Surface Water Modelling
SWAT+ Project Report
Case Study: Upper Sabi

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Introduction

The Soil and Water Assessment Tool (SWAT) plays an important role in hydrology applications. It is widely used for creating hydrologic models and aid watershed planning. SWAT uses hydrologic response units (HRUs) and calculates the results of the model according to the HRUs. HRUs represent the areas with different features in terms of land use, soil and slope classes [1]. With the SWAT+ software, the simulation of the chosen study area can be performed and the results on aspects such as climate change, management practices and land use change can be observed [2].

The Sabi River in southeastern Africa flows through Zimbabwe and Mozambique and is 640 km (400 miles) long [3]. The source of the river is in Zimbabwe and it flows into the Indian Ocean [3]. Most of the rainfall is experienced in February for the catchment. The average annual rainfall for the study area varies between 899mm [4].

In this study, SWAT+ software was used in order to gain some insights about the Upper Sabi region. The effect of the slope on the model was investigated using a model with slopes and one without slopes. The objectives of studies are to set up a hydrological model for the study area and investigate the effects on the performance of the model. Moreover, the differences between models with slopes and without slopes are studied.

Methodology

Model description

The model is operated on a monthly time step. With SWAT+ the surface water quality and quantity will be simulated [2,5]. Thus, the impact of land use, climate change and land management will be observed. There are 23 sub basins in the model and 8 sub catchments which are named Upper Sabi, Odzi, Pungwe, Lower Sabi West, Lower Sabi East, Budzi, Devure and Macheke [4].
The model is simulated over eight years and has components such as weather, surface runoff, lateral flow, precipitation, evapotranspiration and potential evapotranspiration.

Available data

In order to simulate the area of study in SWAT+, specific information about the area should be provided to the software. In this model land use, soil, topography and weather data were utilized. Digital Elevation Model (DEM), land use and soil maps are provided in the form of .tif files.

The outlet for the Upper Sabi region is provided as a shape file in order to define the outlet in the QGIS using SWAT+ software.

The observation data that is used for the study area provides daily flow rates of the area. The flow data starts from 01/10/1982 and ends on 30/09/1990, providing a total of eight years of data. And it is used to compare the results of the model with the observations.

Weather data includes precipitation, temperature, wind speed, solar radiation and relative humidity. In the weather files the latitude, longitude and elevation values can be seen for each of the variables.

Three lookup tables were provided for the study which are usersoil, soil and land use. In the land use lookup table, it can be seen that there are numbers from value 10 to 220 that represent land use of the area. The soil lookup table contains a number and a soil name. Each value represents a different type of soil. In order to provide properties for every soil type usersoil lookup table is used.

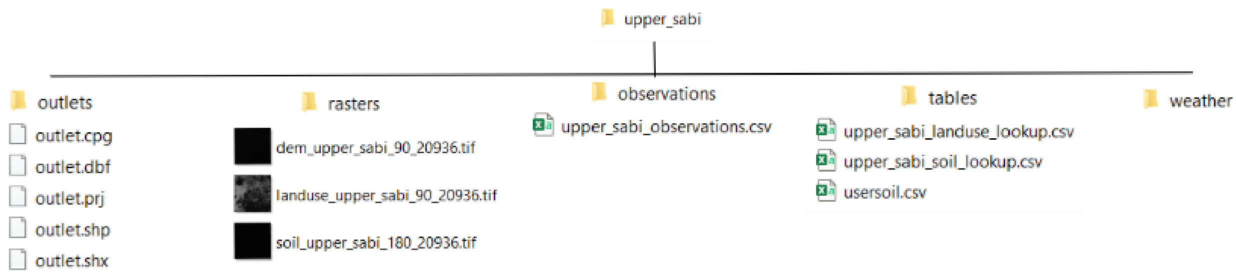

Fig. 1 - Available Data

Model setup

To set up this model in SWAT+, generally five steps are needed, which is shown in the flowchart below [1]. The following information demonstrated how we set up the model step by step:

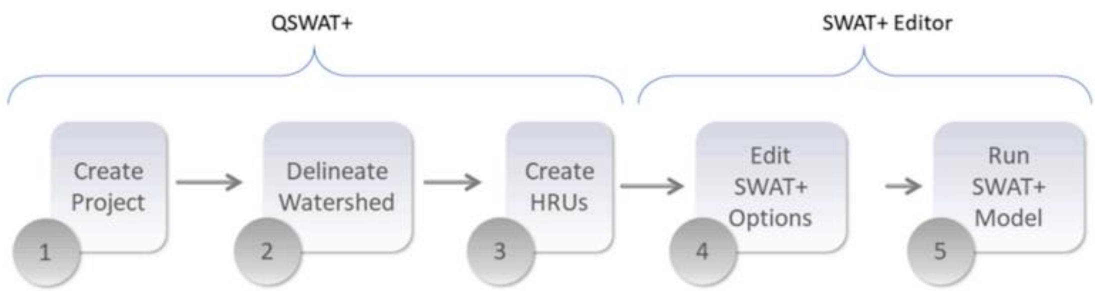

Fig. 2 - The flowchart to set up a model in SWAT+ by Chawanda, C.J., Arnold, J., Thiery, W. et al. (2020)

1. First, QGIS was opened and SWAT+ started to create a new project and import the available data from the upper Sabi basin. It is then possible to visualize the situation of the soil texture, land use, and slope of this area in QSWAT+.

2. The second step is to delineate watersheds, the DEM, stream network, and outlet was selected. If there is more than one outlet, the "select inlet/outlets" button can be used to set the threshold. The DEM inversion method was used to create the landscape.

3. Creating HRUs is the third step, land use and soil use maps were selected then defined by csv files. There are different methods for creating HRUs, one is filter by area. By Selecting this method, the number of HRUs was 3078. Another one is filtering the dominant HRUs, this produced a smaller amount of HRUs, 217 (see Fig 3).

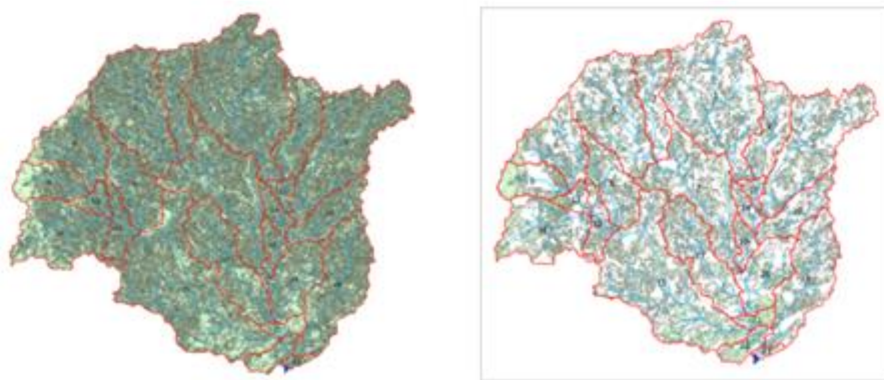

Fig. 3 - Plot compare the map of Full HRUs (left) VS Dominant HRUs (right)

The slope bands (%) were set in this step as well. To validate how much the slope classes will influence the result of modelling results, 3 kinds of slope classes were taken into consideration, [0,999], [0,4,999], and [0,4,12,999]. After several tests, it was decided to generate the model with 4 slope classes [0,4,12,999]. Because it is also a part of our specific task, the details will be described there.

4. In the 4th step, the modified project was imported to the SWAT+ editor, where project information can be seen. For example, for the land-use distribution, it showed ⅓ agriculture, ¼ forest, the rest was mainly grasses and shrubs. Next, in the editor, the weather generation data and weather station data was imported. While setting the basin codes, the "Penman-Monteith method" was selected as the Potential ET method code, because the PM equation is sensitive to vegetation-specific parameters and is commonly used to estimate the net evapotranspiration (ET) in SWAT+. And for the water routing method, "variable storage method" was selected.

5. The simulation period was chosen from 01.01.1982 to 31.12.1990, with a 1 year warm-up period. Output model components were recorded using a monthly time step.

6. Next, the output was visualised in QSWAT+. Both dominant HRU and filter by area models were visualised. The time period chosen was from the beginning of 1983 to September of 1990. The plots of observed flow with modeling flow are shown below. In figure 4, when NSE of two plots is compared, for full HRUs is it 0.63, for dominant HRUs the NSE is 0.61, the difference between them is very limited, thus, it was decided to use the dominant HRUs for the further analysis and calibration in SWAT+, because less HRUs means shorter processing time in software.

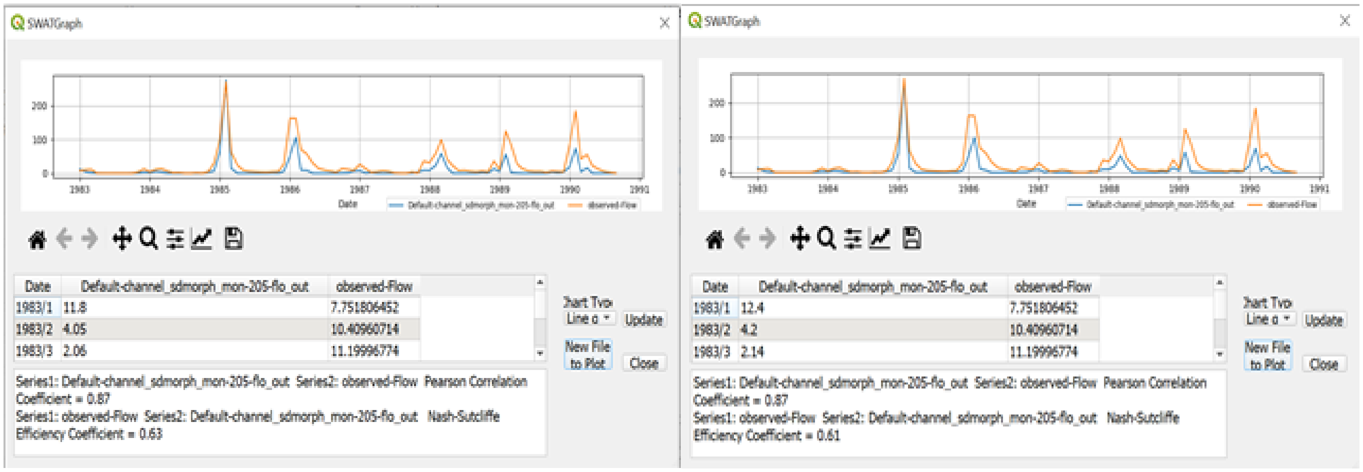

Fig. 4 – Compare the plots of simulated and observed flows for Filter By area (left) and Dominant HRUs (right) methods

Sensitivity analysis

Before the model could be calibrated, a sensitivity analysis was performed in order to identify the parameters which have the greatest effect on the model. Two methods of analysis were utilised, manual and automatic.

Manual sensitivity analysis

The aim of a manual sensitivity analysis is to adjust the values of the parameters to be tested while checking the model performance after each adjustment. By this method it can be seen whether a parameter has a large impact on the model (sensitive) or a small impact (not sensitive).

Method:

1. For each input parameter to be analysed, it was decided whether it will be given a *relative, percentage* or *replace* adjustment. Relative and percentage adjustments were used when the parameter's value is variable over the modelled catchment. A good understanding of the absolute range of a parameter, as well as the range of values already present in the model, is required to utilise the relative adjustment. If a value is constant over the whole catchment and the range was well understood, the replace adjustment was used.
2. An output parameter to record was chosen, which could then be compared to observed data in order to determine the model performance.
3. SWAT+ was run repeatedly, the chosen input parameter was adjusted and the chosen output parameter was measured. The model performance was evaluated by calculating an indicator. E.g Nash-Sutcliffe Efficiency (NSE), Root Mean Squared Error (RMSE), Mean Square Error (MSE) or PBias. These values can be calculated manually using the below formulas (See Appendix) but can also be taken from SWAT+ toolbox.

4. The model performance was plotted against the adjusted input parameters and analysed to deduce whether it was sensitive.

Parameters chosen for analysis[6]:

cn2 - The SCS curve number is a function of the soil's permeability. Adjusted using a percentage change from -30% to +30%.
esco - Soil evaporation compensation factor, affects the depth of soil which can be used for evaporation. Adjusted using a replace change from 0 to 1.
epco - Plant uptake compensation factor, affects the depth of soil which can be used for water uptake by plants. Adjusted using a replace change from 0 to 1.

The model performance was evaluated by measuring the monthly out flow and using the NSE and RMSE taken from SWAT+ toolbox.

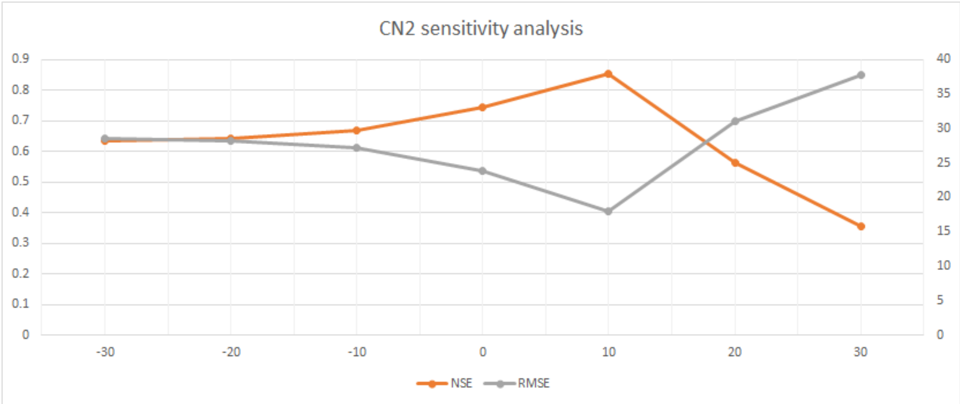

Fig. 5 - Plot of CN2 sensitivity analysis. The left y axis is for NSE and the right y axis is for RMSE. The x axis is the percentage adjustment for CN2.

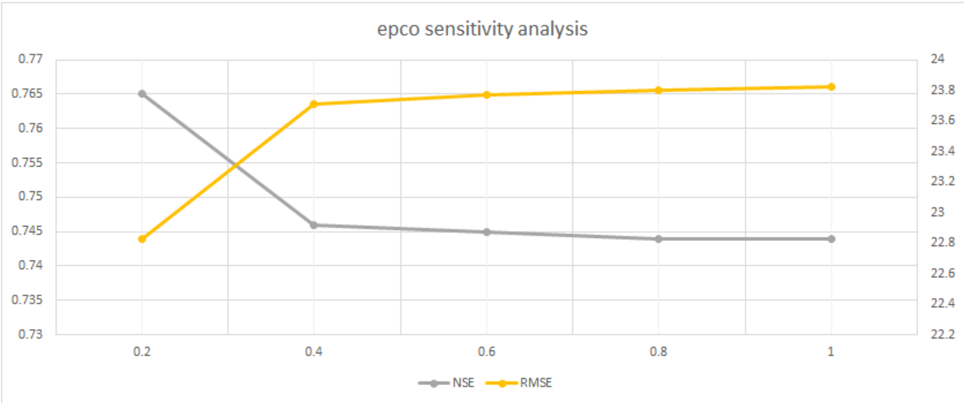

Fig. 6 - Plot of epco sensitivity analysis. The left y axis is for NSE and the right y axis is for RMSE. The x axis is the replaced value of epco.

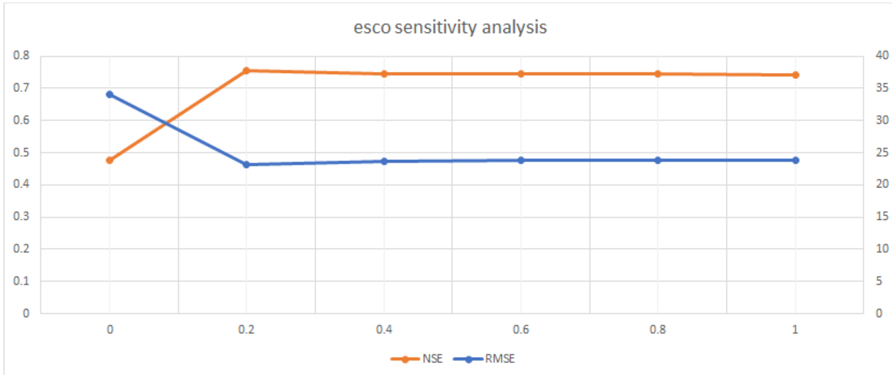

Fig. 7 - Plot of esco sensitivity analysis. The left y axis is for NSE and the right y axis is for RMSE. The x axis is the replaced value of esco.

Examining Fig. 5 it was seen that CN2 is a sensitive parameter as the NSE varied from ~0.35 to ~0.85 over the range of adjusted values. Additionally, it seemed that a ~10% increase of the CN2 produced the best model performance. The RMSE inversely reflected the NSE and so confirms this assessment.

The analysis of epco showed that it is not a sensitive parameter as even across the whole range the NSE only varied by 0.02. However, the related parameter esco did show interesting behaviour in the range 0 - 0.2 with the NSE increasing from ~0.5 to ~0.75 and RMSE decreasing by ~10. For the rest of the range the NSE and RMSE were stable around 0.75 and 25 respectively.

From the above analysis it could be seen that cn2 is a sensitive parameter. Esco is sensitive in the range 0-0.2 however the default value used in the model is 0.95 (see Fig. 8) therefore by default it is already producing a close to maximum model performance. Epco was seen to not be a sensitive parameter.

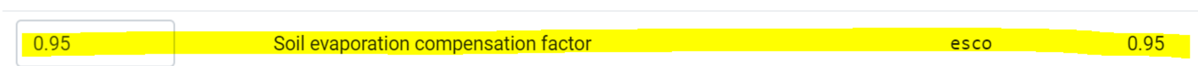

Fig. 8 - A screenshot from SWAT+ editor showing the default esco used in the model.

<u>Automatic sensitivity analysis</u>

Automatic sensitivity analysis was carried out via SWAT+ toolbox using the Sobol method. The Sobol method evaluates sensitivity by running many iterations of the model and summing a parameter's contribution to the variance with the total variance caused by the interaction with other parameters [8].

Parameters chosen for analysis [6]:

cn2 - The SCS curve number is a function of the soil's permeability. Adjusted using a percentage change from -15% to +15%. The range was reduced as it was already known from the manual sensitivity analysis that the maximum performance was around +10%.

esco - Soil evaporation compensation factor, affects the depth of soil which can be used for evaporation. Adjusted using a replace change from 0 to 1.

awc- Available water capacity of the soil layer. Adjusted using a relative change from 0 to 1.

canmx - The maximum amount of water that can be trapped in the canopy when the canopy is fully developed. Adjusted using a replace change from 0 to 10

As the epco was known to not be sensitive it was not included in the automatic sensitivity analysis.

Sensitivity Analysis Method	Observation	Seed	
Sobol	Channel 1 Monthly Flow	20	Number of Samples: 200

Group	Change Type	Name		1st Order Sensitivity
hru	Percent	cn2		0.736165894678647
sol	Relative	awc	mm_H20/mm	0.0429783516906535
hru	Relative	esco		-5.36666361635737E-05
hru	Replace	canmx	mm/H20	-0.0220046666159103

Fig. 9 - Initial test of automatic sensitivity analysis using Sobol method and 20 seed.

Fig 9 confirmed that cn2 was the most sensitive parameter with awc coming in second place. However, for esco and canmax a negative result was returned, possibly because of the low seed number meaning that the Sobol algorithm did not have sufficient iterations. The same test was tried again with 200 seed.

Sensitivity Analysis Method	Observation	Seed	
Sobol	Channel 1 Monthly Flow	200	Number of Samples: 2000

Group	Change Type	Name		↓ 1st Order Sensitivity
hru	Percent	cn2		0.927443737070465
sol	Relative	awc	mm_H20/mm	0.0223236110044451
hru	Replace	canmx	mm/H20	0.0180225375216242
hru	Relative	esco		-7.24040855898562E-06

Fig. 10 - Automatic sensitivity analysis using Sobol method and 200 seed.

This resolved the negative issue for canmx but there was still an issue with esco. This was possibly caused by the fact that a relative change was used from 0-1. Since the default value for esco is 0.95 the relative change would have a max value of 1.95 which is outside of the max range of 1. It was not understood how this would affect the sensitivity analysis but unfortunately due to time constraints it could not be run again. The analysis was rerun with 50 seed without esco and this confirmed the sensitivity ranking which was determined in the other analysis.

Sensitivity Analysis Method	Observation	Seed	
Sobol	Channel 1 Monthly Flow	50	Number of Samples: 400

Group	Change Type	Name		1st Order Sensitivity
hru	Percent	cn2		0.830233060457558
sol	Relative	awc	mm_H20/mm	0.0851539400943963
hru	Replace	canmx	mm/H20	0.0190986074423091

Fig. 11 - Automatic sensitivity analysis using Sobol method and 50 seed, without esco

Calibration

The data was divided into 2 parts for calibration and validation. Calibration was done both manually and automatically. The model was calibrated from the first day of January 1983 until the last day of December 1987 with a one year warm-up period and monthly timestep. Muskingum and Penman-Monteith were chosen as routing and PET methods, respectively.

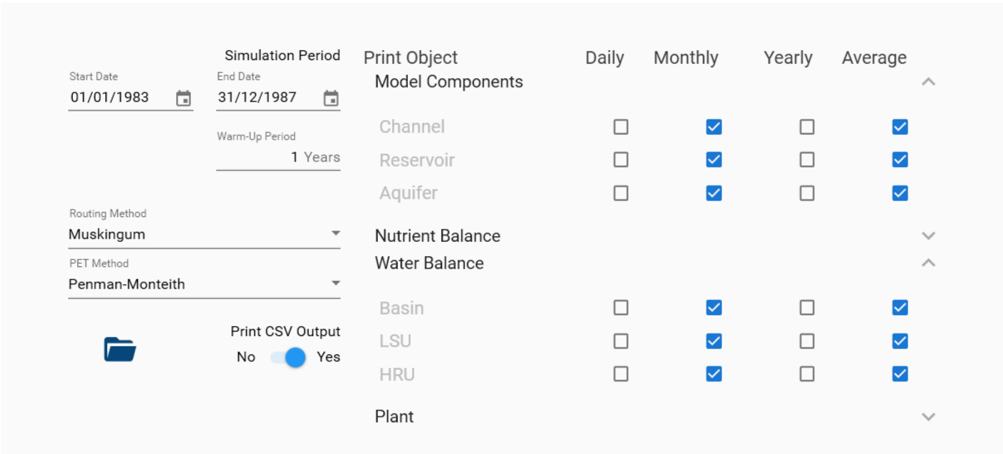

Fig. 12 - simulation period for calibration

Manual calibration

Manual calibration was done by changing the parameters values (cn2, awc and canmx) manually on SWAT+ Toolbox. Different parameters effects on NSE, PBias, MSE, RMSE and observed/simulated discharge graph can be seen by manual calibration.

Automatic calibration

Automatic calibration was done by defining the NSE as objective and maximize as direction and choosing the number of iterations.

Validation

The model was evaluated from the last day of December 1987 until the last day of December 1990 with a one year warm-up period and monthly time-step. Muskingum and Penman-Monteith were chosen as routing and PET methods, respectively.

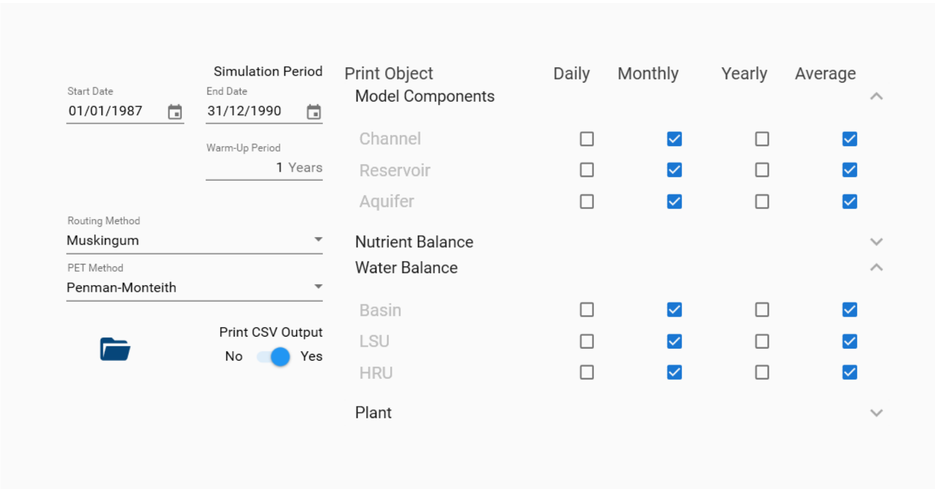

Fig. 13 - simulation period for calibration

Results/ Discussion

The results of the model run with default parameters

The below figure shows recommended ranges for NSE and PBias [10]. These recommended ranges have been used in many scientific papers [11,12]

Performance Rating	RSR	NSE	PBIAS	
			Streamflow	Sediment
Very good	$0.00 \leq RSR \leq 0.50$	$0.75 < NSE \leq 1.00$	$PBIAS < \pm 10$	$PBIAS \leq \pm 15$
Good	$0.50 < RSR \leq 0.60$	$0.65 < NSE \leq 0.75$	$\pm 10 \leq PBIAS < \pm 15$	$\pm 15 \leq PBIAS < \pm 30$
Satisfactory	$0.60 < RSR \leq 0.70$	$0.50 < NSE \leq 0.65$	$\pm 15 \leq PBIAS < \pm 25$	$\pm 30 \leq PBIAS < \pm 55$
Unsatisfactory	$RSR > 0.70$	$NSE \leq 0.50$	$PBIAS \geq \pm 25$	$PBIAS \geq \pm 55$

Fig. 14 -The recommended values for RSR, NSE and PBias by Moriasi et al. (2007)

In SWAT+ toolbox, 1982 to the end of 1990 was modelled, the parameters awc, cn2 and canmx were chosen. Keeping them at default values and running the model, NSE = 0.602 and PBias = 61.265. According to the performance rating figure, 0.602 for NSE was in the range of 0.50 to 0.65, which is satisfactory. For the PBais, it was higher than 25, so it is an unsatisfactory result.

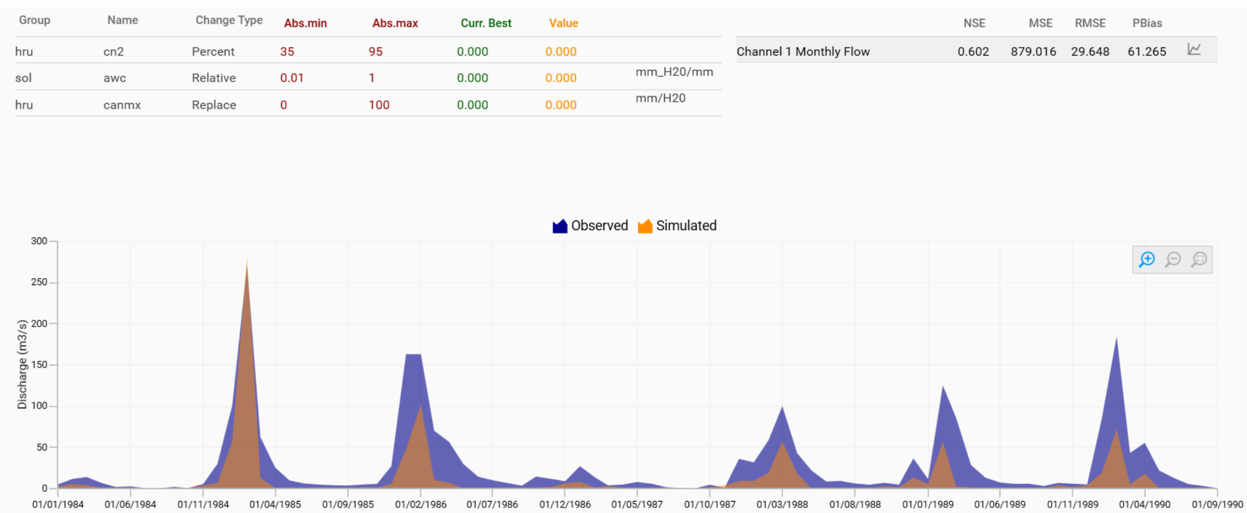

Fig. 15 - The initial calibration result

With regards to the water mass balance check, based on the general water balance equation, a simple water model was introduced. This is:

Precipitation = ET + Surface runoff + Lateral flow, according to the following water balance model figure (Fig 16), the water balance of the initial model can be calculated:

$$749.74 - 705.6 - 24.86 - 0.85 = 18.43 = 2.5\% \text{ error}$$

The water balance error of the initial model was 2.5% and not a very good result.

To analyse the reason for this error, from the initial calibration plot, it was found that the simulated discharge is lower than the observed discharge in most of the period. The underestimation of the discharge could be one of the reason that give the error of the model.

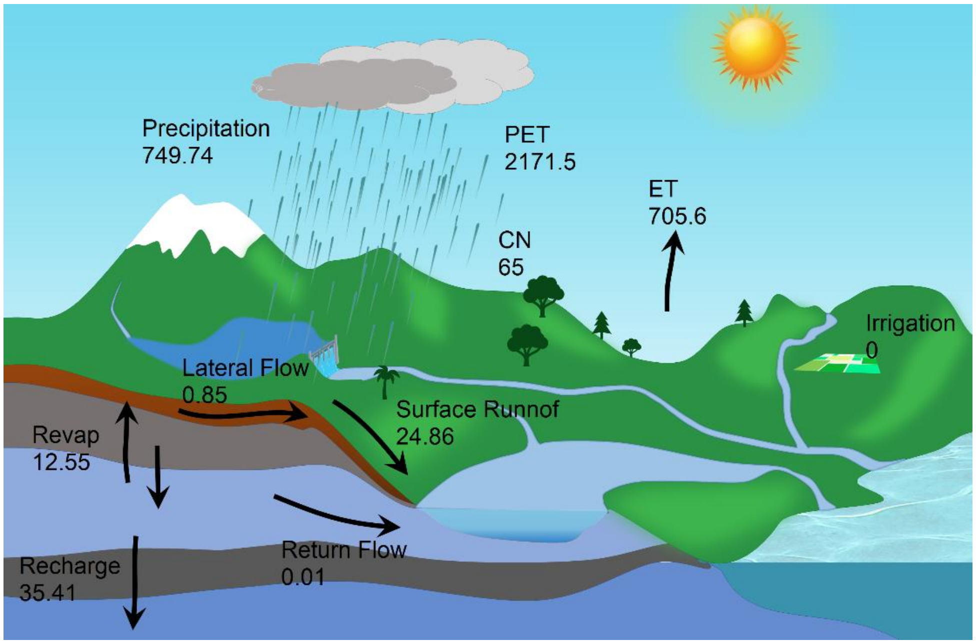

Fig. 16 - The initial water balance check

<u>The results of the model run with default parameters</u>

<u>Calibration</u>

<u>Manual calibration</u>

Fig. 17 - Manual calibration result

The manual calibration was done with 3 parameters including cn2 = 9.495, awc = 0.018 and canmx = 1.600. These values led to NSE = 0.879 and PBias = -0.574. The chart shows both observed and simulated monthly flows from the first of January 1984 (because of the 1 year warm-up period) until the last day of December 1987.

This figure shows that NSE and PBias for manual calibration have very good performance ratings.

Automatic calibration

Fig. 18 - Automatic calibration result

Automatic calibration was done with 20 iterations and Dynamically Dimensioned Search (DDS) calibration algorithm. The goal was maximising the value of NSE and this led to NSE of 0.895. SWAT+ Toolbox used cn2 = 9.781, awc = 0.579 and canmx = 7.489. NSE has a very good performance rating.

Validation:

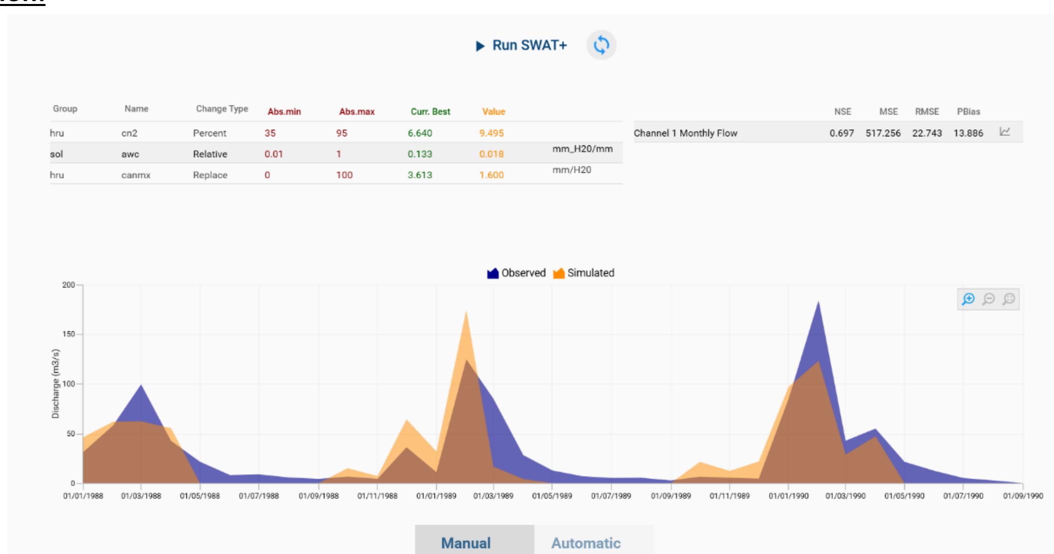

Fig. 19 - Validation result

For the validation part the parameter values from manual calibration were used. This led to NSE = 0.697 and PBias = 13.886. Both NSE and PBias are in good performance levels. The chart shows both observed and simulated flows from the first day of January 1988 (because of a 1 year warm-up period) until the first day of September 1990.

Model check

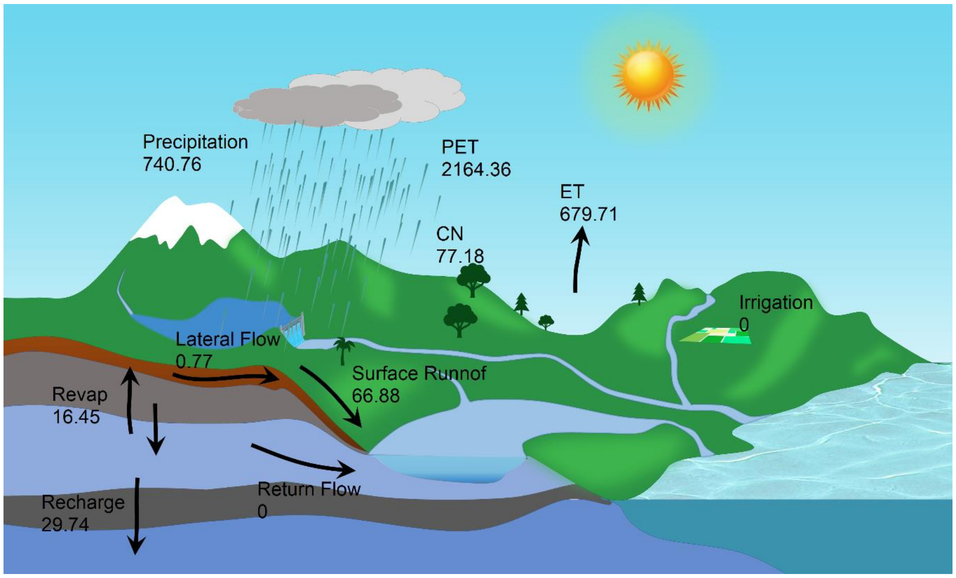

Fig. 20 - Water balance check

740.76 - 679.71 - 66.88 - 0.77= -6.6 <1% error

Specific group task

This was carried out for both filter by area and dominant HRU methods.

Results with filter by area method

First, the slope was considered in 2 slope classes including [0,999]. Then it was changed to 3 and 4 slope classes including [0,4,999] and [0,4,12,999], respectively. The result shows very small changes in peaks and great changes in the number of HRUs. There were 1193, 2309 and 3078 HRUs with 2, 3 and 4 slope classes, respectively. NSE is 0.63 in all conditions.

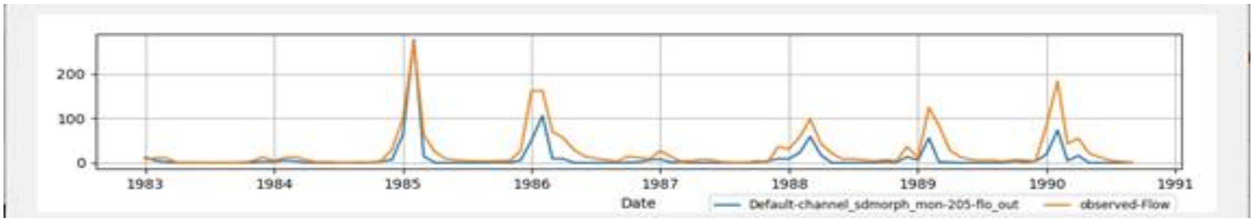

Fig. 21,a: Simulated and observed flow with 2 slope classes

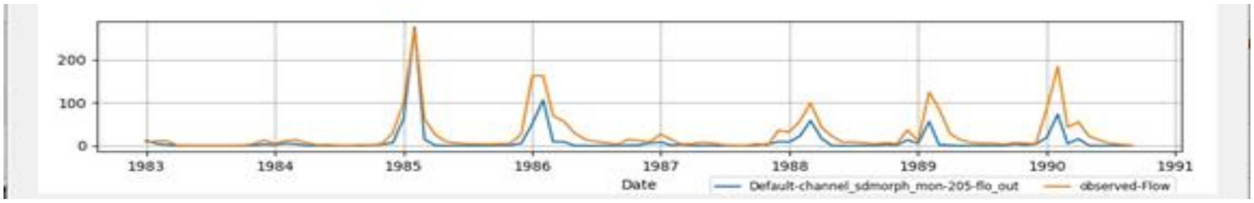

Fig. 21,b: Simulated and observed flow with 2 slope classes

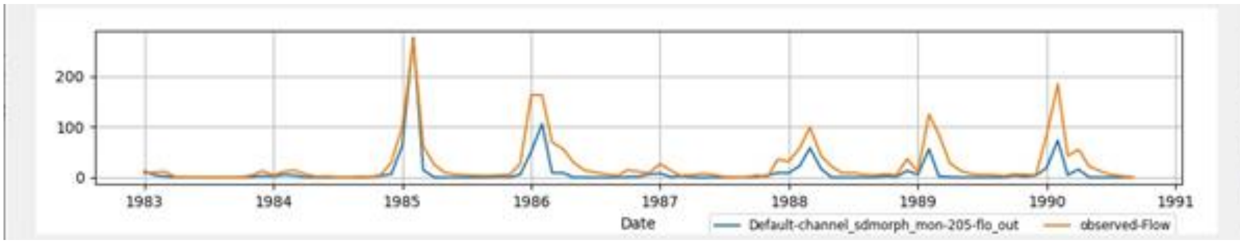

Fig. 21,c: Simulated and observed flow with 2 slope classes

Results with dominant HRU method

The same slope division process was done with the dominant HRU method. However, changing the number of slope classes did not change the number of HRUs since the dominant HRU method had reduced the number HRUs to 217. Again, the result shows small changes in peak values but these changes cannot be observed with our provided plots. The NSE value is 0.6 in all conditions.

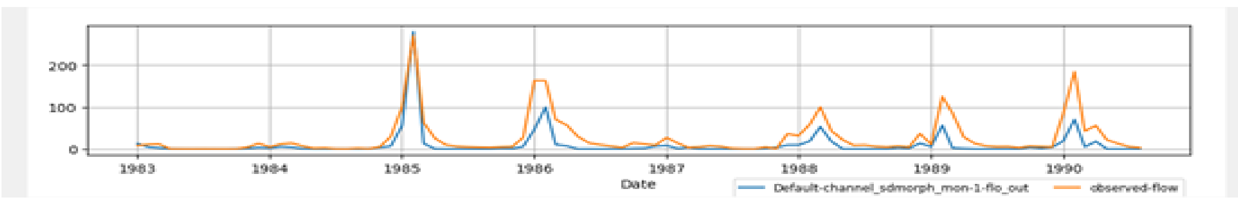

Fig. 22,a - Simulated and observed flow with 2 slope classes

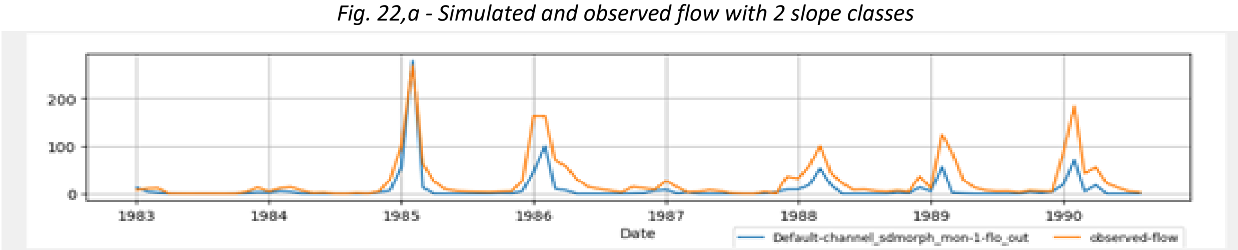

Fig. 22,b - Simulated and observed flow with 3 slope classes

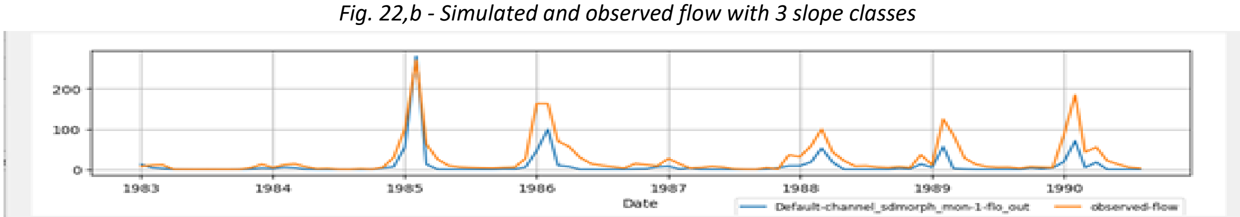

Fig. 22,c - Simulated and observed flow with 4 slope classes

Conclusion

Based on the results obtained it can be seen that the SWAT+ model can be used to accurately model surface water parameters, provided that satisfactory data is provided. After calibrating the model, an NSE of 0.697 for the outflow was achieved (compared with observed data) and a low water balance value was present. This implies that from the weather data provided, SWAT+ model can produce good results that closely match the observation data.

SWAT+ can produce a model using generated weather data however this has not been tested by us and could definitely affect the outcome of the model. Another limitation of this model is that it has been calibrated over a very short time period (3-4 years) and then validated on the succeeding few years afterwards. Ideally a longer calibration period would be us

ed to take into account variation on a longer timescale. This could then be validated on another period that is (ideally) temporally disconnected (10+ years after the end of the calibration period), but of course any study is limited by the time period which the input data covers.

For our model weather data from 1981 was used, however the model could only be calibrated from 1983 onwards as the observed data only began in 1982 and the first year of data was invalid (each day had -1 rainfall). Additionally the model assumes that land use and soil stays constant over the time period, as the time period was short this could be a valid assumption however for longer term modelling this would not be the case.

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Appendix

Formula for calculating NSE[7] and MSE[9], RMSE is the square root of MSE. The desired value for NSE is 1, indicating a model that predicts the observed data exactly. MSE/RMSE should be minimised.

$$NSE = 1 - \frac{\sum_{t=1}^{T}\left(Q_m^t - Q_o^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q}_o\right)^2}$$

where $\overline{Q}_o$ is the mean of observed discharges, and Q_m is modeled discharge. Q_o^t is observed discharge at time t.

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2.$$

where Y is the vector of observed values of the variable being predicted, and Ŷ being the predicted values.

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