J.G.V. van Ramshorst

Groundwater recharge in Myanmar

Estimations in the Chindwin catchment by base flow separation and SWAT

TU Delft

IWMI
International Water Management Institute

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By

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As part of my internship at IWMI during my MSc in Water Management at the Delft University of Technology

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Front page image: Boat on the Chindwin by Jeffry J. Cotner [2015]; http://www.jeffcotner.com/2015/02/14/riverside/

An electronic version of this thesis is available at http://repository.tudelft.nl/.

Preface & Acknowledgements

This report is written as part of my internship at the International Water Management Institute (IWMI) in Vientiane, Laos. This internship was part of my Master of Science in Water Management at the Delft University of Technology. My internship was linked to the internship of Karin Bremer (TU Delft) who estimated groundwater recharge in Myanmar with Water Accounting + (WA+) at the same time in Laos.

I would like to thank the staff/my supervisors at IWMI: Lisa, Robyn and Maarten, who gave feedback and helped me around in Vientiane. I especially want to thank Mansoor for his intensive supervision during the SWAT modelling. I would like to thank Martine for her support from the TU Delft, especially after the internship in finishing the project and report.

Furthermore I would like to thank Karin for working together on this project and her advises and feedback during our stay in Laos and before and after. Last but not least I want to thank my host families and their community in Vientiane which made me feel at home during the 10 week stay in Laos.

Finally I want to mention that the *TBI fonds* funded part of the travel expenses to Laos.

I hope this report contributes to the development of sustainable water management in Myanmar,

Vientiane/Delft, July 2017

Justus van Ramshorst

Abstract

First estimations for the groundwater recharge in the Chindwin basin in Myanmar are presented in this report. This estimations are based on base flow separation and a SWAT model. Multiple base flow separation methods are applied and these are compared with the base flow produced by the SWAT model. This first estimations show a range of 248-670 mm average groundwater recharge per year, which is roughly 11-30% of the average annual rain in the catchment. The upper limit, produced by SWAT, seems to be too high, as the total flow is overestimated due to a rate of evaporation which is too low compared with remote sensing based evaporation. In the Chindwin it appeared that it is rather difficult to separate the base flow due to the highly sensitive alpha parameter, which determines the response behaviour of the base flow, also there seem to be multiple groundwater components. This makes it hard to perform base flow separation, but also increases the difficulty of calibrating the SWAT model, especially the base flow component. However the SWAT model shows a clear spatial groundwater recharge pattern even though it needs further optimization. Optimizing a (hydraulic) model can be cumbersome and especially in a developing environment as Myanmar it is also interesting to look at other possibilities/models, like Water Accounting +, which are more flexible to adapt to changes as new dams or increase in groundwater irrigation.

Contents

Introduction

Chindwin

The Chindwin is a subcatchment of the Irrawaddy in Myanmar (Figure 1). At the most southern part of the Chindwin just before it joins the Irrawaddy the measurement station Monywa is located which is used for base flow separation and calibrating the SWAT model.

In this report is focused on estimating the groundwater recharge for the Chindwin and is a start for estimating groundwater recharge for the whole Irrawaddy basin. Myanmar has been closed for the outside world for several decennia's and since 2011 this no longer the case. However, related to this a lot of research and studies has not been done yet, therefore the estimates from this report are one of the first estimates for groundwater recharge in this region. It is relevant to know the amount of groundwater recharge as this indicates the potential for sustainable groundwater use for irrigation, which is very important for the agricultural based economy of Myanmar. (Pavelic, et al. 2015)

In this report is focused on more conventional methods to estimate the groundwater recharge, however the research in this report is related to (Bremer 2017), which focused on a novel method to estimate groundwater recharge with Water Accounting + (WA+). Furthermore in (Bremer 2017) the flow measurements from the measurement stations are analysed. These flow measurements are used for the base flow separation and calibrating the SWAT model.

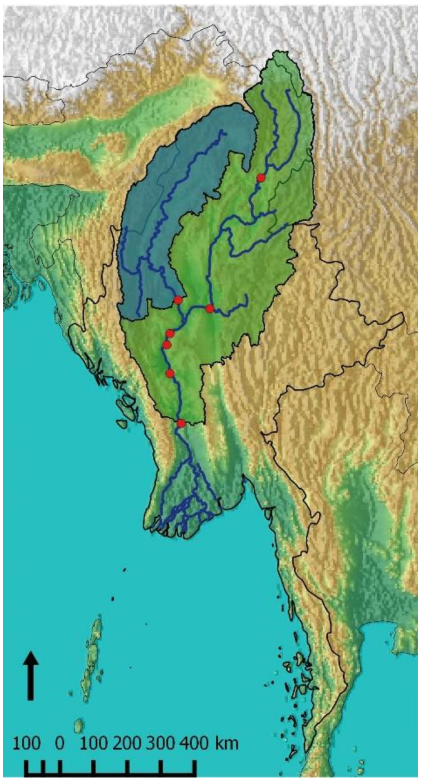

Figure 1: Chindwin (blue), subcatchment of the Irrawaddy in Myanmar. In green the catchment upstream op Pyay, the most southern station with data. The red dot's indicate flow measurement stations.

Base flow separation

The total flow of a river can be considered to consist of two main components, the surface flow and the base flow. The base flow is representing the contribution from groundwater; the surface flow is produced by direct runoff and interflow of precipitation. The surface flow is the fast component and occurs during or directly after rain events, hence during the rainy season for the Chindwin catchment. Base flow represents the slower components and is less dependent on rainfall. In the Chindwin the base flow occurs during the whole year and is the main component during the dry season. The base flow is fed by the groundwater and therefore the base flow is interesting for the estimation of groundwater recharge. There is often defined a third flow component called interflow, which is a lateral flow in the unsaturated zone, this is not defined in the base flow separation, but is used in SWAT (*lateral flow,* Figure 3).

Base flow and groundwater recharge are strongly related. According to (Arnold and Allen 1999) over a certain amount of time, groundwater recharge is equal to base flow + evaporation from groundwater + seepage to deeper layers + change in storage over time, if groundwater extractions are neglected. Equation 1 and Figure 2.

$$\text{GW Recharge} = \text{Q}_{\text{base}} + \text{E}_{\text{soil}} + \text{Q}_{\text{Seepage}} + \Delta\text{Storage}\ [Equation\ 1]$$

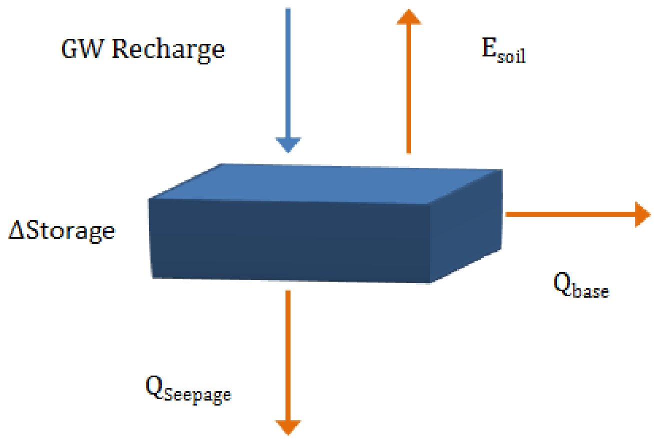

Figure 2: Groundwater balance

Let us assume the average over several years is taken, as is done in this research, then the storage change could be assumed to be zero if no major physical changes take place within the system. In the quickly developing Chindwin/Irrawaddy basin this could lead to problems (in the future). Furthermore the assumption is that there are no or negligible subsurface losses out of or flows into the basin and there is negligible evaporation or extraction from the groundwater. This gives a rough estimation that the base flow is equal to the groundwater recharge, Equation 2.

$$\text{GW Recharge} \approx \text{Q}_{\text{base}}\ [Equation\ 2]$$

SWAT

SWAT (Soil & Water Assessment Tool) is a model which can simulate the hydrological processes in a catchment (Neitsch, et al. 2009). Within this project SWAT is only used to obtain the spatial distribution of the quantity of ground- and surface water in the Chindwin basin. SWAT is also able model the quality of the surface and groundwater and can be used to predict the impact of changes in land use or management practices changes of the climate. Estimating groundwater recharge with SWAT is done more often, a.i. (Arnold, Muttiah, et al. 2000) and (Sun and Cornish 2005). In (Arnold, Muttiah, et al. 2000) the groundwater recharge is estimated for the Upper Mississippi, with SWAT and base flow separation as also is done in this report. Furthermore SWAT is spatially distributed which is interesting to find regions with potential problems or possibilities for irrigation, therefore is chosen to also use SWAT for obtaining a first estimation of the groundwater recharge.

For each defined subbasins it is possible to read out the amount of groundwater recharge, but also other values like base flow and evaporation are given for each of the subbasins. It is possible to read out the amount of evaporation and groundwater recharge etcetera, because land use, soil types and climate data are given as spatial input to the model. This spatial distribution results in, for this model 8525, Hydrological Response Units (HRU's) with all unique physical conditions. Each subbasins is build out of hundreds of HRU's, which gives different flow results for each subbasins.

Each HRU is build according to the structure visible in Figure 2 (Neitsch, et al. 2009). This results in the following water balance (Equation 3a) which is used within SWAT (Neitsch, et al. 2009). Where, P is the precipitation [mm], E is the evaporation [mm], $Q_{surface}$ [mm] is the surface runoff, Q_{base} [mm] is the base flow into the river, $Q_{seepage}$ [mm] is the deep percolation and is account as a loss, ΔS_{tot} [mm] is the change in soil water content and ΔT [days] is the timestep of the model. Following from Figure 3, when zoomed in on the groundwater storage (ΔS_{GW} [mm]) , the following water balance holds (Equation 3b), where is visible that GW Recharge [mm] is not per definition exactly base flow, but there are potential losses like $Q_{seepage}$ [mm] and E_{soil} [mm], as also stated in the base flow separation chapter.

$$\frac{\Delta S_{tot}}{\Delta T} = P - E - Q_{surface} - Q_{base} - Q_{seepage} \; [Equation\ 3a]$$

$$\frac{\Delta S_{GW}}{\Delta T} = GW\ Recharge - Q_{base} - Q_{seepage} - E_{soil} \; [Equation\ 3b]$$

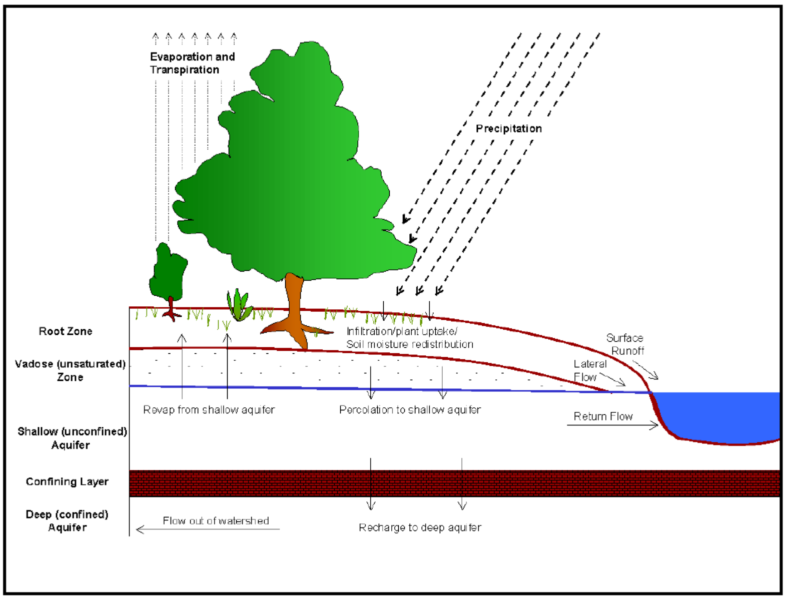

Figure 3: SWAT model structure (Neitsch, et al. 2009)

Now the base flow separation and SWAT are introduced it is clear that these two methods are used to estimate the groundwater recharge in two different ways. The aim of this report is to give a first estimation of the groundwater recharge in the Chindwin catchment in Myanmar. The final result will be a range for the amount of groundwater recharge that is expected based on these two methods.

Method

Base flow separation

Many methods are available for base flow separation. Methods such as HYSEP, IHACRES, Chapman, BFLOW and Eckhardt are available (Chapman 1999) and (Eckhardt 2008). These methods use digital filters which try to capture the low frequency waves of the groundwater flow. High frequency waves are more likely associated with surface flow. An important number which shows the importance of the base flow is the Base Flow Index (BFI), this number shows the proportion of base flow compared to the total flow (Base flow/Total flow).

For the base flow separation the stream flow data of the station in Monywa was used (Bremer 2017). The base flow separations are done in Web-Based Hydrograph Analysis Tool (WHAT).The three options which are available in WHAT are used to separate the base flow, the Local Minimum Method, BFLOW and Eckhardt (Lim, et al. 2005).

The local minimum method determines the minimum values of the hydrograph within a chosen interval in days. The minimum values are connected with straight lines. The discharge under this constructed line is the base flow (Sloto and Crouse 1996).

The BFLOW method is based on the digital filter descripted by Lyne and Hollick (Lyne and Hollick 1979). This methods uses the following two equations to calculate the base flow. First of all the surface flow is calculated for each time step with Equation 4. Resulting from that the base flow can be calculated, as the base flow is the total flow minus the surface flow, Equation 5. Where $Q_{surface}$ [m^3/s] is the surface flow, Q_{total} [m^3/s] is the measured total flow, Q_{base} [m^3/s] is the base flow and α [-] is the filter parameter.

$$Q_{surface} = \alpha * Q_{surface-1} + \frac{(1+\alpha)}{2} * (Q_{total} - Q_{total-1}) \; [Equation\ 4]$$

$$Q_{base} = Q_{total} - Q_{surface} \; [Equation\ 5]$$

The Eckhardt method, is a similar one parameter digital filter like BFLOW, however it contains an extra “subjective” parameter, BFI_{max}, which can be used. The Eckhardt method is fully described in (Eckhardt 2005). The base flow is filtered out directly for each timestep as described in Equation 6. Where BFI_{max} is indicating a BFI upper level instead of a maximum BFI of 1, therefore extreme peaks are filtered out. BFI_{max} is an arbitrary value, nevertheless for perennial streams Eckhardt proposed a BFI_{max} of 0.80 (Eckhardt 2005).

$$Q_{base} = \frac{(1 - BFI_{max}) * \alpha + Q_{base-1} + (1-\alpha) * BFI_{max} * Q_{total}}{1 - \alpha * BFI_{max}} \; [Equation\ 6]$$

When the default settings for the Local Minimum Method, BFLOW, Eckhardt method were used, (extreme) high BFI values were observed (see Figure 4). Furthermore the shape of the base flow is not in accordance with the standard shapes shown in (Savenije 2006) and (Brodie and Hostetler 2005). Based on an expert opinion at IWMI (P. Pavelic 2016) also an arbitrary manual setting has been tested to obtain a different approximation.

SWAT

Before the SWAT model is able to run, after which calibration and validation is possible, some steps have to be taken. First of all the subbasins were delineated. One option is to use a Digital Elevation Map (DEM) of the complete region and to let SWAT delineate the subbasins. Another option is, when available, to insert pre-defined subbasins and streams. For this project predefined streams and subbasins were used, based on a previous project of ICEM (ICEM 2016).

After delineation the HRU's were created. To be able to do this within SWAT, land use and soil data for the complete region were needed. Furthermore the slope is defined based on the DEM inserted. The land use of this project is based on the multiple satellite based data inputs (IWMI 2016). The soil data is extracted from the FAO Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2016). The DEM is obtained through the Digital Elevation Database (DEM 2016).

When the HRU's are created the climate(forcing) was inserted into the model. The climate data contains: precipitation, minimum and maximum temperature, relative humidity, solar radiation and wind speed. The precipitation data is obtained through daily CHIRPS data (CHIRPSdata 2017). The other climate data is downloaded from the Global Weather Data for SWAT (GlobalWeatherData 2016). These rain and climate data needs to be processed to climate data per subbasin. The CHIRPS data contains one raster file per day for the whole catchment. For each subbasin an average value is calculated by zonal statistics with a R-script. The stations containing the other climate data are manually divided between the subbasins after downloading the data. Dividing is based on their location, if the subbasin had stations within its area, these are used. When the subbasin did not contain a weather station, the nearest(s) stations is/are chosen. After dividing the stations, the average values are calculated for each subbasin, resulting in daily average values per subbasin. These data is used as input for creating the weather database for SWAT. After processing all the climate data, SWAT generates the weather database file and next to it, it also creates all the necessary input files per subbasin, which makes it possible to run the final model.

Pre-processing

The delineation of the Irrawaddy catchment resulted in 145 subbasins. The land use and soil data had to be inserted to SWAT as raster files, what in combination with the DEM resulted in 8525 HRU's. As mentioned the climate data had to be converted to daily data per subbasin, which means 145 "virtual" stations, one per subbasin, as SWAT uses only one daily (average) value for each subbasin.

Calibration and validation

Now the SWAT model has all the input data necessary, simulations can be run. The first run (Figure 5) will be done with all the default parameters from SWAT, which are based on the input data. These default parameters for all HRU's are assigned by linking the input data, like land use classes, to the (default) parameter values which are available in the (soil/plant) databases which are integrated inside the SWAT model. The base flow of this first run is also shown in Figure 4. After this first run the SWAT model needs to be calibrated by comparing the hydrographs of the measured and simulated flow and looking at the statistics calculated. This calibration is normally done on the total flow and the base flow. As "measured" base flow, the manual base flow separation from WHAT is used. Also checking the base flow component reduces the risk in a model were the catchment is physically not well captured and the model is useless. The base flow output from SWAT is derived from the return flow component which SWAT gives as output for each subbasins as seen in Figure 4. The return flow is given in mm/time, therefore this needs to be transformed into a flow in m^3/s by using the areas of the subbasins.

Due to time constrains there is chosen to not completely calibrate and validate the SWAT model as normally, as this consumes a lot of time. Therefore a slightly different approach is chosen. As standard, first a sensitivity analysis is done, as shown in Table 2. The sensitivity analysis is done for the parameters which are known to be important (Abbaspour, et al. 2015), (Abbaspour, Yang, et al. 2007) and (Zhang, et al. 2015).This sensitivity analysis is useful for next projects as it gives a clear view which parameters are most sensitive. Furthermore the hydrographs, of the default run, are analysed and deficiencies are mentioned to be able to quickly improve the model later on. Data from 2000 until 2013 was available in SWAT. 2000-2008 is indicated as the calibration period and 2009-2013 is defined as the validation period, however as mentioned calibration and validation are not done.

For the brief analysis of the default run, and normally also for optimizing the model, the simulated and measured flows are compared (see figure 5). Also four statistical numbers (Equation 7 to 10) are reviewed (K. Abbaspour 2015).

I. R^2 – Is used to calculate the correlation between measured and simulated flow. The value of R^2 is between -1 and +1, where +1 is the optimum.

$$R^2 = \frac{\left[\sum\left(Q_{measured,i} - \bar{Q}_m\right)\left(Q_{simulated,i} - \bar{Q}_{simulated}\right)\right]^2}{\sum\left(Q_{measured,i} - \bar{Q}_m\right)^2 \sum\left(Q_{simulated,i} - \bar{Q}_{simulated}\right)^2} \ [Equation\ 7]$$

II. NSE – Nash-Sutcliffe coefficient, needs to be maximized to +1.

$$NSE = 1 - \frac{\sum\left(Q_{measured} - Q_{simulated}\right)_i^2}{\sum\left(Q_{measured,i} - \bar{Q}_m\right)^2} \ [Equation\ 8]$$

III. PBIAS – Percent bias gives the average tendency of the simulated data to be larger or smaller than the observed data. The optimum value is 0. Positive values indicate a underestimation, negative values an overestimate.

$$PBIAS = 100 * \frac{\sum\left(Q_{measured} - Q_{simulated}\right)_i}{\sum Q_{measured,i}} \ [Equation\ 9]$$

IV. RSR – RSR is the RMSE (rooted mean square error) divided by the standard deviation. RSR needs to be minimized to 0 for an optimum.

$$RSR = \frac{\sqrt{\sum(Q_{measured} - Q_{simulated})_i^2}}{\sqrt{\sum(Q_{measured,i} - \bar{Q}_{measured})^2}} \; [Equation\ 10]$$

In addition SWAT-CUP is used to perform the sensitive analysis of the 14 chosen parameters. In SWAT-CUP the SUFI-2 method is used to calculate the accuracy and sensitivity of the combination of the parameters (Abbaspour, Johnson and vanGenuchten 2004) (Abbaspour, Yang, et al. 2007). The sensitivity analysis results in p-values and t-stat values. In (K. Abbaspour 2015) is explained that for this analysis, the larger the value of t-stat, in absolute value, and the smaller the p-value, the more sensitive the parameter is. Where the t-stat value is used to determine the p-value. The p-value ranges from 0-1 and indicates the chance of a parameter of having no effect on the results. When the p-value is < 0.05 this indicates the parameter is (probably) very sensitive and does have an effect on the results. How higher the p-value the less influence is practiced on the results according to this methodology (K. Abbaspour 2015).

Results

Base flow separation

The base flow separations results are shown in Figure 4a-4c.In the same hydrograph plots also the base flow obtained by the default run in SWAT, based on the input, is given. It is visible that the BFI of the manual separation and SWAT are not the same, and therefore their groundwater recharge estimates. The base flows are plot cumulatively in Figure 4c, this shows a clear difference in the slopes of the cumulative sum of the flows, which is directly related to the amount of water. This means the total amount of water between the automatic and manual separations differences a lot. The default SWAT run is in between these two extremes.

In the cumulative plot and the base flow separations (Figure 4) it is visible that the measured base flow decreases in amount over time, at least between 2006 and 2014 the flow is clearly less than before when the log scale separation is observed. While looking at the cumulative plot it is clear that the separations based on the measured flow at Monywa do not have a clear linear straight line, but they bend downwards, hence decrease in steepness. This is confirms the visible drop in the dry season over time on the base flow separation plot. Also it is visible that the SWAT default run does not simulate this drop in flow as the cumulative SWAT plot has clearly a straight line.

While taking a look at the log scale separation plot it is interesting to look at the slope after the peaks. For the manual separation one clear parallel slope is visible. However while looking at the default separations two slopes are visible. One which the manual separation shows as well, however just above the intersection of the manual separation with the default separations the slope changes to a steeper (parallel) slope. This indicates that this part has a different time dependency *K [s]*, hence is from a different source/part of the soil (Savenije 2006).

Using this base flow separation an average groundwater recharge can be calculated. Based on the manual separation a groundwater recharge of approximately 248mm/year is obtained from 2000-2013. 248mm/year of recharge is ~11% of the average rainfall in the Chindwin catchment. For the period of 2005 until 2010 the recharge is 222 mm/year, which is ~10% of the rainfall. The default Local Minimum Method, BFLOW and Eckhardt separations give a groundwater recharge estimation for 2000-2013 of approximately 986 mm/year, 983 mm/year and 900 mm/year, which is ~40-45% of the rainfall. The default SWAT run results in a groundwater recharge estimation of 670mm/year (2000-2013), hence ~30% of the rainfall.

Figure 4a

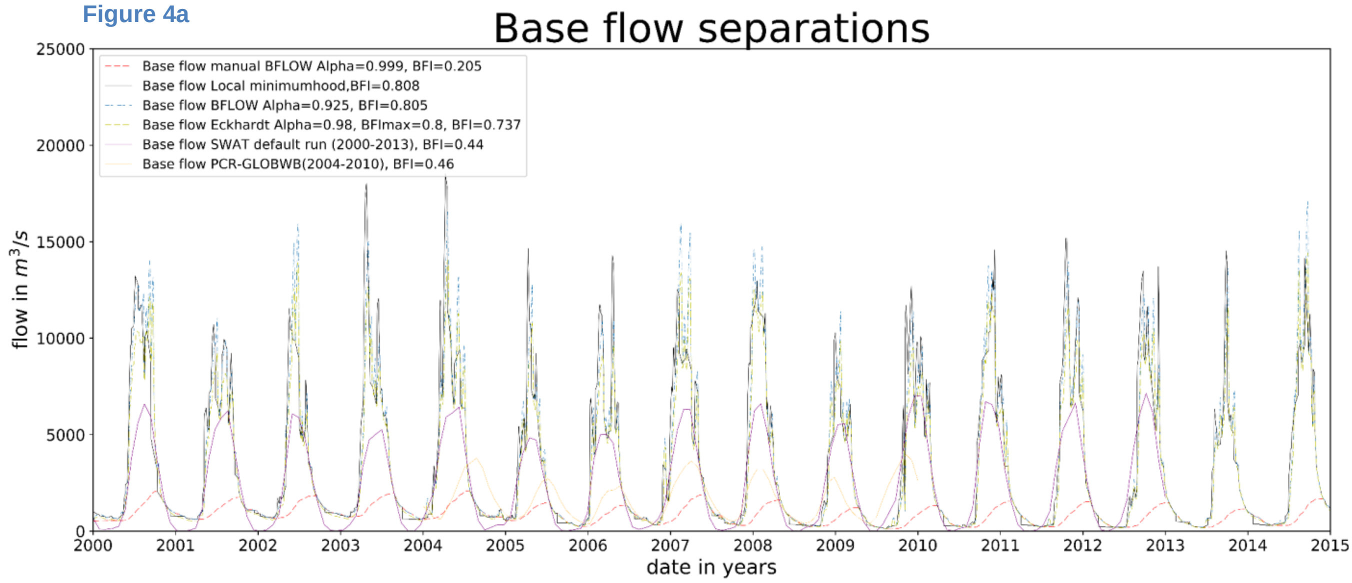

Figure 4b

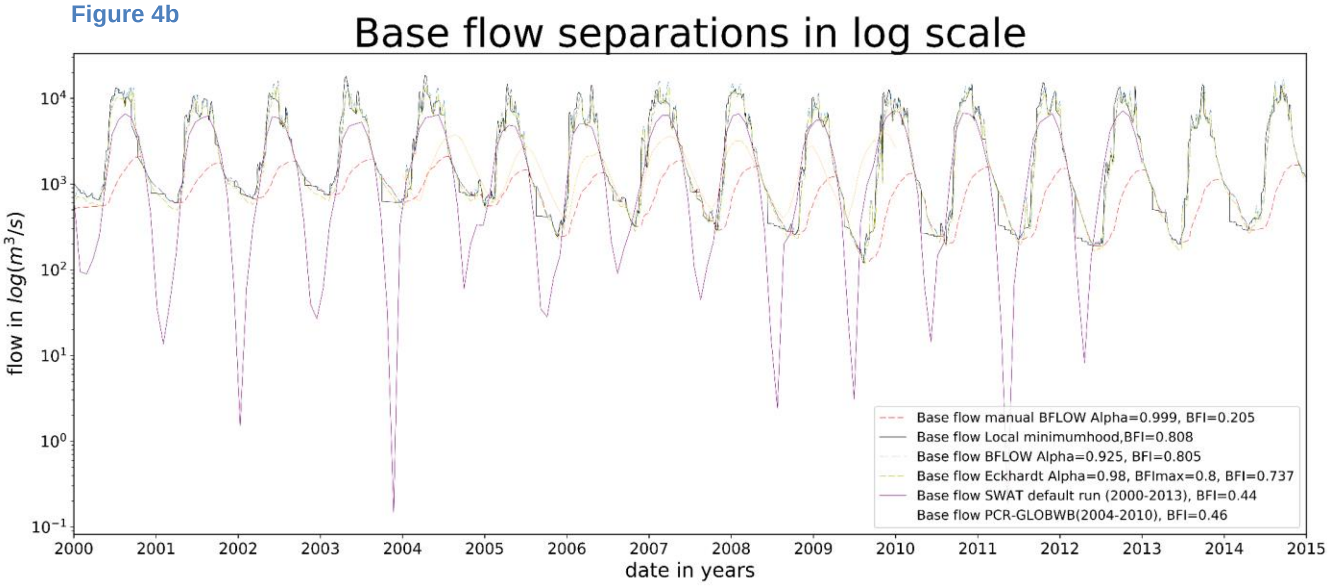

Figure 4c

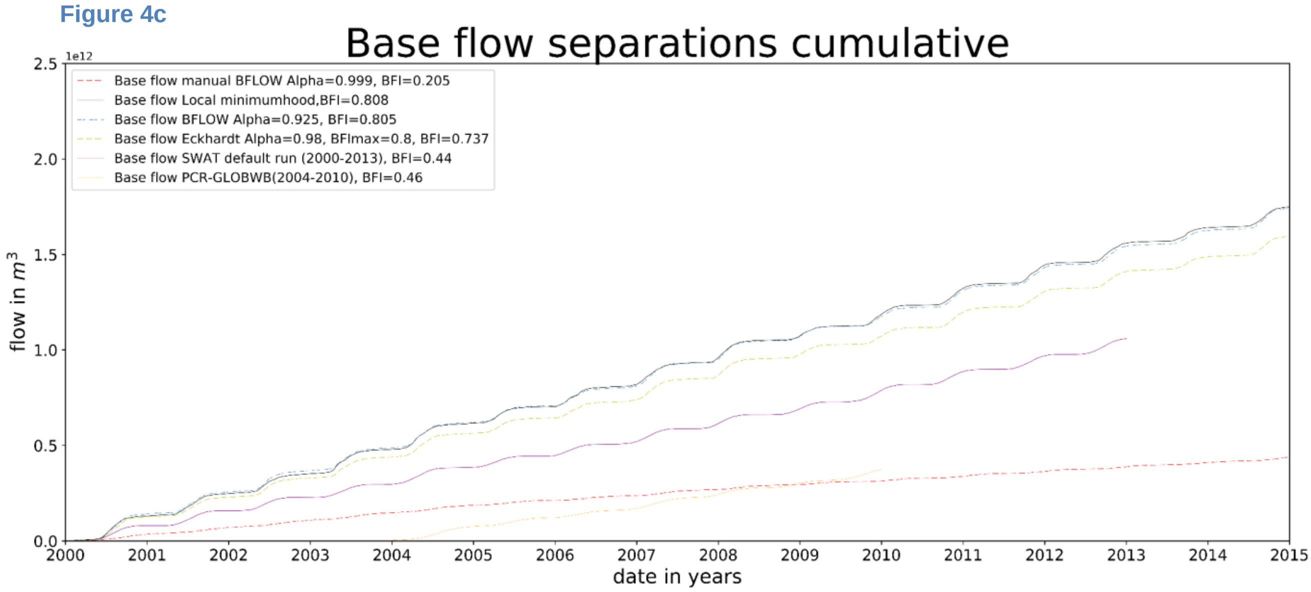

Figure 4: The figures 4a, 4b and 4c show all the base flow separations, the filter parameter alpha and the BFI are shown in the legend. Figure 4a and 4c contain two normal scale axes, figure 4b contains a log(Q) scale of the flow on the vertical axis. Furthermore the values at the vertical axis of figure 4c are times 1e12.

SWAT

First default run

This paragraph shows the results of the first default run in SWAT. Shown in Figure 5 are the measured and simulated hydrographs for the base flow, surface flow and total flow. Furthermore the statistics of the first default run are given in Table 1. The default run directly gives an accurate estimate for the total flow when looking at R^2, NSE, RSR and the hydrograph, however the PBIAS shows the flow is overestimated by ~25%. Furthermore it is interesting to mention that the overestimation of SWAT gets higher over time, when a look is taken at the PBIAS of the total flow in calibration and validation.

For the base flow it is visible that the statistics are indicating a bad relation between simulated and measured, this is because the manual base flow separation is used as “measured” base flow. As seen in earlier in Figure 3 these two estimates are very different from each other. However it is visible that the base flow simulated drops to zero in the dry season, this indicates the physical properties are not well captured yet.

Calibration (2000-2008)

	R^2	*NSE*	*PBIAS (%)*	*RSR*
Total Flow	0.88	0.85	-18.2	0.39
Surface Flow	0.77	0.72	10.4	0.52
Base Flow	0.55	-23.67	148.5	4.94

Validation (2009-2013)

	R^2	*NSE*	*PBIAS (%)*	*RSR*
Total Flow	0.89	0.7	-41.2	0.54
Surface Flow	0.80	0.78	6.0	0.47
Base Flow	0.57	-40.05	-275.0	6.35

Total period (2000-2013)

	R^2	*NSE*	*PBIAS (%)*	*RSR*
Total Flow	0.88	0.8	-25.8	0.45
Surface Flow	0.78	0.74	11.2	0.51
Base Flow	0.47	-25.65	-167.7	5.15

Table 1: The statistical analysis of the default run in SWAT.

Figure 5a

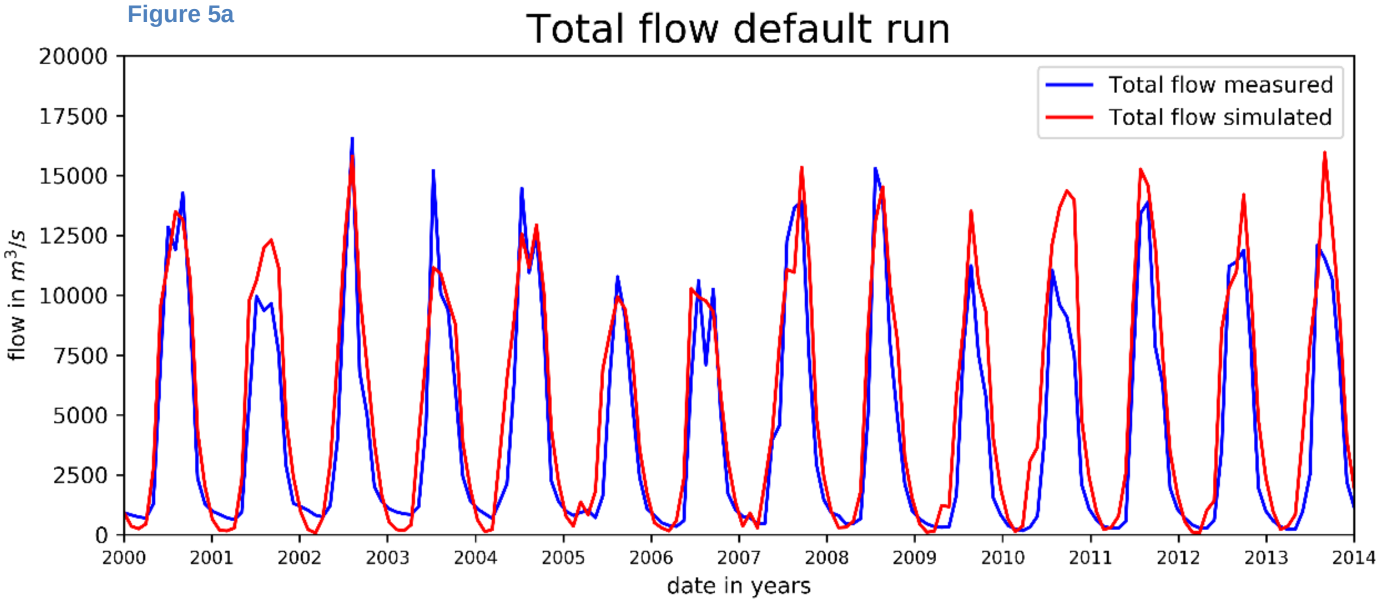

Figure 5b

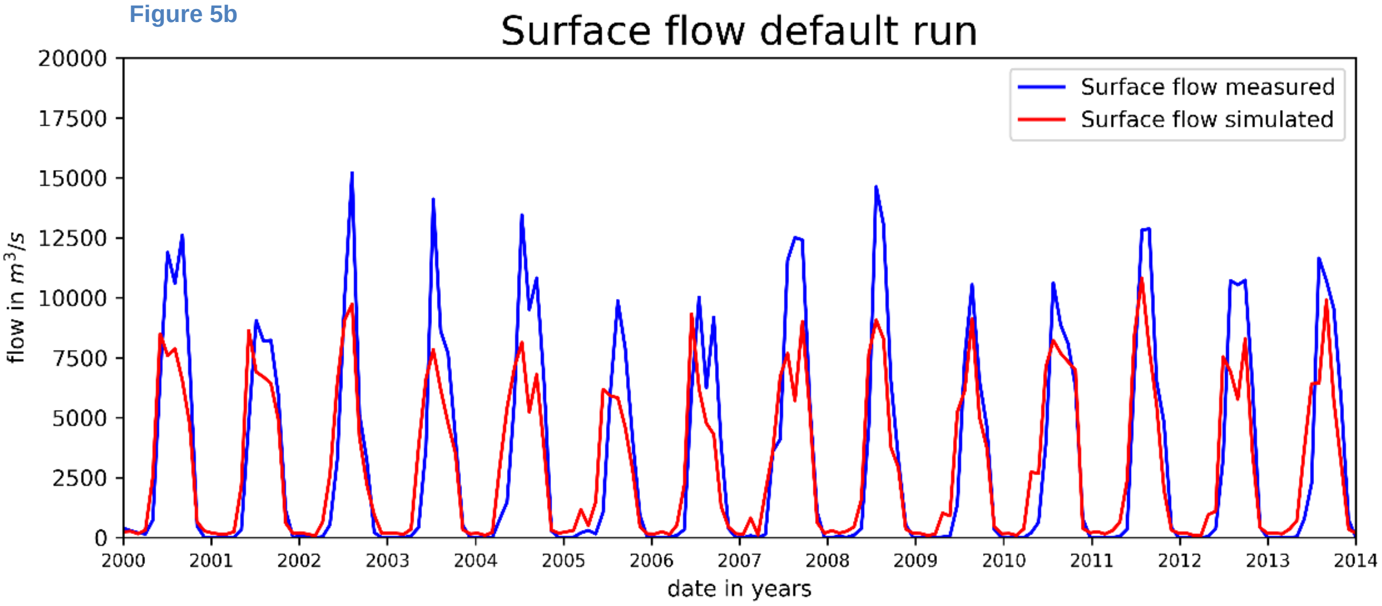

Figure 5c

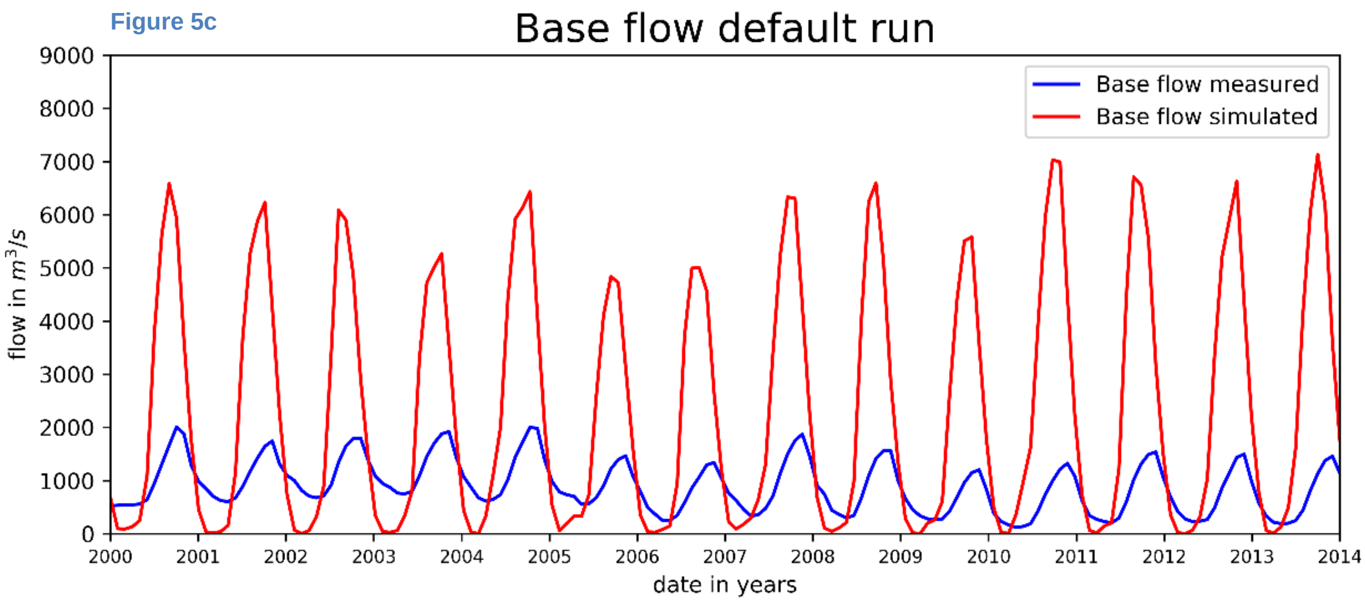

Figure 5: The figures 5a, 5b and 5c show the measured and the by SWAT simulated hydrographs for respectively the total flow, surface flow and base flow.

Sensitivity analysis

Based on previous calibrations and projects, 14 important parameters where chosen to look at in the sensitivity analysis, the parameters are listed in Table 2. There is chosen to do a sensitivity analysis, because this gives a clear first insight in the importance of the parameters in this model. Later on in a next project this can be used to obtain a quick start in calibrating this SWAT model. Table 2 shows the parameter limits, the default values and the sensitivity for each parameter individually. The parameters are ranked from sensitive to less sensitive (1-14), where the P-value is the important value to determine this. As mentioned previously a P-value of < 0.05 strongly indicates this parameter is sensitive and has a big influence on the results. Based on this, parameters 1-4 are sensitive, 5-9 show some sensitivity as well and parameters 10-14 seem to have a lot less influence on the results.

ALPHA_BF seems to be very sensitive and this confirms the difficulties with the base flow separation as ALPHA_BF is related to the alpha constant used with base flow separation. ALPHA_BF, and the alpha used with base flow separation, are both (recession) constants which influence the groundwater flow response and are therefore important in estimating the behaviour of the groundwater flow. CH_K2 is effective hydraulic conductivity in the main channel and indicates how easily water will infiltrate into the ground. CH_N2 is the Manning's roughness coefficient which also indicates the infiltration capacity of water into the ground. CN2 is the curve number for surface run off, which influence the direct/fast run off. GWQMN is the threshold depth of water storage in the ground after which base flow occurs. REVAPMN is the threshold depth of water storage in the ground before E_{soil} or deep percolation (loss in SWAT) occurs. ESCO influences the soil evaporation. SOL_AWC is the available water capacity of the soil. SOL_K is the saturated hydraulic conductivity of the soil. The definitions of all the other parameters used in SWAT are mentioned in (Arnold, et al. 2012).

	Parameter	*file*	*Parameter range*	*Default value*	*Unit*	*T-stat*	*P-value*
1	ALPHA_BF	.gw	0-1	0.048	days	12.42	8.34E-21
2	CH_K2	.rte	-0.01-500	0	mm/hr	-5.40	5.84E-07
3	CH_N2	.rte	-0.01-0.3	0.014	*(-)*	-4.69	1.03E-05
4	CN2	.mgt	35-98	82.05*	*(-)*	4.22	6.16E-05
5	GWQMN	.gw	0-5000	1000	mm	1.66	0.10
6	REVAPMN	.gw	0-1000	750	mm	-1.38	0.17
7	ESCO	.bsn	0-1	0.95	*(-)*	-1.37	0.17
8	SOL_AWC (1+2)	.sol	0-1	0.11*	mm/mm	-1.29	0.20
9	SOL_K (1+2)	.sol	0-2000	9.69*	mm/hr	-1.29	0.20
10	EPCO	.bsn	0-1	1	*(-)*	0.42	0.67
11	GWREVAP	.gw	0.02-0.2	0.02	*(-)*	0.41	0.68
12	SURLAG	.bsn	1-24	4	days	0.39	0.70
13	GW_DELAY	.gw	0-500	31	days	0.06	0.96
14	SOL_Z (1+2)	.sol	0-3500	1300*	mm	0.03	0.98

*where * means spatially distributed, hence this in an average value. 1+2 means layer 1 and 2.*

Table 2: Parameter sensitivity analysis for the 14 chosen parameters.

Groundwater recharge

Following from the default run of SWAT an estimation for the groundwater recharge can be made as well. For the total model period from 2000-2013 the groundwater recharge is 670 mm/year. For the period of comparison, the groundwater recharge from 2005 until 2010 is 685 mm/year. This is roughly 30% of the average rainfall in the Chindwin catchment. As mentioned the total flow is clearly overestimated (25.8%), hence the base flow is probably overestimated as well.

Spatial distribution of groundwater recharge, evaporation, and rain

As the input data of SWAT is spatially and not an average for the whole basin, it possible to extract individual final results for each of the 145 subbasins, or in this case the 37 subbasins for the Chindwin catchment. This results amongst others in a spatially distribution of the groundwater recharge, rain and evaporation. These results are shown in Figures 6 to 8. It is visible that the recharge is strongly related to the amount of rain. Furthermore it is the wettest in the northeast and also wetter in the southwest. It is the driest in the southeast, near the dry zone of Myanmar. Furthermore the evaporation is higher in the east, on the east side of the mountain range, where the altitude is lower than in the mountains and therefor hotter.

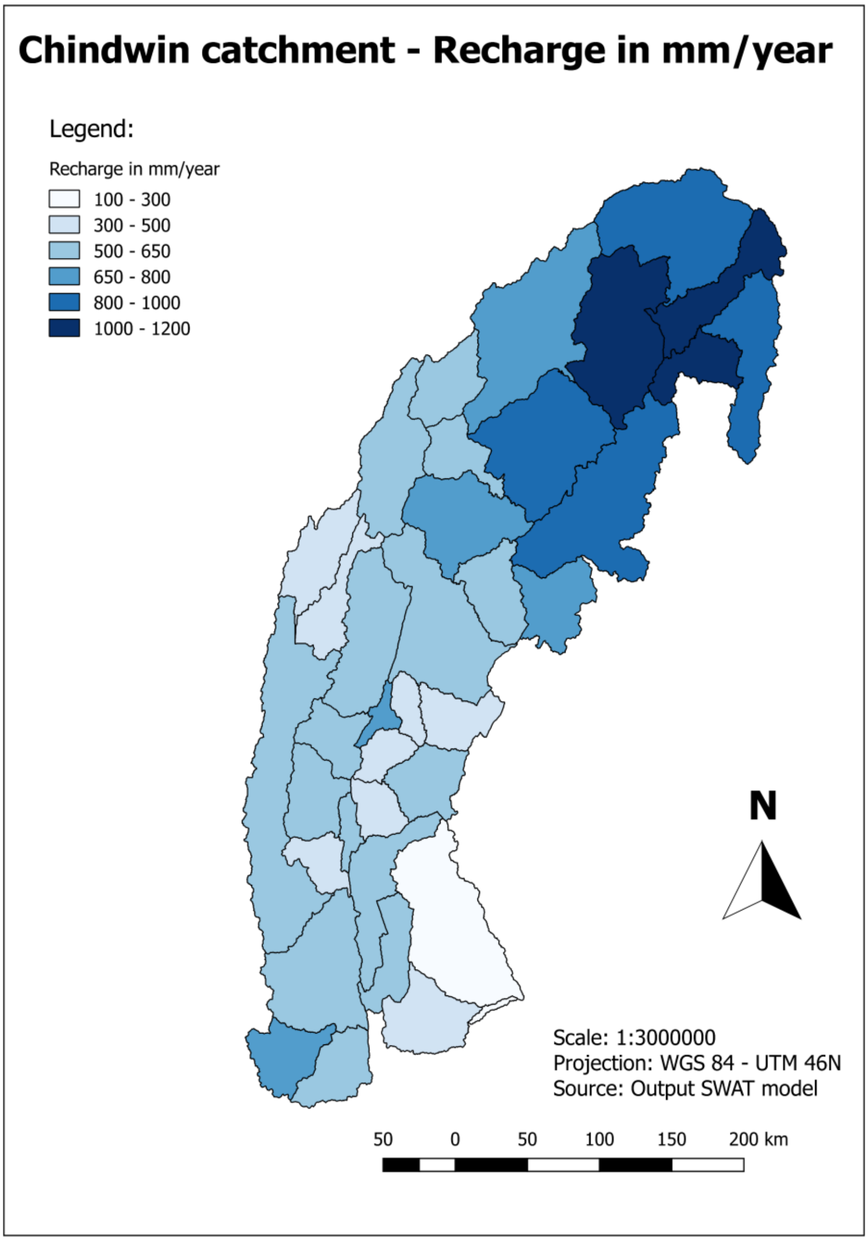

Figure 6: Spatial distribution of the groundwater recharge in mm/year for the Chindwin catchment.

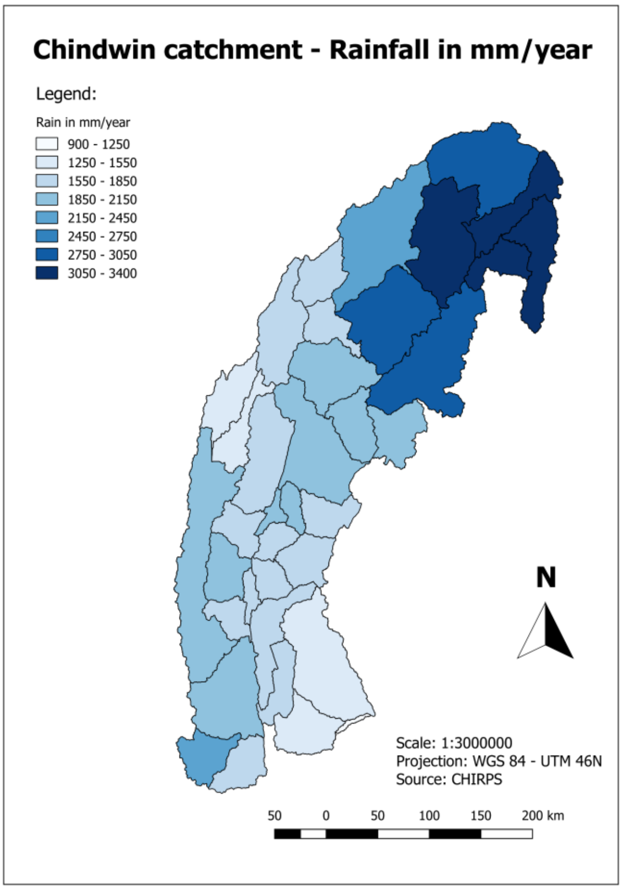

Figure 7: Spatial distribution of the rainfall in mm/year for the Chindwin catchment.

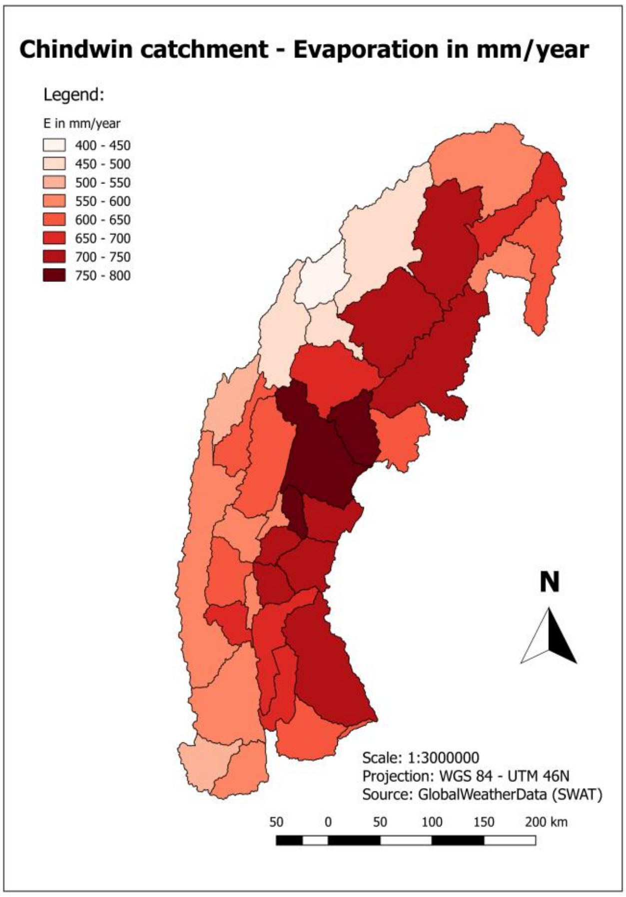

Figure 8: Spatial distribution of the evaporation in mm/year for the Chindwin catchment.

Discussion and Conclusions

Base flow separation

Several methods are used to try to separate the base flow from the total flow. As described the default base flow separations are giving very high BFI's. Manually a lower base flow is separated based on an expert opinion (P. Pavelic 2016). The results of the manual separation are however not reproduced by the default run by SWAT. Nevertheless the shapes of the manual separated base flow and the SWAT default run are more accordingly to the expected shapes in (Savenije 2006) and (Brodie and Hostetler 2005). Also a groundwater recharge of 40-45% of the rainfall is much higher and the double of the rough range of 10-20% of rainfall which would be expected generally (P. Pavelic 2016). Taking into account that the default run of SWAT overestimates the total flow by 25%, the base flow resulting from SWAT will decrease after calibrating, if the ratio base/total flow stays roughly the same this will lead to an estimate of roughly 25% of the rain. Additionally taking into account the Chindwin catchment is mountainous with a lot of hillslopes, fast (sub)surface flow is expected to be dominant over the slow groundwater flow (Savenije 2010). Lastly, in (Zaw, Srivastav and Tint 2016) is shown by estimating GW recharge as rainfall minus actual evaporation and direct runoff, based on RS and GIS, that a recharge of 15% of the rain is expected in a similar area close to Monywa. Concluding, the default separations seem to be too high and the actual recharge seems to be in between the manual and the default SWAT run, this means roughly between ~11-30% of the rain, 248-670mm/year.

Furthermore, the different slopes of default base flow separation on the log scale plot indicate there are two groundwater components. This would mean there is a slower and faster groundwater flow part. The manual separation is only showing the slower groundwater component, while the default runs also totally include another faster component. The default SWAT run partly uses this faster component. Concluding, in this catchment it is important to make a clear distinction on what is seen as base flow, hence which flow is seen as the important factor for groundwater recharge which in the end can determine sustainable irrigation use.

Also it is necessary to mention that the annual base flow is dropping over time, a negative trend is visible when looking at the cumulative and separation plots. This raises the question where the water is going. Therefore a good topic for further research is: Is the amount of (informal) irrigation already expanding since 2005-2006? One more remark is that the SWAT model is not simulating this drop over time, hence is missing the change over time. This is probably due to that the evaporation is based on climate and land use data and these are (relatively) constant during the SWAT simulations and therefore SWAT does not take into account additional (groundwater) irrigation and/or land use changes.

A detail which should be kept in mind, is that it is not possible to verify the base flow with real values, as this data is not available and is also very time consuming and therefore undesirable to obtain. Hence, it is not possible to conclude which estimate describes the base flow the best in reality (Eckhardt 2008). This means separating and choosing a certain base flow is arbitrary and gives no 100% guarantee that the results exactly describe reality, especially with almost no previous project within this area. Nevertheless, taking into account all the above, the estimate of ~248-670mm/year, 11-30% of the average rainfall within the Chindwin catchment, looks like a realistic first estimate of the groundwater recharge within the whole Chindwin basin.

SWAT

First of all, the statistics from Table 1 are observed. The statistics for the base flow, which are very important for estimating the groundwater recharge, shows statistics which are far off compared to the manual separation. This is because these are two completely different estimates, hence this makes it impossible to calibrate SWAT based on this manual separation and that these statistics are therefore not useful. This points at a problem when calibration on the base flow needs to be done. If it is preferable to calibrate the SWAT model also based on the base flow, another base flow separation needs to be distinguished which is assumed to be correct, hence this is not easy. Furthermore when the default run is observed it is seen that the base flow drops to (almost) zero in the dry season, this could indicate that the storage in the soil is not enough. Concluding it is hard to indicate the correctness of the base flow of the default run of SWAT, however the drop in the dry season indicates the base flow does not capture all the physical properties of the base flow yet and calibration is preferable. Most likely the base flow and the drop to zero flow can be optimized by looking at the groundwater parameters in SWAT, for example GWQMN, GW_REVAP or REVAMPM as is given as example in (Abbaspour, et al. 2015).

When the total flow is observed it is visible that the NSE, R^2 and RSR values are accurate and that the shape of the flow, as seen in the hydrographs, is much better than the shape of the base flow. However the PBIAS of the total flow shows a clear overestimation of the measured flow by the SWAT model by roughly 25%. This overestimation is probably caused by an underestimation of the evaporation as the average value of ~640 mm/year is too low for this area when it is compared with the remote sensing based evaporation from (Bremer 2017). Therefore too much water is ending up in the river.

The sensitivity analysis shows which parameters are most sensitive and are interesting to look at when calibration of this model is started. The analysis indicates that ALPHA_BF, CH_K2, CH_N2 and CN2 are sensitive and have a lot of influence on the results. ALPHA_BF is very sensitive and this confirms the difficulties during base flow separation as these alpha values are related.

It is clear the model needs to be optimized later on, however this default run is already a start in the right direction. With help of the sensitivity analysis and the available hydrographs, first the base flow needs to be optimized as well as the amount of evaporation. Therefore it is necessary to obtain a new base flow separation which can be used to calibrate the base flow in SWAT. Separating this base flow is not easy, as the sensitivity of ALPHA_BF and the difficulties which are described, however spending time on separating the base flow will improve the SWAT model.

Recommendations & Future work

Knowing that the model is not optimized yet, there still seems to be a clear spatial pattern. In the northeast of the Chindwin catchment it seems to be wetter and therefore there is also expected more groundwater recharge. In the southwest there seems to be slightly more rain. South-east, close to the dry zone a clear drier pattern is visible. However for follow up projects it is the question if SWAT is the best solution to obtain a spatial distribution as SWAT is quite time consuming and takes a lot of input data. Therefore it is interesting to compare these results with a less time consuming and more flexible way, for example the Remote Sensing based Water Accounting +, as is done in (Bremer 2017).

Finally it is good to keep in mind that estimating groundwater recharge from the base flow separation at this moment gives a rough estimation because no major physical changes are done to the Chindwin/Irrawaddy basin, which is an important assumption. However in a fast developing country as Myanmar it is not unlikely that the hydrologic system will change in the future, when for example big dams are built. Also an increasing use of groundwater for irrigation would lead to that the evaporation from groundwater is no longer zero/negligible. This again indicates it is interesting to look at more flexible methods like WA+ to be able to estimate the groundwater recharge in the (rapid) changing future.

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