size, spatial and temporal variations in these factors complicate hydrologic cycles. Mathematical models and geospatial analytical tools, therefore, are needed to study hydrologic processes and their responses (Singh and Woolhiser, 2002).

SWAT (Soil & Water Assessment Tool) has been useful for spatial analyses at different watershed scales (Weber et al., 2001). The model was developed by USDA Agricultural Research Service (USDA-ARS) to assess the impacts of land use management on water, sediment, and agricultural chemical yield in complex watersheds over a long period of time (Arnold et al., 1998). As a physically-based model, SWAT uses hydrologic response units (HRUs) to describe spatial heterogeneity in land cover and soil types within a watershed. The model estimates relevant hydrologic components such as surface runoff, groundwater flow, evapotranspiration, and soil moisture change for each HRU.

Overwinter snow accumulation greatly alters stream flow regimes in the Upper Peninsula of Michigan, particularly in areas that receive enhanced “lake effect” snowfall from westerly winds passing over Lake Superior. Winter precipitation accumulates from approximately November through April due to below-freezing temperatures, and is released only during snowmelt events in late spring. The purpose of this study is to (1) examine applicability of SWAT model, especially its snow melting algorithm in the northern Michigan, and (2) define critical hydrologic parameters that associated with snow melting processes.

2.2. METHODS AND MODEL DESCRIPTION

2.2.1. Site Description

The study site is located in the Ontonagon River Watershed, a 3,460 km^2 drainage basin to Lake Superior. Covering portions of five counties (Ontonagon, Houghton, Iron, and Gogebic of Michigan, and Vilas of Wisconsin) in the Upper Peninsula Michigan and northern Wisconsin, the watershed extends 70 km in east-west direction and 50 km in north-south direction. The river drains northward, from an elevation of 574 m in the headwaters to 183 m at the river mouth on Lake Superior (Figure 1).

The watershed lies in the cold temperature region, its weather is affected by different factors from both local, regional, and lakes. Annual precipitation is from 800 mm to 1000 mm with considerable spatial and temporal variation. Annual precipitation, especially lake-effect snowfall, is greatest near the shore of Lake Superior and decreases with distance inland from the shoreline. July receives the highest rainfall during a year (80 mm to 130 mm), while January and December showed the highest snowfall. The highest daily snowfall (45 mm in January) occurred in Ontonagon, Ontonagon County (8 km from the lake shore) and the lowest (18 mm in January) occurred in Watersmeet, Gogebic (64 km from the lake shore).

Annual average air temperature ranges from -2.5 °C to 0 °C, with highest in July (around 13 °C) and lowest in January (around -17 °C). Mean air temperature is over 0°C from May through October, and it is below a freezing point for the other six months from November through April. With monthly average air temperature near zero and daily air temperature fluctuating either above or below 0 °C in April and October, these two months are the most hydrologically sensitive periods in the watershed.

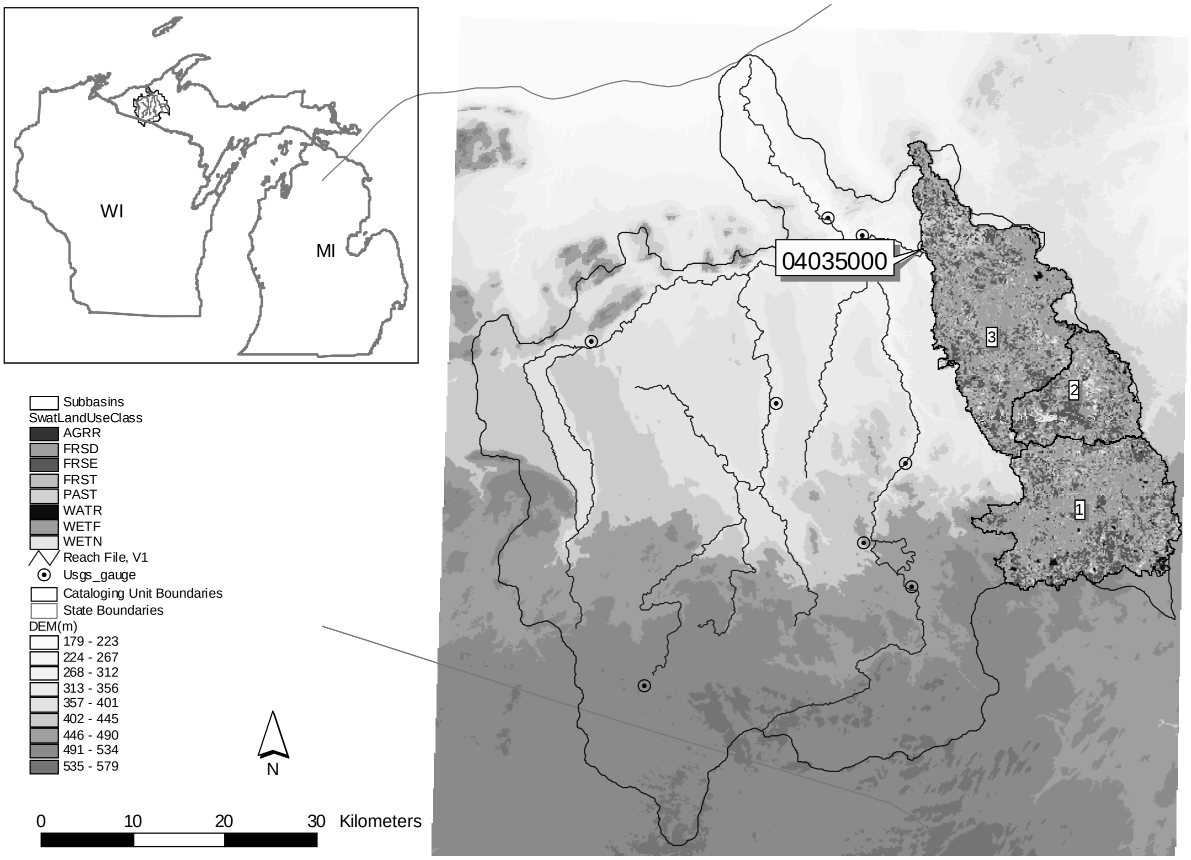

Fig. 1. Geographic location of the Ontonagon River Watershed (A USGS gauging station is represented by a circle with a dot, a contributing drainage to USGS gauging station 04035000 and land cover of three subwatersheds are shown in an insert).

The watershed is within the Laurentian Mixed Forest Province. Pleistocene glaciation (ground moraine and lacustrine deposits) exerts a significant effect on geology. The dominant types of bedrock geology included: hard rocks of the Canadian Shield with a relatively thin cover of glacial material in the western portion of the watershed, and Cambrian sandstone and overlying strata of limestone and dolomite in the eastern and northern portion of the watershed. Soils were developed from coarse-textured glacial deposits, including end moraines, ground moraines, and glaciofluvial deposits, as well as finer-textured glaciolacustrine deposits along the Lake Superior shoreline. Major soils in the Ontonagon watershed included Gogebic-Dinkey in the east and south, and Ontonagon-Bergland in the central and north region (USDA ARS, 1991). Formed mostly from sandy parent materials, these soils tend to have high hydraulic conductivity and limited water storage capacity. The watershed was covered with 90% forest: 49% mixed forest, 21% evergreen forest, 11% deciduous forest, and 9% forested wetlands (US EPA, 1994).

2.2.2. Data Collection

Spatial data used in the study included a digital elevation model (DEM), land use and land cover, and soil data. A digital elevation model with a scale of 1:24,000 (30 m DEM) was downloaded from the Seamless Data Distribution System, National Center for Earth

Resources Observation and Science (EROS), USGS (http://seamless.usgs.gov/) and processed with ArcGIS 9.1. Land cover is from National Land Cover Data (NLCD) 1992, and spatial soil data is from the State Soil Geographic (STATSGO) database.

Daily stream flow records were obtained from six USGS gauging stations, with periods from 1942 and 1944 to 1971 and 2004 (Table 1) (http://nwis.waterdata.usgs.gov/mi/nwis/sw). Six weather stations in the study area were selected. Daily maximum and minimum air temperature and daily precipitation were obtained from the National Climatic Data Center (NCDC). The earliest available precipitation data began in 1938 and the latest is in 2005 (Table 2).

Table 1. Six USGS Gauging Stations used for the SWAT calibration and validation.

Station ID	Name	Drainage area (km^2)	Data period	Latitude	Longitude
04040000	Ontonagon River near Rockland	3471	1942-2004	46.7158	-89.2105
04035500	Middle Branch Ontonagon River near Rockland	1738	1942-2004	46.6992	-89.1600
04035000	East Branch Ontonagon River near Mass	704	1942-1979	46.6900	-89.0733
04039500	South Branch Ontonagon River at Ewen	901	1942-1971	46.5328	-89.2769
04033000	Middle Branch Ontonagon River near Paulding	425	1942-2004	46.3569	-89.0772
04037500	Cisco Branck Ontonagon River at Cisco Lake Outlet	131	1944-2004	46.2533	-89.4514

Table 2. Six Weather Stations for SWAT Calibration and Validation.

COOP ID	Name	County	Periods(prep)	Elevation (m)	Latitude	Longitude
206220	Ontonagon 6 SE	Ontonagon	1977-2005	240	46.8333	-89.2000
200718	Bergland Dam	Ontonagon	1938-2005	396	46.5833	-89.5500
204328	Kenton	Houghton	1940-2002	355	46.4833	-88.8833
208680	Watersmeet 5 W	Gogebic	1938-1999	495	46.2833	-89.2833
200647	Beechwood 7 WNW	Iron	1949-1990	506	46.1833	-88.8833
474383	Lac Vieux Desert	Vilas	1945-2005	515	46.1167	-89.1167

2.2.3. Snow Melting and Modeling

Annually, about half of precipitation occurs in the form of snowfall in the Upper Peninsula. A snowpack development begins in November and begins to progressively ripen and release melt water to stream in April, resulting in the highest discharge of a year.

Two algorithms are used for simulating snow accumulation and melt, that is, energy balance (U.S. Corps of Engineers, 1956; Anderson and Crawford, 1964) and temperature index approach (degree-day method). Though hydrologically significant, there are few hydrologic models which have been designed primarily as snowmelt models. Normally, the snowmelt routine is added to the precipitation section where the water input to the main part of the hydrologic model is determined. An energy balance model has an intensive requirement for meteorological data, but the degree-day method requires only air temperature data (Rango and Martinec, 1995). The latter is commonly used in hydrologic models. In a degree-day method, the snow melt is calculated as a linear function of the temperature difference between average air temperature (or average of snow pack and maximum air temperature) and the base or threshold temperature for snow melt.

A general form of the degree-day method is as follows:

$$M = C_m(T_a - T_b)$$

where

M is snow melt (mm day^{-1})

C_m is degree day coefficient (mm day^{-1} $^{o}\text{C}^{-1}$)

T_a is air temperature

T_b is a base temperature

C_m could range from 7.3 to 3.6 mm day^{-1} $^{o}\text{C}^{-1}$ in an Iowa watershed on forest cover, to 1.4 to 6.9 mm day^{-1} $^{o}\text{C}^{-1}$ in rural areas (Huber and Dickinson, 1988), and to 3.5 mm day^{-1} $^{o}\text{C}^{-1}$ in urban area in Sweden.

In SWAT, the snow melt is calculated using a modified degree-day method as a linear function of the difference between the average snow pack-maximum air temperature and the threshold temperature for snow melt (Neitsch et al., 2001):

$$SNO_{mlt} = b_{mlt} \cdot sno_{cov} \cdot [\frac{T_{snow} + T_{mx}}{2} - T_{mlt}]$$

where SNO_{mlt} is the amount of snow melt on a given day (mm H_2O), b_{mlt} is the melt factor for the day (mm day^{-1} $^{o}\text{C}^{-1}$), sno_{cov} is the faction of the HRU area covered by snow. T_{snow} is the snow pack temperature, T_{mx} is the maximum air temperature, and T_{mlt} is the base temperature above which snowmelt is allowed.

2.2.4. Model Setup and Simulation

The U.S. EPA program, Better Assessment Science Integrating Point and Nonpoint Sources software system 3.1 version (BASINS 3.1), was used to assemble spatial datasets and to delineate watersheds. SWAT calibration was conducted separately for each of six USGS gauging stations in the watershed due to diverse geology and landscape characteristics. The result presented in the paper is based on the results for USGS gauging station 04035000 (Figure 1).

The contributing watershed to the gauging station 04035000 was divided into 3 sub-watersheds based on availability of air temperature and precipitation. The three sub-watersheds were further divided into a total of 206 hydrologic response units (HRUs) based on land use and soil types (Neitsch et al., 2001). Characteristics of sub-watershed and HRUs were calculated and used in the SWAT simulation. A baseflow filter, based on daily discharge records, was used to estimate the baseflow recession constant (0.0029) (Arnold and Allen, 1999). Runoff was estimated by using the SCS Curve Number method from daily precipitation record. Priestley-Taylor model was used to estimate PET. The Muskingum method was used for channel water routing. Simulation results from January 1, 1969 to December 31, 1971 were used for parameter calibrations. Daily discharge from January 1, 1972 to December 31, 1973 was used for model validation.

2.2.5. Evaluation

Besides graphic comparison of the simulated discharge against the measured discharge, two numeric criteria were used to evaluate the modeling results: a deviation of discharge and a model coefficient of efficiency. The deviation of discharge (D) was calculated as follows:

$$D = \frac{Q_{usgs} - Q_{swat}}{Q_{usgs}} \times 100$$

where Q_{usgs} is the observed total volume and Q_{swat} is the simulated total volume for a specified period of time. In the modeling simulation, results were considered satisfactory when D was below 10% and excellent when D was less than 5%.

The model coefficient of efficiency (E) was estimated based on Nash and Sutcliffe (1970):

$$E = 1 - \frac{\sum_{i=1}^{n}(q_{usgs} - q_{swat})^2}{\sum_{i=1}^{n}(q_{usgs} - \overline{q_{mean}})^2}$$

where q_{usgs} is the observed daily discharge (cms), q_{swat} is the simulated daily discharge (cms), and $\overline{q_{mean}}$ is the mean observed daily discharge (cms) during the evaluation period. E is similar to a correlation coefficient obtained from a linear regression. However, E compares the measured values to the 1:1 line, in which measured values equals estimated values (perfect fit), rather than to the best-possible-fit regression line (Saleh et al., 2000; Van Liew and Garbrecht, 2003).

2.3. RESULTS AND DISCUSSION

2.3.1. Subwatershed Drainage Characteristics

Drainage features were summarized in Table 3 and 4. Areas range from 114 km^2 in subwatershed 2 to 295 km^2 in subwatershed 3. Topography is relatively gentle with a slope from 4.9 to 5.3 %. Forest coverage is 80.3%, 79.3%, and 72.9% in subwatershed 1, 2 and 3, respectively (Table 4). Forested wetlands range from 7.6% in subwatershed 2 to 14.9% in subwatershed 3. While soils were dominated by Gogebic and Rubicon in subwatershed 1 and 2, soils were more diverse in subwatershed 3.

Table 3. Characteristics of subwatersheds corresponding to USGS gauging station 04035000.

Subwatershed	Area km^2	Len1[a] m	Slo1[b] %	Csl[c] %	Wid1[d] m	Dep1[e] m	Elev[f] m	HRUs[g]
1	264	35018	5.3	0.5	36.6	1.2	468	73
2	114	26864	5.3	0.4	22.1	0.9	406	60
3	295	35131	4.9	0.5	39.1	1.3	368	73

[a] Stream reach, longest path within the sub-watershed.
[b] Sub-watershed slope.
[c] Reach slope.
[d] Stream reach width.
[e] Stream reach depth.
[f] Elevation of the sub-watershed centroid.
[g] Number of hydrologic response units.

Table 4. Landuse types of three subwatersheds.

Subwatershed 1		Subwatershed 2		Subwatershed 3	
Landuse types	%	Landuse types	%	Landuse types	%
FRSD[a]	40.7	FRSD	33.8	FRSD	34.7
FRSE[b]	21.9	FRSE	27.4	FRSE	19.2
FRST[c]	17.7	FRST	18.1	FRST	19.0
WETF[d]	11.4	WETF	7.6	WETF	14.9
Others	8.7	others	13.2	others	12.3

[a] FRSD: Deciduous Forest.
[b] FRSE: Evergreen Forest.
[c] FRST: Mixed Forest.
[d] WETF: Forested wetland.

2.3.2. Calibration and Validation

As indicated in Table 5, the initial simulation with default parameters resulted in a large deviation of total stream flow (18.3%) and low model efficiency of coefficient (-0.38). Stream flow was significantly underestimated by the SWAT simulation during the three-year periods. Simulated monthly discharges showed a little seasonal pattern. An excellent agreement between monthly observed discharge and simulated values was achieved, with a deviation of 0.46% and model's coefficient of 0.94. Peak flows, which generally occurred

Table 5. Deviation (D) and Nash and Sutcliffe coefficient (E) for model calibration and validation.

SAWT run	Periods	D (%)	E
Default	Jan 1, 1969-Dec 31, 1971	18.3	-0.38
Calibration	Jan 1, 1969-Dec 31, 1971	0.46	0.94
Validation	Jan 1, 1972-Dec 31, 1973	8.34	0.83

in April, were well matched by simulated values, except about 15% underestimation in 1970 (Figure 2). Parameter validation was conducted with two-year periods from 1972 to 1973. Deviation of 8.34% and Nash & Sutcliffe value of 0.83 indicated a satisfied result. In most months, the time series plot between measured monthly stream flow and simulated discharge suggested a good agreement, except a 38% underestimation on May 1973, which most possibly was caused by errors of measurement (Figure 3).

Eight parameters were chosen in the calibration (Table 6). Among these eight parameters, two of them, baseflow recession constant (ALPHA_BF) and maximum canopy storage (CANMX), were used as mandatory parameters, while others were chosen based on trial-and-error processes. Our primary studies indicated that groundwater is made up 75% to 89% percent of stream flow in the Upper Peninsula (Wu and Johnston, 2005). Therefore,

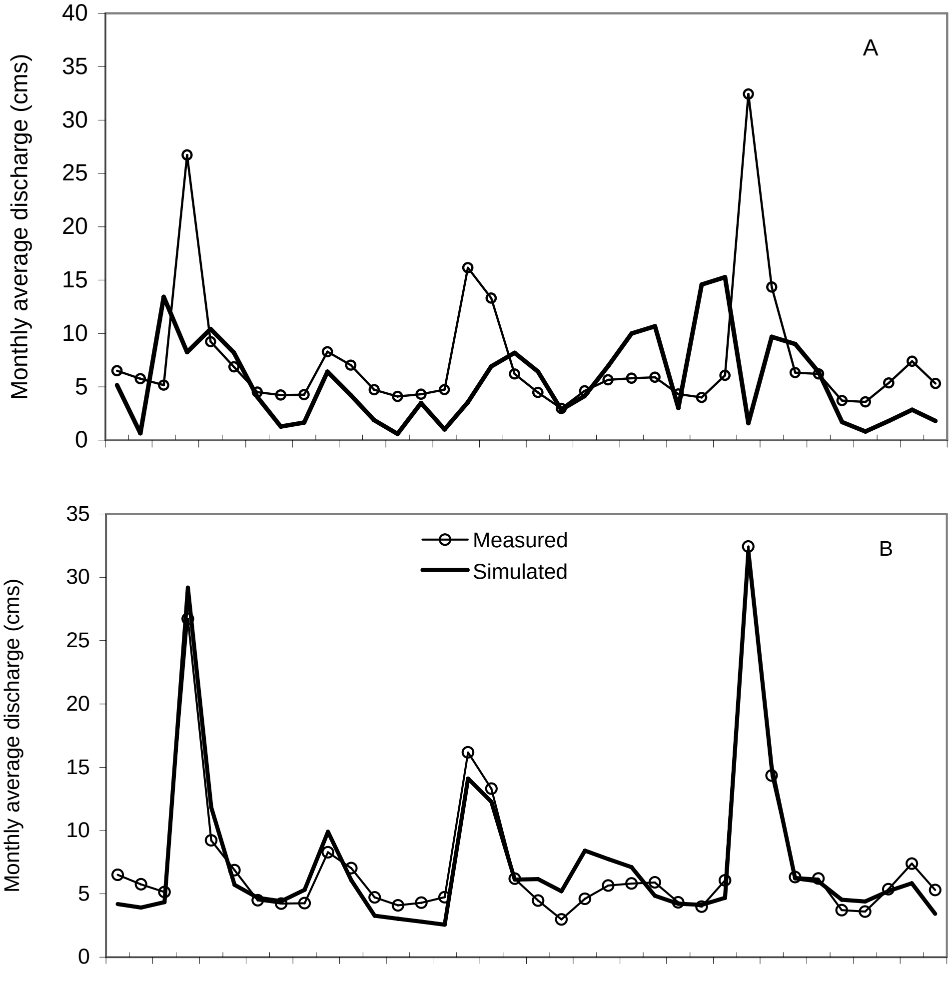

Fig. 2. Time series plots of measured and simulated monthly average discharge with default parameters (A) and calibrated parameters (B) in subwatershed 04035000.

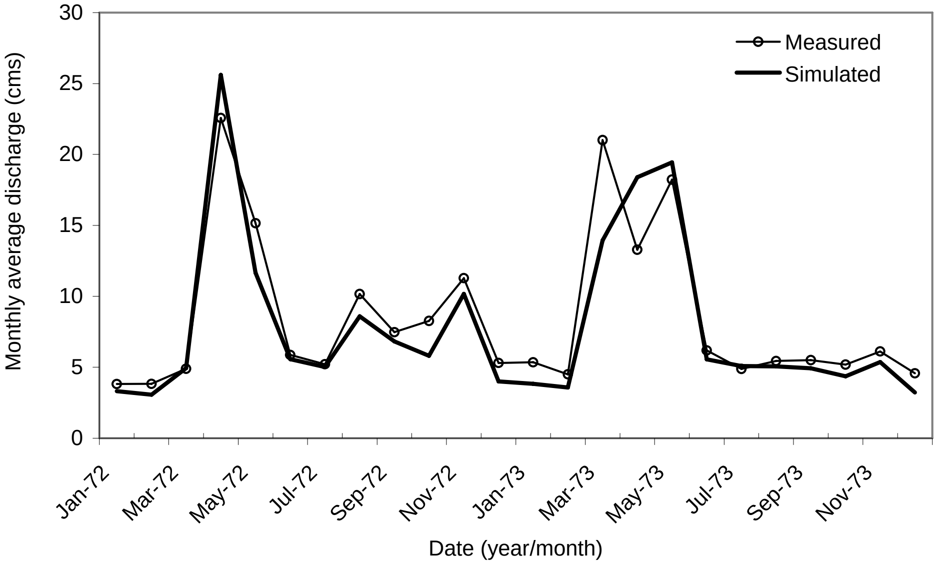

Fig. 3. Time series plot of measured and simulated monthly average discharge during validation period from 1972 to 1973 in subwatershed 04035000.

Table 6. Calibrated parameters based on consequence in the SWAT calibration.

Parameters [a]	Default value	Adjusted value	D (%)	E
ALPHA_BF(days)[b]	0.049	0.0029	20.21	-0.31
CANMX (mm)[c]	0	2.5	21.85	-0.32
TIMP[d]	1	0.05	17.1	0.88
SMTMP(°C)[e]	0.5	2	15.8	0.89
SMFMN (mm day^{-1} ^{o}C^{-1})[f]	4.5	0.5	13.9	0.89
SMFMX(mm day^{-1} ^{o}C^{-1})[g]	4.5	2.5	11.4	0.92
ESCO[h]	0	1	9.98	0.93
EPCO[i]	0	0.15	0.46	0.94

[a] Source: Soil and Water Assessment Tool User's Manual, Version 2000 (Neitsch et al., 2001).

[b] Baseflow recession constant.

[c] Maximum canopy storage.

[d] Snow temperature lag factor

[e] Threshold temperature for snow melt.

[f] Melt factor on December 21.

[g] Melt factor on June 21.

[h] Soil evaporation compensation coefficient.

[i] Plant uptake compensation factor.

amounts and patterns of groundwater recharge are important for simulating stream flow in the study site. However, groundwater recharge is complex, which is related to duration and intensity of precipitation, and characters of soil, topography and land covers. A baseflow recession constant, a parameter to describe the rate of groundwater enters a stream, is used in the SWAT model. Based on Arnold and Allen (1999), 0.0029 was estimated using 10-year long daily stream flow records and used in this study. Compared with commonly used values, which range from 0.3 to 1.0, the baseflow recession constant of 0.0029 is very small, suggesting slow drainage and huge storage in shallow aquifers in the study site.

Heavy forest cover in the study watershed suggests significant impacts of forest canopy on hydrology. One of the impacts is canopy interception. CANMX was used in the SWAT to reflect forest canopy influence. Previous studies showed that the storage capacity ranges from 0.3 to 6.6 mm for conifers, 0.03 to 2.0 mm for hardwoods, 0.3 to 2.0 mm for shrubs, and 1.0 to 1.5 mm for grasses (Zinke, 1967). A 2.5 mm was used for all forested HRU in this study.

A good agreement of calibration is most likely a combined effect from all selected parameters. However, sensitivity of each parameter varies. The results indicated that snow temperature lag factor (TIMP) and plant water uptake compensation factor (EPCO) were the most critical for model simulation in this study (Table 6). TIMP accounts for snow pack density, snow pack depth, and snow exposure due to canopy or slope direction. The deeper the snow pack, the more the temperature would depend on air temperature during preceding days. As TIMP approached 1, snow pack temperature is more affected by the mean air temperature on the current day. In this study TIMP of 0.05 was adjusted from its default value 0, suggesting that the current temperature of snow pack is mostly influenced by air temperature in the previous day. There are two possible explanations for the lag time in response of the snow pack to air temperature changes: (1) the thickness of the snow pack, which reaches up to 70 cm during February (Figure 4), and (2) shading from dense forest canopy and north-facing slopes.

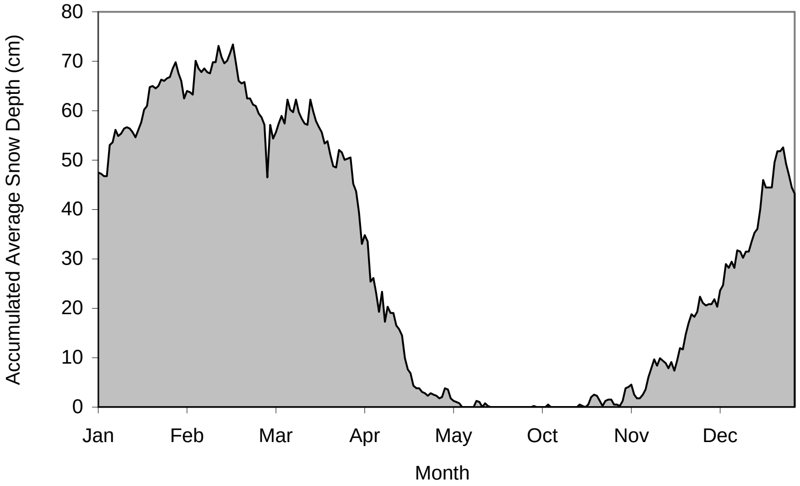

Fig. 4. Accumulated average snow depth in Bergland Dam, Ontonagon River Watershed, Michigan (200718) from 1994 to 2004.

EPCO factor in the SWAT model explains how available soil water would be used to meet plant water uptake, either from upper layers or from deeper profiles. When EPCO is near 1, soil water from deeper soil profiles would be used, whereas when EPCO is near 0, soil water from the top layers would most likely be used. EPCO of 0.15 was adjusted in this study, indicating most water used by vegetation would be from the upper soil profile, because of a relative higher ground water table, sufficient soil moisture, and limited transpiration in growing seasons.

The Nash and Sutcliff value (E) could represent a degree of a temporal agreement between measured stream flow and simulated discharge. The lower E value suggests a great discrepancy of temporal patterns even though there exists a good agreement between total stream volumes. The study found that TIMP was closely related to the Nash & Sutcliffe coefficient, while TIMP has minimal impact on deviation of total stream flow. The E value would significantly decrease when TIMP was larger than 0.1 during the three-year periods, suggesting an important impact of snow pack temperature on snow melting processes. Errors in estimation of snow pack temperature would lead to a temporal difference of simulated stream flow. In contrast to TIMP, EPCO posed a significant impact on total stream flow but with minimal influence on the model's coefficient (Figure 5 and Table 6).

Even though results for monthly simulation of stream flow were satisfactory, a comparison of daily stream discharge patterns reflected more detailed fluctuation, particularly during the spring (Figure 6). The cause of the discrepancy between daily measured data and SWAT simulated values for 1969 through 1971 is uncertain, but may be due to weakness of the snow melting algorithm, and/or huge spatial variations in air temperature and precipitation measurement. Other authors (Qi and Grunwald, 2005) have questioned the snowmelt algorithm used in the SWAT model. An alternative reason for the poor performance of the model on a daily scale in the Ontonagon watershed may be inadequate representation of the spatial variation of precipitation and air temperature, because only one weather station was used in this 673 km^2 watershed, where lake-effect s

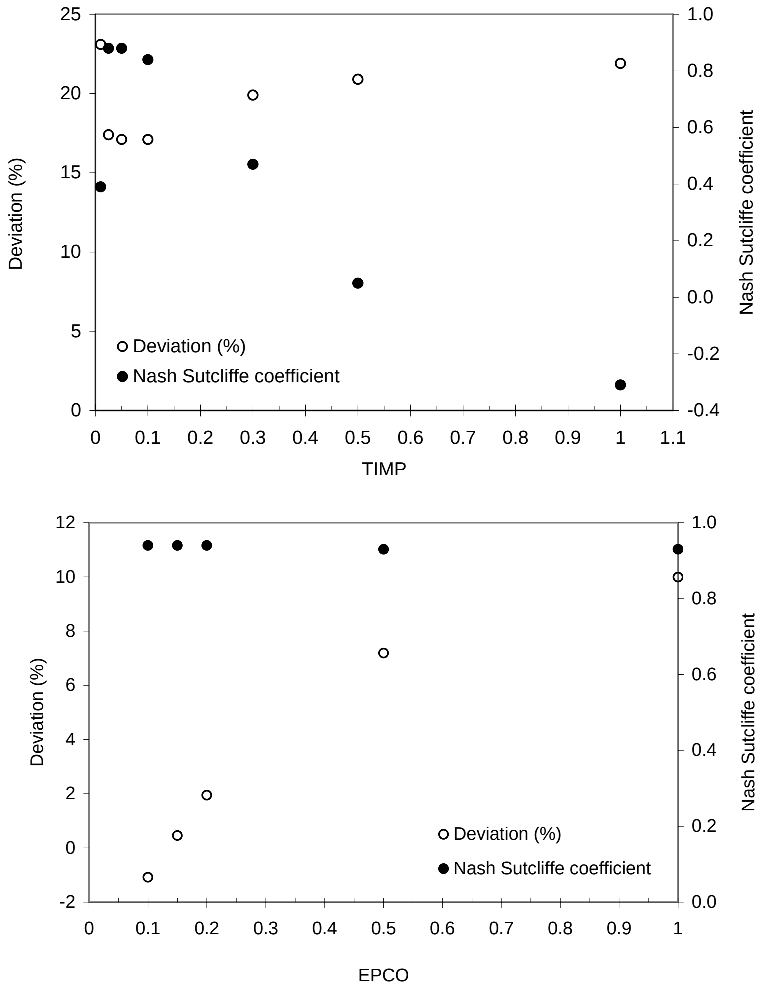

Fig. 5. Sensitivity of snow temperature lad factor (TIMP) and plant water uptake compensation factor (EPCO) in 04035000 watershed.

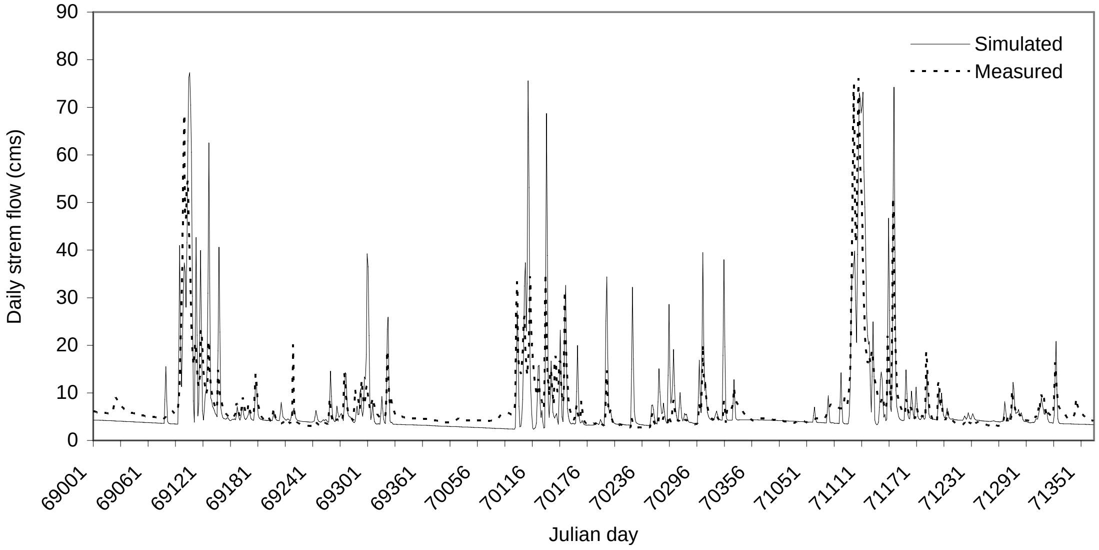

Fig. 6. Comparison of time series plot of measured and simulated daily stream flow (1969-1973).

nowfall could be significant. Therefore possible errors and uncertainty in estimation of precipitation, thus depth of snow pack, and in air temperature thus snow pack temperature might lead to fluctuation of daily stream flow estimation. Possible precipitation lapse and temperature lapse rates should be developed and used in SWAT simulation in this study if more accurate results are expected (Fontaine et al., 2002).

2.4. CONCLUSIONS

SWAT model was used to simulate hydrology in the snow-melt dominated watershed in Northern Michigan. Overall, the simulation gives an excellent agreement between observed discharge and simulated stream flow on a monthly basis.

Eight hydrologic parameters were selected and tested. Snow temperature lag factor (TIMP) and plant water uptake compensation factor (ESCO) were found the most critical parameters. The results suggest importance of snow pack temperature and soil water allocation on hydrologic processes in the study site. Degree-day method used in SWAT model was demonstrated to be promising based on this study. Discrepancy of SWAT simulation might be most likely caused by spatial variations and measurement errors in precipitation and air temperature. Precipitation and air temperature lapse rates should be developed and used for modeling snow melting in such snow-dominated watersheds.

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