Calibration and Validation of SWAT Model for Low Lying Watersheds: A Case Study on the Kliene Nete Watershed, Belgium

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Abstract: Use of easily accessible; public domain modelling software called Soil and Water Assessment Tool (SWAT) and its testing in watersheds has become essential to check developers' claims of its applicability. The SWAT model performance on Kliene Nete Watershed (Belgium) is examined. Given the watershed's characteristic of a low lying; shallow ground water table, the test becomes an interesting task to perform. This paper presents calibration and validation of the watershed covering area of 581km^2. Flow separation is carried on using Water Engineering Time Series PROcessing tool (WETSPRO) and shows that around 60% of the total flow is contributed by base flow. Altogether seven SWAT model parameters have been calibrated with heuristic approach for the time frame of 1994-1998. Validation of these calibrated parameters in another independent time frame (1999-2002) is carried out. The parameter CH_k2 (Channel Effective Hydraulic Conductivity) is found to be the most sensitive. Nash Sutcliff Efficiency (NSE) values for the calibration and validation periods are found to be 74 and 67 percentage, respectively. These 'goodness-of-fit' statistics, supported by graphical representations, show that the SWAT model can simulate such watershed with reasonable accuracy.

Key words: SWAT, WETSPRO, Kliene Nete Watershed (Belgium), NSE

Introduction

Models are used in decision making applications to select an optimal courses of action, and are often constructed to enable reasoning within an idealized logical framework about the processes. Watershed models are essential for studying hydrologic processes and their responses to both natural and anthropogenic factors, but due to model limitations in the representation of complex natural processes and conditions, models usually must be calibrated prior to application to closely match reality (Bastidas *et al* 2002). Stream-flow, which is known as integrated process of atmospheric and topographic processes, is of prime importance to water resources planning (Kahya and Dracup 1993). This becomes an essential task for low lying catchments that are more susceptible to flooding and inundation; hence, subsequent water resources planning and management on such catchment becomes a top priority.

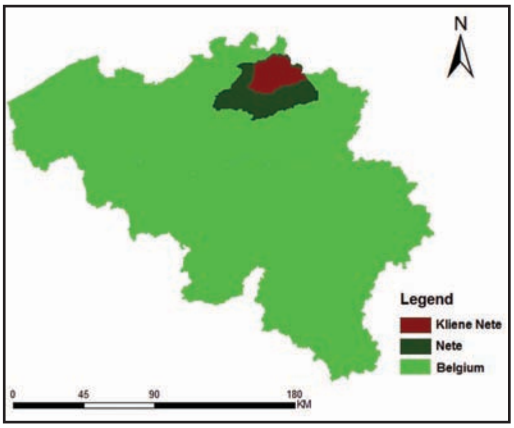
Use of process based, easily accessible, public domain modelling software like the Soil and Water Assessment Tool (SWAT) is an easy option for hydrologists while considering watershed modelling. Here, a case study is conducted for a 581km^2 Kliene Nete watershed in Belgium. The main objectives of the study are: (a) to see the simulation ability of SWAT in the case of a low-lying, low ground water tablecatchment, and (b) to see the most sensitive parameters for such a catchment. It is difficult to measure the most sensitive parameters of such a model, to which a physical meaning is often assigned, as well as a spatial representativeness, and of which the value normally is obtained in the calibration process (Refsgaard and Storm 1996, Heuvelmans *et al* 2004). For this case, the analysis of sensitive parameters was achieved by sensitivity analysis, which is new in the SWAT 2005 version (Griensven 2005). Although SWAT 2005 offers an 'auto-calibration' option, an heuristic approach has been applied to calibrate. The auto-calibration algorithm is based on maximizing certain objective functions; hence, it will return parameter values accordingly. Despite being fast and less subjective, automated calibration has major limitations by the assumption made for the objective function and the existence of local minima that are closely related to the number of model parameters (Willems 2000). Hence, automated calibration should be used with caution. On the other hand, the heuristic approach, which is time-consuming, makes the use of modelers' knowledge and experience and, therefore, can prove to be useful.

Materials and Method

The watershed

The Flanders region of Belgium is subdivided into 11 catchments. Among them, Kleine Nete is sub-catchment of Nete Catchment and is located northeast of Brussels; it has an area of about 581km^2 at Grobbendonk. Kleine Nete River has its source near Retie in the Belgian province of Antwerp. In Grobbendonk, the river is joined by the water of the Aa. It flows in a southwest direction past the towns of Herentals and Nijlen before joining the Grote Nete at Lier. See Map 1.

The elevation of the watershed varies from 7.62 m to 92.76 m, with a mean elevation being 23.17 m; hence, it is a relatively flat catchment. Sand is the predominent soil type in the catchment. It covers almost 94% of the watershed, followed by land dunes covering around 5%, and clay

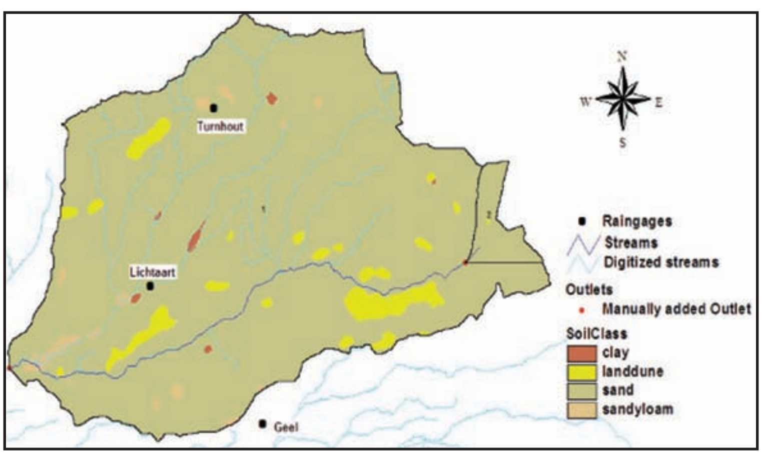


Map 1 Belgium, Nate Basin and Kliene Nete Watershed

around 1%. The watershed has almost 55% as agricultural area (covered by pasture, corn, etc.), 25% as mixed forest, and the rest as high density residential area.

The modeling tool

SWAT is a continuous time model that operates on a daily time step at catchment scale, a physically based semi-distributed hydrological model developed by the U.S. Department of Agriculture in order to quantify the impact of land management practices on water quantity, sediment and water quality in large complex watersheds with varying soils, land use and management conditions over a long period of time (Arnold *et al* 1998, Neitsch *et al* 2001). The SWAT



Map 2. Soil Types

is a process-based model that assesses long-term impacts of management practices including empirical relationships. The model has been widely used but also further developed in Europe (Griensven *et al* 2002). It simulates at the hydrologic response units (HRU) level. HRUs are lumped land areas within the sub-basin with unique combinations of soil-type, land-use and management. It is limited to working with a minimum time step of one day and at least two sub-basins.

The data

Hydro-meteorological data such as daily mean temperature (°C), daily rainfall (mm), daily mean relative humidity (%), daily mean wind speed (m/s), number of sunshine hours per day (-) are used. Apart from this, land-use data, soil data, digital elevation module (50m x 50m resolution), and river network are used for model build-up. For calibration and validation, daily river series observed at flow gauging station 52 (Grobbendonk) are used.

Setting the SWAT model

As AVSWATX is designed for use in the USA, to adapt it for use in Belgium some default files such as 'crop.dat', 'crop.dbf', 'fert.dat', 'fert.dbf', 'urban.dat, 'urban.dbf', 'usersoil.dbf' and 'userwgn.dbf' are modified. For the model built up, the Nete watershed is digitized using the SWAT extension in Arc View 3.2, with the projection type set as Lambert conformal conic and spheroid type set as International 1909. The threshold of 1000 ha and the digitized streams shape file are used for the digitizing process.

HRU's	Landuse	Soil Type	% covered
1	Berm	Sand	14
2	Berm	Land dune	01
3	Pasture	Sand	20
4	Corn	Sand	39
5	Forest	Sand	24
6	Forest	Land dune	02

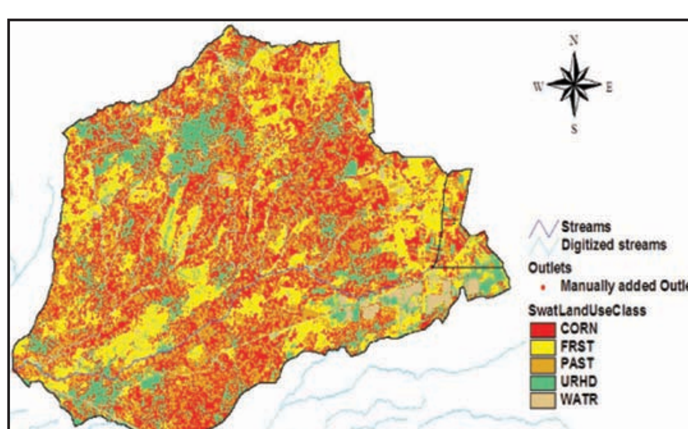
Table 1. Different HRU's and Percentage of Coverage for Kleine Nete Basin

Subsequently, land use and soil type maps are incorporated into the model. (See Maps 2 and 3.) After overlaying these data threshold values of 5% for land data and 3% for soil data are chosen. This is to limit the number of HRU's that would result for the given combination of land use and soil data. The Penman-Monteith method is used for calculation of evapo-transpiration and the Muskingum method is used for flow routing. The resulted HRU's are shown on Table 1.

Result and Discussion

Flow filtering

A time series of total rainfall-runoff discharges can be split into its subflows (such as the overland flow, the subsurface flow or interflow, and the groundwater flow or baseflow) using a numerical digital filter technique. Its



Map 3. Land Use

physical interpretation is based on the linear reservoir modelling concept (Willems 2003). It is the essential technique to be implemented after the model built up so that evaluation of calibration processes in terms of different flow components such as baseflow, surface flow and total water yield can be made. Water Engineering Time Series PROcessing Tool (WETSPRO) software is used for this filtering process. (WETSPRO was developed by Prof. P. Willems, Hydraulics Laboratory, Katholieke Universiteit Leuven, Belgium.) WETSPRO is a time series processing tool that allows the users to conduct:

- Sub-flow filtering.
- Peak flow selection and related hydrograph separation; for quick flow and slow flow periods; and related low flow selection.
- Construction of the different model evaluation plots.

Parameter	Description	Relative Sensitivity
Ch_k2	Channel Effective Hydraulic Conductivity	4.890
surlag	Surface Runoff Lag Time	2.510
ch_n	Manning Coefficient for Channel	0.692
CN2	Initial SCS Runoff Curve number for Wetting Condition-2	0.139
SLSUBBSN	Slope of Sub-basin	0.108
SLOPE	Average Slope Steepness	0.074
GWQMN	Threshold Depth for shallow aquifer for flow	0.063
ALPHA_BF	The Base Floe Alpha Factor	0.039
canmx	Maximum Canopy Storage	0.033
SOL_AWC	Soil Available Water Capacity	0.021
sol_k	Saturated Hydraulic Conductivity of Soil	0.017
rchrg_dp	Deep Aquifer Percolation Factor	0.013
GW_REVAP	Ground Water "Revap" Coefficient	0.013
sol_z	Soil Depth from Surface to Bottom of layer	0.010
GW_DELAY	Ground Water Delay Time	0.009
ESCO	Soil Evaporation Compensation Factor	0.008
sol_alb	Moist Soil Albedo	0.005
BIOMIX	Biological Mixing Efficiency	0.002
epco	Plant Uptake Compensation Factor	0.001
REVAPMN	Threshold Depth of water in shallow aquifer for "revap"	0.000

Table 2. Parameters Used for Flow Calibration and Their Relative Sensitivity

The WETSPRO tool makes use of a continuous time series of any hydrological variable as input (Willems 2009). Analysis of observed flows on WETSPRO shows that about 60% of the flow is contributed by base flow.

Sensitivity analysis

Sensitivity analysis refers to the identification of some few parameters that have important effects in the model. It is the prior step to model calibration. It speeds up the optimization process by concentrating on finding the optimum values for a limited number of parameters that govern the model, and it is performed using LH-OAT (LH (Latin-Hypercube) - OAT (One-factor-At-a-Time)) technique. The description of parameter used for stream-flow calibration and their relative sensitivity resulted after sensitivity analysis is presented in Table 2.

Calibration and validation

Calibration is the process of gathering the conceptual parameters, and is done as a forerunner to testing of the model hypothesis. During calibration, parameters of unmeasured variables are estimated using information that is available from the real system. The 11 years of observed series at flow gauging station 52 (Grobbendonk) is divided into three time frames, namely: the 'warming-up', 'calibration' and 'validation' periods from 1992-93, 1994-98 and 1999-2002, respectively. The provision of the warming up period is to initialize unknown variables such as moisture content. An heuristic approach (i.e., manual calibration based on experience) is used to decide which parameters to adjust to obtain 'good' fit. During the validation period, the model is run with the same model parameters obtained from the calibration period to see how well the calibrated parameters work in another independent period.

Generally the effects of the parameters on the system include those impacting the surface response (CN2, SOL_AWC, and ESCO), those impacting the subsurface response (GW_REVAP, REVAPMN, GWQMN, ALPHA_BF, GW_DELAY, RCHRG_DP, etc.), and those impacting the shape of the hydrograph (Ch_k2, SURLAG, ALPHA_BF, etc.). For our case, viewing the pre-calibrated result on temporal level as well as global level and seasonal level, following parameters, were optimized as shown in Table 3. This calibration followed after making systematic use of sensitivity analysis results and problem at hand.

CN_2 was calibrated to adjust the surface flow, and it was increased to 90 for HRU–BERM (urban) because of its higher potential to contribute to surface runoff. Another

Parameter	Units	File Type	State	HRU					
				BERM	BERM	PASTURE	CORN	FOREST	FOREST
CN_2	-	*.mgt	Initial	77	77	60	77	60	60
			Final	90	90	80	80	60	60
GWQMN	mm	*.gw	Initial	0	0	0	0	0	0
			Final	350	450	350	350	350	450
SURLAG	day	*.bsn	Initial	4					
			Final	1					
ESCO	-	*.hru	Initial	0.95	0.95	0.95	0.95	0.95	0.95
			Final	0.95	0.95	0.4	0.3	0.4	0.4
Ch_N2	-	*.rte	Initial	0.014					
			Final	0.02					
Ch_k2	mm/h	*.rte	Initial	0					
			Final	0.45					
ALPHA_BF	days	*.gw	Initial	0.048	0.048	0.048	0.048	0.048	0.048
			Final	0.048	0.048	0.01	0.3	0.5	0.5

Table 3: Optimized Parameters with Their Initial and Final Values

parameter to adjust the same flow component was ESCO, which accounts for the easiness with which water from lower layers is available for evaporation. Lower value accounts for higher evapotranspiration. The value of ESCO was decreased to 0.3 for corn fields because of its high potential for evapotranspiration and less canopy cover. For adjusting subsurface flow (baseflow), GWQMN was adjusted. The value of GWQMN was increased to 350 mm and 450 mm for sandy and land dune, respectively, because of lower water holding capacity of sand compared with land dune. The default value of 0.014 for Ch_N2 is, of course, unrealistic; hence, it was increased to 0.02, a typical value for channel having predominant sandy soil. For low lying catchments under study, where ground water depth is near or above the river bottom, parameter Ch_k2 adjusts the water exchange from ground water to river and was found to be very sensitive to adjust the shape of hydrograph, especially for low flows. ALPHA_BF was also used to smoothen the shape of hydrograph, especially for recession period, and it was increased to 0.5 for HRU–FOREST because of higher root depth distribution of forest; hence, higher water holding capacity. Optimized parameters are listed on Table 3.

After tuning the above stated parameters (Table 3), the Nash-Sutcliff Efficiency (NSE), a widely used 'goodness-of-fit' statistics indicator to access the goodness of model to simulate the flows (Nash and Sutcliffe 1970), was found to be

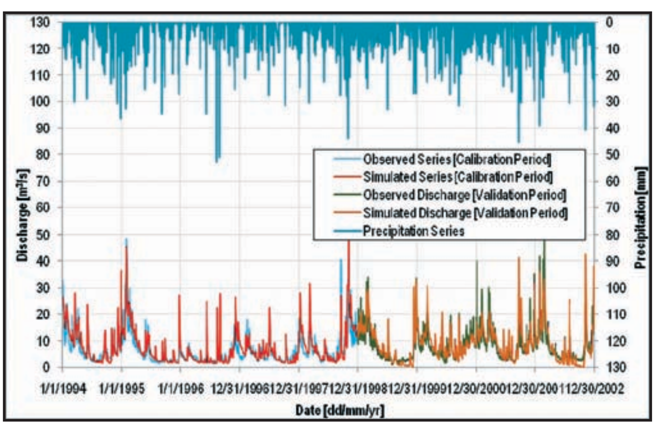


Figure 1. Observed and Simulated Discharge Series for Calibration and Validation Periods

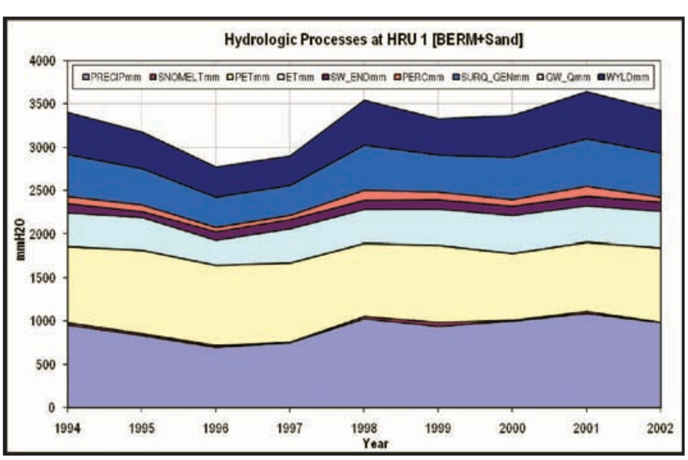


Figure 2: Hydrological Processes at HRU1 (BERM+SAND)

74 percentage for the calibration period and 67 percentage for the validation period. Figure 1 shows the observed and simulated hydrograph both for the calibration period and the validation period. Apart from the flow comparison in temporal level, hydrological processes have also been accessed to HRU Level as shown in Figure 2. Only HRU-1 (BERM+Sand) is presented as the representative one. As can be read from the figure, the hydrological processes have followed the trend of precipitation. Precipitation on 1998 (calibration period) and 2001 (validation period) was highest and the response on water yield was clearly high on those years. Most importantly, the soil water content showed no marked difference with trend of precipitation which reflects good performance of the model because the soil water content should be almost constant whatever the trend of precipitation is.

Conclusions

By tuning seven parameters, the calibration and validation of the SWAT model for a low lying catchment (Kliene Nete) was carried out. The parameter CH_k2, which allows interaction between the ground water flow and river flow, was found to be the most sensitive for such catchment. The NSE value was found to be 74 percentage for calibration and 67 percentage for the validation period. The slight underperformance of the model in validation period may be due to the fact that there is significant change in precipitation during the calibration period (852.7 mm/year) and the validation period (1002.5 mm/yr). Performance of the model is also known to be affected by a significant change in trend of annual average precipitation (Pipat *et al* 2005).

Owing to the general trend of the NSE value for acceptance of rainfall-runoff model, this calibration can be adjudged as good because of having NSE around 70 percentage, which is quite acceptable for water engineering problem assessment and application. The fairly matching of hydrograph as well as hydrological processes on each HRU's also supports it. The calibrated parameter values can also be used for further stream-flow simulations in this catchment.

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