Journal of Hydrology 511 (2014) 719–735

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

SWAT-CS: Revision and testing of SWAT for Canadian Shield catchments

Congsheng Fu [a,*], April L. James [a], Huaxia Yao [a,b]

[a] Department of Geography, Nipissing University, 100 College Drive, Box 5002, North Bay, Ontario P1B 8L7, Canada
[b] Dorset Environmental Science Centre, The Ministry of Environment, 1026 Bellwood Acres Road, Dorset, Ontario P0A 1E0, Canada

A R T I C L E I N F O

Article history:
Received 17 November 2012
Received in revised form 11 January 2014
Accepted 6 February 2014
Available online 19 February 2014
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Ercan Kahya, Associate Editor

Keywords:
SWAT
Canadian Shield
Catchment hydrology
Interflow
Macroprore flow
Harp Lake

S U M M A R Y

Canadian Shield catchments are under increasing pressure from various types of development (e.g., mining and increased cottagers) and changing climate. Within the southern part of the Canadian Shield, catchments are generally characterized by shallow forested soils with high infiltration rates and low bedrock infiltration, generating little overland flow, and macropore and subsurface flow are important streamflow generation processes. Large numbers of wetlands and lakes are also key physiographic features, and snow-processes are critical to catchment modeling in this climate. We have revised the existing, publicly available SWAT (version 2009.10.1 Beta 3) to create SWAT-CS, a version representing hydrological processes dominating Canadian Shield catchments, where forest extends over Precambrian Shield bedrock. Prior to this study, very few studies applying SWAT to Canadian Shield catchments exist (we have found three). We tested SWAT-CS using the Harp Lake catchment dataset, an Ontario Ministry of Environment research station located in south-central Ontario. Simulations were evaluated against 30 years of observational data, including streamflow from six headwater sub-catchments (0.1–1.9 km^2), outflow from Harp Lake (5.4 km^2) and five years of weekly snow water equivalent (SWE). The best Nash–Sutcliffe efficiency (NSE) results for daily streamflow calibration, daily streamflow validation, and SWE were 0.60, 0.65, and 0.87, respectively, for sub-catchment HP4 (with detailed land use and soil data). For this range of catchment scales, land cover and soil properties were found to be transferable across sub-catchments with similar physiographic features, namely streamflow from the remaining five sub-catchments could be modeled well using sub-catchment HP4 parameterization. The Harp Lake outflow was well modeled using the existing reservoir-based target release method, generating NSEs of 0.72 and 0.67 for calibration and verification periods respectively. With significant changes to the infiltration module (introducing macropore flow and reduced bedrock percolation), more than 90% of interflow was generated close to the soil–bedrock interface and the contribution of groundwater flow to total runoff was reduced to small amounts, consistent with hydrological process understanding in this terrain. These two changes also allowed for a positive linear relationship between NSE of SWE and Q, whereas prior to these changes there was a negative relationship. With these key revisions to the infiltration and bedrock percolations modules, it is concluded that SWAT-CS can reasonably capture key hydrological processes within Canadian Shield catchments. Further testing will examine water quality modeling and larger-scale applications.

1. Introduction

Canadian Shield catchments in Ontario are under increasing pressure from various types of development (e.g., mining in northern locations, roads and increased shoreline development in the south), with potential impact of both point and nonpoint source pollution. Of particular interest to this study are the declining calcium concentrations observed in many Ontario lakes which has threatened the health of aquatic ecosystems (Jeziorski et al., 2008) and thus emphasizes the importance of understanding catchment and lake water and nutrient balance (Yao et al., 2011). Despite these pressures, use of distributed hydrologic and nonpoint source pollution models in Shield catchments as investigatory tools is limited, likely due to limited year-round population (and thus a lack of policy process-driven demand), and the lack of data and readily available models already tested for landscape conditions. Catchment management tools for Shield catchments are in critical and immediate need. Dynamic catchment models including representation of terrestrial, stream, and lake components are also lacking for specific study of the calcium cycle.

* Corresponding author. Address: Room 307, Bronwell Building, 260 Glenbrook Road, Storrs, CT 06269, USA. Tel.: +1 860 771 1702.
E-mail address: anlexiaoming@163.com (C. Fu).

http://dx.doi.org/10.1016/j.jhydrol.2014.02.023
0022-1694/

Recent reviews provide extensive comments on the advantages and disadvantages of existing catchment models for forested systems (e.g., Becker et al., 2009). Table 1 provides an overview of four widely-used catchment scale nonpoint source pollution models offering a range of hydrologic, hydrochemical, and spatial representation. Two other commonly used nonpoint source pollution models – the Annualized Agricultural Nonpoint Source (AnnAGNPS) model (Bingner and Theurer, 2001) and Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) model (Beasley et al., 1980), are similar to the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Table 1) and Hydrological Simulation Program-Fortran (HSPF) model (Bicknell et al., 1993; Table 1), so they are not included in the comparison here. We chose SWAT to study the hydrologic and biogeochemical cycling of a forested Canadian Shield catchment, due to its comprehensive delineation of hydrological and biogeochemical processes, open source access, ease of modification, and its extensive applications.

The SWAT model (Arnold et al., 1998) is a physically based continuous-time model (computational time step is daily) for assessing water resource and nonpoint source pollution problems. SWAT was originally developed for agricultural landscapes but recent applications are expanding its use to new landscapes and diverse land use (e.g., Miller et al., 2002; Mapfumo et al., 2004; Troin and Caya, 2013). These applications have occurred worldwide, especially in the US and Europe, and include studies by government agencies (Gassman et al., 2007; Douglas-Mankin et al., 2010; Tuppad et al., 2011). In the US, SWAT has been incorporated into the BASINS (Better Assessment Science Integrating point and Nonpoint Sources) toolbox by U.S. Environmental Protection Agency (EPA, Di Luzio et al., 2004). In Canada, SWAT is the primary hydrological model included in Agriculture and Agri-Foods Canada's Watershed Evaluation of Beneficial Management Practices (WEBs) program (AAFC, 2010), including applications in seven agricultural catchments across the country. More than one thousand academic papers on SWAT were found as part of our literature review (CARD, 2013).

The Canadian Shield covers over half of Canada and extends into the US (Fig. 1). As a result of glaciation during the last ice age, very thin soil lies on the top of the Precambrian rock, with many bare bedrock outcrops (Gunn et al., 2004). With the effect of post-glacial rebound and because the catchments are very young, numerous rivers, lakes, marshes and bogs (wetlands) exist. Vegetation is mainly coniferous forests, and trees are larger (in height and diameter) and closer together in the southern areas.

Overland flow rarely occurs in forest headwater catchments due to the large hydraulic conductivity (usually around 10^{-4} m/s) of forest soils (reviewed by Fu et al., 2012a), except in areas of: (a) bare soil, (b) bedrock outcrop, (c) riparian zones, (d) rainfall on water surface of stream, ponds, wetlands and lakes, (e) hillslope concavities (e.g., plot A in Fu et al., 2012b), (f) organic layers (act as "thatched roof" per the description in Buttle and Turcotte, 1999), and (g) rainfall on frozen land surface. In addition, observations from forest hillslopes at diverse sites around the globe (e.g., Tromp-van Meerveld et al., 2007; Graham et al., 2010; Katsuyama et al., 2005; Onda et al., 2006; Fu et al., 2012a) indicate that subsurface flow generated at the soil–bedrock interface is the dominant component of hillslope runoff, and macropores are the main passage way by which rainwater infiltrating into the soil reaches the soil–bedrock interface. The limited occurrence of overland flow, and the importance of macropore flow and subsurface flow generated at the soil–bedrock interface have also been documented in forest catchments on the Canadian Shield (Renzetti et al., 1992; Peters et al., 1995; Buttle and Turcotte, 1999; Buttle et al., 2004).

The SWAT model was designed as a large-scale management model, especially for agricultural areas. The flow components in SWAT include overland flow, interflow that is generated in sequence from top to bottom of the soil profile, and groundwater flow from unconfined shallow aquifers. While overland flow rarely occurred on forested hillslopes, interflow is mainly generated at the soil–bedrock interface (not in sequence from top to bottom), and the kind of groundwater flow from phreatic aquifers in thick-soil areas does not generally exist in forested headwater catchments. As a result, existing hydrological modules in SWAT may require modification in order to reasonably implement SWAT to forested headwater catchments. In addition, Canadian Shield catchments are characterized by numerous wetlands and lakes and the substantial contribution of snowmelt to streamflow, which require additional assessments in SWAT.

Currently, only a limited number of SWAT studies have been reported for specific Canadian Shield conditions, as shown in Fig. 1. Wu and Johnston (2007) conducted a SWAT study in a forested catchment (901 km^2) in northern Michigan, which was characterized by high hydraulic conductivity and limited storage capacity in soils, wetlands and lakes. They reported that the performance of a drought specific calibrated model (monthly streamflow NSE from 1950 to 1965 of 0.80) was much better than that of an average – calibrated model (monthly streamflow NSE from 1950 to 1965 of 0.40). In their study catchment baseflow contributed substantially to streamflow (>50%) and as a result, bedrock percolation

Table 1
Characteristics of several watershed scale hydrologic and nonpoint source pollution models.

–	SWAT (Arnold et al., 1998)	Hydrological Simulation Program-Fortran (HSPF; Bicknell et al., 1993)	WATFLOOD (Kouwen et al., 1993)	MIKE SHE (Refsgaard and Storm, 1995)
Spatial representation	First level: sub-basin; Second level: Hydrologic Response Unit (HRU)	Divides catchment on basis of land use, each land use has pervious and impervious parts	First level: grid network; second level: Group Response Unit (GRU)	Grid network
Representations of hydrological processes	Empirical or semi-empirical formulas	Empirical or semi-empirical formulas	Empirical or semi-empirical formulas	Partial difference equations
Representation of chemical processes	Comprehensive	Comprehensive	Not as comprehensive as SWAT	Not as comprehensive as SWAT
Advantages	Open source software and easy to modify; widely used	Time step from 1 min to 1 day	Incorporates remotely sensed data; easy to be connected with other system models	Completely physically-based
Disadvantages	Conflict with theory of hillslope hydrology at small scale	Conflict with theory of hillslope hydrology at small scale	Conflict with theory of hillslope hydrology at small scale; modeling effects at small scales are not as good as at large scales	Highly demanding in input data; Computationally intensive