RAIN-ON-SNOW MELT AND GLACIER MELT IN CLEVER MODEL

Charles Luo, BC River Forecast Centre, January 2023

Revised March 12, 2024

1. Excerpt from Technical Reference for CLEVER Model

The following paragraphs are excerpted from the Technical Reference for The CLEVER Model – A Real-time Flood Forecasting Model for British Columbia (Luo, 2015)
(External link: http://bcrfc.env.gov.bc.ca/freshet/cleverm_ref/CLEVER_TechRef.pdf. Internal link G:\2MODELS\CLEVER_MODEL\0Documents\CLEVER_TechRef.pdf), pages 16-18:

As discussed in Section 3.1, in this study, a watershed is divided into a number of subcatchments, which are further simplified into a series of individual nodes. The water balance of each subcatchment is calculated as a single node. The water balance equation is given by:

$$W = R + M + G - E - I \tag{18}$$

in which W (≥0) is the net water input to the subcatchment and has the unit of mm/hour, and this unit is used for all the terms on the right-hand side of the equation as this study employs an hourly time step, R is the rainfall, M is the snowmelt, G is the groundwater seepage to the system or the channel link which connects this subcatchment to the downstream flow gauge station, E is the evapotranspiration, and I is the infiltration to the unsaturated soil and the recharge to the groundwater.

As most watersheds in BC are snow-dominated, simulating snowmelt with acceptable accuracy becomes critical for real-time flood forecasting during the snowmelt freshet season. Though the energy balance method provides a physics-based estimation of snowmelt, its extensive data requirements always frustrate its practice, and therefore, operational systems for snowmelt prediction take the temperature-index method as a substitution (Gray and Prowse, 1992). Besides the temperature-index method, the UBC Watershed Model provides a method to simulate daily snowmelt by dividing a subcatchment into several elevation bands and using the simplified energy balance method, which is driven by daily maximum and minimum temperatures, to simulate snowmelt in each of the elevation bands (Quick and Pipes, 1977). The SWAT model (Arnold et al., 1998) proposed a temperature-index method to estimate the daily snowmelt by relating the snowmelt rate to the mean daily temperature and the snowpack temperature. Debele et al. (2009) employed one of the most commonly used temperature-index methods to estimate the daily snowmelt – the sinusoidal equation, which assumes that the potential daily snowmelt rate varies between two ranges: the maximum (assumed to occur on June 21st) and the minimum (assumed to occur on December 21st) following the sinusoidal function based on the day of the year. Debele et al. (2009)

found that it is possible for the less detailed temperature-index equations to perform as equal, or sometimes even better, as the energy budget approach. Both these two temperature-index methods and other temperature-index equations depend on the mean daily temperatures to estimate the snowmelt rate.

However, this study adopts an hourly time step and therefore hourly, rather than daily, snowmelt must be estimated. Simple disaggregation of the daily snowmelt rate to the hourly rate is not working because that the existing temperature-index methods rely on the mean daily temperatures. Consequently, in order to use the temperature-index method to estimate hourly snowmelt on a subcatchment scale, an equation dependent on the hourly temperature rather than on the mean daily temperature becomes necessary. The most common expression of the temperature-index method proposed by Gray and Prowse (1992) is used as the basic form of the hourly snowmelt equation:

$$M = M_f(T_i - T_b) \quad (19)$$

where M is the snowmelt in an hour (mm/hour), M_f is the melt factor, T_i is the air temperature at the time step (hour) and T_b is the base temperature, at which snow starts to melt.

A test run of Eq. (19) in a smaller subcatchment with an hourly time step was carried out. The results showed that this equation did not sufficiently accurately estimate snowmelt. In order to obtain better estimations of snowmelt on a subcatchment scale with an hourly time step, modifications to Eq. (19) were made. In this study, the following transformation of Eq. (19) is employed to simulate the snowmelt on a subcatchment scale with an hourly time step:

$$M = c_a c_d M_f(T_i - T_b)^{\beta} \quad (20)$$

where c_a is a correction factor related to the snowpack covering area over the subcatchment, c_d is the correction factor related to the ordinal date in the year, and β has a value between 0 and 1. The snowpack covering area correction facto (c_a) is calculated every time step (hour) by comparing the snowpack area with the subcatchment area. The ordinal date correction factor (c_d) is a linear function of the ordinal date which defines the maximum and minimum snowmelt rates of the year. And c_a and c_d are subject to calibration. And β is a constant related to the size of the subcatchment and also subject to calibration. Note that Eq. (20) reduces to Eq. (19) when c_a, c_d and β are equal to 1.

2. Excerpt from Western Snow Conference 2021 paper

The following paragraphs are excerpted from the Western Snow Conference 2021 paper (Luo, 2021), An Improved Temperature-Index Snowmelt Model on A Watershed Scale Using an Hourly Time Step for Real-Time Flood Forecasting in British Columbia, Canada (External link: http://bcrfc.env.gov.bc.ca/freshet/cleverm_ref/Luo_WSC2021_2021Luo.pdf page 100-101. Internal link: G:\2MODELS\CLEVER_MODEL\2Conferences\WesternSnowC2021\Luo_WSC2021.pdf, Pages 2-3):

There is 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:

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

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:

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

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.

3. Revising calculation of ordinal date correction factor

In the above document (Luo, 2021), a method of conceptual calculation of the ordinal date correction factor (c_d) was also provided. However, in the 2023 version of CLEVER Model, this method has been revised Figure 1 below.

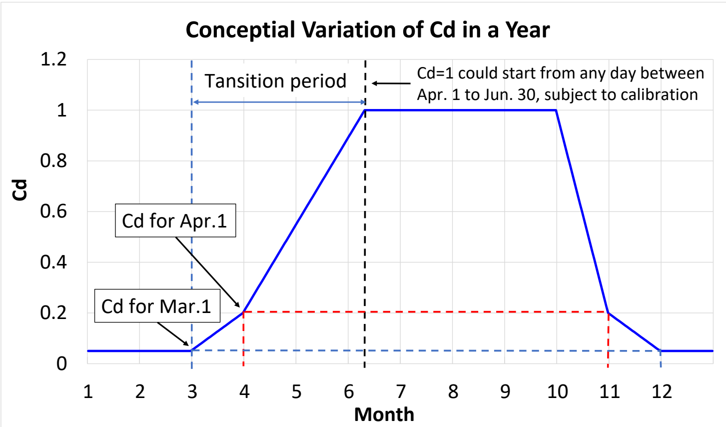

Figure 1. Conceptual variation of Cd in a year.

4. Simulating rain-on-snow (ROS) melt:

When rain-on-snow event is occurring, Equation (20) in Luo (2015), or Equation (4) in Luo (2021), is modified as

$$M = (c_a c_d M_f + \gamma R)(T_i - T_b)^{\beta} \tag{20A}$$

where *R* is the hourly rainfall, and γ is the rain-on-snow melt factor, which is subject to calibration. When $\gamma = 0$ or $R = 0$, Equation (21A) reduces to Equation (20).

5. Glacier melt:

Glacier melt sets off only after the snowpack covers have gone. However, on a watershed scale in the CLEVER Model, when SWE < 20% of the maximum SWE, the glacier melt starts and is given by the following equation:

$$M_g = c_g c_d M_f (T_i - T_b)^{\beta} \tag{20B}$$

where M_g is the glacier melt, c_g is a correction factor related to glacier coverage in the watershed, which is subject to calibration, and is different from c_a (the correction factor related to the snowpack covering area).

References:

Gray, D.M., Prowse, T.D. 1992. Chapter 7 Snow and Floating ice, in: Maidment, D.R. (Ed.), Handbook of Hydrology, McGraw-Hill Inc., pp. 7.1-7.58.

Luo, C. 2015. Technical Reference for the CLEVER Model – A Real-time Flood Forecasting Model for British Columbia. BC River Forecast Centre, Victoria, Canada: http://bcrfc.env.gov.bc.ca/freshet/cleverm_ref.html.

Luo, C., 2021. An improved temperature-index snowmelt model on a watershed scale using an hourly time step for real-time flood forecasting in British Columbia, Canada. Proceedings of Western Snow Conference 2021, Webex virtual meeting, April 14, 2021, p99-103. http://bcrfc.env.gov.bc.ca/freshet/cleverm_ref/Luo_WSC2021_2021Luo.pdf

References for rain-on-snow melt:

Anderson, Eric 2006. Snow Accumulation and Ablation Model – SNOW-17, US National Weather Service. https://www.weather.gov/media/owp/oh/hrl/docs/22snow17.pdf (accessed Jan. 18, 2023).

References for glacier melt:

Hock, Regine, Glacier melt: a review of processes and their modelling. Progress in Physical Geography 29, 3 (2005) pp. 362–391

Saelthun, N.R., 1996. The "Nordic" HBV model, Description and documentation of the model version developed for the project Climate Change and Energy Production. Hydrology Department, NVE Norwegian Water Resources and Energy Administration, Publication No. 7, July 1996.