Evaluation of CLEVER Model performance in Kiskatinaw basin during June 15, 2016 storm event in Peace Region, British Columbia

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Abstract: The CLEVER Model was developed for the purpose of operational real-time flood forecasting in British Columbia. This is a hybrid model comprised of a lumped watershed routing sub-model and a one-dimensional distributed open-channel routing sub-model. A heavy storm event occurred in the Peace region on June 15, 2016. The Kiskatinaw River is a non-regulated tributary of the Peace River. This paper evaluates the model's performance with respect to the model calibration and forecast during the storm event. The model forecasted a flood of 10- to 100-year return period magnitude two days ahead of the actual flood occurring and provided a meaningful flow estimate for flood response in the Kiskatinaw basin under the conditions that coincided with missing observational discharge data.

Keywords: real-time flood forecast, hybrid model, unit hydrograph, kinematic wave

1. Introduction

Flood events in northern British Columbia are commonly caused by either spring season snowmelt-driven runoff events or upslope precipitation events caused by so-called 'wrap-around' deep low pressure cells that result from synoptic-scale upper atmospheric lows that affect the region during June and July. Examples of 'wrap-around' lows that have caused flooding include historically significant events in June 2001 and 2011. Forecasting flood events driven by deep low pressure cells is often complicated by the orthographic effects of the terrain in eastern BC as well as the unpredictability of the small, highly unstable, low pressure storm systems. The British Columbia River Forecast Centre (RFC) is responsible for monitoring and forecasting the streamflow conditions during the freshet snowmelt season and the fall storm season across the province. In order to facilitate operational real-time flood forecasting covering the entire province, a hybrid large-scale watershed model, the Channel Link Evolution Efficient Routing, or CLEVER, Model (Luo, 2015; Luo et al., 2015; Luo, 2016), which consists of a lumped-watershed routing sub-model and a distributed open-channel routing sub-model, was developed at the RFC in 2013. After extensive testing and improvements completed over 2014-15, the model was used in flood forecast operations at the RFC during the 2016 freshet season.

On June 15, 2016, a storm event occurred in northeastern BC, affecting communities south of the Peace River including Chetwynd and Dawson Creek. This was the first heavy rainfall event since 2013 when the CLEVER Model was developed, and thus provided a valuable opportunity to evaluate the model's performance. To evaluate the model's performance, the Kiskatinaw River was chosen for several reasons including: the Kiskatinaw River experienced a significant runoff response to the storm event; the river is not regulated and; climate stations located within or close to the basin boundaries ensured the meteorological conditions of the storm were recorded.

In the following sections, the model is summarized and a test storm event is described. The model performance is evaluated with respect to the model calibration and real-time forecasts for three days during the storm event.

2. Model physics, functionality, and performance evaluators

2.1 Model physics

The CLEVER Model consists of a lumped watershed routing sub-model and a distributed open channel routing sub-model. Due to the large size of BC's watersheds, a watershed is first divided into a number of relatively homogenous sub-basins. These sub-basins are further simplified into individual nodes in the lumped watershed routing sub-model. The water balance in the hydrologic cycle, including precipitation, snowmelt, evapotranspiration, infiltration, etc., is calculated at these nodes and the surface runoff in a sub-basin is routed with the unit hydrograph. Channel links are created to connect the nodes of the individual sub-basins. The outlet of a sub-basin is also the location of a Water Survey of Canada (WSC) hydrometric station which provides discharge data for model calibration. Figure 1 shows the process of watershed simplification and the conceptual design of the model. Details of the lumped watershed routing sub-model can be found in Luo (2015) and Luo et al. (2015).

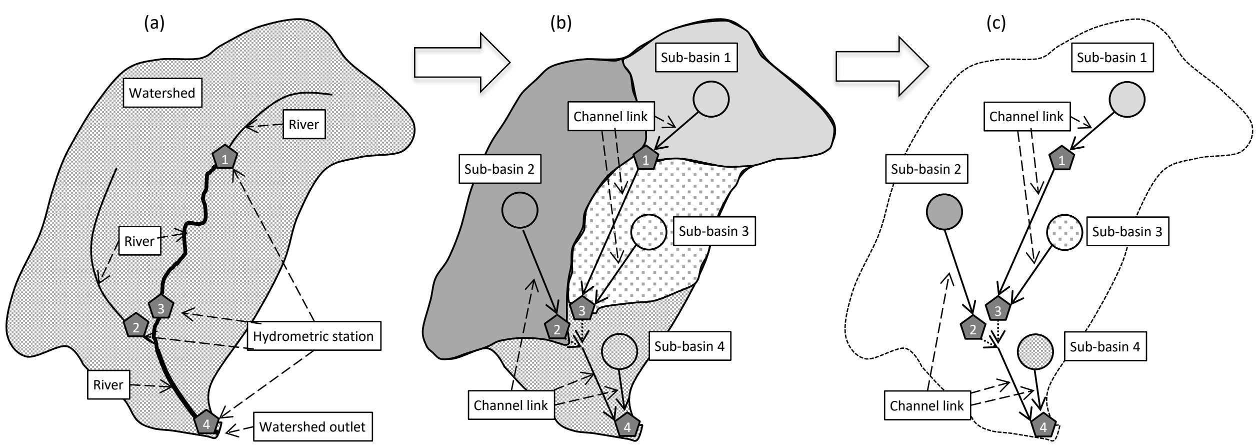


Figure 1. Watershed simplification and conceptual CLEVER model design. A) Model characterization of the watershed including WSC stations for calibration. B) Watershed is divided into sub-basins and hydrology of sub-basin nodes is derived. C) Channel links connect sub-basin nodes and flow is routed to watershed outlet.

Kinematic wave routing is used for the distributed open-channel routing sub-model. In order to overcome the difficulties faced by commonly used schemes for flow routing in regulated sub-basins, a stable and less grid size dependent high-resolution scheme for the kinematic wave was developed. The Preissmann scheme (Preissmann, 1961) is employed to discretize the continuity equation of the Saint-Venant equations. The scheme employs a method similar to the SIMPLE model (Patankar and Spalding, 1972) to solve the finite difference equation iteratively. The high-resolution scheme includes the Minmod flux limiter (Roe, 1981) and is therefore stable, or oscillation free. The scheme is less grid size dependent with respect to numerical dispersion and diffusion and therefore allows more flexible selection of spatial and temporal increment size. Details of this scheme can be found in Luo (2016).

2.2 Model functionality

Although the CLEVER model design and testing are described elsewhere (i.e., Luo, 2015, Luo et al., 2015, Luo, 2016), a brief description is given here to facilitate understanding of the results described in Section 4. The CLEVER model allows for one or more meteorological stations as data input for a sub-basin, along with a WSC station for discharge calibration. For a given node, each meteorological station is weighted depending on the location of the station relative to the watershed and to the location of the WSC gauge that serves as the calibration node. The weights given for the input meteorological stations are kept constant following initial calibration at the start of the freshet season. However, additional meteorological factors (for precipitation and temperature) can be adjusted to fine-tune the model calibration to account for different watershed characteristics that affect the rainfall-runoff relationship. In this way, the model can effectively account for antecedent conditions that reflect recent meteorological forcing (i.e., precipitation events during the previous 1 to 5 days or temperature trends).
Each node of the model is calibrated based on the previous 20 days of observed discharge data and from this calibration and the subsequent input meteorological forecast data (daily temperature and precipitation forecasts from Environment Canada's GEM-Regional and GEM-Global models), the 10-day forecast hydrograph is generated.

2.3 Statistical indicators for evaluation of model performance

Model performance in calibration and forecast is evaluated both visually and statistically. The statistical indicators for model calibration and forecast include: (1) the coefficient of model efficiency (C_e), which describes how well the volume and timing of the simulated hydrograph compares to the observed hydrograph. Values closer to 1 indicate the simulated hydrograph has a better fit to the observed hydrograph (Nash and Sutcliffe, 1970); (2) the coefficient of model determination (C_d), which measures how well the shape of the simulated hydrograph reflects the observed hydrograph. This metric assesses the timing of changes in the hydrograph. Values closer to 1 indicate the simulated hydrograph is a closer fit to the observed hydrograph (Nash and Sutcliffe, 1970); (3) the percentage volume difference (dV) of the simulated hydrograph relative to the observed hydrograph (Nash and Sutcliffe, 1970); (4) the relative mean absolute error (era) of the simulated hydrograph to the observed hydrograph (Lettenmaier and Wood, 1992); and (5) the square of the Pearson product moment correlation coefficient between the simulated and observed hydrographs (r^2). The closer the value is to 1 indicates a better fit to the observed hydrograph.

3. June 15, 2016 storm in the Peace Region, northeastern BC

On June 15, 2016, a deep low-pressure system from northern Alberta drifted northwest sending a severe storm across northeastern BC. From the precipitation data collected at a total of 32 stations in these regions including 27 BC Ministry of Forests, Lands and Natural Resource Operations fire weather stations (FW), 3 Environment Canada climate stations (EC) and 2 BC Ministry of Environment and BC Hydro automated snow pillow stations (ASP), the 24-hour total rainfall on June 15, 2016 ranged from 10 to 90 mm in the region. Figure 2 shows the hyetograph from measured rainfall data from these 32 stations for the day (7 am June 15 to 7 am June 16, 2006) of this heavy rainfall event. Figure 2 shows three areas of high rainfall totals with the highest rainfall amounts close to the Kiskatinaw River basin (shaded).

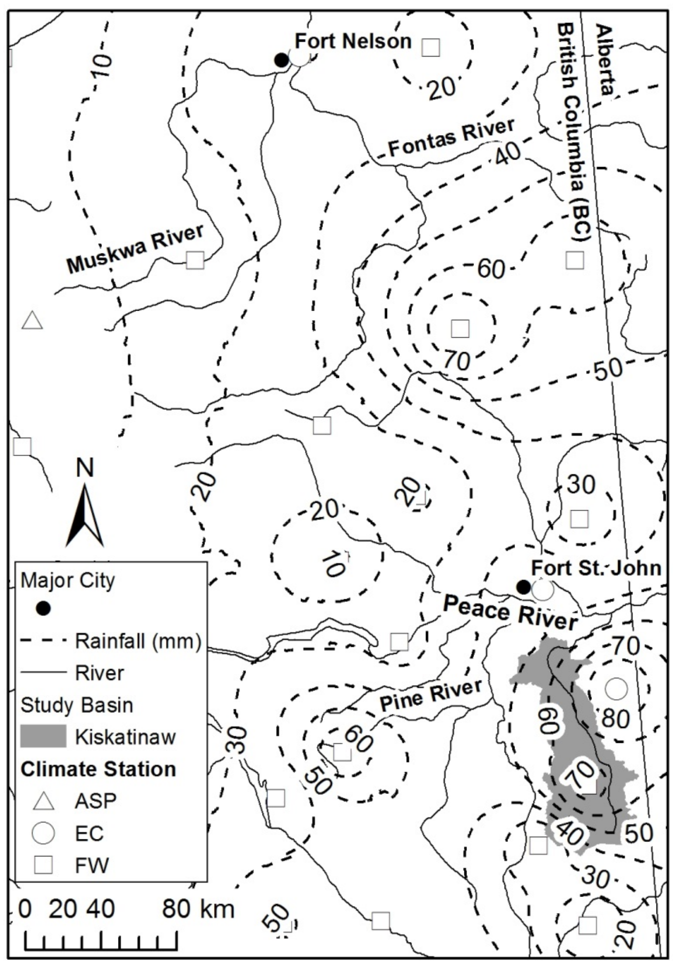


Figure 2. Twenty-Four-hour hyetograph over the study region from observed rainfall 7AM June 15 to 7AM June 16, 2016. Note: The shaded area south of Fort St. John is the Kiskatinaw River basin; ASP – automated snow pillow station; EC – Environment Canada climate station; FW – fire weather station.

The Kiskatinaw River is a non-regulated tributary of the Peace River. The river originates in the Southern Alberta Upland Ecoregion (Demarchi, 2011) close to the border of BC and Alberta. The drainage area upstream of the WSC hydrometric station (07FD001) is about 3700 km2. Figure 3 shows the Kiskatinaw River basin at a regional scale and the contours of the rainfall totals of the June 2016 event. During the storm event, estimated rainfall over the study watershed ranged from 30 to close to 80 mm, most of the basin received greater than 50 mm, and 73 mm was recorded at the Noel fire weather station.

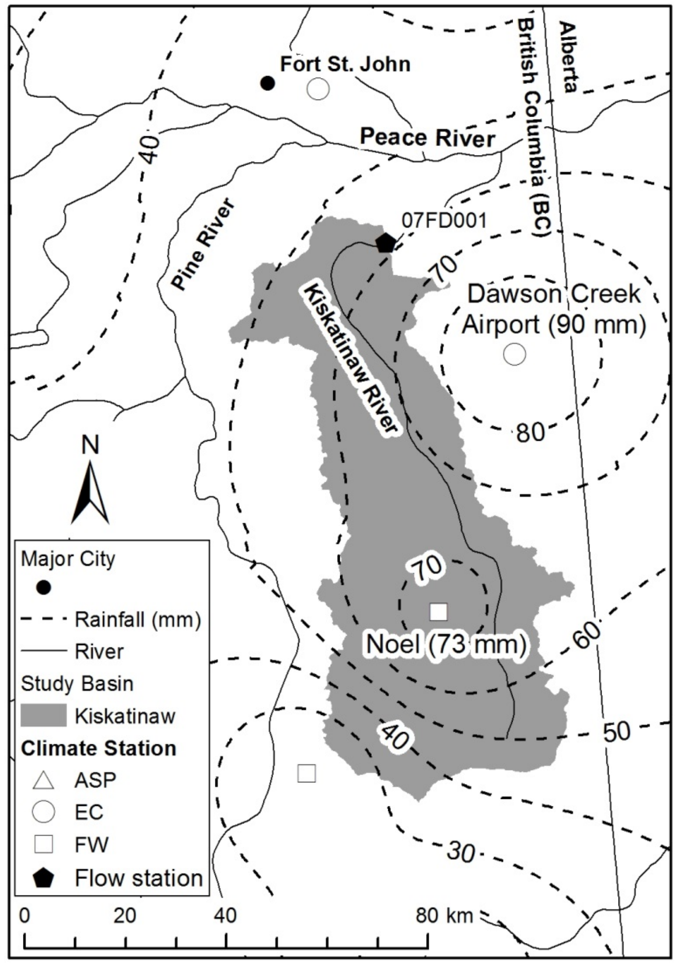


Figure 3. The Kiskatinaw River basin and contours of 24-hour rainfall totals of June 2016 event.

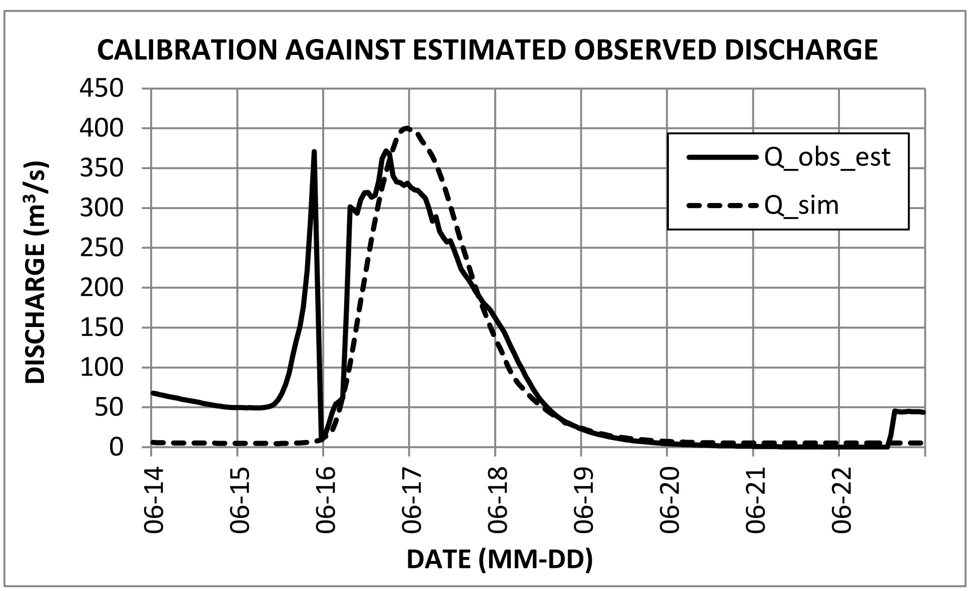
4. Results

4.1 Model calibration

The model was calibrated daily and simulated hydrographs were recorded daily during the freshet season as part of the daily forecasting operations at the RFC. The entire calibration for the flood event was completed after the event. Daily model calibration is particularly important for accurate flood forecasting during the freshet season due to continually changing hydrometeorological and watershed conditions. However, during the storm event, the real-time discharge data at the WSC station Kiskatinaw River near Farmington (07FD001) was not reported shortly after the flood began (near midnight on June 15, 2016) and the only available hydrometric data for this station was water level. Discharge data were not reported because the hydrometric conditions at the time were outside of the existing rating curve for the station. To calibrate the model under the circumstances, an older rating curve from the WSC station with a broader water level range was used. This approach allowed for estimates for the missing discharge data. Figure 4 (a) shows the model-simulated hydrograph compared with the observed and estimated discharge data. Visually, this simulated hydrograph was sufficient, aside from the data spike on late June 15, 2016 which indicates when the existing rating curve failed. Statistically, the coefficient of model efficiency (Ce), the coefficient of model efficiency (Cd) and the percentage volume difference (dV) were 0.72, 0.78 and -21%, respectively. These numbers demonstrate model calibration was reasonably good.

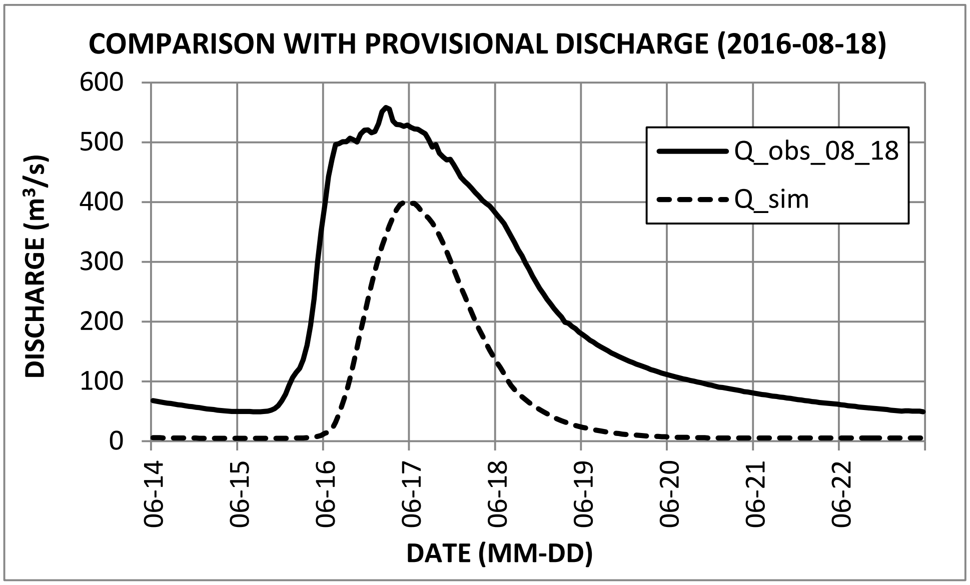
After the event, the WSC published adjusted provisional discharge data for the Kiskatinaw River station (accessed on August 18, 2016). The updated provisional discharge data was almost complete with only a few hours of missing data. Figure 4 (b) is a comparison of the simulated hydrograph generated during the event operational runs (i.e., not generated by re-running the model later) with the observed hourly average discharge calculated from the adjusted provisional WSC data (accessed on August 18, 2016). Visually, the simulated hydrograph underestimated the peak and the water volume. However, the shape and trend of the simulated hydrograph are close to that of the observed hydrograph. Statistically, the coefficient of model efficiency (Ce), the coefficient of model efficiency (Cd) and the percentage volume difference (dV) are -0.42, 0.87 and -96%, respectively. These statistics concurred with the visual comparison and the value of Cd demonstrates that the shape and timing of the simulated hydrograph fit the observed hydrograph from the adjusted provisional discharge data (Figure 4 (b)) better than the estimated observed hydrograph (as shown in Figure 4 (a)).

Subsequently, the WSC discharge data were adjusted again (accessed on September 1, 2016 and unchanged as of the time of submission) and the peak discharges from June 16th and 17th were removed (Figure 4c). Although a comparison of the simulated and revised WSC data suggest the model underestimates the event discharge again, the missing data preclude further evaluation of the model relative to the updated WSC data.

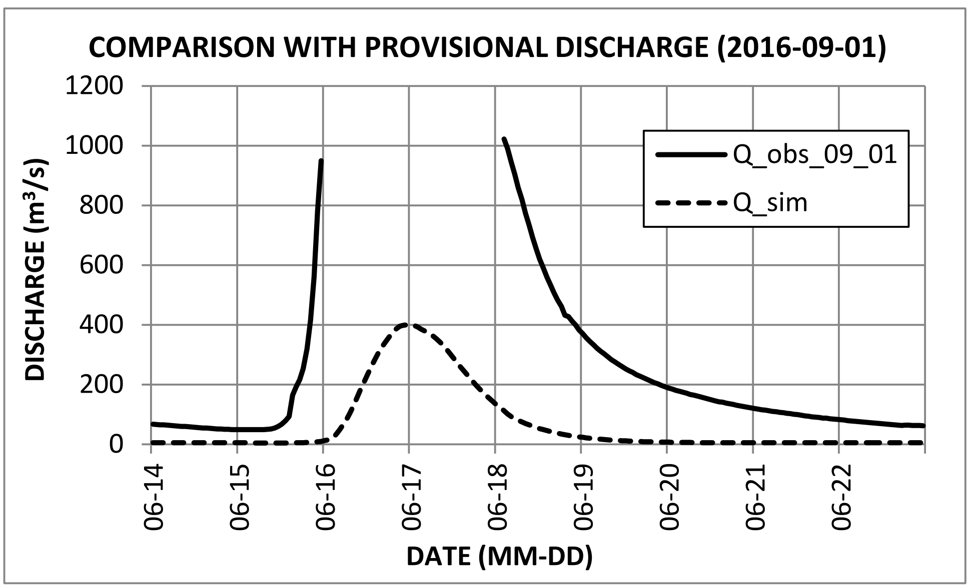


(a)

Figure 4. Comparison of CLEVER simulated hydrograph and WSC discharge data (continued next page).



(b)

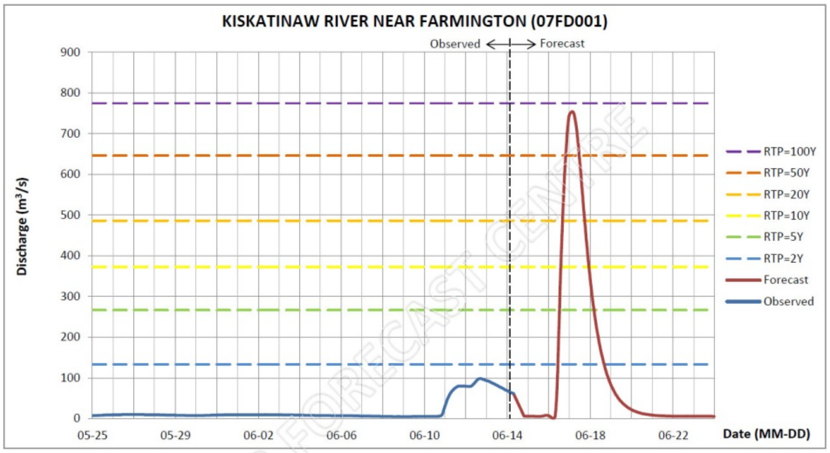


(c)

Figure 4. Comparison of CLEVER simulated hydrograph and WSC discharge data. (a) Simulated hydrograph and WSC estimated discharge data, (b) simulated hydrograph with WSC provisional discharge data (accessed on August 18, 2016), (c) simulated hydrograph with WSC provisional discharge data (accessed September 1, 2016).

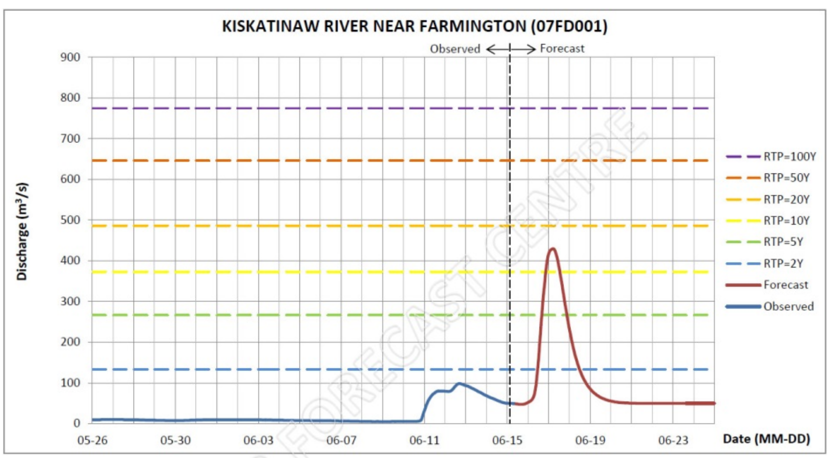
4.2 Model forecasts

The model produced three operational, real-time flood forecasts for the Kiskatinaw River during the storm event on June 14th, 15th, and 16th (Figure 5). In the figures, observed discharge is depicted to the left of the vertical dashed line and the forecasted discharge is on the right side of the vertical dashed line. Horizontal dashed lines indicate the return period flows for a given interval and the daily flows are tabulated below the hydrograph, including color coding to indicate the return period flows. As these are forecasted flows from the time of the event, it is not possible to compare how well the forecast hydrographs fit the observed hydrograph.



Reading at 7AM (m³/s)	Forecast Daily Discharge (m³/s): MAX / AVERAGE / MIN									
Tue 2016-06-14	Tue 2016-06-14	Wed 2016-06-15	Thu 2016-06-16	Fri 2016-06-17	Sat 2016-06-18	Sun 2016-06-19	Mon 2016-06-20	Tue 2016-06-21	Wed 2016-06-22	Thu 2016-06-23
	8	8	742	755	336	81	21	8	6	5
64	**7**	**6**	**291**	**604**	**185**	**45**	**13**	**7**	**5**	**5**
	6	5	0	355	86	22	8	6	5	5

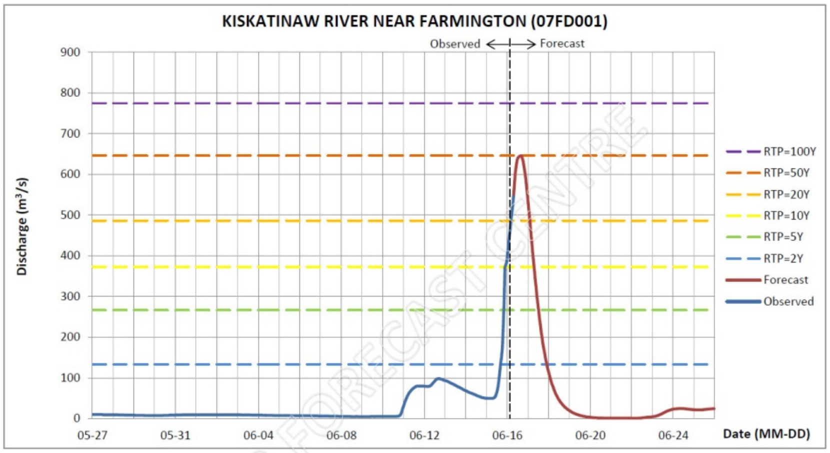
(a) *Colour Scheme for Return Periods:* 1-Yr | 2-Yr | 5-Yr | 10-Yr | 20-Yr | 50-Yr | 100-Yr



Reading at 7AM (m³/s)	Forecast Daily Discharge (m³/s): MAX / AVERAGE / MIN									
Wed 2016-06-15	Wed 2016-06-15	Thu 2016-06-16	Fri 2016-06-17	Sat 2016-06-18	Sun 2016-06-19	Mon 2016-06-20	Tue 2016-06-21	Wed 2016-06-22	Thu 2016-06-23	Fri 2016-06-24
	51	413	430	227	84	55	50	49	49	49
49	**48**	**189**	**364**	**141**	**66**	**52**	**49**	**49**	**49**	**49**
	47	52	238	86	55	50	49	49	49	49

(b) *Colour Scheme for Return Periods:* 1-Yr | 2-Yr | 5-Yr | 10-Yr | 20-Yr | 50-Yr | 100-Yr

Figure 5. Operational, real-time flood forecasts for Kiskatinaw River on (a) June 14, (b) June 15 and (c) June 16, 2016 (continued next page).



Reading at 7AM (m^3/s)	Forecast Daily Discharge (m^3/s): MAX / AVERAGE / MIN									
Thu 2016-06-16	Thu 2016-06-16	Fri 2016-06-17	Sat 2016-06-18	Sun 2016-06-19	Mon 2016-06-20	Tue 2016-06-21	Wed 2016-06-22	Thu 2016-06-23	Fri 2016-06-24	Sat 2016-06-25
	646	528	110	19	3	1	4	22	24	24
400	**550**	**292**	**53**	**9**	**1**	**1**	**2**	**13**	**23**	**22**
	274	118	20	3	1	1	0	4	22	21

(c) *Colour Scheme for Return Periods:* *1-Yr* *2-Yr* *5-Yr* *10-Yr* *20-Yr* *50-Yr* *100-Yr*

Figure 5. Operational, real-time flood forecasts for Kiskatinaw River on (a) June 14, (b) June 15 and (c) June 16, 2016.

Figure 6 shows the forecast hydrographs that are plotted with the observed hydrograph (accessed on August 18, 2016, also shown in Figure 4b). The observed peak flow was 558 m^3/s (based on hourly average of instantaneous WSC data), at 6 p.m. June 16, 2016. For the model forecast on June 14, 2016, the hourly average peak flow was 755 m^3/s and the estimated peak time was 2 a.m. June 17, 2016. This model forecast over-estimated the peak flows by 35% and the timing by 8 hours. For the model forecast on June 15, 2016, the hourly average peak was 430 m^3/s and the estimated peak time was 3 a.m. June 17, 2016. The June 15th forecast under-estimated the peak by 23% and over-estimated the peak time by 9 hours. For the model forecast on June 16, 2016, the hourly average peak was 646 m^3/s and estimated peak time was 4 p.m. June 16, 2016. The June 16th forecast over-estimated the peak by 16% and under-estimated the peak time by 2 hours.

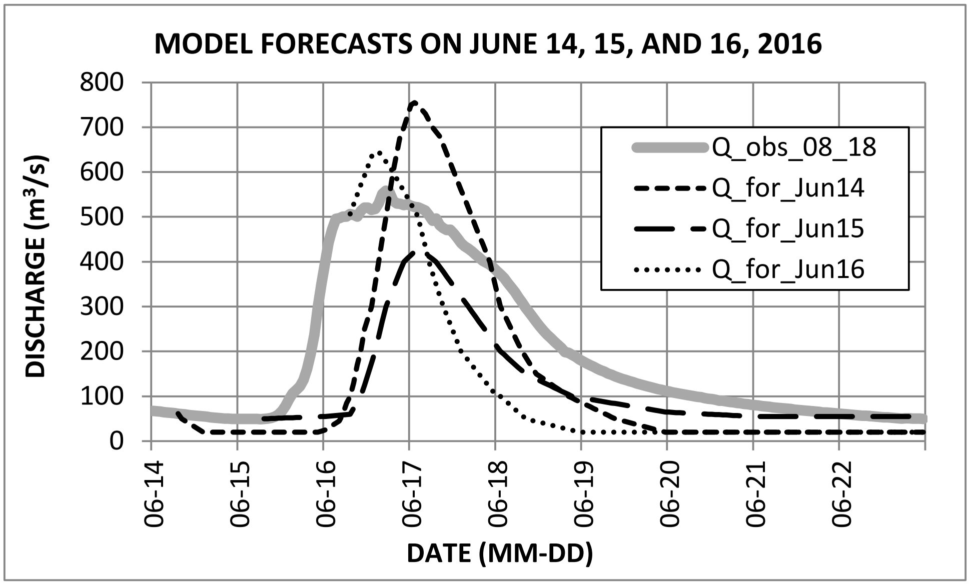


Figure 6. Comparison of model forecast hydrographs with observed hydrograph from provisional WSC data (accessed on August 8, 2016).

These forecast results reflect the influence of the forecast rainfall (precipitation) and the model adjustment to this rainfall. Table 1 lists the climate stations used for the simulation in the Kiskatinaw River basin, the forecast rainfall on June 14, 15 and 16, 2016, observed rainfall, and the model parameters for the rainfall adjustment. The original forecast rainfall data was from the GRIB2 dataset produced by the Numerical Weather Prediction (NWP) regional and global models of Canadian Meteorological Centre (CMC) of the Meteorological Service of Canada. The original forecast rainfall was downscaled to the locations of the two climate stations and input to the model for calibration. Details of the rain event show that the 24 hour forecast rainfall tended to exceed the observed rainfall data (Table 1). For example, on June 14th, the forecast rainfall for the following day at the Noel station (NOE) was 172.3 mm and the weighted average rainfall was 139.5 mm, these were 2.35 and 1.78 times greater than the observed rainfall respectively.

The precipitation adjustment factor to the rainfall was small compared to the latter days of the event (Table 1, 0.2 for June 14, 2016). This indicates that proportionately less rainfall would translate to runoff for the given model parameters on June 14th. However, the model still over-estimated the peak flows. The over-estimation of the forecast rainfall is largely responsible for the over-estimation of the forecast peak of the flood.

For the model forecast on June 15, the under-estimation of the peak is due to the combined results of the slight under-estimation of the rainfall (particularly at the Dawson Creek station (YDQ) and the apparent under-estimate of the precipitation adjustment factor (0.3,

Table 1). For the model forecast on June 16, 2016, the over-estimation of the peak is due to increasing the precipitation adjustment factor to 0.4 (Table 1). The difference of the forecast peak flow timing is due to the combined results of the intensity of forecast rainfall and the distribution of the daily rainfall into the hourly rainfall (details in Luo, 2015). However, a time difference less than 10 hours between the forecast and observed peak time is generally insignificant for a watershed of this size, and the forecast peak flow timing can be deemed accurate from the perspective of operational real-time flood forecast.

Table 1. Forecast and observed precipitation and model adjustment

TYPE OF DATA	DATE OF DATA	PRECIPITATION (mm) NOE W=0.7	YDQ W=0.3	WEIGHTED AVERAGE	MODEL ADJUSTMENT TO PRECIPITATION RUN DATE	FACTOR
FORECAST 2016-06-14	2016-06-14	14.4	20.2	16.1	2016-06-14	0.25
	2016-06-15	172.3	63.0	139.5		
	2016-06-16	33.2	29.1	32.0		
	2016-06-17	0.8	1.7	1.1		
FORECAST 2016-06-15					2016-06-15	0.30
	2016-06-15	73.1	72.0	72.8		
	2016-06-16	11.4	24.8	15.4		
	2016-06-17	0.1	0.8	0.3		
FORECAST 2016-06-16					2016-06-16	0.40
	2016-06-16	9.7	17.7	12.1		
	2016-06-17	1.8	0.1	1.3		
OBSERVED	2016-06-14	31.0	8.8	24.3		
	2016-06-15	73.2	89.8	78.2		
	2016-06-16	7.2	12	8.6		
	2016-06-17	0	0	0.0		

Note: NOE-fire weather station: Noel (437); YDQ-Environment Canada climate station: Dawson Creek Airport (1182289); W-weight.

5. Conclusions

Recorded streamflow data from the Kiskatinaw River during the mid-June 2016 storm event, was missing for the peak flow period (late June 15 to early June 18, 2016). To complete flow forecasts for the event, the CLEVER Model was calibrated against estimated observed discharge data and produced flood forecasts for the Kiskatinaw River, daily from June 14, 2016 to June 16th. The river peaked at 6 pm on June 16th, reaching 558 m^3/s, which is close to the 50-year flow event. The flood forecast from June 14th, modestly over-estimated the peak flow by 35% and the time of the peak by 8 hours. As the storm began to affect the region, the forecasts changed as a result of the observed rainfall on June 15th and 16th respectively. Subsequent forecasts were improved in terms of the relative difference in peak flows (-23% and +16% respectively). June 16th flow forecast was within two hours of the observed peak flows. The magnitude of the forecast flood varied from greater than the 10- to almost the 100-year return period flows and the forecasted time of peak flow ranged from the afternoon on June 16 to early morning June 17, 2016. The range of peak flow estimates and the timing of the peak flow reflect both inaccuracies in the forecasted precipitation totals as well as small adjustments to the model parameters during the storm event. However, given the observed discharge data was not reported during the event as well as the size of the basin, the range in forecasts are deemed suitable to provide a realistic and meaningful guideline for flood protection in the Kiskatinaw River basin during the heavy storm event on June 15, 2016.

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