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# Calibration and Validation Of Swat For Sub-Hourly Time Steps Using Swat-Cup

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## Abstract

SWAT is a semi-distributed, lumped parameter, continuous time model that simulates hydrology and water quality in watersheds. Traditionally, the model operated at a daily time step and it estimated the influence of landuse and management practices on water and agricultural chemical yields in a watershed. The daily time step format may not be sufficient to capture the impact of flashy storms where peak flows last for minutes only and are not reflected in daily average flows. A sub-hourly SWAT model for urban applications was developed but is not widely used. The main goal of this study was to present a basic methodology to calibrate sub-hourly SWAT models using SWAT-CUP. SWAT was tested using data from the Blunn Creek Watershed in Austin, Texas. The model was calibrated and evaluated using two separate representative 2-year periods bracketing hydrologic conditions experienced in the watershed. Results show that the sub-hourly SWAT provides reasonable estimates of stream flow for multiple storm events.

***Keywords:*** *Sub-hourly, SWAT, SWAT-CUP, SUFI-2, Uncertainty, Hydrological Modelling*

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## 1. Introduction

SWAT (Soil & Water Assessment Tool) is a river basin scale model developed to quantify the impact of land management practices in large, complex watersheds [1]. Since SWAT is a distributed hydrological model, there are potentially many parameters that can affect the stream flow assessment. Investigating the potential impact of all these parameters can be a very difficult task due to the high number of input parameters at one of several different levels of detail: watershed, subbasin, or HRU and which also highly interlinked and interdependent on each other. Most of the available SWAT studies use a daily time step format to assess hydrological changes. [2,3,4]. A sub-hourly time step was developed and released in 2010 [5]. The intention was to increase accuracy in modeling single storm events, peak flows and provide essential hydrologic metrics that maybe important predictors of stream health and in studying the impact of low impact development. A sub-hourly time step format accounts for high temporal resolution that is needed in urban scenario analysis including controlling for stormwater runoff, reducing potential flooding and providing healthy environment for aquatic life. On the other hand, sub-hourly time step model results in a more complex model since it accounts for more details than daily or monthly time steps, thus making the calibration-validation process more complicated. The complexity of modern hydrologic models requires narrowing model parameters down to just those that have the greatest influence on the processes being modeled. Sensitivity analysis is one method used before the calibration process in order to study the variability in model outputs with respect to changes in individual model parameters. This type of analysis is considered essential in order to determine the parameters that should be included in the calibration process [6]. These methods also assist in facilitating model evaluation in terms of the accuracy of the fit of simulated data to measured or historical data using several combinations of input parameters.

Most hydrological models must be calibrated so their predictions can be used for tasks ranging from regulation to research [7]. Distributed hydrological models often incorporate inputs from numerous sources including weather, soils, land use, surface water, groundwater and management practices. Manual calibration depends heavily on the modeler adjusting model parameters until the output match closely the measure data. This can be difficult and time-consuming process due to the complexity of some large scale models with many objectives and the numerous interactions between these objectives [8]

The process of calibration entails testing a model's ability to accurately simulate the behavior of the system of interest using known inputs and uncertain parameters, and comparing the outputs to observed data [7]. These parameters can be

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quantified through direct measurement or in some cases, these input parameters are unknown and must be estimated using the current literature or through the calibration process itself. It is important that every possible effort be made to minimize the difference between simulated and measured data. This would be essential to estimate high flows and potential flooding and erosion in addition to assessing the impact of Best Management Practices (BMPs) scenarios. Additionally, to make informed decisions concerning remedial action or environmental compliance, there should be a clear demonstration that model simulations are reasonably representative of the site being studied [9].

Therefore, utilizing an automated model such as SWAT-CUP, a program designed to integrate various calibration/uncertainty analysis algorithms into the SWAT model, rather than manual calibration becomes very important to save time and achieve higher accuracy. SWAT-CUP provides good visualization of calibration parameters and allow the user to perform several sensitivity, calibration and validation analyses of SWAT.

Model validation follows model calibration. The validation process involves using observed or measured data of a different time period than the calibration period and analyzing the goodness-of-fit (estimation responses) and checking whether the calibrated model's predictive performance is in accordance with observed/ measured data. The definition of sufficient accuracy of the validation process can vary based on the use and model's goals [10].

The wider use of SWAT using sub-hourly data for more accurate hydrologic modeling depends on a demonstrated successful calibration and validation of SWAT and uncertainty analysis. This research offers a framework for evaluating sub-hourly SWAT models using data from the Blunn Creek Watershed in Austin, Texas. The selection of the watershed was based on various criteria including; climatic conditions and potential flashy storms, current and future urban development and finally availability of measured data.

## Model and Calibration and Sensitivity Program Description

### *SWAT*

The hydrologic model used for this study was the SWAT 2012 model, a semi-distributed, lumped parameter, river basin scale, continuous time step model developed to assess and predict hydrological processes and changes in large basins [1]. This model was developed to operate on a daily time step and it is often used to estimate the impact of land use and management on water and agricultural chemical yields in a watershed. The major components of the model include hydrology, soil, land management, plant growth, pesticides, nutrients, weather, reservoir routing, and erosion.

A sub-daily time step SWAT model was initially developed and added to SWAT 2005 in order to simulate rainfall-runoff processes and realistically capture the long-term flow and water quality trends in watersheds that are experiencing urbanization [5]. It is worth mentioning at this point that buildup/washoff cannot be done on daily basis to estimate first flush water quality while it can be easily done using subhourly time step models. Additional efforts are needed to improve low flow predictions since low flows are dominated by base flow and SWAT still utilizes soil water and ET estimation routines at daily time steps [5].

### *SWAT-CUP*

SWAT Calibration and Uncertainty Procedures (SWAT-CUP) is a program designed to integrate various calibration/uncertainty analysis algorithms into the SWAT model. These algorithms include SUFI-2 [11], GLUE [12], and ParaSol [13]. SWAT-CUP allows the user to select one of these algorithms and run the procedure several times until convergence between simulated and observed objectives is reached [14].

SUFI-2 is a multi-site semi-automated inverse modeling routine [11]. Calibration in SUFI-2 is achieved when two rules, termed the P-factor and the R-factor, are satisfied. The P-factor, which ranges between 0 percent and 100 percent is the percentage of measured data bracketed by the 95 percent Prediction Uncertainty (95PPU). The R-factor, which ranges between 0 and infinity, is the average width of the 95PPU band divided by the standard deviation of the measured data. A Latin Hypercube is used to sample from the distributions of each uncertain parameter to create n parameter sets and n values for each output. Then an objective function is calculated using the simulated output and measured values for that same output. A matrix that uses a relationship between a change in the objective function that corresponds to a change in each parameter value is generated to assess the simulations. Goodness- of- fit is assessed and the process is done again, narrowing the uncertainty bands on each parameter. A perfect match between observed and simulated flows is indicated by Nash-Sutcliff (NS) and coefficient of determination, R2, values of 1. This would reflect a simulation where, based on parameter uncertainty, 100 percent of the observed data fell within the 95PPU; however, due to measurement errors and conceptual model uncertainty, this is a rare occurrence. SUFI-2 starts by assuming a large parameter uncertainty that is within a physically meaningful range, to ensure the measured data fall within the 95PPU [11]. The model decreases this uncertainty range gradually while monitoring the values of goal factors (e.g. Objective functions such as NS) between the measured and simulated data. Generally, model calibration can be considered satisfactory if Nash Sutcliffe (NS) value > 0.50 [15]. The NS coefficient can be expressed as follows [16]:

$$NS = 1 - \frac{\Sigma(Qo - Qm)^2}{\Sigma(Qo - \overline{Qo})^2} \qquad \text{(Equation 2)}$$

Where: $Q_o$ is observed values
$Q_m$ is modeled values
$\overline{Qo}$ is average observed values

SUFI-2 allows several iterations, and in each iteration previous parameter ranges are updated by calculating the sensitivity matrix and the equivalent of a Hessian matrix [17], followed by the calculation of a covariance matrix, 95 percent confidence intervals of the parameters, and a correlation matrix. Parameters are updated so the new ranges are always smaller than the previous iteration and continue until centered around the best simulation [11]. In addition to being widely used in the literature, SUFI-2 procedures were applied due to its easy implementation in comparison to other procedures and the low number of model runs needed to reach good prediction [18].

## Methodology

### *SWAT Setup*

The case study is based on research conducted in Austin, Texas and specifically the Blunn Creek Watershed (Figure 1). The watershed was estimated to have 34.8 percent impervious cover in 2003 and the creek has a length of 4.82 km. The study area is a rapidly urbanizing 2.58 km2 watershed with a total population of 6,000 as of 2013 and is expected to increase by 12 percent in less than 10 years [19]. Part of the selection of this model is driven by plans by the City of Austin to evaluate the impact of low impact development structures on stream health in all watersheds within city limits. Very few studies were done in urban environments using SWAT although current effort in SWAT development is targeting urban applications [20].

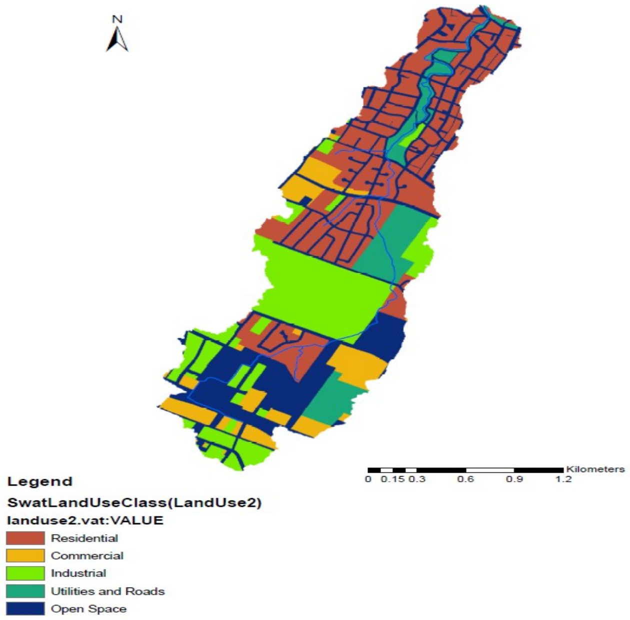


**Figure 1. Blunn Creek Watershed in Austin, Texas**

SWAT was run using 15-minute rainfall data from the Flood Early Warning System (FEWS) and Water Quality Monitoring (WQM) sections at COA (http://www.austintexas.gov/department/flood-early-warning-system), sub-hourly temperature data from the Austin and Austin-Bergstrom NOAA weather stations (WGEN_US_COOP_1960_2010), a 3-meter integer Digital Elevation Model (DEM) developed by COA based on 2003 LIDAR data and SSURGO soils data from NRCS. A landuse raster layer develop by COA was used. Geometry of the channels for each sub-basin was modified after conducting a cross section analysis for the DEM layer. The cross section analysis was done by converting the DEM layer using an interpolation line tool under 3D Analyst menu in ArcGIS, creating a profile graph (Figure 2) and calculating the dimensions of an equivalent trapezoidal cross-section [21]. The data was then included in SWAT's main channel input file (.rte).

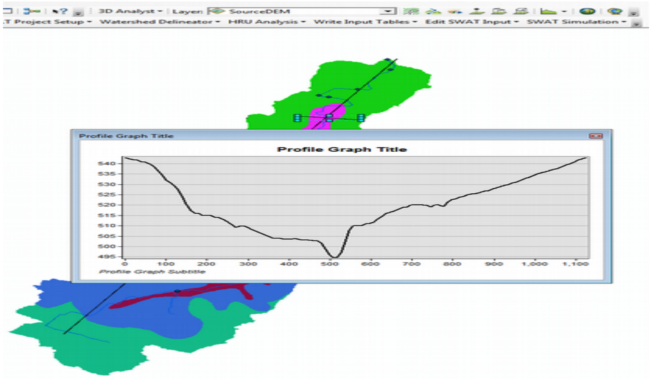


**Figure 2. Screenshot of Cross section analysis for the DEM layer using 3D Analyst tool in ArcGIS that can be directly used in ArcSWAT.**

### *SWAT-CUP Setup*

A sub-hourly 15minute time step SWAT model was run through the ArcGIS environment. Because the default output is in a daily time step, the output file was modified to include sub-hourly output. It is worth noting that SWAT-CUP version 5.1.4.2 used in this study is designed for daily, monthly and yearly time steps and while it was assumed that sub-hourly input data can be read and processed as well, minor modification to the fig.fig file located in the TXINOUT folder in a SWAT project by including a new saveconc command for sub-hourly output. This command saves flow, sediment and water quality data from a specified point to a file in SWAT that is directly used by SWAT-CUP. A case study was designed and SWAT-CUP was applied using SUFI-2 calibration and uncertainty parameters.

### *Calibration Parameter Selection*

The primary parameters responsible for streamflow simulation for the Blunn Creek Watershed are shown in Table 1.

Table 1. Initial calibration parameters given by SWAT-CUP

| **Parameter name** | **Description** |
|---|---|
| **r__CN2.mgt** | Initial SCS runoff curve number for moisture condition II |
| **v__ALPHA_BF.gw** | Baseflow alpha factor (1/day) |
| **v__GW_DELAY.gw** | Groundwater delay (days) |
| **v__GWQMN.gw** | Threshold depth of water in the shallow aquifer required for return flow to occur (mm) |
| **v__GW_REVAP.gw** | Threshold depth of water in the shallow aquifer for "revap" to occur |
| **v__ESCO.hru** | Soil evaporation compensation factor |
| **v__CH_N2.rte** | Manning roughness for main channel |
| **v__CH_K2.rte** | Effective hydraulic conductivity |
| **v__ALPHA_BNK.rte** | Baseflow alpha factor for bank storage |
| **r__SOL_AWC(1).sol** | Available water capacity of the soil layer (mm H2O/ mm soil) |
| **r__SOL_K(1).sol** | Saturated hydraulic conductivity (mm/hr) |
| **r__SOL_BD(1).sol** | Moist bulk density (g/cm$^3$) |
| **v__SFTMP.bsn** | Snowfall temperature (ºc) |

Observed stream discharges at USGS Station 08157700 were retrieved in 15-minute format from USGS (USGS, 2014). The stream data was only available for the two-year period of 1998-1999 which was used for calibration and for the 2-year period of 2001-2002 which was used for validation purposes. A 24-year simulation from 1986 to 2010, using the weather data from COA, was executed for the sensitivity analysis, excluding outputs from the first two years that were used as a warmup period for antecedent conditions. The minimum and maximum ranges suggested by the SWAT-CUP analysis were used to define the parameters. The calibration and validation periods were representative typical flow regime for this creek according to COA staff.

### *Uncertainty Analysis*

In this study, an uncertainty analysis was performed after each calibrating procedures based on the ranking results provided by statistical measurements such as; P-factor, R2 and NS. Default values suggested by van Griensven et al. [22] were chosen as minimum and maximum ranges for the respective model parameters (Table 1). The objective function type was selected to be NS coefficient with 0.5 minimum value of objective function threshold to separate the behavioral solutions (with NS better than 0.5) from the non-behavioral ones (with NS lower than 0.5). The effect of using behavioral solutions is to obtain smaller p factor, or a smaller prediction uncertainty [23]. The output of the initial run was generated in 15-minutes time steps. The pre-processing procedures, which include running the Latin Hypercube Sampling program was executed followed by running SUFI-2 procedures. The analysis for all parameters utilized in the initial run was generated in conjunction to calibration outputs. Only the most sensitive parameters based on t-statistic (measures the size of difference relative to the variation in sample data) and p-value (measures how extreme the observation is) were selected for a second run of calibration [23].

## Results

### *SWAT-CUP and Calibration Parameter Selection*

The results of a global sensitivity analysis of stream-flow parameters using Latin hypercube regression systems resulted in eight parameters selected for calibration, which are ALPHA_BF, GW_DELAY, GWQMN, CH_N2, CH_K2, SOL_AWC, ESCO, SOL_K (Table 2). These parameters were ranked based on a t-test and their p-value in terms of significance.

**Table 2. Parameter sensitivities for SUFI-2**

| **Parameter Name** | **t-stat** | **P-value** |
|---|---|---|
| **V__CH_K2.rte** | 5.36 | 0 |
| **V__GW_DELAY.gw** | -5.24 | 0 |
| **V__GWQMN.gw** | -2.98 | 0.0035 |
| **V__CH_N2.rte** | 1.95 | 0.053 |
| **V__ALPHA_BF.gw** | 1.33 | 0.18 |
| **R__SOL_AWC(..).sol** | 1.28 | 0.2 |
| **R__SOL_K (..).sol** | 0.51 | 0.61 |
| **V__ESCO.hru** | -0.46 | 0.64 |

Table 3 shows the minimum and maximum ranges of the parameters as defined van Griensven et al. [22] and the fitted value for the sub-hourly calibration for Blunn Creek as obtained from SUFI-2. Note that the qualifier "v" in the parameter name means that the parameter value is replaced by the fitted value and "r" means that the existing parameter value is multiplied by (1 + the fitted value) [11].

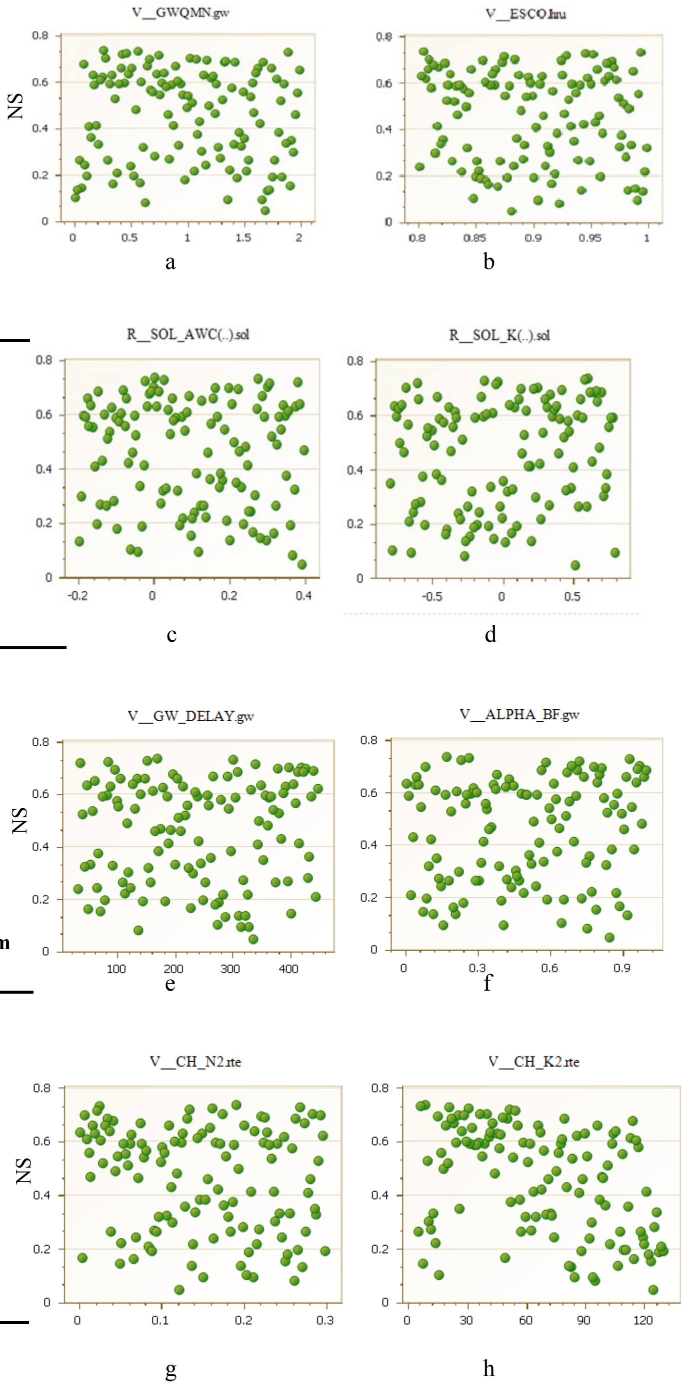
Table 3. Stream flow calibration parameter uncertainties

| **Parameter Name** | **Fitted Value** | **File name** | **Minimum value** | **Maximum value** |
|---|---|---|---|---|
| **V__ALPHA_BF.gw** | 0.17 | .gw | 0 | 1 |
| **V__GW_DELAY.gw** | 168.25 | .gw | 30 | 450 |
| **V__GWQMN.gw** | 0.25 | .gw | 0 | 2 |
| **V__ESCO.hru** | 0.80 | .hru | 0.8 | 1 |
| **V__CH_N2.rte** | 0.038* | .sub | 0 | 0.3 |
| **V__CH_K2.rte** | 8.64 | .sub | 5 | 130 |
| **R__SOL_AWC(..).sol** | 0.0025 | .sol | -0.2 | 0.4 |
| **R__SOL_K(..).sol** | 0.61 | .sol | -0.8 | 0.8 |

*Value Manually generated

The Manning coefficient (Ch_N2) fitted value suggested by SWAT-CUP was not realistic in the initial run (0.26). One possible explanation is that baseflow was not being well simulated in SWAT due to lack of input in precipitation during non-rainy days. Based on COA staff, the baseflow could be, at the time, resulting from residents emptying swimming pools into the stream. This resulted in water balance errors and that was compensated by SWAT-CUP by increasing the Manning roughness coefficient. The Manning coefficient value was calculated manually using Manning equation, observed flow data and geometry of the channel.

The distribution of the number of simulations in the parameter sensitivity analysis was plotted after comparing the parameter values with the objective functions for the sub-hourly calibrations (Figure 3). The x-axis in this figure is the parameter value and the y-axis is the objective function value (NS).



a b

c d

e f

g h

**Figure 3. Sensitive parameters during sub-hourly calibration for the Blunn Creek Watershed vs. objective function. a: Threshold depth of water in the shallow aquifer required for return flow to occur, b: Soil evaporation**

**compensation factor, c: Available water capacity of the soil layer, d: Saturated hydraulic conductivity, e: Groundwater delay, f: Base flow alpha factor, g: Manning roughness for main channel, h: Effective hydraulic conductivity.**

*Calibration and Validation results*

After observing model performance and running initial iterations using SWAT-CUP with all input parameters to be optimized, it was noticed that the baseflow was systematically overestimated at the outlet of the watershed (in subbasin 1), and there is a delayed shift in the flow peaks. To show this, a blow up of the result graph for the dates between 01/01/1998 and 06/19/1998 is shown in Figure 4.

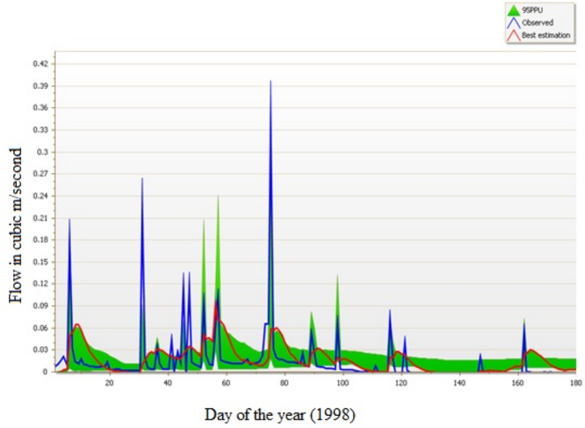


**Figure 4. Flow results with initial parameters for half of 1998 during the calibration period.**

The following steps were taken to adjust input parameters values based on SWAT-CUP to improve the results. Baseflow factor (ALPHA_BF) was increased, deep percolation (GWQMN) was increased, and the groundwater revap coefficient (GW_REVAP) was increased. To correct the peak flow delay, the slope (HRU_SLP) was increased, and the value of overland flow rate (SLSUBBSN) was decreased. Figure 5 shows the improvement in the results after applying these steps. The new values for the five parameters adjusted are shown in Table 4. Clearly, adjusting the previous parameters resulted in simulated data that match the observed data better with respect to peak flow and time to peak. It is worth noticing that 3 of the five parameters manually adjusted that impacted the calibration results were not selected by SWAT-Cup as most sensitive. This shows that while users can use SWAT-CUP to do initial calibration runs, fine tuning the calibration should be done on any parameters that could impact results regardless of SWAT-CUP sensitivity results. It is worth noting that The SWAT BFLOW Program [24] was run and the results gave and ALPHA_BF of 0.28, 0.15, and 0.11 for the three passes, respectively. Both the original fitted value and the adjusted value fell within that range.

Table 4. Manually adjusted parameters to reduce baseflow and match peak flow times.

| Variable | Old | New |
|---|---|---|
| **ALPHA_BF: Baseflow alpha factor [1/day]** | 0.17 | 0.11 |
| **GWQMN: Threshold depth of water in the shallow aquifer required for return flow to occur [mm]** | 0.25 | 1 |
| **GW_REVAP: Groundwater "revap" coefficient** | 0.11 | 0.13 |
| **SLSUBBSN: Average slope length [m]** | 60.9 | 15.2 |
| **HRU_SLP: Average slope stepness [m/m]** | 0.08 | 0.2 |

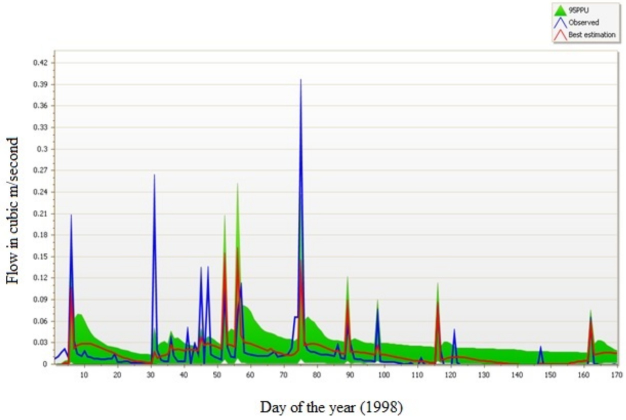


**Figure 5. Flow results after manual adjustment of five parameters for half of 1998 during the calibration period.**

The goodness-of-fit/best estimation and efficiency of the model before and after calibration were tested using the main objective functions R2 and NS. The highest value achieved for R2 and NS was 0.74 for each.

The water balance of the model results for the calibration period was calculated in order to assess the validity of the model (Figure 6). The inflow of the water balance is precipitation and the return flow originated by groundwater as it is defined in SWAT 2012 manual [25]. The outflow/losses are represented by surface runoff, evapotranspiration and percolation. It should be noted that irrigation application was applied with a frequency of nine applications for each HRU and with a total volume of 227.84 mm as SWAT output file showed for the 24-years simulation period. The following land uses were excluded from irrigation application: parks, undeveloped lands, open spaces, transportation and infrastructure, and camp ground. The error percentage was calculated by dividing (outflow-inflow) by (inflow) multiplied by 100.

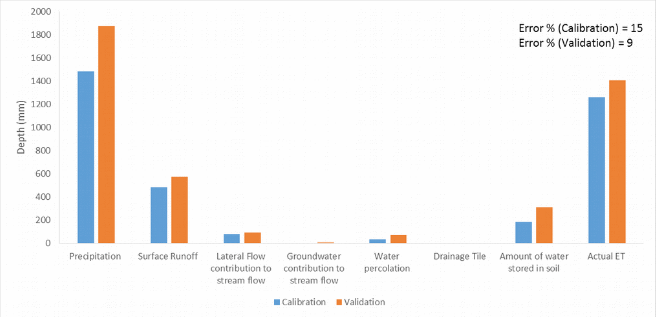


**Figure 6. Average annual water balance components and error percentages (comparing observed inflows flows to calibrated and validated flows) at the Blunn Creek Watershed**

Validation procedures for the period between 2001 and 2002 were conducted to ensure the validity of the calibration process. NS value for validation was 0.67 and R2 value equals to 0.70 for the sub-hourly time step model. A scatter graph of the results is shown in Figure 7. All in all, the comparison between observed and simulated stream flow showed that there is a good agreement between the observed and simulated discharge which was verified by higher values of R2 and NS. Results also showed that the p-factor, which is the percentage of observations bracketed by the 95 % prediction uncertainty (95PPU), brackets 56 % of the observations and r-factor equals to 0.54 which are acceptable percentages based on Singh et al., [26] (Table 5; Figure 7).

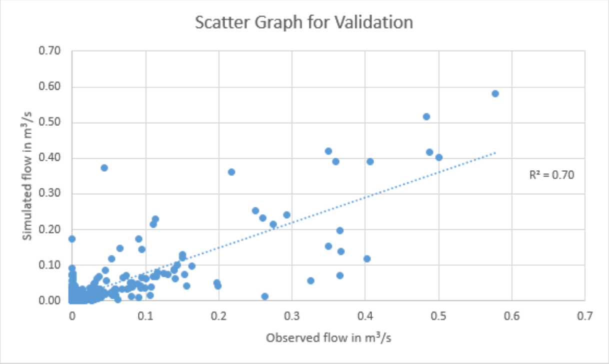


**Figure 7. Scatter graph showing observed and simulated flows for the validation period.falspha**

Table 5. Results of measures that reflect the significance of the analysis for the validation.

| **Variable** | **Value** |
|---|---|
| p-factor | 56% |
| r-factor | 0.54 |
| $R^2$ | 0.70 |
| NS | 0.67 |

It should be noted that both calibration and validation procedures were run each for an entire two-year period preceded to another two years warming up period. These results show that SWAT-CUP can be used to calibrate and validate SWAT when used for sub-hourly time steps. Accordingly, SWAT can be used to estimate peak flow times during a storm and can be used for applications that occur at a sub-hourly scale such as low impact development hydrology.

### Conclusions

Sub-hourly simulation model has been developed successfully using SWAT 2012 and calibrated using SWAT-CUP and SUFI2 procedures. SWAT-CUP presented an effective graphical interface in order to visualize calibration components such as observed data, simulated data, 95 PPU and the best fit model. The sensitivity analysis adopted for stream flow calibration was successful and contributed to optimizing the total number of uncertainty parameters and accordingly more efficient calibration procedures. SUFI-2 gave good results in minimizing the differences between simulated and observed data for the sub-hourly time step model. The results from SUFI for subhourly simulations was not enough to give acceptable results. Problems in simulating baseflow (between events) originally produced low NS and R2. Manual adjustments based on knowledge of SWAT and the watershed were done to improve the modeling results. Adjustments were also made to 5 parameters including 3 parameters that SUFI 2 did not deem sensitive but did in fact improve the results. It is recommended that SUFI-2 be used as a guide for initial calibration, but to look at more parameters when fine tuning the results. The P-factor and R-factor calculated using SUFI-2 procedures and manual calibration have provided good agreement by bracketing around 52- 55 percent observed data on a sub-hourly basis. Results showed acceptable matching between simulated and observed flows for the Blunn Creek Watershed for the simulation period. The presented study showed that the sub-hourly SWAT model results in a reasonable stream flow hydrograph under multiple storm events. Calibrated stream flows for a 2-year period with 15- min simulation had (R2= 0.74) and (NS =0.74). Validation procedures for a 2-year period showed acceptable correlation between simulated and observed data, NS value was 0.67 and R2 value was equal to 0.70. This study showed how a sub-hourly model can be run using SWAT and calibrated using SWAT- CUP and manual calibration. Calibrating and validating a sub-hourly model for a long duration instead of single storm was attained.

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