Calibration and Validation of SWAT for the Neponset River Watershed in Boston

Jawon Lee*

보스턴 넷폰셋강의 수질체계에 대한 스왓모델의 교정과 유효성 검증

이 자 원*

Abstract : A validation study has been performed using the Soil and Water Assessment Tool(SWAT) model with data collected for the Neponset River watershed, which includes roughly 130 square miles of land located southwest of Boston. All of this land drains into the Neponset River, and ultimately into Boston Harbor. This paper presents the methodology of a SWAT model. The calculated contribution of the baseflow to the streamflow is far too high whereas the interflow is strongly underestimated. Alternatively, the modified and calibrated model yields far better results for the catchment. The modification allows hydrological processes to be modeled while not restraining the applicability of the model to catchments with other characteristics. For this study, the SWAT 2005 model is used with ArcGIS 9.1 as an interface, and sensitivity analysis is performed to provide rough estimated values before adjusting sensitive input parameters during calibration period.
Key Words : SWAT, Neponset River Watershed, hydrological modeling, HRUs, validation, calibration, sensitivity

요약 : SWAT 기법은 자연지형을 기반으로 수질관련 현상을 지속적으로 분석하고 예측하며 복합적인 수질 체계를 연구하는데 널리 쓰여왔다. 이는 기후와 관련된 온도, 강수량을 주 데이터로 소규모 지역단위부터 광범위한 지표면의 수질 체계를 토양, 토지이용 행태, 그리고 경사면의 정도와 연계시켜 지역적 토양과 수질의 특성을 파악한다. 모든 자료는 일간으로 구성되며 첫 일정 연도는 데이터의 셋업과정으로 분석이 되고 중간의 일정 연도는 변화정도를 파악하는 기간으로 활용이되며, 마지막 일정연도는 검증과정으로 분석이 된다. SWAT 기법은 수질오염은 물론, 지표면의 오염형태를 파악함으로써 농업활동의 분석과 연구에 도움을 주고, 도시에서 배출되는 오염원의 유형과 그 것이 주변지역에 미치는 영향을 도출해 내어 지역 환경개발에 유익한 모델 기법이다. 지역적인 수질 환경을 모델화시키기 위하여 수치의 교정과정이 필요하고 지속적인 연구로 활용하기 위하여 어떠한 인자가 가장 민감하게 반응하는 가에 관한 차후 분석이 뒤따르고 있으며, 결과화된 수치의 유효성 검증이 중요시되고 있다. SWAT 2005 버전은 ArcView 3.3과 ArcGis9.1에서 공간분석이 가능하다.
주요어 : 수질 체계, 토양, 토지이용, 경사면, 수질 환경의 모델화, 교정, 차후 분석, 검증

1. Introduction

Water quality modeling is emerging as a key component of Total Maximum Daily Load assessments and other watershed-based water quality studies. Numerous water quality models have been developed that differ greatly in terms of simulation capabilities, documentation, and technical support. One of the more widely used water quality models in the Soil and Water Assessment Tool (SWAT), which is developed to assess the water quality impacts of agricultural and other land use for a range of watershed scales, including large river basins (Arnold et al., 1998). Detailed documentation on the model inputs is provided in Neitsch et al.(2002a), and the model theory documentation is presented in the Neitsch et al. (2002b) and in Arnold et al.(1998). Previous applications of SWAT have compared favorably with measured data for a variety of watershed scales and conditions (Arnold, and Allen, 1996; Srinivasan, Arnold, and Jones, 1998; Kirsch, and Arnold, 2002; Arnold et al., 1999; Saleh et al., 2000; Santhi et al., 2001).

* Full time Researcher/Instructor, Environmental, Earth and Ocean Science Department, University of Massachusetts, Boston.

However, an ongoing need in the use of SWAT is to test it with measured data for different scales, land use, topography, climate, and soil conditions.

SWAT is continuous time models and can simulate numerous management practices, operate on a daily time step, and estimate surface runoff by using a modified curve number(CN) method (USDA, 1972). This model requires users to input a baseline CN parameter, and this parameter is modified by using different equations. Calibration and validation of simulation models are necessary before their use for practical purposes(Davis et. al., 2000). This process confirms accuracy in depicting field conditions, as well as confirming the model inputs that affect performance. For instance, the CN method uses an empirical equation that might better be used to transform a rainfall frequency distribution to a runoff frequency distribution than to predict runoff for individual events (Hjelmfelt, 1991). The CN parameter is not constant, but varies from event to event. Thus, selecting an appropriate CN value to reflect the effect of surface cover, management, land use, and antecedent moisture conditions in estimating single-event runoff is a crucial task(Shirmohammadi et al., 1997).

SWAT has algorithms that modify CN on a daily basis to reflect changing conditions. The user selects a baseline CN value as well as parameters that control some aspect of daily CN selection, and those user-selected parameters differ between the two models. Daily CN is adjusted by antecedent moisture condition (AMC) in the model. AMC is influenced by all processes that impact soil water. The model has internal procedures for estimating soil moisture, and these influence the AMC parameter that modifies the CN on a daily basis.

For the model, Ksat has been identified as an important calibration parameter. Ksat relates soil water flow rate (flux density) to the hydraulic gradient, and is a measure of the ease of water movement through the soil (Neitsch et. al., 1999). The other hydrologic parameter that has been identified as being critical for water balance calculations in SWAT is the available water capacity (AWC) in the soil layer.

Many former researcher suggested that these differences could reflect that a daily comparison challenged the temporal resolution of the model's daily time-step and daily input data. Because of the need for accurate daily prediction of runoff and associated water-quality parameters, a goal of hydrologic models used for water quality simulation must be to provide accurate daily predictions.

Due to spatial variability, budget constraints or access difficulties model input parameters always contain uncertainty to some extent. However, a model user has to assign values to each parameter. The model is then calibrated against measured data to adjust the parameter values according to certain criteria. This implies that the modeler has a clear understanding of all the parameters used as input to the model and of the processes represented in the model. Parameters that are not well understood may be left unchanged even though they are sensitive or are adjusted to implausible value. Not knowing the sensitivity of parameters can also result in time being uselessly spent on non-sensitive ones. Focus on sensitive parameters can lead to a better understanding and to better estimated values and thus reduced uncertainty (Lenhart T. et al., 2002).

Therefore sensitivity analysis as an instrument for the assessment of the input parameters with respect to their impact on model output is useful not only for model development, but also for model validation and reduction of uncertainty (Hamby, 1994).

The objective of this study is to test SWAT by comparing predicted stream flows with corresponding measured values at the outlet of the Neponset River in Boston, which is a row-crop dominated watershed typical of much of Massachusetts. And also this study is to determine the combination of baseline CN and Ksat, AWC for the model that provides the best simulation of measured daily runoff for the management practice as calculated by SWAT. This study also focused on evaluating the methods used to calibrate and validate the model, and on interpreting the calibration results. An overview of the data inputs and modeling assumptions is provided including a description of how some of the SWAT inputs are derived. The sensitivity analysis is performed to provide rough estimated values before adjusting sensitive input parameters during calibration period. The calibration and validation process is described including the effect of selecting alternative climate data inputs to achieve a more accurate replication of measured data at the watershed outlet.

2. Data set up and Methodology

1) Study Area

The Neponset River Watershed includes parts

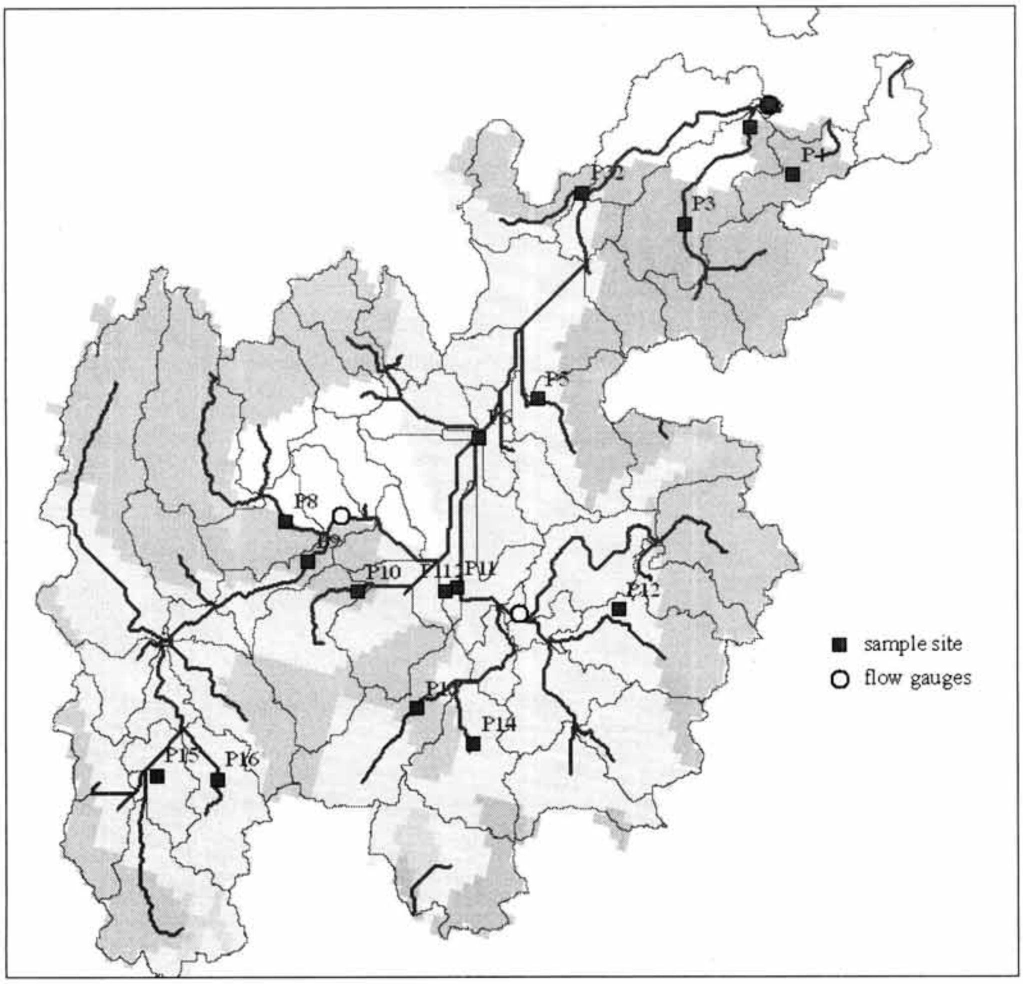

Fig 1. Neponset Watershed and Flow Gauges

of 14 cities and towns: Boston, Canton, Dedham, Dover, Foxborough, Medfield, Milton, Norwood, Randolph, Quincy, Sharon, Stoughton, Walpole and Westwood. Roughly 300,000 people live in the watershed.

The Neponset River itself runs for 30 miles through the middle of the watershed. The River starts in Foxboro, near the Foxboro Stadium, and ends in Dorchester/Quincy, near the Boston Gas tank by I-93. Because the Neponset River ultimately enters Boston Harbor, the Neponset River Watershed is itself a part of the larger Boston Harbor Watershed, along with the Mystic River Watershed to the north of Boston, the Charles River Watershed to the west of Boston and the Weymouth-Weir River Watersheds, which, like the Neponset River Watershed, originate south of Boston.

2) SWAT Model Description

The SWAT model is a watershed scale simulation model. It's a used as a simulator for Water Resource in Rural Basin model. It is developed by the USDA Agricultural Research Service to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with various soils, topography, and land use management conditions over long periods of time (Neitsch et.al., 1999). SWAT model components include weather, hydrology, soil temperature, plant growth, nutrients, pesticides, and land management. This study focused on the hydrology component and other influential parameters (AWC, Ksat) in the soil database and on CN in the management file. A detailed discussion of the model components is included in Arnold et. al.(1998).

The SWAT 2005 version is used with interface of ArcGIS 9.1. The SWAT model has been used effectively under various conditions. Srinivasan et al.(1998) used CN and the REVAP coefficient (related to ground-water flow) for runoff calibration. In another study by Arnold et al.(2000), AWC and soil evaporation compensation coefficient(ESCO), along with CN, are adjusted until all the monthly average measured and simulated runoff differences are within 10%, and R-square value are as high as 0.89 and not less than 0.63 for the three studied watersheds.

The procedure used to estimate runoff in SWAT codifies daily CN nonlinearly based on soil moisture in the entire profile. The relationship assumes CN1 at wilting point, CN2 at field capacity, and CN approaching 100 at saturation. Soil moisture is estimated by a soil water balance. Water enters the soil profile via infiltration and bypass flow and exits via soil surface evaporation, plant uptake, deep seepage, and lateral discharge. The Ksat parameter is used to estimate the time allowed for percolation to drain water in excess of field capacity to the next deeper layer, if percolation time for a layer exceeds 24 hour, soil water in excess of field capacity is carried forward to the next day.

Among the three available potential Evapotranspiration(ET) methods in SWAT, Penman-Monteith method is selected at the suggestion of the programmers of SWAT. The SWAT model calculated crop ET directly by using crop-specific parameters. A plant uptake compensation factor (EPCO) accounted for the sharing of plant uptake demand by adjacent soil layers.

3) Model Input Data

The landuse or landcover, topographic and soil data required for the SWAT simulation. Weather inputs for SWAT included daily values of precipitation, maximum and minimum temperature, relative humidity, solar radiation, and wind speed. Precipitation data, and temperature data measured on-site are used in the model, and weather station has to be selected. The STATGO (State Soil Geographic) database and SURGO (soil survey geographic) database are provided for soil data, and in this study, STATGO data is used for the models.

Each subwatershed delineated within SAT is

Table 1. SWAT input parameters and Result

parameter	description	unit	Default value	P (a)	Difference (%)	*Sr* values (b)		
						Water yeild	Strom flow	Base flow
Surface response								
CN2(forest)	SCS curve number Antecedent moisture condition II for forested landuse	-	55.0	50.0	±25	0.03	1.20	-0.47
CN2(crop)	For crop landuse	-	77.0	76.0	±18.8/-25	0.74	4.22	-0.73
ESCO	Soil evaporation compensation factor	Fraction	0.95	0.74	±25	0.38	0.26	0.44
SOL_AWC	Available soil water capacity	Volume	0.09-0.19	0.10-0.20	±8.6	-0.45	-0.53	-0.42
SOL_BD	Soil bulk density	g cm-3	1.40-1.73	1.40-1.73	±6.2	-0.04	-0.94	0.34
Subsurface								
SHALLIST	Initial depth of water in the shallow aquifer	mm	0.5	800	±25	0.00	0.00	0.00
CW_DELAY	Tune required for water leaving the bottom of the root zone to reach the shallow aquifer	day	31	1	±25	0.00	0.00	0.00
GW_REVAP	Rate of transfer from shallow aquifer for percolation to deep aquifer to occur	-	0.02	0.02	+0.05	0.00	0.00	0.00
GWQMN	Threshold water depth in shallow aquifer for return to reach to occur	mm	0	0	+15	0.00	0.00	0.00
ALPHA_BF	Baseflow alpha factor, lower number means a slower response	day	0.048	0.039	±25	0.01	0.00	0.02
SOL_K	Saturated hydraulic conductivity	mm h-1	8 - 500	8 - 500	±25	0.01	0.00	0.01
Basin								
SURLAG	Surface lag coefficient,	-	4.0		±25	0.00	0.00	0.00
CH_K2	Effective hydraulic conduntivity in main channel alluvium	mm h-1	0.0		+150	0.00	0.00	0.00

note : (a) calibrated parameter base value
(b) Sr is relative sensitivity, which is model outputs that is calibrated value

simulated as a homogeneous area in terms of climatic inputs. However, the subwatersheds are further subdivided into hydrologic response units (HRUs) that are assumed to consist of homogeneous land use and soils. The percentage of the subwatershed that is covered by a specific HRU is input into SWAT. A landuse threshold of 10% is used when the HRUs are created, which limited the landuse to categories that covered at least 10% of a given subwatershed.

Each data collected from 1998 to 2007 based on daily time set for running model. The first 2 years are warm-up period and as after the seven years are evaluated with respect to remaining year is predicted.

The digital elevation model (DEM) data used in the study consisted of a 30m grid and is obtained from the MGIS.

3. Calibration and Sensitive Analysis

A sensitivity analysis can provide a better understanding of which particular input parameters have greater effect on model output. Monte Carlo simulation (MCS) is a technique that quantifies the input parameters influence on the model output. Sohrabi et al.(2002) used MCS to estimate uncertain in SWAT flow, sediment, and nutrient loading outputs, given a mean, range, and distribution for the input parameters for the Piedmont physiographic region of Maryland. The manual calibration method outlined in the SWAT 2005 user's guide is used to minimize the sum of squared differences of the annual averages of the various components of the water budget (SSDwbc), and maximize the Nash and Sutcliffe(1970) model efficiency(NSE). The SWAT input parameters and defualt values are seen as Table 1. Sensitivity is expressed by a dimensionless index I, which is calculated as the ratio between the relative change of model output and the relative change of a parameter. The two investigated approaches differ in the way the ranges of parameter variation are defined. To assess the calculated sensitivity indices are ranked into four classes as like Table 2.

Table 2. Sensitivity Classes

index	sensitivity
$0.00 \leq I < 0.05$	Small to negligible
$0.05 \leq I < 0.20$	Medium
$0.20 \leq I < 1.00$	High
$1.00 \leq I$	Very high

First, the surface flow component of average is balanced by adjusting the runoff curve numbers for forested and cropped landuse. An effort is made to keep the CN close to standard table values. Next, SOL_AWC, GW_REVAP, REVAPMN, and GWQMN are adjusted to match the simulated baseflow and baseflow calculated from stream measurements. Once the proportion of surface flow to subsurface flow is established, the model ET output is matched to observe ET by adjusting values for ESCO. With the major components of the modeled water balance nearly corresponding to the observed values, SSDwbc is minimized. These additional parameters are adjusted to maximize the monthly NSE: SHALLST, SURLAG, and ALPHA_BF. Readjustment of a parameter is frequently necessary after the value of a subsequent parameter is reset. Finally, to attempt to maximize the daily NSE, adjustments are made. The calibrated parameters became the base values about which the parameter sensitivity coefficients are calculated.

4. Result

The manually calibrated model parameter values have been identified in Table 1. Results are negatively influenced when seasonal tropical

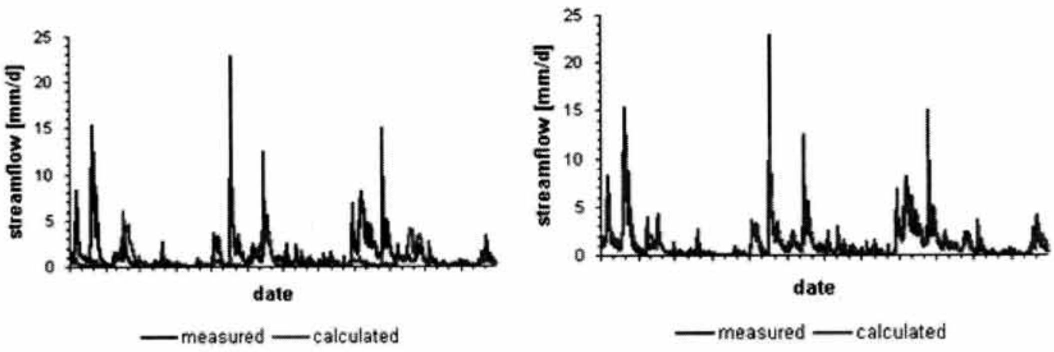

Fig 2. Comparison of the Result with Calibrated Model

storms occurred during a dry year. The objective of the calibration is to minimize the SSDwbc between the observed and simulated water budget components while maximizing the daily model efficiencies. The results of the calibration are simply summarized as like Fig 2. The simulated baseflow is calculated as the difference between total water yield and stormflow. This result shows that uncalibrated modeling results and indicates the poor and inconsistent results common without calibration for the models.

The most sensitive parameters for total water yield are CN2, soil available water content (SOL_AWC), and soil evaporation compensation factor. The most sensitive parameters for storm flow are CN2, CN for forested land, ESCO, SOL_BD, and SOL_AWC. For base flow, the most sensitive parameters are CN2(both crop and forested land), ESCO, and SOL_AWC. Identification of the sensitive SWAT parameters in the Neponset river watershed provides modelers in the coastal plain physiographic region with focus for SWAT calibration.

5. Conclusion and Discussion

The comparison of modeling results, with and without calibration, clearly points to the importance of adjusting critical input parameters, such as CN, Ksat (SOL_K), and AWC, for runoff simulation. The model did significantly better with calibrated parameters than with initial assumptions based on readily available field information and database values.

The SWAT model required CN2 values higher than the recommended other manual guide or so. As a result, higher CN2 is needed as an input, to compensate for lower daily AWC. The difference in CN values could be related to the differences in ET estimation by the model. Seasonal weather change has to be concerned as well, which produces negative value.

In this time, the purpose of the study is limited to present SWAT model to assess the water and soil and look into the important of calibration model, but also this study should be developed with regional condition such as pollutant by human settlement, land cover change through the regional development or redevelopment. It should be more useful to find pollutant source, and track the flux of the material with moving of soil and water.

Reference

Arnold J.G., and Allen P.M., 1996, Estimating hydrologic budgets for three Illinois watersheds, *Journal of Hydrology* 176, 57-77.

______, Srinivasan R., Muttiah R.S., Williams J.R., 1998, Large area hydrologic modeling and assessment, Part I: Model development, *Journal of the American Water Resources Association* 34, 7389.

_______, 1999, Automated method for estimating baseflow and groundwater recharge from stream flow record, *Journal of American Water Resources Association* 35(5), 1037-1051.

Davis D.M., Gowda P.H., Mulla D.J., and Randall G.W., 2000, Modeling Nitrate Nitrogen leaching in response to Nitrogen Fertilizer rate and Tile drain depth or spacing for southern Minnesota, USA, *Journal of Environmental Quality* 29, 1568-1581.

Hamby D.M., 1994, A review of techniques for parameter sensitivity analysis of environmental models, *Environmental Monitoring and Assessment* 32, 135-154.

Hjelmfelt A.T., 1991, Investigation of Curve Number procedure, *Journal of Hydraulic Engineering* 117(6), 725-737.

Kannan N., White S.M., Worrall F., and Whelan M.J., 2007, Sensitivity analysis and identification of the best evapotranspiration and runoff options for hydrological modeling in SWAT-2000, *Journal of Hydrology* 332(3/4), 456-466.

Kirsch K., Kirsch A., and Arnold J.G., 2002, Predicting sediment and phosphorus loads in the rock river basin using SWAT, *Trans. ASAE* 45(6), 1757-1769.

Lenhart T. et al., 2002, Comparison of two different approaches of sensitivity analysis, *Physics and Chemistry of the Earth* 27, 645-654.

Nash J.E., and Sutcliffe J.E., 1970, River flow forecasting through conceptual models, Part I, Journal of Hydrology 10, 282-290.

Neitsch S.L., Arnold J.G., Kiniry J.R., and Williams J.R., 2002a, *Soil and Water ASwsessment Tool User's Manual,* Temple, TX: Blackland Research Center, Texas Agricultural Experiment Station.

_______, 2002b, *Soil and Water Assessment Tool Theoretical documentation,* Temple, TX: Blackland Research Center, Texas Agricultural Experiment Station.

Shilpa A., Mankin K.R., McVay K.A., Janssen A., Barnes P.L., and Pierzynski G.M., 2007, Calibration and validation of ADAPT and SWAT for field scale runoff prediction, *Journal of the American Water Resources Association* 43(4), 899-909.

Shirmohammadi A., Yoon K.S., Rawls W.J., and Smith O.H., 1997, Evaluation of CN procedures to predict runoff in GLEAMS, *Journal of the American Water Resources Association* 33(5), 1069-1076.

Shrinivasan R., et al., 1998, Large area hydrologic modeling and assessment Part II, Model application, *Journal of the American Water Resources Association* 34(1), 91-101.

http://www.brc.tamus.edu/swat/

http://www.mgis.org/

http://www.ncgc.nrcs.usda.gov/

(접수 : 2008. 1. 14, 채택 : 2008. 2. 4)