pilot study as described in this report, a water allocation model, based on the WEAP framework, has been developed. As pilot area the Pungwe River basin in central Mozambique has been used, which is under management of ARA-Centro.

The most important conclusions from this study can be summarized as:

- Current water shortages in the Pungwe Basin are relatively low. The biggest problem is low flow conditions during the dry period which lead to salt intrusion and therefore saline water intake by Mafabisse and FIPAG.
- An increase in water abstractions can alter the system in a way that water shortage will become a large problem with negative consequences on people and economy. As long as development in irrigation is limited to about 10,000 hectare impact will be relatively modest. A further expansion of water demands, either by irrigation or other sectors, will lead to severe water shortages if no appropriate actions are taken.
- The option to retain water in small-scale reservoirs has been evaluated using the water allocation model developed during this pilot study. If 25,000 hectare irrigation would be developed, storage capacity of about 100 million cubic meter of water is needed. Obviously other water saving options could be considered as well.

The most relevant recommendations for further activities are:

- The model as developed in this study can be improved using updated datasets and information. More extensive use of remote sensing combined with data collected on the ground will improve model reliability even further.
- A further analysis on the impact of the Beira Agricultural Growth Corridor project on water resources is needed. Focus should be on impact and by a more rigorous analysis of effectiveness of mitigation measures.

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