Improving the robustness of uncertainty algorithms in quantification of uncertainty in water balance forecasting

S. Samadi1*, D. L. Tufford2, G. J. Carbone3

1. Instructor, Department of Civil and Environmental Engineering, University of South Carolina (USC), Columbia, South Carolina 29208, USA
2. Research Associate Professor, Department of Biological Sciences, University of South Carolina, Columbia, South Carolina 29208, USA.
3. Professor, Department of Geography, University of South Carolina, Columbia, South Carolina 29208, USA


Abstract

Recent studies have highlighted the potential challenges in US southeastern (SE) watersheds from climate variability. There may be shifts in water balance due to complexity of the flow generation processes that determine how water is partitioned in these landscapes. The main objective of this study was to capture the feedback relationships among the water balance components using the Soil & Water Assessment Tool (SWAT) watershed-scale streamflow model linked with the Sequential Uncertainty Fitting (SUFI-2) and Particle Swarm Optimization (PSO) parameter uncertainty algorithms in the Waccamaw River watershed, a low-gradient forested watershed on the coastal plain of the southeastern United States. Water balance uncertainty analysis suggested close correspondence of the model with the physical behavior and system dynamics during different hydroclimatological periods in the 2003-2007 calibration interval. SUFI-2 water balance analysis revealed that surface runoff, ground water, and lateral flow contributed 22.2%, 3.9% and 0.4% of the total water yield during simulation period while PSO analysis indicated 16.7%, 13.2% and 0.3% of their contributions respectively. Both uncertainty methods found that 71.1% of the total rainfall was lost by evapotranspiration during the simulation interval. The total water yields using both algorithms were over predicted by up to 14.0% of the annual rainfall inputs during the dry period (2007); this was related to the extra contribution of shallow aquifer flow to the river system. Both algorithms also specified that surface flow and ground water runoff dominated the water balance during October and December respectively. The distribution of predictive uncertainty was least in the wet year (2006) and was greatest towards the end of dry period, particularly within alluvial riparian floodplains.

Water balance estimation with uncertainty quantification can be a useful step in understanding the dynamic nature of a coastal plain landscape, and it may lead to more useful solutions of analytical flow processes through the watershed system.

Key Words: SWAT; Sequential Uncertainty FItting Algorithm (SUFI-2); Particle Swarm Optimization (PSO); Water Balance; Uncertainty Quantification; Coastal Plain Watershed.

Introduction

Water balance studies involve the study of water movement in the atmosphere and on the land surface and subsurface portions. There are dynamical responses between the climate, land use properties and water balance components. Flow partitioning and movement is usually expressed in terms of a dynamic water balance process, which can be manifested in various characteristic signatures of watershed responses at a range of different time scales. Hydrologists increasingly wonder how flow may be partitioned in different hydrological conditions through a watershed system as this result can affect ecohydrology and ecosystem service provision.

The distributed hydrological model (i.e. Soil and Water Assessment Tool (SWAT) model) has been tested on multiple sites in the southeastern USA (Fernandez et al., 2005; Amatya and Jha, 2011; Tufford et al. 2013) and has predicted the coastal plain hydrological properties well. This research explores the variability of annual and monthly water balances values using two
different kinds of uncertainty codes during wet and dry conditions. In this study, we examined two algorithms - Sequential Uncertainty FItting (SUFI-2), developed by Abbaspour et al. (2007), and Particle Swarm Optimization (PSO) -- proposed by Eberhart and Kennedy, (1995), during the period, 2003-2007.

Method

Study Area

The Waccamaw River watershed, located in North and South Carolina, was selected for this research (Figure 1). The study area is 311,685 ha (delineated by SWAT model). The climate of the region is specified as humid subtropical and precipitation in the summer is dominated by convection storms; in the winter by frontal boundaries. The long-term annual average temperature (1946–2009) is 16.88 °C, and averaged annual precipitation is a little more than 1300 mm in the same period. The high temperature during the same period was 41.66 °C while the low temperature was −14 °C. Subtropical humid climate condition heavily influences the hydrologic balance of the watershed by regularly providing available water in the developing wetlands; since approximately 60% of the watershed is covered by forest and forested wetland land covers.

![Figure 1 Location map of the study area](image)

SWAT Model and Uncertainty Algorithms

The Soil and Water Assessment Tool model is a physically based semi-distributed hydrologic model initially developed by Arnold et al., (1993). SWAT simulates water quality and quantity over a long term period, and requires inputs of climate data, soil information, topography and land use properties. In model set up, SWAT requires gauging station data at the outlet of subwatershed and finally delineates watershed boundary by defining an outlet position. The hydrological cycle simulated in the SWAT is based on the water balance equation found by Winchell et al., (2007).

In this research eighteen physically based hydrologic parameters were incorporated to the uncertainty frameworks for sensitivity analysis during simulation period (2003-2007). Some of those parameters showed more sensitivity to the flow generation while some were moderately sensitive and some were completely insensitive. SWAT model was then optimized using the final parameter ranges and water balance components were estimated during different hydrological conditions.

Results

Rainfall and Stormflow Analysis During simulation period

In the coastal plain watershed flow depends on rainfall amount, its frequency and spatially distribution, and initial condition. Rainfall data for the simulation period was analyzed to address rainfall characteristics and variability. Rainfall was above average rain in 2003 and 2006 and below average in 2007. Annual precipitation during 2004 and 2005 was near normal. During 2003-2007 period, approximately 56% of the annual rainfall occurred from June through October with August being the wettest month (≈169 mm). It should be noted that rainfall events below 20-30 mm during summer season may fail to produce significant stormflow, most likely due to high ET demands especially in the forest and wetland land covers.

Water Balance Results using SUFI-2 Algorithm

The main water balance components of the Waccamaw watershed include: the total amount of precipitation falling on the sub-watersheds during the forecast lead time, and the net amount of water that leaves the watershed and contributes to the reach (water yield). The water yield includes surface runoff, lateral flow (water flowing laterally within the soil profile that enters the main channel), groundwater flow (water from the shallow aquifer that returns to the reach) minus the transmission losses (water lost from tributary channels in the HRU via transmission through the bed and becomes recharge for the shallow aquifer during the time step) and evapotranspiration value.

SUFI-2 results indicated that 71.17% of the annual precipitation is lost by evapotranspiration process in the watershed during the entire period. Surface runoff
contributed 16.73%, the ground water contributed 12.51% and finally lateral flow contributed 0.72% to the total water yield during simulation period respectively. A portion of surface flow (16.73%) agrees with Feyereisen et al., (2007) and the field-based study of Shirmohammadi et al., (1984) who stressed that the portion of surface flow in the coastal plain watershed is less than 30% of total water balance quantities. Figure 2 shows water components in the Waccamaw watershed during the 2003-2007 simulation interval. Figure 2 indicates that surface flow is very high during September and October and very low in May and June. It also revealed that evapotranspiration exceeded precipitation during March, April, and May although the largest flux was generated during July. Maximum precipitation occurs in July and August. Surface runoff is at its annual maximum during September and October because precipitation is still high but ET has sharply declined.

In addition both algorithms demonstrate that more than 86% and 68% of water flux were lost by active evapotranspiration process in dry (2007) and wet (2006) periods, respectively. The seasonal pattern of their contributions indicated that during wet months (January-June) most of the streamflow originates from surface runoff due to higher rainfall values while during dry months (July-September) groundwater is the main contributor to the river system. If we consider total precipitation amount during the dry year equal to 100%, the total water outflow is equal to 114.01%. This excess amount (+14.01%) is the water flux of pervious wet year and indicated that watershed is still responding to the pervious wet conditions by redeeming water in the wet period and releasing it to the river system during dry season. In other words, this excess water flux is extra shallow aquifer contribution which is related to previous rainfall events in 2006 or so. Furthermore shallow aquifer contribution is higher than other components and dominates water components during May, September and November (2007), respectively.

Water Balance Results using PSO Algorithm

Based on PSO outputs, annual evapotranspiration, surface flow, ground water and lateral flow contributed 70.5% (930.5 mm), 16.53% (218.22 mm), 13.10% (173 mm) and 0.26% (3.44 mm) to the river system during 2003-2007 period. PSO estimated that February (30.11%) and October (30.76%) contributed the highest surface flow values. While ground water contribution was less varied during different months and totally contributed 13%-16% to the river system. PSO estimated that ground water and surface water contributions in dry period are 19. 05% and 8.33% while it is 12.81% and 18.17% in wet period, respectively.

Summary and Discussion

In this research both SUFI-2 and PSO algorithms predicted water balance variability simulated by the SWAT model. In addition, based on different predictions of water balance components, the
streamflow responses demonstrated that SWAT was effective for simulating the dynamic nature of a coastal plain landscape. Testing of the SWAT model in a low gradient coastal plain watershed system suggested that the model can be applied in other coastal plain watersheds to achieve the best practice for water resources management and planning purposes. In addition, the results of this study can serve as a fundamental estimation of water balance components in a typical coastal plain watershed and can be used as a reference for other similar landscapes. Future works should focus on elaborating on the relationships of each water balance components on hydrological response that can capture the influences of landscape dynamics and land use changes on water balance quantities.

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References