AN IMPROVED TEMPERATURE-INDEX SNOWMELT MODEL ON A WATERSHED SCALE USING AN HOURLY TIME STEP FOR REAL-TIME FLOOD FORECASTING IN BRITISH COLUMBIA, CANADA

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ABSTRACT

One of the important indicators of a good real-time flood forecasting system is its time efficiency or the ability to produce timely forecasts. The majority of watersheds in British Columbia, Canada are large-scale snowmelt-dominated watersheds. Therefore, a simple but efficient snowmelt model helps improve time-efficiency of the real-time flood forecasting system. The temperature-index snowmelt model is one of this kind. However, it is more accurate when applied on a forest stand scale rather than on a watershed scale, and its time step is usually one day. The real-time flood forecasting system in British Columbia is the CLEVER Model, in which a watershed is simplified into a single node, and which adopts an hourly time step. In this study, the commonly used equation of temperature-index snowmelt model was improved and adapted to the application on a watershed scale using an hourly time step so that relative high forecasting accuracy and time efficiency were both achieved in the CLEVER Model. (KEYWORDS: time-index method, snowmelt model, real-time flood forecasting, watershed model.)

INTRODUCTION

Most watersheds in British Columbia (BC), Canada are large-scale snowmelt-dominated watersheds located in the interior. These watersheds present significant heterogeneity, which poses great challenges to real-time flood forecasting with respect to forecasting accuracy and time efficiency. In order to address these challenges, the Channel Links Evolution Efficient Routing (CLEVER) Model (Luo, 2015) was developed in the BC River Forecast Centre in 2013 and put into operational functioning for real-time flood forecasting in BC as of 2015. The CLEVER model is a hybrid watershed model including a lumped and conceptual watershed routing sub-model and a fully distributed, physics-based open channel routing sub-model. In the CLEVER Model, a large-scale watershed is split into several relatively homogeneous sub-basins that are further simplified into individual nodes, which are connected with a series of open channels or channel links. In the open channel routing sub-model, an improved kinematic wave scheme is adopted so that it is more efficient for routing the wide-tooth-comb-wave hydrographs observed in the highly regulated Peace River, allowing the model to use larger temporal and spatial increments so that relative high accuracy and time efficiency are both achieved (Luo, 2021). The upstream boundary conditions for the open channel routing sub-model are discharges from the output of the lumped watershed routing sub-model, which are derived from the instantaneous unit hydrograph (IUH). Snowmelt is the major net water input to the IUH for watersheds in BC interior during the freshet snowmelt season. Consequently, snowmelt simulation is one of the most important components in the watershed routing sub-model of the CLEVER Model.

Theoretically, the physics-based energy balance approach may be the best method for snowmelt modeling. However, the extensive requirements of parameters and data for the energy balance model are sometimes overwhelming. Moreover, it was found that very localized climate factors, such as humidity, wind speed, vegetation cover and canopy effects, must be accounted for in detail so that the energy balance model simulates snowmelt correctly (Marks et al., 1999). From this perspective, the energy balance approach is more accurate for snowmelt models which are on a forest stand scale or applied to very small and homogeneous basins. The UBC Watershed Model presented a simplified energy balance method for daily snowmelt simulation for elevation bands in a watershed (Quick and Pipes, 1977). The model is driven by daily maximum and minimum temperatures only. This is an efficient method for snowmelt modeling if it is applied to the lumped watershed models with elevation bands but may not be applicable to other types of lumped watershed models. Because the air temperature data is much easier to obtain though measurements and forecasts, it is more practical for most operational forecasting systems that do not involve elevation bands to employ the temperature-index method to simulate snowmelt. It has been found that snowmelt estimated by the temperature-index method is comparable with that calculated by the energy balance method (Gray and Prowse, 1992). In the coming sections, the common form of the temperature-index equation is

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given, improvements and reasons in this study are explained, and applications of the improve snowmelt model to four watersheds in the Middle Fraser River are presented.

DERIVING IMPROVED TEMPERATURE-INDEX MODEL

The most common expression of the temperature-index snowmelt equation proposed by Gray and Prowse (1992) can written as below:

$$M = M_f(T_i - T_b) \tag{1}$$

where M is the snowmelt in a time step, M_f is the melt factor, T_i is the air temperature at time step i and T_b is the base temperature, at which snow starts to melt. The unit for temperatures is degree Celsius (°C). In most studies, the time step is one day, and the air temperature T_i is the mean daily temperature. Therefore, this expression is also referred to as the Degree Day method, with M in mm/day and M_f in mm/day-°C.

In the SWAT model (Neitsch et al., 2009), T_i is defined as the average of the daily maximum air temperature and the snowpack temperature. Meanwhile, the SWAT model substitutes the single and constant melt factor M_f with two parameters, the fraction of basin area covered by snow, and a melt factor which is a sine function of the ordinal day in a year with the maximum on June 21 and minimum on December 21.

In this study, Equation (1) at an hourly time step was first employed in the CLEVER Model to simulate snowmelt on a watershed scale. It was immediately noticed that the melt factor is not constant with the ordinal day over a year. Therefore, Equation (1) was first improved according to the SWAT model as below:

$$M = c_a c_d M_f(T_i - T_b) \tag{2}$$

where M is the snowmelt in an hour (mm/h), c_a is a correction factor related to the snowpack covering area during the receding period, c_d is the correction factor related to the ordinal day in a year. Both c_a and c_d are smaller than or equal to 1 but greater than 0.

After testing Equation (2) in a series of watersheds in BC, it was found that the maximum value of c_d may not necessarily occur on June 21 due to differences of localized climate conditions including vegetation, human disturbances (wildfires) and climate change impacts. Based on the author's experience in snowmelt simulation in BC watersheds, this study adopts a flexible day for the maximum c_d, which could be any day after April 1 and June 31, and which is subject to calibration. After the day of the maximum c_d, the value of c_d is maintained constant in the model until all the current year's ripe snow has melted. Theoretically, the day of the minimum c_d may also be flexible and should be the first day when the watershed receives the first snowfall (new snow) of the year. However, for simplicity, the day of the minimum c_d in this study is set to October 1 after noticing the facts that most current year's snowpack in most BC watersheds has melted by the end of September and some watersheds in BC interior start seeing new snow in October. It was also found that the small value of c_d since the new snow of the year are almost constant until next March 1. Consequently, c_d is a multi-segmental linear function of the day in a year. Figure 1 shows the c_d for four sub-basins in the Middle Fraser River watershed, BAKR-Baker Creek (A=1567 km^2), SJBC-San Joes River (A=2180 km^2), WSRD-West Road River (A=12,432 km^2), and NAZK-Nazko River (A=3207 km^2). The NAZK is a sub-basin of the WSRD. For these four

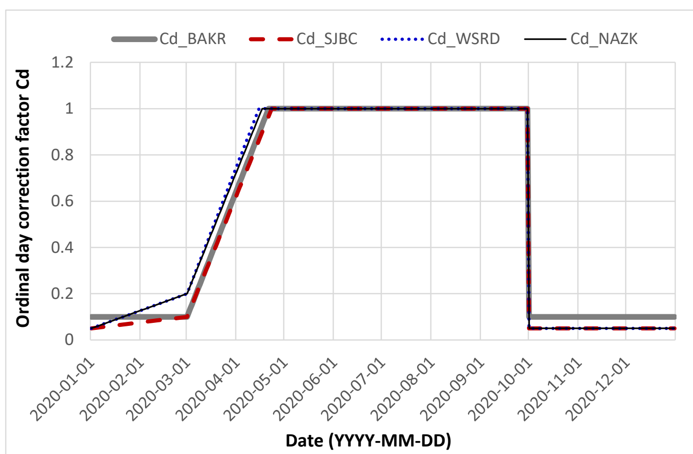


Figure 1. Ordinal day correction factor c_d for three sub-basins in Middle Fraser River

specific watersheds, the dates of the maximum c_d are different in 2020, which are Aril 21, Aril 23, April 15, and April 17, 2020, respectively. These dates were determined during the model calibration and are subject to further calibration in future years.

There are no data of snow cover in BC watersheds available in this study, and thus the effects of the snowpack covering area over a watershed during the snow accumulation period is incorporated in the melt factor M_f, which is subject to calibration. The snow covering correction factor during the snowpack receding period is given by:

$$c_a = \left(\frac{SWE_i}{SWE_{max}}\right)^{\alpha} \tag{3}$$

where SWE_i is the snow water equivalent (SWE) at time step i, SWE_{max} is the maximum SWE up to the current modeling day, and α is the snowpack covering area receding power, which is smaller than or equal to 1 and subject to calibration.

When Equations (1) and (3) were applied to the watershed routing sub-model, it was found that the snowmelt was not simulated correctly, especially when air temperatures were rising significantly in a short time. Under such circumstances, the rising slope of the simulated hydrograph was flatted than that of the observed for some watersheds and steeper for some others. This implies that the relationship between the snowmelt and the air temperature may not necessarily be linear in this study.

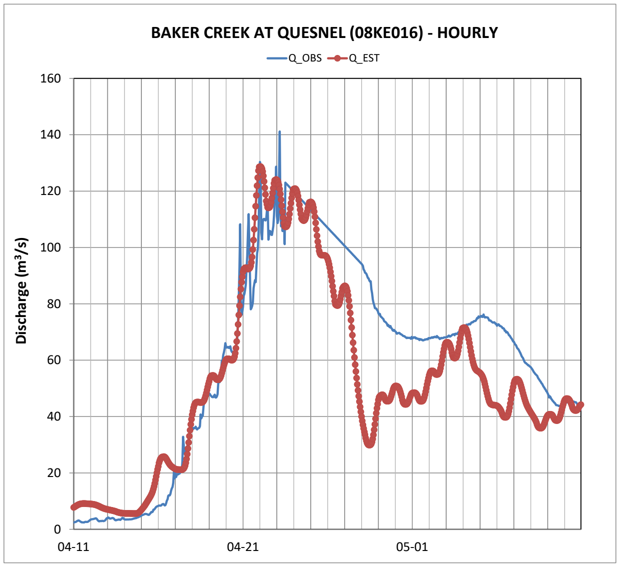
The long wave radiation is the important energy for snowmelt especially for vegetation covered watersheds and its relationship with the temperature is nonlinear (linear with the 4th power of the surface temperature). Moreover, as Gray and Prowse (1992) pointed out that air temperatures usually lag and attenuate short-term variations in net radiation in the daytime. The above and the hourly time step in this study may result in a flatter rising slope in the simulated hydrograph (underestimated). On the other hand, when air temperatures rise significantly and rapidly, the snowpack may not have enough time to produce such a large amount of melt in an hour as Equation (2) estimated. Meanwhile, rapid rising of air temperatures in the daytime means rapid increasing of incident short wave radiation. Under the circumstances, a large portion of radiation may be absorbed by vegetation for photosynthesis in a vegetation covered watershed. These may result in a steeper slope in the simulated hydrograph (overestimated). Based on the above reasoning, Equation (2) is revised as:

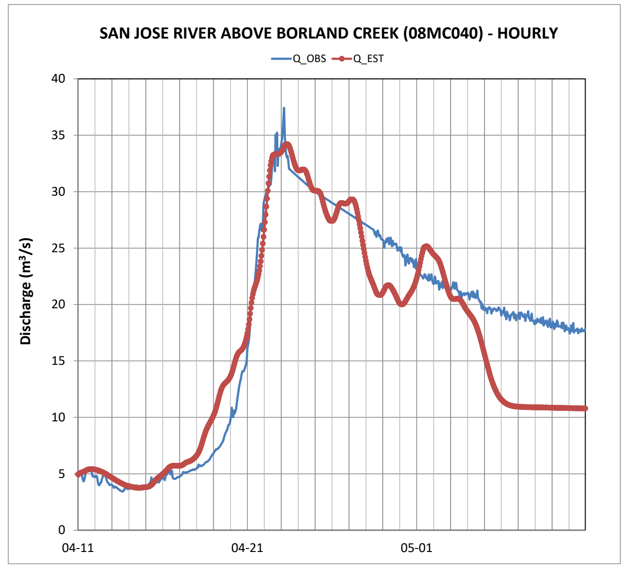
$$M = c_a c_d M_f (T_i - T_b)^{\beta} \tag{4}$$

where β is the temperature power and may be smaller than, equal to or greater than 1, which is determined through model calibration. When $\beta = 1$, Equation (4) reduces to Equation (2). This is the improved temperature-index snowmelt model for the watershed routing sub-model in the CLEVER Model.

APPLICATION

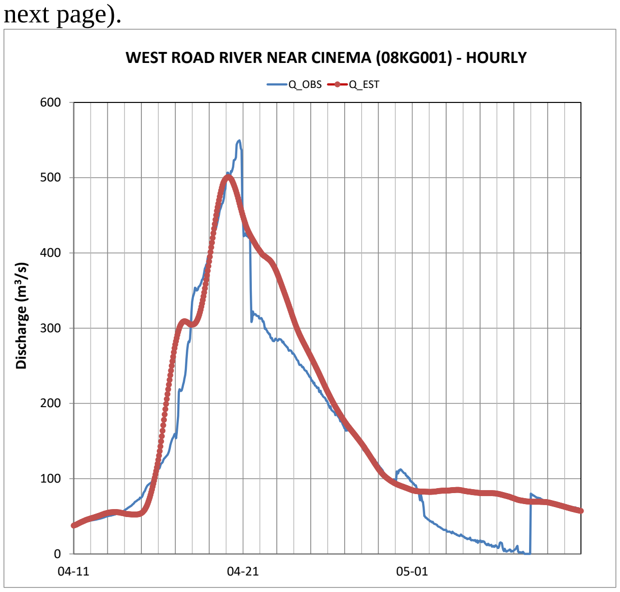
Equation (4) is applied to all the watersheds across BC which are modeled in the CLEVER Model. Air temperatures in the Middle Fraser River basin increased significantly from about 0 °C on April 1 to about 20 °C on April 20, 2020, while precipitation was almost 0 during this period. This provided an opportunity to verify the applicability of Equation (4). Figure 2 shows the best calibrated snowmelt hydrographs comparing with the observed discharges in 4 watersheds in the Middle Fraser River (BAKR, SJBC, WSRD and NAZK) during this high temperature event in April 2020. The gauge for NAZK was inactive and the observed discharges were estimated from the data for WSRD. All the observed discharges were provisional. In the simulation of Figure (2), the melt factor M_f, snowpack covering area receding power (α) and the temperature power (β) for the four watersheds are 0.33, 0.3, 0.9 for BAKR, 0.1, 0.3, 1.1 for SJBC, and 0.35, 0.5, 0.75 for both WSRD and NAZK, respectively.

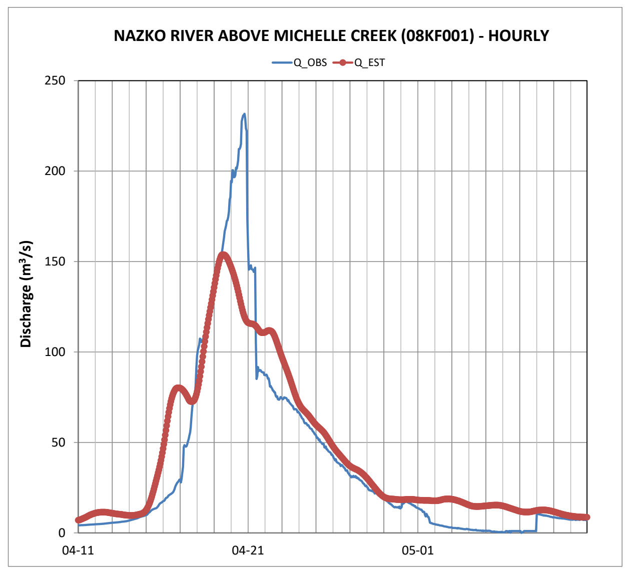




(a) BAKR: $M_f = 0.33, \alpha = 0.3, \beta = 0.9$ (b) SJBC: $M_f = 0.1, \alpha = 0.3, \beta = 1.1$

Figure 2. Best calibrated snowmelt hydrographs for four watersheds: BAKR, SJBC, WSRD and NAZK (continued next page).





(c) WSRD: $M_f = 0.35, \alpha = 0.5, \beta = 0.75$ (c) NAZK: $M_f = 0.35, \alpha = 0.5, \beta = 0.75$

Figure 2. Best calibrated snowmelt hydrographs for four watersheds: BAKR, SJBC, WSRD and NAZK.

CONCLUSIONS

From the above analysis, it can be concluded that (i) the common expression of the temperature-index equation requires modification for applications on a watershed scale using an hourly time step, (ii) the maximum melt factor may not necessarily occur on June 21, and (iii) the improved temperature-index snowmelt model presented in this study is more appropriate for the CLEVER Model – the real-time flood forecasting system in BC.

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