A Water Balance-Based Soil and Water Assessment Tool (SWAT) for Improved Performance in the Ethiopian Highlands

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Abstract

The Soil Water Assessment Tool (SWAT) is a watershed model widely used to predict water quantity and quality under varying land use and water use regimes. To determine the respective amounts of infiltration and surface runoff, SWAT uses the popular Curve Number (CN). While being appropriate for engineering design in temperate climates, the CN is less than ideal when used in monsoonal regions where rainfall is concentrated into distinct time periods. The CN methodology is based on the assumption that Hortonian flow is the driving force behind surface runoff production, a questionable assumption in many regions. In monsoonal climates water balance models generally capture the runoff generation processes and thus the flux water or transport of chemicals and sediments better than CN-based models. In order to use SWAT in monsoonal climates, the CN routine to predict runoff was replaced with a simple water balance routine in the code base. To compare this new water balance-based SWAT (SWAT-WB) to the original CN-based SWAT (SWAT-CN), several watersheds in the headwaters of the Abay Blue Nile in Ethiopia were modeled at a daily time step. While long term, daily data is largely nonexistent for portions of the Abay Blue Nile, data was available for one 1,270 km^2 subbasin of the Lake Tana watershed, northeast of Bahir Dar, Ethiopia, which was used to initialize both versions of SWAT. Prior to any calibration of the model, daily Nash-Sutcliffe model efficiencies improved from -0.05 to 0.39 for SWAT-CN and SWAT-WB, respectively. Following calibration of SWAT-WB, daily model efficiency improved to 0.73, indicating that SWAT can accurately model saturation-excess processes without using the Curve Number technique.

Introduction

Hydrologic models are used primarily to predict water quantity, peak flows, and export of water quality constituents from a watershed. One common method to determine the runoff volume in these models is the Natural Resource Conservation Service Curve Number (CN) technique. This method was initially designed for determining runoff volume for engineering design purposes, but has since been adapted for use as a tool in many temporal watershed models, including the USDA’s Soil and Water Assessment

Tool (SWAT). While useful for design purposes, the CN approach has been shown to be less than ideal when used to model runoff both spatially and temporally (see Garen and Moore, 2005).
In addition to the general problems the CN has in representing spatial variability of runoff and differentiating between runoff generating processes, the method was developed by curve fitting rainfall-runoff data only from the United States and is not necessarily accurate for all landscapes. To correct for this SWAT was modified and adjusted for watersheds in the Blue Nile River Basin in Ethiopia, where the CN approach has been shown to be inaccurate in predicting runoff events.

Under Ethiopian conditions, runoff is mainly generated by saturation excess mechanisms and runoff from a given amount of rain is less in the beginning of the rainfall season than at the end (Liu et al. 2008). Although the CN method can be adapted to predict saturation excess such as this, it inaccurately assumes that similar rainfall patterns produce the same amount of runoff independent of the time of the year. This is well illustrated in Figure 1, where we applied the standard CN approach to the Anjeni watershed in the Ethiopian Highlands that has 16 years of rainfall-runoff data. It is obvious that when we calibrate the method to the storms at the end of the rainfall season, the storms at the beginning of the rainy season with less than 500 mm of cumulative precipitation are under-predicted. Therefore, in order to apply SWAT to Ethiopian conditions, the original CN method has to be replaced by a more mechanistic approach that uses soil water balances to calculate when the soil is saturated and consequently produces runoff.

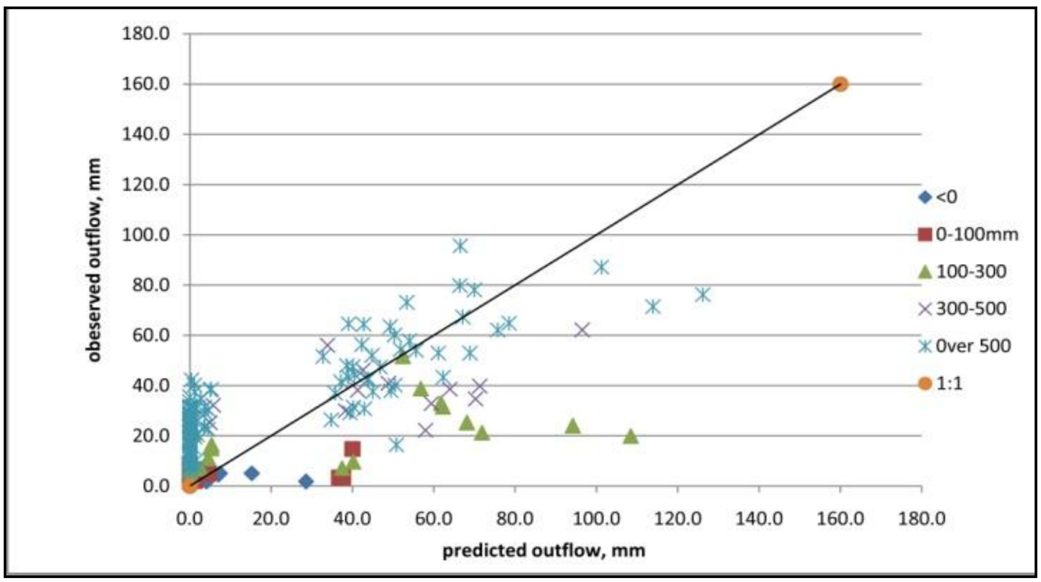

Figure 1: CN predicted runoff for an Ethiopian watershed. Runoff is grouped in ranges of cumulative rainfall.

Methods

To adjust the SWAT program to account for saturation excess runoff, a new subroutine was created in the code which circumvented the original CN calculations and used water balances to calculate saturation. The new, saturation-driven SWAT model results were then compared to the original CN-based SWAT results for a simulated period from January, 1996 to December, 2005. The new model was then calibrated using an adjusted version of SWAT's auto-calibration tool.

Original Curve Number Approach

An initial CN is assigned for each specific landuse/soil combination in the watershed, and these values are read into the SWAT program. SWAT then calculates upper and lower limits for each CN following a probability function described by the NRCS to account for varying antecedent moisture conditions (CN-AMC) (USDA-NRCS, 2004). SWAT determines an appropriate CN for each simulated day by using this CN-AMC distribution in conjunction with daily soil moisture values determined by the model. This daily CN is then used to determine a theoretical storage capacity, *S*, of the watershed for each day the model is run. The storage is then indirectly used to calculate runoff volume, *Q*, by means of the following equations:

$$CN = \frac{1000}{10 + \frac{S}{25.4}} \qquad 1$$

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad 2$$

Where S is watershed storage, P is precipitation, and I_a is initial abstraction. All terms are in mm of water, and by convention I_a is assumed to be equal to $0.2*S$.

New Water Balance Approach

To replace the CN, a simple soil water balance was calculated for each day of simulation. The modified model is therefore called SWAT-Water Balance or SWAT-WB for short. While SWAT's soil moisture routine grossly simplifies processes that govern water movement through porous media (in particular, partly-saturated regions), for a daily model, the water balance has been shown to be proficient (Guswa et al., 2002). We then used SWAT's soil moisture calculations to determine the amount of storage available for any given area of the watershed for every day of simulation. This, we called the available soil storage (mm), τ:

$$\tau = D(\varepsilon - \theta) \qquad \text{eq. 3}$$

Where D is the effective depth of the soil profile (unit-less), ε is the total soil porosity (mm), and θ is the volumetric soil moisture for each day (mm). The porosity is a constant value for each soil type, whereas θ varies by the day and is determined in SWAT. The effective depth is used in the calibration process and represents the portion of the soil profile in which the moisture content controls the amount of water able to infiltrate in one day. This available storage is then used to determine what portion of rainfall events can be held by the soil and what portion will runoff:

$$Q = \begin{cases} 0 & \text{if} P < \tau \\ P - \tau & \text{if} P > \tau \end{cases} \qquad \text{eq. 4}$$

Watershed description

The new SWAT-WB was initially tested on a watershed in the Blue Nile River basin in Ethiopia. The Gumera watershed, located northeast of Bahir Dar, is a 1270 km2, heavily (~95%) cultivated, watershed in the Lake Tana basin. Elevation of the Gumera watershed ranges from 1797 to 3708 meters above sea level and predominant soils are generally characterized as chromic and haplic luvisols (24% and 63%, respectively) (FAO-AGL, 2003).

Daily precipitation and temperature data for a period from 1996 until 2005 were used, while other historic climate data (relative humidity, wind speed, solar radiation) were gathered from the United States' National Climatic Data Center for the nearest station (NCDC, 2007).

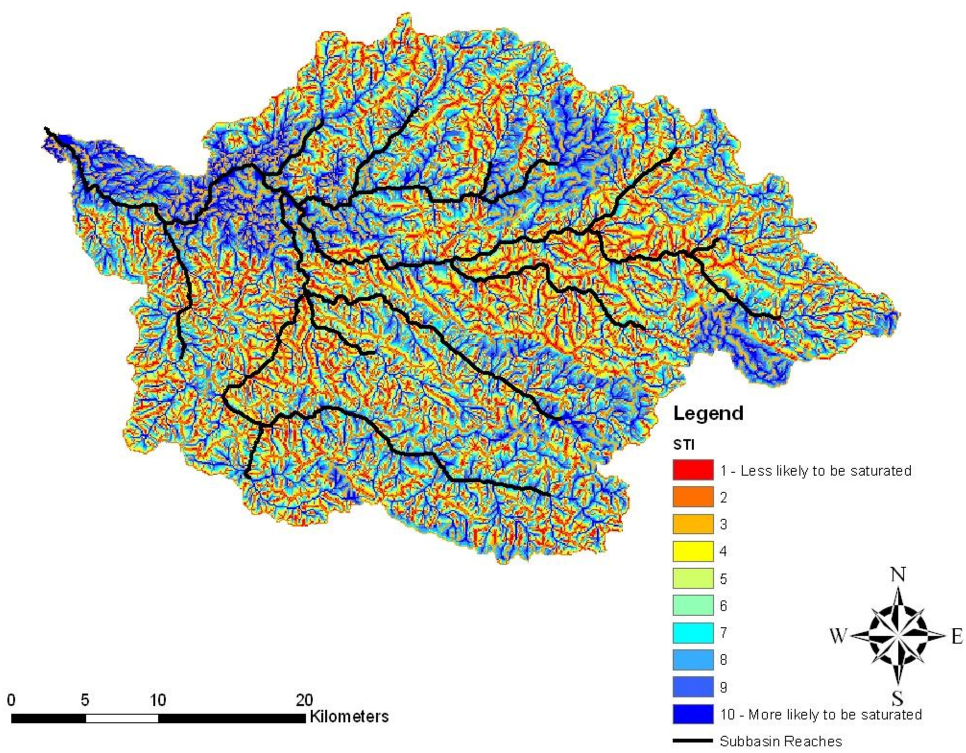

Figure 2: Soil topographic index for the Gumera basin

Results

The Gumera basin was modeled using both the original version of SWAT (SWAT-CN) and the new CN-free, water-balanced based version (SWAT-WB). In addition to these comparisons, the SWAT was also run using soil topographic indices (STI) in place of the traditional soils map required by the model, Figure 2. Previous research has indicated that STIs can be used to more accurately predict runoff generating areas (when saturation-excess is the driving force), which led to the decision to adjust the effective depth, *D*, based on the STI (see Easton et al., 2008 and Lyon et al., 2004). The STI for Gumera was then used in both SWAT-CN and SWAT-WB. Prior to any calibration, SWAT-WB returned drastically improved daily results over both SWAT-CN runs (with and without STI). Daily Nash-Sutcliffe model efficiencies were negative for both CN-based runs, indicating that simply taking the mean streamflow would have been a better predictor than SWAT; whereas SWAT-WB resulted in a daily model efficiency of 0.51. Upon calibration of hydrologic parameters using SWAT's auto-calibration tool, the daily model efficiency of SWAT-WB was 0.73.

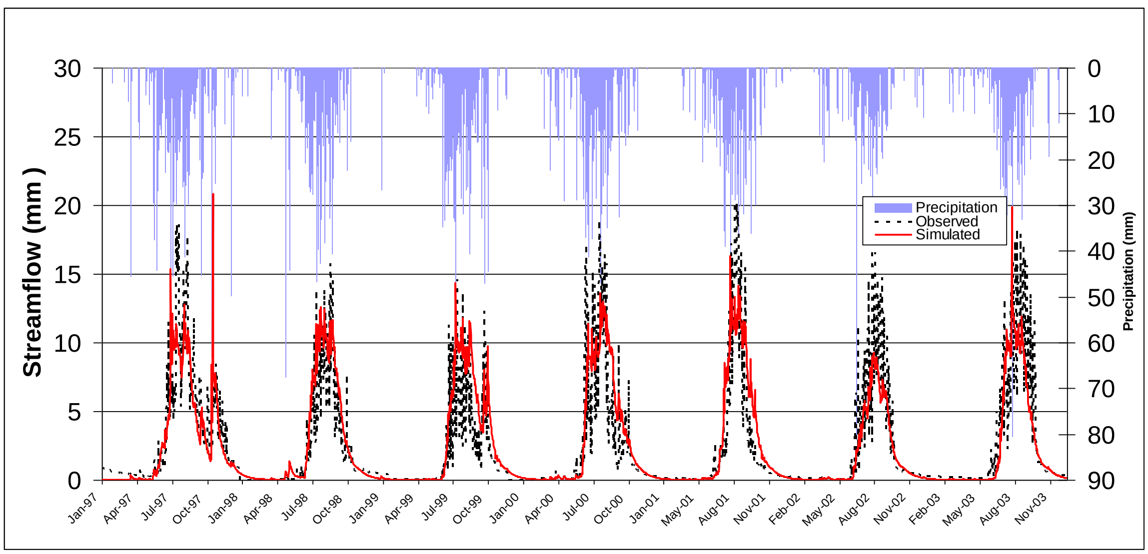

Figure 3: Observed rainfall and streamflow, as well as calibrated streamflow values modeled with SWAT-WB for the Gumera basin for 1997-2003.

Discussion

SWAT CN and most other watershed models have been developed for temperate climates where rainfall is generally well distributed throughout the year. Running models developed in the temperate climate for Ethiopia conditions with a monsoonal climate are problematic. Temperate models assume that there is a nearly unique relationship between precipitation amounts or intensity and runoff generated. This is not the case for Ethiopia as demonstration by the results of Liu et al (2008) where for three watersheds with more than 16 years of record, the rainfall relationship was far from unique. The first rains after the dry season all infiltrate and nearly no runoff is generated. As the rainfall season progresses more and more rainfall becomes runoff. Since the intensity of the rain did not affect the runoff amounts for a given storm, the runoff mechanism is saturation excess runoff (Liu et al., 2008).

Water balance models are consistent with saturation excess runoff process because the runoff is related to the available watershed storage capacity and the amount of precipitation. The implementation of water balances into runoff calculations in the Blue Nile basin is not a novel concept and often performs better (as did our results) than more complicated models in Ethiopia type landscapes (Johnson and Curtis, 1994; Conway, 1997; Ayenew and Gebreegziabher, 2006; and Liu et al., 2008). These water balance models are typically computed with monthly or yearly values because the models are generally not capable of separating base- inter- and surface runoff flow. However, to truly model erosion and sediment transport, large events must be captured by the model and daily simulations are required to do so. Thus SWAT-WB not only maintains a water balance but also calculates the interflow and the base flow component and also gives a reasonable prediction of peak flows. SWAT-WB is therefore more likely to capture sediment transport than either SWAT-CN or water budget models with monthly time steps. Note that by choosing to run models on a daily time step, the model performance always is significantly worse than for monthly or yearly time steps.

SWAT-WB is more in tune with the runoff processes that occur in the Ethiopian highlands than other models that base their runoff prediction on the NRCS curve number method. The calculations that serve as a foundation for NRCS curve number technique assume that the moisture condition in the soil can be determined by taking into account the five day previous rainfall events. As indicated above, the moisture content in monsoonal climates is changing during the first 500 mm of effective precipitation, or approximately 1-2 months. SWAT-WB, on the other hand, determines runoff volume simply by calculating the available storage in each soil profile. This value is not dependent only upon the five previous days' rainfall (as the CN method is), but instead allows for progressive saturation as the rainy season continues.

Conclusion

Daily modeling of peak streamflow and surface runoff was improved by replacement of the CN method with a water balance routine in the SWAT model. In addition to improving model efficiencies, it is also predicted that the new water-balance-based SWAT will be a better predictor of the location of runoff-generating areas of a watershed due to the inclusion of soil topographic indices. By removing the curve number and calibrating the water balance routine based on STIs, daily Nash-Sutcliffe efficiencies improved from -0.02 to 0.73, while R^2 values increased from 0.27 to 0.74.

These results indicate that SWAT performs better in a saturation-excess controlled watershed when a water balance routine is used to calculate daily runoff volumes instead of the traditional Curve Number. Further research will ideally demonstrate that these adjustments are appropriate for any region where saturation-excess runoff is dominant, not just the Ethiopian highlands.

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