Modelling crop production in water-scarce basins with SWAT

Case studies of the Limpopo River basin and in Ethiopia

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In the EAU4Food project the challenges African agriculture is facing today are addressed: the agricultural productivity must increase. At present the increase in food production cannot keep up with the population growth. In the coming years irrigation will gain importance, but at the same time the availability of fresh water and the sustainable use of the resources is under increasing pressure. Hence, new approaches are required to increase food production in irrigated areas in Africa, while ensuring healthy and resilient environments. The need to use less water to produce crops requires innovative approaches. By using models the aim is to analyse feasible measures to improve water efficiency and to reduce negative impacts. The SWAT model has been applied in the Limpopo basin in Southern Africa and the Gumselasa catchment in Ethiopia. SWAT is a conceptual, physically based hydrological model using response units representing homogeneous land use, management, ground slope, and soil characteristics. The objective of the Limpopo basin case study is to use the SWAT model to study the effect of irrigation and fertilization management operations on crop yields. If both irrigation and fertilizer operations are applied, crop yields increase considerable. In the Gumselasa irrigation scheme over-irrigation and seepage water from the storage dam are causing soil salinity problems. Better management of the irrigation system would result in lower soil salinity. The model applications will be used further for analysis of agricultural production changes and their effects on water quantity and quality.

Keywords: Limpopo river basin, SWAT model, crop yields, irrigation, small holder farmers, groundwater, dams

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Photo cover: Limpopo River at Chokwe, Mozambique (photo Erik Querner)

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Summary

The Food and Agriculture Organization (FAO) of the United Nations estimated that 70% more food needs to be produced by 2050 to meet the growing global demand driven by a larger and more affluent population and associated changes in consumption patterns. Increasing population growth in Africa during the last decades has resulted in growing pressure on land resources. As land use has become more intensive, land and people have become more vulnerable to climate events. With a large population living in rural areas, people are highly dependent on water resources as it influences the agricultural production.

This study was carried out within the European Union project EAU4FOOD, which focusses on agricultural innovations in Africa. The project seeks to address the challenges African agriculture is facing today, as agricultural production cannot keep up with agricultural demand. Irrigation and fertilisers management will gain importance in terms of raising crop production, but in areas where water resources are vulnerable, the use of fresh water must be sustainable. New approaches are required to increase crop production in irrigated areas. In order to test different irrigation and management operations, hydrological models can be used to estimate the effect of different operations on water quantity and crop yields.

The Soil and Water Assessment Tool (SWAT) was used to set up irrigation scenarios in relation to crop yields and water allocation management. The SWAT model is a physically-based catchment scale model. The model has been used to simulate hydrological and environmental processes under multiple climates and management conditions throughout the world, and is extremely useful to link crop yields and basin hydrology (Neitsch et al., 2011). The aim of this project was to set up the SWAT model for the Limpopo River basin (Southern Africa) and the Gumselasa catchment (Ethiopia), and to study the relation between crop yields and the hydrology. Scenarios were defined to study the effect of irrigation and fertilization management operations.

Limpopo basin
The Limpopo river basin (415.000 km^2) is situated in four countries: South Africa, Mozambique, Botswana and in Zimbabwe. A large portion of the population in the Limpopo River basin is depending on agriculture for livelihoods, and it is one of the most important economic activities in the basin. Crop production is variable and unreliable primarily because of the low and short rainfall. Crop yields are overall much lower than in areas where rainfall is higher. The agricultural system in the Limpopo River basin can be divided between commercial and small holder farming. Small holder farms are mostly owned by one owner or by a community and have small land sizes. Commercial farms are characterized by large land sizes and utilize advanced production technologies, which results in much higher crop yields. The large scale commercial farms are mainly focused on vegetable and fruit production, such as tea, citrus and tropical fruits such as mango and banana, whereas small holder farms mainly have crops such as maize, sorghum and wheat.

In the SWAT modelling setup the basin was divided into 113 sub basins. In this process, also the stream network, channel length, average slope of the channel and other sub basin parameters were derived. Land use map of the Limpopo River basin was made of multi-temporal Landsat ETM images of 30 m resolution and MODIS images of 250 m resolution. The soil data was derived from the Soil and Terrain Database for Southern Africa (SOTERSAF, version 1.0). In the SWAT model, 16 reservoirs within the Limpopo river basin were considered, based on their capacity and area. In a large river basin such as the Limpopo River, input data will have a varying impact on model results. Model behaviour will be as good as the data used as model input.

Different management scenarios were defined for small holder farms to study the impact of the management practices on the water balance, stream flow, irrigation water and crop yields. In general, it was assumed that there are two cropping seasons for small holder farms: a summer cropping

season which lasts from October 1 to March 31 with maize and a winter cropping season which lasts from April 1 to September 31 with wheat. These crops are generic crop types in the Limpopo River basin. Four scenarios were implemented in the SWAT model, to study the effect of irrigation and fertilizer application on the hydrology and crop yields. In the baseline scenario (BS), no irrigation and fertilizer were applied. No additional nutrients were applied to agricultural lands. In the scenario IA irrigation on small holder farms was applied. Application of irrigation was based on plant water stress. Water for irrigation was extracted from the shallow aquifer and from reservoirs. In scenario FA fertilizer operations for small holder farms were applied. In scenario CS, both irrigation and fertilizer application were modelled, with the same inputs as scenarios IA and FA.

The baseline scenario was modelled for an initial model response on the basic inputs. Average annual crop yields (maize, wheat) are generally low (<1 ton/ha) in Southern Africa, especially at smallholder farms. The baseline scenario results are similar; without any additional management inputs, average annual crop yields were less than 1.5 t/ha. Especially on smallholder farms average crop yields are low; commercial farms produce in general higher crop yields. The scenario with irrigation application generates higher crop yields; almost 2 t/ha. In the scenario with fertilizer application, crops were fertilized with 100 kg/ha/year. The scenario with both irrigation and fertilizer application produces the highest crop yields; between 2.5 and 4 t/ha/year.

Increasing crop yields and crop productivity will influence the basin hydrology. Comparing the model results of scenario BS and CS, in all sub basins the river discharges decreased when implementing irrigation and fertilizer application. River discharges even decreased with more than 20% in some sub basins. Extraction of water for irrigation came from the shallow aquifer; this resulted in decrease in subsurface and groundwater flow. When applying both irrigation and fertilization (CS), ETa increased in almost all sub basins. In scenario CS, increase in ETa was the result of more (optimal) crop growth, and thus an increase in plant transpiration. In terms of water balance, water is going out of an HRU by (sub-)surface and groundwater flow and evapotranspiration. Comparing the results of scenarios BS and CS, the fraction of water leaving an HRU by (sub-)surface flow reduced, while the fraction of water leaving through evapotranspiration increased. Comparing the changes for each country revealed that most changes occurred in the South African part of the Limpopo River basin. As most of the larger reservoirs lie in South Africa, it is likely that the management factor contributes to these changes.

The SWAT model can be used for the Limpopo River basin, as shown in this study. Management operations scenarios can be added to the model to study the effectiveness of the operations. However, more knowledge about rainfall distribution through the Limpopo River basin and reservoir management is necessary for better uncertainty prediction results. So the SWAT model is useful for modelling the Limpopo River basin, but depending on further aim of research, more data is needed.

Gumselasa

In Ethiopia, soil degradation is a major issue since agriculture and deforestation have been practiced. Studies conducted in Ethiopia have reported that conversion of forest land into arable land with the aim of expanding cultivated land has caused land degradation and often soil erosion. Together with frequent droughts and erratic rainfalls, these issues have led to major food insecurities and famine for many years. To minimize the impact of rainfall variability through the provision of water supply on crop yields and crop production, adequate water management for irrigation is needed. In the last two decades micro-dams were constructed to reduce the impact of rainfall variability and to improve the agricultural production through irrigation.

Gumselasa is located in the north Ethiopian province Tigray. It has a total area of 50078 km^2, from which 19% is suitable for cultivation, and a population of more than 3.8 million. The Gumselasa catchment is located 40 km south of Mekelle, the capital of Tigray. The catchment has a total area of 23.5 km^2 and receives on average 700 mm per annum. Most of these rains (~85%) fall in the rainy season, between June and September. The Gumselasa irrigation scheme was launched in 1996 by constructing a dam in the catchment (1.9 mln m^3). The dam provides water during the dry season. Part of the downstream agricultural land is irrigated with seepage water from the dam. However, seepage water and over-irrigation are causing soil salinity problems. Therefore, it should be necessary to improve the water management. More than 60% of the land use in the catchment is cultivated land, other land use types are open grazing land, plantation, and settlements. During rainy season, between June and September, cultivated land is covered with crops, which are mainly rain fed. Main crop types are tef, maize, wheat, unions, garlic, potatoes and pies.

The Gumselasa catchment was divided in SWAT into 41 sub catchments. In the watershed delineation, also the stream network, channel length, average slope of the channel and other sub basin parameters were created. A land use map was made of land use data from field observations and literature. The cultivated land was divided between rain fed and irrigated cultivated land and further subdivided in land which is irrigated through water from the reservoir and which is irrigated through seepage water. The remaining land use was classified as sparse natural vegetation. The soil map used in the SWAT model is derived from the ISRIC soil map of Africa, with a pixel resolution of 1 km.

The monthly water balance on the Gumselasa catchment is presented using simulations on a daily base with the SWAT model for the period 1993 and 2010. The total water balance in the catchment is calculated as precipitation and irrigation as incoming fluxes, evapotranspiration as outgoing flux, what is remaining in the basin is the total water yield, which is the sum of surface runoff, lateral flow and groundwater contribution to stream flow. Total precipitation within the catchment highly fluctuates between the seasons. In rainy season precipitation can be as high as 700 mm per month, while in dry season there is almost no rain at all. The actual evapotranspiration varies between 100 mm in rainy season to about 10 mm in dry seasons.

The salinity levels in the irrigated area increased in the last decade and in particular along the natural drainage stream. A spread sheet model was used to calculate river and soil salinity, based on river flows. The river was divided into three river segments, which is corresponding to sub basin outflow. Water in the river has normal to low salinity rates, both in dry (November-April) and rainy season (May-October). However, soil salinity is much higher. Soils are considered saline if the electric conductivity is >4 dS/m. In some months, actual evapotranspiration rates exceeds precipitation rates, which reveals that a large part of the cultivated land is irrigated with water from the streams. High evapotranspiration rates results in higher salinity rates due to the remaining salts if water for irrigation from the river evaporates. Although the estimation of the salinity is was calculated with a simple spread sheet model, it revealed that soil salinity is a problem in this area. Bad irrigation and land management is one of the reasons that soil salinity is increasing. Better management would result in lower soil salinity.

An initial assessment of the use of the SWAT hydrological model for the Gumselasa catchment was made. Results show that the model inputs have to be more detailed to give more accurate output results. Also, the performance of the model cannot be compared with data from the field, as there is no field data available. For further research, it is recommended to update the land use and soil map from field data and to measure the river flows downstream of the dam.

1 Introduction

The Food and Agriculture Organization (FAO) of the United Nations estimated that 70% more food needs to be produced by 2050 to meet the growing global demand driven by a larger and more affluent population and associated changes in consumption patterns (FAO, 2012). Currently, almost 870 million people in the world are suffering from food shortages and hunger, from which the majority lives in developing countries. African countries show the highest rates of people with underweight; during 2005-2011, 16 African countries showed underweight rates of more than 20 percent, with the highest levels recorded in the Horn of Africa. Although global crop production has expanded threefold over the past 50 years, more crop production is needed to meet the growing demand for food (FAO, 2012).

In developing countries, 80 percent of crop production growth would be as a result of higher yields and increased cropping intensity, the remaining 20 percent coming from land expansion (Bruinsma, 2009). To achieve an increase in agricultural productivity in sub-Saharan Africa, major investments in improving soil and crop management will be required. There is a large gap between potential and actual yields, especially on small holder farms. Potential crop growth at a given location is determined by genotype and climate, whereas actual crop yields result from the interaction between growth-limiting and growth-reducing factors (De Wit, 1992).

Increasing population growth in Africa during the last decades has resulted in growing pressure on land resources. As land use has become more intensive, land and people have become more vulnerable to climate events. With a large population living in rural areas, people are highly dependent on water resources as it influences the agricultural production. In Southern Africa, short and intense rainy seasons with unreliable rainfall lead to frequent losses in crop production or even crop failure. Rural areas often receive less than 500 mm/year of rainfall, which is theoretically the minimum required for successful dry land cropping (De Villiers et al., 2004).

Different models have been developed to study crop yields and its influencing factors, e.g. IFSM (Integrated Farm System Model; Rotz et al., 2012), EPIC (Erosion Productivity Impact Calculator; Williams et al., 1989) and SVAT (Soil Vegetation Atmosphere Transfer; Mo et al., 2005). A limitation of many of these physically-based models is that they do not link crop yields and crop management to the local hydrology, which could be used to study the interaction between crops (vegetation) and hydrology where water resources are limited.

This study was done within the European Union project EAU4FOOD, which focusses on agricultural innovations in Africa. The project seeks to address the enormous challenges African agriculture is facing today, as agricultural production cannot keep up agricultural demand. Irrigation management will gain importance in terms of raising crop production, but in areas where water resources are vulnerable, the use of fresh water must be sustainable. New approaches are required to increase crop production in irrigated areas. In order to test different irrigation and management operations, hydrological models can be used to estimate the effect of different operations on water quantity and crop yields.

To set up different irrigation scenarios in relation to crop yields and water allocation management, the Soil and Water Assessment Tool (SWAT) hydrological model was used. The SWAT model is a physically-based, catchment scale model which is used to simulate over long periods of time. The SWAT model has been used and validated to simulate ecological, hydrological and environmental processes under multiple climates and management conditions throughout the world, and is extremely useful to link crop yields and basin hydrology over a long period of time (Neitsch et al., 2011).

Model applications
The aim of this project was to set up the SWAT model for the Limpopo River basin (Southern Africa) and the Gumselasa catchment (Ethiopia), and to study the relation between crop yields and the hydrology. Scenarios were defined to study the effect of irrigation and fertilization management operations. The main research questions were:
- Is the SWAT hydrological model applicable for modelling a data-scarce basins such as the Limpopo River and the Gumselasa?
- Is the SWAT hydrological model applicable for modelling an area where basin hydrology is affected by management impacts?
- What are the responses of crop yields in the Limpopo river basin on irrigation and fertilization input? Do these yields vary spatially and/or temporally?
- What is the response of the Limpopo basin hydrology on irrigation and fertilization applications?
- Is it possible to reduce the soil salinity in the Gumselasa catchment?

Outline of report
In Chapter 2 a description of the SWAT model is given, together with the uncertainty algorithm SUFI-2 and assessment of the model performance. Chapter 3 gives a description of the Limpopo basin, the SWAT model set-up and the scenarios analysis on water for irrigation and application of fertilisers. In Chapter 4 the SWAT application for the Gumselasa catchment in Ethiopia is presented. Chapter 5 gives the conclusion and recommendations of this study.

Annex 1 provides a tutorial on how to set-up a SWAT model application. Annex 2 describes the set-up of the model for the Limpopo case and the SWAT model inputs and adjustments are given in Annex 3.

2 Soil and Water Assessment Tool (SWAT)

2.1 SWAT model

To investigate the role of irrigation and fertilizer application on the local hydrology and crop yields, the Soil and Water Assessment Tool (SWAT) model was used. SWAT is a physically based, hydrological model which can predict the water quantity and quality on irrigated arable land in a catchment over a long period of time. SWAT has been tested in different tropical watersheds (Neitsch et al., 2011). The SWAT model is based on the principles of the water balance:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - \omega_{seep} - Q_{gw}\right) \quad [1]$$

Where SW_t is the soil water content [mm], SW_0 is the initial soil water content on day 1 [mm], t is the time [days], R_{day} is the daily precipitation [mm], Q_{surf} is the amount of surface runoff [mm], E_a is the evapotranspiration [mm], ω_{seep} is the amount of water entering the unsaturated zone [mm] (consists of the infiltration rate minus the capillary rise), and Q_{gw} is the amount of return flow [mm]. The model defines two phases; the land phase and the water, or routing, phase of the hydrological cycle. The land phase controls the amount of water and sediment movement, and the water phase is the movement of water in the catchment.

The SWAT model divides the catchment in multiple sub-catchments depending on the number of tributaries within the catchment. The size of the sub-catchments varies from place to place and on the nature of topology and stream network system of the area. Each sub-catchment is divided into multiple Hydrologic Response Units (HRUs). HRUs are lumped land areas with unique land cover, soil, slope and management combinations. This can reflect differences in e.g. evapotranspiration and runoff. Each HRU in a sub-catchment is liable for water and sediment movement, nutrients and pesticides loadings that are routed through channels and reservoirs towards the watershed outlet. The advantage of defining HRUs is that it increases the accuracy of the predicted water and sediment loadings from the catchment and gives a better description of the water balance for each individual HRU, as it has no interaction with other HRUs (Neitsch et al., 2011).

2.2 SWAT water balance components

2.2.1 Surface runoff

The SWAT model provides two approaches to estimate surface runoff; the SCS curve number method (USDA SCS, 1972) and the Green & Ampt infiltration (1911) method. In this study, the SCS curve number method was used, because this method estimates the surface runoff as a function of the soil's permeability, land use and antecedent soil water conditions. The method provides a consistent basis for estimating the amount of runoff under varying land use and soil types, and is easy to use when the land use is known. The SCS curve number method estimates surface runoff from daily rainfall using initial abstractions and a retention parameter. The SCS curve number equation is:

$$Q_{surf} = \frac{\left(R_{day} - 0.2\,S\right)^2}{\left(Rday + 0.8\,S\right)} \quad [2]$$

Where Q_{surf} is the accumulated runoff [mm]. R_{day} is the rainfall depth for the day [mm] and S is the retention parameter [mm]. The initial value of the retention parameter S [mm] is defined as:

$$S = 0.9 * S_{max} \quad [3]$$

The maximum retention parameter S_{max} [mm] is defined as:

$$S_{max} = 25.4 * \left(\frac{100}{CN} - 10\right) \qquad [4]$$

Where *CN* is the curve number for the day. The SCS curve number method is a function of the permeability of the soil, land use and antecedent soil water conditions. The SCS defines three antecedent soil moisture conditions (CN): I – dry (wilting poin), II – average moisture, and III – wet (field capacity). Typical curve numbers for moisture condition II are listed in multiple tables (e.g. Neitsch et al., 2011; Dingman, 1994). These values are appropriate for a 5% slope, to adjust the curve number to a different slope, the following equation is used (Williams, 1995):

$$CN_{2s} = \frac{CN_3 - CN_2}{3} * [1 - 2 * exp(-13.86 * slope)] + CN_2 \qquad [5]$$

Where CN_{2s} is the moisture condition II curve number adjusted for slope, CN_3 is the moisture condition III curve number for the default 5% slope, CN_2 is the moisture condition II curve number for the default 5% slope, and *slope* is the average fraction slope of the sub-catchment. A more detailed description of the surface runoff calculation is given by Neitsch et al. (2011).

2.2.2 Evapotranspiration

Evapotranspiration is the sum of evaporation from rivers, lakes and bare soil, and transpiration from vegetative surfaces. The SWAT model estimates values of the actual evaporation and transpiration separately. The actual evapotranspiration is calculated by using the potential evapotranspiration (PET); the PET is the volume of water that can be evaporated and transpired if enough water is available. The daily PET can be estimated by SWAT through three different methods: Penman-Monteith, Hargreaves or Priestley-Talor. In this study, the Penman-Monteith (Monteith, 1965) method was used to calculate the daily PET, which required relative humidity [-], solar radiation [MJ/m^2/day], wind speed [m/s] and air temperature [°C] as input data. The Penman-Monteith equation is given by:

$$\lambda E = \frac{\Delta * (H_{net} - G) + \rho_{air} * c_p * \frac{[e_z^0 - e_z]}{r_a}}{\Delta + \gamma * \left(1 + \frac{r_c}{r_a}\right)} \qquad [6]$$

Where λE is the latent heat flux density [MJ/m^2/d], E is the depth rate evaporation [mm/d], Δ is the slope of the saturation vapor pressure-temperature curve, *de/dT* [kPa/°C], H_{net} is the net radiation [MJ/m^2/d], G is the heat flux density to the ground [MJ/m^2/d], ρ_{air} is the air density [kg/m^3], c_p is the specific heat at constant pressure [MJ/m^2/d], e_z^0 is the saturation vapor pressure of air at height *z* [kPa], e_z is the water vapor pressure of air at height *z* [kPa], γ is the psychrometric constant [kPa/°C], r_c is the plant canopy resistance [s/m], and r_a is the diffusion resistance of the air layer (aerodynamic resistance) [s/m].

The actual evapotranspiration is the sum of soil water evaporation and transpiration by vegetation. Soil water evaporation was estimated by using exponential functions of soil depth [mm] and water content [-]; a detailed description of these functions is given by Neitsch et al., 2011. Transpiration was simulated as a linear function of the PET and leaf area index (LAI [-]) and is given by:

$$E_t = \frac{E_0' * LAI}{3.0} \qquad 0 \leq LAI \leq 3.0 \qquad [7]$$

$$E_t = E_0' \qquad LAI > 3.0 \qquad [8]$$

Where E_t is the maximum transpiration on a given day [mm H_2O], E_0' is the potential evapo-transpiration calculated by the Penman-Monteith equation [mm H_2O], and *LAI* is the leaf area index. The value for transpiration is the amount of transpiration that will occur on a given day when the plant is growing under ideal conditions. The actual amount of transpiration may be less than this due to a lack of water in the soil profile or nutrient deficits (Neitsch et al., 2011).

2.2.3 Soil-water interaction

The movement of water through the soil can be along various pathways; removal from the soil by evaporation or plant uptake, percolation, or lateral movement in the profile. The lateral movement through the soil is calculated by the kinematic storage model provided by Sloan et al. (1983). This model simulates two-dimensional subsurface flow, based on slope, slope length, and saturated hydraulic conductivity. The SWAT model uses the storage routing methodology to calculate percolation for each soil layer in the profile. A more detailed description of the soil-water interaction is given by Neitsch et al. (2011).

2.2.4 Groundwater

The SWAT model incorporates shallow and deep aquifers. The shallow aquifer water balance consists of recharge entering the aquifer, groundwater flow, the amount of water moving into the soil zone in response to water deficits and the amount of water extracted from the aquifer by pumping. The deep water aquifer water balance consists of percolation from the shallow aquifer into the deep aquifer and the amount of water extracted from the deep aquifer by pumping, which are both not included in this research. The SWAT uses different empirical and analytical techniques to account for all these components of the ground water distribution (Neitsch et al., 2011). Water routing in the SWAT model was done by using the Muskingum routing (Chow et al., 1998) method provided by SWAT, which is a variation of the kinematic wave equation.

2.2.5 Plant growth and crop yields

Plant growth in SWAT is calculated with a simplification of the Environmental Policy Integrated Calculator (EPIC) crop model (Williams et al., 1984). The model simulates the leaf area development, biomass accumulation and crop yield for different plant species. SWAT calculates crop yields as a function of the above-ground biomass of the crop and the harvest index, on the day of harvest:

$$yld = bio_{ag} * HI \qquad [9]$$

Where yld is the crop yield [kg/ha], bio_{ag} is the above-ground biomass on the day of harvest [kg/ha] and HI is the harvest index on the day of harvest. The harvest index will be between 0.0 and 1.0, and may have harvest indices greater than 1.0 if roots are also harvested. A more detailed description of crop growth in SWAT is given by Neitsch et al. (2011).

2.2.6 Soil nutrients

Nitrogen, phosphorus and potassium are the most important minerals for plant growth. Nitrogen is held in the soil in three major forms; organic nitrogen associated with humus, mineral forms held by soil colloids, and nitrogen in solution. In SWAT, nitrogen can be added to the soil by fertilizer, manure or residue application, fixation by symbiotic or non-symbiotic bacteria and rain. It is extracted from the soil by plant uptake, leaching, volatilization, denitrification and erosion. A more detailed description of soil nutrients is given by Neitsch et al. (2011).

2.3 Model analysis

2.3.1 Sequential uncertainty fitting (SUFI)

To evaluate the performance of the SWAT model, application of the sequential uncertainty fitting algorithm (SUFI-2) was carried out. This algorithm is combined with SWAT in the SWAT Calibration and Uncertainty Programs (SWAT-CUP) package. SUFI-2 is a semi-automatic inverse modeling procedure which combined calibration and uncertainty analysis. It accounts for all sources of uncertainty, e.g. parameters and measured data. The model output uncertainty is quantified by the 95% prediction uncertainty (95PPU) calculated at the 2.5% and 97.5% levels of the cumulative distribution function of the output variables (Zhou et al., 2012). Yang et al. (2008) founded that the

SUFI-2 analysis technique needed the smallest number of model runs to achieve a good solution and prediction uncertainty in relation with SWAT (Schuol et al., 2008).

2.3.2 Assessment of model performance

To assess the model behavior, the *P-factor* and *R-factor* were used to quantify the goodness of uncertainty performance. The *P-factor* is the percentage of data covered by the 95PPU and (max. value 100%), and the *R-factor* is the average width of the band divided by the standard deviation of the corresponding measured variable (Sun and Ren, 2013). Statistical criteria were used to evaluate the SWAT model performance, including the coefficient of determination (R^2) and the Nash-Sutcliffe efficiency (NSE). These statistical criteria were calculated during the SUFI-2 algorithm. The Nash-Sutcliffe efficiency is commonly used for estimating hydrological model parameters, and is calculated as:

$$NSE = 1 - \frac{\sum_{t=1}^{N}(Q_{s,t} - Q_{o,t})^2}{\sum_{t=1}^{N}(Q_{o,t} - \bar{Q}_o)^2} \qquad [10]$$

Where $Q_{s,t}$ is the simulated stream flow value at *t* moment, $Q_{o,t}$ is the observed stream flow value at *t* moment, and $\bar{Q}_o$ is the mean observed stream flow value and *N* is the number of observations. The range of *NSE* is from -∞ to 1, with 1 indicates a perfect fit between the observed and simulated data (Nash and Sutcliffe, 1970). The R^2 is calculated as:

$$R^2 = \frac{\left[\sum_{t=1}^{N}(Q_{o,t} - \bar{Q}_o)(Q_{s,t} - \bar{Q}_s)\right]^2}{\sum_{t=1}^{N}(Q_{o,t} - \bar{Q}_o)^2 \sum_{t=1}^{N}(Q_{s,t} - \bar{Q}_s)^2} \qquad [11]$$

Where $\bar{Q}_s$ is the mean simulated stream flow value. R^2 ranges from 0 to 1, where 1 means a perfect fit (Zhou et al., 2012).

3 Limpopo River basin – Southern Africa

3.1 General background

This study focused on the Limpopo River basin, which is located in Southern Africa between 22°S - 26°S latitude and 26°E - 35°E longitude (Figure 3.1). The Limpopo river basin has a drainage basin of approximately 415 000 km^2. It spreads out over four countries; 44% of the basin is situated in South Africa, 21% in Mozambique, 19% in Botswana and 16% in Zimbabwe. The Limpopo River is approximately 1750 km long and has 24 main tributaries. It originates in the central part of Southern Africa, towards the coastal plains of Mozambique and flows out in the Indian Ocean (FAO, 2004).

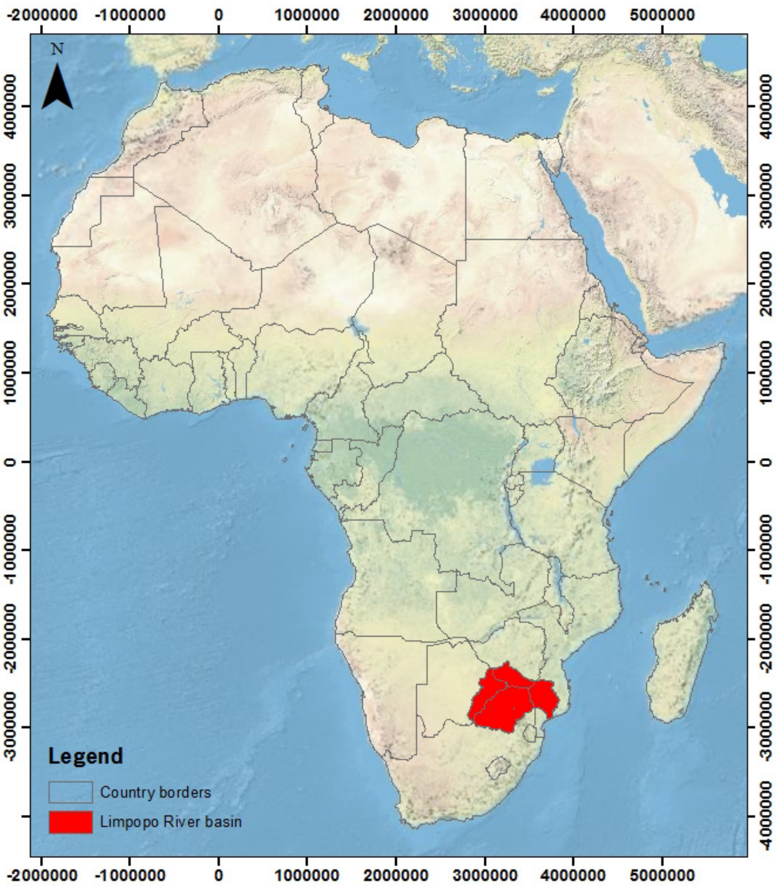


Figure 3.1 *Location of the Limpopo River basin.*

The climate of the Limpopo River basin is predominantly semi-arid, dry and hot. The central river basin is arid, dry and hot. The South African Highveld part of the basin is temperate with summer rainfall and cool to hot summers. The coastal plain of Mozambique is mainly warm-temperature with no dry season and hot summers. The mean annual precipitation decreases fairly uniform to the west, with the highest precipitation on the Drakensberg Escarpment, and there is a north-south gradient towards the Limpopo river. Precipitation varies from 200 mm in the hot and dry areas to 1.500 mm in the high rainfall areas. Major part of the basin receives less than 500 mm rainfall per year. Generally, summers in the Limpopo River basin are warm and the winters are mild. Average daily temperatures in the Limpopo river basin can be 40° C during summer and below 0° C during winter. Temperature rates are closely related to altitude and proximity to the ocean (Figures 3.2 and 3.3). The mean maximum daily temperature in a large part of the basin area varies from 30-34 °C in summer to 22-26 °C in winter. The mean minimum daily temperature varies from 18-22 °C in summer to 5-10 °C in winter. The annual evaporation varies between 1000 and 2700 mm. Summer periods with high evapotranspiration rates coincides with the rainfall season, which is reducing the effectiveness of rainfall, runoff, soil infiltration and groundwater recharge (Ekblom et al., 2012).

Seasonal distribution of rainfall over the catchment influences the hydrology in the Limpopo river basin. Almost 95% of the rainfall falls between October and April, and therefore most of the streams in the Limpopo River basin have a dry river bed during the dry season. Droughts and storms enhance the fluctuations in river flows and water availability significantly, resulting in water scarcity and floods. To retain water in the Limpopo River basin, 138 major dams have been constructed; 13 dams have a storage capacity of more than 100 Mm^3, where the Massinger dam in Mozambique is the largest one. Dry land conditions are predominant in the Limpopo river basin. The basin is mainly covered by grassland, savannah and shrub land (68%), and about 26% is cropland, from which only 1% is irrigated. Wetlands cover about 3% and the remaining 3% is divided between forest and urban (Spaliviero et al., 2011). Due to deforestation activities during the last 60 years, most of the original forest cover was lost, which was the result of the expansion of agricultural land.

As a large portion of the population in the Limpopo River basin is depending on agriculture for livelihoods, it is one of the most important economic activities in the basin. Crop production is variable and unreliable primarily because of the low and short rainfall. Crop yields are overall much lower than in areas where rainfall is higher (FAO, 2004). The agricultural system in the Limpopo River basin is divided between commercial and small holder farming. Small holder farms are mostly owned by one owner or by a community and have small land sizes (average of 1.5 ha). They are characterized by low crop yields (< 1 t/ha) and production is mainly used for domestic use with a small surplus which are sold on local markets. This traditional agriculture mostly uses family labour. As many small holder farms cannot afford chemical fertilizers, fertilization is mainly done by manure. Commercial farms are characterized by large land sizes (average of more than 700 ha) and utilize advanced production technologies, which results in much higher crop yields. The large scale commercial farms are mainly focused on vegetable and fruit production, such as tea, citrus and tropical fruits such as mango and banana, whereas small holder farms mainly have crops such as maize, sorghum and wheat (FAO, 2004).

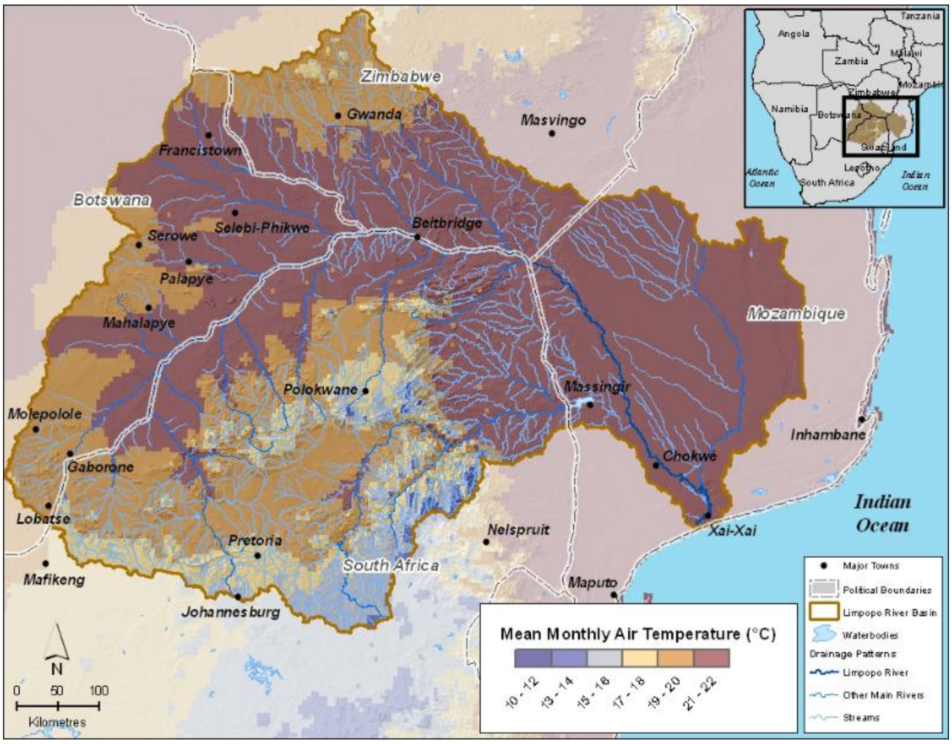


Figure 3.2 *Mean monthly air temperature [°C].*

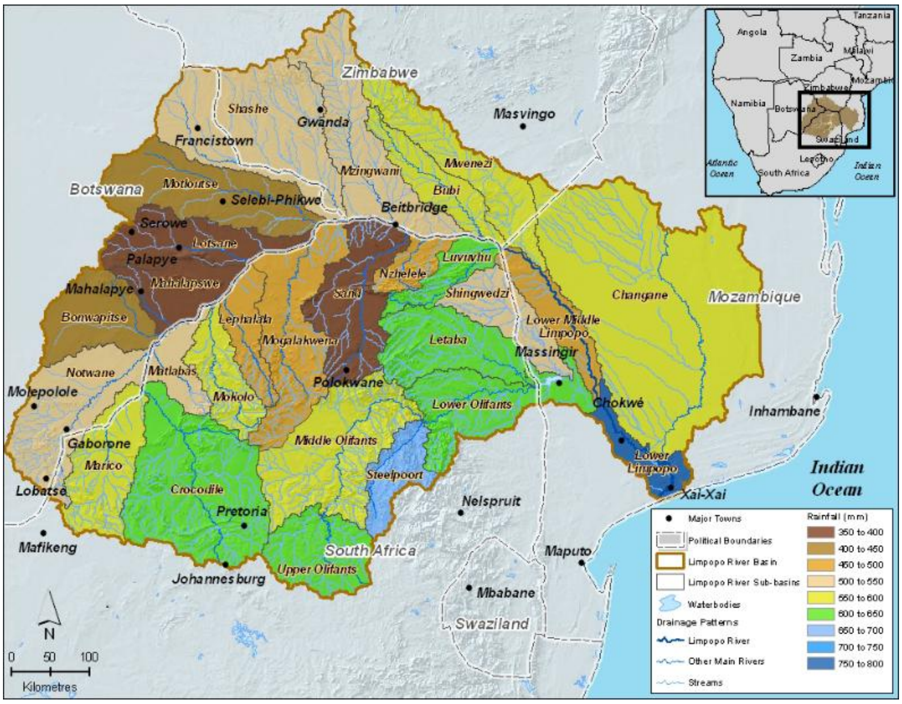


Figure 3.3 *Mean annual temperature [°C] in the Limpopo river basin (Limpoporak, 2013).*

3.2 SWAT model set-up

In this study, SWAT modelling was carried out in an ArcGIS10.0 interface. The ArcSWAT version 2012.10.0 was used. In Appendix 1 the SWAT tutorial shows the set-up of the SWAT model in ArcSWAT.

3.2.1 Watershed delineation

The boundary of the river basin, sub basins and the stream network were delineated by using a SRTM digital elevation model (DEM) with a 90m resolution. As shown by Figure 3.4, there is a clear distinction between the Highveld area in the southern part and the Lowveld area in the eastern part of the Limpopo River basin. The Limpopo River basin was divided into 113 sub basins. In this process, also the stream network, channel length, average slope of the channel and other sub basin parameters were derived.

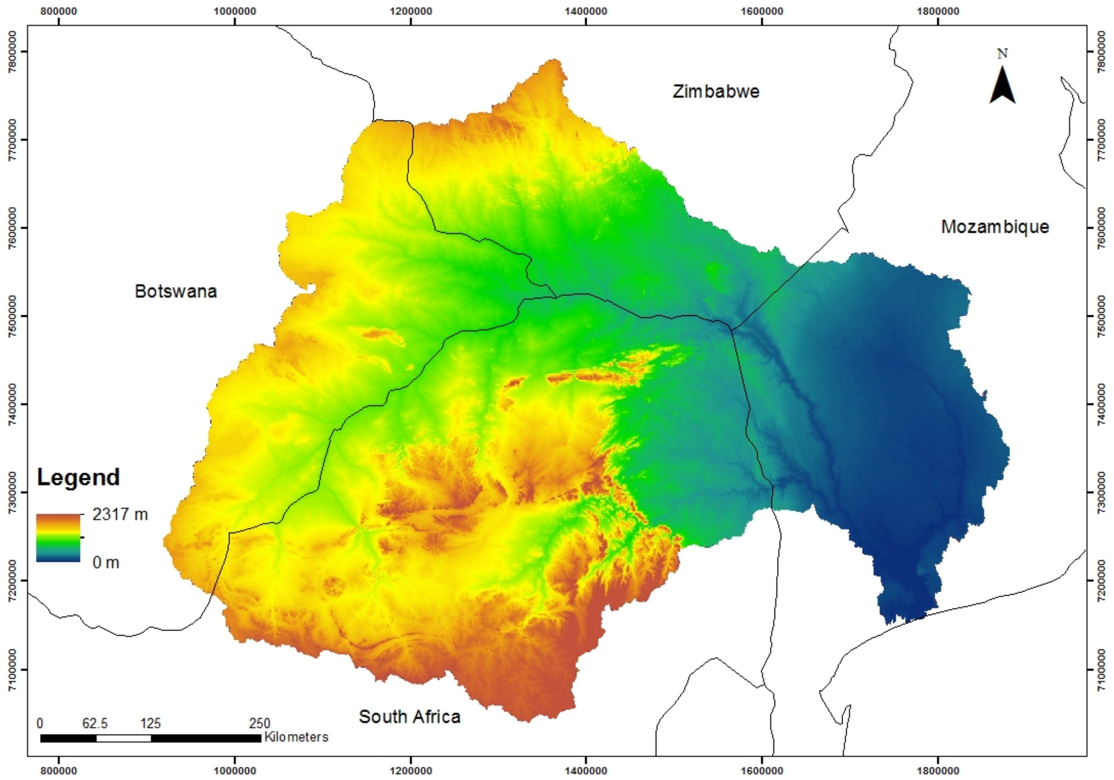


Figure 3.4 *Digital elevation model (DEM) of the Limpopo river basin, Southern Africa.*

3.2.2 Land use data

Land use map of the Limpopo River basin was made of multi-temporal Landsat ETM images of 30 m resolution and MODIS images of 250 m resolution (Figure 3.5). Most of the agricultural land is found in the southern part of the Limpopo, which lies mainly in South Africa; this is the same for urban area. Most small holder cultivated land is found in the middle of the Limpopo River basin, which is actually close to the Limpopo River. To compare the images of both satellites, the Landsat images were up scaled to 250 m resolution. Classification was based on the unsupervised Decision Tree method. The Decision Tree method classified pixels based on several conditional statements. The conditional statements were based on NDVI maps and the National Land Cover 2000 (NLC2000) of South Africa, applied to the whole Limpopo River basin image (Danes et al., 2012). The basin was divided into ten land use classes; woodland, bush land, grassland, forest plantation, water/wetlands, bare rock/soil, commercial cultivated and irrigated land, commercial cultivated dry land, small holder cultivated dry land and urban. According to Table 4.1, there is a major difference between the areal extension of the land use map made with the Decision Tree method and the land use classification provided by the National Land Cover 2000 map. Because agricultural land was the main focus of this study, it was chosen to reduce the area of agricultural land.

Table 3.1
Distribution of land use types, Limpopo River basin.

Land use	% Area land use map	% Area calculated by the NLC2000 – South Africa
Woodland	28.4	31.7
Bush land & High Fynbos	44.3	40.8
Grassland	3.2	8.9
Forest plantation	3.5	1.0
Water/wetlands	0.1	0.4
Bare rock/soil	1.1	0.8
Cultivated and irrigated land (commercial)	0.2	1.9
Cultivated dry land (commercial)	2.9	6.2
Cultivated dry land (small holder)	14.8	4.8
Urban/built up	1.5	3.5

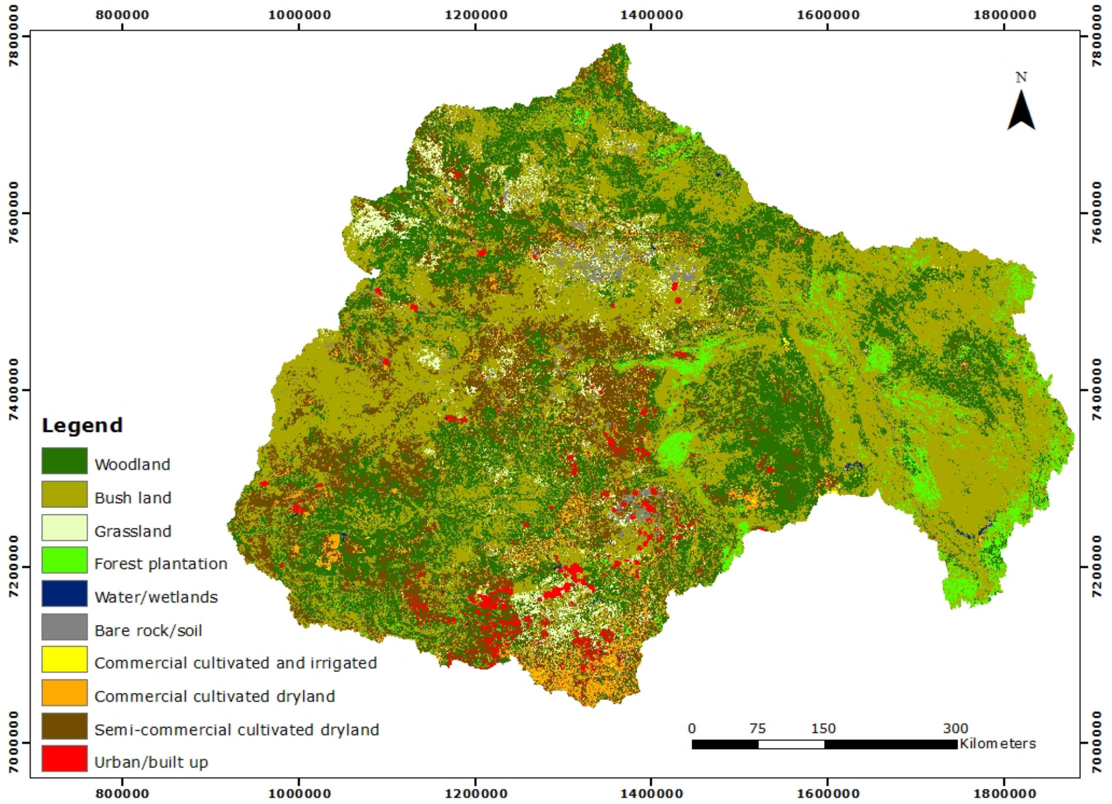


Figure 3.5 *Land use map of the Limpopo River basin, Southern Africa.*

3.2.3 Soil data

Soil map for the Limpopo basin is needed as an input for the SWAT modelling. Soil map and soil data was derived from the Soil and Terrain Database for Southern Africa (SOTERSAF, version 1.0). The soil map has a scale of 1:2 million, and includes spatial and soil attribute data for eight southern African countries. The data were compiled in a cooperation between ISRIC, FAO and UNEP (Batjes, 2004). Not all required SWAT input parameter values were available; these values were based on data in the existing SWAT soil database.

3.2.4 Climate data

Climate data was derived from the SWAT model homepage (Global Weather Data for SWAT, http://globalweather.tamu.edu). From this climate model generator, 391 points of weather data were used to cover the entire Limpopo River basin. Daily values of precipitation, temperature, solar radiation, wind speed and humidity were available for the Limpopo River basin.

3.2.5 Groundwater

The subsurface in the Limpopo River basin is assumed as one layer. Little information about hydrogeology is available for the Limpopo River basin; therefore it is assumed that there is only one aquifer. The aquifer is overlying the hydrological base. For the aquifer, the hydrological data of SADC was used (SADC, 2010). According to this data, the groundwater delay factor was set on 15 days and it was assumed that there was no recharge to the deep aquifer (Arnold et al., 1993).

3.2.6 Reservoirs in the Limpopo river basin

In the SWAT model, 16 reservoirs within the Limpopo river basin were implemented, based on their capacity and area. The capacity and area values were derived from AQUASTAT data; missing area values in AQUASTAT were derived from ArcGIS Bingmaps. Figure 3.6 and Table 3.2 show the largest reservoirs with their location, river, capacity and area. They all were already operational before the start of the SWAT modelling (1998). There are much more reservoirs in the Limpopo River basin, but many of them are small dams with a capacity of less than 5 Mm^3, and have a negligible effect on the basin hydrology.

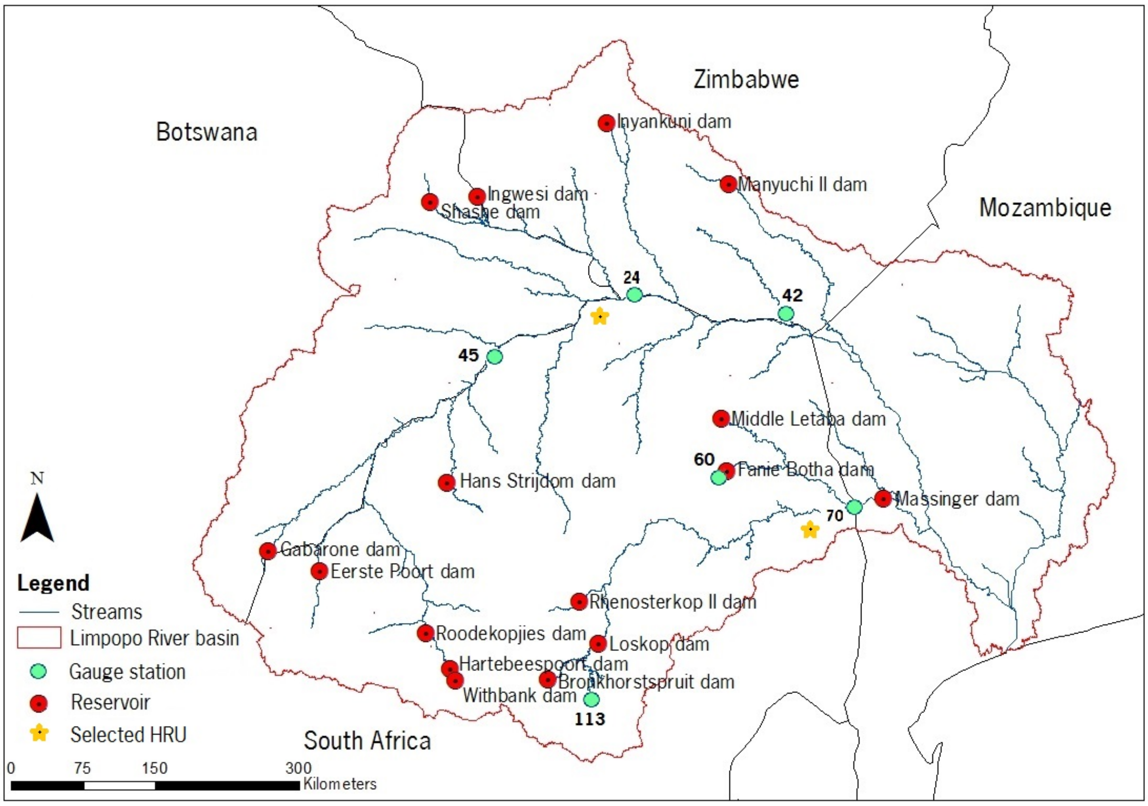


Figure 3.6 *Locations of reservoirs, gauge stations and selected HRUs.*

As multiple reservoirs have water supply as main purpose, water was extracted from these reservoirs for water consumption. No actual data was available for the actual amount of water consumption for each reservoir, but the rate of water removal was estimated using the total water need for urban population in the Limpopo River basin (625.6 * 10^6 m^3/year), based on the storage capacity in each reservoir. Only the urban population was chosen, because most of the rural population get their water for consumption from storage dams or streams (Table 3.3).

Table 3.2

Reservoirs in the Limpopo river basin used in the SWAT model.

Reservoir	Country	River	Capacity	Area	Water use
			[Mm^3]	[ha]	
Massingir	MO	Olifants	2256.0	15,070.0	Irrigation, hydroelectricity
Loskop	SA	Olifants	348.1	3,700.0[1]	Irrigation
Manyuchi II	ZI	Mwenezi	319.0	3,300.0	Irrigation
Eerste Poort	SA	Marico	230.0	3,911.5[1]	Irrigation
Rhenosterkop II	SA	Elands	205.8	3,733.8[1]	Water supply
Hartebeespoort	SA	Crocodile	194.6	2,205.2[1]	Irrigation
Middle Letaba	SA	Middle Letaba	173.0	2,096.5[1]	Irrigation, water supply
Fanie Botha	SA	Great Letaba	160.2	1,286.1[1]	Irrigation
Hans Strijdom	SA	Mogol	148.7	934.3[1]	Irrigation, water supply
Gabarone	BO	Ngotwane	144.0	2,166.81	Water supply
Withbank	SA	Olifants	104.0	753.6[1]	Water supply
Roodekopjies	SA	Crocodile	102.6	1,380.9[1]	Irrigation
Shashe	BO	Shashe	85.0	1,529.5[1]	Water supply
Inyankuni	ZI	Inyankuni	81.8	493.3[1]	Water supply
Ingwesi	ZI	Ingwesi	69.8	904.8[1]	Irrigation
Bronkhorstspruit	SA	Bronkhorstspruit	58.9	897.9[1]	Irrigation, water supply

[1]Areas are based on estimations in Google Earth.

Table 3.3

Water consumption for each reservoir in the Limpopo River basin.

Dam	Country	Percentage of total water consumption [%]	Daily water consumption [10^4 m^3]
Shashe	Botswana	3	2.2
Gabarone	Botswana	4	3.3
Rhenosterkop II	South Africa	42	35.9
Withbank	South Africa	14	11.7
Inyankuni	Zimbabwe	37	32.4

The reservoirs included in this SWAT model are not discussed in the results. They were only implemented into the model to give a representative situation according to the current Limpopo River basin situation. Because no information was available for the extraction of irrigation water from the reservoirs, it was chosen to extract water for irrigation from the shallow aquifer. However, many of the commercial farms are irrigating with water from reservoirs and water from the reservoirs is extracted out of the river basin. This will affect the water balance in the basin, but due to a lack of data availability, figures of water extraction are not known. Thus, reservoir management is not discussed.

3.2.7 Scenario definitions

Different management scenarios were defined for small holder farms to study the impact of the management practices on the water balance, stream flow, irrigation water yields and crop yields with the SWAT model. In general, it was assumed that there are two cropping seasons for small holder farms; a summer cropping season which lasts from October 1 to March 31 with maize (*Zea mays* L.) and a winter cropping season which lasts from April 1 to September 31 with wheat (*Triticum aestivum*). These crops are generic crop types in the Limpopo River basin. Four scenarios were implemented in the SWAT model, to study the effect of irrigation and fertilizer application on the hydrology and crop yields (Table 3.4). In the baseline scenario (BS), no irrigation and fertilizer were applied. In this scenario, only water for consumptive use was removed from the reservoirs according to Table 4.3. No additional nutrients were applied to agricultural lands. In scenario II, irrigation on small holder farms was applied. Application of irrigation was based on plant water stress. Water for irrigation was extracted from the shallow aquifer and from the reservoirs. In scenario III, fertilizer operations of small holder farms were applied. As many of the chemical fertilizers are too expensive to use in small holder farms, only fertilization as manure was applied (FAO, 2004). Between the two crop seasons, 50 kg/ha of manure was applied on the agricultural farms, which resulted in a total of 100 kg/ha/year (FAO, 2004; Anderson et al., 2013). In scenario IV, both irrigation and fertilizer application were modelled, with the same inputs as scenarios II and III. For scenario analysis, two random HRUs were selected with the same soil type (lithosols), slope (0-2%) and land use (small holder agriculture) in different parts of the basin (Figure 3.6).

Table 3.4
Scenario description.

Scenario		Management operation	Description
I	BS	No irrigation, no fertilizer application	Baseline
II	FA	Application of fertilizer	Manure as fertilizer (100 kg/ha/year)
III	IA	Application of irrigation	Auto irrigation (plant water stress)
IV	CS	Application of fertilizer and irrigation	Manure as fertilizer (100 kg/ha/year) and auto irrigation (plant water stress)

3.2.8 Model performance – SWAT-CUP

To make an assessment of the model performance, the simulated discharge data of the baseline scenario was analysed by using six discharge gauge stations in the Limpopo River basin (Table 3.5). Monthly discharge data between January 2001 and December 2005 was used for model analysis. For the uncertainty analysis, the SUFI-2 method with SWAT-CUP software was used. SWAT-CUP is an open source uncertainty analysis software program built for analysing SWAT results. Uncertainty results are found in paragraph 3.3.1.

Table 3.5
Gauging stations and the assigned sub basin in SWAT (for the locations see Figure 3.6).

Gauge station	Sub basin
Beit bridge	24
Bubye River@Zimbabwe	42
Limpopo River@Botswana	45
Upper Letaba River	60
Engelhartdam@Letaba	70
Krokodil River@Nooitgedacht	113

3.3 Results and discussion

3.3.1 Model performance

SWAT model performance was tested with the SWAT-CUP SUFI-2 uncertainty analysis technique. First, a parameter sensitivity analysis was done for 10 different parameters on the baseline scenario. Table 3.6 shows the selected parameters used for SUFI-2 uncertainty analysis technique, with their range and final fitted value.

Table 3.6

Parameters selected for sensitivity analysis.

Parameter	Definition	Range			Fitted value
CN2	Initial SCS runoff curve number for moisture condition II	-0.2	-	0.2	-0.134[1]
Alpha_bf	Baseflow recession constant [-]	0	–	1	0.625
Gwqmn	Threshold water level in shallow aquifer for baseflow [mm H2O]	0	–	2	0.53
Gw_revap	Groundwater re-evaporation coefficient	0	–	0.2	0.057
ESCO	Soil evaporation compensation factor	0.8	–	1.0	0.823
CH_N2	Manning's 'n' value for main channel	0.0	–	0.3	0.1395
CH_K2	Effective hydraulic conductivity in main channel alluvium [mm/hour]	5.0	–	130	121.875
Alpha_bnk	Bank flow recession constant	0.0	–	1.0	0.235
Sol_awc	Available water capacity of soil layer [mm/mm]	-0.2	–	0.4	0.1871
Sol_k	Saturated hydraulic conductivity of first layer [mm/hr]	-0.8	–	0.8	0.6321
Sol_bd	Moist bulk density [Mg/m3]	-0.5	–	0.6	0.01151

[1] The fitted value is the percentage change of the original value.

Table 3.7

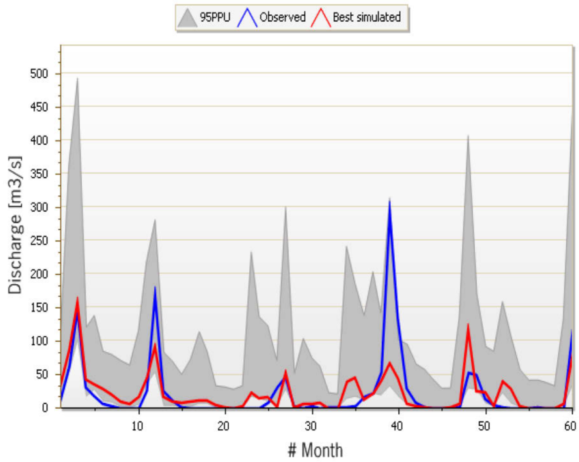
Statistical summary of the observed and simulated discharge data.

Gauge station (sub basin #)	R^2	NSE	R-factor	P-factor
24	0.46	0.45	2.14	0.53
42	0.36	-0.04	0.71	0.50
45	0.24	-5197.7	149.6	0.08
60	0.27	0.02	1.28	0.50
70	0.03	-0.33	0.75	0.58
113	0.04	-0.10	0.15	0.03

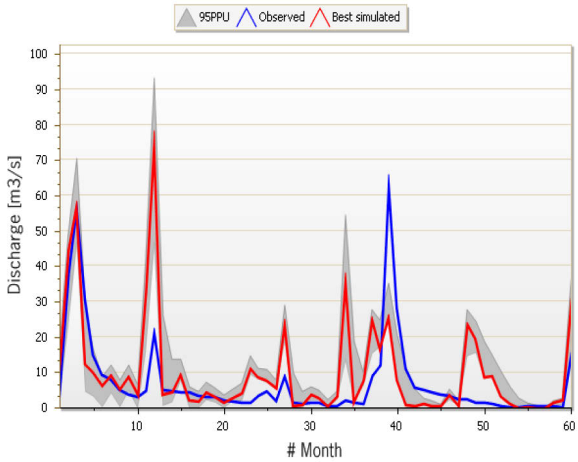
The final fitted parameter values described in Table 3.7 were used for model performance analysis. Monthly model analysis was carried out for the period 2001 to 2005. Only gauge stations in the South African part of the Limpopo River basin were available for model analysis, which implies that a large part of the basin is not considered. Results of model analyses were made within a 95% prediction uncertainty range (95PPU). Final results of the 95PPU plots for six simulated and observed discharge gauge station data are shown in Figure 3.7. The table shows P-factor and R-factor, as well as the coefficient of determination (R^2) and the Nash-Sutcliffe efficiency (NSE). The plots in Figure 3.7 show varying uncertainty prediction results. Multiple factors can be the result of the variation in uncertainties. One reason can be that, as SWAT only uses one rainfall station per sub basin, therefore local variation in precipitation with a sub basin is not taken into account. Also rainfall intensity can highly influence the amount of surface flow and thus stream flow. Second, the managing factor in the basin can also have impact on the observed discharge. Management behaviour of the reservoirs will have an impact on the discharge downstream, especially in terms of droughts and floods. This is related to extensive modifications of the water fluxes. Surface runoff is not only reduced by reservoirs, but also collected, stored and applied as irrigation (Andersson et al., 2013). Also, some of the larger reservoirs in the Limpopo River basin are built to store water for outside the river basin. That water is assumed as a loss (Limpoporak, 2013; Van der Zaag et al., 2010).

Huang et al. (2013) used SWIM (Soil and Water Intergraded Model) to model the Limpopo River basin. Calibration and validation of discharge at two locations show less uncertainties than the results of this study. However, they tested the model for discharge data between 1972 and 1980. During that period, the management impact on the local hydrology could be far less than it is today. With the limiting available management data, it is likely that simulated discharge is less accurate, especially in terms of reservoir management. Therefore, model output of earlier periods could give better results. To verify this statement, SWAT discharge results of earlier decades should be compared with observed discharge data. However, due to a lack of earlier meteorological data, this is not done in this study.

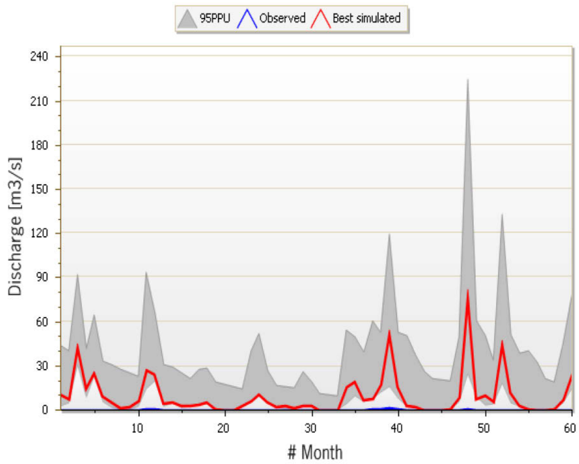
In a large river basin such as the Limpopo River, input data will have a varying impact on model results. Model behaviour will be as good as the data used as model input. Although the Limpopo River basin is a data scarce area, the SWAT model is applicable for ungauged basins (Srinivasan et al., 2010). The agreement between observed and simulated discharge is expected to decrease more downstream due to error propagation (Abbaspour et al., 2007; Dillah and Protopapas, 2000; Dubus and Brown, 2002). However, this is found in ungauged basins where the human impact is small. This is not found in this study when comparing uncertainty results (Table 3.7) with the location of the gauge station in the basin (Figure 3.8). It is likely that the management impact in this system is so large, that river flows are dominated by this factor.



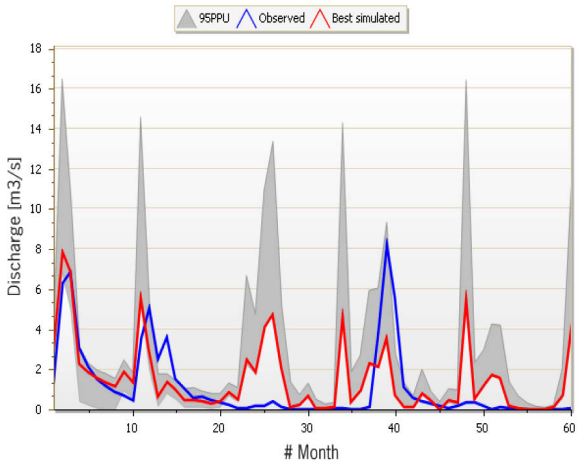
a) Sub basin 24



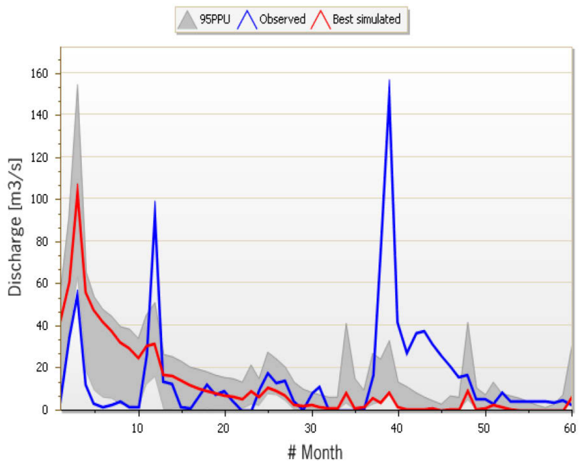
b) Sub basin 42



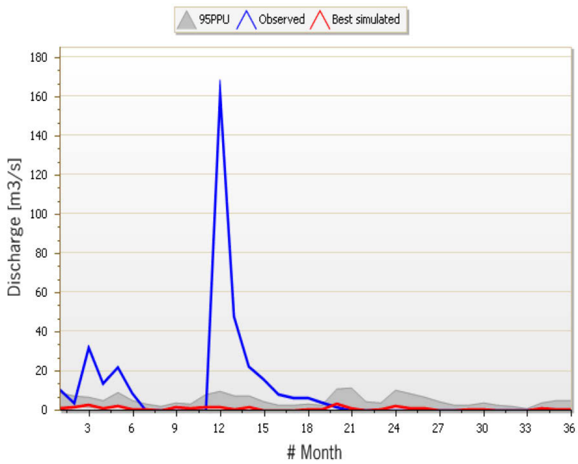
c) Sub basin 45



d) Sub basin 60

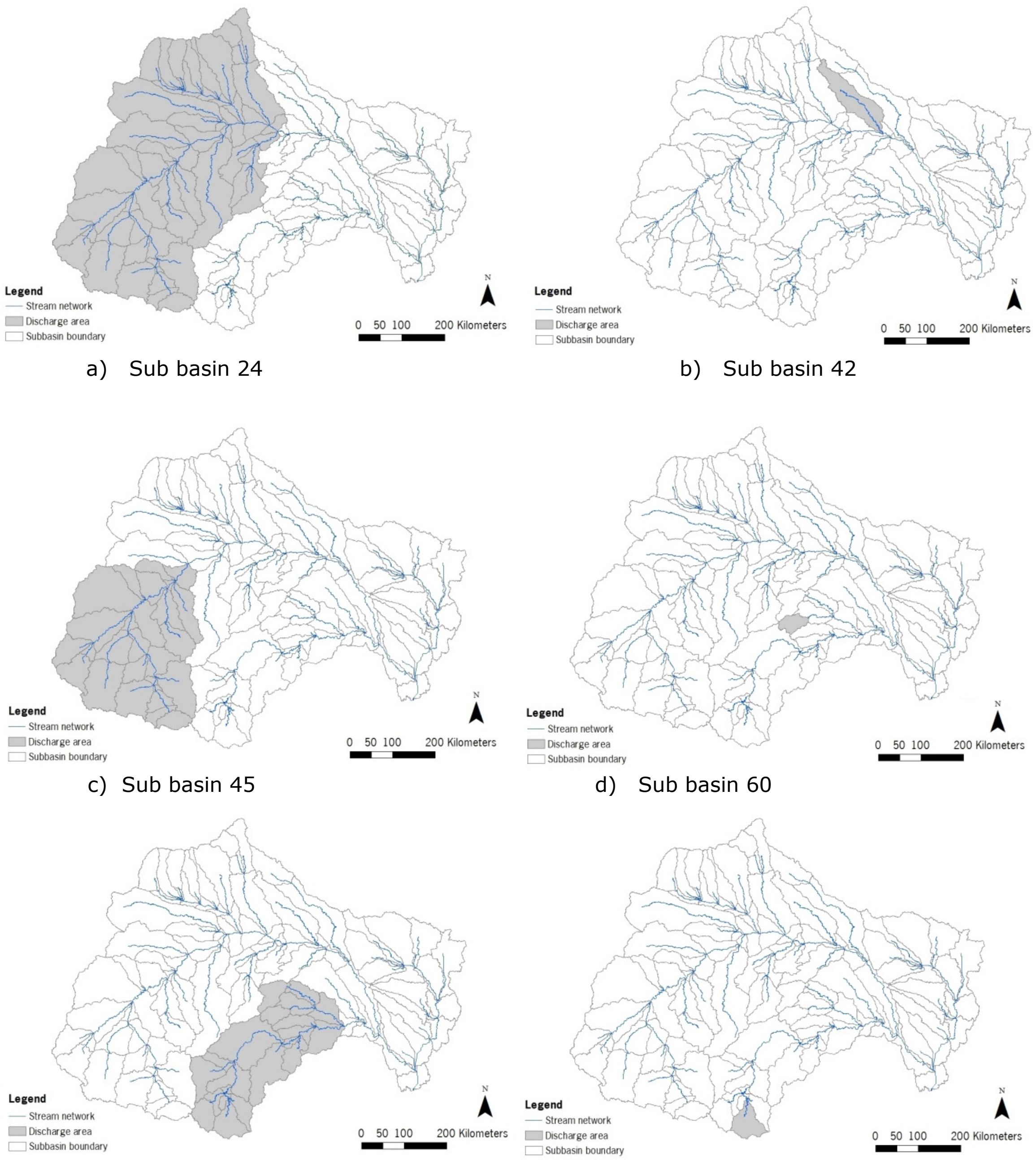


e) Sub basin 70



f) Sub basin 113

Figure 3.7 *Plots of observed and simulated discharge data, Limpopo River basin (the 95% prediction uncertainty range is shaded in grey).*

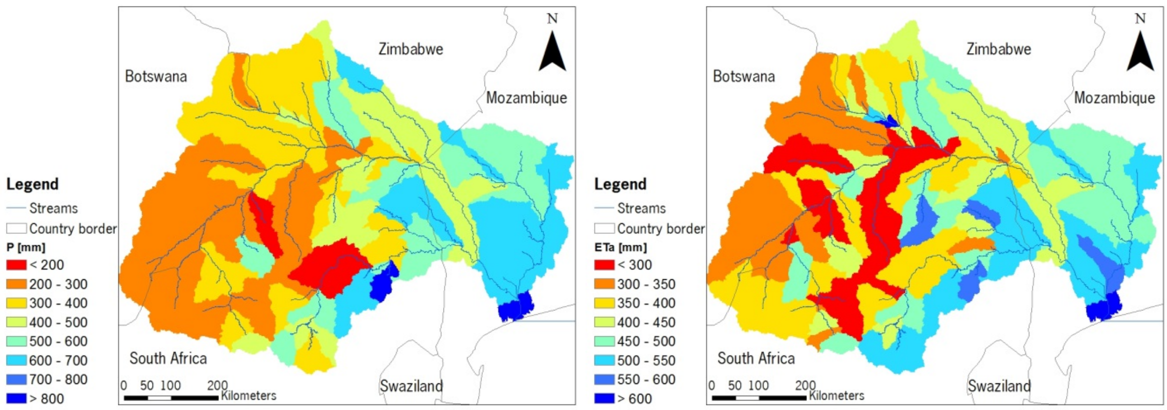


a) Sub basin 24
b) Sub basin 42
c) Sub basin 45
d) Sub basin 60
e) Sub basin 70
f) Sub basin 113

Figure 3.8 *Upstream catchment of the gauge stations.*

3.3.2 Analysis of meteorological data

The water balance was reviewed to examine the general model behaviour and water balance parameters in the Limpopo River basin. Figure 3.9a shows the mean annual precipitation [mm] between 2001 and 2010 in the Limpopo River basin. There is an increase in precipitation rates towards the coastal plains of Mozambique, where the annual precipitation can be more than 800 mm. In general, Botswana receives the lowest precipitation rates. The overall precipitation pattern is comparable with other results (Figure 3.9; FAO, 2004; Andersson et al., 2013).



a) b)

Figure 3.9 *Mean annual precipitation [mm] (a) and the mean annual evapotranspiration (ET_a) [mm] (b) in the Limpopo River basin (period 2001 – 2010).*

Figure 3.9b shows the mean annual actual evapotranspiration (ET_a) [mm] in the Limpopo River basin between 2001 and 2010, calculated with the FAO Penman-Monteith reference evapotranspiration equation (Monteith, 1965). The spatial variation of ET_a within the Limpopo River basin is very large because of the variations in land use, precipitation and irrigation. Annual ET_a rates are higher towards the coastal plains of Mozambique, where precipitation rates are also higher.

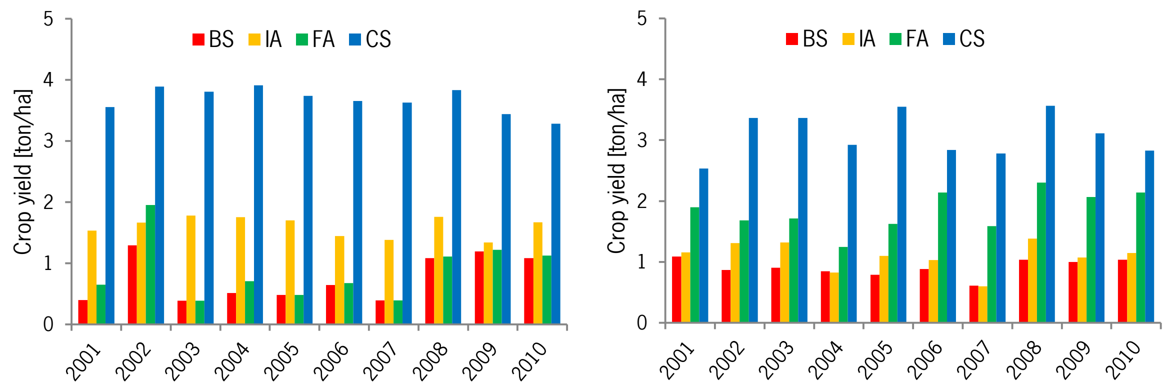
3.3.3 Scenario analysis

To analyse the impact of irrigation and fertilizer management operations on crop yields and the local hydrology, four scenarios were modelled with SWAT. Two random HRUs were selected with the same soil type (lithosols), slope (0-2%) and land use (smallholder farm) for analysing model results. Locations of the selected HRUs are found in Figure 3.6. A baseline scenario (BS) was modelled for an initial model response on the basic inputs (paragraph 0). Average annual crop yields (maize, wheat) are generally low (<1 ton/ha) in Southern Africa, especially at smallholder farms (Akpalu et al., 2011; Andersson et al., 2013; FAO, 2004). The baseline scenario results are similar; without any additional management inputs, average annual crop yields were less than 1.5 t/ha (Figure 3.10). Especially on smallholder farms average crop yields are low; commercial farms produce in general higher crop yields.

The scenario with irrigation application (IA) generates higher crop yields; almost 2 t/ha in Figure 5.4a and between 0.5 and 1.5 t/ha in Figure 3.10b. In the scenario with fertilizer application (FA), crops were fertilized with 100 kg/ha/year. HRU24 (Figure 3.10a) shows varying results in crop yields over the years; between 0.5 t/ha and almost 2 t/ha. HRU70 (Figure 3.10b) generates more crop yield; between 1.5 and 2.5 t/ha.

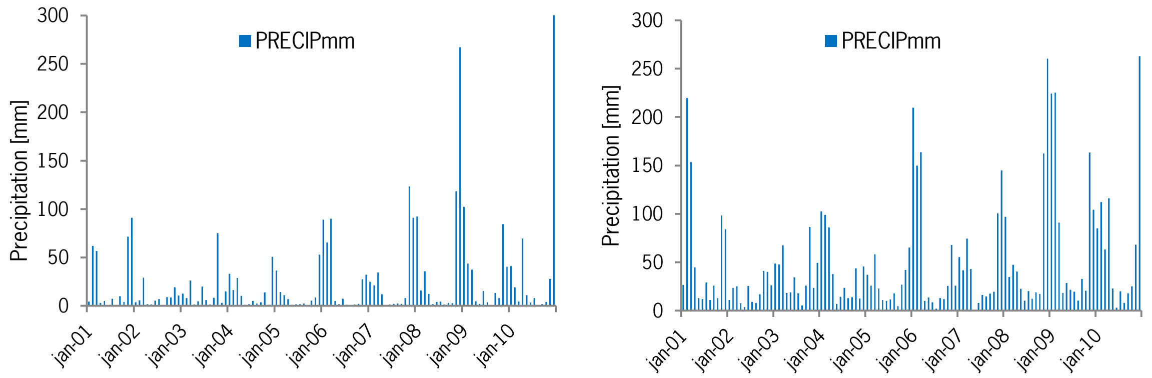
The scenario with both irrigation and fertilizer application (CS) produces the highest crop yields; between 3 and 4 t/ha/year in HRU24 (Figure 5.4a) and between 2.5 and 3.5 t/ha/year in HRU70 (Figure 3.10b). The application of irrigation is the response of plant water stress, so the amount of precipitation is important in terms of the amount of water applied and how often the fields were irrigated. Sub basin 24 receives on average 300 to 400 mm/year, while sub basin 70 receives on average 500-600 mm/year (Figure 3.11). Sub basin 70 receives also more precipitation during the dry season, which enhances more crop growth. Therefore, irrigation application was less often in sub basin 70, as a result of less crop water stress. This resulted in minor differences in crop yields between scenario BS and IA. Sub basin 24 received less precipitation, so crops had more water stress, especially during dry season, and irrigation was applied more often. This resulted in higher crop yields. Yearly precipitation in HRU24 (Figure 3.11) varied between 50 mm and 700 mm over the years and had a clear discrimination between dry and wet season. Crop yields in scenario BS and FA were affected by how much precipitation the HRU received. If the HRU was irrigated, crop yields became less sensitive for precipitation patterns. In general, an area needs to receive 500 mm of rainfall per year for successive crop growth without irrigation (Wösten et al., 2013). HRU70 received in total more than 500 mm rainfall per year, so crops can still grow without being irrigated.

In HRU24, crop yields did not change much with and without fertilizer application, while significant changes occurred between scenario BS and FA in HRU70. In some years, crop yields almost doubled in HRU70 (Figure 3.10). The major soils in the Limpopo River basin have low soil fertility, so it is likely that any additional nutrients have an impact on the crop yield. However, in HRU24 the difference in crop yield between scenario BS and FA is not much. This suggests that the soil is enough fertile. Although data from literature suggest that soils in the Limpopo River basin are not fertile enough to maintain crop productivity, there is no data to validate this. So either the SWAT model overestimates the soils nutrients, or this part of the basin is fertile enough to produce almost the same crop yield as scenario BS. Analysing the relative importance of either irrigation or fertilization suggests that water and nutrients constrain smallholder crop yields. Andersson et al. (2013) concluded that for the Limpopo River basin, water is the limiting factor which constrains crop yields. However, these constraints are highly depending on the location in the Limpopo River basin.



a) HRU24 b) HRU70

Figure 3.10 *Annual crop yields [ton/ha] for HRU24 (a) and HRU70 (b) in the Limpopo River basin.*



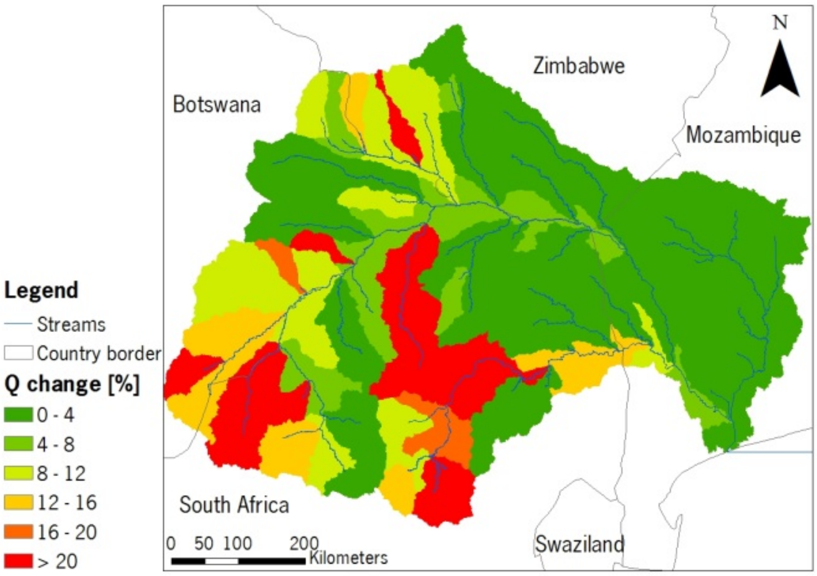
a) HRU24 b) HRU70

Figure 3.11 *Monthly precipitation [mm] for HRU24 (a) and HRU70 (b) in the Limpopo River basin.*

3.4 Discussion

The type of vegetation and the local hydrology have a strong correlation. Increasing crop yields and crop productivity will influence the basin hydrology. Comparing the model results of scenario BS and CS, in all sub basins the river discharges decreased when implementing irrigation and fertilizer application (Figure 3.12a). Same results were obtained in Love et al. (2010). River discharges even decreased with more than 20% in some sub basins. Extraction of water for irrigation came from the shallow aquifer; this resulted in decrease in subsurface and groundwater flow. Not only river discharges changed, but also ET_a changed between scenario BS and CS (Figure 3.12b). When applying both irrigation and fertilization, ET_a increased in almost all sub basins. In scenario CS, increase in ET_a was the result of more (optimal) crop growth, and thus an increase in plant transpiration. In terms of water balance, water is going out of an HRU by (sub-) surface and groundwater flow and evapotranspiration. Comparing the results of scenarios BS and CS, the fraction of water leaving an HRU by (sub-) surface flow reduced, while the fraction of water leaving through evapotranspiration increased. Comparing the changes for each country revealed that most changes occurred in the South African part of the Limpopo River basin. As most of the larger reservoirs lie in South Africa, it is likely that the management factor contributes to these changes.

a)



b)

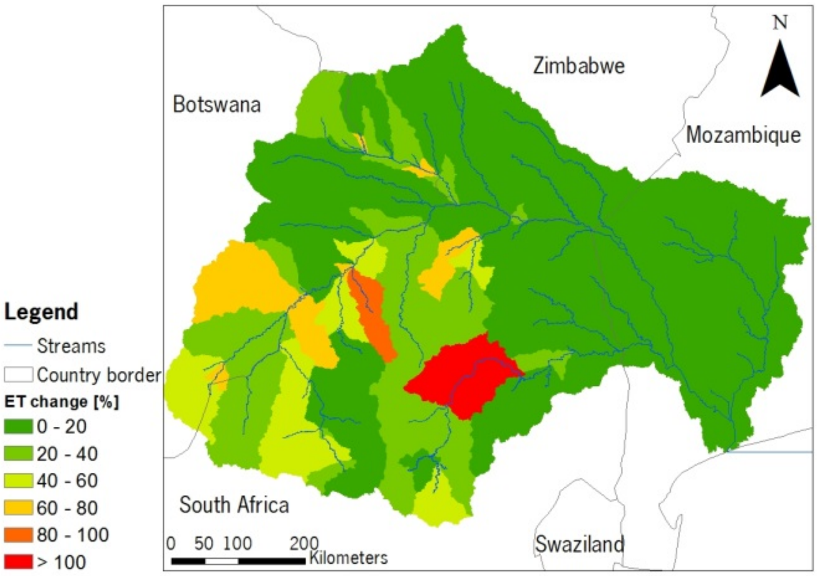


Figure 3.12 *Relative decrease [%] of discharge (a) and increase of ET_a (b) between the scenario BS and CS.*

3.5 Conclusions

In this study, the SWAT hydrological model was used for modelling the Limpopo River basin. Different management operation scenarios studied the effect on crop yields for smallholder farms. The SWAT model is used by many people worldwide, and is tested and validated in multiple environments. Even in data-scarce areas, SWAT can generate reliable model outputs. Available hydrological and meteorological data of this area is limited and a large part of the basin is ungauged. Only six discharge gauge stations were available for model analysis. Varying results of the uncertainty analysis between the observed and simulated discharge are related to the limited input data and management impact. During the last decades, more than 160 reservoirs were built into the Limpopo River basin. Especially the reservoirs with the biggest capacities had large impact on the hydrology downstream. To study the effect of the management impact, it is recommended to use SWAT in earlier decades, where the human impact was minor. Due to lack of meteorological data, this was not done in this study.

The SWAT model is primarily built for the Limpopo River basin to analyse crop yields and crop production for smallholder farms. Scenarios for irrigation and fertilizer application were defined to study the effect of irrigation and fertilization on crop yields and basin hydrology. Low crop yields (<1 t/ha/year) were generated without application of irrigation and fertilizers. In areas where annual average precipitation is small, crop yields were highly dependent on rainfall. If annual precipitation was above 500 mm, crop yields were less dependent on rainfall. If both irrigation and fertilizer operations was applied, crop yields increased to 2.5-4 ton/ha/year. Water or nutrient constrains in terms of crop growth highly depending on the location of the smallholder farm in the Limpopo River basin. Some fields had almost no water limitations, where other fields had almost no nutrients limitations. Scenario analyses also showed changes in the local hydrology. In all sub basins, river flows decreased when irrigation and fertilizer operations were applied, while the average annual ET_a increased when irrigation and fertilizer operations were applied.

The SWAT model can be used for the Limpopo River basin, as shown in this study. Management operations scenarios can be added to the model to study the effectiveness of the operations. However, more knowledge about rainfall distribution through the Limpopo River basin and reservoir management is necessary for better uncertainty prediction results. So the SWAT model is useful for modelling the Limpopo River basin, but depending on further aim of research, more data is needed.

4 Gumselasa catchment – Ethiopia

4.1 General background

In Ethiopia, soil degradation is a major issue since agriculture and deforestation have been practiced. Studies conducted in Ethiopia have reported that conversion of forest land into arable land with the aim of expanding cultivated land has caused land degradation and often soil erosion (Woldeamlak and Stroosnijder, 2003; Mulugeta et al., 2005). Together with frequent droughts and erratic rainfalls, these issues have led to major food insecurities and famine for many years. To minimize the impact of rainfall variability through the provision of water supply on crop yields and crop production, adequate water management for irrigation is needed. According to Belay and Bewket (2013), the use of proper irrigation instead of traditional irrigation management has increased crop yields and thus, contributed to higher household incomes in the past decade.

In the last two decades, to reduce the impact of rainfall variability and to improve the agricultural production through irrigation, 54 micro-dams were constructed in Tigray province of Northern Ethiopia. Therefore, the Gumselasa irrigation scheme was launched by constructing a dam in the Gumselasa catchment.

Gumselasa is located in the north Ethiopian province Tigray. The Tigray region has a total area of 50 078 km^2, from which 19% is suitable for cultivation, and a population of more than 3.8 million people (Haregeweyn et al., 2005). The Gumselasa catchment is located 40 km south of Mekelle, the capital city of Tigray. The catchment is relatively small, with a total area of 23.5 km^2.

The Province of Tigray is characterized by a tropical semi-arid climate. Precipitation ranges from 450 mm annual in northern, eastern and central Tigray to 980 mm in the southern and western part of the province. The Gumselasa catchment receives on average 700 mm per annum. Most of these rains (~85%) fall in rainy season, between June and September. The mean annual temperature is 19°C; mean daily maximum and minimum temperatures vary between 20-30°C and 8-15°C, respectively. The topography of Tigray consists mainly of highland plateaus up to 3900 m a.s.l., and a lowland area in the north western part with elevation as low as 500 m a.s.l. (Haregeweyn et al., 2005; Girmay and Singh, 2012).

The Gumselasa catchment has a poor vegetation cover. Vegetation cover which is relatively dense, is only found in small, protected areas such as around churches, homesteads and plantations. Dominating tree and shrub species include *Acacia etbaica, Schinus molle, Euclea schimperi* and *Eucalyptus* sp (Girmay et al., 2009). More than 60% of the land use in the catchment is cultivated land, the other land use types are open grazing land, plantation, settlement and water body. Open grazing land is defined as areas where heavy grazing and firewood collection have caused degradation. During rainy season, between June and September, cultivated land is covered with crops, which are mainly rain fed. Main crop types are tef (*Eragrostis tef*), maize (*Zea mays* L.), wheat (*Triticum turgidum*), unions, garlic, potatoes and pies. Spatial and temporal variability of rainfall and the occurrence of dry spell during the seasons cause often drought stress to crops (Tsegay et al., 2012). Furrows are used to convey water through the fields, as traditional irrigation management technique. Farmers determine the depth and interval of irrigation by assessing the soil dryness and the crop condition.

The Gumselasa irrigation scheme is provided with water from a micro-dam constructed in 1996 by the Regional Government. The dam was constructed within the framework of Sustainable Agriculture and Environmental Rehabilitation in Tigray. The main purpose of the dam is to provide water supply during dry season in the downstream area of the catchment. Distribution of water is mainly carried out during daytime, which requires the opening and closure of the inlet at a certain time. Part of the downstream agricultural land is irrigated with seepage water from the dam. However, seepage water and over-irrigation are causing soil salinity problems, which is a major problem in the area. Therefore, it should be necessary to improve farmers techniques of water management.

4.2 SWAT model setup Gumselasa

In this case study, SWAT2012 version 10.0 was used within an ArcGIS10.0 interface.

4.2.1 Watershed delineation

Watershed delineation in the Gumselasa catchment was done with a Shutter Radar Thematic Mapper (SRTM) digital elevation model (DEM), with a resolution of 90m. The Gumselasa catchment was divided into 41 sub catchments. In the watershed delineation, also the stream network, channel length, average slope of the channel and other sub basin parameters were created.

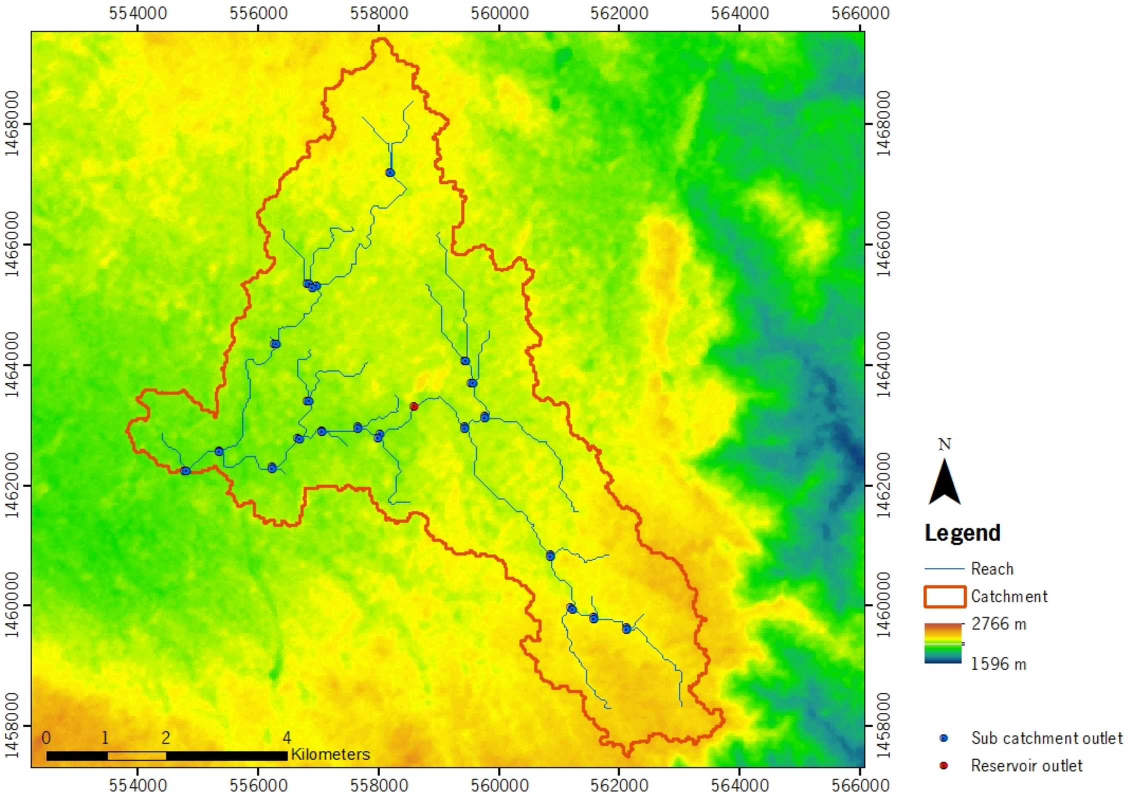


Figure 4.1 *Digital elevation model of the Gumselasa catchment, Ethiopia.*

4.2.2 Land use map

No proper land use map for the Gumselasa catchment was available. A land use map was made of land use data from field observations and literature. Land use of the catchment is mainly dominated by cultivation. The cultivated land was divided between rain fed and irrigated cultivated land. The irrigated land use was then divided between cultivated land which is irrigated through water from the reservoir and which is irrigated through seepage water. The remaining land use was classified as sparse natural vegetation.

4.2.3 Soil map Gumselasa

No detailed soil map of the Gumselasa area was available. The soil map used in the SWAT model is derived from the ISRIC soil map of Africa, with a pixel resolution of 1 km. SWAT model input parameters were derived from literature. Main soil types in this area are vertisols, luvisols, cambisols and regosols. The dominant soil consists of black clay soil. The remaining part is light calcareous soil which is mainly found in the steeper parts of the catchment.

4.2.4 Gumselasa dam

The total storage volume of the Gumselasa dam is 1,902,000 m^3. Engineers estimated that only 1,366,485 m^3 net storage water can be used for irrigation due to evaporation loss, human and animal consumption, dead storage, etc. The dam was made out of concrete and has a height of 1 meter. Water is distributed from the two main canals to secondary, tertiary and quaternary canals. The two main canals are 3 and 2.4 km long. First part of these main canals are made of concrete.

Table 4.1
Characteristics of the Gumselasa dam (Haregeweyn et al., 2005).

	Dam location, UTM		Elevation	US	DS	Reservoir area when full	Dam height
	X	Y	[m]	[10^3 m^3]	[10^3 m^3]	[ha]	[m]
Gumselasa	558 642	1 463 566	2,146	1900	476	48	13.5

4.3 Results and discussion

The monthly water balance on the Gumselasa catchment is presented using simulations on a daily base with the SWAT hydrological model between 1993 and 2010. The first three years was the warming up period, so these years were not included in the final results.

4.3.1 Water balance in the catchment

The total water balance in the catchment is calculated as precipitation and irrigation as incoming fluxes, evapotranspiration as outgoing flux, what is remaining in the basin is the total water yield, which is the sum of surface runoff, lateral flow and groundwater contribution to stream flow. No other losses or incoming water sources were assumed.

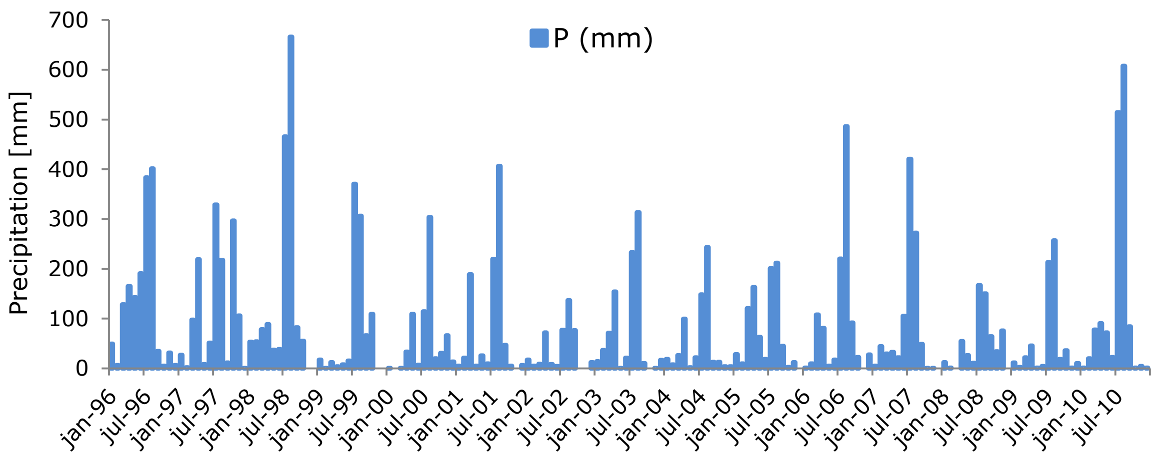


Figure 4.2 *Monthly precipitation [mm] in the Gumselasa catchment between 1996 and 2010.*

Total precipitation within the catchment highly fluctuates between the seasons. In rainy season precipitation can be as high as 700 mm per month, while in dry season there is almost no rain at all (Figure 4.2). The actual evapotranspiration [mm] shifts between 100 mm in rainy season to about 5 mm in dry season (Figure 4.3). Incoming irrigation water results in higher evapotranspiration rates than precipitation rates in some dry months. It was expected that evapotranspiration rates were higher, especially in rainy season. Model errors can be the raison of these relatively low rates. However, vegetation density is low, which can result in lower transpiration rates. Also soil input parameters can be of influence in actual evapotranspiration rates.

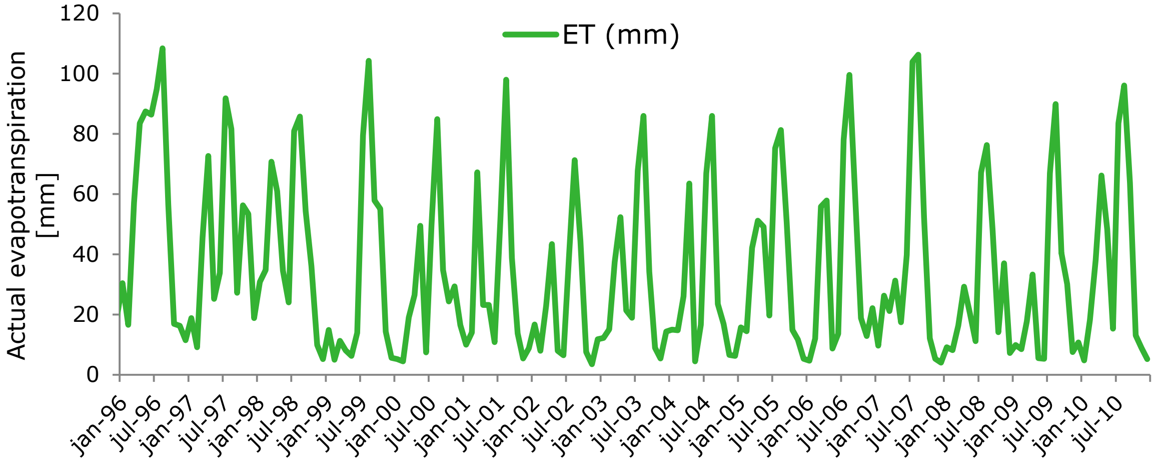


Figure 4.3 *Monthly actual evapotranspiration [mm] in the Gumselasa catchment between 1996 and 2010.*

The total water yield [mm] in the basin is the sum of the surface runoff, lateral flow and groundwater flow. Surface runoff and groundwater flow (Figure 4.4 and Figure 4.6) are negligible. However, lateral flow contribution to stream flow is quite significant (Figure 4.5).

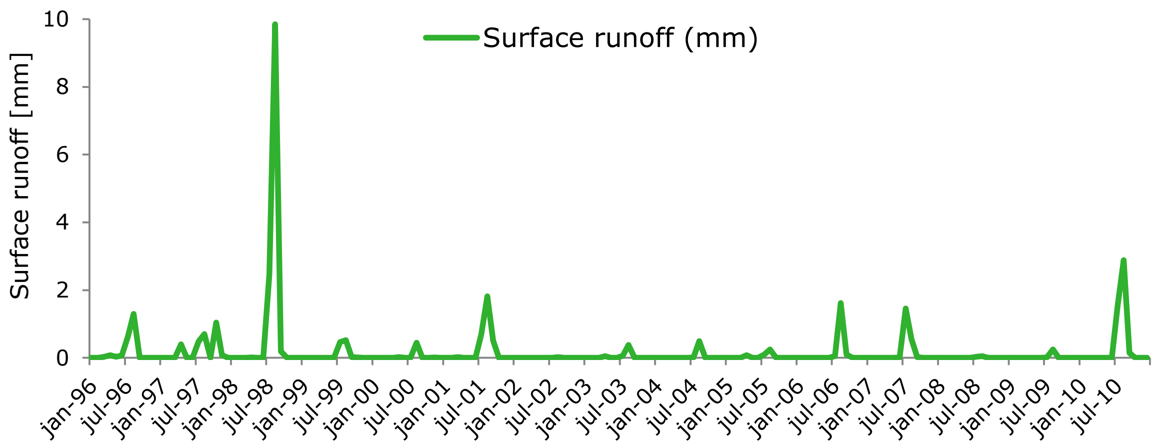


Figure 4.4 *Amount of monthly surface runoff [mm] contributed to stream flow in the Gumselasa catchment between 1996 and 2010.*

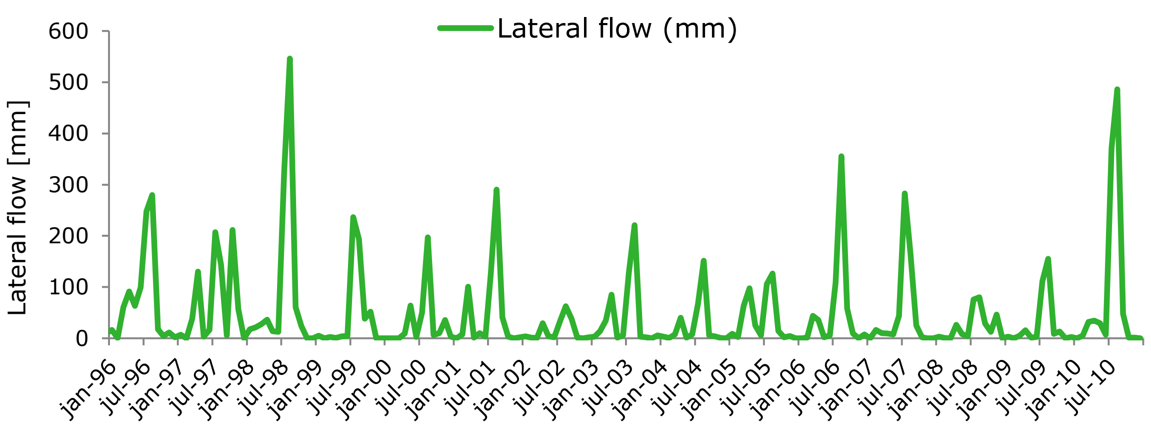


Figure 4.5 *Amount of monthly lateral flow [mm] contributed to streamflow in the Gumselasa catchment between 1996 and 2010.*

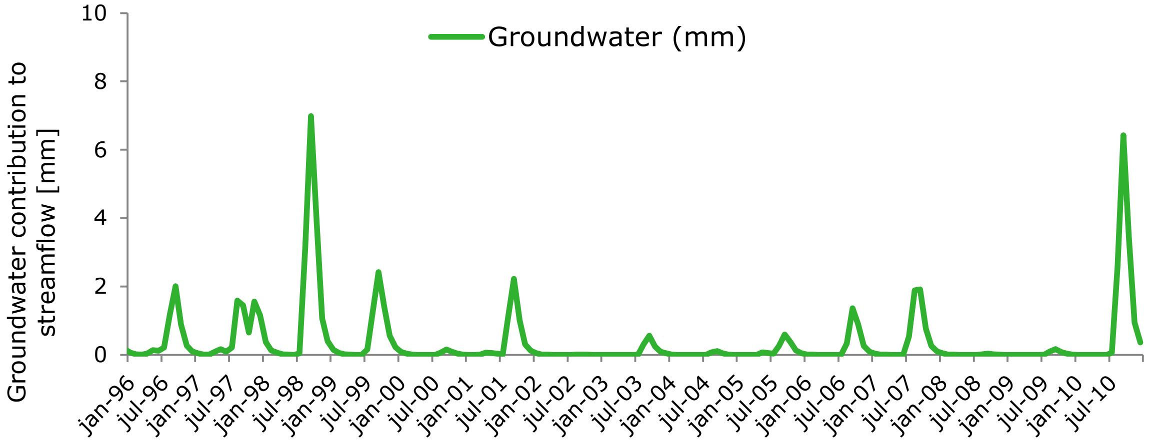


Figure 4.6 *Amount of monthly groundwater contribution to streamflow [mm] in the Gumselasa catchment between 1996 and 2010.*

4.3.2 Reservoir results

The change in reservoir volume of the Gumselasa dam was also modelled in the SWAT project (Figure 4.7). Maximum volume of the reservoir was set on 1.9 mln m^3. Reservoir volume fluctuates between the maximum storage volume (1.9 mln m^3) and almost 1.0 mln m^3. However, no external losses (human and animal consumption) were modelled. Due to this, in reality the volume of the reservoir will be lower.

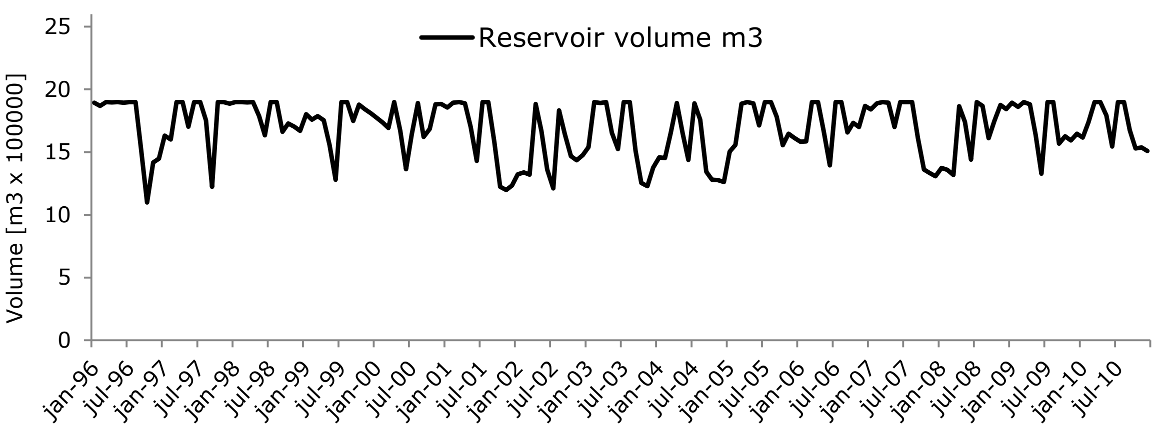


Figure 4.7 *Change in reservoir volume [m^3] between 1996 and 2010.*

As the model calculated little amounts of surface runoff, not much sediment is flowing into the reservoir. It is assumed that in reality much more sediment is flowing in, which will result in sedimentation in the reservoir and thus, a decrease in water storage volume.

4.3.3 Soil and river salinity

As already mentioned, saltation of the soil is a problem in this catchment. A spread sheet model was used to calculate river and soil salinity, based on river outflow (Rhoades et al., 1999) as shown in Figure 4.8. The river was divided into three river segments, which is corresponding to sub basin outflow. Segment 1 is the reservoir outflow, and thus the beginning of the irrigated cultivated land. Segment 2 is the river outflow at the end of the canal. Segment 3 is the river outflow where the cultivated land is irrigated with seepage water. Water in the river has normal to low salinity rates (0.03-1.00 dS/m), both in dry (November-April) and rainy season (May-October). However, soil salinity is much higher (<1.0-25.0 dS/m). Soils are considered saline if the electric conductivity is >4 dS/m. This means that in the segments 1 and 2, soils are slightly to severe saline. Soils are severe saline at the outflow point at the reservoir and decrease towards segment 2. In some months, actual evapotranspiration rates exceeds precipitation rates, which reveals that a large part of the cultivated land is irrigated with water from the streams. High evapotranspiration rates results in higher salinity rates due to the remaining salts if river water evaporates. There is almost no difference between the wet and dry season, this was indeed expected, and as evapotranspiration rates are much higher in dry season. Although this was calculated with a simple spread sheet model, it revealed that soil salinity is a problem in this area. Bad irrigation and land management is one of the reasons that soil salinity is increasing. Better management would result in lower soil salinity.

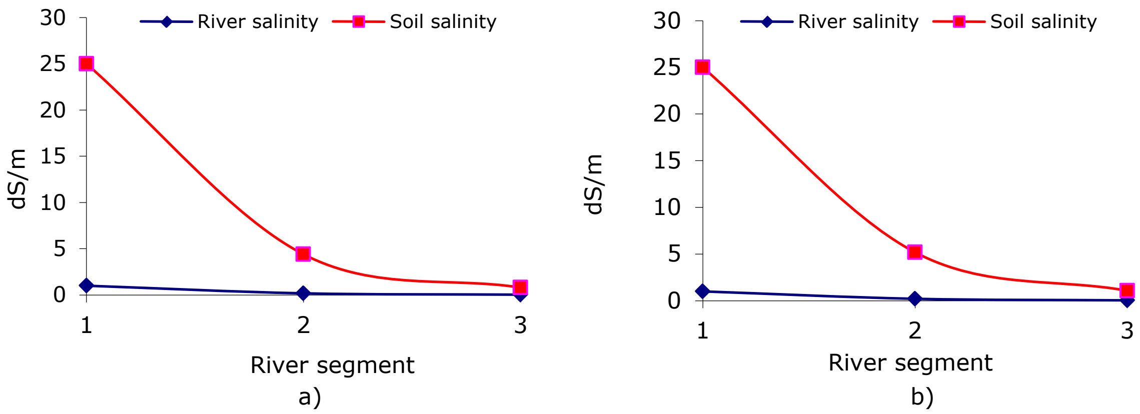


Figure 4.8 *Estimated soil and river salinity for three river segments during rainy season (a) (May-October) and dry season (b) (November-April).*

4.4 Conclusions

An initial assessment of the use of the SWAT hydrological model for the Gumselasa catchment was made. Results show that the model inputs have to be more detailed to give more accurate output results. Also, the performance of the model cannot be compared with data from the field, as there is no field data available. For further research, it is recommended to update the land use and soil map from field data and to have field data from the river outflow point at, for example, the reservoir outlet.

An assessment of the water balance in the Gumselasa catchment reveals that lateral flow is the biggest component of the water balance, while surface runoff is almost negligible. The net actual evapotranspiration rate is low in wet season, in comparison with the amount of precipitation. In dry season actual evapotranspiration is relatively high. Reservoir volume shifts between 1.0 and 1.9 * 10^6 m^3, which is the actual volume of the reservoir. External losses were not accounted in the SWAT model, such as human or animal consumption. An initial assessment of soil and river salinity shows low river salinity, but high soil salinity. Especially at the outflow area of the reservoir, soil is severe saline. Here, most of the cultivated land is irrigated, which results in higher soil salinity. River water is used for irrigation, which contains salts and remains behind when the water evaporates. Soil salinity is probably the reason of bad irrigation and land management. To reduce soil salinity for example, the irrigation scheme must be better regulated and farmers have to do better land management.

5 Conclusions

The physically-based model SWAT was used to simulate regional groundwater and surface water flow in basins with spatially-variable geo-hydrological conditions and land use. Due to the size of the model and the large number of parameters, the model could not be fully calibrated. The aim of the project, was to use the SWAT model in order to examine several scenarios with different changes to improve crop production. The SWAT model was primarily built for the Limpopo River basin to analyse crop yields and crop production for smallholder farms. Scenarios for irrigation and fertilizer application were defined to study the effect of irrigation and fertilization on crop yields and basin hydrology. Low crop yields (<1 t/ha/year) were generated without application of irrigation and fertilizers. In areas where annual average precipitation is small, crop yields were highly dependent on rainfall. When annual precipitation was above 500 mm, crop yields were less dependent on rainfall. If both irrigation and fertilizer operations was applied, crop yields increased to 2.5-4 ton/ha/year. Water or nutrient constrains in terms of crop growth are highly depending on the location of the smallholder farm in the Limpopo River basin.

The scenario analyses also showed changes in the local hydrology. In all sub basins, river flows decreased when irrigation and fertilizer operations were applied, while the average annual ETa increased when irrigation and fertilizer operations were applied. The vegetation and the local hydrology have a strong correlation. Increasing crop yields and crop productivity will influence the basin hydrology. Comparing the model results of the baseline scenario and when implementing irrigation and fertilizer application, in all sub basins the river discharges decreased. River discharges even decreased with more than 20% in some sub basins. Extraction of water for irrigation came from the shallow aquifer; this resulted in decrease in subsurface and groundwater flow. When applying both irrigation and fertilization, ETa increased in almost all sub basins.

Management operations scenarios can be added to the model to study the effectiveness of the operations. However, more knowledge about rainfall distribution through the Limpopo River basin and reservoir management is necessary for better uncertainty prediction results. So the SWAT model is useful for modelling the Limpopo River basin, but depending on further aim of research, more data is needed.

For the Gumselasa catchment an initial assessment of the use of the SWAT hydrological model was made. Results show that the model inputs need to be improved to give more accurate output results. Also, the performance of the model cannot be compared with data from the field, as there is no field data available. For further research, it is recommended to update the land use and soil map from field data and to have field data from the river outflow point at, for example, the reservoir outlet. An initial assessment of water balance in the Gumselasa catchment reveals that lateral flow is the biggest component of the water balance, while surface runoff is almost negligible.

An initial assessment of soil and river salinity shows low river salinity, but high soil salinity. Especially at the outflow area of the reservoir, soil is severe saline. Here, most of the cultivated land is irrigated, which results in higher soil salinity. River water is used for irrigation, which contains salts and remains behind when the water evaporates. Soil salinity is probably the reason of bad irrigation and land management. To reduce soil salinity for example, the irrigation scheme must be better regulated and farmers have to do better land management.

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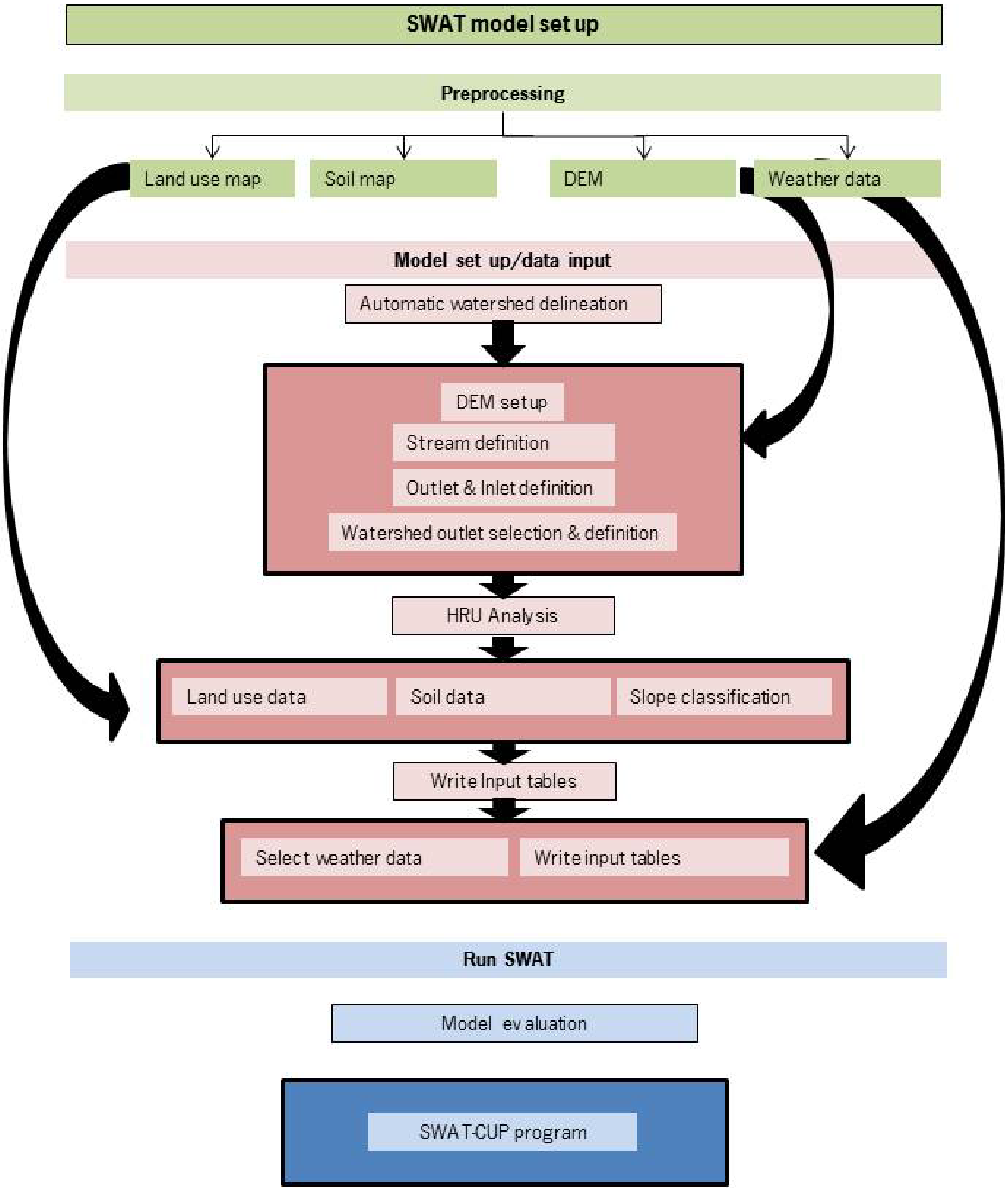
Annex 1 ARCSWAT 2012 Tutorial



Install ArcSWAT in ArcGIS environment. Just follow the provided steps. Pay attention to the downloaded version of ArcSWAT. Download the ArcSWAT software for the according version of ArcGIS. If you have ArcGIS 10.0, download SWAT2012 10.0.

After installing ArcSWAT, open ArcMap. Toggle ArcSWAT to the toolbar ('Customize' > 'Toolbars' > check 'ArcSWAT'). Enable Spatial Analyst and SWAT extension ('Customize' > 'Extensions' > Check 'Spatial Analyst', 'SWAT HRU Delineator', 'SWAT Project Manager' and 'SWAT Watershed Delineator'). *Also, the keyboard language has to be set in English (US).*

1. Prepare the data set

Digital Elevation Model (DEM)
A Digital Elevation Model is needed as an input for SWAT modelling, for watershed delineation, routing and slope classification. Free sources of DEM are GTOPO30 (1km resolution), SRTM (90m resolution) and ASTER (30m resolution).
http://gdex.cr.usgs.gov/gdex/ provides free available GTOPO30, SRTM as well as ASTER data.

Land use map
A land use map is necessary as an input for SWAT modelling. Make sure that at least 95% of the land use map is covering the whole watershed (otherwise you cannot proceed with the HRU definition). The land use map has to have the same projection as the DEM and the soil map. Land use classes can be defined according the SWAT land use database, or new land use types can be added to the SWAT land use database (in the SWAT toolbar: 'Edit SWAT Input' > 'Databases' > 'Plant/land cover'). Each land use class has to be unique (classes can be redefined in the HRU Definition section.

A land use map can be a shape file as well as a grid.

A land use lookup table can be made in case of many classes, or if the project has to set up multiple times. The lookup table has to have a .txt extension and the format according to Figure A1.

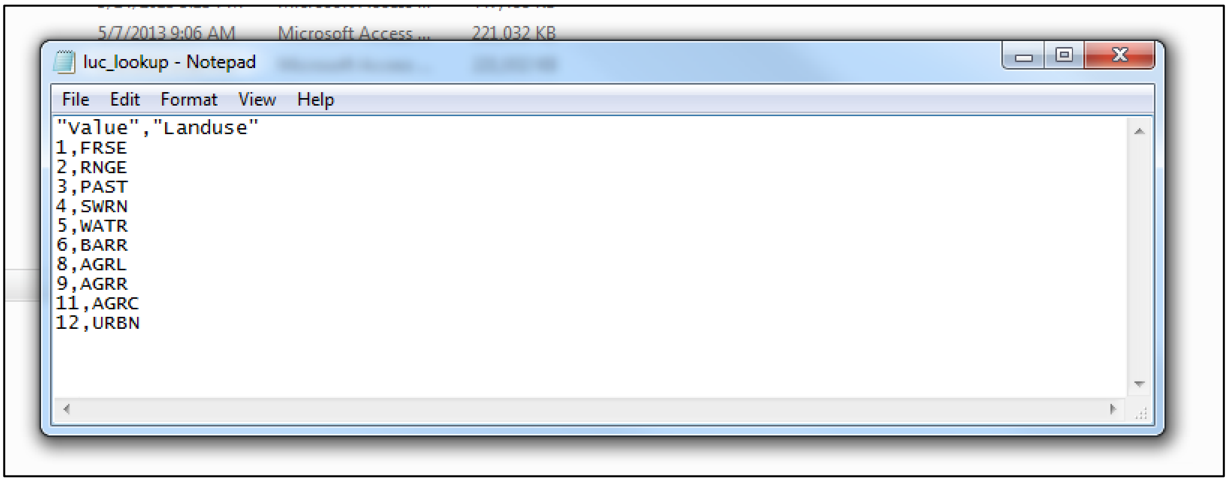
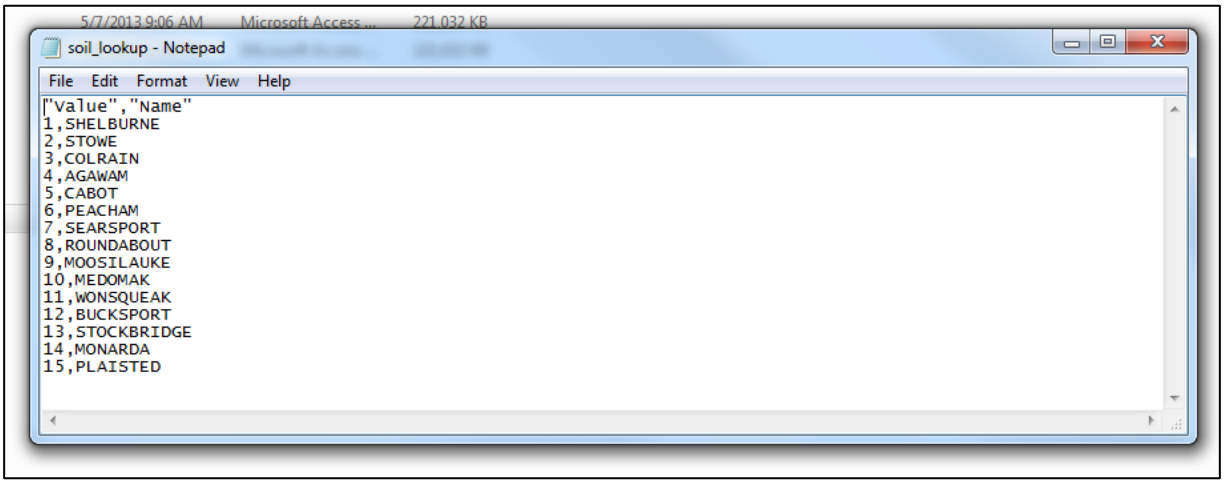


Figure A1 *Format land use classes lookup table.*

Soil map
A soil map is necessary as an input for SWAT modelling. Make sure that at least 95% of the soil map is covering the whole watershed (otherwise you cannot proceed the HRU definition). The soil map has to have the same projection as the DEM and the land use map. The soil types can be defined according the SWAT User soil database, or new soil types can be added to the User Soil database ('Edit SWAT Input' > 'Databases' > 'User Soils').

A soil map can be a shape file or a grid.

A soil type lookup table can be made in case of many classes, or just to save some time. The lookup table has to have a .txt extension and the format according to Figure A2.




```
"Value","Name"
1,SHELBURNE
2,STOWE
3,COLRAIN
4,AGAWAM
5,CABOT
6,PEACHAM
7,SEARSPORT
8,ROUNDABOUT
9,MOOSILAUKE
10,MEDOMAK
11,WONSQUEAK
12,BUCKSPORT
13,STOCKBRIDGE
14,MONARDA
15,PLAISTED
```

Figure A2 *Format soil types lookup table.*

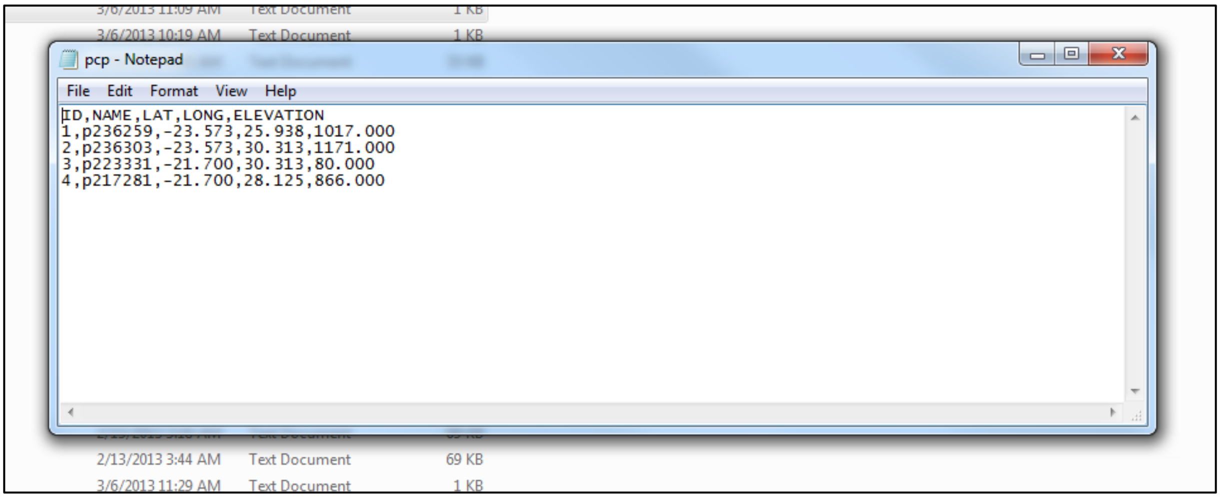
www.isric.org provides free sources of soil data. Also http://www.fao.org/nr/land/soils/digital-soil-map-of-the-world/en/ provides a digital soil map of the world (1km resolution).

<u>Weather data</u>
Observed weather data is necessary as an input for SWAT if the project is located outside the US. Only US weather data is included in the SWAT database. Global weather data can be obtained by a weather data generator provided by SWAT: http://globalweather.tamu.edu/. Data downloaded from this website are already in the right input format.

If weather data is not obtained by the SWAT weather data website, weather data have to be stored in the right format. Multiple files are needed; one .txt file with the name(s) and the location(s) of the station(s) (Fig. A3), and a .txt file for each station and for each meteorological variable (Fig. A4). Make sure that the location table and data table(s) are in the same directory folder.

<u>Other inputs</u>
If the stream network and watersheds cannot be based on the DEM, than shape files of the stream network and watersheds must be created.

Depending on the aim of research, other specific data can be obtained for adjusting the model (e.g. management operations, bacteria loadings and land use update).




```
ID,NAME,LAT,LONG,ELEVATION
1,p236259,-23.573,25.938,1017.000
2,p236303,-23.573,30.313,1171.000
3,p223331,-21.700,30.313,80.000
4,p217281,-21.700,28.125,866.000
```

Figure A3 *Weather station location table.*

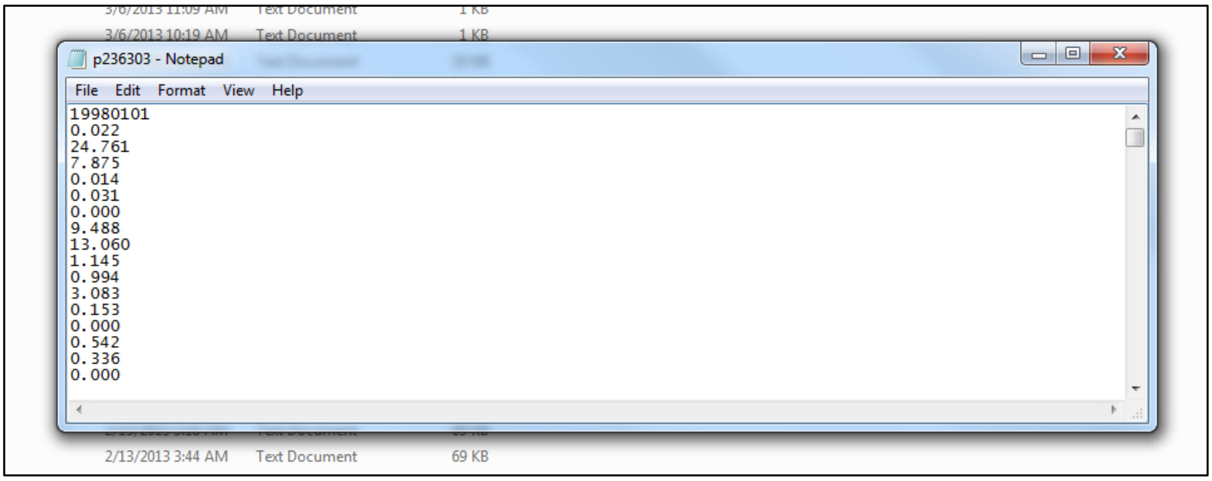


Figure A4 *Weather data table.*

2. SWAT Project Setup

<u>New SWAT project</u>
Open ArcMap. Click SWAT Project Setup > New SWAT Project. Define the project folder (on D: drive, or other internal hard drive. Do not define a project on an external hard drive, this will slow down the model).

In this directory, you can also delete, copy or open any existing SWAT project.

Watershed Delineator
Automatic Watershed Delineator
DEM setup

Define the location of the Digital Elevation Model (DEM) (make sure that the DEM is projected), Figure A5. Click on the DEM projection setup icon and define the Z unit.

If a mask of the study area is available, check the 'Mask' box and define the location of the mask.

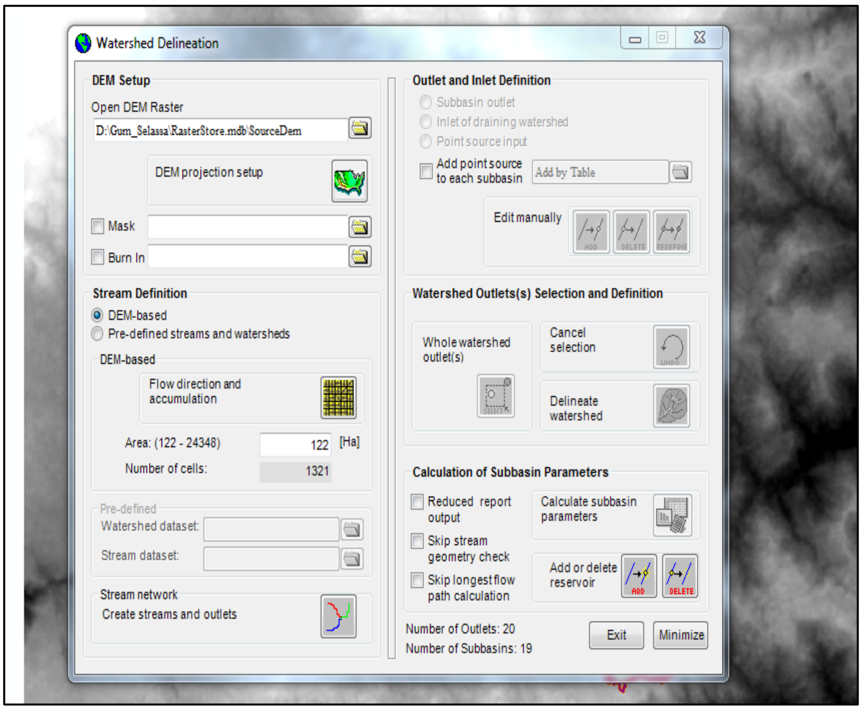


Figure A5 *Automatic Watershed Delineator.*

Stream Definition
DEM-based: click on the ‘Flow direction and accumulation’ icon. ArcGIS is now calculating the threshold area for each sub basin. It gives the minimum and maximum hectares per area, this is only an indication, not a threshold value. Choose a value depending on the aim of the project.

Pre-defined streams and watersheds: select the watersheds and stream dataset.

After the flow direction and accumulation is calculated, click the ‘Create streams and outlets’ icon. SWAT will create the stream network and will define the outlet points.

Outlet and Inlet Definition
In this section, outlet points can be edited, added and/or removed, as well as inlet points can be defined.

In the SWAT Limpopo River Basin and SWAT Gumselasa catchment projects, specific outlet points were added on the reservoir locations. Unfortunately, no outlet or inlet points can be added which are not located on the stream network. To create more streams in the network, the number of hectares in the ‘Stream Definition’ can be reduced.

Watershed Outlet(s) Selection and Definition
In this section, the watershed outlet(s) will be defined. First, click the ‘Whole Watershed Outlet’ icon and select the outlet of the watershed. After defining the watershed outlet, click the ‘Delineate Watershed’ icon. The model will now delineate the whole watershed.

Calculation of Sub basin Parameters
Click the ‘Calculate Sub basin Parameters’. This will take quit a long time in case of a large watershed and/or many sub basins. To reduce the calculation time, check the ‘Reduce report output’, ‘Skip stream geometry check’, and/or ‘Skip longest flow path calculation’ boxes.

In the last step, reservoirs can be defined. Click in the according sub basin, the outlet of the reservoir will be located on the outlet point of the sub basin.
To terminate the watershed delineation, always click ‘Exit’.

Watershed reports
Select a report to review the calculated statistics.

HRU Analysis
Before beginning the HRU Analysis, make sure that the appropriate land use and soil map are already available, as well as the lookup tables (see Prepare input data).

Land use map: select the land use types according to the provided SWAT database, or add land use types in the database (‘Edit SWAT Input’ > ‘Database’ > ‘Land cover/Plant Growth’ > ‘Add New’). For you own convenience, provide a land use lookup table in the right format.

Soil map: select the soil types according to the provided SWAT database, or add new soil types in the database (‘Edit SWAT Input’ > ‘Database’ > ‘User Soils’ > ‘Add New’). For you own convenience, provide a soil type lookup table in the right format.

Land use/Soils/Slope definition
(see Figure A6)

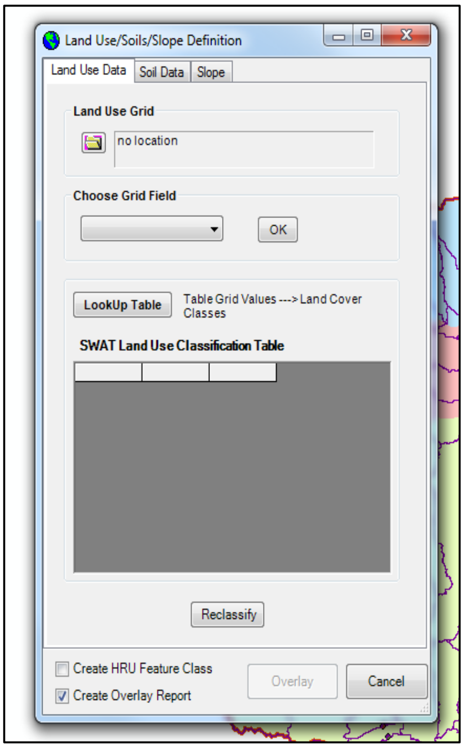


Figure A6 *HRU Analysis; Land use/Soils/Slope definition.*

Click the 'Open folder' icon. Select the Land Use layer from the map, or load the Land Use dataset from disk.

Choose grid field; 'Value' or 'Count'. Value is the value assigned to the land use class. Count gives the amount of pixels for each class. Click 'OK'.

Click 'Lookup Table' if a lookup table is made. This table assigns the land use class value to the land use in the SWAT database. An error appears when the table is not in the right format or is not recognized in the database.

Manually selection of land use class is also possible > double click on the empty box behind the class value and select the land use type from the SWAT database.

Click 'Reclassify'.

Soil Data
Click the 'Open folder' icon. Select the Soil layer from the map, or load the Soil dataset from disk.

Choose grid field; 'Value' or 'Count'. Value is the value assigned to the land use class. Count gives the amount of pixels for each class. Click 'OK'.

From the Soil Database options, check 'UserSoil'.

Click 'Lookup Table' if a lookup table is made. This table assigns the soil type value to the soil type in the SWAT database. An error appears when the table is not in the right format or is not recognized in the database.

Manually selection of land use class is also possible > double click on the empty box behind the soil type value and select the soil type from the SWAT database.

Click 'Reclassify'.

Slope
Select 'Single Slope' or 'Multiple Slope'.

If Single Slope is selected > click ‘Reclassify’.

If Multiple Slope is selected > define the number of classes (depends on the study area and purpose of the project). Define the upper limit of each slope class.

In the SWAT Limpopo River Basin project, 5 slope classes were defined (0-2%, 2-4%, 4-6%, 6-8% and >8%).

Click ‘Reclassify’. After reclassifying of land use, soil and slope, the ‘Overlay’ icon is greyed out. Click ‘Overlay’.

HRU definition and HRU Thresholds

Choose the type of HRU Definition.

If ‘Multiple HRUs’ are chosen, select the type of threshold > ‘Percentage’ or ‘Area’.

In the SWAT Limpopo River Basin project and the SWAT Gumselasa project, ‘Multiple HRUs’ were chosen, with Percentage as threshold. For both projects, the threshold values were: land use 10%, soil 20% and slope 20%.

Land Use Refinement
If necessary, the land use classes can be split into multiple land use classes or land use types can be exempt. No location can be defined to these adjustments.
Click ‘Create HRUs’.

Write Input Tables
Weather Data Definition
Select the Weather Generator Data from the Locations Table (already defined in the SWAT-User Weather Stations database; ‘Edit SWAT Input’ > ‘Database’ > ‘User Weather Stations’ > ‘Add New’).

If measured meteorological data is available, select the locations of the Rainfall, Temperature, Relative Humidity, Solar Radiation and/or Wind Speed data tables. Make sure that the tables are in the right format (see Section 1.4).

In the SWAT Limpopo River Basin project and the SWAT Gumselasa project, meteorological data was used from the Global Weather Data for SWAT (http://globalweather.tamu.edu).

Write SWAT Input Tables
Select all the tables to write.
Click ‘Create Tables’.

Edit SWAT Input
Depending on the project and data availability, in this section the SWAT database can be edited as well as the input for each file written in the ‘Write Input Tables’ section. When editing is finished, click on ‘Rewrite files’.

SWAT Simulation
Click ‘Run SWAT model’. Define the simulation period (the period defined by SWAT is based on the available climate

Annex 2 SWAT model setup Limpopo river basin

Original Geodatabase: D:\Limpopo ...
Latest version: Limpopo setup

Watershed delineation

Dem setup

DEM from D\Limpopo\Grid\DEM

Error: number -2147467259. Solution:??. My solution: opening a new SWAT document and loading the DEM before clicking the watershed delineation (And perhaps close and open ArcGIS).

Stream network

From DEM
Defined HA: minimum Ha (gives 107 subbasins)

Error: number -2147217256, 'object is not defined on a project'. Solution: ??. After a couple of tries to reload the SWAT project it worked.

Outflow

Southern-most point in Mozambique

HRU definition

Land use map

10 classes;

1 Woodland	6 Bare rock/soil
2 Bushland & High Fynbos	7 Cultivated and irrigated land (commercial)
3 Grassland	8 Cultivated dryland (commercial)
4 Forest plantations	9 Cultivated dryland (semi-commercial)
5 Water bodies	10 Urban/built up

Error with uploading the land use grid (ERROR: grids must be in the same projection). Reload the ArcSWAT project and upload again the land use map.

Soil map

Error with uploading shape file soil map. Conversion from shape file to raster, raster is working (even with many soil classes).

Slope map

5 slope classes: 0-2, 2-4, 4-6, 6-8, 8-9999 %.
Error:

Write input tables

Weather stations

First, put the user weather station into the database at 'Edit SWAT input'. After that, define the weather station location table (wgnstation), and the other weather location tables (precipitation, temperature, etc.).

Tables to be made: wgnstation.txt
precipstation.txt
tempstation.txt
slrstation.txt
wndstation.txt
hmdstation.txt

(And then the tables with the actual measured data)
Error: 'table pstation has not the correct fields'. Solution:
Error: 'invalid bracketing of [filename.mdb]*, when writing single weather location tables, wgn location table works fine*. *Solution:*

<u>Write SWAT input tables</u>
Write all input tables.
Error: 'conversion from string 12/31/3000 to date is not valid'. Solution: change language settings to English.

Edit input data

<u>Reservoirs</u>
Input of principal and emergency spillway. The maximum default is most of the time too low; change this maximum default in Database\SWAT2012.mdb --> resrng.

Annex 3 SWAT inputs and adjustments

SWAT inputs and adjustments for the Limpopo Basin

Land cover (ID)

Map location: D:\Limpopo\GIS-data\grids\landuse

Name	SWAT code	Crop code	RDMX [default, m]	RDMX [m]	Manning's n (default=0.14)
Woodland	FRSE	8	3.5	1.3	0.05
Bush land	RNGE	15	2.0	1.3	0.05
Grassland	PAST	12	2.0	1.0	0.05
Forest plantation	SWRN	17	2.0	2.0	0.05
Water/wetlands	WATR	18	0.0	0.0	0.05
Bare rock/soil	BARR	118	0.1	0.3	0.05
Commercial cultivated and irrigated	AGRL	1	2.0	1.3	0.05
Commercial cultivated dry land	AGRR	2	1.3	1.6	0.05
Semi-commercial cultivated dry land	AGRC	3	2.0	1.6	0.05
Urban/built up	URBN		-	-	0.05

Soil (ID)

Map location: D:\Limpopo\Input data\soil_cluster

Name	Database name*	Clay [-]	Silt [-]	Sand [-]	Sol_BD
ZW61	Shelburne	15	18	67	1.48
ZA314	Stowe	46	25	29	1.17
ZA484	Colrain	28	29	43	1.31
BW22	Agawam	30	11	59	1.55
ZA153	Cabot	6	5	89	1.51
ZW85	Peacham	7	2	91	1.52
MZ15	Searsport	16	6	78	1.22
ZA33	Roundabout	30	27	43	1.29
ZA50	Moosilauke	28	29	43	1.31
BW25	Medomak	16	26	58	1.36
ZA291	Wonsqueak	12	19	69	1.18
ZW87	Bucksport	19	29	52	1.37
ZW75	Stockbridge	81	13	6	1.63
ZA190	Monarda	9	24	67	1.20
ZA39	Plaisted	30	27	43	1.29

*Other parameter values are default database name.

Weather data

Obtained from website of Global Weather Data for SWAT (http://globalweather.tamu.edu)

Check if observed data is correct converted to each sub basin:

1. Make shape file of observed data points.
2. Make shape file of the center point of each sub basin.
3. Compare the center point to the nearest observed data point.

Groundwater

Parameter	Default	New value
gw_delay	30	15
Rchrh_dp	0.05	0.00
Gw_revap	0.02	0.1
Revapmn	1.00	0.50

Reservoirs (+ID)

Change the maximum volumes and hectares in the resrng file.

Name	Subbasin #	Princ V	Emer V	Princ A [Ha]	Emer A [Ha]
Inyankuni	1	8180	8998	3300	3630
Manyuchi II	4	31.900	35.090	904	994
Ingwesi	5	6981	7679	1530	1682
Shashe	6	8500	9350	1286	1415
Middle Lethaba	50	17.300	19.030	2096	2305
Fanie Botha	60	16.020	17.622	897	986
Massinger	69	225.600	248.160	493	542
Hans Strijdom	72	14.870	16.357	15070	16577
Gabarone	88	14.400	15.840	2166	2382
Rhenosterkop II	98	20.580	22.638	753	838
Eerste Poort	100	23.000	25.300	934	1027
Loskop	105	34.810	38.291	2205	2420
Roodekopjies	106	10.260	11.286	3733	4106
Hartebeespoort	108	19.460	21.406	3911	4302
Bronkhorstspruit	111	5890	6479	1380	1518
Withbank	112	10.400	11.440	3700	4070

Management

Land cover	CN2*	Final CN2 values (adjusted after calibration)
FRSE	60	
RNGE		
PAST	79	
SWRN		
WATR	98	
BARR	86	
AGRL	81	
AGRR	81	
AGRC	77	
URBN	89	

*Assumed: hydrological soil group is based on default in database.

Operations

Operation scheme:

Day	Month	Year	Operation
1	1	1	Auto-irrigation*
2	1	1	Auto-fertilization*
1	3	1	Harvest and kill
1	4	1	Planting/beginning growing season (winter season)
1	9	1	Harvest and kill
1	10	1	Planting/beginning growing season (summer season)

* Auto-irrigation and auto-fertilization operations are optional and depend on the type of scenario.

Parameter settings:

1. Planting/beginning growing season
   PLANT_ID: Land cover/plant identification number from database (same as according land use).
   CNOP: SCS curve number for moisture condition II.
2. Harvest and kill
   Only day and year of harvest is required.
3. Auto-irrigation
   WSTRS_ID: Water stress identifier, typically between 0.90-1.0 (plant water demand), default is 0.
   IRR_SCA: Auto irrigation source code, default is 0.
   IRR_NOA: Auto irrigation source location = number of reach that water is removed from (same as sub basin), default is 0.
   IRR_EFF: Irrigation efficiency (0.0-100.0 mm), default is 0.
   IRR_MX: Amount of irrigation water applied, default is 0.
   IRR_ASQ: Surface runoff ratio (0-1), default is 0.

4. Auto-fertilization
   Auto-fertilization is scheduled a day after start of the auto-irrigation operation, to prevent model errors in case they are applied at the same time.
   AFERT_ID:

Name operation schedule:

fert+irrAGRC:	Irrigation and fertilizer application
fertAGRC	Only fertilizer application
irrAGRC	Only irrigation
Baseline	No irrigation and no fertilizer application

Auto-irrigation parameter set:

Land use	IRR_EFF [-]	W_STRS	IRR_MX [mm]	IRR_SCA
AGRL (com. cult&irr)	0.70	0.95	50	1 (reach)
AGRR (com. dry land	0.50	0.95	50	1 (reach)
AGRC (semi-com.)	0.30	0.95	50	3 (shallow aq.)

Auto-fertilization parameter set:

Land user	AUTO_NSTRS	AUTO_NAPP	AUTO_NYR	AUTO_EFF	AFRT_SURFACE
AGRL (com. cult&irr)	0.90	15	30	1.3	1.0
AGRR (com. dry land	0.90	15	30	1.3	1.0
AGRC (semi-com.)	0.90	11	22.5	1.3	1.0

Calibration
Stream flow between 2001-2005 (monthly) = calibration period.

Gauge station: Beit bridge (sub basin 24, lon: 29.98, lat: -22.23), Engelhartdam (sub basin 70, lon: 31.64, lat: -23.84).

Model calibration:
1. When having multiple gauge stations: first calibrate the most upstream gague station, than downstream.
2. Check different ET methods
3. Adjust CN2 values
4. If base flow is too high:
   - Increase GW_revap (.gw), max.= 0.20
   - Decrease revapmn (.gw), min.= 0.0
   - Increase gwqmn
5. If simulated flow is higher than observed flow:
   - Decrease CN2
   - Change sol_awc (.sol) and ESCO (.sub)
6. If there is too little base flow and too high surface runoff:
   - Adjust infiltration
   - Adjust interflow
   - Adjust base flow recession parameter

Final adjustments:
1. Manual calibration helper:
   CN2 * 0.90

Validation
Stream flow between 2006-2010 (monthly).

Final model adjustments [scenarios]

Only the mentioned adjustments are made, everything else remained unchanged.

Simulation name	Adjustment
Base line	Crop is not fertilized - not irrigated
Scenario I	Crop is fertilized – not irrigated
Scenario II	Crop is not fertilized – irrigated
Scenario III	Crop is fertilized - irrigated

Land use	HRU #	HRU #	HRU #	HRU #	HRU #
Semi-com	300019	380016	490022	860016	770020
Com irr	300014	380012	490016	860011	770016
Com dry	300017	380014	490018	860014	770019

Scenarios

Simulation name	Adjustment
Baseline	Crop is not fertilized - not irrigated
Irrigation	Crop is fertilized – not irrigated
Scenario II	Crop is not fertilized – irrigated
Scenario III	Crop is fertilized - irrigated

SWAT inputs and adjustments for Gum Selassa catchment

Land cover (ID)

Name	SWAT code
Irrigated cultivated land (command area)	AGRC
Semi-irrigated cultivated land (seepage area)	AGRR
Rainfed cultivated land	

Soil (ID)

The FAO world soil map was used in this project. According to this map, there is only one soil type in the catchment.

SWAT errors

Watershed delineation

Error: number -2147467259. Solution: opening a new SWAT document and loading the DEM before clicking the watershed delineation (and perhaps close and open ArcGIS).

Error: number -2147217256, ‘object is not defined on a project’. Solution: ??. After a couple of tries to reload the SWAT project it worked.

NB. This is a bug in the SWAT 10.0 version.

HRU definition

Error with uploading the land use grid (ERROR: grids must be in the same projection). Reload the ArcSWAT project and upload again the land use map. Make sure that the land use map is projected.

Error with uploading shape file soil map. Convert the soil map from shape file to raster, raster is working (even with many soil classes).

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The mission of Wageningen UR (University & Research centre) is 'To explore the potential of nature to improve the quality of life'. Within Wageningen UR, nine specialised research institutes of the DLO Foundation have joined forces with Wageningen University to help answer the most important questions in the domain of healthy food and living environment. With approximately 30 locations, 6,000 members of staff and 9,000 students, Wageningen UR is one of the leading organisations in its domain worldwide. The integral approach to problems and the cooperation between the various disciplines are at the heart of the unique Wageningen Approach.

To explore the potential of nature to improve the quality of life

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