INFLUENCES OF POTENTIAL EVAPOTRANSPIRATION ESTIMATION METHODS ON SWAT'S HYDROLOGIC SIMULATION IN A NORTHWESTERN MINNESOTA WATERSHED

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ABSTRACT. *The Soil and Water Assessment Tool (SWAT), a widely used watershed hydrology and water quality model, provides three different methods (Hargreaves, Priestley-Taylor, and Penman-Monteith) for estimating potential evapotranspiration (PET) and the corresponding actual evapotranspiration (AET). Although these methods have been extensively tested, the effects of using them within SWAT's framework are largely unknown. The objective of this study was to test the three PET methods within SWAT's framework using data collected in the Wild Rice River watershed, located in northwestern Minnesota. The performance of the SWAT models was measured using three statistics: the Nash-Sutcliffe coefficient* (E_j^2)*, coefficient of determination* (R^2)*, and performance virtue* (PV_k)*. The three models were independently calibrated and validated using the observed daily stream flows at two USGS gauging stations. The simulated stream discharges were compared with the corresponding observed values and the estimated evapotranspiration examined in accordance with the wet-environment areal evapotranspiration* (E_{TW}) *derived from the evaporation data for Williams Lake, located about 100 km southeast of the study watershed. The use of the three PET methods resulted in different values for two calibration parameters, namely the soil evaporation compensation factor and SCS curve number. At the lower station, which is near the watershed outlet, the observed annual mean discharge (8.33* m^3/s*) during the model validation period was predicted to be 10.25, 10.87, and 9.69* m^3/s *by SWAT-Penman, SWAT-Priestley, and SWAT-Hargreaves, respectively. The annual mean discharge (10.83* m^3/s*) was more accurately predicted during the model calibration period, with an absolute error of less than 0.5* m^3/s*. The prediction errors for the upper station were comparable with those for the lower station. In addition, all three models exhibited good performance when simulating the monthly, seasonal, and annual mean discharges* ($E_j^2 > 0.75$ *and* $PV_k > 0.80$) *and satisfactory performance when predicting the daily stream flows* ($E_j^2 > 0.36$ *and* $PV_k > 0.70$)*. In estimating evapotranspiration for the study watershed, SWAT-Hargreaves seemed to be slightly superior to the other two models, while SWAT-Priestley might be more appropriate for an* E_{TW} *value greater than 8.0 mm/d. Nevertheless, the AET values estimated by the three models shared a concurrent spatial pattern and temporal trend, and were insignificantly different from each other at a 5% significance level (p-values > 0.05). The results indicated that after calibration, using the three ET methods within SWAT produced very similar hydrologic (AET and discharge) predictions for the study watershed.*

Keywords. *Complementary relationship, Cool climate, Discharge, ET estimation methods, Evapotranspiration, Hydrologic modeling, Model performance.*

Evapotranspiration, a collective term that includes evaporation from the plant canopy, transpiration, sublimation, and evaporation from the soil, is the primary mechanism by which water is removed from a watershed (Dingman, 1994). It is thus an important component of the hydrologic cycle in the watershed, so accurate quantification of actual evapotranspiration (AET) is crucial to evaluating the effects of changing land use on water yield, environmental assessment, and development of best management practices to protect the quality of both surface and ground water (Irmak et al., 2005). Unfortunately, direct measurement of AET is difficult, time consuming, and costly because AET is related to a number of factors that may vary both spatially and/or temporally, including changes in leaf area, plant height, crop characteristics, rate of crop development, degree of canopy cover, canopy resistance, soil and climate conditions, and management practices (Doorenbos and Pruitt, 1977).

A practical approach to this problem is to compute AET based on the potential evapotranspiration (PET), which can be estimated using an appropriate method with available climate data as inputs. PET is generally defined as the amount of water that could evaporate and transpire from a vegetated landscape with no restrictions other than the atmospheric demand (Thornthwaite, 1948; Penman, 1948; Jensen et al., 1990). There are approximately 50 methods available to estimate PET, but these methods give inconsistent values due to their different assumptions and input data requirements, or because they were developed for specific climatic regions

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(Grismer et al., 2002; Lu et al., 2005). In terms of their input data requirements, these methods can be grouped into three classes: temperature-based methods, radiation-based methods, and combination methods. Among these, three commonly used methods, namely the temperature-based Hargreaves method (Hargreaves and Samani, 1985), radiation-based Priestley-Taylor method (Priestley and Taylor, 1972), and combination Penman-Monteith method (Penman, 1956; Monteith, 1965), were incorporated into the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), a widely used watershed hydrology and water quality model.

Amatya et al. (1995) compared these three methods, among others, by applying them to intensive meteorological data collected from three forested sites in eastern North Carolina. Daily, monthly, seasonal, and annual reference evapotranspiration (REF-ET) rates were compared for all three locations. The results indicated that of the three methods of interest here, the Hargreaves method overpredicted annual REF-ET by 15% on average, whereas the estimates obtained using the Priestley-Taylor method were in best agreement with the daily and monthly Penman-Monteith estimates for two sites. They concluded that the Priestley-Taylor method had a better performance than either the Hargreaves or the Penman-Monteith methods. In another recent study, Lu et al. (2005) compared the Priestley-Taylor and Hargreaves methods, along with four other methods, across a physiographic gradient of 36 forested watersheds in the southeastern U.S. Their results indicated that the Hargreaves method gave higher PET values than the Priestley-Taylor method, and that the Priestley-Taylor method performed better than the Hargreaves method. Similarly, Loescher et al. (2005) found that the Priestley-Taylor method had a better performance than the Penman-Monteith method for estimating PET from a wet tropical forest in Costa Rica. However, the generally better performance of the Priestley-Taylor method reported in these studies might be because all were conducted in areas with the type of warm, humid climate conditions for which the method was originally developed.

In contrast, Martinez-Cob and Tejero-Juste (2004) showed that the Hargreaves method, which was originally developed for California's dry climate, also worked well for windy locations under the semiarid conditions in northeastern Spain. Further, Federer et al. (1996) compared the Penman-Monteith and Priestley-Taylor methods, along with seven others, using data from seven locations that spanned a large climatic gradient in the continental U.S. and Puerto Rico. They concluded that the differences in the values of PET estimated by the different methods could be hundreds of millimeters for a particular location or a cover type and could exceed 700 mm/year for hot and dry areas. They also concluded that PET for grasslands, savanna, and conifer surfaces did not differ systematically from reference PET for short green crops.

For watershed studies, the major purpose of estimating PET is to determine AET, because AET represents the water that will actually be lost from the watershed. Hence, it is important to identify how the AET values are different when computed based on the PET values estimated using different methods. In a study designed to address this issue, Vörösmarty et al. (1998) extended the study conducted by Federer et al. (1996) by evaluating the sensitivity of PET methods to the AET values computed by a macro-scale hydrologic model. They found that monthly water balance calculations were indeed sensitive to the PET method used and warned that a PET method should be validated in the field before it is used. This extended study again covered a large climatic gradient across the continental U.S. and Puerto Rico, but was too coarse for watershed application purposes because the data used were from just seven locations. Further, this study failed to address how the simulated discharges were affected by using one of the methods instead of another, which is a significant concern for watershed studies.

As mentioned above, SWAT provides three PET estimation methods, namely Hargreaves, Priestley-Taylor, and Penman-Monteith. As there are inconsistent descriptions of these methods in the literature, this study applies the approach given by Neitsch et al. (2002a). To date, the choice of method for SWAT applications (e.g., Du et al., 2005; Narasimhan et al., 2005) has been subjective due to a general lack of information on how SWAT's simulation performance is likely to be affected by selecting one of the three methods rather than another. The studies cited above and elsewhere fail to address this issue, and as a result the potential errors from using one of these three PET estimation methods within SWAT's framework are largely unknown. The objective of this study was therefore to test these three PET estimation methods within SWAT's framework using data collected in the Wild Rice River watershed.

The Wild Rice River watershed, located in northwestern Minnesota, differs markedly from the warm and humid coastal watersheds studied by Amatya et al. (1995), Loescher et al. (2005), and Lu et al. (2005), and from the semiarid watershed studied by Martinez-Cob and Tejero-Juste (2004). It is characterized by broad, flat alluvial floodplains, river terraces, and gently sloping upland, and has a cool, windy, and moderately wet climate (Houston Engineering, 2001). The stream flows in spring (March to May) are predominantly generated from melting snow, whereas rainfall runoff is the dominant source for stream flows in summer (June to August) and fall (September to November). In winter (December to February), the stream flows are very low due to the river being frozen, but a snowpack accumulates that melts the following spring. To quantify the hydrologic characteristics, a water year is defined as December to November in this study.

MATERIALS AND METHODS

DESCRIPTION OF SWAT

SWAT was developed by Arnold et al. (1998) to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land use, and management practices. It is a physically based, continuous time, distributed parameter hydrologic model that uses spatially distributed data on soil, land use, topography, and weather for hydrologic modeling and operates on a daily time step. SWAT is composed of three major components, namely subbasin, reservoir routing, and channel routing. Each of the components includes several subcomponents. A complete description of these components and subcomponents can be found in Neitsch et al. (2002a). Herein is a brief description of the hydrology subcomponent, one of the eight subcomponents of the subbasin component.

For modeling purposes, SWAT divides a watershed into a number of subbasins. Portions of a subbasin that posses unique land use/management/soil attributes are grouped together and defined as a single hydrologic response unit (HRU) (Neitsch et al., 2002a, 2002b). Using a water balance equation, runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. The equation has six variables, which represent the soil moisture content, the amount of precipitation, surface runoff, AET, the amount of water entering the vadose zone from the soil profile, and the return flow. The AET variable represents the water actually removed from the HRU through evaporation from the plant canopy, transpiration, sublimation, and evaporation from the soil. SWAT first evaporates any rainfall intercepted by the plant canopy. Next, SWAT calculates the maximum amount of transpiration and the maximum amount of sublimation/soil water evaporation using an approach similar to that of Ritchie (1972). The actual amount of sublimation and evaporation from the soil is then calculated. If snow is present in the HRU, sublimation will occur. Only when no snow is present will evaporation from the soil take place. In SWAT, AET is usually computed based on the PET estimated using one of the aforementioned three methods. Soil water evaporation is estimated as an exponential function of soil depth and water content based on PET and a soil cover index based on the aboveground biomass. Transpiration is simulated as a linear function of the leaf area index, root depth, soil water content, and PET. The Hargreaves method requires three inputs, namely extraterrestrial radiation and the daily maximum and minimum temperatures. The Priestley-Taylor method, on the other hand, needs data on mean daily temperature and net radiation, which is rarely measured directly but usually derived from solar radiation and extraterrestrial radiation. As a combination method, the Penman-Monteith method requires more inputs, which include net radiation, air temperature, relative humidity, and wind speed.

Study Watershed

The 433,497 ha Wild Rice River watershed, located in northwestern Minnesota (fig. 1), was selected for this study. According to land use and land cover (LULC) data from the U.S. Environmental Protection Agency (EPA), the land use within this watershed consists of 67% agriculture, 18% forest, 7% pasture, and 8% wetland and/or open water. Agriculture dominates the western part of the watershed, but there is a large amount of forest acreage in the eastern part. The land between these two areas is distributed pasture. Wetland and/or open water are intermingled with the forest and/or pasture. Although the LULC data were developed from aerial photography surveys carried out in the 1970s and 1980s combined with land use maps and surveys (EPA, 2003), they are effectively up-to-date because there have been only negligible changes in the land use types for the study watershed over the past two decades (Stoner et al., 1993; Offelen et al., 2002, 2003). The soils in the western part are predominantly clay, which is very fertile for agriculture but has a very low permeability, resulting in a poor internal drainage. Towards the east, the soils tend to be clay loam and/or sandy loam mixed with sands and gravels, while the eastern part is composed primarily of clay and silt, with a loamy texture, a dark to moderately dark color, and poor to good internal drainage. The watershed has a very low topographic relief (Houston Engineering, 2001); its local relief is less than 5 m and global relief is only up to 350 m, with the elevation ranging from 255 to 600 m. The precipitation and temperature within the watershed vary negligibly with topographic elevation (M. M. Ziemer, personal communication, 2004).

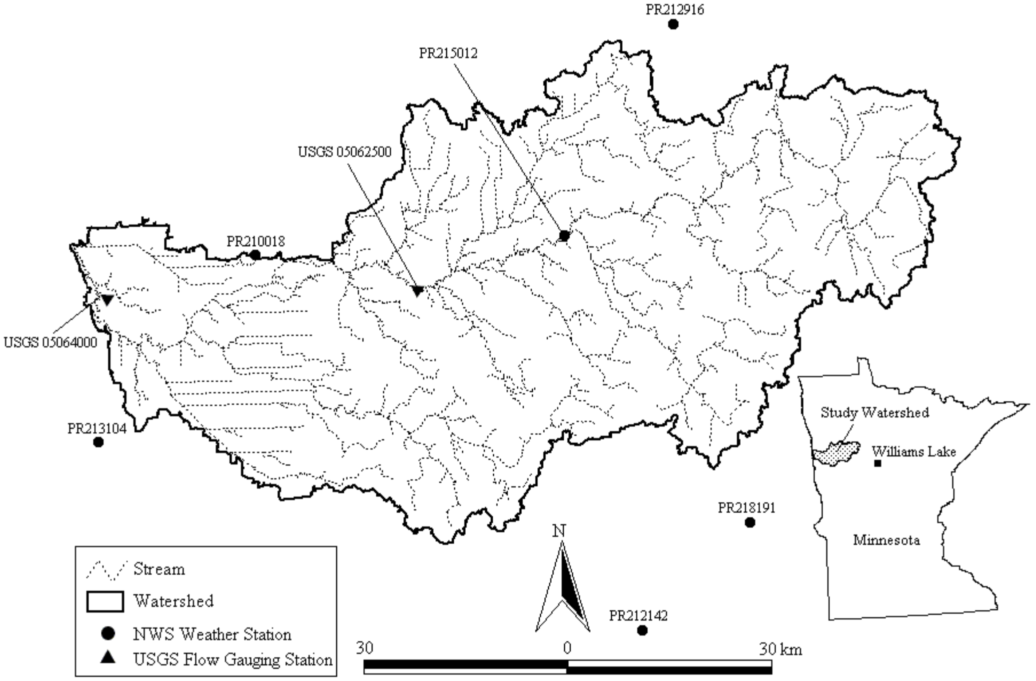

Figure 1. Map showing the location and boundary of the Wild Rice River watershed, Minnesota, along with the National Weather Service (NWS) precipitation and temperature stations and the U.S. Geological Survey (USGS) flow gauging stations, which supplied the data used in this study. The numbers in the labels of the NWS stations are the 6-digit COOP IDs for these stations.

The National Weather Service (NWS) National Climate Data Center (NCDC) collects data on the daily precipitation and minimum and maximum temperatures at stations PR210018 and PR215012, which are located within the watershed, and at four other stations, PR212142, PR212916, PR213104, and PR218191, which abut the watershed (fig. 1). The numbers in these labels signify the 6-digit NWS COOP IDs (cooperative station identifiers) for these stations. The NWS has found that the data measured at these six stations provide good information on the spatial and temporal distributions of precipitation and temperature in the study watershed (M. M. Ziemer, personal communication, 2004). The data indicate an annual average precipitation of 607 mm, 24% of which (148 mm) is in the form of snowfall. The annual average daily temperature ranges from −44°C in winter to 30°C in summer, with a mean of 4.6°C. However, for a given year, the daily temperature could vary from −47°C to 13°C in winter, from −33°C to 34°C in spring, from 0°C to 37°C in summer, and from −31°C to 35°C in fall.

The U.S. Geological Survey (USGS) monitors daily stream flows within the study watershed at two stations, labeled USGS 05062500 and USGS 05064000 in figure 1. Station USGS 05062500, for which the upstream drainage area is 241,900 ha, monitors the upper half of the watershed, and station USGS 05064000, for which the upstream drainage area is 404,030 ha, is located near the watershed outlet in the west. There is a complete data record of daily stream flows for 17 and 22 years for stations USGS 05062500 and USGS 05064000, respectively. A complete description of the data availability and quality can be found in Wang and Melesse (2005). The data indicate that in spring, the daily peak discharges range from 4 to 230 m^3/s at station USGS 05062500 and from 7 to 290 m^3/s at station USGS 05064000. Near the watershed outlet, the annual average daily peak discharge in spring is close to 80 m^3/s.

Model Input Data

In this study, the basic model inputs included the 30 m USGS National Elevation Dataset (NED), the EPA 1:250,000 scale LULC, and the USDA-NRCS (Natural Resources Conservation Service) State Soil Geographic database (STATSGO). NED was developed by merging the highest-resolution, best-quality elevation data available across the U.S. into a seamless raster format (USGS, 2001a). LULC was developed by combining the data obtained from 1970s and 1980s aerial photography surveys with land use maps and surveys (EPA, 2003). As mentioned above, there have been negligible changes in the types of land use in the past two decades for the Wild Rice River watershed. Hence, the LULC data were an appropriate choice for this study. Data for STATSGO are collected at the USGS 1:250,000 scale in 1° × 2° topographic quadrangle units, and then merged and distributed as state coverages. The STATSGO data has a county-level resolution and can readily be used for river-basin water resource studies (USDA-SCS, 1993). The NED and LULC data were downloaded from the USGS website at http://edc.usgs.gove/geodata, and the STATSGO data was downloaded from the USDA-NRCS website at http://www.ncgc.nrcs.usda.gov/branch/ssb/products. In addition to these three datasets, the USGS National Hydrography Dataset (NHD) was also used as a model input. NHD offers a comprehensive set of digital spatial data that contains information about surface water features such as lakes, ponds, streams, rivers, springs, and wells (USGS, 2001b). This study utilized the NHD stream feature as the reference surface water drainage network to delineate subbasins for the study watershed for modeling purposes.

The ArcView Interface for SWAT 2000, developed by Di Luzio et al. (2002), was used to delineate the boundaries of the entire watershed and its subbasins, along with their drainage channels. The boundaries for the subbasins were determined by trial and error to ensure that the delineated drainage channels closely matched the drainage network suggested by the NHD data. As a result, the watershed was subdivided into 485 subbasins, with sizes ranging from 0.9 to 5386 ha. Further, LULC and STATSGO were used to define multiple HRUs for each of the 485 subbasins. With the SWAT-recommended threshold levels of 20% and 10% for land use and soil, respectively (Di Luzio et al., 2002), the interface defined one to three HRUs for each subbasin, resulting in a total of 993 HRUs for the watershed. The default or initial values for the parameters used to configure the model were automatically extracted and/or estimated from these datasets by the interface. In SWAT, these parameters are grouped at the levels of watershed, subbasin, and HRU, and are described in detail by Neitsch et al. (2002a).

The data on daily precipitation and minimum and maximum temperatures for the six NWS stations (fig. 1) were preprocessed into database files with the SWAT-required format for a simulation period extending from 1 October 1970 to 30 November 1997. This simulation period was selected because it had minimal missing data on precipitation and temperature and because complete records on daily stream flows were available for 17 and 22 water years at stations USGS 05062500 and 05064000, respectively, which made it possible to calibrate and validate the model (Wang and Melesse, 2005). The missing values for daily precipitation and minimum and maximum temperatures, along with solar radiation, wind speed, and relative humidity, were simulated by the weather generator that is incorporated in the SWAT software package (Neitsch et al., 2002a).

Influence Assessment Methods

The three SWAT models, with PET estimated using the Penman-Monteith method, Priestley-Taylor method, and Hargreaves method, respectively, were independently calibrated and validated using the observed daily stream flows. For description purposes, in the following context, the model using the Penman-Monteith method was designated SWAT-Penman, and the models using the Priestley-Taylor and Hargreaves methods were designated SWAT-Priestley and SWAT-Hargreaves, respectively. The simulation period from 1 October 1970 to 31 November 1974 was used to define the model initial conditions, i.e., the initial values for the model parameters such as soil moisture and depth of water in shallow and deep aquifers. The calibration periods were from 1 December 1989 to 31 November 1997 for station USGS 05062500 and from 1 December 1985 to 31 November 1997 for station USGS 05064000. The validation periods were from 1 December 1974 to 31 August 1983 for station USGS 05062500 and from 1 December 1974 to 31 August 1984 for station USGS 05064000. The rationale for the selection of these calibration and validation periods can be found in Wang and Melesse (2005).

In a previous study, Wang and Melesse (2005) showed that three snowmelt-related parameters in SWAT, namely snowmelt temperature (variable SMTMP), maximum snowmelt factor (variable SMFMX), and snowpack temperature lag factor (variable TIMP), were sensitive for the hydrologic simulation in the study watershed. Eight additional parameters were identified as sensitive in previous studies (e.g., Lenhart et al., 2002; Saleh and Du, 2004; Singh et al., 2005), namely the surface runoff lag coefficient (variable SURLAG), Muskingum translation coefficients for normal and low flows (variables MSK_CO1 and MSK_CO2, respectively), SCS curve number (CN2), threshold depth of water in the shallow aquifer required for return flow to occur (variable REVAPMN), groundwater "revap" coefficient (variable GW_REVAP), threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (variable GWQMN), and soil evaporation compensation factor (variable ESCO). These 11 parameters were adjusted using the PEST (Parameter ESTimation) software developed by Doherty (2001, 2002, 2004) to minimize an objective function comprised of three components.

ESCO is incorporated into SWAT to allow the modification of the depth distribution used to meet the soil evaporation demand to account for the effect of capillary action, crusting, and cracks. SWAT uses the parameter CN2 to estimate surface runoff and initial abstractions that consist of surface storage, interception, and infiltration. Detailed descriptions of these 11 calibration parameters can be found in Neitsch et al. (2002a, 200b). The starting values and ranges for these parameters (table 1) were selected based on Neitsch et al. (2002a, 2002b) and Wang and Melesse (2005).

The three components of the objective function were the summed weighted squared differences over the aforementioned calibration periods between: (1) model generated and observed daily stream flows, (2) monthly volumes calculated on the basis of modeled and observed daily stream flows, and (3) exceedence times for various flow thresholds calculated on the basis of modeled and observed daily stream flows. To ensure that high flows did not dominate the parameter estimation process simply because of their large numerical values, weights assigned to the individual daily stream flow observations were calculated using the formula suggested by Doherty and Johnston (2003). This formula gave appropriately greater weights for lower flow observations than for higher ones. As a result, all of the flow observations used to calibrate the SWAT model may play a role in the objective function that was minimized by the PEST software. Subsequently, the PEST-determined values for these parameters were manually adjusted to further refine the model.

The calibrated SWAT-Penman, SWAT-Priestley, and SWAT-Hargreaves models were then executed to simulate the daily stream flows. The simulated stream flows from these three runs were compared with each other and with the corresponding observed values. The comparisons were implemented at daily, monthly, seasonal, and annual time steps using visualization plots and/or statistics. Typical plots showing the simulated versus observed stream flows were used to identify the overall fit, whereas the plots showing the stream flows simulated by the three models were used to explore the relative prediction discrepancies. Further, Bonferroni's multiple t-test (Neter et al., 1996; R. Fitch Software, 2002) was performed to identify whether the stream flows simulated by the three models were significantly different at a 5% significance level. The null hypothesis was that the simulated stream flows came from the same population, and that the hypothesized mean differences between the simulated flows were zero.

In order to detect whether the three models had a similar simulation performance, two commonly used statistics, namely the Nash-Sutcliffe coefficient (E_j^2) (Nash and Sutcliffe, 1970) and coefficient of determination (R^2), and one newly developed statistic, the performance virtue (PV_k) (Wang and Melesse, 2005), were computed using the simulation results for each of the three runs. The E_j^2 and R^2 values were used to determine the model performance on an individual station basis, while the PV_k values were used to judge the model performance from the watershed perspective. E_j^2 can range from $-\infty$ to 1.0, with higher values indicating a better overall fit and 1.0 indicating a perfect fit. PV_k is defined as the weighted average of the Nash-Sutcliffe coefficients, deviations of volume (Van Liew and Garbrecht, 2003), and error functions (Lee et al., 1972) across the two evaluation stations in the study watershed. As with E_j^2, a value of 1.0 for PV_k indicates that the model exactly simu-

Table 1. List of calibration parameters.[a]

Parameter	Definition	Starting Value	Range	Calibrated Value
SMTMP (°C)	Snowmelt base temperature	0.5	0.0 - 3.0	1.5
SMFMX (mm H_2O/°C-day)	Maximum snowmelt factor	4.5	1.4 - 6.9	6.5
TIMP	Snowpack temperature lag factor	0.5	0.01 - 1.0	0.3
SURLAG (day)	Surface runoff lag coefficient	1.5	1.0 - 12.0	2.0
MSK_CO1	Muskingum translation coefficient for normal flow	0.35	0.0 - 10.0	1.5
MSK_CO2	Muskingum translation coefficient for low flow	0.35	0.0 - 10.0	1.5
REVAPMN (mm H_2O)	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur	100.0	0.0 - 500.0	10.0
GW_REVAP	Groundwater "revap" coefficient	0.05	0.0 - 0.2	0.02
GWQMN (mm H_2O)	Threshold depth of water in the shallow aquifer required for return flow to occur	100.0	0.0 - 5000.0	5.0
ESCO	Soil evaporation compensation factor	Default[b]	0.01 - 1.0	+0.7; +0.3; +0.05[c]
CN2	SCS curve number for soil moisture condition II	Default[b]	60.0 - 95.0	+3.0; −3.0; +3.0[c]

[a] The starting values and ranges for the parameters were based on Neitsch et al. (2002a, 200b) and Wang and Melesse (2005). For convenience, the models using the Penman-Monteith, Priestley-Taylor, and Hargreaves methods are designated SWAT-Penman, SWAT-Priestley, and SWAT-Hargreaves, respectively.

[b] The values for these parameters were derived by the ArcView Interface for SWAT 2000 and varied from one hydrologic response unit (HRU) to another.

[c] The default values for these parameters were adjusted up (+) or down (−) on an HRU basis by the SWAT-Penman, SWAT-Priestley, and SWAT-Hargreaves models, respectively.

lates all three aspects (silhouette, volume, and peak) of the observed stream flow hydrographs for both of the gauging stations (Wang and Melesse, 2005). Based on the author's experience, a model is judged to have a poor performance when PV_k is less than 0.6, an acceptable performance when PV_k is between 0.6 and 0.7, a satisfactory performance when PV_k is between 0.7 and 0.8, and a good performance when PV_k is greater than 0.8. For each of the stations, based on Motovilov et al. (1999), the model performance was judged to be "good" for values of E_j^2 greater than 0.75 and "satisfactory" for values of E_j^2 between 0.75 and 0.36.

Further, the evapotranspiration for the watershed estimated by each of the three models was examined in accordance with the wet-environment areal evapotranspiration derived from the evaporation data for Williams Lake (Sturrock et al. 1992). The lake, fed by a closed drainage basin 227 ha in size, has a surface area of 36 ha, mean depth of 5.2 m, and maximum depth of 9.8 m. Because it is located only about 100 km southeast of the Wild Rice River watershed (fig. 1), the physical and climatic conditions in the lake area are very similar to those of the watershed. In addition, no other sources were found that provide more data on evaporation, so the results from this lake study are currently the best available data on evaporation in the region. Hence, the evaporation for Williams Lake estimated using the energy budget method by Sturrock et al. (1992) was taken as the assessment base in this study. The assessment was to examine how the evapotranspiration estimated by the models conforms to the complementary relationship that defines the complementary feedback mechanism between actual and potential evapotranspiration. This complementary relationship has been described in detail by several researchers (e.g., Bouchet, 1963; Morton, 1983, 1986; Hobbins et al., 2001) and is expressed as:

$$\mathrm{PET} + \mathrm{AET} = 2E_{TW} \qquad (1)$$

where E_{TW} is the wet-environment areal evapotranspiration, the evapotranspiration that would occur if the soil-plant surfaces of the area were saturated and there were no limitations on the availability of water.

The complementary relationship is essentially based on empirical observations, supported by a conceptual description of the underlying interactions between evapotranspiring surfaces and the atmospheric boundary layer (Hobbins et al., 2001). Bouchet (1963) found that when water availability becomes limited under conditions of constant energy input to a given land surface-atmosphere system, AET falls below its potential and a certain amount of energy becomes available. This energy excess, in the form of sensible heat and/or longwave back radiation, increases the temperature and humidity gradients of the air passing overhead and leads to an increase in PET equal in magnitude to the decrease in AET. If water availability is increased, the reverse process occurs, and AET increases as PET decreases. Thus, PET ceases to be an independent causal factor, or climatologically constant forcing function, and instead is predicated on the prevailing conditions of moisture availability. Morton (1986) and Hobbins et al. (2001) elaborated on the complementary relationship.

Morton (1986) indicated that E_{TW} may be estimated from the corresponding evaporation from a lake-size wet surface (E_W). The ratio of E_{TW} to E_W (i.e., the k value) is always greater than unity and tends to be constant for a given month within a hydrologic region. Because the data required to estimate the values for k were unavailable for Williams Lake, the monthly ratios, computed using the data presented by Morton (1986) for Dauphin Lake in Manitoba, Canada, were used in this study. Although Dauphin Lake is located about 500 km northwest of Williams Lake, both lakes are within the Northern Plain area. Hence, it was reasonably assumed that using these ratios for the k values would cause only a minor bias for this study. Further, Morton (1986) indicated that for lakes with an average depth of less than 30 m, which is the case for Williams Lake, E_W may be very close to, and thus can be considered to be equal to, the lake evaporation, or E_L. Thus, $E_{TW} = k \times E_L$. A model is judged to be better when its estimated evapotranspiration has a closer approximation to the complementary relationship.

Moreover, the average annual values of estimated AET for the subbasins were plotted to examine the spatial pattern of the discrepancies between the model estimations. The temporal trend was further scrutinized on the watershed level by examining the annual time series of the AET values estimated by the three models. In addition, Bonferroni's multiple t-test was performed to identify whether the AET values came from the same population at a 5% significance level. The null hypothesis was that the hypothesized mean differences would be zero. The AET annual time series were also plotted against the observed discharges at station USGS 05064000 to investigate whether the discrepancies varied with hydrologic conditions as measured by water yield. For convenience, the discharges were expressed as the equivalent runoff depths in mm, calculated as the ratios of the volumes that were computed by integrating the discharges over the assessment period for the drainage area of 404,030 ha upstream of the station.

RESULTS AND DISCUSSION

MODEL CALIBRATION AND VALIDATION

The SWAT-Penman, SWAT-Priestley, and SWAT-Hargreaves models were independently calibrated by adjusting the aforementioned 11 parameters to make the simulated stream flows closely match the corresponding observed values at station USGS 05062500 from 1 December 1989 to 31 November 1997 and at station USGS 05064000 from 1 December 1985 to 31 November 1997. The adjustments were implemented using PEST followed by manual refinements. As a result, the three models took identical values for the parameters except for ESCO and CN2 (table 1). The ESCO parameter was adjusted up by 0.7, 0.3, and 0.05 from its default or initial values, derived by the ArcView Interface for SWAT 2000, for the SWAT-Penman, SWAT-Priestley, and SWAT-Hargreaves models, respectively, whereas the CN2 parameter was adjusted up by 3.0 from its default values for the SWAT-Penman and SWAT-Hargreaves models but adjusted down by 3.0 for the SWAT-Priestley model. A sensitivity analysis (Lenhart et al., 2002) revealed that CN2 and ESCO were very sensitive to SWAT's prediction of evapotranspiration. This might explain why the SWAT models using the three different ET estimation methods took distinctly different values for CN2 and ESCO. However, the three models had a comparable simulation performance after calibration (tables 2 through 5).

Table 2. Statistics of the annual mean discharges when predicted by the SWAT model with the potential evapotranspiration (PET) estimated using the Penman-Monteith, Priestley-Taylor, and Hargreaves methods (designated SWAT-Penman, SWAT-Priestley, and SWAT-Hargreaves, respectively).[a]

		SWAT-Penman				SWAT-Priestley				SWAT-Hargreaves			
Station	Observed (m^3/s)	Predicted (m^3/s)	R^2	E_j^2	PV_k	Predicted (m^3/s)	R^2	E_j^2	PV_k	Predicted (m^3/s)	R^2	E_j^2	PV_k
Calibration					0.89				0.94				0.86
USGS 05062500[b]	7.53	7.91	0.82	0.80		7.59	0.91	0.90		6.67	0.86	0.77	
USGS 05064000[c]	10.83	11.35	0.73	0.72		11.26	0.88	0.87		10.40	0.77	0.74	
Validation					0.82				0.79				0.85
USGS 05062500[b]	4.91	5.34	0.93	0.90		5.68	0.92	0.78		4.86	0.91	0.91	
USGS 05064000[c]	8.33	10.25	0.82	0.68		10.87	0.84	0.60		9.69	0.84	0.75	

[a] R^2 is the coefficient of determination, E_j^2 is the Nash-Sutcliffe coefficient, and PV_k is performance virtue.

[b] For station USGS 05062500, the calibration period is from 1 December 1989 to 30 November 1997, and the validation period is from 1 December 1974 to 31 August 1983.

[c] For station USGS 05064000, the calibration period is from 1 December 1985 to 30 November 1997, and the validation period is from 1 December 1974 to 31 August 1984.

Table 3. Statistics of the seasonal mean discharges when predicted by the SWAT model with the potential evapotranspiration (PET) estimated using the Penman-Monteith, Priestley-Taylor, and Hargreaves methods (designated SWAT-Penman, SWAT-Priestley, and SWAT-Hargreaves, respectively, for description purposes).[a]

		SWAT-Penman				SWAT-Priestley				SWAT-Hargreaves			
Station	Observed (m^3/s)	Predicted (m^3/s)	R^2	E_j^2	PV_k	Predicted (m^3/s)	R^2	E_j^2	PV_k	Predicted (m^3/s)	R^2	E_j^2	PV_k
Calibration													
USGS 05062500[b]	7.53	7.72	0.88	0.87		7.56	0.92	0.91		7.10	0.90	0.88	
Winter	2.32	2.24	0.89	0.88		2.35	0.86	0.82		2.17	0.89	0.88	
Spring	14.87	15.22	0.82	0.82		15.98	0.88	0.86		14.64	0.85	0.84	
Summer	9.06	11.16	0.96	0.85		9.53	0.99	0.98		8.08	0.94	0.91	
Fall	3.89	3.02	0.17	−0.21		2.49	0.27	−0.04		1.77	0.20	−0.44	
USGS 05064000[c]	10.82	11.29	0.87	0.87	0.86	11.20	0.92	0.92	0.91	10.34	0.88	0.88	0.86
Winter	2.39	2.33	0.75	0.75	0.89	2.53	0.67	0.51	0.76	2.31	0.74	0.74	0.88
Spring	25.03	24.37	0.82	0.80	0.66	25.78	0.92	0.90	0.65	24.32	0.83	0.81	0.66
Summer	11.17	13.58	0.90	0.84	0.59	12.51	0.87	0.83	0.63	11.05	0.87	0.83	0.64
Fall	4.52	4.89	0.06	−0.52	0.61	4.02	0.20	0.10	0.59	3.70	0.02	−0.34	0.54
Validation													
USGS 05062500[b]	4.78	5.17	0.95	0.92		5.51	0.95	0.90		4.73	0.95	0.94	
Winter	1.31	1.35	0.13	−1.42		1.63	0.09	−15.47		1.38	0.10	−2.53	
Spring	11.36	11.99	0.90	0.87		13.10	0.93	0.80		12.14	0.90	0.87	
Summer	4.70	5.85	0.96	0.88		5.82	0.96	0.89		4.26	0.99	0.98	
Fall	1.96	1.68	0.73	0.74		1.67	0.37	0.37		1.28	0.52	0.42	
USGS 05064000[c]	8.19	10.14	0.90	0.86	0.83	10.73	0.92	0.85	0.79	9.60	0.90	0.89	0.86
Winter	1.57	2.48	0.27	−10.54	−1.65	2.97	0.17	−19.94	−5.80	2.53	0.25	−10.51	−1.86
Spring	18.78	20.67	0.90	0.88	0.64	23.03	0.95	0.82	0.60	21.57	0.91	0.86	0.63
Summer	9.21	12.48	0.80	0.72	0.56	12.36	0.84	0.76	0.57	10.21	0.85	0.82	0.63
Fall	2.65	4.34	0.49	−1.42	0.53	3.87	0.32	−1.09	0.56	3.50	0.26	−0.96	0.55

[a] R^2 is the coefficient of determination, E_j^2 is the Nash-Sutcliffe coefficient, and PV_k is performance virtue.

[b] For station USGS 05062500, the calibration period is from 1 December 1989 to 30 November 1997, and the validation period is from 1 December 1974 to 31 August 1983.

[c] For station USGS 05064000, the calibration period is from 1 December 1985 to 30 November 1997, and the validation period is from 1 December 1974 to 31 August 1984.

Table 4a. Statistics of the monthly mean discharges for the calibration periods when predicted by the SWAT model with the potential evapotranspiration (PET) estimated using the Penman-Monteith, Priestley-Taylor, and Hargreaves methods (designated SWAT-Penman, SWAT-Priestley, and SWAT-Hargreaves, respectively).[a] (cont.)

		SWAT-Penman				SWAT-Priestley				SWAT-Hargreaves			
Station	Observed (m^3/s)	Predicted (m^3/s)	R^2	E_j^2	PV_k	Predicted (m^3/s)	R^2	E_j^2	PV_k	Predicted (m^3/s)	R^2	E_j^2	PV_k
USGS 05062500[b]	7.53	7.89	0.89	0.86		7.57	0.92	0.90		6.65	0.90	0.88	
Jan.	2.10	2.06	0.01	0.61		2.22	0.02	0.25		2.02	0.01	0.62	
Feb.	2.15	2.04	0.76	0.73		1.98	0.86	0.84		2.02	0.79	0.75	
Mar.	7.60	9.43	0.27	−0.02		9.32	0.48	0.29		9.24	0.27	0.03	
Apr.	23.33	23.38	0.95	0.91		24.50	0.95	0.90		22.85	0.95	0.92	
May	13.95	12.86	0.88	0.86		14.13	0.93	0.92		11.81	0.93	0.86	
June	7.30	8.58	0.91	0.76		8.29	0.88	0.78		7.06	0.86	0.84	

Table 4a (cont.). Statistics of the monthly mean discharges for the calibration periods when predicted by the SWAT model with the potential evapotranspiration (PET) estimated using the Penman-Monteith, Priestley-Taylor, and Hargreaves methods (designated SWAT-Penman, SWAT-Priestley, and SWAT-Hargreaves, respectively).[a]

		SWAT-Penman				SWAT-Priestley				SWAT-Hargreaves			
Station	Observed (m^3/s)	Predicted (m^3/s)	R^2	E_j^2	PV_k	Predicted (m^3/s)	R^2	E_j^2	PV_k	Predicted (m^3/s)	R^2	E_j^2	PV_k
July	13.03	14.97	0.95	0.91		12.32	0.95	0.93		10.72	0.89	0.82	
Aug.	6.79	9.93	0.97	0.68		7.99	0.99	0.95		6.47	0.95	0.92	
Sept.	3.58	4.54	0.41	−1.16		3.40	0.48	0.22		2.42	0.41	0.12	
Oct.	3.86	2.78	0.28	0.14		2.40	0.28	0.10		1.69	0.29	−0.10	
Nov.	4.23	1.73	0.30	−0.42		1.66	0.60	−0.31		1.20	0.26	−0.79	
Dec.	2.38	2.39	0.98	0.98		2.61	0.96	0.88		2.25	1.00	0.98	
USGS 05064000[b]	10.82	11.29	0.86	0.86	0.81	11.20	0.90	0.90	0.85	10.34	0.88	0.88	0.82
Jan.	2.24	1.95	0.57	0.36	0.66	2.24	0.46	−0.29	0.38	1.97	0.56	0.33	0.66
Feb.	2.16	2.28	0.50	0.39	0.65	2.28	0.64	0.49	0.64	2.29	0.47	0.32	0.64
Mar.	11.84	13.89	0.36	0.10	0.60	13.20	0.50	0.37	0.61	13.91	0.37	0.14	0.60
Apr.	42.65	41.94	0.90	0.90	0.66	43.21	0.93	0.93	0.65	42.12	0.91	0.91	0.66
May	21.17	17.29	0.84	0.77	0.62	20.92	0.90	0.90	0.66	16.94	0.85	0.77	0.61
June	9.79	10.44	0.88	0.84	0.62	11.81	0.85	0.76	0.61	9.41	0.85	0.85	0.65
July	15.65	17.74	0.70	0.68	0.62	15.38	0.68	0.68	0.65	14.32	0.66	0.65	0.62
Aug.	8.02	12.55	0.97	−8.26	0.48	10.34	0.98	−5.37	0.58	9.42	0.97	−6.05	0.62
Sept.	4.28	7.56	0.20	−3.44	0.49	5.53	0.28	−0.57	0.61	5.45	0.11	−1.49	0.56
Oct.	4.69	4.10	0.21	−2.88	0.59	3.53	0.30	−2.28	0.56	2.99	0.20	−3.17	0.50
Nov.	4.58	3.00	0.24	−0.01	0.51	3.00	0.61	0.39	0.51	2.65	0.20	−0.15	0.48
Dec.	2.73	2.72	0.73	0.71	0.66	3.01	0.74	0.36	0.63	2.61	0.78	0.77	0.65

[a] R^2 is the coefficient of determination, E_j^2 is the Nash-Sutcliffe coefficient, and PV_k is performance virtue.

[b] The calibration period is from 1 December 1989 to 30 November 1997 for station USGS 05062500, and from 1 December 1985 to 30 November 1997 for station USGS 05064000.

Table 4b. Statistics of the monthly mean discharges for the validation periods when predicted by the SWAT model with the potential evapotranspiration (PET) estimated using the Penman-Monteith, Priestley-Taylor, and Hargreaves methods (designated SWAT-Penman, SWAT-Priestley, and SWAT-Hargreaves, respectively).[a]

		SWAT-Penman				SWAT-Priestley				SWAT-Hargreaves			
Station	Observed (m^3/s)	Predicted (m^3/s)	R^2	E_j^2	PV_k	Predicted (m^3/s)	R^2	E_j^2	PV_k	Predicted (m^3/s)	R^2	E_j^2	PV_k
USGS 05062500[b]	4.94	5.32	0.93	0.90		5.67	0.93	0.87		4.87	0.92	0.91	
Jan.	1.20	1.11	0.89	0.86		1.40	0.59	−1.39		1.13	0.80	0.73	
Feb.	1.19	1.22	0.41	−0.01		1.22	0.59	0.50		1.27	0.35	−0.32	
Mar.	3.99	5.40	0.35	−0.77		4.79	0.55	−0.33		5.49	0.36	−0.77	
Apr.	20.73	21.26	0.92	0.86		23.14	0.91	0.77		21.72	0.90	0.84	
May	9.68	9.31	0.93	0.89		11.37	0.98	0.84		9.22	0.94	0.92	
June	5.45	5.66	0.92	0.92		6.87	0.88	0.78		5.04	0.94	0.93	
July	7.02	9.07	0.97	0.90		8.10	0.98	0.96		6.25	1.00	0.98	
Aug.	1.66	2.80	0.92	−0.99		2.50	0.76	−1.28		1.49	0.78	0.44	
Sept.	1.36	1.58	0.58	0.52		1.22	0.21	0.12		1.08	0.42	0.37	
Oct.	2.07	1.81	0.74	0.66		1.77	0.53	0.46		1.35	0.66	0.52	
Nov.	2.43	1.65	0.76	0.46		2.02	0.43	−0.27		1.42	0.56	0.09	
Dec.	1.56	1.74	0.87	0.59		2.28	0.74	−3.16		1.76	0.83	0.22	
USGS 05064000[b]	8.24	10.12	0.85	0.83	0.82	10.71	0.83	0.80	0.78	9.59	0.85	0.84	0.84
Jan.	1.32	1.54	0.57	−0.04	0.63	2.09	0.46	−4.90	−1.07	1.62	0.52	−0.54	0.44
Feb.	1.45	1.78	0.61	0.04	0.62	1.87	0.68	0.20	0.61	1.83	0.57	−0.02	0.61
Mar.	7.52	10.27	0.27	−0.10	0.55	9.51	0.44	0.20	0.59	10.72	0.24	−0.25	0.53
Apr.	37.18	36.30	0.86	0.86	0.66	39.46	0.83	0.82	0.63	38.06	0.84	0.84	0.65
May	12.22	15.42	0.81	0.15	0.61	20.11	0.90	−0.48	0.53	15.91	0.84	0.20	0.60
June	11.25	12.60	0.40	0.36	0.64	14.37	0.56	0.35	0.56	11.52	0.42	0.41	0.64
July	14.33	18.27	0.88	0.84	0.57	16.98	0.85	0.81	0.61	14.78	0.90	0.84	0.64
Aug.	2.13	6.58	0.92	0.01	0.20	5.73	0.84	0.07	0.30	4.32	0.95	0.54	0.48
Sept.	1.72	4.44	0.60	−4.48	0.37	3.06	0.39	−1.07	0.52	3.07	0.31	−1.43	0.50
Oct.	3.16	4.56	0.56	−1.15	0.55	3.93	0.47	−0.34	0.58	3.69	0.45	−0.61	0.55
Nov.	3.04	4.02	0.55	−1.24	0.56	4.62	0.35	−4.12	0.54	3.73	0.38	−1.45	0.56
Dec.	1.85	3.92	0.25	−12.64	0.44	4.77	0.47	−19.71	0.29	3.95	0.29	−12.85	0.44

[a] R^2 is the coefficient of determination, E_j^2 is the Nash-Sutcliffe coefficient, and PV_k is performance virtue.

[b] The validation period is from 1 December 1974 to 31 August 1983 for station USGS 05062500, and from 1 December 1974 to 31 August 1984 for station USGS 05064000.

Table 5. Statistics of the daily discharges when predicted by the SWAT model with the potential evapotranspiration (PET) estimated using the Penman-Monteith, Priestley-Taylor, and Hargreaves methods (designated SWAT-Penman, SWAT-Priestley, and SWAT-Hargreaves, respectively).[a]

		SWAT-Penman				SWAT-Priestley				SWAT-Hargreaves			
Station	Observed (m^3/s)	Predicted (m^3/s)	R^2	E_j^2	PV_k	Predicted (m^3/s)	R^2	E_j^2	PV_k	Predicted (m^3/s)	R^2	E_j^2	PV_k
Calibration					0.76				0.80				0.77
USGS 05062500[b]	7.54	7.92	0.73	0.64		7.59	0.76	0.70		6.66	0.75	0.70	
USGS 05064000[c]	10.83	11.31	0.68	0.67		11.22	0.71	0.70		10.35	0.70	0.69	
Validation					0.68				0.65				0.70
USGS 05062500[b]	4.94	5.32	0.69	0.62		5.67	0.69	0.59		4.87	0.69	0.64	
USGS 05064000[c]	8.23	10.13	0.52	0.50		10.73	0.50	0.46		9.59	0.53	0.52	

[a] R^2 is the coefficient of determination, E_j^2 is the Nash-Sutcliffe coefficient, and PV_k is performance virtue.

[b] For station USGS 05062500, the calibration period is from 1 December 1989 to 30 November 1997, and the validation period is from 1 December 1974 to 31 August 1983.

[c] For station USGS 05064000, the calibration period is from 1 December 1985 to 30 November 1997, and the validation period is from 1 December 1974 to 31 August 1984.

From the watershed perspective, the three models had a good performance in predicting the annual mean discharges ($PV_k \geq 0.86$). The discharges for winter were predicted well ($PV_k \geq 0.76$), and the discharges for the other three seasons were predicted with an acceptable or a marginally acceptable accuracy ($PV_k \geq 0.54$). For most months, the three models had an acceptable or a marginally acceptable performance in predicting the monthly mean discharges, while the discharges for two or three months might be predicted with a poor accuracy by one of the models (table 4a). For instance, the three models all had a poor performance in predicting the monthly mean discharges for November. The SWAT-Penman model also had a poor performance for both August and September, whereas the SWAT-Priestley and SWAT-Hargreaves models had a poor performance only for January and October, respectively. Further, the daily discharges were predicted with a marginally good performance by all three models (table 5).

The performance compatibility of the three models was also noticed for each of the two evaluation stations. At both stations, the predicted discharges were close to the corresponding observed values (tables 2 through 5). In terms of E_j^2 and R^2, the three models had a good or marginally good performance in predicting the annual mean discharges, whereas the seasonal mean discharges were predicted with a good accuracy for the seasons, except for fall for station USGS 05062500 and fall and winter for station USGS 05064000. The discharges for fall were predicted with a poor accuracy by all three models. As with the seasonal mean discharges, the monthly mean discharges might be predicted with a good accuracy for some months but with a poor accuracy for the others. Nevertheless, for a given station, the performances of the three models in predicting the monthly mean discharges were consistent, i.e., when a model had a good (or poor) performance for a given month, the other two models had a good (or poor) performance for that month as well, and vice versa. In addition, the daily discharges at both stations were predicted with an acceptable accuracy by all three models.

Subsequently, the calibrated models were used to simulate the stream flows for the validation periods from 1 December 1974 to 31 August 1983 for station USGS 05062500 and from 1 December 1974 to 31 August 1984 for station USGS 05064000. The statistics, computed from the simulated discharges and the corresponding observed values, indicated that the models had similar performances for the validation periods as for the calibration periods (tables 2 through 5). From the watershed perspective, the models might also predict the annual mean discharges with a good accuracy ($PV_k \geq 0.79$). In addition, the models exhibited consistent performances in predicting the seasonal and monthly mean discharges at both stations. As with the calibration periods, the daily discharges for the validation periods were predicted with an acceptable accuracy by all three models, both from the watershed perspective and for each of the stations.

SIMULATED STREAM DISCHARGES

During the evaluation years, the annual mean discharges with a higher value were generally predicted more accurately by the SWAT-Priestley model, whereas the discharges with a lower value were usually predicted better by the SWAT-Hargreaves model (figs. 2a and 2b). This might be because the SWAT-Priestley model possibly has a better estimation of evapotranspiration for the years with higher discharges, while for the years with lower discharges, the evapotranspiration tends to be estimated better by the SWAT-Hargreaves model.

For station USGS 05064000, all three models tended to overpredict discharges with a value less than 13 m^3/s but underestimate discharges that were higher (fig. 2a). For station USGS 05062500, the models tended to overestimate discharges with a value less than 10 m^3/s but underpredict the higher discharges (fig. 2b). Not surprisingly, the discharges with a higher value usually corresponded to wet hydrologic conditions (i.e., more precipitation), and the discharges with a lower value corresponded to dry hydrologic conditions (i.e., less precipitation). Hence, one explanation might be that the models tended to underestimate the evapotranspiration for dry hydrologic conditions but overestimate the evapotranspiration for wet hydrologic conditions. Further, the three models tended to differ more widely on predictions for discharges with a lower value than for discharges with a higher value. This is likely because the evapotranspiration for the dry hydrologic conditions was estimated by the three models with a larger discrepancy.

For a given year, the larger prediction discrepancies usually occurred for spring and summer. Because of the consistency between the two evaluation stations, only the seasonal mean discharges at station USGS 05064000 for the selected years from 1982 to 1984 and from 1986 to 1987 are

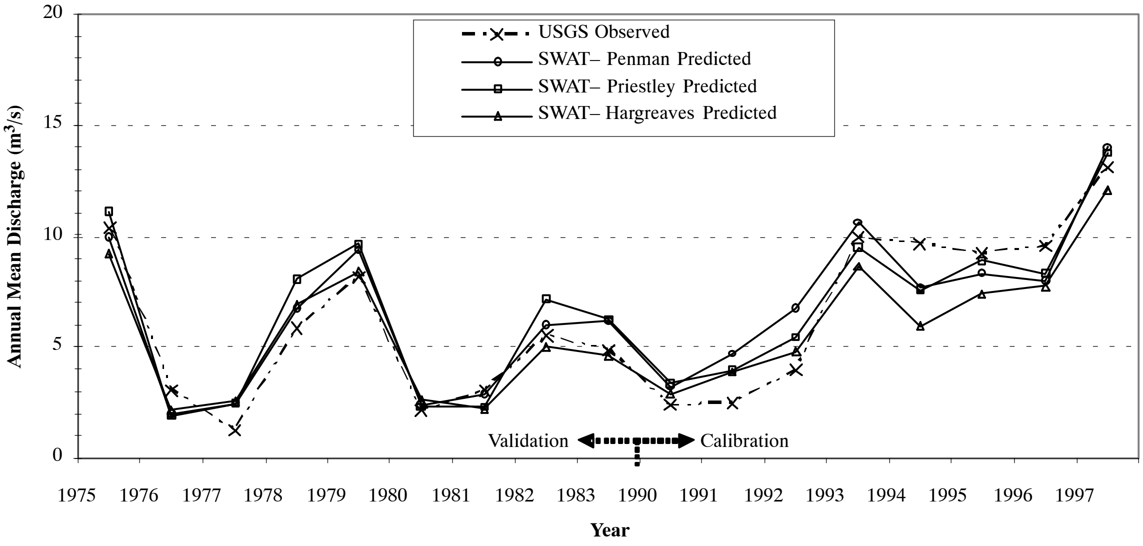

Figure 2a. Observed and SWAT-predicted annual mean discharges at station of Wild Rice River at Twin Valley (USGS 05062500).

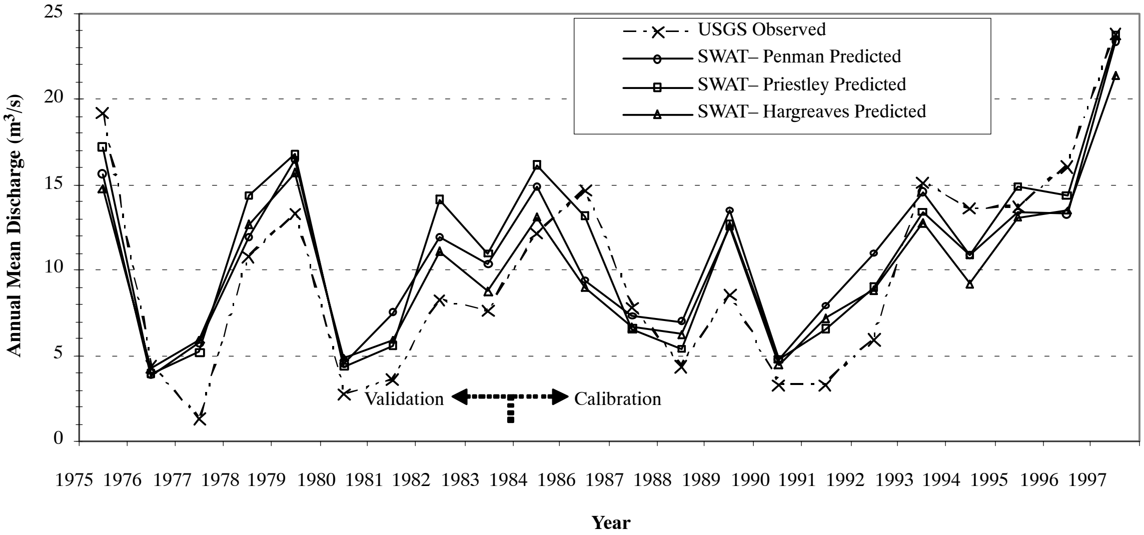

Figure 2b. Observed and SWAT-predicted annual mean discharges at station of Wild Rice River at Hendrum (USGS 05064000).

shown in figure 3. During spring and summer, evapotranspiration became an important component of the hydrologic cycle in the Wild Rice River watershed (Houston Engineering, 2001). The prediction discrepancies for these two seasons might be because the evapotranspiration estimated by the three models were so different from each other. Overall, the SWAT-Hargreaves model may predict the seasonal mean discharges more accurately than the other two models for the study watershed. However, the SWAT-Priestley model may give a better prediction of the discharges for the seasons with a greater value (e.g., spring 1986). The values predicted by the SWAT-Penman model tended to be greater than those predicted by the SWAT-Hargreaves model but smaller than those predicted by the SWAT-Priestley model. Again, this might be because the SWAT-Hargreaves model tended to overestimate the evapotranspiration for wet hydrologic conditions, whereas the other two models tended to underestimate the evapotranspiration for dry hydrologic conditions. Figure 4a shows the monthly mean discharge hydrograph for 1983, a typical year when the SWAT-Hargreaves model had a better prediction, and figure 4b shows the hydrograph for 1986, a typical year when the SWAT-Priestley model had a better prediction. Similarly, the obvious prediction discrepancies between the models occurred for the months when evapotranspiration was active (e.g., March and July in 1983) and the discharges were higher (e.g., March and July in 1983, and April and May in 1986).

For station USGS 05064000, during the calibration period, the three models had a comparable prediction of the daily discharges with a value greater than 5 m^3/s (fig. 5a). Nevertheless, the discharges with a lower value may be predicted more accurately by the SWAT-Priestley model than the other two models. During the validation period, while all three models tended to overpredict the daily discharges with a value greater than 2 m^3/s, they did so consistently, so the prediction discrepancies between the models were not obvious (fig. 5b). Similarly, although the daily discharges with a lower value were predicted more accurately by the SWAT-Priestley model, the SWAT-Penman model tended to further underestimate the low flows when compared to the calibration period. One explanation might be that the discrepancies in the evapotranspiration estimated by the

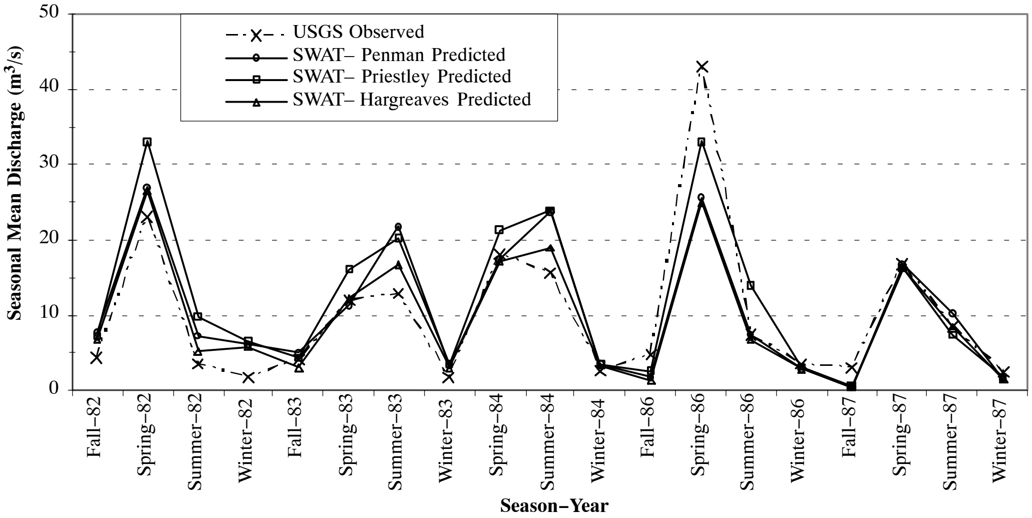

Figure 3. Observed and SWAT-predicted seasonal mean discharges at station of Wild Rice River at Hendrum (USGS 05064000) for the selected evaluation years.

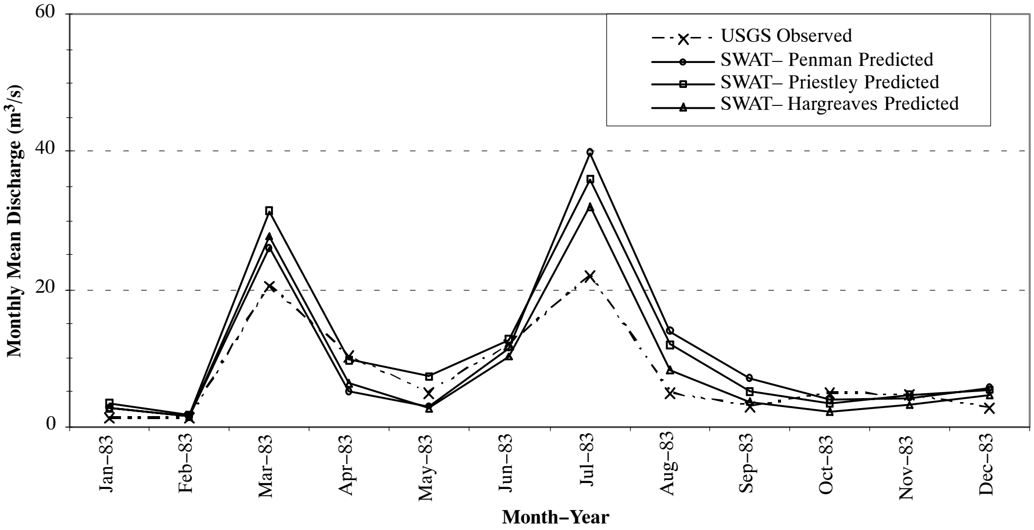

Figure 4a. Observed and SWAT-predicted monthly mean discharges at station of Wild Rice River at Hendrum (USGS 05064000) for 1983, a typical year when the SWAT-Hargreaves model had a better prediction.

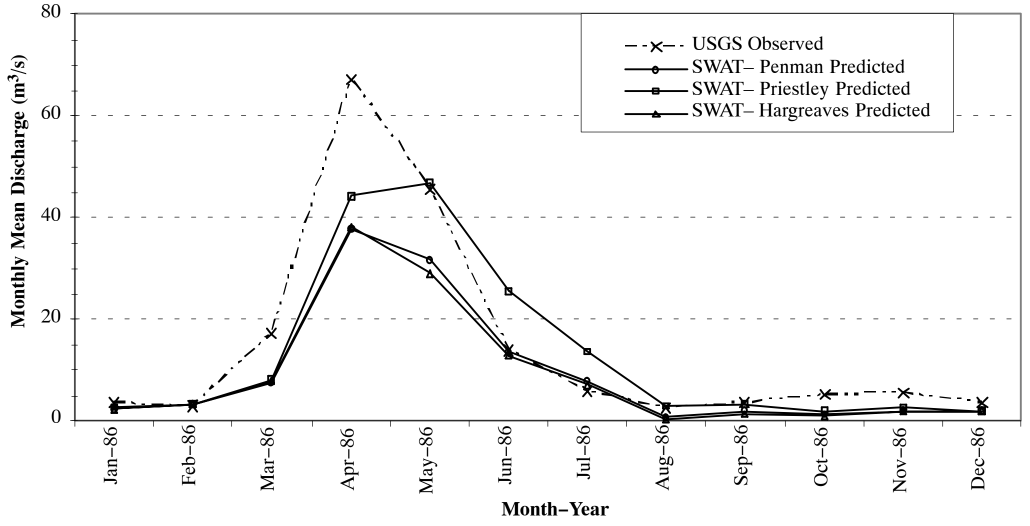

Figure 4b. Observed and SWAT-predicted monthly mean discharges at station of Wild Rice River at Hendrum (USGS 05064000) for 1986, a typical year when the SWAT-Priestley model had a better prediction.

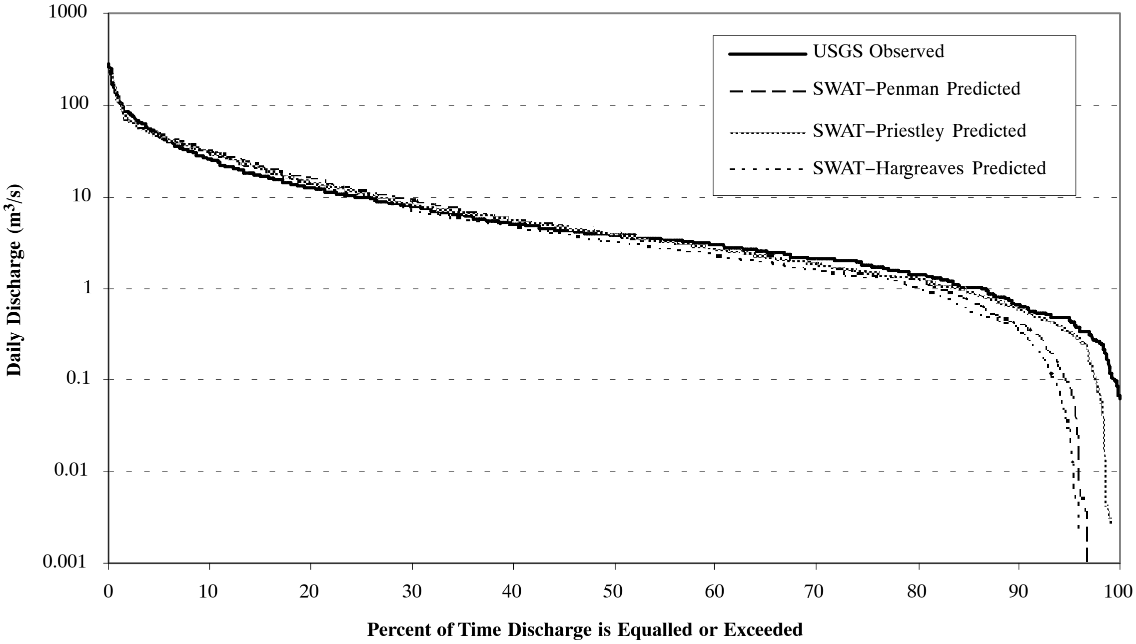

Figure 5a. Duration curves of the daily discharges observed by the U.S. Geological Survey (USGS) and predicted by the SWAT models at station of Wild Rice River at Hendrum (USGS 05064000) for the calibration period.

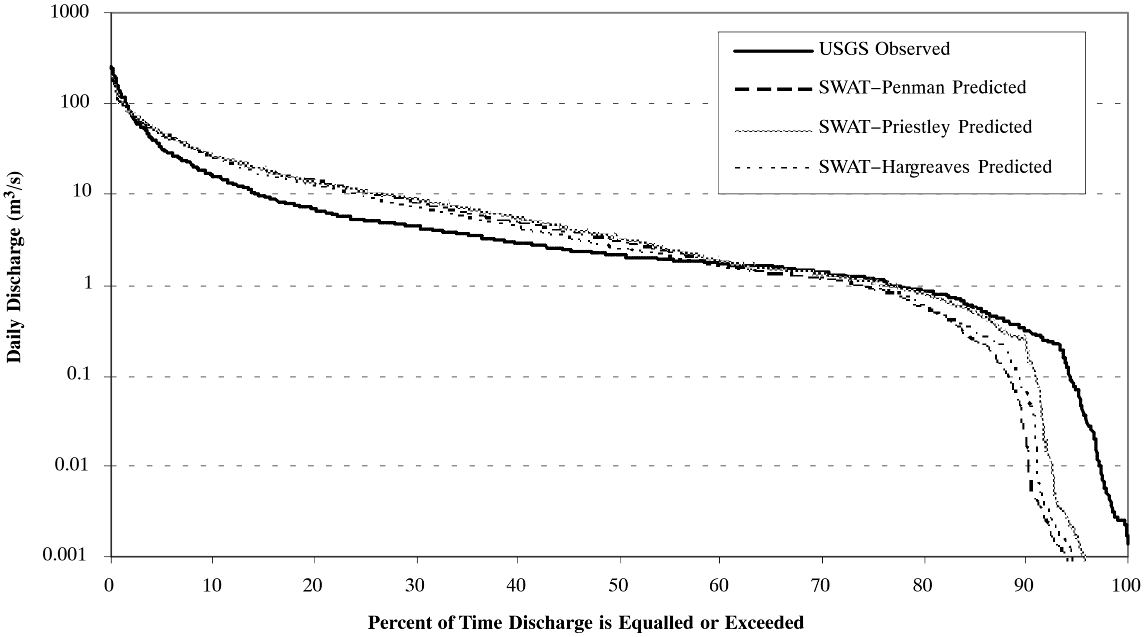

Figure 5b. Duration curves of the daily discharges observed by the U.S. Geological Survey (USGS) and predicted by the SWAT models at station of Wild Rice River at Hendrum (USGS 05064000) for the validation period.

three models had less influence on predicting the higher daily discharges than the lower ones. The duration curves generated from the simulated and observed daily discharges for station USGS 05062500 presented very similar information and thus are not shown here. Notwithstanding, Bonferroni's multiple t-test indicated that the daily discharges predicted by the three models were insignificantly different from each other at a significance level of 5% (p-values > 0.05). Further, during the calibration periods, the predicted daily discharges were statistically identical to the corresponding observed values, whereas during the validation periods, the predicted daily discharges were significantly different from the corresponding observed values (p-values = +0.00).

ESTIMATED EVAPOTRANSPIRATION

Table 6 lists the *k* values used in this study. These values were applied to both the study months (May to September) and energy budget periods from 1982 to 1986 in which Sturrock et al. (1992) presented their results. For a given study month, E_{TW} was computed by multiplying the *k* value and E_L for that month. For an energy budget period spanning only one month, E_{TW} was computed by multiplying the *k* value for that month and E_L for that budget period, whereas for an energy budget period spanning two months, E_{TW} was computed by multiplying the average of the *k* values for those months and E_L for that budget period.

Table 6. *k* values used in this study.[a]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
k	1.00	1.00	1.11	1.13	1.30	1.36	1.22	1.28	1.63	1.10	1.00	1.00

[a] *k* is the ratio of the wet-environment areal evapotranspiration to the evaporation from a lake-size wet surface. The values were determined using the evaporation data for Dauphin Lake in Manitoba, Canada (Morton, 1986).

For most of the energy budget periods, the three models tended to either over- or underestimate the evapotranspiration from the study watershed (fig. 6). The SWAT-Penman model consistently overestimated the evapotranspiration for the periods with an E_{TW} value less than 4.0 mm/d, and also tended to overestimate the evapotranspiration for the periods with an E_{TW} value between 4.0 and 8.0 mm/d. However, it tended to underestimate the evapotranspiration for the periods with an E_{TW} value greater than 8.0 mm/d. In contrast, for the periods with an E_{TW} value less than 4.0 mm/d, the SWAT-Priestley model consistently underestimated the evapotranspiration, but the evapotranspiration estimated by the SWAT-Hargreaves model seemed to conform to the complementary relationship given in equation 1. For the periods with an E_{TW} value greater than 4.0 mm/d, these two models had a consistent estimation of the evapotranspiration, i.e., both models concurrently either over- or underestimated the evapotranspiration for that period. Nevertheless, the evapotranspiration estimated by the SWAT-Priestley model more closely approximated the complementary relationship for the periods with an ETW value greater than 8.0 mm/d. Throughout the energy budget periods from 1982 to 1986, a paired t-test indicated that the evapotranspiration time series estimated by the SWAT-Hargreaves model conformed to the complementary relationship at a 5% significance level (p-value = 0.67). The conformity was marginally significant for the SWAT-Priestley model (p-value = 0.06) but insignificant for the SWAT-Penman model (p-value = 0.03). An examination of the monthly evapotranspiration estimated by the models found similar results (tables 7 and 8).

These findings further explained the performances of the models when simulating the stream flows discussed above and were in general agreement with the conclusions of previous studies (e.g., Amatya et al., 1995; Federer et al., 1996; Martinez-Cob and Tejero-Juste, 2004; Lu et al., 2005). One explanation might be that the Priestley-Taylor method may be more appropriate for wet hydrologic conditions, while for dry hydrologic conditions, the Hargreaves method is probably a better estimator. For transitional hydrologic conditions, any of the three methods could be used to estimate the evapotranspiration, with no obvious difference.

The evapotranspiration estimated by the three models exhibited the same spatial pattern. Figure 7 shows the estimated AET values for some of the 70 subbasins selected

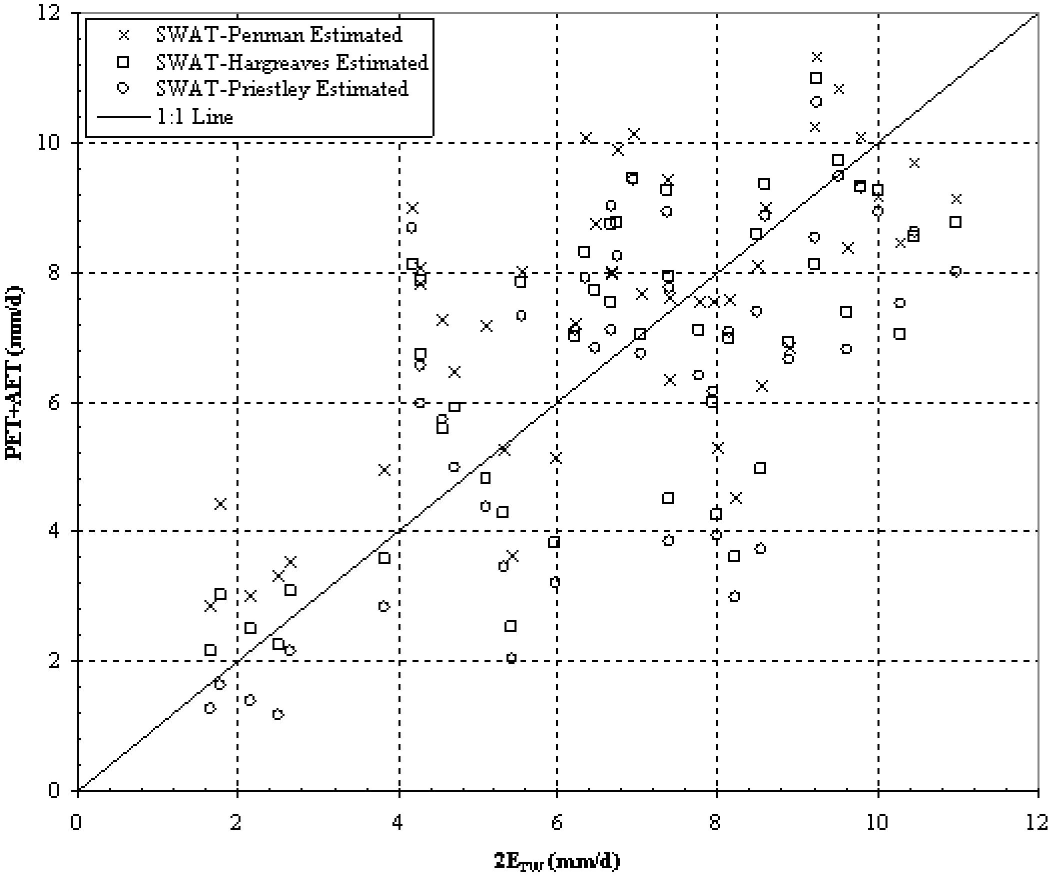

Figure 6. Plot showing the summation of model-estimated potential evapotranspiration (PET) and actual evapotranspiration (AET) for the Wild Rice River watershed versus the wet-environment areal evapotranspiration (E_{TW}). E_{TW} was derived from the evaporation data from Williams Lake for the energy budget periods used by Sturrock et al. (1992). Hence, the points in this plot correspond to the budget periods.

Table 7. Monthly total evapotranspiration estimated by the three models for the Wild Rice River watershed in accordance with the evaporation from Williams Lake (all values in cm). Blank cells are due to the unavailability of lake evaporation data.[a]

			SWAT-Penman			SWAT-Hargreaves			SWAT-Priestley		
Month	E_L	E_{TW}[b]	PET	AET	Fn[c]	PET	AET	Fn[c]	PET	AET	Fn[c]
1982											
May	--	--	17.5	7.9	--	12.5	8.7	--	11.1	9.0	--
June	--	--	16.1	5.8	--	14.3	7.3	--	13.3	8.7	--
July	9.3	11.3	18.3	10.1	5.73	16.8	10.5	4.56	14.9	10.8	3.00
Aug.	9.2	11.8	15.7	7.7	−0.16	14.4	7.2	−1.89	12.8	8.6	−2.16
Sept.	5.2	8.5	13.7	4.6	1.31	9.2	3.4	−4.41	7.0	3.6	−6.28
1983											
May	--	--	16.2	6.0	--	12.5	7.4	--	10.7	8.1	--
June	8.5	11.6	17.6	8.6	3.15	14.8	9.8	1.55	14.1	10.7	1.66
July	12.0	14.6	20.0	12.3	3.02	17.0	14.1	1.86	16.3	14.4	1.39
Aug.	11.5	14.7	18.7	9.8	−0.93	16.0	10.0	−3.51	13.4	10.4	−5.69
Sept.	7.0	11.4	13.0	6.2	−3.57	8.8	5.4	−8.62	6.6	4.8	−11.50
1984											
May	6.4	8.3	20.1	5.6	8.98	13.7	6.0	3.04	12.2	7.9	3.51
June	7.1	9.7	16.8	8.6	6.13	14.6	10.4	5.66	13.3	10.5	4.49
July	11.0	13.4	21.8	7.7	2.64	17.6	7.0	−2.28	16.7	9.1	−1.01
Aug.	10.0	12.8	20.6	5.8	0.81	15.8	5.1	−4.76	14.3	6.3	−5.04
Sept.	8.0	13.0	11.6	2.9	−11.57	8.2	2.9	−14.97	6.3	2.7	−17.03
1985											
May	7.3	9.5	17.0	9.1	7.12	13.8	10.4	5.17	11.5	9.8	2.31
June	6.5	8.8	16.3	10.1	8.73	13.6	11.2	7.07	13.1	11.4	6.75
July	9.7	11.8	19.1	11.0	6.42	16.9	12.8	6.02	15.7	12.8	4.86
Aug.	8.5	10.9	15.6	9.7	3.55	12.5	9.6	0.40	11.7	9.5	−0.51
Sept.	6.5	10.6	10.3	6.1	−4.83	7.4	5.9	−7.85	6.4	5.3	−9.46
1986											
May	6.1	7.9	19.4	10.5	14.00	13.7	10.7	8.47	11.6	10.0	5.67
June	11.2	15.2	18.7	10.3	−1.50	15.7	11.8	−2.92	14.8	12.6	−3.06
July	11.0	13.4	18.7	11.2	2.98	16.1	11.5	0.79	15.1	12.6	0.88
Aug.	10.0	12.8	16.2	7.2	−2.25	13.8	6.7	−5.02	12.2	7.9	−5.49
Sept.	6.0	9.8	10.1	5.5	−3.89	7.7	5.3	−6.61	6.0	4.5	−9.06

[a] E_L is the monthly lake evaporation reported by Sturrock et al. (1992), E_{TW} is the wet-environment areal evapotranspiration, PET is the potential evapotranspiration, and AET is the actual evapotranspiration.

[b] $E_{TW} = k \times E_L$, where k is a monthly-varied constant based on the evaporation data for Dauphin Lake in Manitoba, Canada (Morton, 1986).

[c] $F_n = PET + AET - 2E_{TW}$. According to the complementary relationship (Bouchet, 1963; Morton, 1983, 1986; Hobbins et al., 2001), F_n should be close to zero.

Table 8. Five-year (1982-1986) average monthly evapotranspiration estimated by the three models for the Wild Rice River watershed in accordance with the evaporation from Williams Lake (all values in cm).[a]

			SWAT-Penman			SWAT-Hargreaves			SWAT-Priestley		
Month	E_L	E_{TW}[b]	PET	AET	Fn[c]	PET	AET	Fn[c]	PET	AET	Fn[c]
May[d]	6.6	8.6	18.8	8.4	10.03	13.7	9.0	5.56	11.8	9.2	3.83
June[e]	8.4	11.4	17.4	9.4	3.92	14.7	10.8	2.64	13.8	11.3	2.25
July	10.6	12.9	19.6	10.4	4.16	16.9	11.2	2.19	15.7	11.9	1.82
Aug.	9.8	12.5	17.4	8.0	0.31	14.5	7.7	−2.85	12.9	8.6	−3.68
Sept.	6.5	10.6	11.7	5.1	−4.38	8.3	4.6	−8.36	6.5	4.2	−10.54

[a] E_L is the monthly lake evaporation reported by Sturrock et al. (1992), E_{TW} is the wet-environment areal evapotranspiration, PET is the potential evapotranspiration, and AET is the actual evapotranspiration.

[b] $E_{TW} = k \times E_L$, where k is a monthly-varied constant based on the evaporation data for Dauphin Lake in Manitoba, Canada (Morton, 1986).

[c] $F_n = PET + AET - 2E_{TW}$. According to the complementary relationship (Bouchet, 1963; Morton, 1983, 1986; Hobbins et al., 2001), F_n should be close to zero.

[d] Average of three years (1984-1986).

[e] Average of four years (1983-1986).

for the study (subbasins 60 through 100). Plotting the estimated AET values for other subbasins revealed a similar pattern, so these data were omitted for conciseness. The estimated evapotranspiration varied from one subbasin to another. This variation might be due to the heterogeneity in the land use and soil properties in addition to the variability of the climate conditions across the watershed. For a given subbasin and on an annual average basis, while the three models concurrently gave a higher or lower AET value, the SWAT-Hargreaves model tended to give a higher AET value than the other two models. However, for the summer months, when it was relatively warmer and wetter, the SWAT-Priestley model tended to give higher AET values (tables 7 and 8). Further, the differences between the AET values predicted by

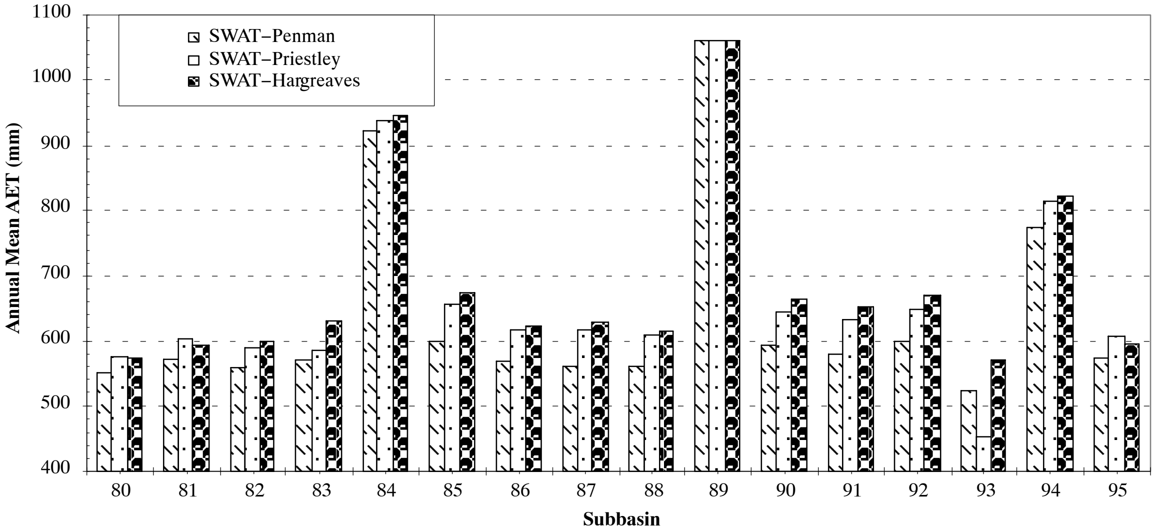

Figure 7. Plot showing the computed annual average actual evapotranspiration (AET) values for the selected subbasins. The AET values were computed by averaging the corresponding values throughout the 12 water years from 1986 to 1997, i.e., the calibration period for station USGS 05064000.

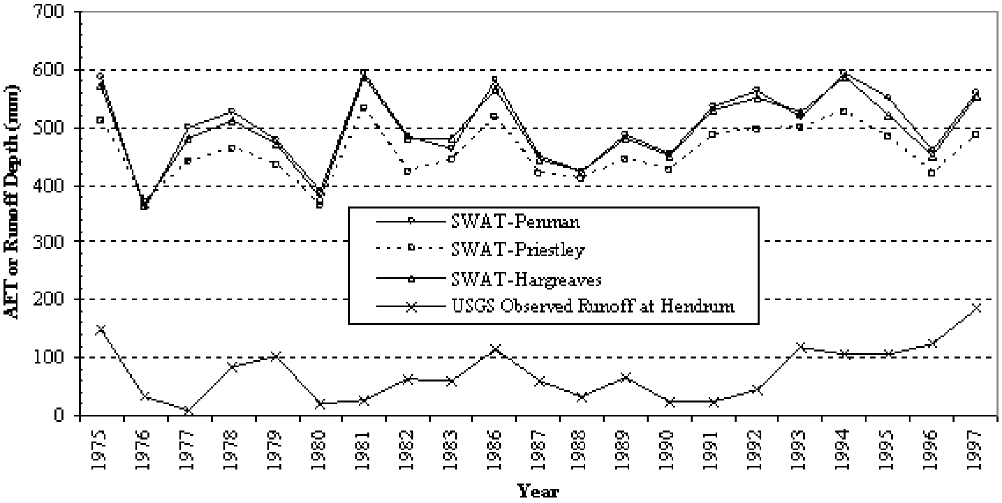

Figure 8. Plot showing the computed annual actual evapotranspiration (AET) for the Wild Rice River watershed and observed runoff at station USGS 05064000. The AET values were computed as the area-weighted averages across the 485 subbasins, resulting from subdividing the watershed for modeling purposes.

the three models seemed to be dependent on the dominant land use within the subbasin. For the water-dominated subbasins (e.g., subbasin 89), there was only a negligible difference, whereas for the subbasins dominated by agriculture (e.g., subbasin 60) or by forestry (e.g., subbasins 67, 84, and 94), the differences could range from a few mm to 100 mm. This is in agreement with Federer et al. (1996). One explanation might be that the models are sensitive to the resistibility of the plants to transpiration and the soil's evaporation limitations (Neitsch et al., 2002a).

For the study watershed, the differences between the AET values estimated by the models varied from year to year (fig. 8). Overall, AET was estimated to have a negligible difference by the SWAT-Penman and SWAT-Hargreaves models for a given year, but large differences between these two models and the SWAT-Priestley model occurred for the years with a greater runoff depth. For instance, the difference in the estimated AET values reached about 72.0 mm for 1997, implying that using the SWAT-Priestley model rather than the other two models would exert an almost 38.8% lower effect due to AET on the predicted runoff from the watershed. Again, this might be because the Priestley-Taylor method is more appropriate for wet hydrologic conditions, whereas the Hargreaves method is probably a better estimator for dry hydrologic conditions. Nevertheless, Bonferroni's multiple t-test indicated that the estimated AET values were insignificantly different from each other at a 5% significance level (p-values > 0.05).

CONCLUSIONS

This study assessed the influences of the three PET estimation methods within SWAT's framework on the model's hydrologic simulation performance in the Wild Rice River watershed, located in northwestern Minnesota. For convenience, the model using the Penman-Monteith method was designated SWAT-Penman, and the models using the Hargreaves and Priestley-Taylor methods were designated

SWAT-Hargreaves and SWAT-Priestley, respectively. The three models were independently calibrated and validated using the daily stream flows observed at stations USGS 05062500 and USGS 05064000. The stream discharges and evapotranspiration, predicted by the three calibrated models, were used to investigate the influence of each on SWAT's overall performance.

The three calibrated models took different values for the parameters ESCO and CN2. The SWAT-Hargreaves model had the lowest value for ESCO but a value for CN2 identical to that of the SWAT-Penman model, whereas the SWAT-Priestley model had the lowest value for CN2. Notwithstanding, all three models had a comparable performance in simulating the stream flows, both from the watershed perspective and for each of the evaluation stations. However, the discharges with a higher value were generally predicted more accurately by the SWAT-Priestley model, whereas the discharges with a lower value were usually predicted better by the SWAT-Hargreaves model. The values predicted by the SWAT-Penman model tended to be greater than those predicted by the SWAT-Hargreaves model but smaller than those predicted by the SWAT-Priestley model.

Overall, for the study watershed, the SWAT-Hargreaves model seemed to be slightly superior to the other two models in accordance with the complementary relationship. As with the findings obtained by examining the simulated stream discharges, the SWAT-Hargreaves model may be superior for situations with an E_{TW} value less than 4.0 mm/d, and the SWAT-Priestley model may be more appropriate when the E_{TW} value is greater than 8.0 mm/d. When E_{TW} is between 4.0 and 8.0 mm/d, any of the three models could be used to estimate the evapotranspiration, with none performing noticeably better than the others. Further, the AET values estimated by the three models shared a concurrent spatial pattern and temporal trend. The variation from one subbasin to another might be due to the heterogeneity in the land use and soil properties, in addition to the variability of the climate conditions across the watershed. The variation from year to year might indicate that the three models would be sensitive to the hydrologic conditions when estimating the evapotranspiration for the study watershed but might give insignificantly different AET values.

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