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Comparing and Modifying Eight Empirical Models of Snowmelt Using Data from Harp Experimental Station in Central Ontario

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Authors' contributions

This work was carried out in collaboration between all authors. HY designed the study, performed the calculations for most models used, and wrote the first draft of the manuscript. CMC assisted in data collection and processing, and took part in draft writing. AJ assisted in refining of analyses and manuscript. CF and AJ conducted SWAT calibration and application. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

Aims: To modify two empirical models of snowpack and snowmelt, and compare eight such models.
Study Design: Test and modify the models by using five years of snow measurements from Harp Lake.
Place and Duration of Study: Dorset Environmental Science Centre, Ontario Ministry of Environment, and Department of Geography, Nipissing University, between January 2009 and August 2012.
Methodology: The old daily-run WINTER model was the first model. It was modified to create a second model. The enhanced-temperature-index (ETI) model was slightly modified to be the third model. Modified WINTER and ETI were combined into the fourth model. Hydrology model BROOK90 and SWAT were used as the fifth and sixth model, also daily-run. Operating the WINTER and ETI in hourly steps created the seventh and

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eighth model. The calculated snow water equivalent (SWE) by each model was evaluated against the observed data to give a coefficient of efficiency (CE). Accuracy and performance of the models were compared based on CE values.
Results: Modified WINTER model improved original WINTER by 20.7% (CE increased 20.7%). The performance of ETI model was 27.6% higher than the original WINTER. The new combination model produced additional improvement by 40.7 % over the original WINTER, or by 16.5% over the modified WINTER or 10.3% over the ETI. Running the model with hourly time steps rather than daily steps increased model's accuracy: hourly WINTER raised CE by 15.4% and hourly ETI raised CE by 7.9%. Two watershed hydrology models BROOK90 and SWAT performed even better than the above six simpler snow models.
Conclusion: It is suggested that the daily combination model be considered if only daily data is available, or hourly WINTER and ETI models be used if hourly runs are desired while new calibration are required when applying them to any new locations. If data requirements by BROOK90 or SWAT are met, these hydrology models would be tried.

Keywords: Snowpack; melt; empirical model; temperature; radiation; precipitation; compare.

1. INTRODUCTION

Snow and ice are important components of the hydrologic cycle in mountainous or cold regions, and play a key role in water supply to ecosystems and societies over a vast portion of the world (Young et al., 2006; Ewing and Fassnacht., 2007). In the background of increasingly more interest and attention to the relation of water resources and climate changes, a number of recent studies have improved our understanding and calculation of glacier, ice and snow processes (Pellicciotti et al., 2008; Carenzo et al., 2008; Buttle, 2009). However, snowpack dynamics (snowpack formation and snowmelt) in forests or forested watersheds has been perhaps one of the most difficult processes to estimate or model satisfactorily (Ewing and Fassnacht, 2007; Buttle, 2009; Price, 1988) Furthermore, one of the important impacts of climate change on water resources is the earlier occurrence of snowmelt and increased frequency of rain-on-snow events (Clow, 2010; Campbell et al., 2011), and the earlier snowmelt could lead to an increase in spring evapotranspiration or a decrease in water yield at some coniferous catchments (Tague et al., 2009). Therefore, more studies and investigations on reliable and operational estimation methods of snowmelt are needed.

Among the two major methods, physically-based models (e.g. energy flux and balance) and empirical models (e.g. temperature-based index method), the physically-based models have been more successfully applied to open areas (Carenzo, 2009; Pellicciotti et al., 2008; Strasser et al., 2002; Woo and Young 2004; Bruland et al., 2004). Energy flux processes over open snow surfaces are less complicated and more representative meteorological and snow feature data is available. Energy balance models applied to forested areas can perform well when intensive experimental or observatory data can be provided (e.g. the Intensive Study Areas of NASA, Frankenstein, S., 2007). However, affects of tree canopy and poor field data (not representative of conditions with a lack of spatial heterogeneity) could reduce a model's performance (Logan, 1976), or make it perform at the same level as an empirical model, or even worse than an empirical model (Scheider et al., 1983). In many situations energy balance models are impossible to use due to the unavailability of required data (Price, 1988).

On the other hand, empirical models have been demonstrated to reproduce a large part of the variations in snowpack water equivalence (SWE) at both open and forested areas (Pellicciotti et al., 2008; Buttle, 2009; Price, 1988), although they are not physically sound and do not explain in detail about snowpack dynamics. Information on snowmelt is needed mostly in areas and regions where the data required to run a physical model are not available; therefore, operational and empirical models of snow processes still have to be provided for hydrologic modeling in the context of water resource management. Among the existing models, individual models have not been well compared or assessed to provide a general selection reference for model users, and the possibility of improving these models needs to be explored.

In this study, several daily-run empirical models were evaluated based on temperature and precipitation, or based on temperature and solar radiation, trying to improve the accuracy of some models by making changes to the formulas, and comparing the performance of daily-run and hourly-run versions. As a result, eight models (or versions) were compared with each other, using 5-years time series of SWE measurement data collected from an experimental head-water watershed located in central Ontario, Canada. A suggestion of model selection or usage can be drawn based on the performance ranking of the eight models.

2. MATERIALS AND METHODS

2.1 Study Area and Data Collection

The study watersheds have eight small inland lakes, managed by the Dorset Environmental Science Centre (DESC), and located in the District of Muskoka and Haliburton County, Ontario, Canada (Fig. 1). They are representative areas of the boreal ecozone on the Southern Canadian Shield landscape which shows humid continental climate with mild summer and long cold winter. Environmental monitoring including hydrology, meteorology, stream and lake water chemistry and aquatic biology has been conducted since 1976. For a 29-hydroyear period of 1978-2007, annual precipitation ranges from 760 to 1276 mm with an average of 1008 mm (Yao, H. et al., 2009). Annual runoff ranges from 159 to 1051 mm with an average of 540 mm. About 45.3 % of the runoff appears in March to May (spring snowmelt season), 30.1 % in October to December, and only 24.6 % is in the remaining 6 months. Mean annual temperature ranges from 3.4 (1993/94) to 6.4 (2005/05) ºC, with an average of 5.0ºC. The hottest July and coldest January has a mean temperature of 18.6 and -10.1ºC respectively.

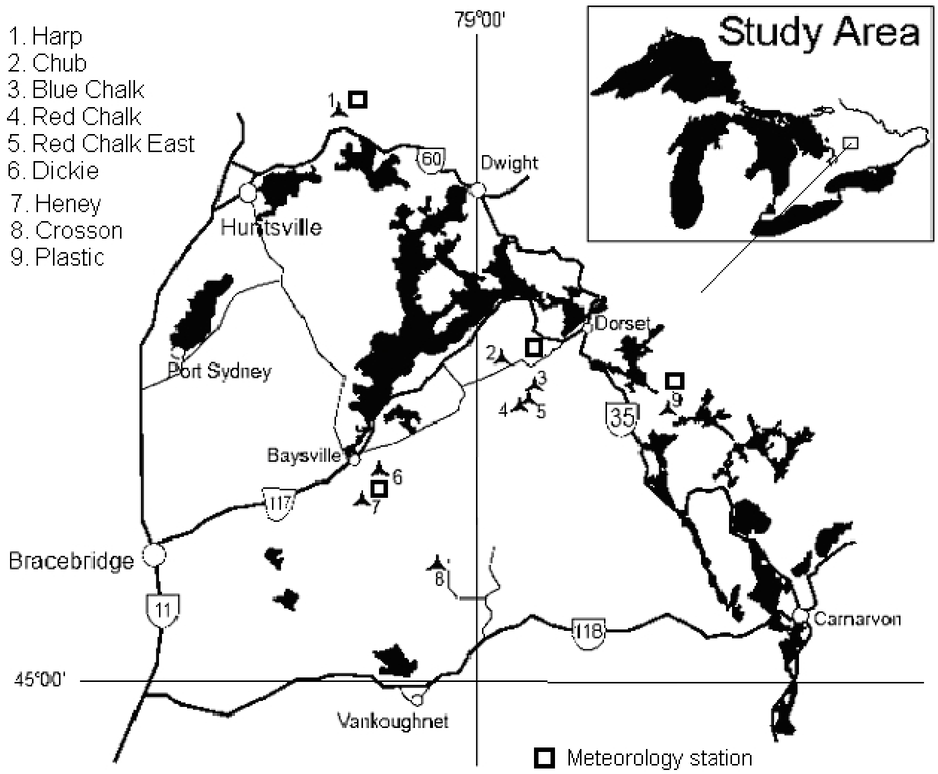


Fig. 1. Study area and locations of watersheds

Harp Lake has a lake area of 71.4 ha and a drainage area of 470.7 ha respectively (Figure 2). The snow collection was conducted at the HP4 sub-watershed of Harp Lake to its west, during the winter and spring season for five consecutive years (1987-88, 1988-89, ……, 1991-92). The collection site had six collection points, and three samples were taken from each point to determine water equivalence of the snowpack (Water Resources Branch, 1989; Findeis, 1993), using a Utah metal snow corer. The SWE measurements were started usually in December and ended in April or early May, with typical frequency of weekly samples, and an increased frequency during snow melt.

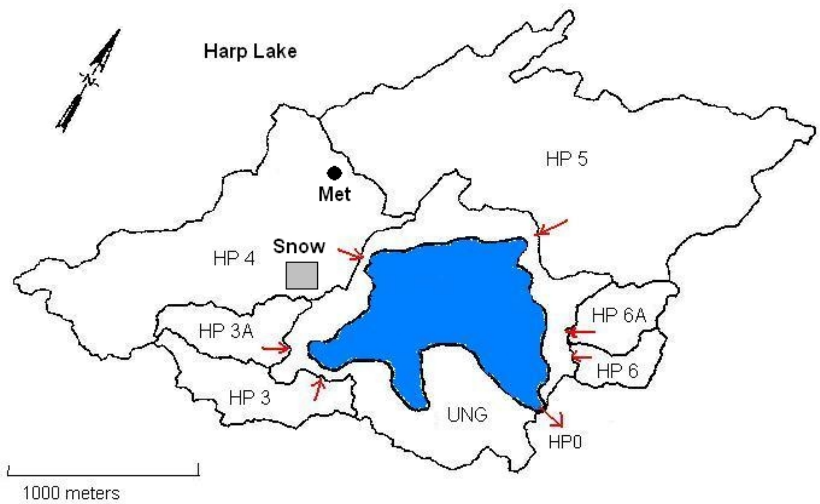


Fig. 2. Harp Lake watershed and snow core measurement locations (Snow: snow core site; Met: meteorology station; HP1 etc.: inlet sub-watersheds into the lake or total watershed at the outlet with their flows monitored; UNG: ungauged sub-watersheds without flow monitoring).

Since 1978 hourly and daily meteorological data were collected at the meteorology station about 1 km away from the snow sample site (Fig. 2). The met station was built in a small-scale opening in the forests. Air temperature, precipitation and solar (incoming short-wave) radiation were used in this study for the five selected years.

2.2 Methods and Models

The timely process of snowpack at a point or on an area is described by a SWE balance equation:

$$SWE_2 = SWE_1 + SNOW - SUB - Xmelt \tag{1}$$

where SWE_2 is the SWE value (mm) at the end of a calculation time step (usually a day or an hour), SWE_1 is the value at the end of the previous step, *SNOW* is the snowfall (i.e. mm/d) within the present step, *SUB* is the snow loss (i.e. mm/d) through sublimation (solid snow changes to vapour), and *Xmelt* is the snow loss (mm/d) through melting into liquid water. When the time step is selected and calculation methods for *SUB* and *Xmelt* are determined, the changing process of SWE can be calculated from step to step, and the calculated SWE process can be tested against the observed SWE.

Different treatments to *SNOW*, *Xmelt* and *SUB* are considered to pursue for a better-performing model. As a result, eight models have been tried.

2.2.1 Daily WINTER model

The WINTER model was used to estimate snow accumulation and melt based on daily mean air temperature *T* and daily precipitation *P* as follows (Buttle, 2009; Scheider et al., 1983).

$$\begin{aligned} &Xmelt = 0 && if\,(T \le b) \\ &Xmelt = a \cdot T && if\,(T > b \quad and \quad P = 0) \\ &Xmelt = (c + d \cdot P)T + e && if\,(T > b \quad and \quad P > 0) \end{aligned} \tag{2}$$

Where *Xmelt* is daily melt rate of the snowpack (mm/d). Parameter *b* is a threshold temperature, if the daily temperature is below *b*, all precipitation of the day (*P*) is assumed to be snowfall (*SNOW*=*P*) and accumulates in the snowpack, and no melt occurs for that day. If *T* is larger than *b*, all precipitation is assumed to be rainfall, no snow is added to the snowpack (*SNOW*=0), and a melt occurs in the snowpack. The melt is accounted for in two cases: dry or wet condition. In the dry condition (no rainfall), melt rate is calculated only using air temperature and with only one parameter *a*. In the wet condition (having rainfall), the melt rate is calculated by using both temperature and rainfall (mm/d) and using three parameters (*c*, *d* and *e*). Snow sublimation is thought negligible and not included in the model. Buttle and JM (2009) has applied the WINTER model to the same watershed and the same snow core data that we are using. The original model and Buttle's parameter values are treated as the first of the eight snowpack models in our study, and named as "Wmod_old".

2.2.2 Modified WINTER model

A minor change is made to modify the old WINTER model structure. In the Wmod_old, when *b* is larger than 0.0 (such as 1.2 ºC), a temperature only slightly larger than the threshold (like *b*+0.001) would produce a certain melt rate (if *a*= 1.9 then *Xmelt* is 1.9 X 1.201 or 2.282 mm/d), while the melt rate should actually be very small (close to 0.0) according to the definition of the threshold concept. Therefore the formula (2) is changed into the following format to solve this concern.

$$\begin{aligned} &Xmelt = 0 && if\,(T \le b) \\ &Xmelt = a \cdot (T - b) && if\,(T > b \quad and \quad P = 0) \\ &Xmelt = (c + d \cdot P)(T - b) + e && if\,(T > b \quad and \quad P > 0) \end{aligned} \tag{3}$$

This modified model is named "Wmod_new". The new and old versions are both daily-run models.

2.2.3 ETI model

The ETI (enhanced temperature index) model was proposed and applied to several places in Europe and South America (Pellicciotti et al., 2008; Carenzo, 2009) for calculating hourly melt rate of ice or snow. Based on temperature and radiation this model has been compared to energy balance models in their studies. It is supposed that the hourly ETI model structure is applicable to our study area. For daily-run purposes a slightly modified ETI formula is expressed as:

$$Xmelt = g(T - f) + h(1 - i)R \qquad if\,(T > f)$$
$$Xmelt = 0 \qquad if\,(T \le f) \tag{4}$$

where daily melt *Xmelt* (mm/d) is calculated from daily-mean temperature *T* and daily incoming shortwave radiation *R* (W/m^2). Parameter *f* is a threshold temperature similar to parameter *b* from the WINTER model (formula 3), which is used to determine whether and how much snowfall happens in a day, *i* is the albedo of snow surface, and the parameters *g* and *h* are coefficients. All the four parameters in the daily-run model will be calibrated with SWE data. The term $g{\cdot}T$ in the original model has been modified to *g(T-f)*. Snow sublimation is not explicitly considered, or it has been implicitly included in the formula (4). This model is named as “ETI”.

2.2.4 Combination of WINTER and ETI

After some trials with the WINTER and ETI models, it was possible to increase a model’s performance by combining the two models into one. Also mechanistically all the air temperature (*T*), shortwave radiation (*R*) and rainfall (*P*) over snowpack affect the available energy. A new melt formula which includes the three variables deserves a try. It is expressed as:

$$Xmelt = 0 \qquad if\,(T \le j)$$
$$Xmelt = k \cdot (T - j) + l \cdot R \qquad if\,(T > j \quad and \quad P = 0) \tag{5}$$
$$Xmelt = (m + n \cdot P)(T - j) + l \cdot R + o \qquad if\,(T > j \quad and \quad P > 0)$$

The six parameters (*j, k, l, m, n, o*) have a similar meaning or function as they appear in the two models: *j* is the threshold temperature, *k* and *l* are used in dry melting, *m*, *n*, *l* and o are used in wet melting.

Different from the above three models, the snow sublimation is accounted for this time. Liston and Sturm, (2004) indicated that the winter sublimation in the Arctic region is a fundamental component of arctic hydrologic cycle. Daily sublimation during late winter in a southern boreal forest (the loss from intercepted snow) was once simulated as 0.16 to 0.72 mm/d by Parviainen and Pomeroy (2000). The sublimation loss from snowpack under the tree canopy would probably be appreciable, although quite less than the sublimation rate on the canopy. As an approximate estimation the daily sublimation rate is calculated from potential evapotranspiration as follows.

$$SUB = q \cdot \frac{L_w}{L_s} E_p \tag{6}$$

where the specific latent heat of vaporization L_w and specific latent heat of sublimation L_s are given a constant number of 2,453 and 2,838 kJ/kg, *q* is a canopy extinction coefficient and reflects the effects of the canopy upon heat and energy transfer and is valued at 0.465 for this study. The potential evapotranspiration E_p is calculated by a modified Makkink formula by Yao, H. (2009).

$$E_p = 0.671(0.439 + 0.01124 \cdot T)\frac{R}{L_w} - 0.0132 \quad (7)$$

The basis for equation (6) is that the potential sublimation rate for a location is proportional to the potential evapotranspiration by a factor of L_w/L_s, and actual sublimation on the snowpack is further influenced by the canopy's extinction. As a result, the formulas (5), (6) and (7) provide a new model and it is named "Combi". Snow sublimation is considered only in the Combi model and BROOK90 model among the eights in our study.

2.2.5 BROOK90 Model

Snowpack and snowmelt are one part of the catchment hydrology model BROOK90 (Federer et al., 2003; Federer, 2011, BROOK90: A simulation model for evaporation, soil water, and streamflow, http://www.ecoshift.net). In BROK90, the traditional assumption of snowmelt being proportional to the excess of mean daily temperature was modified by considering groundmelt, cold content of the snowpack, refreezing rain, seasonal effects, and effects of canopy cover, slope and aspect. Its melt rate is determined by two formulas:

$$SNOEN = MELFAC * 2 * DAYLEN * SLFDAY * T * e^{-LAILMT * LAI - SAILMT * SAI} \quad (8)$$

$$Xmelt = (SNOEN + RTHR * Max(T,0) * CVLQ) / LF \quad (9)$$

where *SNOEN* is energy flux to snow surface (MJ/m^2/d), *MELFAC* is the melting degree-day factor for a day with a daylength of 0.5 d and no canopy, *DAYLEN* is the daytime fraction of a day, *SLFDAY* is the ratio of potential insolation on the slope to that on a horizontal surface, and the parameters *LAIMLT* and *SAIMLT* express the dependence of *SNOEN* on leaf area index (*LAI*) and stem area index (*SAI*). The major controlling input is still the temperature *T*. Snow melt *Xmelt* is dependent on the energy flux *SNOEN*, throughfall of rain *RTHR*, and two constant: the specific heat of water *CVLQ* and the latent heat of fusion of water *LF*. When we applied the BROOK90 model to the HP4 sub-catchment (Yao, 2012; unpublished manuscript), the entire hydrology model was run with necessary input datasets for the five years, and snowpack and melt results were generated and used for our analyses. This method for snowmelt is named "BROOK90".

2.2.6 SWAT model

The Soil-Water-Assessment-Tool (SWAT) was widely used for water resources and environmental management (Arnold and Fohrer, 2005), and was modified for the Canadian Shield landscape (Fu et al., 2012; unpublished manuscript). Two formulas are used to calculate daily snow melt.

$$T_{snow} = T_{snow1} \cdot (1 - \text{a}) + T \cdot \text{a} \quad (10)$$

where T_{snow} is the snow pack temperature on a given day (°C) and T_{snow1} is the snow pack temperature on the previous day (°C), T is the mean air temperature on the current day (°C), and λ is a snow temperature lag factor.

$$Xmelt = b_{mlt} \cdot SNO_{cov} \cdot \left[\frac{T_{snow} + T_{mx}}{2} - T_{mlt}\right] \quad (11)$$

where *Xmelt* is the amount of snow melt on a given day (mm/d), b_{mlt} is the melt factor for the day (mm/day/°C), SNO_{cov} is the fraction of land area covered by snow, T_{mx} is the maximum air temperature on a given day (°C), T_{mlt} is the base temperature above which snow melt is allowed (°C).

$$b_{mlt} = \frac{(b_{mlt6} + b_{mlt12})}{2} + \frac{(b_{mlt6} - b_{mlt12})}{2} \cdot sin\left(\frac{2®}{365} \cdot (d_n - 81)\right) \quad (12)$$

Where b_{mlt6} and b_{mlt12} are the melt factors for June 21 and December 21 respectively (mm H_2O/day-°C, d_n is the Julian day number of the year. It can be seen that the snow melt module in SWAT is temperature based. Similarly to BROOK90, the entire SWAT model was applied to the HP4 sub-catchment to simulate hydrological processes, and resulted daily series of snowpack and snowmelt for five years were used for our analysis and comparison. This method is named “SWAT”.

2.2.7 Hourly WINTER model

The Hourly or diurnal changes could be taken into consideration if the hourly input data is available. Hourly accounting of snow accumulation and melt might provide a better representation than the daily model, based on three reasons. First, the separation of precipitation into snowfall or rainfall by using a daily-mean temperature may not reflect the actual precipitation status. For example, if the mean temperature is 0.1 ºC and less than a threshold of 0.5 ºC, the precipitation in that day is identified as snowfall. But actually the precipitation may have occurred in the daytime when the temperature may have been higher than 0.5 ºC and fallen as rain. Hourly division is able to capture the real snow or rain falls. Second, temperature and shortwave radiation fluctuate greatly within a day; a simple average may not lead to melt rates which fit well with actual collective melt in a 24 hour period. Third, the influence of rainfall events on snow melt may significantly differ between daytime and night time. Therefore, hourly modeling of snow processes was also tried and compared to the daily runs.

The hourly WINTER model takes the same structure as formula (3), only the unit becomes an hour and the parameters are re-calibrated. It is named “W_hour”.

2.2.8 Hourly ETI model

Similarly, formula (4) is used with hourly data series and re-calibrated parameter values, formulating an hourly ETI model “ETI_hour”.

2.2.9 Calibration and comparison

The required input data, number of parameters, calibration methods and outputs of the eight models are listed in Table 1. For BROOK90 and SWAT, only the information related to snowpack and snowmelt is included, all other items simulating other hydrological processes are not listed. Their input data are basically same – air temperature and precipitation; the number of parameters are similar; the outputs are same – time series of snowmelt and SWE.

Table 1. Basic information of eight models used

Model	Input data	Number of parameters	Calibration method	Functionality or output
Wmod_old	Daily temperature, precipitation	5	Trial-and-error	Melt rate, SWE
Wmod_new	Daily temperature, precipitation	5	Trial-and-error	Melt rate, SWE
ETI	Daily temperature, solar radiation	4	Trial-and-error	Melt rate, SWE
Combi	Daily temperature, precipitation, solar radiation	6	Trial-and-error	Melt rate, SWE
BROOK90	Daily temperature, precipitation	3	Its own routines	Melt rate, SWE
SWAT	Daily temperature	4	Its own routines	Melt rate, SWE
W_hour	Hourly temperature, precipitation	5	Trial-and-error	Melt rate, SWE
ETI_hour	Hourly temperature, solar radiation	4	Trial-and-error	Melt rate, SWE

Except for BROOK90 and SWAT, all parameter calibrations with the other six models are achieved through an error-and-trial procedure. First, each parameter for a model is adjusted to search for a better value range which can reduce the deviation (correlation coefficient R^2) of estimated SWE from the observed SWE. Second, the multiple parameters in a model are further adjusted together to find an improved set of values that further reduce the R^2. With BROOK90, the parameters are determined by referring to the recommended values (Federer, 2002; BROOK90: A simulation model for evaporation, soil water, and streamflow, http://www.ecoshift.net) and adjusting to our specific catchment. With SWAT, its parameters are calibrated by its own routines and adjusted for our catchment (Fu et al., 2012; unpublished paper).

The popular Coefficient of Efficiency (CE) index as proposed by Nash and Sutcliffe, (1970) is used to justify the accuracy of each model, and to compare the performance amongst the eight models.

$$CE = 1 - \frac{\sum (E_{est} - E_{obs})^2}{\sum (E_{obs} - E_{mean})^2} \quad (13)$$

Where E_{est} and E_{obs} are the modeled and observed SWE for a given date, E_{mean} is the mean of all observed data for the study period. During the model calibrations and model comparisons, the ground-truth data of SWE in five snow seasons from the monitoring program have been used.

3. RESULTS AND DISCUSSION

3.1 SWE Results

Calculations with each model begin and end on a fixed date: November 1 and May 31, to produce SWE series of same duration length for evaluation, whereas snow accumulation and melt happen usually between late November and early May. Meteorological inputs for the five snow seasons (1987-88 to 1991-92) are shown in Fig. 3. Distributions of temperature and precipitation (especially the latter) in a season can vary significantly between years which may affect snow pack dynamics.

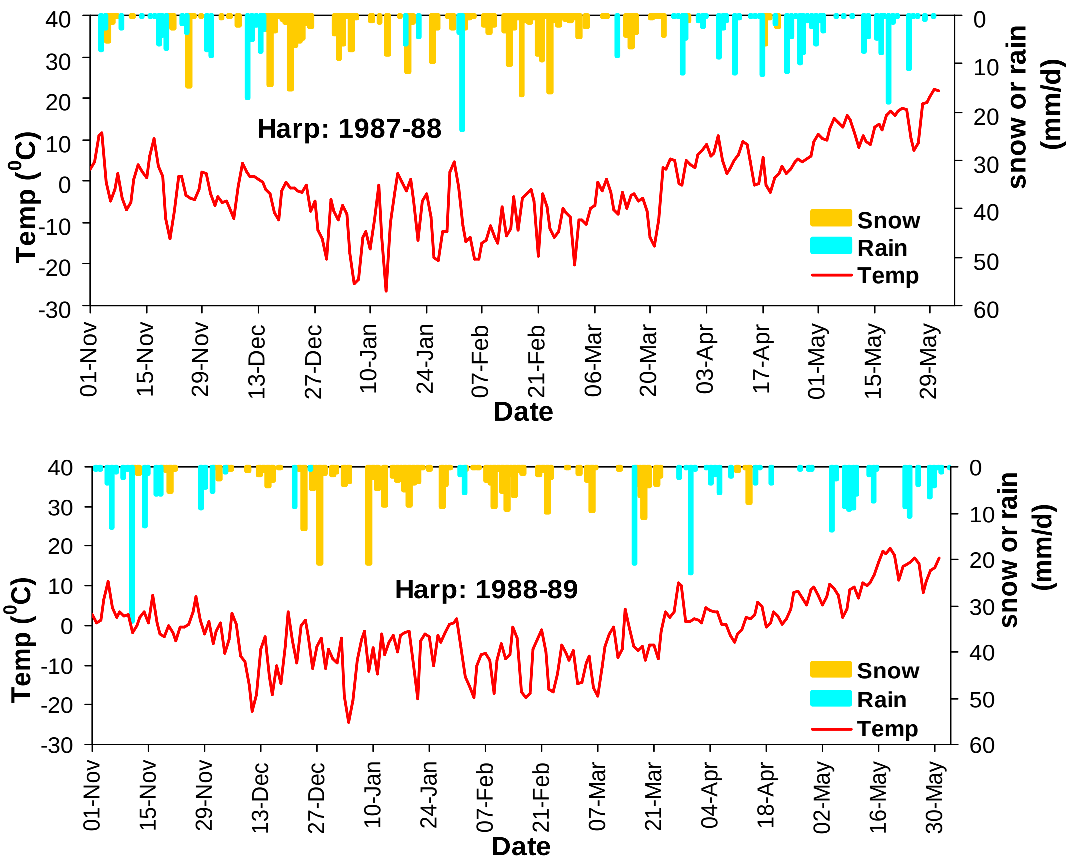
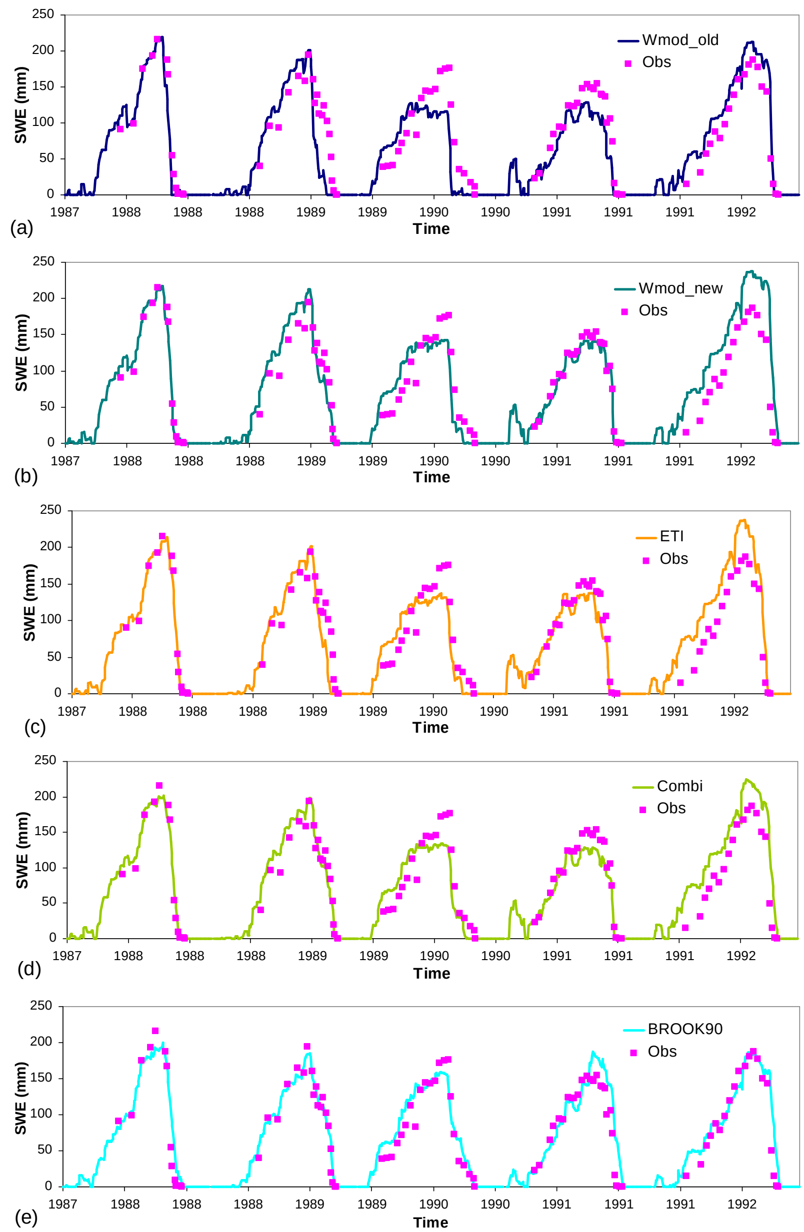


Fig. 3 Meteorological inputs at Harp watershed site (only two years shown; Temp: daily mean air temperature)

Calculated SWE series of five snow seasons (212 days for each season) are plotted in a figure together with the observed SWE (Fig. 4). The observed SWE is more scattered along the time scale axis than the modeled results. For the first snow season (1987-88), eight models did not show a significant difference in SWE process. For the next three seasons (1988-89, 1989-90, 1990-91), the Wmod_old produced greater deviation from observed SWE than did the other seven models. But for the last season (1991-92), the Wmod_old worked better than other seven models. Among the seasons, most models worked better in 1987-88, 1988-89 and 1990-91 than in 1989-90 and 1991-92. Overall, the Combi, BROOK90, SWAT and two hourly models produced better SWE than other 3 models, although the difference among eight models results were not strong or clear by just looking at the figure.



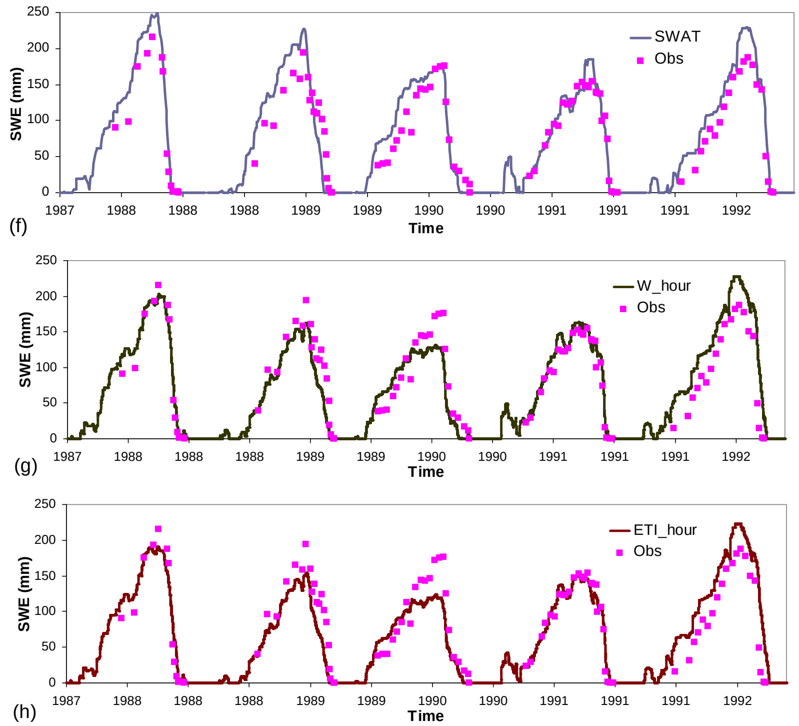


Fig. 4 Calculated SWE process vs. observed SWE for 5 snow seasons, by each of eight models respectively: (a) Wmod_old, (b) Wmod_new, (c) ETI, (d) Combi, (e) BROOK90, (f) SWAT, (g) W_hour, and (h) ETI_hour. The time interval on the time axis is a day for sub-figures (a) to (f), and is an hour for (g) and (h).

When comparing the hourly model's and daily model's results (comparing Fig. 4g with 4b, or Figure 4h with 4c), the W_hour produced better results than its daily counterpart Wmod_new, and the ETI_hour produced better results than its counterpart ETI. This shows that an hourly run of either WINTER or ETI model would increase its accuracy against a daily run.

In order to compare and evaluate each of the 8 models, their parameter values are listed in Table 2. The data number of observed SWE during five snow seasons together is 101 (101 days having SWE observation). A CE value is obtained with formula (13) for each model by using the 101 data points and is also listed in Table 2. A performance rank of the 8 models, from best to least (from largest CE to smallest), is then determined. For verification purpose, the correlation coefficient R^2 of the calculated SWE and observed SWE for each model is listed in the table too, and a ranking based on R^2 value is a little different from the performance ranking based on CE value. The same four models have been identified as the best models by both rankings.

Table 2. Model parameters calibrated, coefficient of efficiency (CE), and ranks

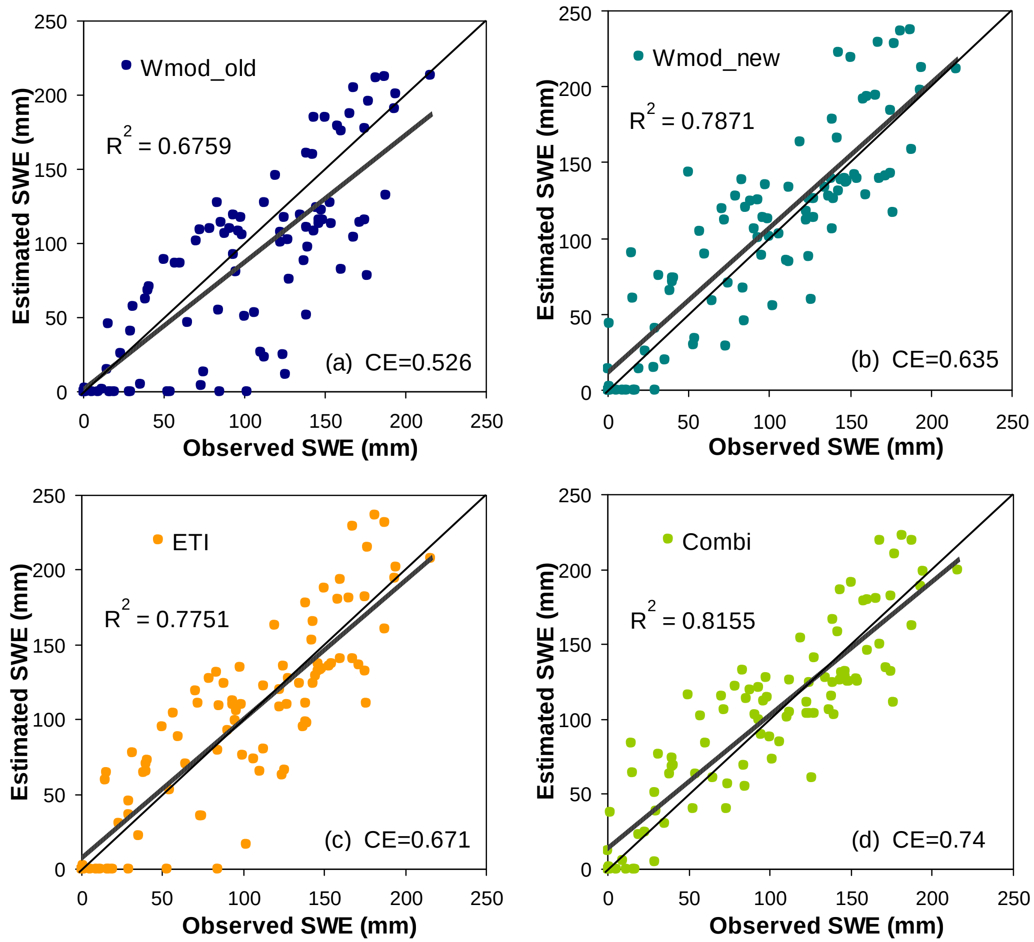
Model	Parameters	CE	Performance rank	Correlation R^2 (rank)
Wmod_old	a=1.9 b=0.8 c=3.5 d=0.03 e=1.6	0.526	8	0.676 (8)
Wmod_new	a=1.9 b=0.3 c=2.8 d=0.025 e=0.0	0.635	7	0.787 (5)
ETI	f=-0.1 g=1.2 h=0.06 i=0.37	0.671	6	0.775 (6)
Combi	j=0.0 k=1.95 l=0.001 m=1.5 n=0.014 o=0.0	0.740	3	0.816 (3)
BROOK90	MELFAC=0.6 LAIMLT=0.2 SAILMT=0.5	0.854	1	0.877 (1)
SWAT	λ=0.11 T_{mlt}=0.825 b_{mlt6}=2.4 b_{mlt12}=2.4	0.792	2	0.871 (2)
W_hour	a=0.085 b=0.7 c=0.05 d=0.0008 e=0.025	0.733	4	0.783 (4)
ETI_hour	f=0.5 g=0.058 h=0.0004 i=0.38	0.724	5	0.748 (7)

The CE values clearly demonstrated what has been seen from Fig. 4. The modified WINTER daily model (Wmod_new) has improved the accuracy (CE) from 0.526 with Wmod_old to 0.635. The daily ETI model performed almost the same as Wmod_new and better than Wmod_old. The combination effort (Combi) did improve the daily models, increasing CE from 0.635 or 0.671 to 0.740.

On the other hand, the hourly model W_hour performed better than its daily counterpart Wmod_new, increasing CE from 0.635 to 0.733, and the hourly ETI_hour performed better than its daily counterpart ETI, increasing CE from 0.671 to 0.724. Furthermore, SWAT and BROOK90 which are more physically-based models have further improved the accuracy of snow melt modeling, increasing CE from level 0.74 to 0,792 or 0.854.

The five models: BROOK90, SWAT, Combi, W_hour and ETI_hour have close and higher CE values, and therefore should be favored while a choice has to be made between them depending on data availability and application purpose.

The estimated and observed SWE (101 data points) are shown in Figure 5, with their linear correlation lines and the 1:1 gradient line (center line). For Wmod_old (Fig. 5a), the correlation line is substantially away from the center line, and the points are more scattered than the other models, leading to smallest CE or R^2 values. The Wmod_new tends to overestimate SWE (Fig. 5b). The five models of ETI, Combi, BROOK90, W_hour and ETI_hour show similar correlation lines: close to the center line, doing well for medium SWE, tending to overestimate for smaller SWE range and to underestimate for larger SWE range. The SWAT model tends to underestimate SWE. However, the scattering extent determines the correlation coefficient or CE index, with BROOK90 and SWAT results having smallest scattering or largest CE.


Wmod_old
R2 = 0.6759
(a) CE=0.526
Estimated SWE (mm)
Observed SWE (mm)
Wmod_new
R2 = 0.7871
(b) CE=0.635
ETI
R2 = 0.7751
(c) CE=0.671
Combi
R2 = 0.8155
(d) CE=0.74
0
50
100
150
200
250

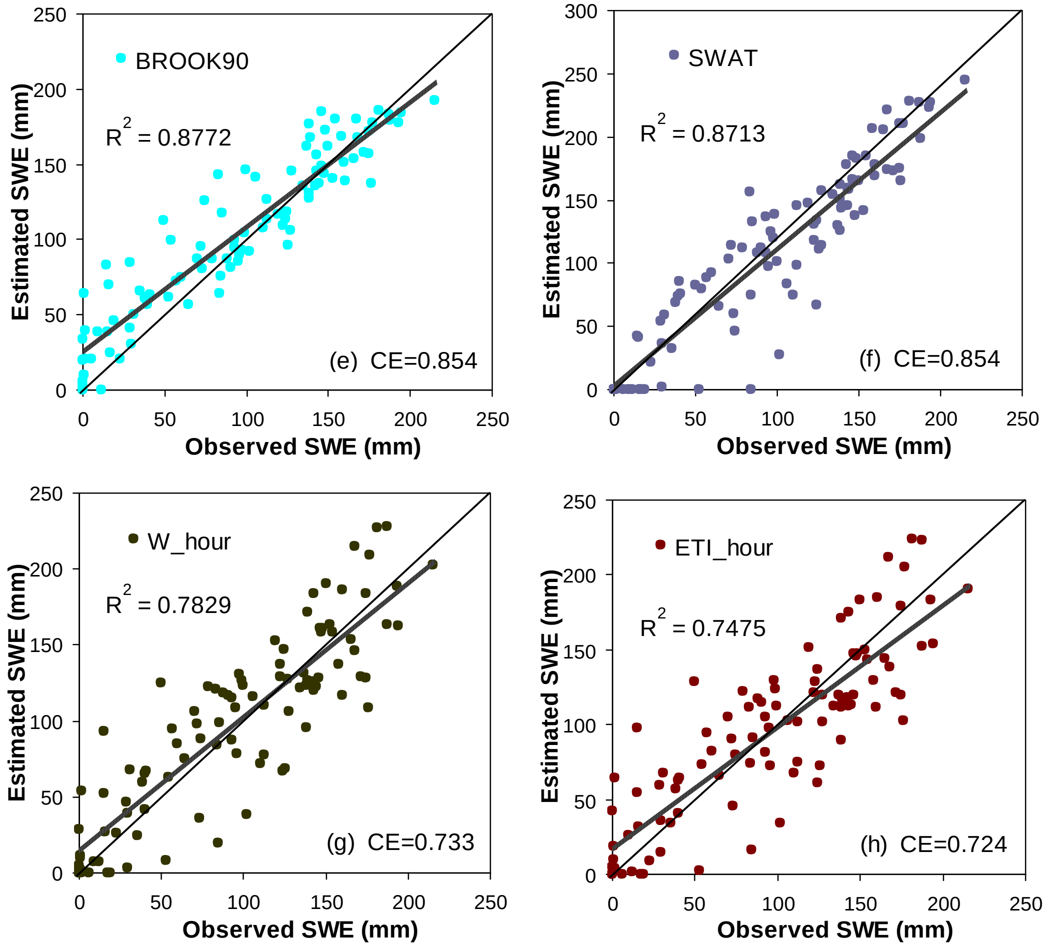


Fig. 5. Estimated SWE vs. observed SWE (solid circle points) for each of 8 models: (a) Wmod_old, (b) Wmod_new, (c) ETI, (d) Combi, (e) BROOK90, (f) SWAT, (g) W_hour, and (h) ETI_hour. The dotted lines and correlation coefficient R^2 values represent linear correlations between the estimated and observed, and solid lines represent center 1:1 lines.

3.2 Discussion

Certain improvement has been achieved by proper modification and re-calibration of existing models while the resulting 'better' models and suggested performance rank should not be viewed as permanent or necessarily applicable to sites outside the study area. The eight models as tested did not show vital differences in their abilities and the comparison results might change if a more precise calibration were conducted or if approached by other researchers. What needs to be remembered is that empirical models rely on location and the quality of field data used. A major message from the study is read like this: any empirical model could work well for snow accumulation and melt processes, and room does exist to modify and improve many models but the room is not revolutionarily encouraging. Comprehensive modeling like BROOK90 or SWAT, or hourly accounting could be preferable.

The errors and deviations of a model are caused by various possibilities: model structure, whether or not all important variables are included, data quality etc. For example, wind blowing is a factor affecting redistribution of snow and snow depth, and none of the models has considered it explicitly. All models displayed a much greater deviation from observation in 1991-92 than in other years, which could be led by modeling error or by extraordinary mistakes in collected SWE and meteorology data.

Carenzo et al. (2009) indicated that the temperature parameter *g* and radiation parameter *h* in their hourly ETI model changed with climate pattern, locations on the earth and data used. Their proposed average *g* is 0.055 and *h* is 0.0093 for the glaciers in Switzerland. Our calibrated numbers for Harp Lake area are 0.058 for *g* and 0.0004 for *h*. Therefore, the temperature parameter value would be closely similar from Switzerland glaciers to Canadian forests, but the radiation parameter value would be much different. The *h* takes a much smaller value in our site than in their site most likely because the ice/snow melt on glaciers are more sensitive to solar radiation than in forest-covered snow.

The models tested represent a snow accumulation and melt process at a point of interest or a point location with data, and their results could be treated as an average condition of snow packs on a limited area or watershed. They do not provide detailed spatial distribution of SWE for a region when the input data is not spatially distributed. The actual distribution of SWE is very complex. For example, the small-scale variability of solar radiation, a controlling factor, was found to be due to topographic influences over an arctic catchment (Pohl et al., 2006). The topographic and vegetation canopy variations could cause complicated spatial variation in radiation and snow packs. These concerns are not addressed in the present paper.

4. CONCLUSION

In this study, significant efforts have been made to investigate snow process simulation via modifying and improving two empirical models, and comparing eight models as a whole in Ontario, Canada. The original daily WINTER model, once used in the Dorset area, was modified slightly in its melt formulation and recalibrated using 5 years of data from a forested site, and the modification increased its performance (CE) by 20.7%. The ETI model as proposed by previous researchers was applied to the same study sites with minor modification, and its performance is 27.6% higher than the original WINTER model. A new combination model of the modified WINTER and ETI models produced additional improvement by 40.7 % over the original WINTER, or by 16.5% over the new WINTER or 10.3% over the ETI. Running the model with hourly time steps rather than daily steps increased model's accuracy: hourly WINTER raised CE by 15.4% and hourly ETI raised CE by 7.9%. Furthermore, two typical watershed hydrology models BROOK90 and SWAT performed even better than the above six simpler snowmelt models. A performance ranking of the eight models was set up: BROOK90, SWAT, Combi, W_hour, ETI_hour, ETI, Wmod_new, and Wmod_old. It is suggested that the daily combination model Combi be considered if only daily data is available, or the hourly WINTER and ETI models be used if hourly runs are desired while new calibration are required when applying them to any new locations. If data requirements by BROOK90 or SWAT are met and heavier calibration is not concerned, these two hydrology models would be tried. Future researches may include more experimental sites and utilization of remote sensing data to support these comparisons. The SWE information has been provided to local resources and environmental management agency, and will be useful to regional management work.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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