Hydrological analysis and modelling of the Pungwe River Basin, Mozambique

A study performed under the 'Water Planning Tools to Support Water Governance' (WatPlaG) project

July 2014

Authors

Wilco Terink

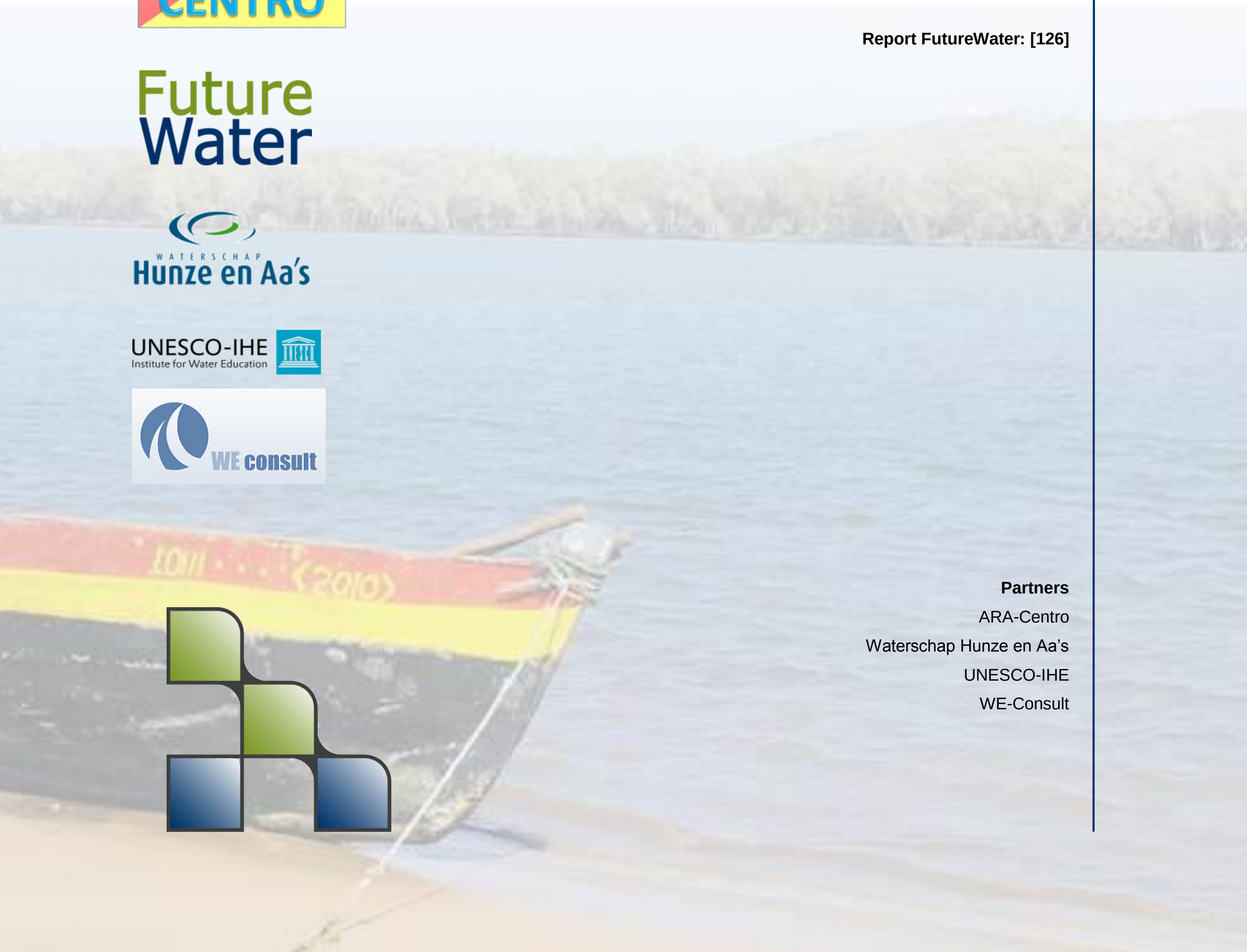
Peter Droogers

Client

ARA-Centro

Partners for Water

Report FutureWater: [126]



Partners

ARA-Centro

Waterschap Hunze en Aa's

UNESCO-IHE

WE-Consult

1 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" (WatPlaG). The project was granted on 16-May-2013 and will run from 1-Mar-2013 to 30-Jun-2014.

The contract number is PVWS13001.

The project partners are:

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

Table of contents

Tables

Figures

1 Introduction

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. 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 is expected to continue the coming decades.

Large water shortages are projected if no new reservoirs will be built 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 number of reservoirs 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"*.

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. The current report focuses on this activity, which is the hydrological analysis and modelling of the Pungwe River Basin. The objective of the current study is to perform a hydrological 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.

This report describes the physical assessment of the water resources within the Pungwe basin, while a second report (Droogers et al., 2014) will focus on the water demand and unmet demand within the Pungwe Basin. That report will provide information on the effect of socio-economic developments (e.g. irrigation, population increase, reservoir expansion, etc.) on the Pungwe River Basin's water resources.

2 Pungwe River Basin characteristics

2.1 General

The Pungwe River Basin (Figure 1) is located (between the latitudes 18S and 20S and the longitudes 33E and 35E) in the Sofala and Manica provinces, which are in the central part of Mozambique. The Pungwe River, with a total length of approximately 400 km and a drainage area of 31,000 km^2, is shared by Zimbabwe and Mozambique. 340 km of its length is located within Mozambique.

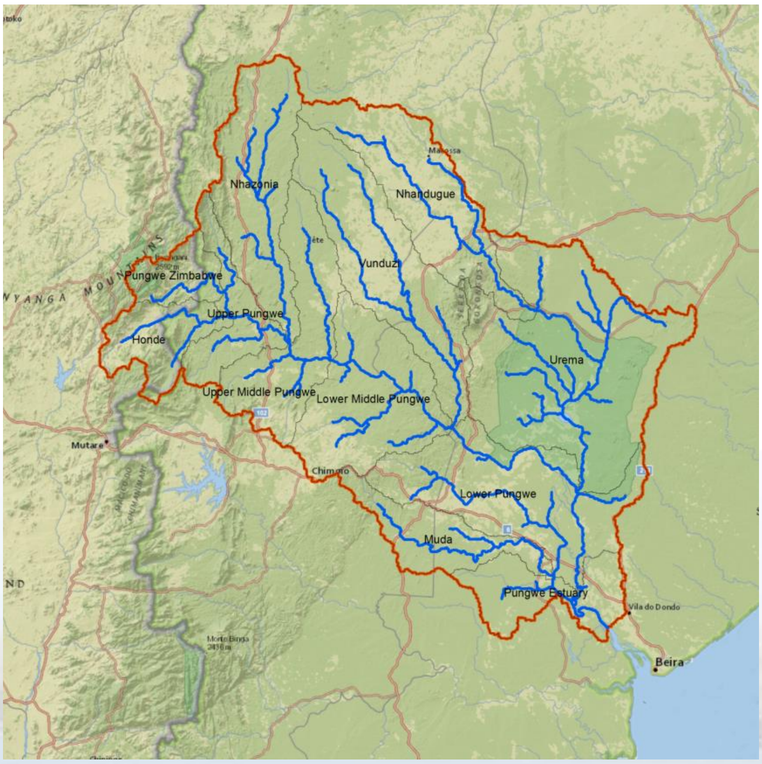


Figure 1: The Pungwe River Basin.

The Pungwe River rises from the foothills of Mount Inyangani in eastern Zimbabwe. This most upstream part of the Pungwe River has altitudes that range between 1500 and 2500 MASL. Eastwards of the mountains, the river flows through a plateau at 1000-300 MASL, down to the confluence with the Vunduzi River (SWECO & Associates, 2004). From here and downstream, the plateau falls rather rapidly to an altitude of less than 100 m. The part from Bué Maria and downstream is considered 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 the main discharge is transported through this stream during the dry period. The streams join again 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 Pungwe Estuary, which is the most easterly sub-basin, is situated just a few meters above sea level. Here seawater intrusion is frequent during high tide in the Indian Ocean, and the land is often flooded during the rainy season.

2.2 Climate[1]

The region of the Pungwe River Basin has a climate with a dry and a wet season. The dry season is between April and October and the wet season from November to March. The Pungwe River basin stretches over two climate types. In the west is the humid mountainous climate of the high mountains that forms the border between Zimbabwe and Mozambique. In this region, the mean annual rainfall can reach above 2000 mm, and the temperature is substantially lower than in the surrounding, non-mountainous areas.

Table 1 provides an overview of the mean annual precipitation (MAP) and mean annual (potential) evaporation (MAE) for each of the sub-basins within the Pungwe River Basin, based on the period 1960-1980. The Pungwe Zimbabwe sub-basin has by far the highest rainfall with more than 2000 mm/year on average. Although this sub-basin area contributes to only 5% of the total basin area, its contribution to the river discharge is substantially (Table 2) due to its high rainfall. Also the Vunduzi sub-basin shows slightly higher rainfall that probably is because of the higher altitudes at Gorongosa. There is a sharp gradient going eastwards, and only 10 km from the mountains, the mean annual rainfall has decreased to around 1000 mm and less. In the mountains there is normally rain every month of the year, with a concentration in November-April, while the area east of the mountains has a pronounced concentration of the rain for the warm season November-March/April, and mainly no precipitation at all from May to October. In the eastern region, near Beira, the climate is classified as tropical humid, with a temperature variation from 22 °C in July to 29 °C in January. The mean rainfall varies from 300 mm in January to 20 mm in July. The amount of precipitation is varying a lot from year to year, and during a very dry year, the precipitation gives almost no runoff peaks in the rivers, due to the high temperature, and hence high evaporation.

Table 1: Mean Annual Precipitation (MAP) and Mean Annual (potential) Evaporation (MAE) for each sub-basin of the Pungwe River Basin, based on the period 1960-1980 (SWECO & Associates, 2004).

Subbasin name	Area (km^2)	MAP (mm)	MAE (mm)
Pungwe Zimbabwe	687	2 020	1 450
Honde	1 245	1 340	1 450
Upper Pungwe	1 360	1 130	1 450
Nhazonia	2 846	1 140	1 450
Upper Middle Pungwe	2 400	900	1 450
Lower Middle Pungwe	2 990	950	1 380
Vunduzi	3 439	1 140	1 450
Nhandugue	2 830	850	1 450
Urema	5 572	900	1 590
Lower Pungwe	3 512	1 050	1 590
Muda	1 336	1 050	1 380
Pungwe Estuary	2 933	1 180	1 400

[1] This section is based on the study by SWECO & Associates (2004)

The potential evaporation seems not to vary much over the Pungwe River Basin. Highest values are found at the Urema and Lower Pungwe sub-basins with almost 1 600 mm/year.

Table 2: Distribution of water availability in Mozambique and Zimbabwe for the Pungwe River basin based on the period Oct 1960 to Sep 1981. The long-term available water resources are judged to be 5-15% lower than the values given in the table (SWECO & Associates, 2004).

Point	*Area [km^2]*	*Natural MAR [MCM/year]*	*Natural MAR [mm/year]*	*Percentage of total*
Total inflow from Zimbabwe	1463	1191	814	28%
Local inflow in Mozambique	29687	3004	101	72%
Pungwe at outlet	31150	4195	135	-

2.3 Land use

Although 83% of the Pungwe River Basin is covered with forest (SWECO & Associates, 2004), the basin has a high agricultural potential, as there is rather little arable land in use and the forest, classified as deciduous or semi deciduous miombo forest, is not very dense. The continuous source of water in the rivers draining the mountains gives good possibilities for irrigation if the necessary infrastructure is supplied. In the low-altitude parts of the basin the vegetation is savannah or prairie. The Gorongosa National Park, one of the largest national parks in Southern Africa, is situated within the northeastern part of the Pungwe basin.

2.4 Soils

The western parts of the basin consist of argillaceous red soils of a considerable depth. In the mountainous areas the soils are shallower, but can reach larger depths in the valleys. The soils of the region below the plateau are more varying and are classified as clayey – sandy fluvial dark soils, fertile fluvial soils or shallow soils without agricultural potential.

2.5 Water related issues

Various water related issues are apparent within the Pungwe River basin. During several workshops and project meetings with ARA-Centro, it seems that the most relevant water related issues are:

- During the dry season the river flows can become too low in order to serve all water users.
- During the wet season the river flows can become very high and flooding occurs regularly in the lower parts of the downstream regions of the river basin. In 2000 several people drowned during floods caused by a cyclone.
- Salt intrusion is a serious problem in the Pungwe Estuary during high tides in the Indian Ocean.
- There is hardly any flood protection infrastructure so timely flood warnings are the only way to reduce the damage due to floods. The present flood warning system is based on water levels measured by ARA-Centro. When water levels exceed a certain warning level, ARA-Centro signalizes this and a flood warning message is spread over the flood

prone areas. In such a situation, however, the warning is rather late and appropriate planning tools are therefore required.

- In general the water quality of the rivers is rather good. But locally downstream of cities and industries water quality problems exist due to pollution. This pollution should be managed by infrastructure like purification plants and by regulations described in permits. A special problem is pollution by small scale gold mining in the upstream parts of the rivers. This causes erosion and pollution of the rivers with silt and sometimes also with mercury.
- Several new irrigation schemes are planned to increase the Mozambican food production. For this purpose the World Bank has developed the so called Beira Agricultural Growth Corridor project (BAGC). On the long term this project will develop 190,000 ha of irrigated agriculture.

3 Models to understand the processes

3.1 Understanding the hydrological processes

In order to perform a hydrological analysis and modelling study of the Pungwe River Basin, it is essential that the user has good knowledge of the physical processes within their basin of interest. These processes can be studied if historical measurements (e.g. rainfall, temperature, discharge, river extractions, etc.) are available and of good quality. Thus in order to perform a thorough hydrological modelling study, one first has to check the quality and availability of historical measurements. The analysis of historical measurements is described in Section 4.

If the quality of the historical data is good, then the physical processes involved in the circulation of water throughout the earth and the atmosphere can be understood. These processes are a complex mechanism of energy exchange and different ways of transportation. A schematization of the different processes involved in global the water cycle is shown in Figure 2. Many of these processes are also likely to occur in the Pungwe River Basin, except for water storage in ice and snow. Hydrological models can be used as a tool to study and get a better understanding of the physical processes occurring within a river basin like e.g. the Pungwe River Basin. These tools can be used to study, for example, the impact of climate change on water availability, the impact of land use change on river flows, the impact of reservoir expansion or allocation, and the effect of management strategies on the water availability and sediment yield.

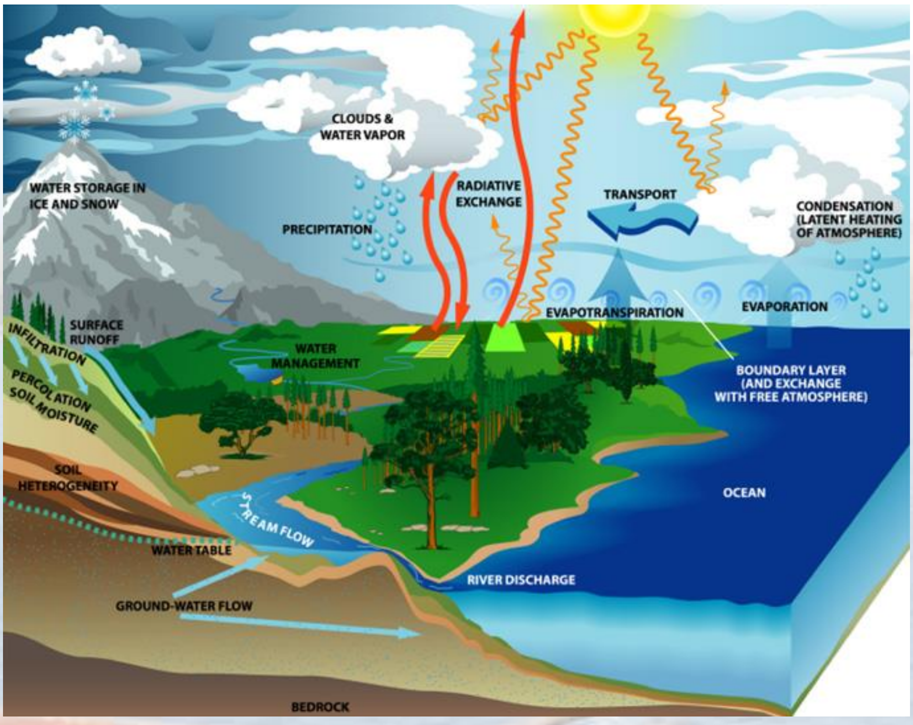


Figure 2: Schematization of the global water cycle.

In hydrology, often the water balance is used to verify if all the hydrological fluxes are in the correct order of magnitude. The water balance uses a control volume, where all the ingoing fluxes minus the outgoing fluxes should be equal to the change in storage:

$$dS = Q_{in} - Q_{out}$$

with *dS* the change in storage, Q_{in} the sum of ingoing fluxes, and Q_{out} the sum of outgoing fluxes. This principle can be applied to the Pungwe river basin as well, where the basin itself can be seen as the control volume. A schematization of the Pungwe River Basin as control volume with the in- and outgoing fluxes is shown in Figure 3. The Pungwe River Basin doesn't receive water from an upstream river, and therefore the in- and outgoing fluxes are:

- In:
  - Rain
- Out:
  - Evapotranspiration
  - Outflow to the sea

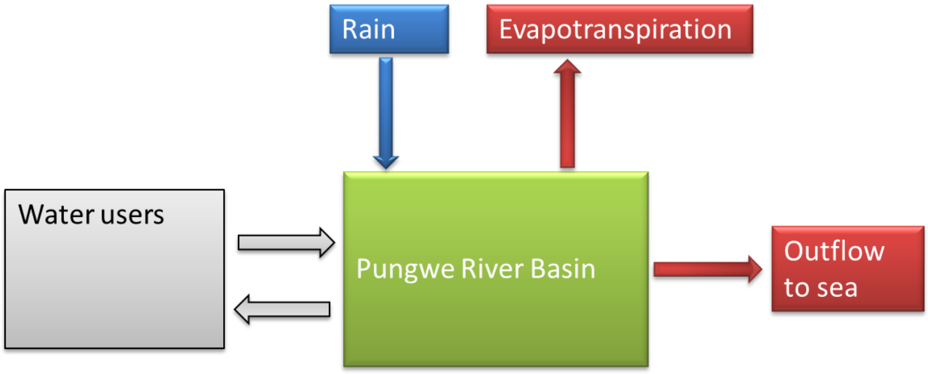


Figure 3: Schematization of the Pungwe River Basin as control volume, with the in- and outgoing fluxes.

Considering the schematization of the Pungwe River Basin (Figure 3), it is essential to have good quality data on rainfall, evapotranspiration, and discharge measurements. In addition to this, several water users (agriculture, FIPAG, Mafambisse) are located within the Pungwe River Basin. All these users extract water from the river, and a certain amount of this water is eventually discharged again to the river. If the amount, frequencies, and locations of all these river extractions and return flows are known, then the hydrologist can use this information to build a better hydrological model.

3.2 Model selection

The objective of the current study is to perform a hydrological assessment of the Pungwe River Basin. In order to complete this objective, a hydrological model needs to be selected and setup to meet the hydrological conditions in the Pungwe River Basin.

Worldwide, a huge number of hydrological models are available to analyze the soil-water relationships at the field and basin level. A distinction exists between conceptually based (lumped) and physically based models. A conceptual hydrological model lumps all the hydrological processes into a number of parameters that can be optimized in order to match the simulated streamflow with the observed streamflow at a downstream gauge location. These models are often used in poorly gauged basins because the user is in that case only interested in the river discharge on one location within the basin. It is possible that the calibrated model parameters lead to good simulations at the most downstream point, but that these parameters will not hold for other locations within the river basin. Therefore, it is better to use a physically based model if one is interested in the river discharge at multiple locations, and one wants to study the effects of certain scenarios. For the current study it is important that:

- The model is physically based rather than conceptual based to ensure the possibility to simulate the river discharge at multiple locations and to study the effects of possible future scenarios:
    - Land use changes
    - Change in management of reservoirs, agricultural practices
    - Reservoir allocation and/or extensions
    - Additional water users
    - Etc.
- User-friendly interface.
- Public domain (free of charge).
- Large user-group worldwide.
- Excellent documentation, including training materials.
- Successfully applied in other studies worldwide (good user experience).

Based on these criteria it was decided to select the Soil and Water Assessment Tool (SWAT) [Neitsch et al., 2000] for the hydrological assessment of the Pungwe River Basin. SWAT was chosen because it is a basin-scale physically based model, which is capable of studying the effects of future scenarios, it has a user-friendly interface, it is available in the public domain and has a large user-group worldwide, and it has successfully been applied in several previous studies in Kenya [Kauffman et al., 2007; Hunink et al., 2009, 2010], Morocco [Terink et al., 2011], and China [Brandsma et al., 2013].

3.3 Soil Water and Assessment Tool (SWAT) concepts

SWAT (http://swat.tamu.edu/software/swat-model/) is a river basin model developed originally by the USDA Agricultural Research Service (ARS) and Texas A&M University and is currently one of the world's leading spatially distributed hydrological models.

A distributed rainfall-runoff model – such as SWAT – divides a catchment into smaller discrete calculation units for which the spatial variation of the major physical properties are limited and hydrological processes can be treated as being homogeneous. The total catchment behavior is a net result of manifold small sub-basins. The soil map and land cover map within sub-basin boundaries are used to generate unique combinations, and each combination will be considered as a homogeneous physical property, i.e. Hydrological Response Unit (HRU). The water balance for HRU's is computed on a daily time step. Hence, SWAT will distribute the river basin into units that have similar characteristics in soil, land cover and that are located in the same sub-basin. The main processes that are implemented in the SWAT model are illustrated in Figure 4.

Irrigation in SWAT can be scheduled by the user or automatically determined by the model depending on a set of criteria. In addition to specifying the timing and application amount, the source of irrigation water must be specified, which can be: canal water, reservoir, shallow aquifer, deep aquifer, or a source outside the basin.

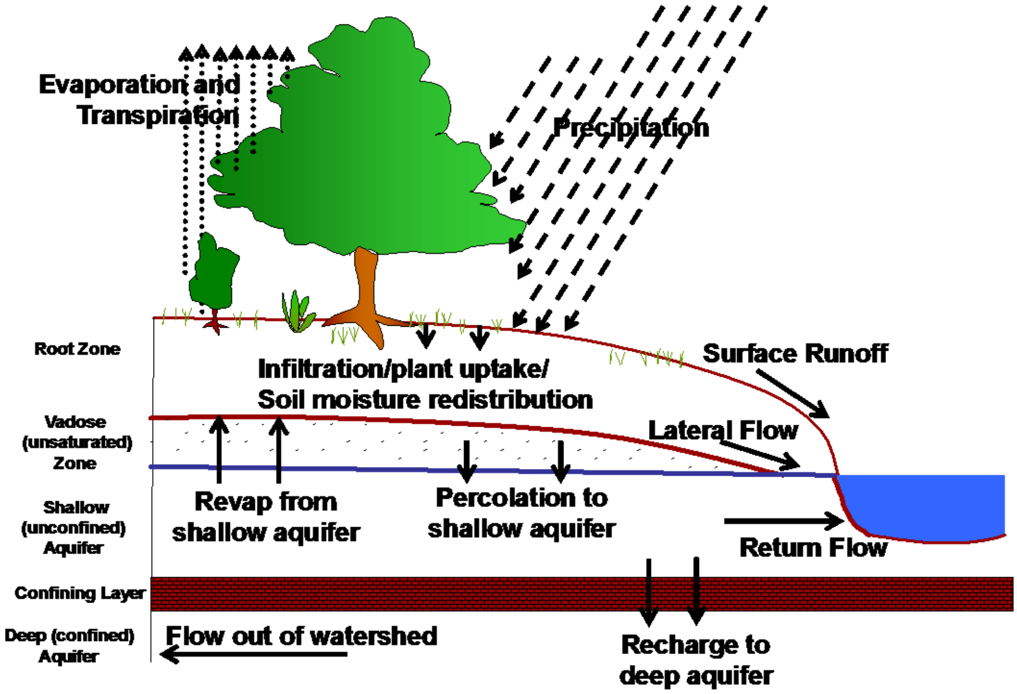


Figure 4: Main physical processes as implemented in the SWAT model.

SWAT can deal with standard groundwater processes (Figure 4). Water enters groundwater storage primarily by infiltration/percolation, although recharge by seepage from surface water bodies is also included. Water leaves groundwater storage primarily by discharge into rivers or lakes, but it is also possible for water to move upward from the water table into the capillary fringe, i.e. capillary rise. As mentioned before, water can also be extracted by people for irrigation purposes. SWAT distinguishes recharge and discharge zones.

Recharge to unconfined aquifers occurs via percolation of excessively wet root zones. Recharge to confined aquifers by percolation from the surface occurs only at the upstream end of the confined aquifer, where the geologic formation containing the aquifer is exposed at the earth's surface, flow is not confined, and a water table is present. Irrigation and link canals can be connected to the groundwater system; this can be an effluent as well as an influent stream.

After water is infiltrated into the soil, it can basically leave the ground again as lateral flow from the upper soil layer – which mimics a 2D flow domain in the unsaturated zone – or as return flow that leaves the shallow aquifer and drains into a nearby river (Figure 5). The remaining part of the soil moisture can feed into the deep aquifer, from which it can be pumped back. The total return flow thus consists of surface runoff, lateral outflow from root zone and aquifer drainage to river.

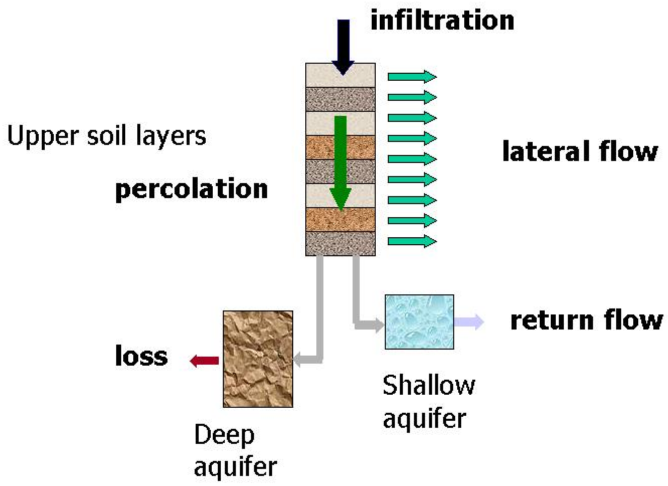


Figure 5: Schematization of the SWAT sub-surface water fluxes.

3.4 Data requirements

In order to build a SWAT model for your basin, some data is essential (baseline data), while other model input data can be seen as additional beneficiary data. The essential baseline input data for SWAT is:

- Digital Elevation Model (DEM);
- Land use / land cover;
- Soil information
- Climate;

If you have the above mentioned data, then you will be able to run the SWAT model and evaluate the simulated discharges. Without the above mentioned data, a SWAT model cannot be build. The Digital Elevation Model is required to delineate your river basin and determine the location of the sub-basins and streams within your basin. Land use / land cover data is required in order to determine the potential evapotranspiration, interception and corresponding water fluxes that enter the soil surface. The soil information in SWAT will be used to determine the soil-physical properties/parameters, which will affect the processes as schematized in Figure 5. Finally, climate data is one of the most essential SWAT baseline data that is required. For climate data it is required to have at least rainfall and maximum and minimum daily temperatures. Since rainfall data and temperature data have a substantial effect on the volumes of generated streamflow, it is very important to have a dense network of climate stations that can produce accurate measurements.

Besides the essential baseline data, SWAT can be fed with additional data that can improve our model outcome. Examples of additional data are reservoir data (location, storage capacity, and management), inlet and outlets for extractions, crop management and irrigation, water quality and sedimentation parameters. For the Pungwe River Basin, no large reservoirs are present, and are therefore not taken into account in the SWAT model. The additional data, however, could improve SWAT model results:

- Crop management and irrigation;
- River extractions;

Detailed crop rotations and irrigation management schedules are unknown, and are therefore implemented into the SWAT model in a simplified way.

A large number of water users are present in the Pungwe River Basin. ARA-Centro has provided a sheet with the water users and their estimated monthly consumption rates. Most of these water consumptions have been estimated during the permit requests, and should be replaced with the actual consumptions as soon as these are known. The water users that extract water from the Pungwe River are shown Table 3. These water extractions have been implemented in the SWAT model.

Table 3: Overview of water users in the Pungwe River Basin with their monthly extraction rates.

Water user	*Average monthly consumption [m^3]*	*Extraction months*
Mafambisse	6,682,701*	Jan-Dec
FIPAG Beira	882,926*	Jan-Dec
Macequesse	61,358	Jan-Dec
Catandica ranch	104,167	Jan-Dec
Deca	7,000	Apr-Oct
Valley Marcs	117,000	May-Oct
Companhia de Vandúzi	265,500	Jan-Dec
Panda Farm	8,000	Jan-Dec
Moz-Agri Lda	7,000	Jan-Dec
Piter Waziwey	7,000	Jan-Dec
Luz de Sol	3,500	Jan-Dec
Cleanstar Mozambique	450	Jan-Dec
Avicola Abilia Antunes	31,500	Jan-Dec
Centro Educacional Nherere	16,675	Jan-Dec

* = based on measurements instead of estimations.

In order to validate the model results, it is required to have (good quality) streamflow measurements on several locations within the Pungwe River Basin that cover a substantial period of time. All these data that is used for the hydrological analysis and modelling of the Pungwe River Basin is described in detail in Section 4. Figure 6 shows a diagram of the input data and modeling components that can be used within SWAT.

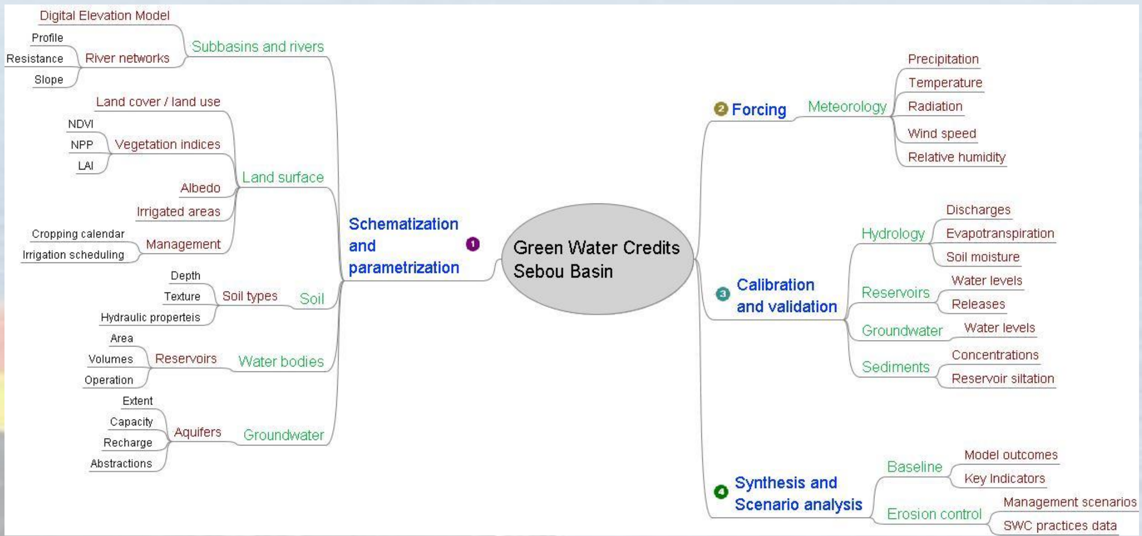


Figure 6: Diagram of SWAT input data and modeling components.

4 Baseline data

4.1 General

This chapter provides an overview of the data that is required to build the SWAT model for your basin of interest, which is in this case the Pungwe River Basin. It is well-known that data availability in Africa is often low, and monitoring networks often have low area coverage. If in-situ data is not available, has gaps, has low quality or small area coverage, then remotely sensed data will be used in order to obtain a good quality map for the desired input parameter, covering the entire basin.

4.2 Digital Elevation Model (DEM)

The basis for the delineation of a watershed in SWAT is a Digital Elevation Model (DEM). Digital Elevation data can be obtained from HydroSHEDS[2]. HydroSHEDS provides hydrographic information in a consistent and comprehensive format for regional and global-scale applications. These data layers are available to support watershed analyses, hydrological modeling, and freshwater conservation planning at a quality, resolution, and extent that had previously been unachievable in many parts of the world. HydroSHEDS offers a suite of geo-referenced data sets (vector and raster) at various scales, including river networks, watershed boundaries, drainage directions, and flow accumulations. HydroSHEDS is based on high-resolution elevation data obtained during a Space Shuttle flight for NASA's Shuttle Radar Topography Mission (SRTM)[3].

Currently, SRTM data at a spatial resolution of 3 arc-second (90 meters) are available for global coverage between 60 degrees North and 56 degrees South latitude. For the Pungwe River Basin, two 3 sec (~90 m spatial resolution) void filled DEMs were downloaded: s20e035 and s20e30. These DEMs are in the WGS1984 geographical coordinate system (lat, lon). SWAT can only work with equal square coordinate systems. The most appropriate equal square coordinate system for this part of Mozambique is WGS1984 UTM36S[4]. Therefore, the two DEMs were mosaicked together, and projected and resampled to a spatial resolution of 250 m in the WGS1984 UTM36S coordinate system. The resulting DEM for the Pungwe River Basin is shown in Figure 7. Based on this DEM, we note that the elevations in the basin range between 0 and 2548 MASL (Meters Above Sea Level). Large elevations are found in the western part and in the region around Gorongosa National Park.

---

[2] http://hydrosheds.cr.usgs.gov/index.php
[3] http://www2.jpl.nasa.gov/srtm/
[4] http://spatialreference.org/ref/epsg/32736/

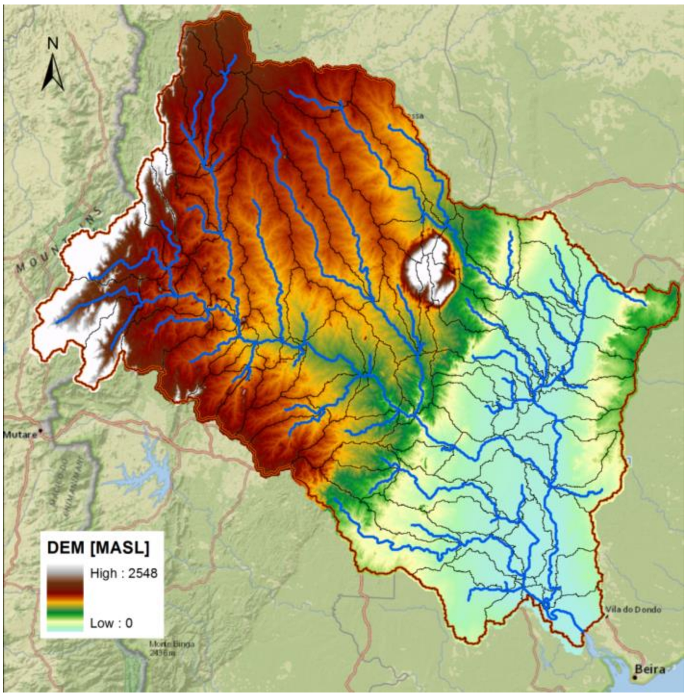


Figure 7: Digital Elevation Model (DEM) for the Pungwe River Basin on a spatial resolution of 250 m.

4.3 Soils

The area of the Pungwe River basin is covered with different soil types (see Section 2.4). Local soil maps are available, but they don't provide the physical parameters that are required for the SWAT model. From a global perspective, the Harmonized World Soil Database[5] (HWSD v1.2) (FAO, 2012) is available for the whole globe. The HWSD is a 30 arc-second (~1 km) raster database with over 16000 different soil mapping units that combines existing regional and national updates of soil information worldwide (SOTER, ESD, Soil Map of China, WISE) with the information contained within the 1:5 000 000 scale FAO-UNESCO Soil Map of the World. Since local soil physical properties are lacking, the Harmonized World Soil Database is considered to be the most detailed available and is therefore used in the current study. It contains mostly all parameters which are required to be used in the SWAT model.

Some physical soil parameters cannot be obtained directly from the HWSD. These physical soil parameters were derived using the pedo-transfer functions (Nemes et al., 2001). These functions use the percentages of clay, silt, organic matter content and bulk density in order to calculate the Mualem-Van Genuchten parameters (Mualem, 1976; Van Genuchten, 1980). The pedo-transfer functions are shown in Figure 8. The required SWAT soil parameters can be found in Table 4. Depending on the number of specified soil layers, these parameters have to be filled in for each soil layer separately. The soil map for the Pungwe River Basin is shown in Figure 9 with the unique HWSD soil classes.

[5] http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/

Continuous pedotransfer functions: a prediction of the Mualem-van Genuchten parameters for the individual soil horizons. The Mualem-van Genuchten parameters were transformed as $K_s^* = ln\ (K_s)$, $a^* = ln\ (a)$, $n^* = ln\ (n\text{-}1)$ and $l^* = ln\ ((l+10)\ /\ (10\text{-}l))$ to comply with a number of physical boundary conditions. θ_s was not transformed. The regressed variables were: C = percent clay, S = percent silt, OM = organic material content, D = bulk density; topsoil and subsoil were qualitative variables having the value of 1 or 0.

$\theta_s = 0.7919 + 0.001691{*}C - 0.29619{*}D - 0.000001491{*}S^2 + 0.0000821{*}OM^2 + 0.02427{*}C^{-1} + 0.01113{*}S^{-1} + 0.01472{*}\ln(S) - 0.0000733{*}OM{*}C - 0.000619{*}D{*}C - 0.001183{*}D{*}OM - 0.0001664{*}topsoil{*}S$
$\alpha^* = -14.96 + 0.03135{*}C + 0.0351{*}S + 0.646{*}OM + 15.29{*}D - 0.192{*}topsoil - 4.671{*}D^2 - 0.000781{*}C^2 - 0.00687{*}OM^2 + 0.0449{*}OM^{-1} + 0.0663{*}\ln(S) + 0.1482{*}\ln(OM) - 0.04546{*}D{*}S - 0.4852{*}D{*}OM + 0.00673{*}topsoil{*}C$
$n^* = -25.23 - 0.02195{*}C + 0.0074{*}S - 0.1940{*}OM + 45.5{*}D - 7.24{*}D^2 + 0.0003658{*}C^2 + 0.002885{*}OM^2 - 12.81{*}D^{-1} - 0.1524{*}S^{-1} - 0.01958{*}OM^{-1} - 0.2876{*}\ln(S) - 0.0709{*}\ln(OM) - 44.6{*}\ln(D) - 0.02264{*}D{*}C + 0.0896{*}D{*}OM + 0.00718{*}topsoil{*}C$
$l^* = 0.0202 + 0.0006193{*}C^2 - 0.001136{*}OM^2 - 0.2316{*}\ln(OM) - 0.03544{*}D{*}C + 0.00283{*}D{*}S + 0.0488{*}D{*}OM$
$K_s^* = 7.755 + 0.0352{*}S + 0.93{*}topsoil - 0.967{*}D^2 - 0.000484{*}C^2 - 0.000322{*}S^2 + 0.001{*}S^{-1} - 0.0748{*}OM^{-1} - 0.643{*}\ln(S) - 0.01398{*}D{*}C - 0.1673{*}D{*}OM + 0.02986{*}topsoil{*}C - 0.03305{*}topsoil{*}S$

Figure 8: Pedo-transfer functions to calculate the Muelam-Van Genuchten parameters (Nemes et al., 2001).

Table 4: Required SWAT soil parameters.

NLAYERS	integer	Number of layers in soil profile
HYDGRP	character	Soil hydrologic group
SOL_ZMX	Float	Maximum rooting depth of soil profile (mm)
ANION_EXCL	Float	Fraction of porosity from which anions are excluded
SOL_CRK	float	Potential or maximum crack volume of the soil profile expressed as a fraction of total soil volume
TEXTURE	Text	Texture of soil layers (optional)
SOL_Z1	Float	Depth to bottom of first soil layer (mm)
SOL_BD1	Float	Moist bulk density of first soil layer (Mg/m3)
SOL_AWC1	Float	Available water capacity of first soil layer (mm/mm)
SOL_K1	Float	Saturated hydraulic conductivity of first soil layer (mm/hr)
SOL_CBN1	Float	Organic carbon content of first soil layer (%)
CLAY1	Float	Clay content of first soil layer (%)
SILT1	Float	Silt content of first soil layer (%)
SAND1	Float	Sand content of first soil layer (%)
ROCK1	Float	Rock content of first soil layer (%)
SOL_ALB1	Float	Moist soil albedo of first soil layer
USLE_K1	Float	USLE equation soil erodibility (K) factor
SOL_EC1	Float	Electrical conductivity of first soil layer (dS/m)

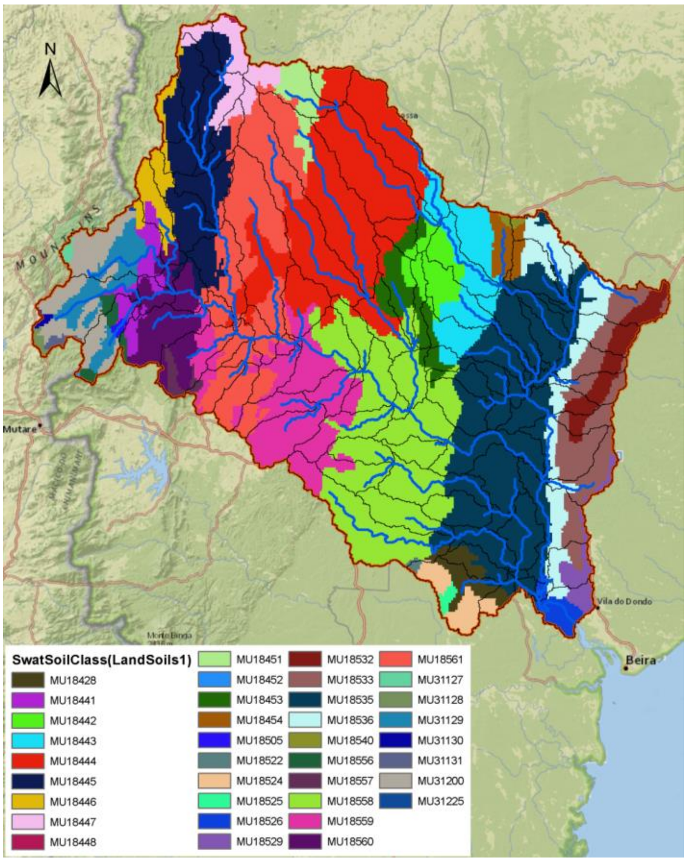


Figure 9: HWSD soil map for the Pungwe River Basin.

4.4 Land use

For the current study the GlobCover2009[6] (GlobCover, 2011) product is used (Figure 10), which is available for the entire globe. This land cover map is used because it is the most accurate map available (300 m resolution), and it has more classes (22) than the locally obtained land cover maps.

GlobCover is an ESA initiative which began in 2005 in partnership with JRC, EEA, FAO, UNEP, GOFC-GOLD and IGBP. The aim of that project was to develop a service capable of delivering global composites and land cover maps using as input observations from the 300 m MERIS sensor on board the ENVISAT satellite mission. The GlobCover 2009 land cover product is the second 300 m global land cover map produced from an automated classification of MERIS FR time series.

For the current study the GlobCover2009 product was resampled to a resolution of 250 m in the WGS1984 UTM36S projection. Since the GlobCover2009 land cover classes have more detail than is required for the SWAT model, the classes were simplified to the SWAT land use classes as can be found in the SWAT2009 user database. The resulting land cover map for the Pungwe River Basin is shown in Figure 11. Based on this map, forest covers 78% of the Pungwe River basin, which is more or less in line with the 83% as found by SWECO & Associates (2004).

---

[6] http://due.esrin.esa.int/globcover/LandCover2009/GLOBCOVER2009_Validation_Report_2.2.pdf

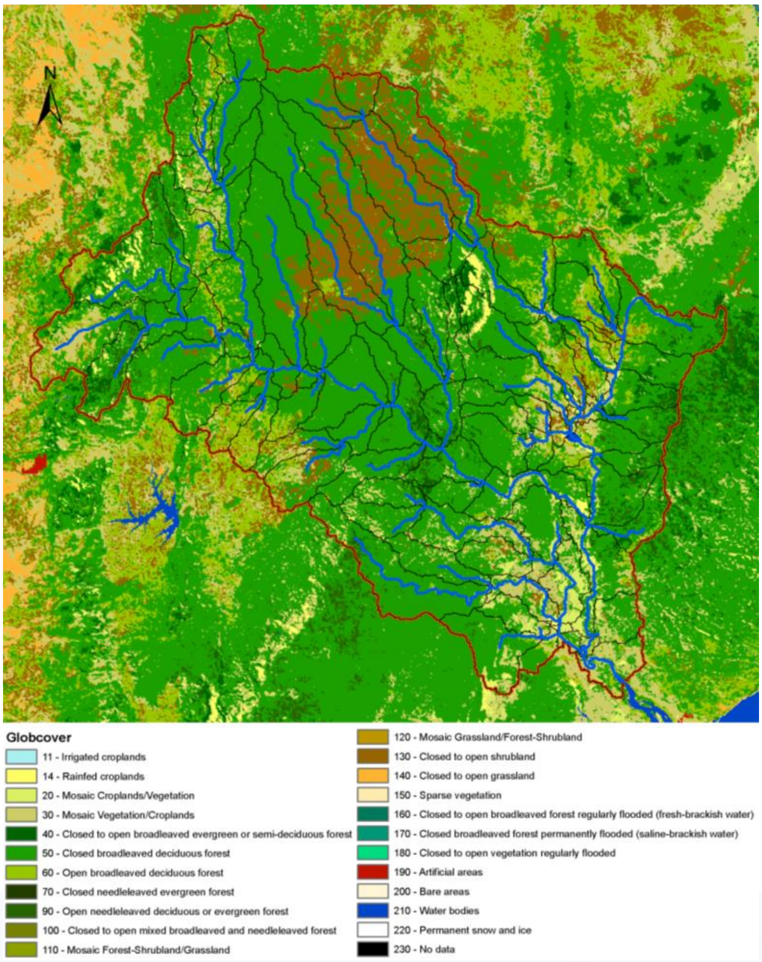


Figure 10: GlobCover2009 land cover product for the Pungwe River Basin.

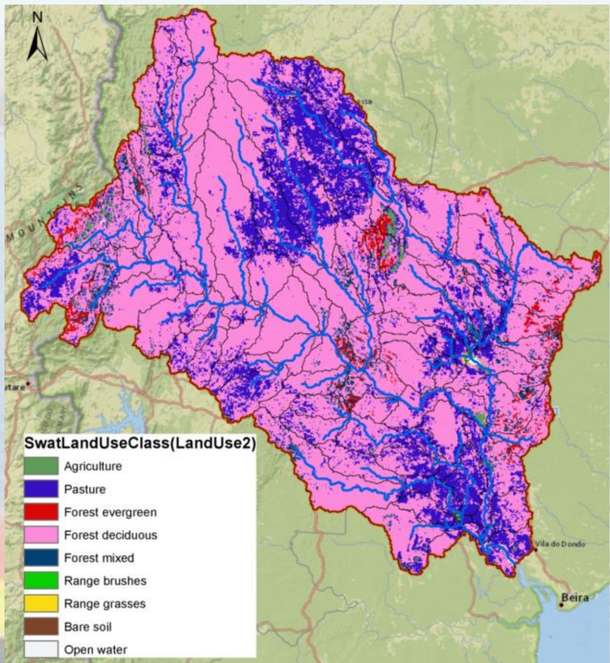


Figure 11: Land cover classes for the Pungwe River Basin.

The land cover data is currently a static product, and in reality this changes over time. Therefore, it is recommended to update the land cover product in the future. Additionally, the type of agricultural crops, planting and harvesting dates, irrigation amount and frequencies are unknown at this stage. Since SWAT has the option to include crop management (irrigation, planting, harvesting, fertilizer applications), it is recommended to update the model with this information as soon it becomes available. Currently, this data was not available, and therefore agriculture is implemented as one homogenous land cover class for the entire basin, without any management.

4.5 Climate

SWAT requires daily rainfall data as well as other metrological input data that depend on the evapotranspiration method used. Several methods are available to calculate the reference evapotranspiration. The most advanced method available, which is the Penman-Monteith method, requires data on temperature, solar radiation, wind speed, and humidity for the calculation of the spatially distributed potential evapotranspiration rates. These parameters are not available for the Pungwe Basin, and therefore the Hargreaves method (Hargreaves et al., 1985) was used for the calculation of the reference evapotranspiration. This method only requires daily minimum and maximum temperatures.

Various sources for rainfall and temperature were evaluated, and are described in the following sections.

4.5.1 Temperature station data

SWAT requires daily maximum and minimum temperatures for the calculation of the reference evapotranspiration. Since local temperature observations from local sources were not available, the weather stations from the public domain Global Summary of the Day (GSOD[7]) database, archived by the National Climatic Data Center (NCDC[8]), were used. This database offers a substantial number of stations with long-term daily time-series. The GSOD database submits all series (regardless of origin) to extensive automated quality control. Therefore, it can be considered as a uniform and validated database where errors have been eliminated. For the current study, nine active stations were found in or nearby the Pungwe River Basin (Figure 12). However, for the modelling period 2001-2010 not all these stations had data available. Given data availability, seven stations were selected to be used for the SWAT model.

Time-series of daily average, maximum, and minimum, temperatures of these seven GSOD stations are shown in Figure 13. It is obvious that also these GSOD stations contain substantial data gaps. Despite the missing values, spatial interpolation of temperature can still lead to accurate results. It is known that temperatures at higher altitudes are generally lower than temperatures at lower altitudes. Many studies use a lapse rate for temperature to calculate the temperature on other locations that are located at higher or lower altitudes. A widely used lapse rate is -6.5°C/km, which means a temperature decrease of 6.5°C per km elevation increase. This value has also been used in this study to obtain high-resolution spatial temperature maps for the Pungwe River Basin. The left plot in Figure 14 shows the average annual temperature for the Punge River Basin, based on the spatial interpolation of the seven GSOD stations for the

[7] http://gcmd.gsfc.nasa.gov/records/GCMD_gov.noaa.ncdc.C00516.html
[8] http://www.ncdc.noaa.gov/oa/ncdc.html

period 2001-2010. The right plot shows the average annual temperature, averaged per sub-basin.

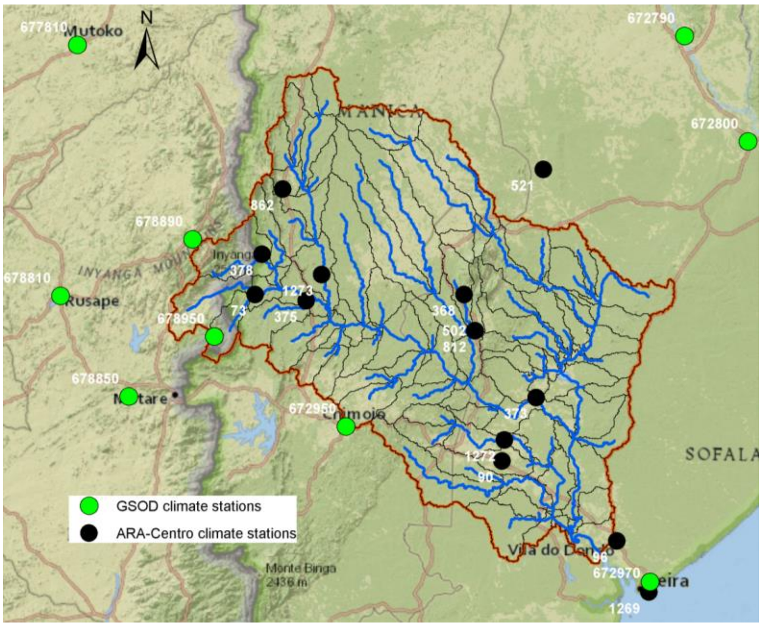


Figure 12: Location of the GSOD and ARA-Centro climate stations. The corresponding station IDs are labelled in white, with the long numbers belonging to the GSOD stations.

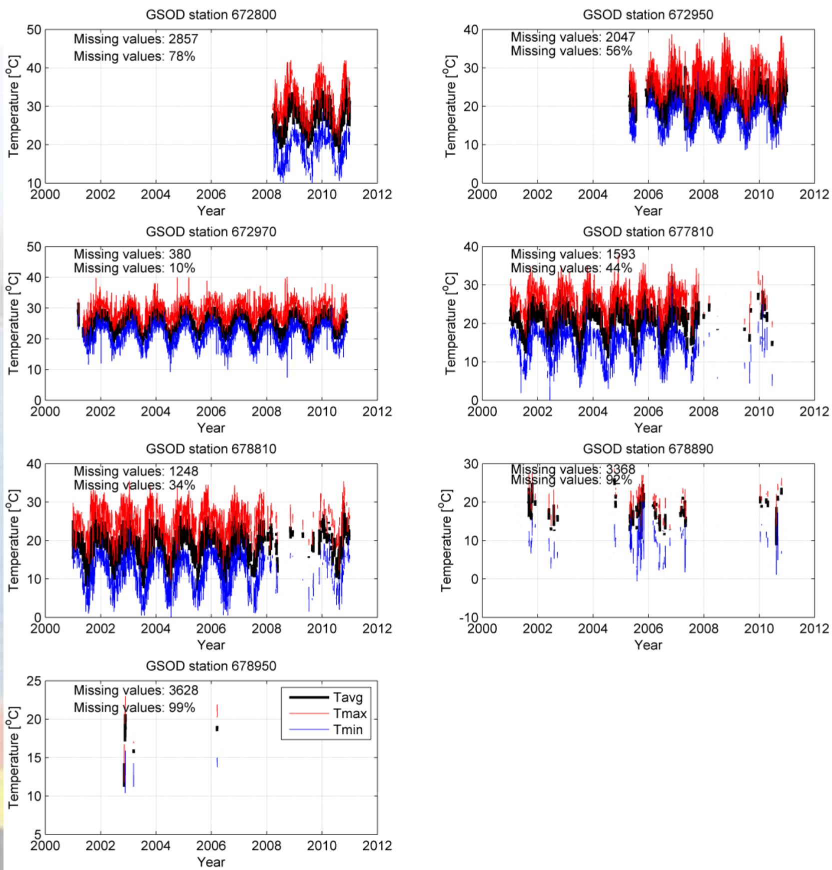


Figure 13: Time-series of daily average, maximum, and minimum temperatures for 7 selected GSOD stations.

It is clear that the spatial interpolation of temperature leads to satisfactory results, with the higher altitudes having lower temperatures, and the lower altitudes having higher temperatures. The western part and the region around Gorongoso National Park have the lowest temperatures, while the remainder of the basin, and especially the southern part has average annual temperatures >25°C. Considering the sub-basin average annual temperatures, it seems that temperatures range between 20.6°C in the western (Zimbabwean) part to 25.7°C in the Pungwe Estuary.

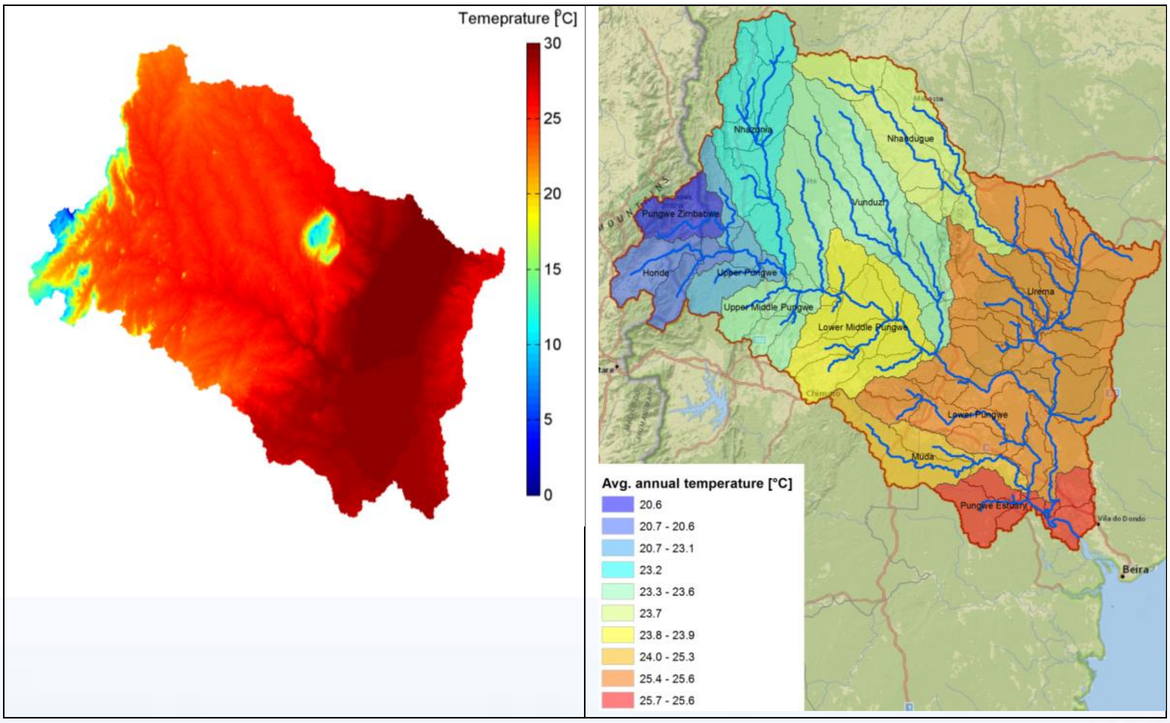


Figure 14: Left: average annual temperature for the Pungwe River Basin, based on the interpolation of 7 GSOD stations for the period 2001-2010. Right: same, but averaged per sub-basin.

4.5.2 Rainfall station data

Rainfall is known to be spatially highly variable. Therefore, a dense station network with accurate rainfall measurements is very relevant for hydrological studies. ARA-Centro has its own network of rainfall stations (black dots Figure 12). Additionally, the same GSOD stations that were used to obtain temperature data also provide daily rainfall values.

Before the rainfall station data can be used in the SWAT model, a quality check has been performed in order to select only the stations that provide reliable rainfall data. A well-known method to verify the quality of rainfall station data is to plot the cumulative rainfall over time. By comparing the cumulative rainfall sums of the various stations, discrepancies identify stations that are not reliable. Possible explanations for these discrepancies may be re-allocation of the station, plantation covering the station, and no-data collection for a certain period of time.

4.5.2.1 ARA-Centro stations

Given the modelling period 2001-2010, seven ARA-Centro stations were selected that provide data for this period. The cumulative rainfall of these stations is shown in Figure 15. It is clear that there is a wetter and drier period during every year, which explains the jumps in all cumulative rainfall sums. From this plot it is already clear that station ID 375 and 862 are not reliable, because they show a longer period with almost no increase in cumulative rainfall, which is likely due to no date measurements during these periods.

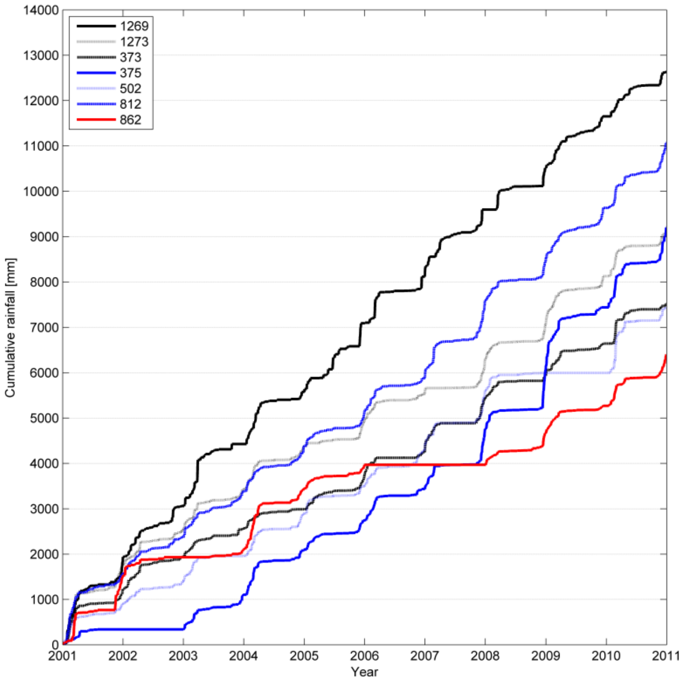


Figure 15: Cumulative rainfall of some pre-selected ARA-Centro rainfall gauges for the period 2001-2010.

Another way to identify unreliable rainfall stations is to plot the cumulative rainfall of each station against the cumulative average rainfall of the selected stations. In Figure 16 we have plotted the average cumulative rainfall of the seven selected stations (Figure 15) against the cumulative rainfall of each of these individual stations. A clear offset identifies unreliable stations. These offsets are clearly visible for station IDs 375, 502, and 862. Therefore, the following ARA-Centro stations were selected to be used in the spatial interpolation of rainfall:

- 1269
- 1273
- 373
- 812

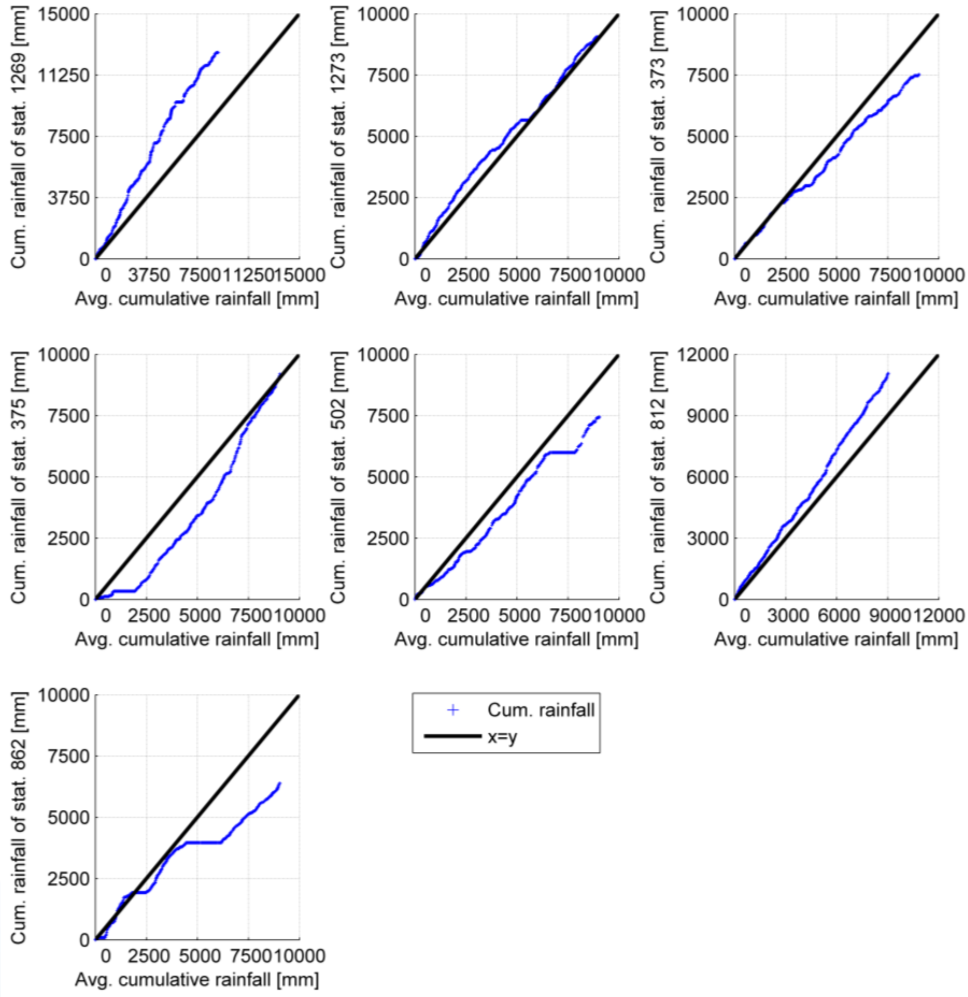


Figure 16: Scatter-plot of the average cumulative rainfall of the pre-selected stations vs. the cumulative rainfall for each of these stations.

4.5.2.2 GSOD stations

From the nine GSOD stations (Figure 12), only three stations had data availability and were considered useful for a reliability analysis for the period 2001-2010. It should be noted that they only have data for the period 2001-2007. The cumulative rainfall of these stations is plotted in Figure 17, together with the cumulative average rainfall of the seven ARA-Centro stations, and the three GSOD stations. No clear discrepancies are visible in this figure. It is also clear that the GSOD stations behave more or less similar to those of ARA-Centro.

A last check was performed by plotting the cumulative rainfall of each GSOD rainfall station against the average cumulative rainfall of the ARA-Centro stations. These results are shown in Figure 18. Based on this figure, it can be concluded that GSOD station 672970 shows some irregularity, and is therefore not useful for hydrological modelling. This leaves the following two GSOD stations suitable for interpolation of rainfall data:

- 677810
- 678810

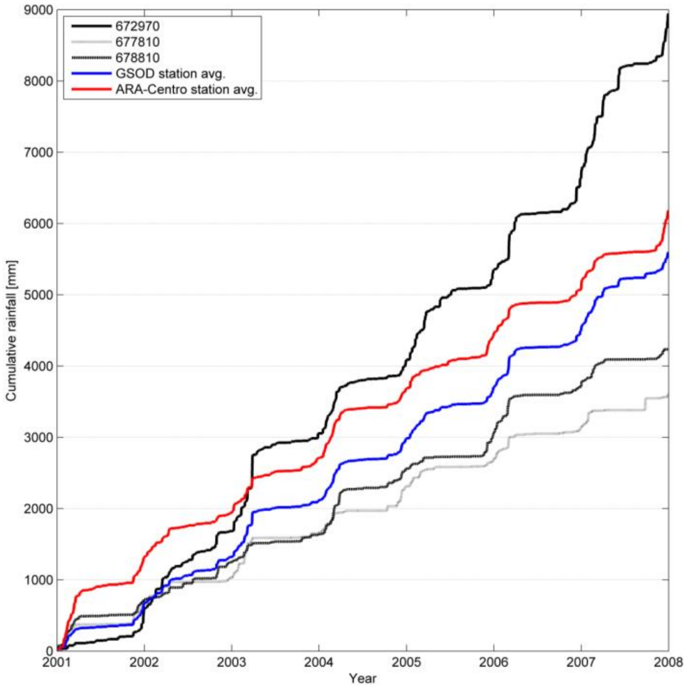


Figure 17: Cumulative rainfall of GSOD stations, the average cumulative rainfall of GSOD stations, and the average cumulative rainfall of the selected ARA-Centro stations.

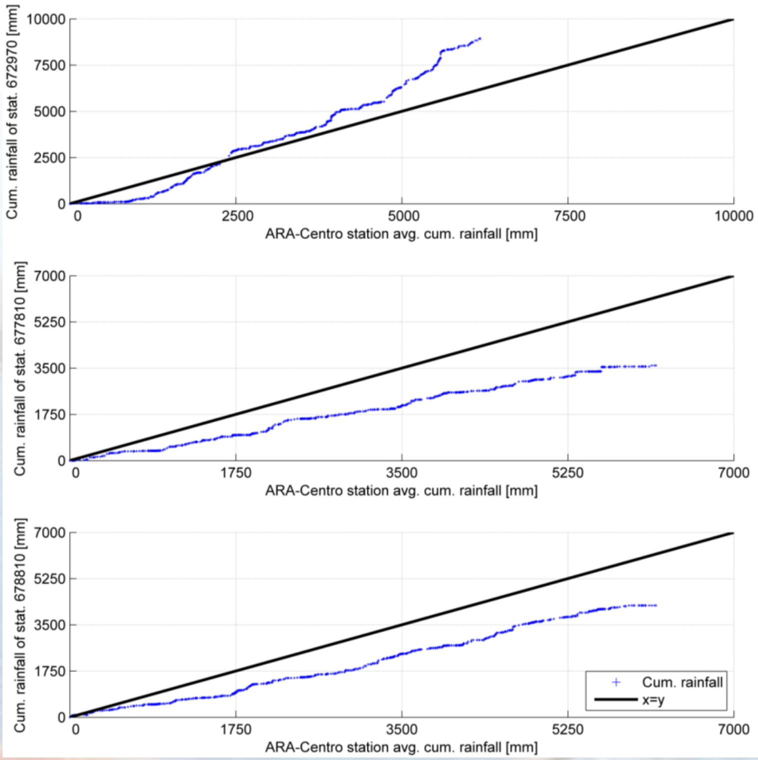


Figure 18: Scatter-plot of average cumulative rainfall of ARA-Centro stations vs. the cumulative rainfall for each of the GSOD stations.

Summarizing, the following stations can be used for rainfall interpolation:

- ARA-Centro (2001-2010):
    - 1269
    - 1273

- 373
- 812

- GSOD (2001-2007):
    - 677810
    - 678810

4.5.2.3 Interpolated rainfall station data

Using the selected rainfall stations, rainfall was spatially interpolated using the inverse distance interpolation technique. Figure 19 (left plot) shows the average annual rainfall for the Pungwe River Basin for the period 2001-2010. The right plot of this figure represents the sub-basin average annual rainfall for this period. These results indicate that the southern part (Pungwe Estuary) and central part (Lower Middle Pungwe) are the wettest parts of the basin, with sub-basin averages varying between 970 and 1028 mm. These results are more or less in line with what was found by SWECO & Associates (2004). However, they found substantially larger rainfall amounts (~2020 mm, period 1960-1980) for the Pungwe Zimbabwe sub-basin. We are focusing on a different period of time, but it is unlikely that a difference of approx. 1000 mm is due to a shift in climate. A study by Mazvimavi (2010) indicates an average annual rainfall rate of 1110 mm for the Zimbabwean part of the Pungwe River Basin. This is more close to what we have found than what was found by SWECO & Associates (2004). In order to verify the reliability of the interpolated rainfall maps, remotely sensed rainfall products have been analyzed as well. This is described in Section 4.5.3 and 4.5.4.

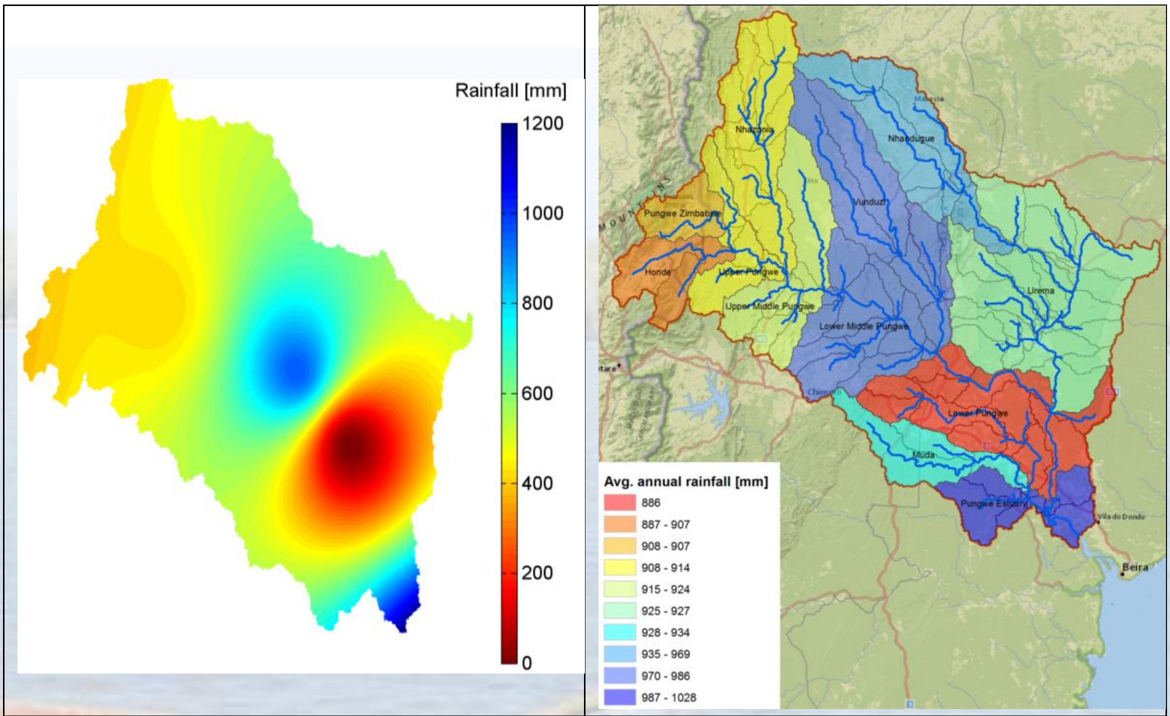


Figure 19: Left: average annual rainfall for the Pungwe River Basin, based on the interpolation of 4 ARA-Centro stations and 2 GSOD stations for the period 2001-2010. Right: same, but averaged per sub-basin.

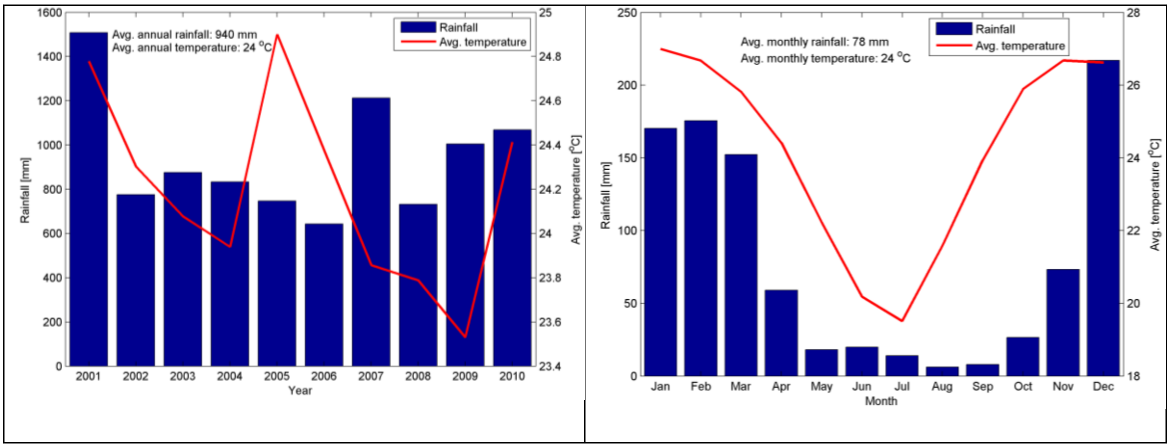


Figure 20: Left: basin average annual rainfall and temperature based on the selected station data. Right: basin average monthly rainfall and temperature based on the selected station data.

Figure 20 shows the basin average annual and monthly rainfall and temperature, based on the interpolated station data. The Pungwe River Basin experienced wet years during 2001 and 2007, while 2006 was a dry year. December through March are the wettest months, while April through October can be characterized as the drier season. Temperatures are higher during the wetter summer months.

4.5.3 FEWS rainfall data

Besides station data, rainfall can be retrieved from satellite imagery, or can be a product of a combination of station and satellite imagery. The FEWS rainfall product (RFE 2.0[9], Xie et al. (1997)) provides accurate daily rainfall estimates for Africa on a spatial resolution of 0.1° (~10 km), and is one of the best rainfall products available for Africa. RFE 2.0 estimates rainfall using a two part merging process; first all satellite data are combined using the maximum likelihood estimation, and secondly Global Telecommunication System (GTS) data are used to remove bias. For more information on the FEWS RFE algorithm, see the RFE 2.0 documents (http://www.cpc.ncep.noaa.gov/products/fews/rfe.shtml).

Figure 21 shows the average annual rainfall based on the RFE 2.0 rainfall product for the period 2001-2010. The right plot of this figure represents the sub-basin averages. The basin averages are shown in Figure 22 for the individual years and months. It is clear that the overall average rainfall is lower than for the interpolated station rainfall. Again 2001 and 2007 can be characterized as being the wettest years, but instead of 2006, FEWS RFE 2.0 indicates 2002 as being the driest year. The monthly variation in rainfall is equal to that of the interpolated station rainfall product. Interestingly, the Gorongosa National Park region is not one of the wettest areas in the Pungwe, as was the case for the interpolated station rainfall product. The Pungwe Estuary is still the wettest area, but also the Pungwe Zimbabwe sub-basin is now part of the sub-basins receiving more rainfall. It is clear that the RFE 2.0 rainfall product results in a better spatial distribution rainfall pattern than the interpolated station data.

---

[9] http://earlywarning.usgs.gov/fews/africa/web/readme.php?symbol=rf

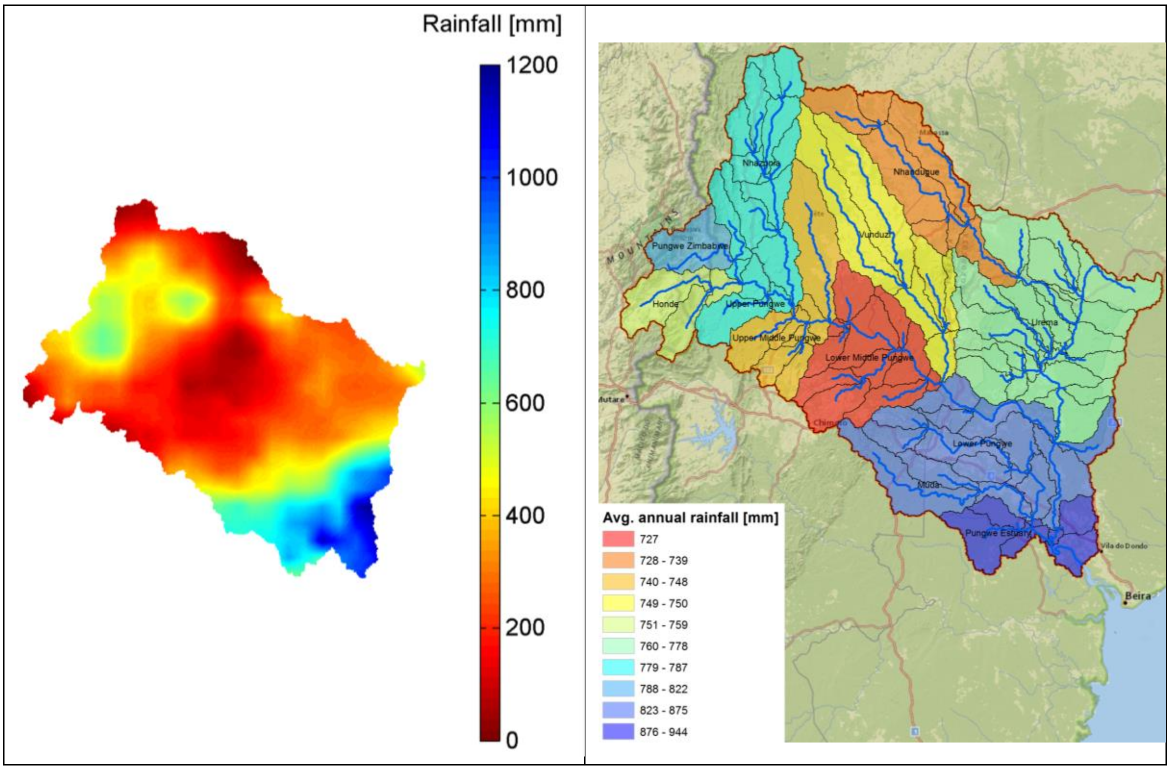


Figure 21: Left: average annual rainfall for the Pungwe River Basin, based on the FEWS RFE 2.0 rainfall product for the period 2001-2010. Right: same, but averaged per sub-basin.

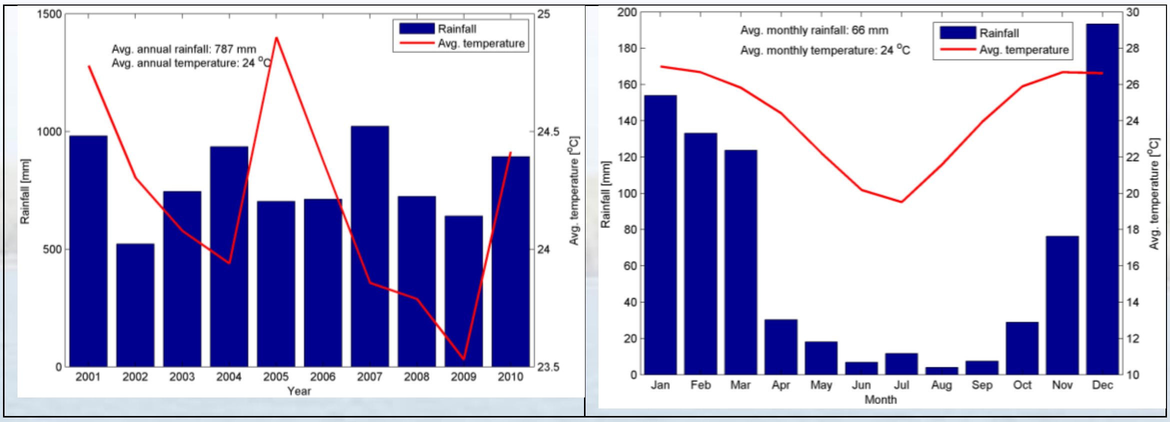


Figure 22: Left: basin average annual rainfall and temperature based on the FEWS RFE 2.0 rainfall product. Right: basin average monthly rainfall and temperature based on the FEWS RFE 2.0 rainfall product.

4.5.4 TRMM rainfall data

A world-wide source of precipitation data is the Tropical Rainfall Measuring Mission[10] (TRMM). TRMM is a satellite with active precipitation radar on-board and has the following characteristics:

- Data is available at a high spatial resolution of 0.25 degrees (approx. 25 km)
- Data is available from 1998 onwards

---

[10] http://trmm.gsfc.nasa.gov/data_dir/data.html

It is recognized that in the first years after launching TRMM, the precipitation data was less accurate than later. However, for the period 2001-2010 is more accurate. For the current study we have analyzed the TRMM 3B42 rainfall product. More information regarding this product can be found at: http://trmm.gsfc.nasa.gov/3b42.html.

Figure 22 shows the average annual rainfall based on the TRMM 3B42 rainfall product for the period 2001-2010. The right plot of this figure represents the sub-basin averages. The basin averages are shown in Figure 24 for the individual years and months. It can be concluded that the overall average rainfall is higher than for the interpolated station rainfall product and FEWS RFE 2.0 product. The spatial distribution is more or less in line with what was found by SWECO & Associates (2004), with the Pungwe Zimbabwe part being wetter. However, the average annual rainfall of 2020 mm (SWECO & Associates, 2004) for the Pungwe Zimbabwe sub-basin is by far higher than was found in any of the three analyzed products in the current study. Based on TRMM 3B42, the average annual rainfall for the Pungwe Zimbabwe sub-basin is ~1000 mm. This is higher than was found for the previous two rainfall products (station data and FEWS RFE 2.0), and also very close to what was found by Mazvimavi (2010). TRMM 3B42 also indicates 2001 and 2007 as being the wettest years, which was true for all analyzed rainfall products so far. Similar as for FEWS RFE 2.0, 2002 can be characterized as being the driest year for the TRMM 3B42 rainfall product. Besides the Pungwe Zimbabwe sub-basin, also the Pungwe Estuary and region around Gorongosa National Park can be classified as wetter areas.

Based on the previous sections it was decided that both FEWS RFE 2.0 and TRMM 3B42 show the best spatial distribution of rainfall, and therefore both products will be tested to be used in the SWAT model.

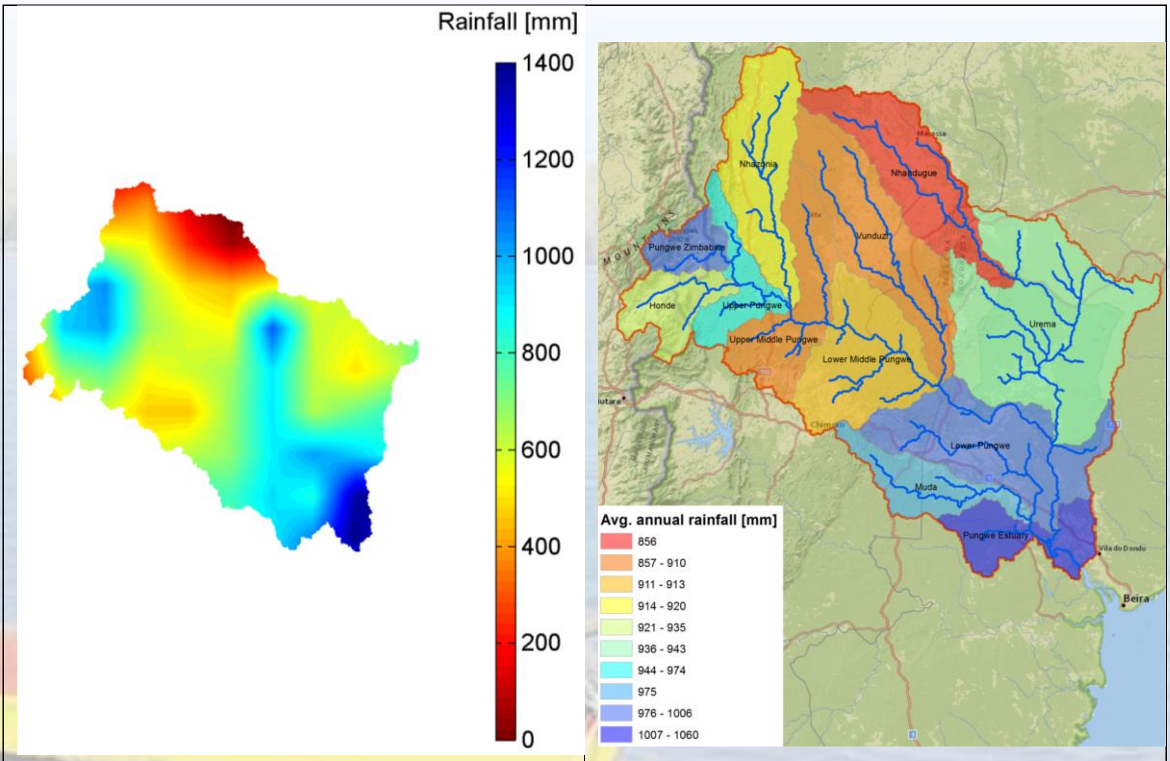


Figure 23: Left: average annual rainfall for the Pungwe River Basin, based on the TRMM 3B42 rainfall product for the period 2001-2010. Right: same, but averaged per sub-basin.

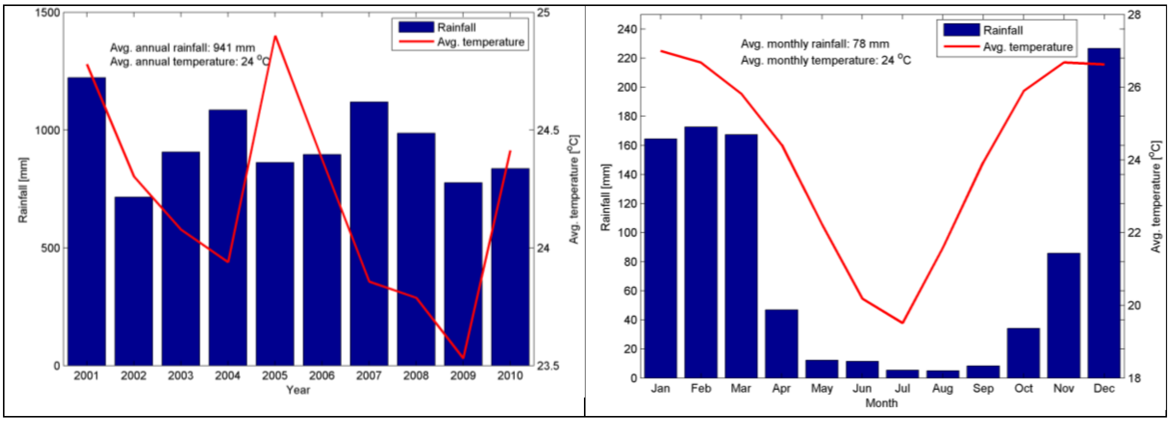


Figure 24: Left: basin average annual rainfall and temperature based on the TRMM 3B42 rainfall product. Right: basin average monthly rainfall and temperature based on the TRMM 3B42 rainfall product.

4.6 Discharge

Discharge data for the Pungwe River Basin was provided by DNA (Direcção nacional de Águas). They provided us with a database containing discharge data for 30 stations. The locations of these stations are represented in Figure 25, and their corresponding names can be found in Table 5.

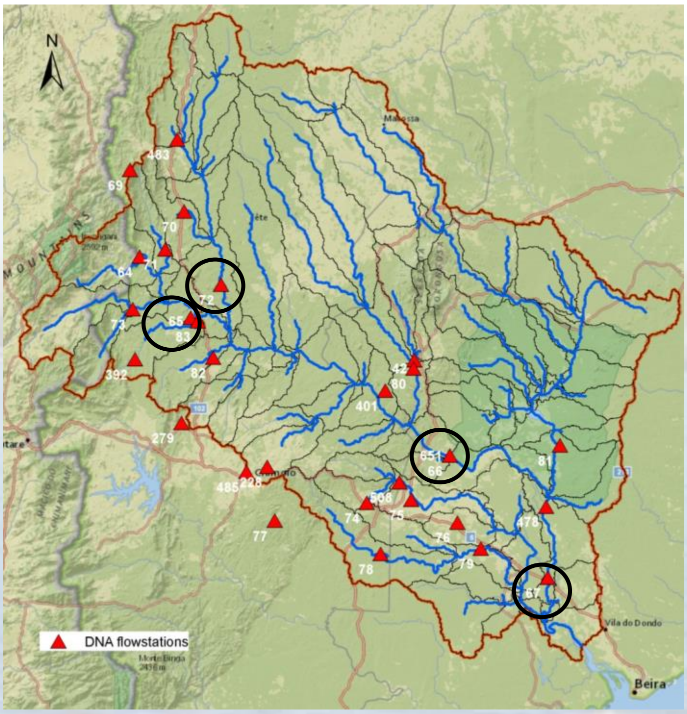


Figure 25: Locations of the DNA flow stations. Circles indicate DNA stations that have sufficient data availability for the period 2001-2010.

The study by SWECO & Associates (2004) focused on the modelling period 1960-1980. This period had good data availability, because during the civil war in Mozambique, which started in 1977 and ended in 1992, discharge data was not or hardly measured, and stations were lost or destroyed. Because the current study focuses on the period 2001-2010, only four stations are left that provide useful discharge data for this period. These stations are marked with circles in

Figure 25 and shaded in Table 5. These stations, except for station ID 651, were also analyzed by SWECO & Associates (2004). Although they focused on a different period, they indicated that these stations provided not reliable to reliable streamflow data, depending on the type of flow measured (Mean Annual Runoff (MAR), daily data, or peaks). A summary of their findings regarding these stations can be found in Table 6. It is clear that all these stations are of major importance, and that these stations should be kept and improved. It is unknown if these improvements have been made after the study of SWECO & Associates (2004).

Table 5: DNA flow station IDs and their corresponding names. The shaded records are DNA stations with sufficient data for the period 2001-2010.

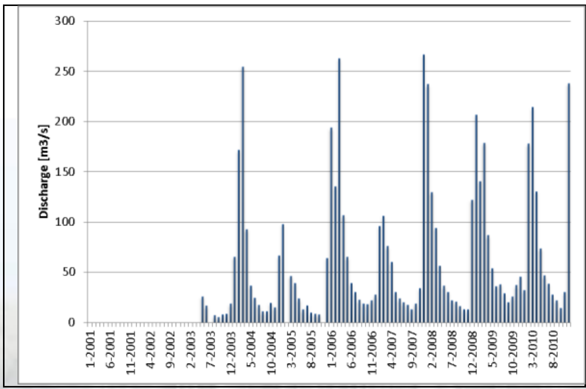
ID	Name
42	Nhandare em Vila Paiva de Andrad
64	Pungue em Fronteira
65	Pungue em E.N.102
66	Pungue em Bue Maria
67	Pungue em Mafambisse EN6
69	Turanhanga em E.N.102 V. Gouveia
70	Nhacangara em E.N. 102
71	Messa. em Antiga Est. de Tete
72	Nhazonia em J.E. da Costa
73	Honde em Mavonde
74	Metuchira em E.N.6
75	Metuchira em Serracao
76	Metuchira em E.N.218 Bue Maria
77	Muda em Zinvari
78	Muda em Antiga SerraþÒo
79	Muda em Lamego
80	Vanduzi em V.Paiva Andrade
81	Urema em E.R.433 Chitengo
82	Mucombeze em E.N.102
83	Mavuzi em ConfluÛncia
228	Mezingaze em Chimoio Barragem
279	Vanduzi em Vanduzi E.N.6 Ponte
392	Mavuzi em Estrada de Mavonde
401	P·ngoÞ em Tacuraminga
478	Dingue Dingue em Cai Cai
483	Nhazonia em E.N.102
485	Mezingaze em Barragem Nova
488	Turanhanga em Confluencia Mugai
508	Metuchira em E.N.1 ponte
651	Pungue em EN1 Ponte Gorongosa

Many discharge measurement locations provide inaccurate results due to the change of river bed because of erosion. It is therefore recommended to construct discharge measurement locations in concrete bedding. Because the number of discharge measurement locations with data availability for the period 2001-2010 is lacking, it is highly recommended to upgrade the current network of discharge measurements. For hydrological assessments, but also for flood-early-warning-systems, continuous flow measurements are required. Summarizing, the quality of the streamflow measurement network can be improved by:

- Restart measuring at the existing locations, and extend the network with more stations, especially in the north and northeastern part of the basin. One gauge downstream of each sub-basin is recommended;
- Improve the quality of the measurements by installing streamflow measurement instrumentation in concrete constructions. This prevents the change of the Q(h)-relation because of change of river bed (erosion);
- Install automatic flow recorders to obtain a continuous record of flow data;

Table 6: Summary of quality check of discharge stations for the period 1960-1980 (SWECO & Associates, 2004).

Station	*MAR*	*Daily data*	*Peaks*	*Importance*	*Recommended actions*
E65	Reliable	Reliable up to 1977, uncertain 78-82, 93-97, not reliable 99-01	Reliable <750 m^3/s, fairly reliable <1700 m^3/s	Very important	Keep
E67	Not reliable	Not reliable <400 m^3/s	Fairly reliable	Medium importance	Keep and improve
E72	Fairly reliable	Fairly reliable <70 m^3/s	Uncertain	Very important	Keep and install data logger equipment



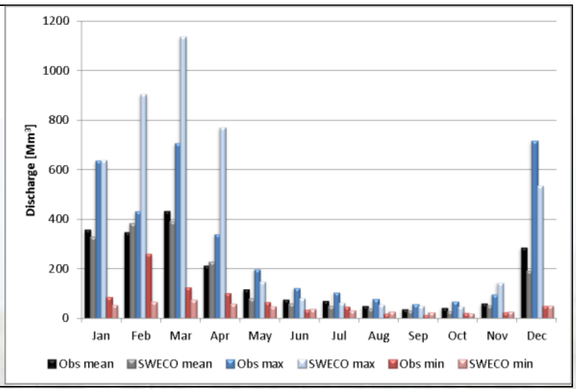


Figure 26: Left: monthly observed streamflow for station E65 for the period 2001-2010. Right: monthly observed average, maximum, and minimum streamflow based on the period 2001-2010, and simulated monthly average, maximum, and minimum streamflow for the period 1960-1980, based on the study by SWECO & Associates (2004).

Figure 26 shows that for station E65 there are no flow records for the period 2001 through April 2003. Average monthly discharge for this station varies between approx. 10 m^3/s and 270 m^3/s. Discharge is highest during the months December-April. It is clear that the average monthly discharge (right plot, Figure 26) hasn't changed a lot between 2001-2010 and 1960-1980. However, SWECO & Associates (2004) simulated a substantial higher maximum monthly flow for February-April 1960-1980, than was observed during 2001-2010. This may indicate that the period 2001-2010 had less extreme rainfall events compared to the period 1960-1980.

Comparable results are shown in Figure 27 for station E72, which is located downstream in the Nhazonia sub-basin. SWECO & Associates (2004) simulated an average monthly streamflow for 1960-1980 that is close to what has been observed during 2001-2010. The maximum monthly streamflow during 1960-1980 has been simulated higher than what has been observed during 2001-2010, indicating a less extremer climate for the latter period. The left plot of Figure

27 indicates missing streamflow records for 2005 and 2010. Monthly streamflow for this station varies approximately between 1 and 73 m^3/s during 2001-2010.

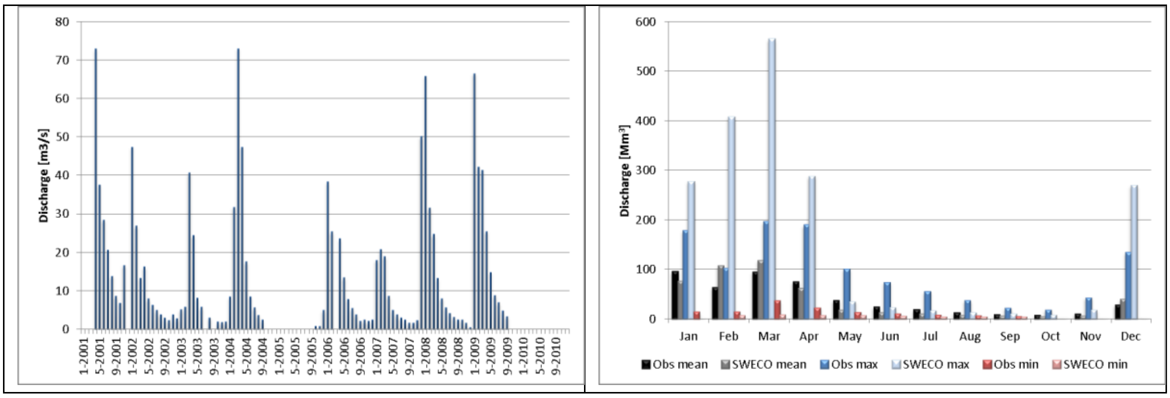


Figure 27: Left: monthly observed streamflow for station E72 for the period 2001-2010. Right: monthly observed average, maximum, and minimum streamflow based on the period 2001-2010, and simulated monthly average, maximum, and minimum streamflow for the period 1960-1980, based on the study by SWECO & Associates (2004).

Figure 28 shows the observed discharge for the period 2001-2010 and the simulated discharge for the period 1960-1980. According to SWECO & Associates (2004), this station provides unreliable data for discharges <400 m^3/s. Since this station is almost at the downstream end of the Pungwe River Basin, tidal influence is affecting this station. Figure 28 shows that this station has no data for 2010. The right plot of this figure shows that SWECO & Associates (2004) have simulated a higher monthly mean and maximum streamflow for the period 1960-1980 then what was observed during 2001-2010. Especially the maximum monthly streamflow is simulated substantially higher, indicating that the period 1960-1980 had more extreme rainfall events than 2001-2010.

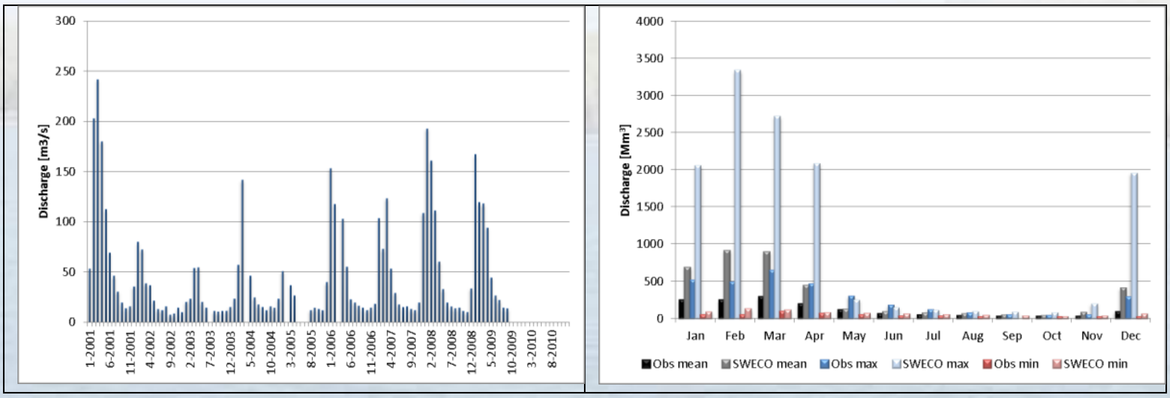


Figure 28: Left: monthly observed streamflow for station E67 for the period 2001-2010. Right: monthly observed average, maximum, and minimum streamflow based on the period 2001-2010, and simulated monthly average, maximum, and minimum streamflow for the period 1960-1980, based on the study by SWECO & Associates (2004).

Comparable results are shown in Figure 29 for station E651, which is located downstream of the Lower Middle Pungwe sub-basin. The left plot of this figure indicates that this station has many gaps, and mainly has data availability during 2003-2006. Both the monthly average and maximum discharge are simulated higher for 1960-1980, then for 2001-2010.

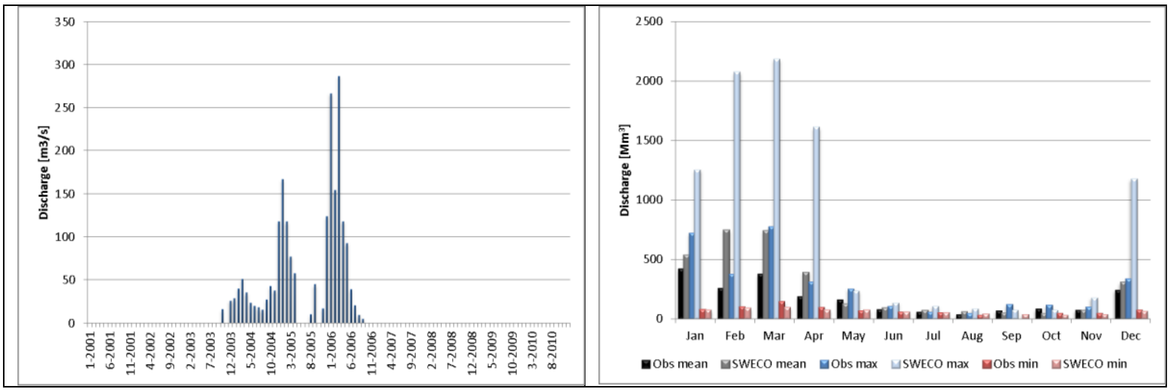


Figure 29: Left: monthly observed streamflow for station E651 for the period 2001-2010. Right: monthly observed average, maximum, and minimum streamflow based on the period 2001-2010, and simulated monthly average, maximum, and minimum streamflow for the period 1960-1980, based on the study by SWECO & Associates (2004).

5 Hydrological modelling

5.1 Model setup

5.1.1 Basin delineation

In SWAT, the basin outlet is defined as the most downstream point of the Pungwe River Basin, which is located near the city of Beira. Consequently, all tributaries upstream of this point belonging to the Pungwe River Basin are included in the analysis.

The DEM forms the base to delineate the catchment boundary, stream network and sub-basins. Using the DEM, SWAT identifies the steepest descend and subsequently the location of the river network and corresponding sub-basins. Basin delineation led to 105 sub-basins within the Pungwe River Basin, with an average sub-basin size of 29,347 ha and an average sub-basin elevation of 349 MASL. The delineation of these sub-basins, along with the streams, is shown in Figure 30.

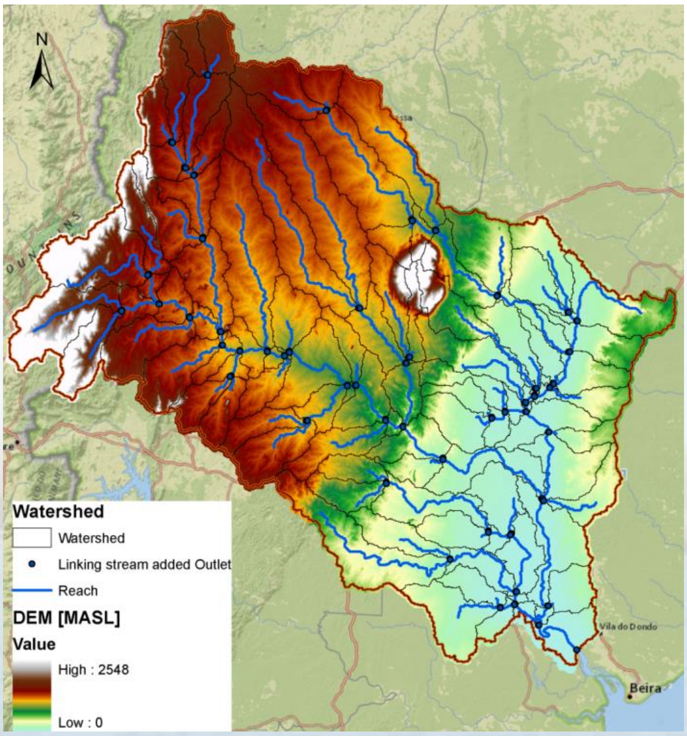


Figure 30: Resulting Pungwe river network and watersheds from the SWAT basin delineation step.

5.1.2 Hydrological Response Units

For the spatial discretization of the sub-basins, SWAT uses the concept of Hydrological Response Units (HRUs) (Neitsch et al., 2000). HRUs are portions of a sub-basin that possess unique land use, management, and soil attributes. In other words, an HRU is the total area in a sub-basin with a specific land use, management, and soil combination. HRUs are used in SWAT since they simplify a run by lumping all similar soil and land use areas into a single response unit. The size of a HRU depends on the size of the total area under consideration.

Implicit in the concept of the HRU is the assumption that there is no interaction between HRUs within one sub-basin. Loadings (runoff with sediment, nutrients, etc. transported by the runoff) from each HRU are calculated separately and then summed together to determine the total loadings from the sub-basin. If the interaction of one land use area with another is important, rather than defining those land use areas as HRUs they should be defined as sub-basins. It is only at the sub-basin level that spatial relationships can be defined. The benefit of HRUs is the increase in accuracy it adds to the prediction of loadings from the sub-basin.

In practice the HRUs are defined by overlaying three data layers:

- Sub-basins;
- Land use;
- Soils;

Based on these three data layers 2349 HRUs (Figure 31) were determined for the Pungwe River Basin. Figure 32 and Figure 33 represent the distribution of land use and slopes, respectively. It is clear that the largest area of the Pungwe is covered with forest, and that the basin is rather flat. About 8% of the basin has slopes >10%.

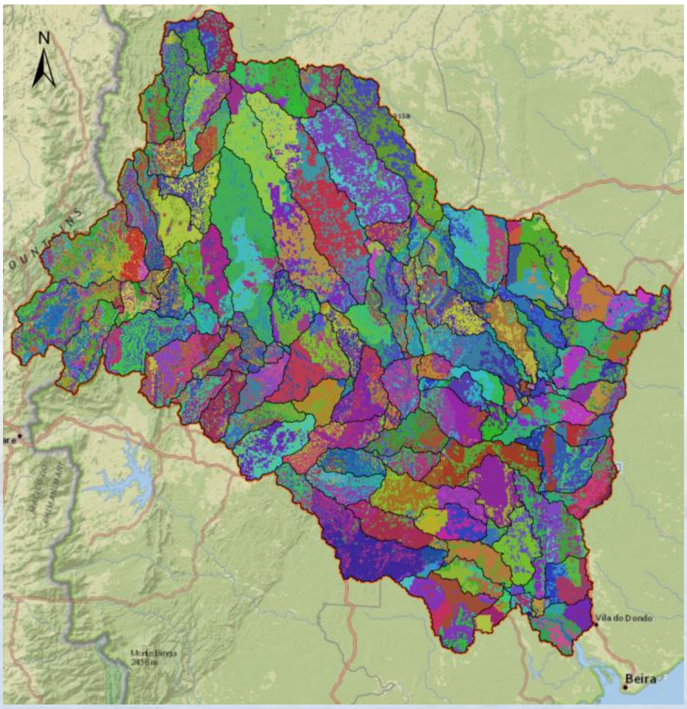


Figure 31: The defined 2349 HRUs (colored) for the Pungwe River Basin.

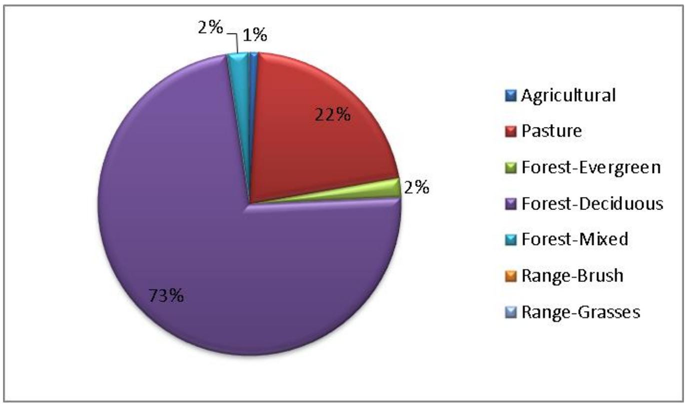


Figure 32: Land use distribution within the Pungwe River Basin.

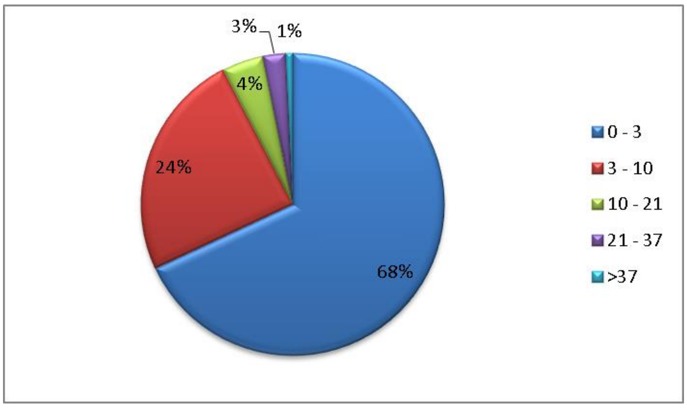


Figure 33: Slope distribution within the Pungwe River Basin.

5.2 Preliminary results

Hydrological model performance is evaluated on a monthly basis only. This is sufficient in order to use the model for strategic decision support. In order to use the model for operational purposes (daily discharges and floods risks) as well, model calibration/validation should be performed on a daily basis as well.

5.2.1 Comparison of TRMM 3B42 and FEWS RFE 2.0 rainfall products

The climatological data, as was analyzed in Section 4.5, forms an important input to the SWAT model. Too high amounts of rainfall lead to overestimated streamflows and vice versa, while too high temperatures lead to large evapotranspiration rates and consecutively underestimated streamflows. Using the temperature stations as denoted in Section 4.5.1, in combination with a lapse rate, high spatial resolution temperature maps were derived.

For rainfall both the TRMM 3B42 and FEWS RFE 2.0 products were compared with each other, but also with the interpolated rainfall station data. It was concluded that the spatial distribution of rainfall was most reliable for the TRMM 3B42 and FEWS RFE 2.0: the interpolated rainfall station data did not show a higher amount of rainfall for the Pungwe Zimbabwe catchment, what should in fact be the wettest part of the catchment. Therefore, it was decided to evaluate the SWAT model performance by forcing the model with both the satellite derived rainfall products.

Table 7 represents the annual water balance and statistics as calculated by the SWAT model for the period 2001-2010, using the TRMM 3B42 and FEWS RFE 2.0 products as input for rainfall. The water balance terms and statistics are explained below:

- P = rainfall [mm]
- ET = actual evapotranspiration [mm]
- Qsim = simulated streamflow [mm]
- dS = change in storage [mm]
- Qobs = observed streamflow [mm]
- Missing obs = missing observations [%]
- Bias = model bias with respect to observed streamflow [%]
- NS = Nash-Sutcliffe coefficient [-]
- ETcontr = Fraction of rainfall that results in evapotranspiration [-]
- Rcoff sim = Fraction of rainfall that results in simulated streamflow [-] (runoff coefficient)
- Rcoff obs = Fraction of rainfall that results in observed streamflow [-]

It is clear that the amount of rainfall for TRMM 3B42 is substantially higher than for FEWS RFE 2.0. This translates into a higher simulated discharge for all streamflow gauges. The evapotranspiration rates are in the order of 550-650 mm, which can be considered as plausible values, given the amount of rainfall. Evapotranspiration rates simulated with the TRMM 3B42 as rainfall product are logically higher than for FEWS RFE 2.0.

Table 7: SWAT annual water balance and statistics for the period 2001-2010, using the TRMM 3B42 and FEWS RFE 2.0 rainfall products.

	TRMM 3B42				*FEWS RFE 2.0*			
Flux [mm]	**E67**	**E651**	**E65**	**E72**	**E67**	**E651**	**E65**	**E72**
P	928	925	971	919	769	759	793	783
ET	632	611	572	628	594	581	537	602
Qsim	273	292	381	269	148	152	237	154
dS	22	23	19	23	27	26	20	27
Qobs	57	140	757	166	57	140	757	166
Statistic								
Missing obs	18%	74%	26%	28%	18%	74%	26%	28%
Bias	80%	52%	-88%	39%	62%	8%	-226%	-13%
NS	-47.94	-3.78	0.53	-1.42	-11.01	0.37	0.08	0.30
ETcontr	0.68	0.66	0.59	0.68	0.77	0.76	0.68	0.77
Rcoff sim	0.29	0.32	0.39	0.29	0.19	0.20	0.30	0.20
Rcoff obs	0.06	0.15	0.78	0.18	0.07	0.18	0.95	0.21

Two statistics that are often used to evaluate model performance are the bias (%) and the Nash-Sutcliffe coefficient (NS (-)). The bias is defined as:

$$bias = \frac{(Q_{m\_avg} - Q_{o\_avg})}{Q_{o\_avg}} * 100$$

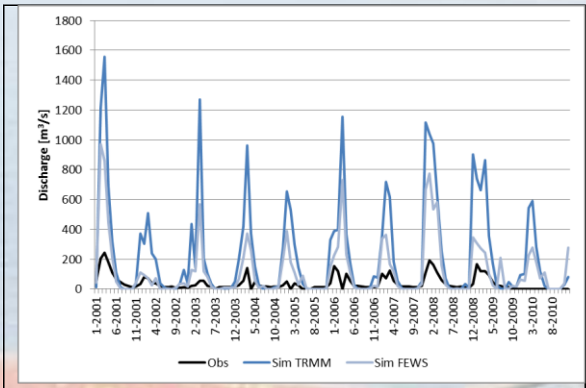
with Q_{m_avg} the average of the simulated (modelled) discharge and Q_{o_avg} the average of the observed discharge. This performance coefficient indicates whether the model simulates too much or too little streamflow in comparison with the observed streamflow. The NS-coefficient is defined as:

$$E = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2}$$

where Q_o is observed discharge, and Q_m is modelled discharge. Q_o^t is observed discharge at time t. NS efficiencies can range from $-\infty$ to 1. An efficiency of 1 (E = 1) corresponds to a perfect match of modelled discharge to the observed data. An efficiency of 0 (E = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (E < 0) occurs when the observed mean is a better predictor than the model.

Given these two performance indicators (Table 7), it is clear that using the FEWS RFE 2.0 rainfall products leads to the best model performance for most gauges: biases are smallest, and the NS-coefficients are highest. Only for gauge E65 (Pungwe Zimbabwe sub-basin) the TRMM 3B42 rainfall product results in a smaller bias and better (higher) NS-coefficient. This is related to the fact that FEWS RFE 2.0 substantially underestimates the rainfall in this upstream (high elevation) sub-basin. Therefore, it can be concluded that FEWS RFE 2.0 is more reliable for the lower altitudes area of the Pungwe River Basin, while TRMM 3B42 is more accurate for the higher altitude areas of the Pungwe Zimbabwe sub-basin.

Figure 34 (left plot) shows the observed vs. the simulated discharge for gauge E67 (Figure 25), using the two different rainfall products. It is clear that both simulations overestimate the observed discharge substantially. It is well-known that gauge E67 is very unreliable (Table 6), mainly because of tidal influence. Therefore, it was decided to focus for the remainder of this study on the gauges that are located more upstream. The right plot of Figure 34 shows the monthly average observed vs. the simulated discharge using the two rainfall products. Discharges are averaged over the period 2001-2010. Also the average discharge (1960-1980) as simulated by SWECO & Associates (2004) is shown. Although a different simulation period, the simulated discharge using the FEWS RFE 2.0 rainfall product is quite comparable to that of the SWECO study.



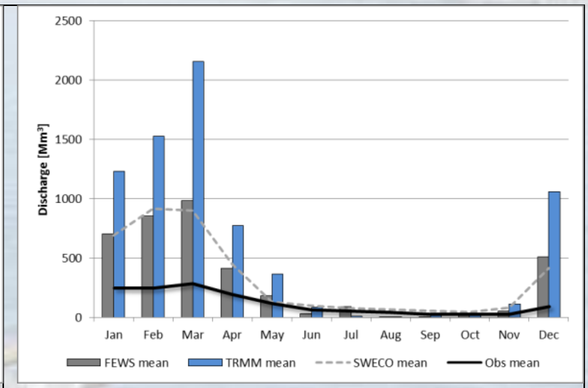


Figure 34: Left: observed vs simulated discharge using TRMM and FEWS rainfall data. Right: same, but monthly averages. All results are based on the period 2001-2010 for station E67. The SWECO mean discharge is based on the period 1960-1980. Note that the observed discharge is very unreliable because of tidal influence.

Results for gauge E65 (Pungwe Zimbabwe) are shown in Figure 35. This figure also proofs that TRMM 3B42 results in a simulated discharge that is more near to the observed discharge than FEWS RFE 2.0, although it still underestimates the observed discharge for this station. In order to improve the SWAT model simulations it was decided to continue with the use of the FEWS RFE 2.0 rainfall product for the entire basin, but to correct the rainfall estimates for the area upstream of gauge E65. This is shown in Section 5.2.2. The time-series of observed and simulated discharges for gauge E72 and E651 are shown in Appendix 1.

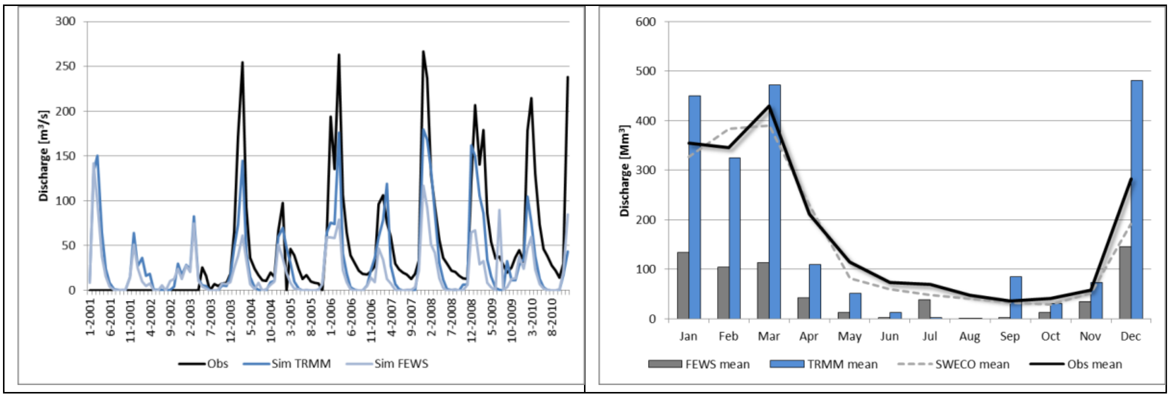


Figure 35: Left: observed vs simulated discharge using TRMM and FEWS rainfall data. Right: same, but monthly averages. All results are based on the period 2001-2010 for station E65. The SWECO mean discharge is based on the period 1960-1980.

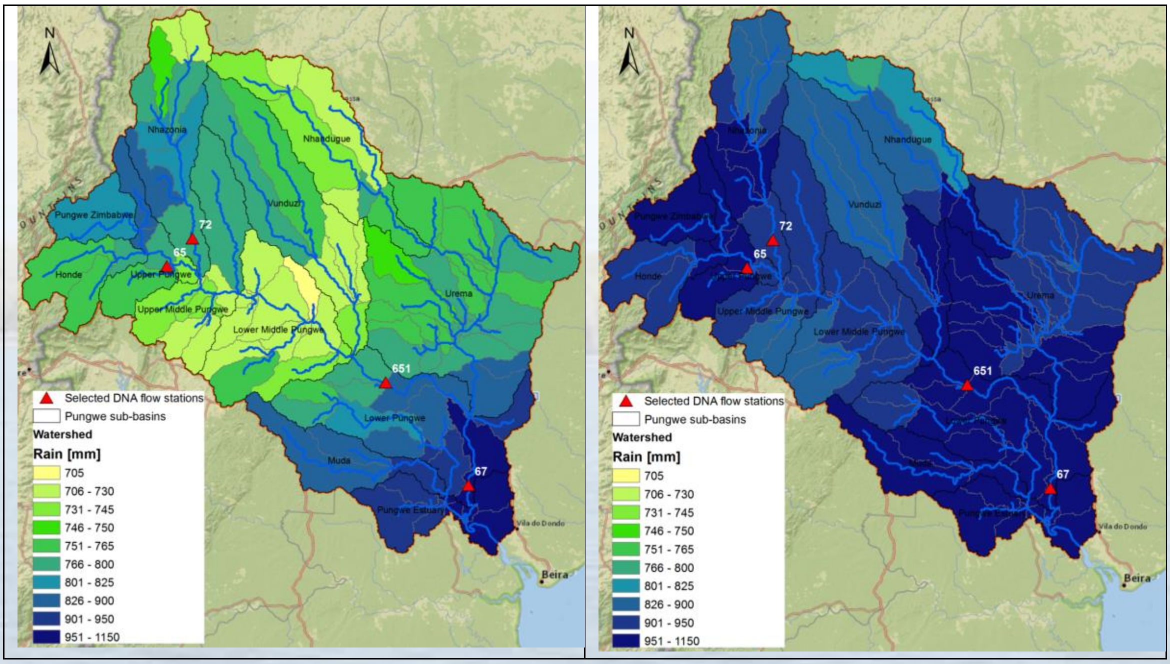


Figure 36: Spatial distribution of annual FEWS RFE 2.0 (left) and TRMM 3B42 (right) rainfall.

5.2.2 Correction of FEWS RFE 2.0 rainfall

The FEWS RFE 2.0 rainfall product was corrected for the area upstream of gauge E65 in order to have a more accurate rainfall estimate for this upstream sub-basin. Corrections of rainfall were conducted on a monthly basis. Figure 37 shows the spatial pattern of the corrected FEWS

RFE 2.0 annual rainfall. If this is compared with the left plot of Figure 36, then we see a substantial increase in rainfall for the area upstream of gauge E65.

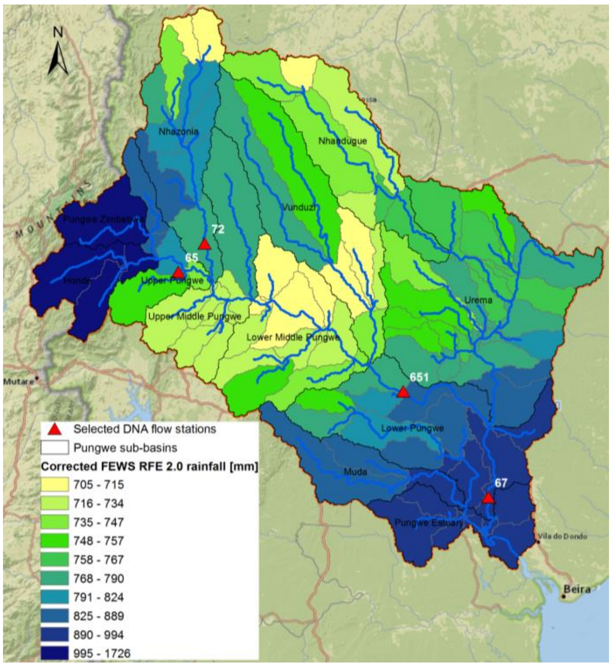


Figure 37: Spatial distribution of corrected annual FEWS RFE 2.0 rainfall.

Table 8 represents the annual water balance and statistics as calculated by the SWAT model for the period 2001-2010, using the corrected FEWS RFE 2.0 product as input for rainfall. A substantial improvement in the bias can be noticed for E65: -6% instead of -226%. The NS-coefficient increased from 0.08 to 0.81, meaning that the model is better capable of simulating the higher peak flow volumes correctly. The amount of annual rainfall has more or less doubled, from 793 mm to 1456 mm. The larger amount of rainfall in the upstream area leads to an increased evapotranspiration flux for that area, but also in a substantial increase in the discharge downstream (E651). The discharge at E651 was already slightly overestimated for the case in which the original FEWS RFE 2.0 rainfall product was used (bias = 8%, NS = 0.37). However, using the corrected rainfall product has a negative effect on the model performance for simulating the discharge downstream (E651): bias increased from 8% to 44%, and NS-coefficient decreased from 0.37 to -1.89.

Visual comparison of observed vs. simulated streamflow for E65 is shown in Figure 38. It is clear that for the first 2.5 years, no observed discharge data is available. The overall model performance for E65, using the corrected FEWS rainfall product, leads to very satisfactory results. The high discharge volumes are well simulated. However, the low flows during the dry season are underestimated, and are sometimes simulated as zero flow. It is clear that some fine-tuning (calibration) is required for this gauge. This is shown in Section 5.3.

Results for E72 are shown in Figure 39. Since rainfall correction was not applied for the area upstream of E72, and E72 is not downstream of E65, results are not affected by this rainfall correction. The bias of -13% is the result of mainly underestimating streamflow during the first two years of simulation, and the low flows during the dry season for the entire simulation period. Therefore, also for this gauge some fine-tuning is required.

Table 8: SWAT annual water balance and statistics for the period 2001-2010, using the corrected FEWS RFE 2.0 rainfall product. Results from the original FEWS RFE 2.0 rainfall product are shown as well.

	Corrected FEWS RFE 2.0			*FEWS RFE 2.0*		
Flux [mm]	**E651**	**E65**	**E72**	**E651**	**E65**	**E72**
P	873	1456	783	759	793	783
ET	599	642	602	581	537	602
Qsim	244	774	154	152	237	154
dS	30	39	27	26	20	27
Qobs	140	757	166	140	757	166
Statistic						
Missing obs	74%	26%	28%	74%	26%	28%
Bias	44%	-6%	-13%	8%	-226%	-13%
NS	-1.89	0.81	0.30	0.37	0.08	0.30
Etcontr	0.69	0.44	0.77	0.76	0.68	0.77
Rcoff	0.28	0.53	0.20	0.20	0.30	0.20
Rcoff obs	0.16	0.52	0.21	0.18	0.95	0.21

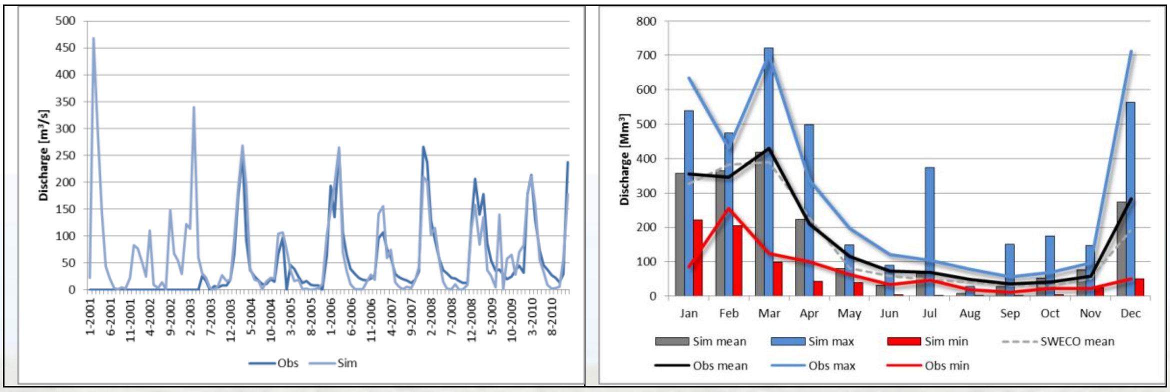


Figure 38: Left: observed vs simulated discharge using the corrected FEWS rainfall data. Right: monthly observed vs simulated discharge (average, maximum, and minimum). All results are based on the period 2001-2010 for station E65. The SWECO mean discharge is based on the period 1960-1980.

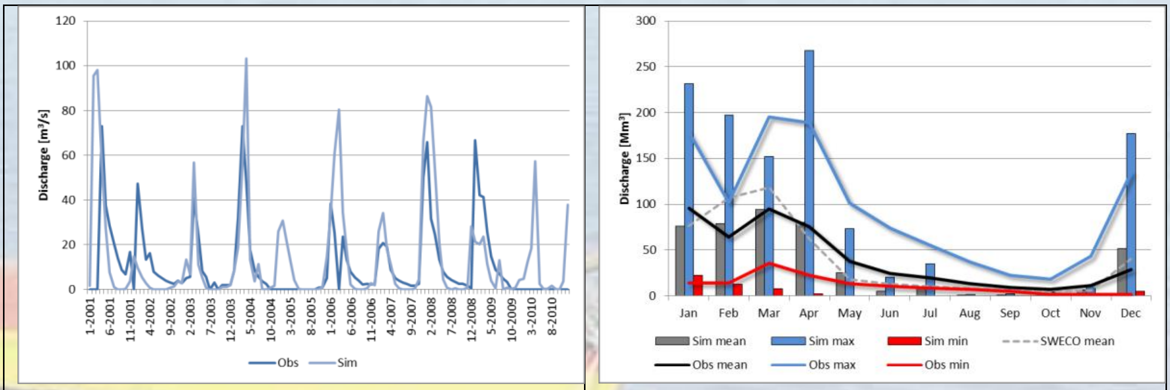


Figure 39: Left: observed vs simulated discharge using the corrected FEWS rainfall data. Right: monthly observed vs simulated discharge (average, maximum, and minimum). All results are based on the period 2001-2010 for station E72. The SWECO mean discharge is based on the period 1960-1980.

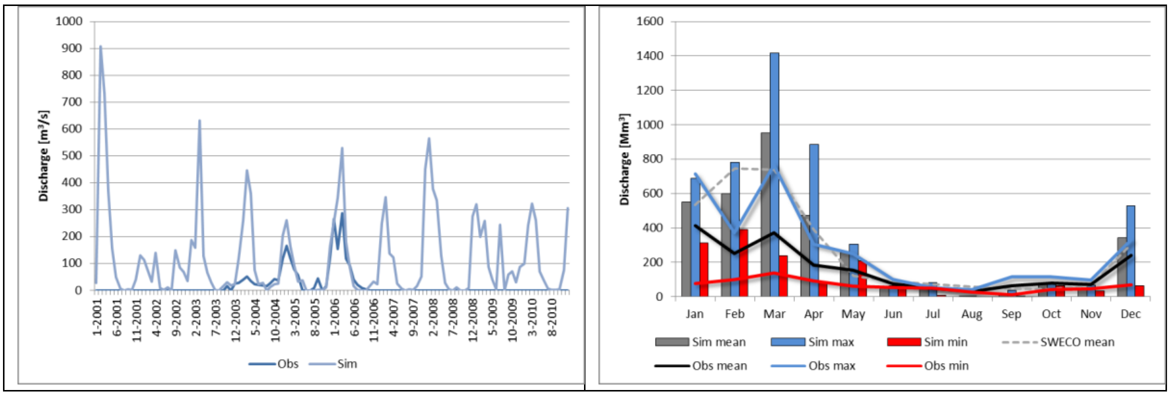


Figure 40: Left: observed vs simulated discharge using the corrected FEWS rainfall data. Right: monthly observed vs simulated discharge (average, maximum, and minimum). All results are based on the period 2001-2010 for station E651. The SWECO mean discharge is based on the period 1960-1980.

As was mentioned before, the higher amount of rainfall in the corrected FEWS RFE 2.0 rainfall product also results in a higher (overestimated) discharge downstream at gauge E651. This is shown in Figure 40. The higher flow volumes are substantially overestimated, while the low flows are simulated too low. It is clear that for this gauge some fine-tuning is required as well.

It is clear that observations for E651 are only available from halfway 2003 through the end of 2006. The high simulated flow peaks during Jan-Apr 2004 can be the result of either an error in the rainfall input, or wrong discharge measurements. These peaks are clearly visible in the right plot of Figure 40: the monthly average, maximum, and minimum simulated discharges for Feb-Apr are all simulated too high with respect to the observed ones.

5.3 Calibration

A parameter sensitivity analysis was performed in order to identify model parameters that affect the simulated discharge the most, both in terms of volume and timing. The following model parameters were selected for sensitivity analysis:

- AWC = Available Water Capacity [-]. Fraction of soil that is available for water storage, and can be used for crops to extract water from;
- CN = Curve Number [-]. The Curve Number is a function of the soil's permeability, land use, and antecedent soil water conditions;
- RCHRG_DP = Deep aquifer percolation coefficient [-];
- ESCO = Soil evaporation compensation coefficient [-];
- GW_DELAY = Delay time for aquifer recharge [days];

The AWC affects the amount of water that is available for evapotranspiration. A larger AWC will therefore result in more evapotranspiration and a reduction of peak discharge. The CN strongly affects the fraction of rainfall that is used for direct surface runoff: higher CN numbers lead to higher peak flows. The deep aquifer percolation coefficient (RCHRG_DP) regulates the fraction of recharge that percolates towards the deep aquifer. The soil evaporation compensation coefficient (ESCO) affects the soil depth distribution that is used to meet the soil's evaporative water demand. If the value for ESCO is reduced, then the model is able to extract more of the evaporative demand from lower soil levels. The aquifer recharge delay time (GW_DELAY) accounts for the drainage time that is required for water to travel from one layer to the underlying layer. This value affects the timing of water release from the soil column.

It seemed that the SWAT model for the Pungwe River Basin was sensitive for all parameters noted on the previous page, especially for the AWC, CN, and GW_DELAY parameters. Setting the same parameter values for the entire basin does not lead to satisfactory results: e.g. multiplying the AWC coefficient by 2 for the entire basin substantially decreases the discharge for E651, which is a positive result for this location, but at the same time it decreases the discharge for E65, which is not a desired result.

It was noticed that for all streamflow gauges low flows were simulated too low. In order to increase the low flows during the dry season, the default values for GW_DELAY were multiplied by three, and RCHRG_DP was set to zero for the entire basin. A larger GW_DELAY results in a delayed flow pattern, meaning that the flows during the wet season become slightly smaller, and that low flows during the dry season increase. Recharge to the deep aquifer can be considered as a loss, and does therefore not add up to the river discharge. The default value for RCHRG_DP (deep aquifer percolation coefficient) is 0.05, meaning that 5% of the groundwater recharge percolates to the deep aquifer. It was decided to set RCHRG_DP to zero in order to have an even more substantial increase in river flow during the dry season.

The modifications in GW_DELAY and RCHRG_DP led to very satisfactory results for E65 and E72. The resulting bias for E65 is -4% and the NS-coefficient 0.80. Time-series of the observed vs. the simulated discharge for E65 after parameter calibration are shown in Figure 41. It can be concluded that the calibration of these two parameters led to the desired results: increase of low flow during the dry season. Also the monthly averages (right plot) look very promising. The maximum monthly discharge in July is overestimated by the SWAT model. This peak occurs in July 2009, and is likely the result of an error in rainfall input because July is normally very dry.

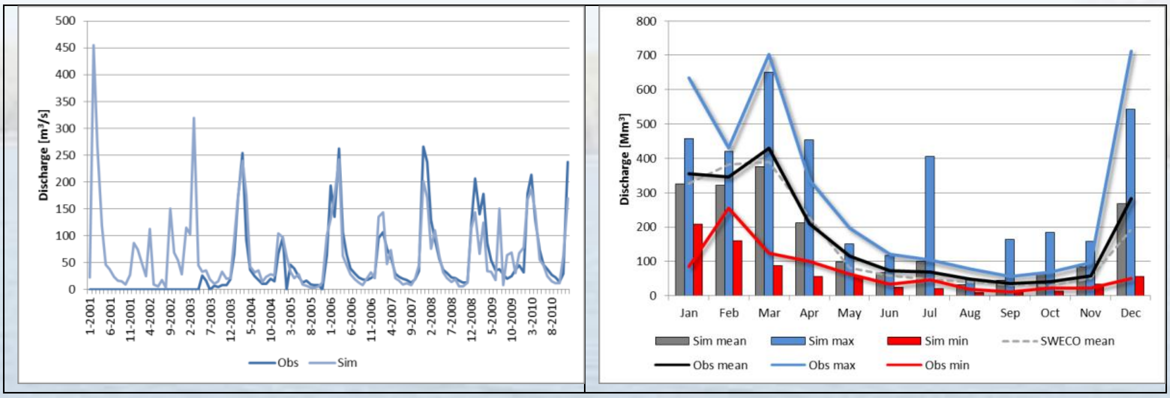


Figure 41: Left: observed vs simulated discharge using the calibrated GW_DELAY and RCHRG_DP parameters. Right: monthly observed vs simulated discharge (average, maximum, and minimum). All results are based on the period 2001-2010 for station E65. The SWECO mean discharge is based on the period 1960-1980.

The calibration of these two parameters led to satisfactory results for E72 as well: the bias improved from -13% to -8%, and the NS-coefficient improved from 0.30 to 0.42. The time-series of observed vs. simulated discharge for E72 are shown in Figure 42. It is clear that also for E72 the low flows are simulated better. There are, however, some discrepancies present between the observed and simulated discharge. A clear example of this is the simulated discharge during March 2006. Since this is the wet season, it is not likely that the river discharge approaches zero. However, there is a clear jump in the measured discharge for this month, with the measured discharge being zero. Because this is the wet season, this is likely due to erroneous discharge measurements during this month. Another discrepancy is present during Jan-Mar 2009, with the river discharge being underestimated. Since the volume of the observed discharge seems to be in line with what has been observed during the same period in other years, it is expected that this underestimation is due to an error in the rainfall input. This again states the importance of having accurate rainfall input data. If these inconsistencies would have been absent, then the performance indicators for E72 will be considerably better.

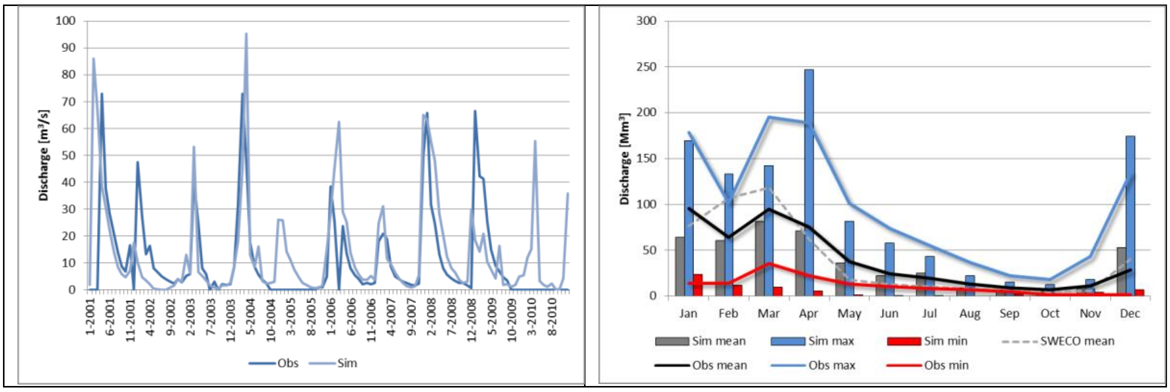


Figure 42: Left: observed vs simulated discharge using the calibrated GW_DELAY and RCHRG_DP parameters. Right: monthly observed vs simulated discharge (average, maximum, and minimum). All results are based on the period 2001-2010 for station E72. The SWECO mean discharge is based on the period 1960-1980.

As was shown in Figure 40 and Table 8, the discharge for gauge E651 was overestimated. SWECO and Associates (2004) indicated that a substantial amount of rainfall evaporates in the lower parts of the Pungwe River Basin. In order to reduce discharge, it is therefore required to increase the amount of actual evapotranspiration in this part of the basin. This can be obtained by increasing the AWC, decreasing the CN, and decreasing the ESCO parameter. After a few trials, it was decided to multiply the default values of AWC by three, divide CN by two, and reduce the ESCO parameter to 0.75. These adjustments were made for the entire basin, except for the areas upstream of gauge E65 and E72.

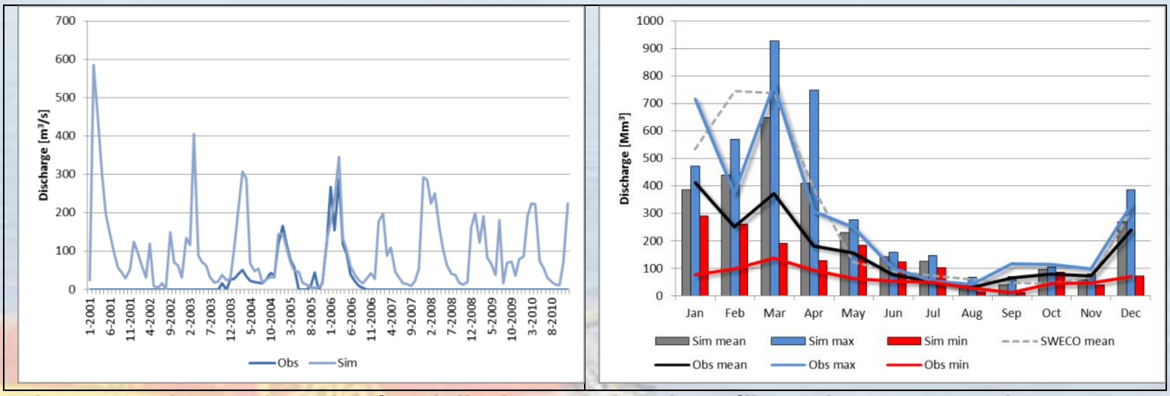


Figure 43: observed vs simulated discharge using the calibrated AWC, CN and ESCO parameters. Right: monthly observed vs simulated discharge (average, maximum, and minimum). All results are based on the period 2001-2010 for station E651. The SWECO mean discharge is based on the period 1960-1980.

Time-series of the observed vs. the simulated discharge, using the calibrated parameters AWC, CN, and ESCO, are shown in Figure 43 for E651. It can be concluded that the increase in evapotranspiration has led to a substantial decrease in discharge volumes. The uncalibrated version of SWAT (Table 8) resulted in a bias of 44% and a NS-coefficient of -1.89 for E651. The calibration of these three parameters resulted in a bias of 31% and a NS-coefficient of -0.23. As can be noticed from Figure 43 the period with measured discharge data is rather short (approx. 4 years of data), and therefore model performance is relatively sensitive for discrepancies. During the period Jan-Apr 2004 the model overestimates the measured discharge substantially. The measured discharge, however, seems to be rather low for this period if compared with the discharge during the same period in other years. It is therefore plausible that discharge was not accurately measured during this period. If we calculate the model performance without the year 2004 taken into account, then model performance is very satisfactory:

- Bias = 3%
- NS-coefficient = 0.83

5.4 Scenario analysis

The calibrated SWAT model can now be used to evaluate certain development scenarios and/or climate change impacts. For the current study we will only explore one future development scenario: the development of irrigated agriculture.

Within the Pungwe River Basun, several new irrigation schemes are planned to increase the Mozambican food production. An important ongoing project is the Beira Agricultural Growth Corridor (BAGC) project. This project aims to develop 190,000 ha of irrigated agriculture on the long term. This project can be explored as a possible future scenario using the SWAT model:

“What will be the effect on water availability downstream of the 190,000 ha of irrigated agriculture?”

It can be assumed that the amount of applied irrigation water is on average 800 mm/year. Taken into account the 190,000 ha of irrigated agriculture, this translates into 1520 MCM irrigation per year. If we assume that this amount is applied during the four driest months (Jun-Sep), then this converts to 380 MCM/month or approx. 147 m^3/s. In order to evaluate the effect of this development scenario, we need to choose a reliable streamflow measurement station. Therefore, we assume that the 190,000 ha of irrigated will be developed upstream of gauge E651, as is illustrated in Figure 44. SWAT was used to simulate the effects of this development scenario. The hydrological effects of this development scenario on water availability, simulated at gauge E651, are shown in Figure 45. The effects on the average monthly water availability are shown in Figure 46.

It is clear that the development scenario of 190,000 ha of irrigated agriculture leads to severe water shortages during the months June through September. Additional scenarios of 95,000 and 12,000 ha of irrigated agriculture have been evaluated as well. It seems that 95,000 ha of irrigated agriculture will also result in water shortages during these months. The current situation (baseline) already shows almost zero flow during these months, however, it seems to be possible to develop 12,000 ha of irrigated agriculture without experiencing water shortages.

Based on the results above it may seem impossible to develop the 190,000 ha of irrigated agriculture. However, during the winter months floods occur regularly, and water is available abundantly. Therefore, the development of one or more reservoirs may be very beneficial in this case. These reservoirs can store excess water during the winter months, and release it during the drier summer months. The location, size, and number of reservoirs may be explored using water allocation models (e.g. the WEAP model). This is explored in the report by Droogers and Terink (2014).

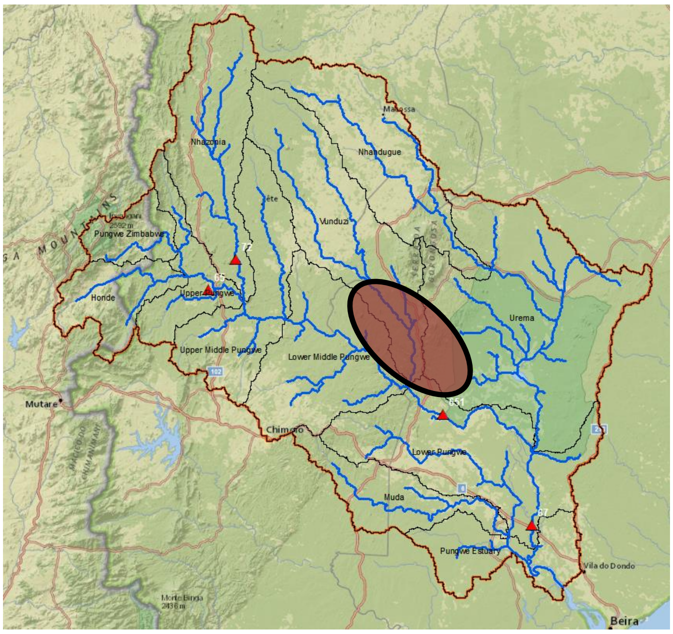


Figure 44: Illustration of scenario of development of 190,000 ha of irrigated agriculture upstream of gauge E651.

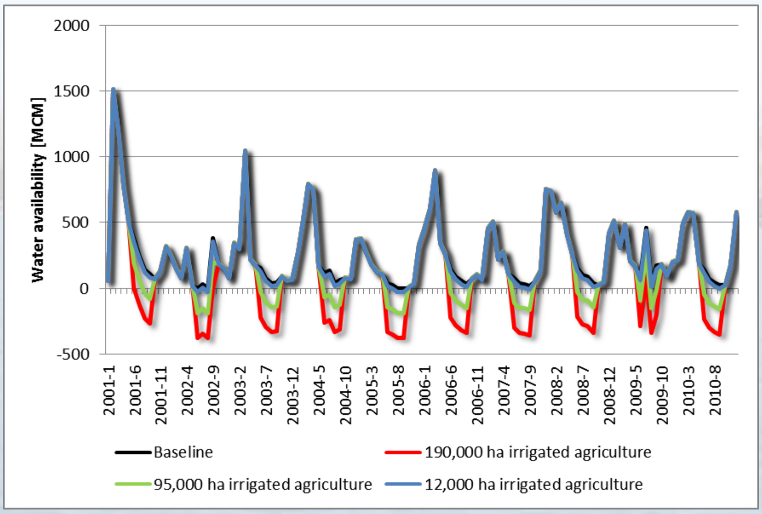


Figure 45: Effects of different irrigation development scenarios on water availability (simulated for gauge E651). Negative values indicate a water shortage. Baseline (current situation) is compared with 190000, 95000, and 12000 ha of irrigation development.

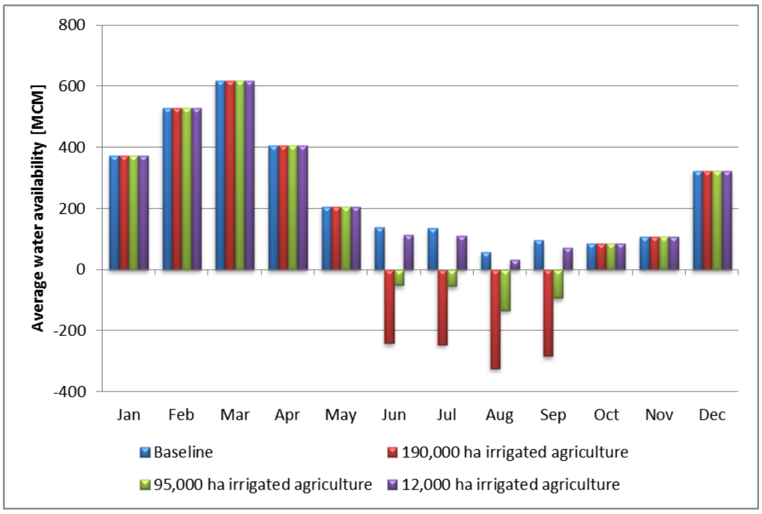


Figure 46: Effects of different irrigation development scenarios on average monthly water availability (simulated for gauge E651). Negative values indicate a water shortage. Baseline (current situation) is compared with 190000, 95000, and 12000 ha of irrigation development.

6 Conclusions and recommendations

6.1 Conclusions

The current study was conducted as part of the **'Water Planning Tools to Support Water Governance'** project. 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 focuses on this activity, which is the hydrological analysis and modelling of the Pungwe River Basin. The objective of this study was to **perform a hydrological 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.

This report demonstrated the various data sets that are available for the Pungwe River Basin, and useful as input to hydrological models. Also methodologies are shown on how-to analyze different sources of meteorological data (rainfall and temperature): from local rain gauges to satellite derived rainfall products. Additionally, an introduction to the Soil Water and Assessment Toolbox (SWAT) model concepts and data requirements were given. Finally, this report describes an approach on how-to conduct hydrological modelling for the Pungwe River Basin using the SWAT model, and preliminary results are shown.

It can be concluded that the meteorological data is lacking in availability and accuracy for the period 2001-2010. From the total number of 23 meteorological stations, only six stations had data with sufficient quality: ARA Centro stations 1269, 1273, 373, and 812, and GSOD stations 677810 and 678810. Unfortunately, these stations are not well distributed throughout the basin, and the higher elevated areas in Zimbabwe are not covered: having no meteorological stations in the Zimbabwean part of the Pungwe River Basin can be considered as critical, because this part receives the largest amount of rainfall. The small number of available stations, and insufficient spatial coverage, led to the fact that the spatial rainfall maps, based on the interpolation of these station data, are not accurate enough to be used for hydrological modelling: the Zimbabwean part of the Pungwe River Basin did not show up as being the wettest part of the basin, while it in reality should be. Two remotely sensed rainfall products were compared as well: FEWS RFE 2.0 and TRMM 3B42. The spatial rainfall distribution of these products was better than for the interpolated rainfall from station data. From these two products, TRMM 3B42 showed the highest amount of rainfall for the Pungwe Zimbabwe sub-basin. Also for temperature the number of available stations was lacking, but a combination of spatial interpolation and a lapse rate of -6.5 °C per km elevation increase resulted in accurate temperature maps for the Pungwe River Basin.

A total of 30 discharge measurement stations are present in the Pungwe Basin. Unfortunately, only four stations provided sufficient data for the period 2001-2010: E67, E65, E72, and E651. Since E67 is located at the downstream end, this station is under high tidal influence, and therefore discharge data from this station cannot be used for model calibration/validation. From the three remaining stations, E651 only seems to have data from halfway 2003 through the end of 2006. In order to conduct a thorough hydrological modelling study, it can therefore be concluded that the number of available discharge stations with data is lacking for the period 2001-2010, and that more discharge measurement gauges are required and monitoring should be more intensive.

Preliminary modelling results showed that discharge was substantially underestimated for the area upstream of gauge E65. This underestimation was less severe with the use of TRMM 3B42 as rainfall product. For the stations E72 and E651, FEWS RFE 2.0 led to better discharge simulations. It can therefore be concluded that TRMM 3B42 gives a better representation of rainfall for the higher altitudes of the Pungwe Zimbabwe sub-basin, and that FEWS RFE 2.0 is more representative for the lower altitude basins. By correcting the FEWS RFE 2.0 rainfall on a monthly basis for the area upstream of E65, model performance increased substantially.

Calibration of the model parameters AWC, GW_DELAY, CN, RCHRG_DP, and ESCO resulted in very satisfactory model performance:

- E65:
  - Bias = -4%
  - NS = 0.80
- E72:
  - Bias = -8%
  - NS = 0.42
- E651:
  - Bias = 3% (based on 2005-2006)
  - NS = 0.83 (based on 2005-2006)

Some discrepancies were present between the observed and modelled discharges for all stations. These were due to either i) errors in rainfall input or ii) erroneous discharge measurements.

The calibrated SWAT model was used to evaluate the effect of one future scenario: the development of irrigated agriculture. The Beira Agricultural Growth Corridor (BAGC) project aims to develop 190,000 ha of irrigated agriculture on the long term. By using the SWAT model it seems that this scenario results in severe water shortages during the months June through September. Even 95,000 ha of irrigated agriculture will lead to water shortages during these months. Without implementing other measures (e.g. reservoirs), it seems that developing 12,000 ha of irrigated agriculture is feasible. Since floods occur regularly during winter months, and water is available abundantly during these months, constructing reservoirs may be a good option for the Pungwe River Basin, and this may allow developing the planned 190,000 ha of irrigated agriculture. The location, size, and number of reservoirs may be explored by using water allocation models, such as WEAP. This is explained in the report by Droogers and Terink (2014).

6.2 Recommendations

It was concluded that the quality and availability of both meteorological and discharge data is lacking for the Pungwe River Basin. In order to perform more detailed hydrological assessments in the future, it is required to intensify monitoring of meteorological and discharge stations, and to perform quality checks on a regular basis. Also adding more meteorological stations in the Pungwe Zimbabwe sub-basin is highly recommended. Since discharge station E67 is under tidal influence, this station does not provide accurate discharge measurements, and therefore it is worthwhile to consider ending measurements for this location.

It was shown that rainfall largely affects the accuracy of your model results: three different rainfall products led to completely different discharge simulations. It was shown that the use of rainfall products derived from remote sensing can lead to satisfactory model results, although not for all locations in the Pungwe River Basin. Nowadays, some advanced rainfall correction methods are available (Hunink et al., 2014), that use a combination of vegetation indices, elevation, and other environmental indices. It would be interesting to investigate and apply these correction methods to data scarce regions, such as the Pungwe River Basin, in order to obtain a more accurate rainfall product to be used for hydrological modelling.

A static land use map has been used in the current version of the SWAT model. It is likely that land use changes over time. Therefore, it is recommended to update the SWAT model with up-to-date land use data. Additionally, no management regarding seeding, harvesting, and irrigation is integrated in the current version of the model. If this information becomes available, then it is recommended to improve the model with this data, because processes such as irrigation can have a significant effect on your available water resources.

The current version of the SWAT model for the Pungwe River Basin was calibrated by matching the simulated discharge with the observed discharge on a monthly basis. This is sufficient in order to use the model for strategic decision support. However, in order to use the model for short-term operational support (e.g. flood-early-warning systems), it is recommended to calibrate the model using shorter time-scales.

References

Brandsma, J., G.A.P.H. van den Eertwegh, P. Droogers, Z. Bai, S. Zhang. (2013). Green Water Management & Credits Toolbox China. Green and Blue Water Resources and Management Scenarios using the SWAT model for the Upper Duhe Basin, China – Feasibility Study. FutureWater Report 126.

Droogers, P., W. Terink. 2014. Water Allocation Planning in the Pungwe Basin, Mozambique. Report FutureWater.

FAO/IIASA/ISRIC/ISSCAS/JRC, 2012. *Harmonized World Soil Database (version 1.2)*. FAO, Rome, Italy and IIASA, Laxenburg, Austria.

Gassman, P., Reyes, M., Green, C., and Arnold, J. (2007). The Soil and Water Assessment Tool: Historical development, applications, and future research directions. American Society of Agricultural and Biological Engineers, 50(4):1211–1250.

Hargreaves, G. and Samani, Z. (1985). Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture, 1(2):96–99.

Hunink, J.E., Immerzeel, W.W., Droogers, P. (2014). A High-resolution Precipitation Two-step mapping Procedure (HiP2P): development and application to a tropical mountainous area. Remote Sensing of Environment, 140:179-188.

Hunink, J., Immerzeel, W., and Droogers, P. (2009). Green Water Credits for the Upper Tana Basin, Kenya. phase II – Pilot Operations. Technical report, FutureWater.

Hunink, J.E., W.W. Immerzeel, P. Droogers, S. Kauffman, (2010). Green Water Credits for the Upper Tana Basin, Kenya. Phase II - Pilot Operations: Biophysical assessment using SWAT. Green Water Credits Report 10 / ISRIC Report 2010/04, ISRIC World Soil Information, Wageningen.

Kauffman, S., Droogers, P., Odada, E., Macharia, P., Gicheru, P., and Dijkshoorn, K. (2007). Green Water Credits. green and blue water resources and assessment of soil and water management scenarios using an integrated modelling framework. Technical report, ISRIC - World Soil Information.

Mazvimavi, D. (2010). Investigating changes over time of annual rainfall in Zimbabwe. Hydrological and Earth System Sciences, 14: 2671-2679. doi: 10.5194/hess-14-2671-2010.

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Research. 12: 513-522.

Neitsch, S., Arnold, J., Kiniry, J., Williams, J., and King, K. (2000). Soil and water assessment tool (swat). theoretical documentation, version 2000. Technical report, Texas Water Resources Institute, College Station, Texas.

SWECO & Associates. (2004). Development of the Pungwe River Basin Joint Integrated Water Resources Mangement Strategy. Monograph Report. Annex I. Sector Study on: Surface Water Resources of the Pungwe River Basin.

Van Genuchten, M.Th. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44 (5): 892–898.

Terink, W., J. Hunink, P. Droogers, H. Reuter, G. van Lynden, S. Kauffman. (2011). Green Water Credits Morocco: Inception Phase. Impacts of Land Management Options in the Sebou Basin: using the Soil Water and Assessment Tool – SWAT. Green Water Credits Report M1. FutureWater Report 101.

Xie, P., Arkin, P.A. (1997). A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. Bulletin of the American Meteorological Society 78(11): 2539-58.

Appendix 1: Observed vs simulated discharges using the TRMM 3B42 and FEWS RFE 2.0 rainfall products

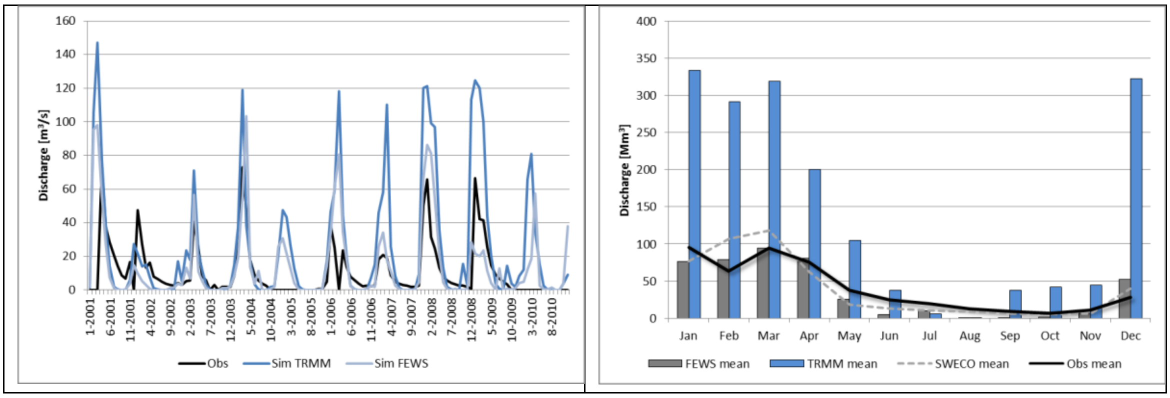


Figure 47: Left: observed vs simulated discharge using TRMM and FEWS rainfall data. Right: same, but monthly averages. All results are based on the period 2001-2010 for station E72. The SWECO mean discharge is based on the period 1960-1980.

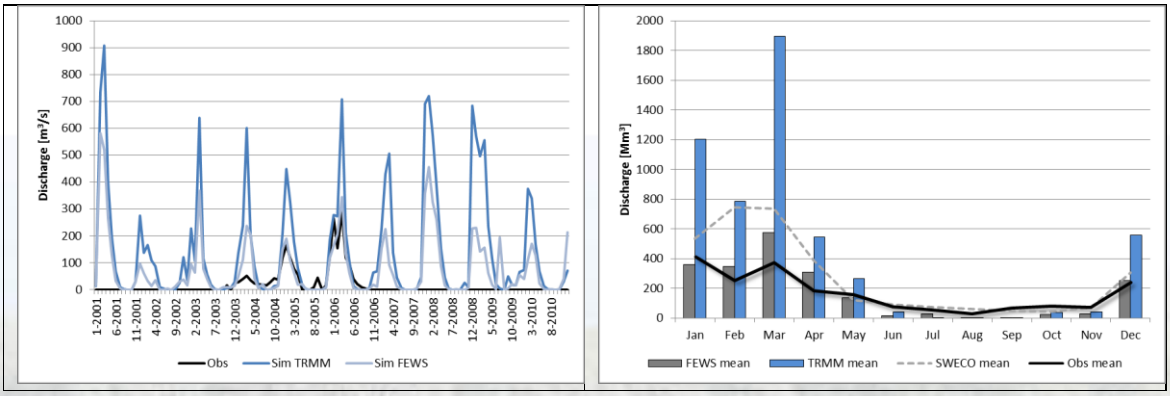


Figure 48: Left: observed vs simulated discharge using TRMM and FEWS rainfall data. Right: same, but monthly averages. All results are based on the period 2001-2010 for station E651. The SWECO mean discharge is based on the period 1960-1980.