How BC River Forecast Centre flood forecasting models simulate impacts of climate change in British Columbia

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Abstract

The British Columbia River Forecast Centre flood forecasting models always face questions if they are able to simulate impacts of climate change such as deforestation due to wildfires, and effects of human activities such as logging and construction of forest roads. The RFC currently operates year-round two flood forecasting models, the CLEVE Model and COFFEE Model. The CLEVER Model is a sophisticated hydrological model and was originally developed for the snowmelt dominated, large-scale watersheds in British Columbia. The COFFEE Model is basically a unit hydrograph model and was originally developed for the coastal storm dominated, small-scale watersheds. A case study for a hypothetical hydrograph in a real wildfire burned watershed in 2023 was carried out, and the results demonstrate that the CLEVER Model can be efficiently and accurately calibrated to changes of watershed physiography using the same climate data input. A simple example is then presented to show that the COFFEE Model is also very efficient in calibrating to changes of watershed physiography.

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1. Introduction

1.1 Climate change in British Columbia

Climate change is a shift in the weather patterns in the year, which used to happen over centuries, but now are happening at a much faster pace (CleanBC, 2024), such as within decades or years. For British Columbia (BC) communities, climate change may mean extreme temperatures and longer and hotter summers with more intense and frequent heat waves, which cause severer drought and more and larger wildfires, and more unpredictable extreme weather events year-round such as extreme rainfall or storms from atmospheric river (AR) events.

As one of the climate change consequences, the 2023 wildfire season has been the most destructive in BC's recorded history by then. A total of 2,245 wildfires burned more than 2.84 million hectares of forest and land between April 1 and October 31, 2023. This is the largest areas burned in the wildfire season in BC's recorded history (BC Wildfire Service, 2023). Thus, it is important that hydrological models for flood forecasting in BC must be able to simulate effectively and accurately the effects of wildfires as a severe consequence of climate change.

1.2 Hydrological implications of climate change in BC

Hydrologically, climate change has significant effects,

(1) Extreme rainfall causes extreme floods.

(2) Increasing spring air temperatures cause early onset of larger snowmelt, which results in higher floods in the early season of freshet and severer drought in the late summer and fall.

(3) Extreme rainfall may also trigger landslides, which alter the watershed physiography resulting in steeper slopes, less vegetation, and/or blockages of river channels. The overall effects of landslides are faster and higher flows and local building-up of high water in the river. However, the impacts may be limited because the scope of the alteration of the watershed physiography by landslides is small.

(4) Wildfires cause deforestation, which also alter the watershed physiography resulting in more snow accumulation, more incident energy for snowmelt, smoother overland surface for water to travel, more evapotranspiration and less infiltration. The overall effects of wildfires may be earlier, faster and higher floods in the freshet or in a wet year, and worse drought in dry seasons or in a dry year.

(5) Human activities such as logging/clearcut and constructing forest roads are not consequences of climate change but have similar hydrological implications as (4), early and higher floods and/or severer drought.

1.3 Flood forecasting implications of climate change in BC

Under climate change impacts, climate variables such as the structure of cloud, vapour movements in both vertical and horizontal directions, vapour amount, etc. could potentially exhibit themselves in a different way. The same measurements recorded on the ground could mean different from that recorded in the larger scale atmosphere. For hydrological modeling, this is partly reflected in the scale relationship between the point and large-scale measurements of climate variables. The complex interaction and change may potentially change the hydrological response in a watershed.

More explicitly, this study discusses the direct climate change impacts on the watershed physiography. From the discussion in the above subsection, it is clear that climate change (and human activities such as logging/clearcut and construction of forest rods as well) has direct impacts on hydrological modeling/flood forecasting in the following two aspects,

(1) changes of input climate data, and,

(2) changes of watershed parameters.

For most hydrological models, it is easy to deal with changes of input climate data – modifying the input data files, which does not require to modify the model structure or methodology.

However, most research/academic hydrological models are difficult or inefficient in tackling changes of watershed parameters. One of the significant drawbacks of research/academic hydrological models is that they are usually designed to run for at least a hydrological year. The parameters are usually calibrated in a previous year or a few previous years and then validated/verified in a later year or a few later years. Therefore, the watershed parameters are held constant for at least two years. It is very difficult or inefficient for research/ academic hydrological models to handle frequent/fast changing watershed parameters, which may be different year by year or even season by season due to climate change or human activities.

Under climate change, an efficient flood forecasting model must be able to calibrate efficiently and accurately the frequent/fast changing watershed parameters.

1.4 BC River Forecast Centre flood forecasting models and their advantages

The BC River Forecast Centre (RFC) runs two operational real-time flood forecasting models year-round, the CLEVE Model (Luo, 2015; 2021; 2024) which is a sophisticated hydrological model and was originally developed for snowmelt dominated, large-scale watersheds in the interior of BC, and the COFFEE Model (Luo, 2018) which is basically a unit hydrograph model and was original developed for coastal storm dominated, small-scale watershed in the BC coast. The advantages of these two models are as follows:

(1) Different from research/academic models, which typically run for at least a year. The

CLEVER Model is run for only a 30-day period with the early 20 days for model calibration and the late 10 days for flow forecasts. And the COFFEE Model is run for only a 15-day period with 10 days for model calibration and 5 days for flow forecasts. The watershed parameters of the CLEVER Model are held constant for only 30 days, and they can be calibrated at any run. The watershed parameters of the COFFEE Model may be held constant for as short as 15 days, and they can be recalibrated after any major rainfall events. Therefore, the model structures of the CLEVER Model and COFFEE Model make them very efficient and effective in calibrating the frequently changing watershed parameters due to climate change and human activities.

(2) Temporally (time-wise), watershed parameters in the CLEVER Model can be calibrated/adjusted within a few days or even a few hours once the signal of changes of watershed physiography shows up in the streamflow data. For the COFFEE Model, the watershed parameters can be re-calibrated after a rainfall event, which usually lasts for a day or longer in the model.

(3) Spatially (space-wise), the watershed parameters are easy to modify and recalibrate for each watershed because the CLEVER Model and COFFEE Model can be run for a single watershed or sub-basin.

(4) The CLEVER Model adopts an hourly time step for the input data and output hourly flows from the beginning when the model was developed in 2013 though the input climate data used a daily time step originally. As of 2024, the input climate data also adopts an hourly time step. The hourly time step for the CLEVER Model helps the model produce more accurate forecasts for instantaneous peak flows. The COFFEE Model adopts a daily time step, but the forecast flows are converted into instantaneous flows.

(5) Both the CLEVER and COFFEE Models produce forecast lower and upper bounds, which helps account for part of the uncertainty due climate change.

2. A case study for CLEVER Model – hypothetical hydrograph for 2023 wildfire burned watershed

One of the climate change consequences is more and larger wildfires as mentioned in the above Section. A watershed with burned vegetation results in different hydrological responses in streamflow. This Section provides a case study showing how the CLEVER Model parameters are adjusted to account for the hydrological effects from the land surface alteration by a wildfire. In this case study, a hypothetical hydrograph is set as the target for the CLEVER Model calibration.

2.1 Wildfire No. G60666

In 2023, 60 wildfires were classified as Wildfires of Note. A Wildfire of Note is a fire that is particularly visible or posing a threat to public safety (BC Wildfire Service, 2023). According to the statistics by BC Wildfire Service (2023), the largest hectares burned in BC in 2023 is the Donnie

Creek wildfire (Fire Number G80280) and the burned area is 619,072.5 hectares (6,191 km^2), and the date of discovery is May 12, 2023. And the second largest is the Big Creek of the Omineca River (G60666) and the burned area is 166,856.9 hectares (1,669 km^2) and the date of discovery is June 7, 2023. There is no real-time flow station for the Donnie Creek, but there is a Water Survey of Canada (WSC) real-time hydrometric station located in the Omineca River, the OMINECA RIVER ABOVE OSILINKA RIVER (07EC002), which is also modeled by the CLEVER Model. This document will use this WSC real-time hydrometric station as an example of model calibration for watershed parameters. Figure 1 is a snipped chart from WSC real-time hydrometric data site for the OMINECA RIVER ABOVE OSILINKA RIVER (07EC002) for 2023. The figure shows a gap of data (missing data) from June 11 to October 25, 2023, which might be a consequence of the wildfire.

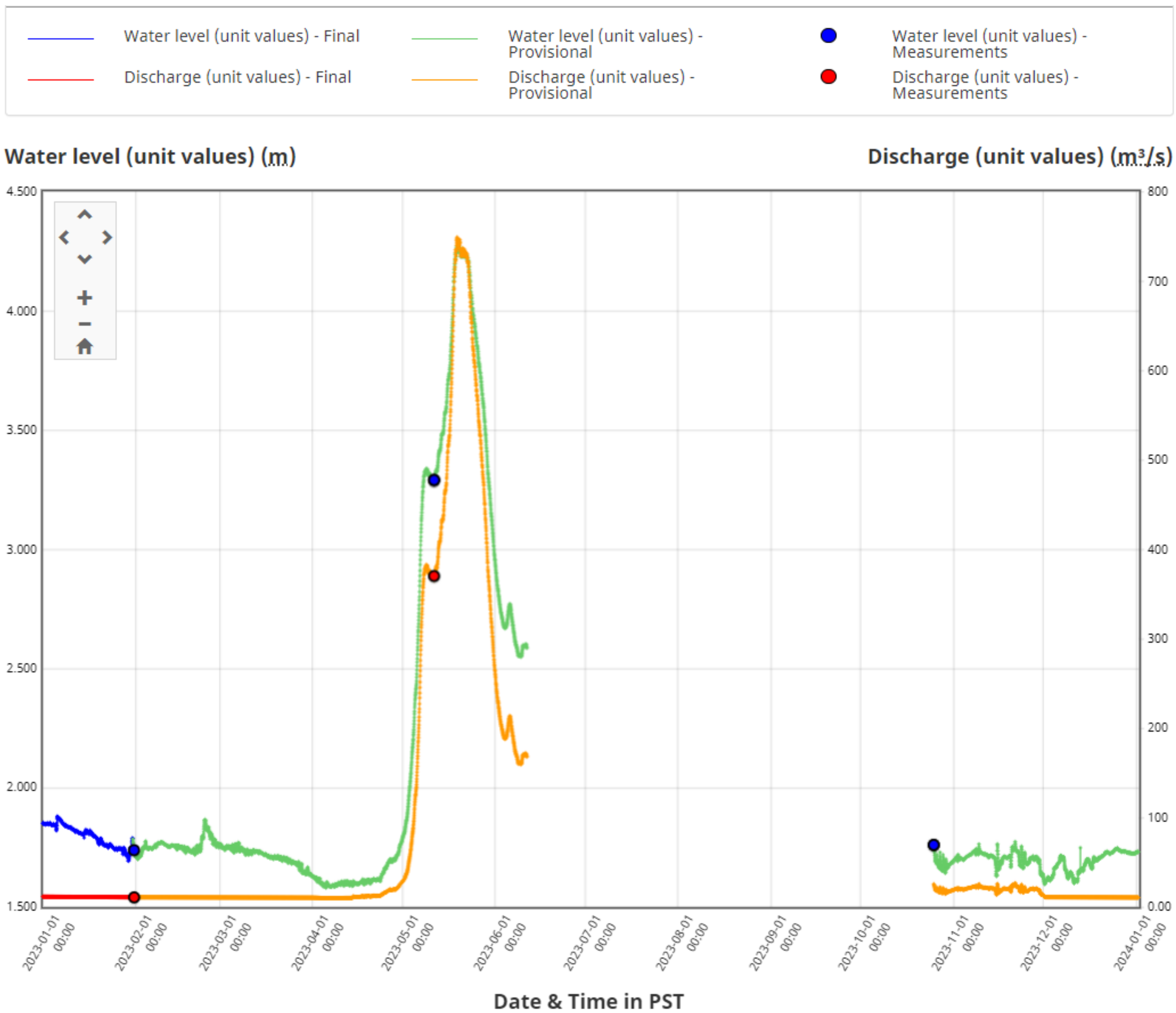


Figure 1. Snipped chart of WSC real-time hydrometric data site for OMINECA RIVER ABOVE OSILINKA RIVER (07EC002) for 2023

2.2 CLEVER Model watershed parameters

The watershed overland flow routing sub-model of the CLEVER Model is a lumped model, which does not include any parameters for land uses and thus does not simulate any watershed physiological characteristics directly. However, the CLEVER Model are able to produce accurate calibrations and forecasts for most of the modeled 349 watersheds in 2023 and 419 watersheds in 2024 across BC, which covers all kind of land uses and vegetation. This means that the CLEVER Model is able to simulate streamflows of all kinds of watershed physiographical conditions because the model incorporates necessary watershed parameters to ensure the simulated hydrographs to agree with the observed ones. Figure 2 is an example of watershed parameters of the CLEVER Model 2023 version.

WATERSHED	OMINECA RIVER ABOVE OSILINKA RIVER (07EC002)						OMIN
AREA (km2)	5519	R (07EC002) - DAILY				WATERSHED TYPE	Natural
AVERAGE ELEVATION (m)	1200	07EC002) - HOURLY					
STORAGE CONSTANT	6.40	CALCULATED FROM AREA AND FACTOR: 1 - 15					
FACTOR TO STORAGE CONSTANT	1.50	CHANGE SHAPE OF HYDROGRAPH, GREATER, FLATTER					
HYDROGRAPH CONSTANT	1.00	CHANGE PEAK OF HYDROGRAPH, GREATER, HIGHER					
FAST FLOW (%)/PEAK SHIFT (h)	1	0	1	1- RUN GROUNDWATER MODEL			
BASE FLOW (m3/s)	1		0	INITIAL GW STORAGE (mm)			
SOIL MOISTRUE DEFICIT (mm)	0.00		2000	MAX GW STORAGE (mm)			
INFILTRATION RATE (mm/h)	0.50		1000	GW RELEASE THRESHOLD (m3/s)			
EVAPOTRANSPIRATION(mm/h)	0.05		0.3	RATE OF RELEASING (1/HOUR)			
ROS MELT(1/C/h)/GLACIER MELT F	0.100	0.055	0.0	LEAK(-)/SOURCE(+)(m3/s)			
SNOWMETL RATE (mm/C/h)	0.240	0.025	0.050	Cd FOR MAR-01/APR-01			
POWER BETA/POWER ALPHA	0.70	0.500	05-07	DATE AS OF WHICH Cd=1			
NUMBER OF CLIMATE STATIONS	ID	WEIGHT	EL (m)	dTX_C	dTN_C	dP_mm	P_factor
3	LVC	0.5	990	0.0	0.0	-10.0	0.50
	MSN	0.3	1047	0.0	0.0	-10.0	0.50
	AKL	0.2	1065	0.0	0.0	-10.0	0.50
<-GO TO MODEL FILE							
<-GO TO FIGURE SHEET		1	RAINFALL PT: 1-INTE,2-COAST				1
	NEW	OLD		UPDATE DISCHARGE DATA ONLY			
INITIAL SWE (mm)	600	600					
				dTX_C	dTN_C	dP_mm	
METHOD OF EXTENDING TO 10 DAY FORECAST			1	0.0	0.0	0.0	
1 - STATIC (T&P AS LAST DAY)/2 - STATIC (T&P AS SET)			1-THIS STN ONLY		EXPORT FORECAST FOR THIS WATERSHED		
3 - FLAT WITH INCREMENT AS SET			2-ALL SUB BASINS				
4 - LINEAR WITH UNIFORM SLOPE			3-DOWSTREAM				
			4-ENTIRE GROUP			1	
RIVER ROUTING METHOD	1	(1-CHANNEL, 2-LAKE)			ADDITIONAL INFLOWS FOR		
	dX(Km)	dT(s)	dX/dT				
	20	3600	5.556				
FLOW GAUGE ELEVATION (m)	700		**1 - RE-LOAD**		RE-CALIBRATE THIS WATERSHED		
DISTANCE FM WTSH CENTRE (Km)	100		INPUT FILES				
SLOPE (S0)	0.005000		**BLANK(DEFAULT) -**				
MANNING ROUGHNESS (N)	0.1		NOT RE-LOAD INPUT FILES				
RIVER WIDTH (m)	90						
TOTAL NUMBER OF dX	5		FORECAST BIAS-CORRECTION (%):				100
TOTAL NUMBER OF dT	720					Linear Hours	0

Figure 2. Example of watershed parameters of CLEVER Model 2023 version

2.3 CLEVER Model calibration in 2023

Any alteration of the watershed physiography will be reflected in the observed hydrograph at the watershed outlet. Once the streamflow picks up the signals from alterations of the watershed physiography, the CLEVER Model can be calibrated to adapt to the alterations as short as 20 days, which is the calibration period of the CLEVER Model in a run.

Figure 3 is the reconstructed model calibration chart for the OMINECA RIVER ABOVE OSILINKA RIVER (07EC002) for May 21, 2023. Assuming that exactly the same heat and rainfall events occur again in May 2024. The watershed area of the OMINECA RIVER ABOVE OSILINKA RIVER (07EC002) is 5,519 km^2, and the total forest/vegetation about 30% of the watershed area was burned out in 2023. It can be expected that the hydrological response in this watershed in 2024 will be different even if the climate conditions might be exactly the same.

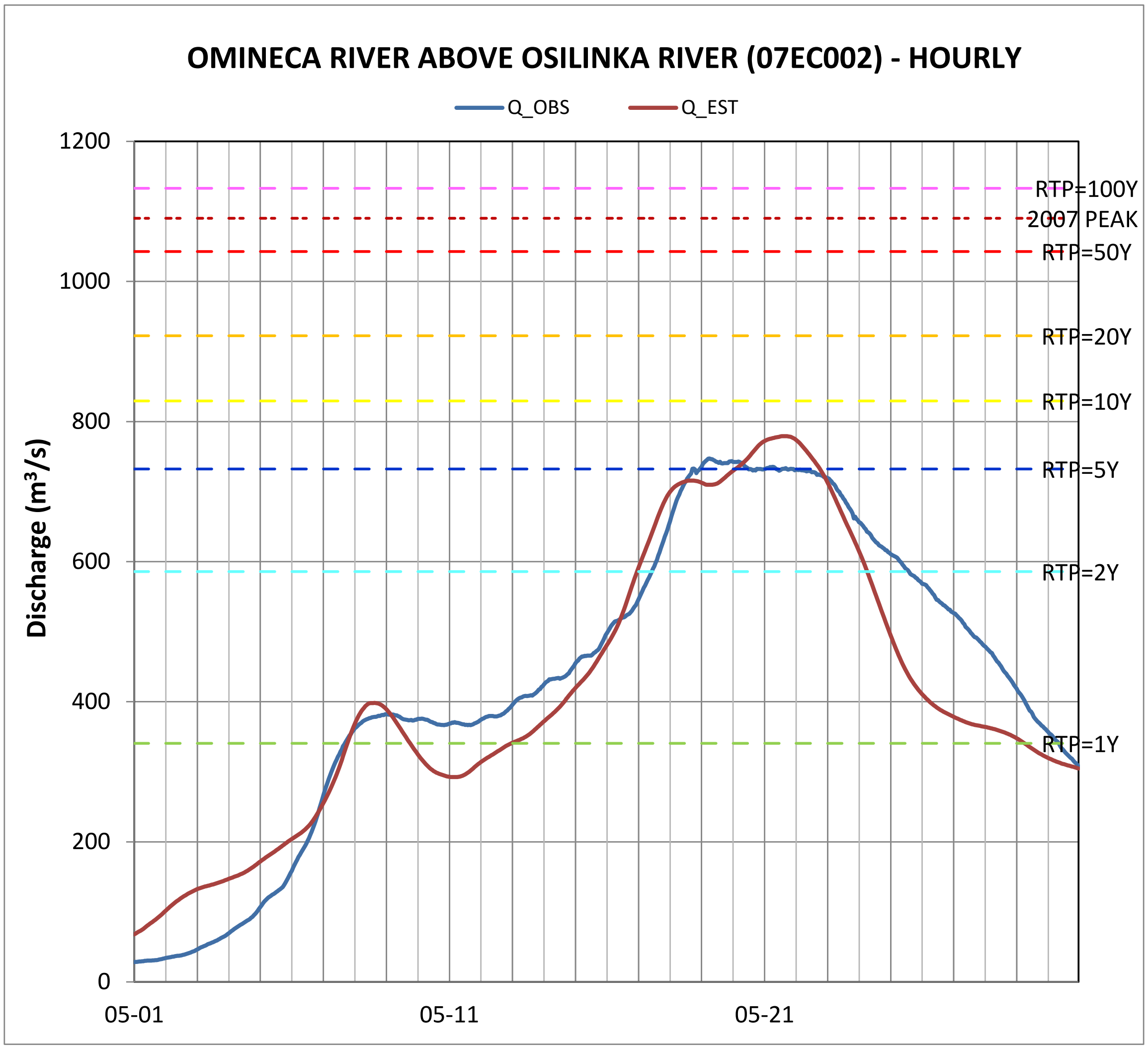


Figure 3. Reconstructed model calibration chart for OMINECA RIVER ABOVE OSILINKA RIVER (07EC002) for May 21, 2023

2.4 Hypothetical “observed” hydrograph for 2024

Figure 4 is the hypothetical “observed” hydrograph for the OMINECA RIVER ABOVE OSILINKA RIVER (07EC002) for from May 1 to 30, 2024. Comparing with the 2023 observed hydrograph, the hypothetical 2024 hydrograph rises and peaks 2 days earlier, and the peak is 30% higher (1.3 times) and 1 day narrower.

The climate conditions are exactly the same as those in 2023.

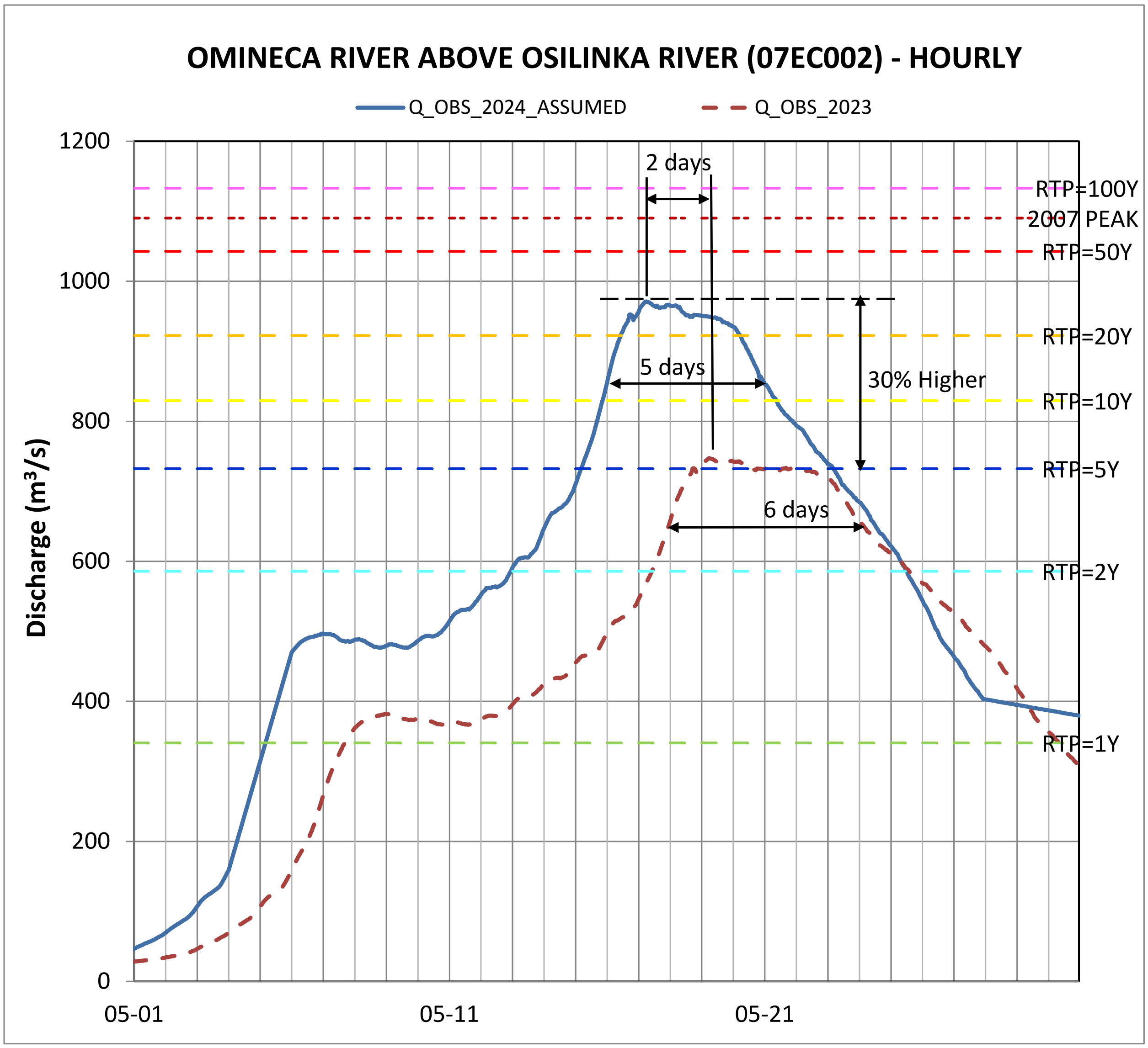


Figure 4. Hypothetical observed hydrograph for OMINECA RIVER ABOVE OSILINKA RIVER (07EC002) for from May 1 to 30, 2024

2.5 Calibrating CLEVER Model for hypothetical "observed" hydrograph for 2024

In order to reproduce the hypothetical "observed" hydrograph with exactly the same climate data that were used to calibrate the model for the observed hydrograph shown on Figure 3, five watershed parameters were changed. Figure 5 shows the watershed parameters that were calibrated (in red rectangles).

WATERSHED	OMINECA RIVER ABOVE OSILINKA RIVER (07EC002)						OMIN
AREA (km2)	5519	R (07EC002) - DAILY				WATERSHED TYPE	Natural
AVERAGE ELEVATION (m)	1200	07EC002) - HOURLY					
STORAGE CONSTANT	5.40	CALCULATED FROM AREA AND FACTOR: 1 - 15					
FACTOR TO STORAGE CONSTANT	1.25	CHANGE SHAPE OF HYDROGRAPH, GREATER, FLATTER					
HYDROGRAPH CONSTANT	1.00	CHANGE PEAK OF HYDROGRAPH, GREATER, HIGHER					
FAST FLOW (%)/PEAK SHIFT (h)	1	-24	1	1- RUN GROUNDWATER MODEL			
BASE FLOW (m3/s)	1		0	INITIAL GW STORAGE (mm)			
SOIL MOISTRUE DEFICIT (mm)	0.00		2000	MAX GW STORAGE (mm)			
INFILTRATION RATE (mm/h)	0.48		1000	GW RELEASE THRESHOLD (m3/s)			
EVAPOTRANSPIRATION(mm/h)	0.05		0.48	RATE OF RELEASING (1/HOUR)			
ROS MELT(1/C/h)/GLACIER MELT F	0.100	0.055	0.0	LEAK(-)/SOURCE(+)(m3/s)			
SNOWMETL RATE (mm/C/h)	0.240	0.025	0.050	Cd FOR MAR-01/APR-01			
POWER BETA/POWER ALPHA	0.70	0.500	05-05	DATE AS OF WHICH Cd=1			
NUMBER OF CLIMATE STATIONS	ID	WEIGHT	EL (m)	dTX_C	dTN_C	dP_mm	P_factor
3	LVC	0.5	990	0.0	0.0	-10.0	0.50
	MSN	0.3	1047	0.0	0.0	-10.0	0.50
	AKL	0.2	1065	0.0	0.0	-10.0	0.50
<-GO TO MODEL FILE							
<-GO TO FIGURE SHEET		1	RAINFALL PT: 1-INTE,2-COAST				1
	NEW	OLD		UPDATE DISCHARGE DATA ONLY			
INITIAL SWE (mm)	600	600					
				dTX_C	dTN_C	dP_mm	
METHOD OF EXTENDING TO 10 DAY FORECAST			1	0.0	0.0	0.0	
1 - STATIC (T&P AS LAST DAY)/2 - STATIC (T&P AS SET)			1-THIS STN ONLY		EXPORT FORECAST FOR THIS WATERSHED		
3 - FLAT WITH INCREMENT AS SET			2-ALL SUB BASINS				
4 - LINEAR WITH UNIFORM SLOPE			3-DOWSTREAM				
			4-ENTIRE GROUP			1	
RIVER ROUTING METHOD	1	(1-CHANNEL, 2-LAKE)			ADDITIONAL INFLOWS FOR		
	dX(Km)	dT(s)	dX/dT				
	20	3600	5.556				
FLOW GAUGE ELEVATION (m)	700		1 - RE-LOAD		RE-CALIBRATE THIS WATERSHED		
DISTANCE FM WTSH CENTRE (Km)	100		INPUT FILES				
SLOPE (S0)	0.005000		BLANK(DEFAULT) -				
MANNING ROUGHNESS (N)	0.1		NOT RE-LOAD INPUT FILES				
RIVER WIDTH (m)	90						
TOTAL NUMBER OF dX	5		FORECAST BIAS-CORRECTION (%):				100
TOTAL NUMBER OF dT	720					Linear Hours	0

Figure 5. Fiver watershed parameters calibrated (in red rectangles)

Comparing Figure 5 with Figure 2, the FACTOR TO STORAGE CONSTANT is reduced from 1.5 to 1.25 so that the STORAGE CONSTANT becomes 1 day shorter (from 6.4 days to 5.4 days). The PEAK SHIFT changes from 0 hour to -24 hours, which means that the estimated peak is shifted backward 24 hours. The INFILTRATION RATE is reduced from 0.50 mm/h to 0.48 mm/h. The groundwater RATE OF RELEASING increases from 0.3 (1/hour) to 0.48 (1/hour). And the DATE AS OF WHICH Cd=1 is set to May 5, 2023, which is two days earlier than that in Figure 2. With the above changes to the five parameters, the simulated hydrograph is successfully moved two days earlier with a narrower peaking period even though the peak is overestimated slightly (only by 7%) (Figure 5).

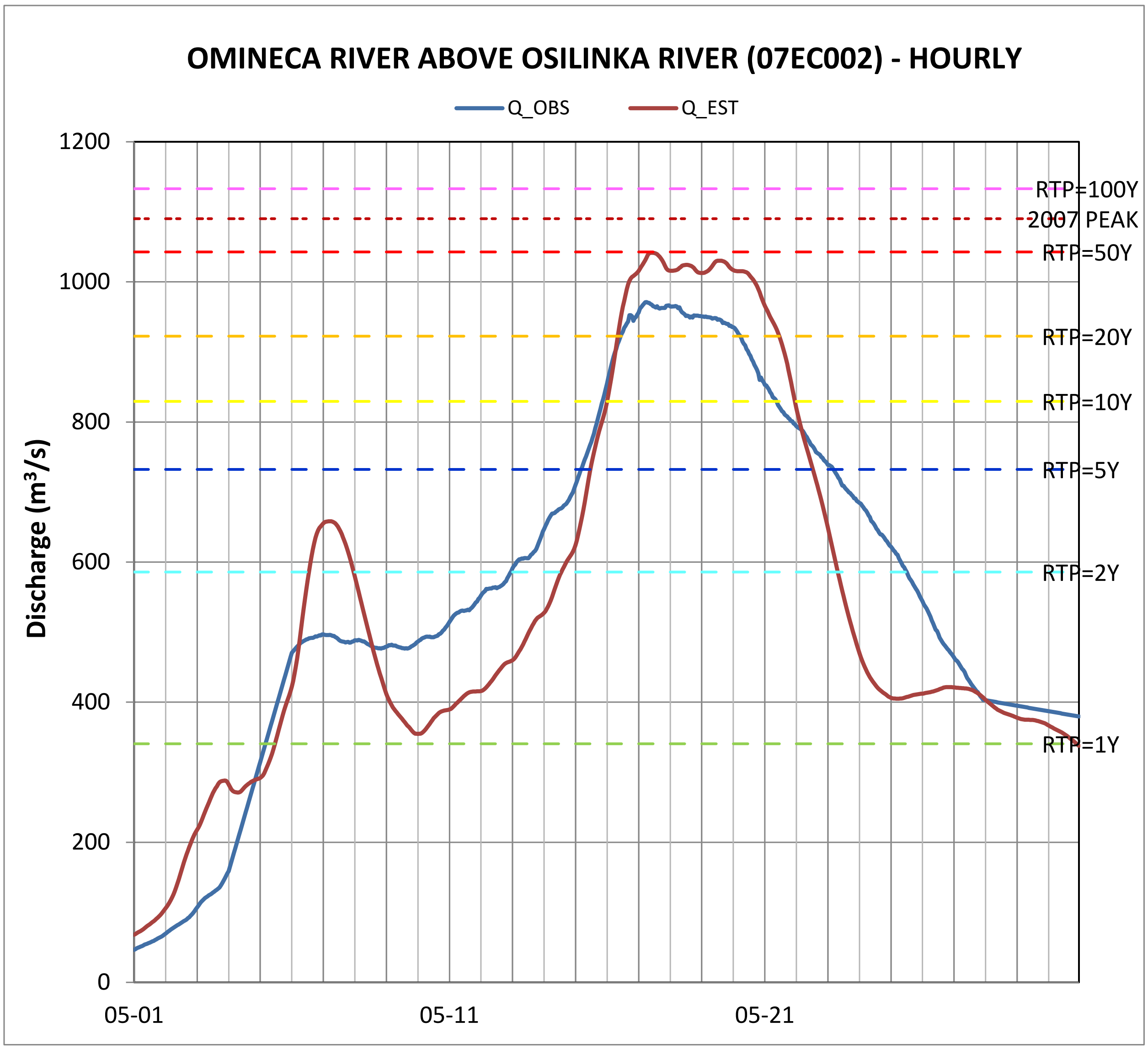


Figure 6. Model calibration chart for the hypothetical "observed" hydrograph for OMINECA RIVER ABOVE OSILINKA RIVER (07EC002) for from May 1 to 30, 2024

Figure 7 is comparison of estimated hydrographs of the 2023 calibration for the real-time observed hydrograph and the 2024 calibration for the hypothetical hydrograph. This figure shows that the CLEVER Model can be efficiently calibrated for different watershed physiographic characteristics even though the input climate data are exactly the same.

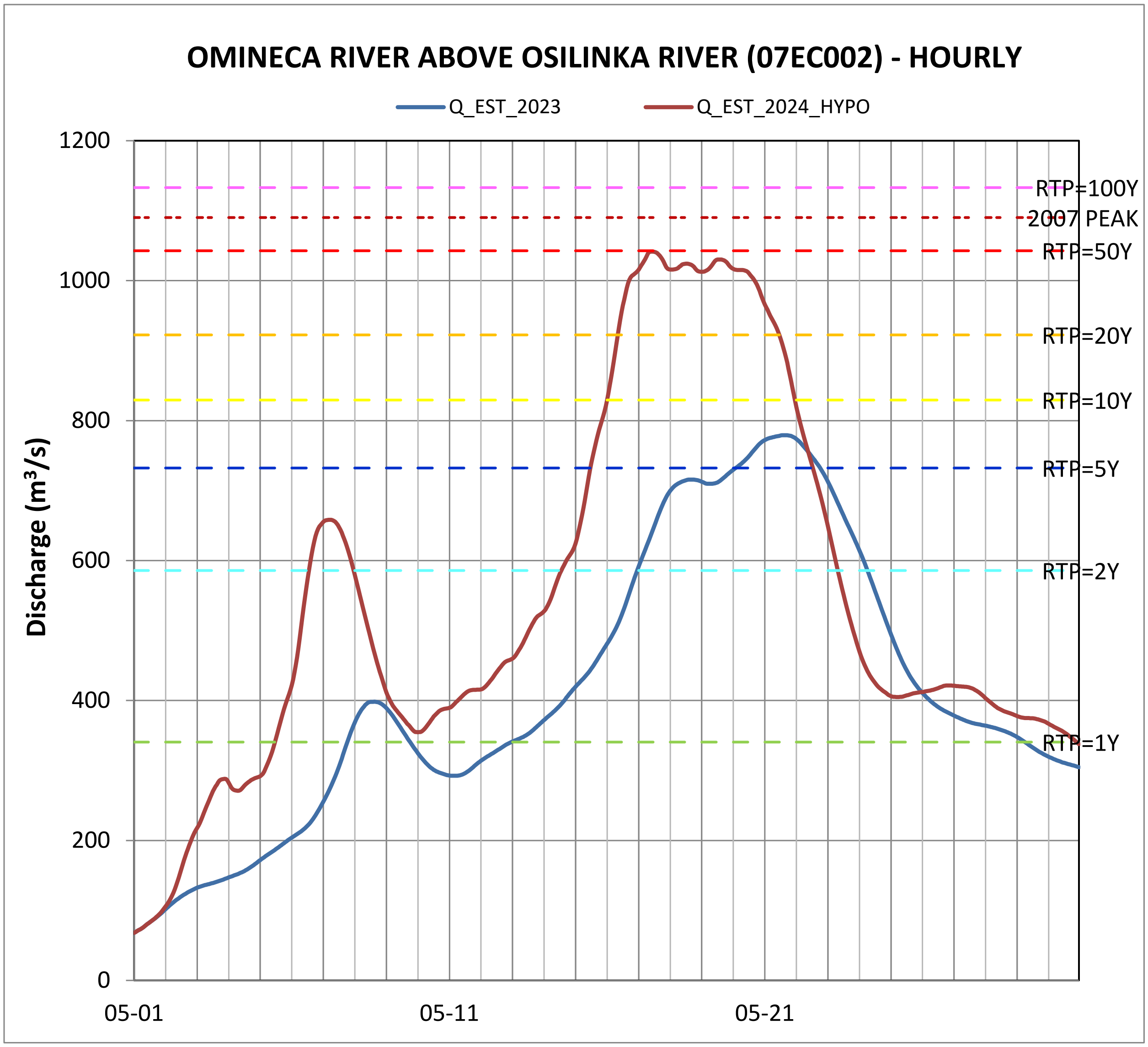


Figure 7. Comparison of model estimated hydrographs for 2023 observed flow and 2024 hypothetical flow

3. Calibrating watershed parameters for COFFEE Model for climate change

The COFFEE Model (Luo, 2018) is basically a unit hydrograph (UH) model that was originally developed for the coastal watersheds, in which floods are mostly the consequence of coastal storm. Most of the watersheds have a much smaller drainage area than those modeled by the CLEVER Model. E.g., the watershed area of one of the COFFEE Model watersheds the ZEBALLOS RIVER AT MOOK PEAK (08HE008) is only 13.5 km^2. The most direct impacts of climate change may be deforestation by wildfires, which has a hydrological consequence of more net rainfall input or snow accumulation. For such a small watershed, this in turn results in increasing of the peak magnitude and decreasing peaking time, which may be as short as a few hours. A few hours shorter of peaking time does not make sense for the COFFEE Model which adopts a daily time step.

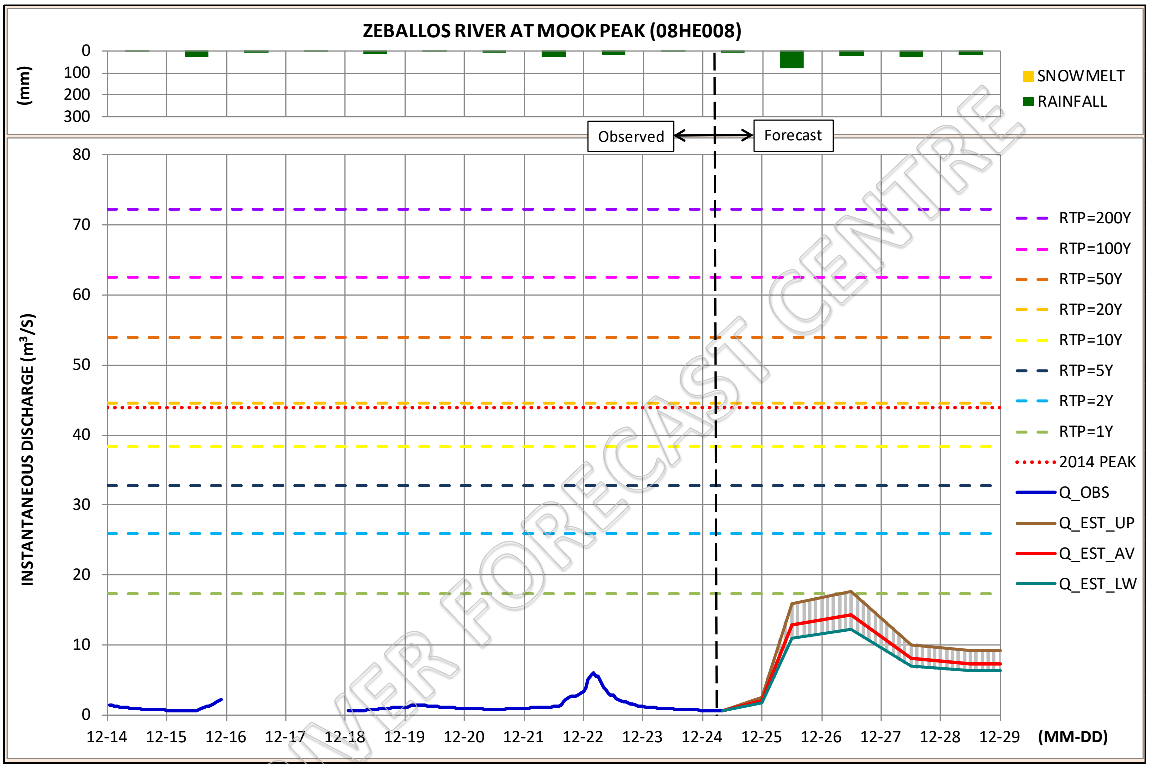
Figure 8 shows the watershed parameters for the ZEBALLOS RIVER AT MOOK PEAK (08HE008) in the COFFEE Model, and the left chart is the original calibration and the right chart is a hypothetical calibration with the P_factor doubled. Figure 9 shows the calibration results (forecast hydrographs) of the above scenarios. It can be seen that the estimated peak for the hypothetical scenario is also about twice that of the original scenario.

ZEBALLOS RIVER AT MOOK PEAK (08HE008)					ZBMP
A(km2)	13.5			Q	NATURAL
ELEV(m)	226				
COEFF	VALUE	UNIT		ADD INFLOWS	
UH/MIN	0	4	days	WTS	T LAG (d)
ADJ UHD	1.00	AV/MIN	MAX		
COEF Q	1.00	1.00	1.00		
BS Q +/-	0	m3/s	0.4882		
SOIL MD	2	mm	0.477		
INFILTR	2	mm/d	BASE Q		
EVAPOTR	1	mm/d		UPDATE FORECAST for this watershed	
SWE0	0	mm			
SM RATE	1.0	mm/C/d			
NO STN	ID	WEIGHT	EL (m)	dP_mm	P_factor
3	TAL	0.5	130	0.0	1.00
	WOC	0.3	156	0.0	1.00
	WRU	0.2	92	0.0	1.00

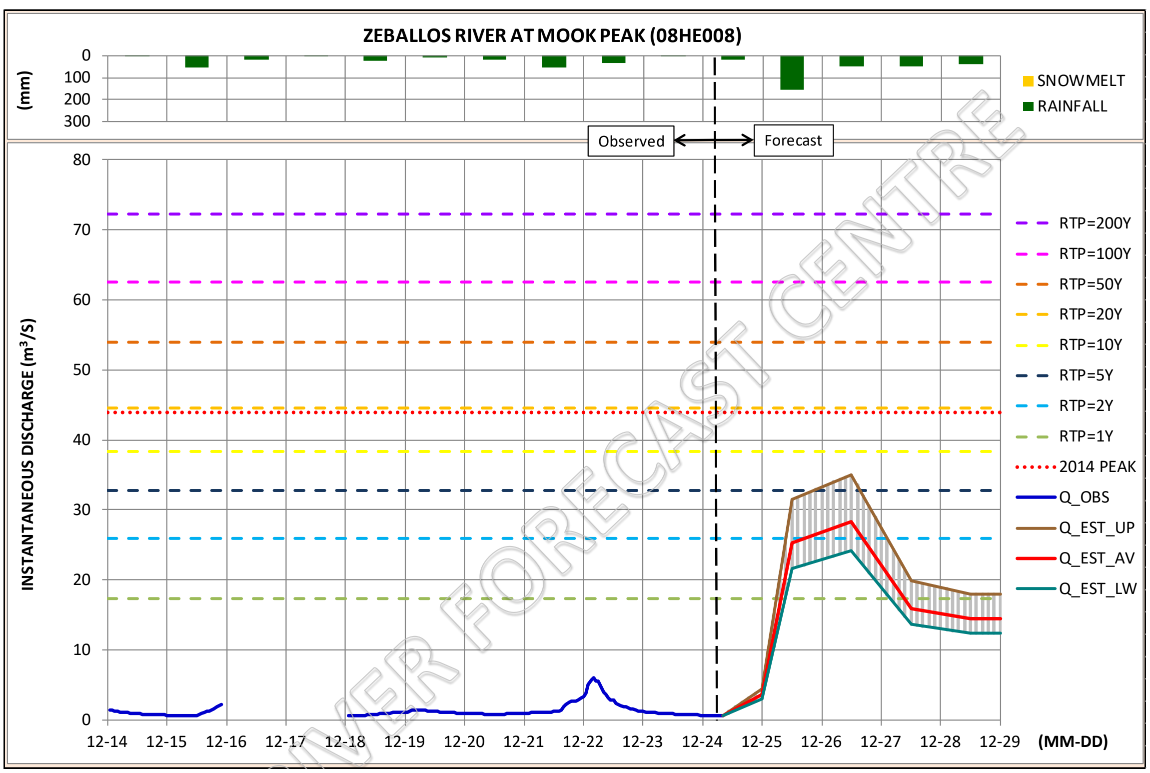
ZEBALLOS RIVER AT MOOK PEAK (08HE008)					ZBMP
A(km2)	13.5			Q	NATURAL
ELEV(m)	226				
COEFF	VALUE	UNIT		ADD INFLOWS	
UH/MIN	0	4	days	WTS	T LAG (d)
ADJ UHD	1.00	AV/MIN	MAX		
COEF Q	1.00	1.00	1.00		
BS Q +/-	0	m3/s	0.507352		
SOIL MD	2	mm	0.49828		
INFILTR	2	mm/d	BASE Q		
EVAPOTR	1	mm/d		UPDATE FORECAST for this watershed	
SWE0	0	mm			
SM RATE	1.0	mm/C/d			
NO STN	ID	WEIGHT	EL (m)	dP_mm	P_factor
3	TAL	0.5	130	0.0	2.00
	WOC	0.3	156	0.0	2.00
	WRU	0.2	92	0.0	2.00

(a) Original calibration (b) hypothetical calibration with P_factor doubled

Figure 8. COFFEE Model watershed parameters for ZEBALLOS RIVER AT MOOK PEAK (08HE008)



(a) Original calibration



(b) hypothetical calibration with P_factor doubled

Figure 9. Calibration results for ZEBALLOS RIVER AT MOOK PEAK (08HE008)

The COFFEE Model is deemed to be a pre-calibrated model, but it can be recalibrated at any time. Typically, it is recalibrated after a major rainfall event or a storm so that the watershed parameters reflect the latest changes in the watershed physiography caused by climate change such as wildfires and/or human activities such as logging/clearcut and building of forest roads.

4. Conclusions

From the above discussion and analysis, it can be concluded that the BC RFC operational real-time flood forecasting models, the CLEVER Model and the COFFEE Model, can be calibrated efficiently and accurately to the fast changing watershed physiography due to climate change and human activities once the signals of changes of watershed physiography show up in the input stream flow data.

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