Evaluation of the CLEVER Model – A Real-time Flood Forecast Model for Large-Scale Watersheds in British Columbia

Charles Luo, Tobi Gardner*, and David Campbell
River Forecast Centre, BC Ministry of Forests, Lands and Natural Resource Operations
3rd Floor, 395 Waterfront Crescent, Victoria, BC V8T 5K7, Canada.
*Corresponding and presenting author. Tel.: +1-250-356-0312; fax: +1-250-356-0605
E-mail address: Tobi.Gardner@gov.bc.ca

Abstract: There are inherent difficulties in flood forecasting in British Columbia, in part, due to the immense geologic and geomorphological variety and the heterogeneity of the snow-dominated watersheds. The range of watershed characteristics, the massive scale of the catchments, and the varied nature of the hydro-meteorological conditions that result in floods, render flood forecasting for short- to intermediate-term particularly difficult. The Channel Links Evolution Efficient Routing Model was developed for the purpose of real-time flood forecasting in B.C. In the model, a spatially large, heterogeneous watershed is divided into a number of relatively homogeneous sub-catchments which are connected through channel links. The model is a hybrid model that consists of a lumped watershed routing sub-model and a one-dimensional distributed open-channel routing sub-model. The lumped watershed routing sub-model routes a sub-catchment as a single node. The water balance of each node is calculated using input precipitation, evapotranspiration, snowmelt, infiltration, and groundwater flows and the excess water is the input to the unit hydrograph for each sub-catchment. The output hydrographs from the watershed routing sub-model are input (upstream boundary conditions) to the distributed open channel routing sub-model, which routes the channel links with an innovated, efficient numerical scheme for the kinematic wave approximation of the Saint-Venant equations. In this paper, the model is evaluated in detail and the results demonstrate that the model is applicable to and practical for real-time flood forecasting in the large-scale watersheds in British Columbia with reasonable accuracy.

Introduction

British Columbia (BC) has seven major watersheds, the Fraser River, the Columbia River (an international river), the Skeena River, the Nass River, the Stikine River, the Liard River (an interprovincial river), and the Peace River (an interprovincial river) (Fig. 1). The total drainage area of these seven watersheds excluding those parts outside BC is 726,986 km^2 (77% of the province land area) and the total length of rivers and their tributaries inside BC is

42,150 km. BC's watersheds are primarily snow-dominated and characterized by their large scale. Large-scale watersheds tend to exhibit great heterogeneity and variability not only spatially but also temporally (Luo, 2000). The heterogeneity of a watershed is mainly from four sources: climate, topography, geology and land uses (Singh, 2012). Besides heterogeneity, the second issue that a real-time flood forecast model for BC's watersheds has to tackle is the model efficiency. This means operationally that the model must be able to complete a run in a very short time, e.g., several minutes, in order to provide timely flood warnings. For this purpose, a hybrid watershed model, the Channel Links Evolution Efficient Routing (CLEVER) Model was developed in this study. A hybrid model is a semi-distributed watershed model, in which distributed and lumped models are linked to each other (Aral and Gunduz, 2006). The model was developed in 2013 and has been tested and improved over the past three years. In this paper, the methodology is briefly reviewed and the model performance is discussed in detail.

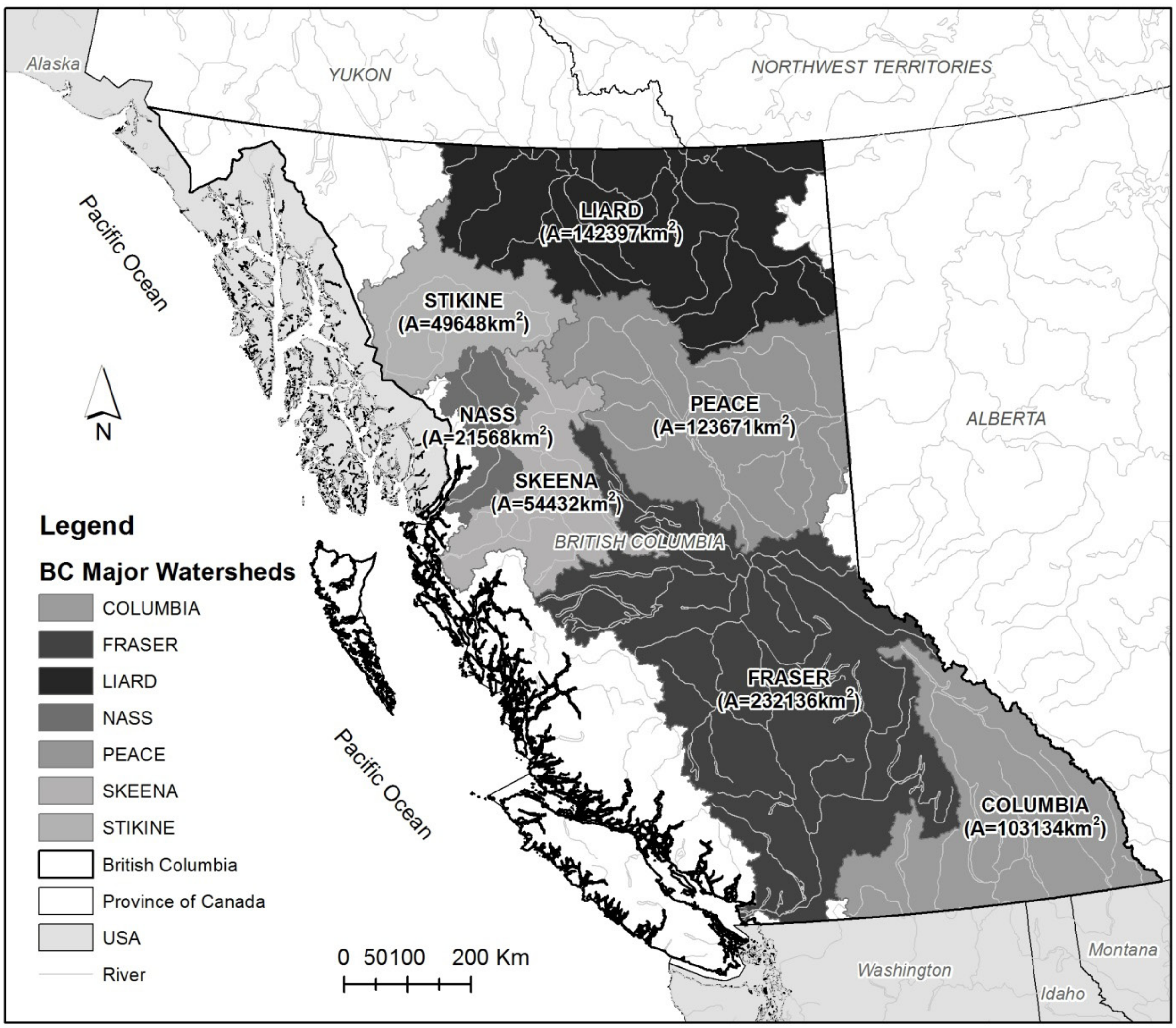

Figure 1. Seven major watersheds in British Columbia.

Methodology

In this study, in order to address the watershed heterogeneity as much as possible, a huge-scale watershed is first split into a number of relatively homogenous sub-catchments which are further simplified into individual nodes that are located in the center of the sub-catchments. A sub-catchment is consequently treated as a single node and the water balance in the hydrologic cycle is calculated and then routed with the unit hydrograph. A channel link is created to connect the sub-catchment nodes. The outlet of a sub-catchment is also the location of the flow gauge station that provides discharge data for model calibration. Figure 2 shows the process of watershed simplification and the model structure.

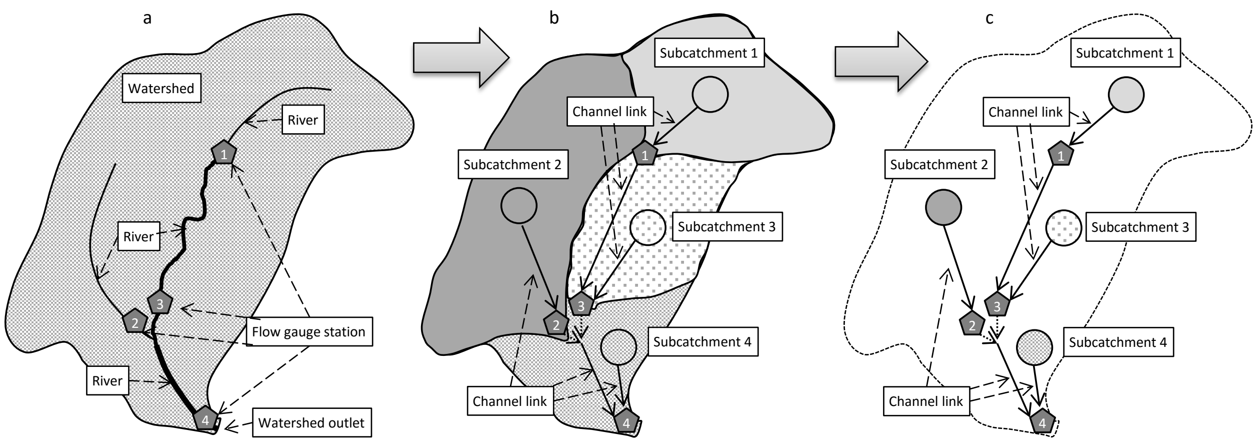

Figure 2. Process of watershed simplification and model structure.

In this study, the kinematic wave simplification of the Saint-Venant Equations is employed to govern the open channel flow in this study:

$$\begin{cases} \frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \\ S_0 = \frac{n^2 Q^2}{A^2 R^{4/3}} \end{cases} \tag{1}$$

in which Q is the flow, x and t are the spatial and temporal coordinates respectively, A is the section area, S_0 is the friction slope, n is the Manning roughness coefficient, and R is the hydraulic radius and is given by $R = A/P$ where P is the wet perimeter.

Using the forward-difference approximation for the first term and the spatial averaged forward-difference approximation for the second term of the continuity equation and discretizing and rearranging the momentum equation in Eq. (1) gives:

$$A_{i,j} = \frac{2\Delta t Q_{i-1,j} - \Delta x\left(A_{i-1,j} - A_{i,j-1} - A_{i-1,j-1}\right)}{2\Delta t V_{i,j} + \Delta x} \tag{2}$$

in which i and j denote the spatial and temporal points on the coordinates respectively, (i, j) is the unknown node, Δx and Δt are the spatial and temporal steps, and $V_{i,j}$ is given by:

$$V_{i,j} = \frac{1}{n}\sqrt{S_0} R_{i,j}^{2/3} \tag{3}$$

An efficient numerical scheme similar to the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) (Patankar and Spalding, 1972) is introduced to solve Eq. (2) iteratively. Pressure is a concept in fluid dynamics and the relevant concept in hydrology is water head or water depth (Luo, 2007). If k-1 and k are used to denote the previous and the current iteration steps, the general form of the iteration equation for Eq. 2 becomes:

$$\left(A_{i,j}\right)^{(k)} = \frac{2\Delta t Q_{i-1,j} + \Delta x\left(A_{i,j-1} - A_{i-1.j} + A_{i-1,j-1}\right)}{2\Delta t\left(V_{i,j}\right)^{(k-1)} + \Delta x} \quad (4)$$

By using Eq. (4) to route the open channel flow, the spatial step can be set as large as 20 km based on testing of various step lengths during model development.

The water balance of each sub-catchment is given by:

$$W = R + M + G - E - I \quad (5)$$

in which W (≥0) is the net water input to the sub-catchment and has the unit of mm/hour, and this unit is used for all the terms on the right 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 sub-catchment 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.

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:

$$M = M_f(T_i - T_b) \quad (6)$$

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.

Assuming that the sub-catchment consists of a cascade of N linear reservoirs, the Instantaneous Unit Hydrograph is given by:

$$u(\tau) = \frac{t^{N-1}e^{-\tau/k}}{k^N(N-1)!} \quad (7)$$

in which u is the unit response to the impulse, τ is the lag time, and k is the storage coefficient.

Model Evaluation

Input Data

Across BC's watersheds there are more than 300 Water Survey of Canada (WSC) real-time hydrometric stations which record real-time water levels and/or discharges of the rivers and creeks, approximately 250 Environment Canada (EC) climate stations, approximately 220 BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO) fire weather stations and 50 automated snow pillows (ASP) which record precipitation, temperature and other climate data. The Meteorological Service of Canada provides 10-day forecast climate data from the Canadian Meteorological Centre (CMC) Numerical Weather Prediction (NWP) Models on local and global scales. These hydrometric, climate and NWP data facilitate the real-time flood forecast modeling over the province by providing input and calibration data.

Model Operation

For modeling efficiency in computing time, the modeling period is set to 30 days, which means that the model only runs a 30-day period, the first 20 days for the model calibration and the last 10 days for the forecast. This does not mean that the model can only produce a 30-day hydrograph but rather means that the model parameters are maintained constant for a time span of 30 days. The 10-day forecast hydrograph starts from the latest hour of the current day, at which the provisional observation flow data has arrived. It is usually difficult to perfectly match the simulated and observed flows at a specific point of time through model calibration. In order to generate the 10-day forecast hydrograph which starts from the latest observed flow (i.e., the first forecast flow is equal to the observed flow), the simulated hydrograph is shifted by a constant increment which is the simulation bias at this time point. For the regulated sub-catchments, the 10-day forecast hydrograph is generated by extending the trend of the observed daily flow of the 19th and 20th days.

Evaluation of Model Calibration

The model was first developed in 2013 for the Fraser River watershed in BC. It has been tested intensively and improved substantially over the past three years. At the current stage (2015) of this study, the modeled area has been expanded from the Fraser River to a total of 71 sub-catchments which are distributed over all the seven major watersheds in BC and cover an area of 583,400 km^2, or 61.5% of the province's land area (Fig. 3). Evaluation of the model calibration was primarily carried out visually during the real-time forecasting season and statistically later by using the coefficient of model efficiency (C_e), the coefficient of determination (C_d) and the percentage volume difference (dV) (Nash and Sutcliffe, 1970). The closer the values of C_e and C_d are to 1 and the value of dV to 0%, the more successful the model is calibrated.

Table 1 and Figure 4 show the statistics for C_e, C_d and dV of the model calibration for the 71 stations or sub-catchments.

Table 1. Statistics of model calibration for the total 71 stations (2015).

Calibration	C_e		C_d		$\|dV\|$		
	Count	%	Count	%	Calibration	Count	%
0.95~1.00	17	24	18	25	<=1%	19	27
0.90~0.95	13	18	14	20	5%~1%	29	41
0.85~0.90	9	13	9	13	10%~5%	13	18
0.80~0.85	9	13	10	14	15%~10%	6	8
Subtotal	48	67.6056	51	72	Subtotal	67	94
0.70~0.80	8	11	8	11	20%~15%	2	3
0.60~0.70	6	8	5	7	25%~20%	1	1
0.50~0.60	2	3	3	4	30%~25%	1	1
<0.50	7	10	4	6	>30%	0	0
Subtotal	23	32.3944	20	28	Subtotal	4	6
Total	71	100	71	100	Total	71	100

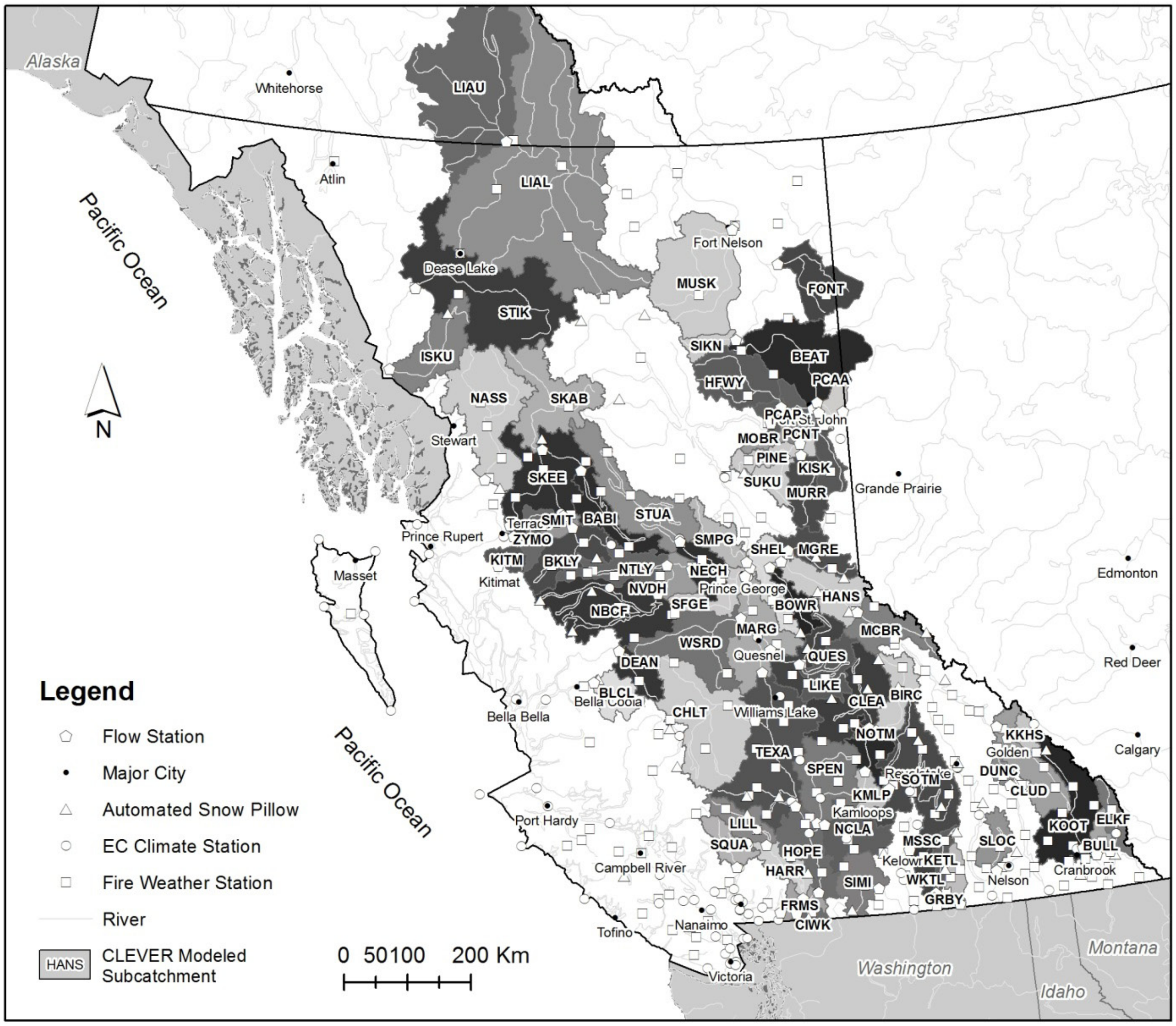

Figure 3. Seventy-one (71) sub-catchments currently covered by the model.

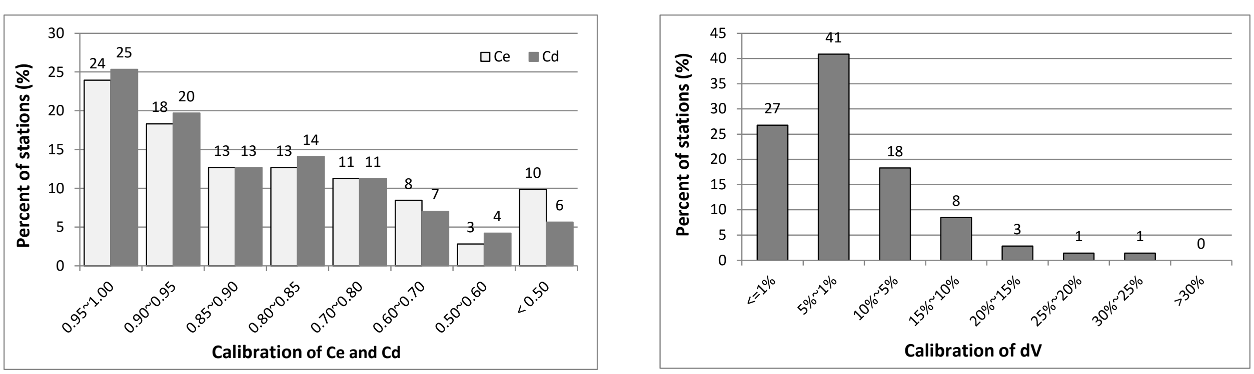

Figure 4. Model calibration statistics for C_e, C_d and dV at 71 stations.

It can be seen Table 1 and Figure 4 that, for the total 71 stations, 68% or 48 stations have a value of C_e greater than or equal to 0.8, 72% or 51 stations have a value of C_d greater than or equal to 0.8 and 94% or 67 stations have a value of dV smaller or equal to 15%. These statistical results demonstrate that the model was well calibrated at most of the stations. Figure 5 shows the calibration result for the WSC station Fraser at Hope (08MF005). It can be seen that the observed and simulated hydrographs agree well.

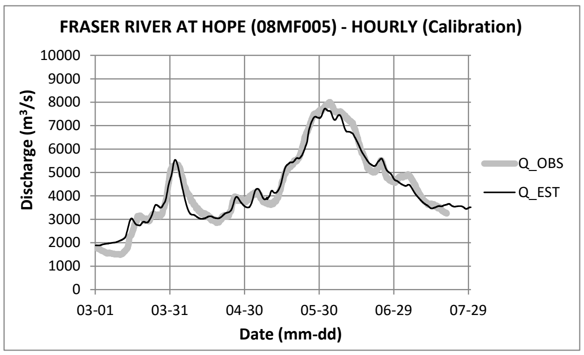

Figure 5. Model calibration for Fraser at Hope (08MF005).

Table 2 shows the model calibration at the 13 key stations over the 7 major watersheds in BC. The model was well calibrated in most of the watersheds except the Peace River especially at the station of Peace River above Alces River (07FD010). The main reason is that the number of climate stations located in this watershed is fewer than in other watersheds across the province and therefore the representativeness of the climate stations is lower. The other reason may be the errors in provisional observed flow data. The under-estimation of water volume at Stikine River at Telegraph Creek (08CE001) is also likely the result of fewer climate stations located in the watershed. In the Fraser basin, the overall calibration is good. However, the lower calibration accuracy at Fraser River at Shelley (08KB001) is probably due to the representativeness of the climate stations and errors in the provisional observed flow data during the early spring.

Table 2. Model calibrations at 13 selected key stations (2015).

Watershed	Station Name and ID	C_e	C_d	dV (%)
Fraser	Fraser River at Shelley (08KB001)	0.86	0.88	-6.1
	Quesnel River near Quesnel (08KH006)	0.97	0.97	-2.4
	Thompson River near Spences Bridge (08LF051)	0.97	0.98	2.7
	Fraser River at Hope (08MF005)	0.97	0.97	-0.2
Columbia	Columbia River at Donald (08NB005)	0.96	0.96	1.1
	Kootenay River at Fort Steele (08NG065)	0.93	0.94	-1.1
Skeena	Bulkley River at Quick (08EE004)	0.96	0.97	-0.8
	Skeena River at Usk (08EF001)	0.97	0.97	-1.7
Nass	Nass River above Shumal Creek (08DB001)	0.93	0.95	3.0
Stikine	Stikine River at Telegraph Creek (08CE001)	0.93	0.95	-7.8
Liard	Liard River at Lower Crossing (10BE001)	0.96	0.96	0.7
Peace	Pine River at East Pine (07FB001)	0.81	0.82	2.0
	Peace River above Alces River (07FD010)	0.62	0.81	14.7

The above modeling calibration results were obtained from 2015, when the provisional instantaneous peak flow recorded at the WSC station Fraser River at Hope (08MF005) was 8119 m^3/s (at 2015-06-03 9:55am), a two-year return period flow. In 2012, the instantaneous peak flow recorded at the same station was 11,900 m^3/s (at 2012-06-22 9:51am) and reflects a relatively high water year. The climate data for the Fraser River watershed are available for 2012 and so the model was run for the four key Fraser River sub-catchments (as shown in Table 2) for that year to verify the model calibration. The verification results are given in Table 3, which demonstrates that the model can also be well calibrated at all the four stations during the high water year (2012).

Table 3. Model verification in the Fraser in a high water year (2012).

Watershed	Station Name and ID	C_e	C_d	dV (%)
Fraser	Fraser River at Shelley (08KB001)	0.96	0.96	0.6
	Quesnel River near Quesnel (08KH006)	0.97	0.98	0.7
	Thompson River near Spences Bridge (08LF051)	0.99	0.99	0.5
	Fraser River at Hope (08MF005)	0.98	0.99	-1.3

Evaluation of Model Forecast

The accuracy of the 10-day forecast flows was evaluated statistically after the forecast and only when all of the observed flow data had become available by using the relative mean absolute error (E_{ra}) and the square of the Pearson product moment correlation coefficient between the forecast and observed flows – r squared (r^2). The closer the value of E_{ra} is to 0% and the value of r^2 is to 1, the better the forecast is.

Table 4 shows the E_{ra} and r^2 statistics of the 10-day forecasts for the total 71 stations or sub-catchments over the entire evaluation period (March 1 to July 20, 2015) and the period of peak flows (May 11 to June 11, 2015). It can be seen from Table 5 that the majority (75% or 53 stations over the entire evaluation period, March 1 to July 20, 2015, and 72% or 51 stations over the peak period, May 11 to June 11, 2015) of the 71 stations have a relative mean absolute error (E_{ra}) smaller or equal to 30%. However, the majority (75% or 53 stations over the entire evaluation period and 59% or 42 stations over the peak period) of the 71 stations have a Pearson product moment correlation coefficient (r^2) smaller than 0.5. These results suggest that the trend of the streamflow could be very difficult to forecast. Table 5 shows the E_{ra} and r^2 at the selected 13 key stations over the 7 major watersheds in BC. It can be seen from Table 5 that the values of E_{ra} of all the 13 stations for the entire evaluation period and 12 stations for the peak period are smaller than 30% and the values of r^2 of most of the 13 stations for the peaking period are greater than or equal to 0.5. One of the most important stations among these 13 stations is Fraser River at Hope

(08MF005), which is located on the northeastern boundary of the Lower Mainland including Metro Vancouver – the most populated region of the province of BC. The forecast error (E_{ra}) is 10% and 6% for the entire evaluation period and the peak period respectively, and the correlation coefficient between the forecast and observed flows (r^2) is 0.61 and 0.74 for the entire evaluation period and the peak period respectively. These values demonstrate that the accuracy of the forecast at Fraser River at Hope (08MF005) is relatively high. Figure 6 shows the model forecast for Fraser River at Hope (08MF005) for 4 weeks through the peak period.

Table 4. Statistics of the 10-day forecasts for the total 71 stations (2015).

Era				
Forecast	Mar.01 - Jul.20		May 11 - Jun.11	
	Count	%	Count	%
<=10%	11	15	13	18
20%~10%	17	24	14	20
30%~20%	25	35	24	34
Subtotal	53	75	51	72
40%~30%	12	17	12	17
>40%	6	8	8	11
Total	71	100	71	100

r squared				
Forecast	Mar.01 - Jul.20		May 11 - Jun.11	
	Count	%	Count	%
>=0.9	0	0	0	0
0.8~0.9	1	1	4	6
0.7~0.8	2	3	9	13
0.6~0.7	11	15	5	7
0.5~0.6	4	6	11	15
<0.5	53	75	42	59
Total	71	100	71	100

Table 5. 10-day streamflow forecasts at 13 selected key stations (2015).

		Mar.01 - Jul.20		May 11 - Jun.11	
Watershed	Station Name and ID	Era (%)	r squared	Era (%)	r squared
Fraser	Fraser River at Shelley (08KB001)	19	0.46	16	0.52
	Quesnel River near Quesnel (08KH006)	13	0.53	14	0.71
	Thompson River near Spences Bridge (08LF051)	8	0.63	7	0.70
	Fraser River at Hope (08MF005)	10	0.61	6	0.74
Columbia	Columbia River at Donald (08NB005)	14	0.35	17	0.44
	Kootenay River at Fort Steele (08NG065)	20	0.33	24	0.42
Skeena	Bulkley River at Quick (08EE004)	18	0.39	17	0.50
	Skeena River at Usk (08EF001)	17	0.42	15	0.52
Nass	Nass River above Shumal Creek (08DB001)	24	0.38	24	0.50
Stikine	Stikine River at Telegraph Creek (08CE001)	26	0.38	41	0.51
Liard	Liard River at Lower Crossing (10BE001)	10	0.66	13	0.85
Peace	Pine River at East Pine (07FB001)	28	0.43	21	0.49
	Peace River above Alces River (07FD010)	22	0.29	21	0.40

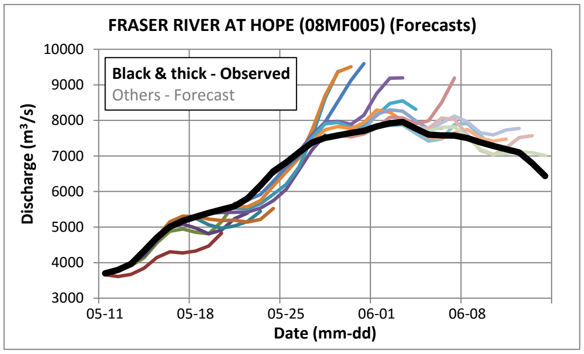

Figure 6. Model forecast result for Fraser at Hope (08MF005) for 4 weeks.

One can see from Figure 6 that there are four days that the model obviously overestimated the peak flow. One of the reasons is that some of the upstream forecast climate stations overestimated the temperature by 2 ^{o}C.

Conclusions

Based on the above evaluation and discussion, it can be concluded that the Channel Links Evolution Efficient Routing (CLEVER) Model is applicable to and practical for real-time flood forecasting in the large-scale watersheds in British Columbia with reasonable accuracy. However, 2015 was the first year that the model was extensive tested and evaluated. Further evaluation will be conducted in the coming years of freshet operation at the River Forecast Centre.

References

Aral, M.M., Gunduz, O., 2006. Chapter 4 Large-scale hybrid watershed model, in: Singh, V.P., Frevert, D.K., (Eds.), Watershed Models. CRC Press, Taylor & Francis Group, Boca Raton, pp. 75-96.

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, Q. 2000. A distributed water balance model in large-scale complex watersheds (LCW) and its application to the Kanto region, Ph.D. dissertation, Department of Civil Engineering, the University of Tokyo.

Luo, Q., 2007. A distributed surface flow model for watersheds with large water bodies and channel loops. Journal of Hydrology 337, 172–186.

Nash, J.E., J.V. Sutcliffe, 1970. River flow forecasting through conceptual models, 1. A discussion of principles. Journal of Hydrology 10, 282-290.

Patankar, S.V., Spalding, D.B., 1972. A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows. International Journal of Heat Mass Transaction 15, 1787–1806.

Singh, V.P., 2012. Chapter 1 Watershed modeling, in: V.P. Singh (Ed.), Computer Models of Watershed Hydrology. Water Resources Publication, pp. 1-20.