The cumulative effects of forest disturbance and climate variability on water resources sustainability in the Similkameen River watershed

(Final Report)

Submitted to Roger Huston
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December 2016

Executive summary

Water resource sustainability is pivotal for community development and environmental protection, particularly in water resource-limited regions. Forest cover change and climate variability are commonly recognized as two major drivers influencing water resource change in forested watersheds. Understanding and managing future water resource availability require comprehensive assessments on how those two drivers affect water resource in any forest-dominant watersheds. The Similkameen River watershed, located in the southern interior of British Columbia, supports several communities, and there is a growing concern over the effects of recent significant mountain pine beetle (MPB) infestation and climate change on water resource sustainability in the watershed. To address this concern, Regional District of Okanagan-Similkameen (RDOS) contracted University of British Columbia (Okanagan) to investigate the possible effects of forest disturbance and climate variability on hydrology in this large-sized watershed (7566 km^2 of the drainage area situated in British Columbia, Canada).

In this report, we first assessed the levels of forest disturbance in the whole Similkameen River watershed as well as its three nested sub-watersheds. Up until the year 2011, the cumulative equivalent clear-cut area (CECA) reached 45.5% of the Similkameen River watershed. Logging accounted for 18.6% and the MPB infestation, which occurred in 2003, accounted for approximately 22.6% in 2011. Forest fires occurred occasionally and the resulting CECA was about 0.8% in 2011. In addition, forest disturbance in three nested sub-watersheds including Similkameen River at Princeton (SRP: 1810 km^2), Tulameen River (1780 km^2), and Similkameen River near Hedley (SRH: 5580 km^2) are 37.1%, 36.7%, and 55.7% of the respective watershed areas. In summary, the whole Similkameen River watershed was heavily disturbed.

We then examined the impacts of forest disturbance on annual mean flows in those three nested sub-watersheds because of availability of long-term hydrology and disturbance data. Two commonly used methods including modified double mass curves (MDMC) and sensitivity-based methods, along with various other statistical analyses were employed for this study. Our results showed that forest disturbance increased annual mean flows of 22.15 mm in the SRP watershed, 21.53 mm in the Tulameen River watershed, and 17.37 mm in the SRH watershed. The relative contributions of forest disturbance to the annual mean flows were 47.70%, 54.89%, and 47.49% in the SRP, Tulameen River, and the SRH watersheds, respectively, demonstrating that forest disturbance and climate variability played a co-equal role in annual mean flow changes, but in opposite directions. Forest disturbance increased annual mean flows, while climate variability decreased them. The impacts of forest disturbance on annual mean flows were greater than those from climate variability in the Tulameen River watershed. In contrast, climate variability played a more dominant role than forest disturbance in the SRP and SRH watersheds. Thus, we conclude that forest disturbance and climate interactively and significantly affected annual mean flows in terms of both magnitude and direction in all three selected watersheds.

The effects of forest disturbance on high flows were also assessed in those three watersheds. Our time series cross-correlation tests showed that forest disturbance significantly increased high flows in the SRP and SRH watersheds, while no significant correlations were detected in the Tulameen River watershed. Our further analyses using the paired-year approach revealed that high flows in the disturbance periods were 13.7% and 11.0% higher than those in the reference periods in the SRP and SRH watersheds, respectively. In summary, forest disturbance has significantly increased high flows in the SRP and SRH watersheds, which may have significant implications for managing floods and protecting public safety.

Our final assessment was to predict how forest disturbance and climate change may affect future water resources in our study watersheds. In this study, two greenhouse emission scenarios (Representative Concentration Pathway (RCP) 4.5 and RCP 8.5) from the average of six General Circulation Models (GCMs) were used to define future climate trends from 2020 to 2050 in the three study watersheds. The average precipitation does not show a significant trend, while the temperature indicates an increasing trend for each scenario. For example, the increased rate of annual mean temperatures in RCP 4.5 and RCP 8.5 are 0.037 ºC/year and 0.045 ºC/year in the SRH watershed. Our preliminary simulations show that future annual mean flows are likely to decrease in all three study watersheds. Forest disturbance might alleviate water stress in terms of annual mean flows in the SPR and Tulameen River watersheds to some extents, but it may play a limited role in the SRH watershed.

The Similkameen River watershed is currently facing water stress, especially in dry seasons. Under a drier climate in the future, this situation would become even more severe. Despite the fact that forest disturbance would increase water availability in terms of annual mean flows, it may not be a good tool to alleviate the effects of future climate changes as forest disturbance has negative impacts on other hydrological variables (e.g., high flows) and various ecosystem functions. Nevertheless, the key findings from this study will provide regional resource managers with useful information on how forest disturbance and climate interactively affect water resource availability so that they can make better decisions to manage water resources sustainably under future forest and climate changes scenarios. Several recommendations are also provided in this report.

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1. Introduction

Forest disturbance (e.g. logging, mountain pine beetle (MPB) infestation, and fire) and climate variability are two major drivers of hydrologic variation in large forested watersheds (>1000 km^2) (Stednick, 1996; Buttle and Metcalfe, 2000; Sharma et al., 2000; Wei and Zhang, 2010; Wei et al., 2013; Zhou et al., 2015). Understanding how forest disturbance and climate variability affect water resource is a prerequisite for designing management strategies for water resource sustainability and protection of various ecosystem functions. Numerous studies have demonstrated that the effects of forest cover changes or forest disturbance and climatic variability on hydrology can be offsetting (Wei and Zhang, 2010; Zhang and Wei, 2012; Liu et al., 2015a) or additive (Zhao et al., 2008; Zhang et al., 2008; Zhang et al., 2011) depending on their changing directions and magnitudes in a watershed. Because of their interactive influence on water resources between forest disturbance and climate, assessing hydrological effects of either forest change or climate variability alone would not lead to a full understanding of hydrological changes. Thus, it is critical to consider both forest change and climate variability when assessing and managing water resource availability and its variations.

Understanding how forest disturbance and climate variability affect water resources require separating their relative contributions to hydrological changes (Wei and Zhang, 2010; Wei et al., 2013). However, such a separation is a challenging topic. The classic paired watershed experiments at the small watershed scale (<100 km^2) are not suitable for large watersheds as it is impossible to locate suitable reference watersheds to make pairs at the large watershed scale. To address this challenge, researcher have developed various approaches to quantify the relative contributions of forest or land cover changes and climatic variability to hydrology; examples of this include double-mass curves coupled with time series analysis (Wei and Zhang, 2010), sensitivity-based method (Li et al., 2007; Zhao et al., 2010), and Tomer-Schilling Framework (Peña-Arancibia et al., 2012; Tomer and Schilling, 2009). Wei et al. (2013) provided a review of these methods, and recommended that because each method or technique has its own strengths and weaknesses, a combination of two or more methods is a more robust approach than using any single method alone.

Another important challenge in large watershed studies is the representation of various forest disturbance types being cumulative over space and time. In order to quantify cumulative forest disturbance of various types, an integrated indicator is needed. Such an indicator should not only represent a variety of forest disturbances but also account for forest disturbance history and recovery processes. Equivalent clear-cut area (ECA) is a widely-used indicator in British Columbia, and it is defined as the area being clear-cut, with a reduction factor to account for hydrological recovery (BC Ministry of Forest and Rangeland, 1999). ECA has been proven to be a good indicator for assessing the relationship between forest disturbance and hydrological variables (Whitaker et al., 2002; Winkler et al., 2005; Chen and Wei, 2008; Lin and Wei, 2008; Wei and Zhang, 2010; Zhang and Wei, 2012; Zhang et al., 2015). Other indicators such as forest cover rate (Liu et al., 2015a), sapwood area (Jaskierniak et al., 2015) and remote-sensing related indicator (e.g. Normalized Difference Vegetation Index (NDVI)) (Yang et al., 2014) have also been used.

The Similkameen River watershed is located in the southern interior of British Columbia. It is split across the international boundary with 7566 km^2 of the drainage area situated in British Columbia, Canada, and 1704 km^2 in Washington State, USA (Summit, 2011). The watershed had been severely disturbed by forest logging and recent MPB infestation. Up until 2011, 45.5% of the watershed had been disturbed. In addition, the watershed belongs to a semi-arid region where water is of great importance for communities and environmental protection. Due to significant forest disturbance and concern over future climate change impacts, a critical need has been identified by the Regional District of Okanagan-Similkameen (RDOS) to assess how forest disturbance and climate variability had affected, and will affect, water resources in the watershed.

Through a contract with UBC (Okanagan), this report addresses the following objectives: 1) quantification of the cumulative forest disturbance levels in three nested watersheds along Similkameen River including Similkameen River at Princeton (SRP), Tulameen River watershed, and Similkameen River near Hedley (SRH); 2) quantification of the relative contributions of forest disturbance and climate variability to annual mean flows in those three selected watersheds; 3) evaluation of the effects of forest disturbance on high and low flows; and 4) prediction of water availability under future climate change and forest disturbance scenarios.

2. Watershed descriptions

The Similkameen River is an international watershed with its headwater in Manning Park that drains to Okanogon River in the USA. It is about 196 km in length, with a drainage area of 7566 km^2 in British Columbia, Canada and 1704 km^2 in Washington State, USA (Summit, 2013). It is located in the southern interior of British Columbia between the Coast Ranges Mountains and the Okanagan Valley. The elevations range from 342 to 2627 meters above sea level (Figure 2.1). The climate across the watershed is characterized by warm summers and cool winters (Summit, 2011). The Similkameen River watershed has a typical snow-dominated hydrological regime. Annual peak flows often occur in May or June (Figure 2.2) as a result of snow melting. Agriculture irrigation is the major water consumer within the watershed. The total volume of water used for agriculture irrigation (licenced off-stream volume in Canada) is about 12% of the total annual water yield of the watershed (Similkameen River at Nighthawk (Station Number: 08NL022) in the USA).

According to the biogeoclimatic ecosystem classification (BEC) system used in British Columbia, most of the Similkameen River watershed is located in the Interior Douglas Fir (IDF), Engelmann Spruce Subalpine Fir (ESSF) and Montane Spruce (MS) biogeoclimatic zones. The Ponderosa Pine (PP) zone can also be found in the watershed. IDF dry cold (IDFdk), IDF very hot (IDFxh), and EESF moist warm (EESFmw) zones are located in the lower elevations of the Similkameen River watershed. With increasing elevation, areas are characterized as MS dry mild (MSdm), MS moist warm (MSmw), ESSF dry cold (ESSFdc) and ESSF very dry cold (ESSFxc). The dominant tree species include lodgepole pine (*Pinus contorta*) and interior Douglas fir (*Pseudotsuga menziesi interior*). Ponderosa pine persists as a climax species on drier sites at the lower elevations. Mixed stands of interior Douglas fir and lodgepole pine are extensive on drier sites at moderate elevations. Lodgepole pine commonly dominates the landscapes in the driest regions due to the presence of stand-replacing crown fires, while Engelmann spruce, hybrid white spruce (*Picea engelmannii x glauca*), and subalpine fir (*Abies lasiocarpa*) are the dominant climax tree species on the wetter sites at higher elevations. Trembling aspen (*Populus tremuloides*) is also a widely distributed early-seral species (BC Ministry of Forests, Lands and Natural Resource Operations, 2015).

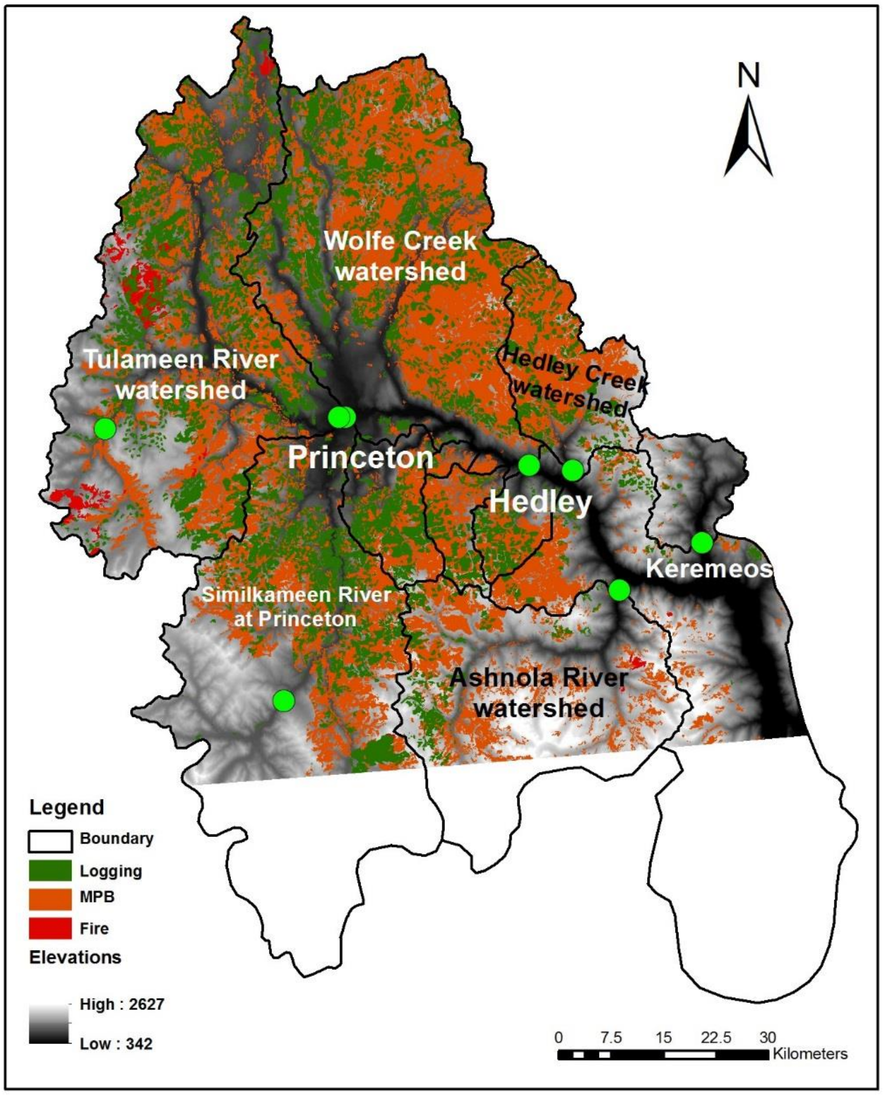

Figure 2.1 Watershed location, elevation, watershed boundaries, major hydrometric stations, and spatial distribution of forest disturbance (logging, Mountain Pine Beetle (MPB) infestation, and fire) in the Similkameen River watershed up until 2011.

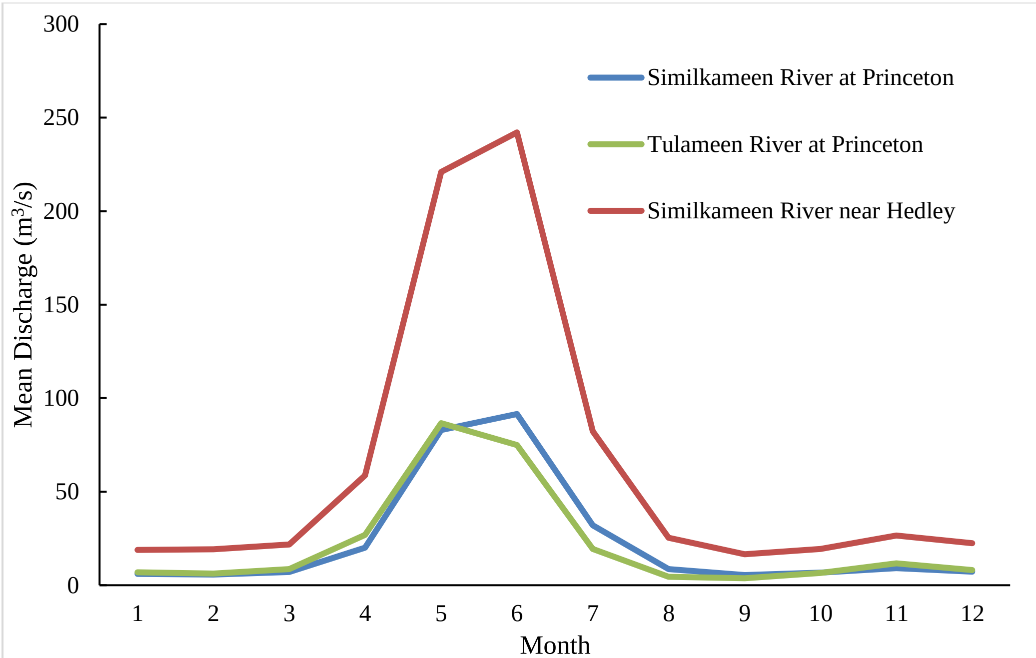

Figure 2.2 Monthly mean discharges in the three watersheds, from upper reaches to lower reaches, in the Similkameen River watershed

In this study, monthly means, maximum and minimum temperatures, and precipitation of the selected watersheds were generated from the ClimateBC dataset (Wang et al., 2006). ClimateBC is a standalone program. It extracts and downscales PRISM (Daly et al., 2002) monthly climate normal data (800 x 800 m) to scale-free point locations, and calculates seasonal and annual climate variables for any specific locations based on latitude, longitude, and elevation. Given the large spatial variations in climate, monthly climate data were derived at the resolution of 800 x 800 m, and area-weighted for each study watershed.

Data on daily stream discharges were downloaded from hydrological data websites maintained by Environment Canada. Three hydrometric stations are used for this study: 1) Similkameen River at Princeton (Station number: 08NL007) with the catchment area of 1810 km^2; 2) Tulameen River at

Princeton (Station number: 08NL024) with the catchment area of 1780 km^2; and 3) Similkameen River near Hedley (Station number: 08NL038) with the catchment area of 5580 km^2.

2.1 Similkameen River at Princeton

The Similkameen River at Princeton (SRP) is 91 km in length, with a drainage area of 1810 km^2, of which 530 km^2 is in the USA (Figure 2.4). Elevation ranges from 630 to 2400 meters above sea level. The average slope is 16.65 degrees. The flow density is 1.24 km/km^2. The average annual precipitation was about 889 mm from 1954 to 2013. Maximum and minimum temperatures are about 8.1 ºC and -2.2 ºC, respectively. Annual runoff depth was 423 mm for the period of 1954 to 2013. The highest monthly flow was 91.5 m^3/s in June and lowest monthly flow was 5.4 m^3/s in September. Currently, the licensed off-streamflow water volume is mainly used for agricultural irrigation and in the mining industry, accounting for 2% of total annual streamflow volume.

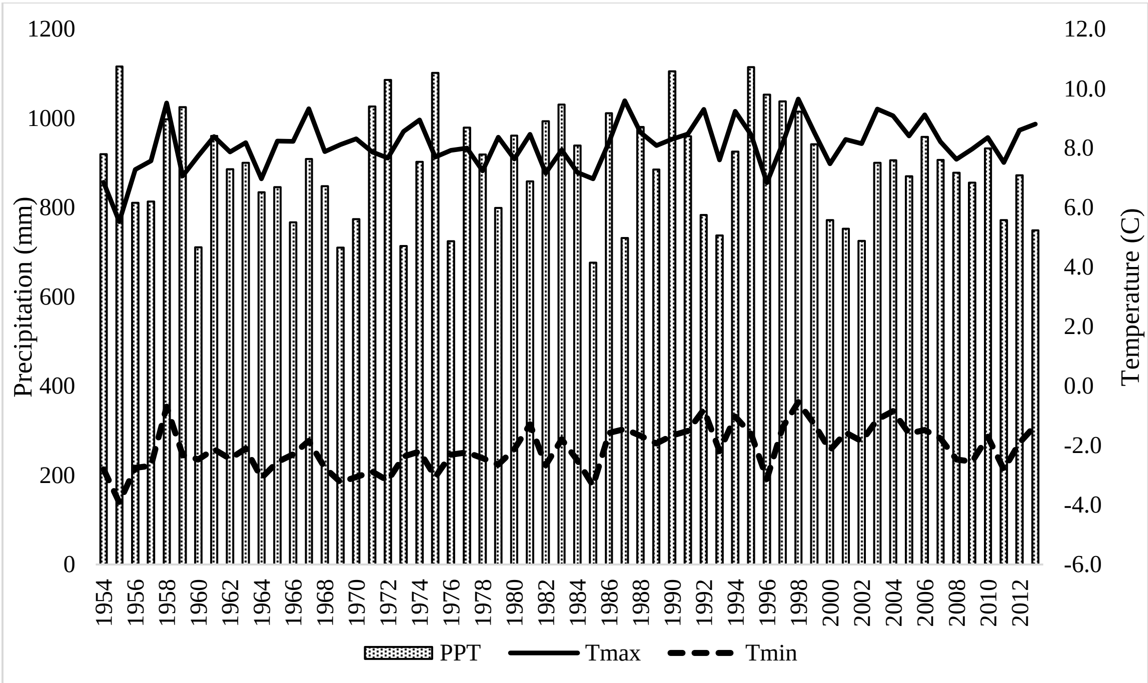

Figure 2.3 Annual precipitation (PPT), maximum (T_{max}) and minimum (T_{min}) temperatures from 1954 to 2013 in the Similkameen River at Princeton

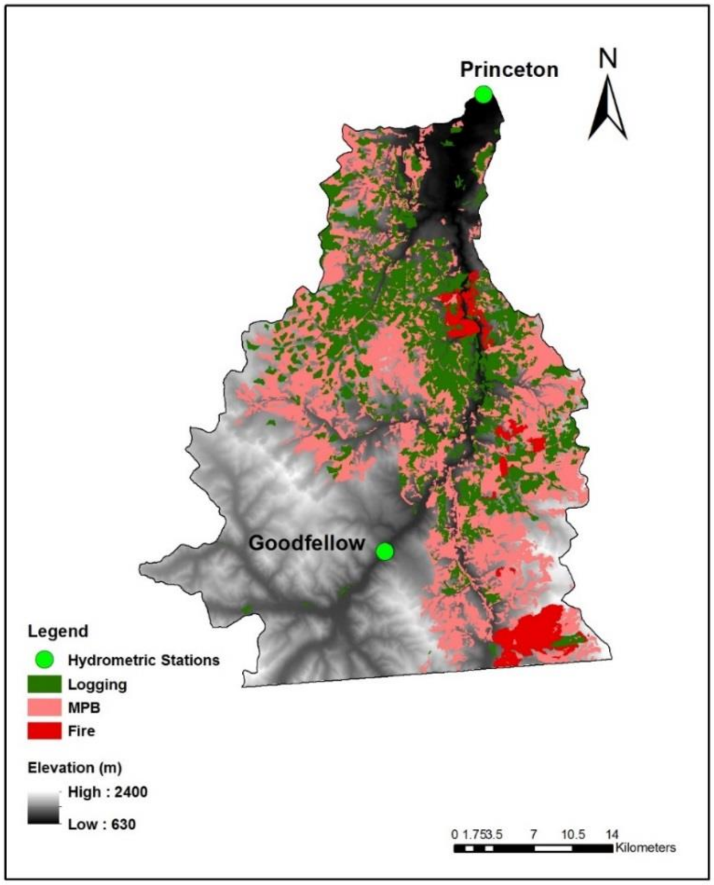

Figure 2.4 Hydrometric stations, elevations, and spatial distributions of forest disturbance (logging, fire, and MPB infestation) in the Similkameen River at Princeton

2.2 Tulameen River watershed

The Tulameen River is the largest tributary of the Similkameen River. It flows into the Similkameen River at Princeton. The drainage area is about 1780 km^2. Elevation ranges from 629 to 2302 meters above sea level (Figure 2.6). The average slope is 14.13 degrees. The flow density is about 0.72 km/km^2. Annual mean precipitation is 926 mm (Figure 2.5). Maximum, minimum, and mean temperatures are 8.7, -1.8, and 3.5 ºC, respectively (Figure 2.5). The annual runoff depth was approximately 391 mm between 1954 and 2013. The highest and lowest monthly flows are

86.6 m^3/s in May and 3.7 m^3/s in September. The licensed off-streamflow water volume is 3.7% of the annual total volume in the Tulameen River.

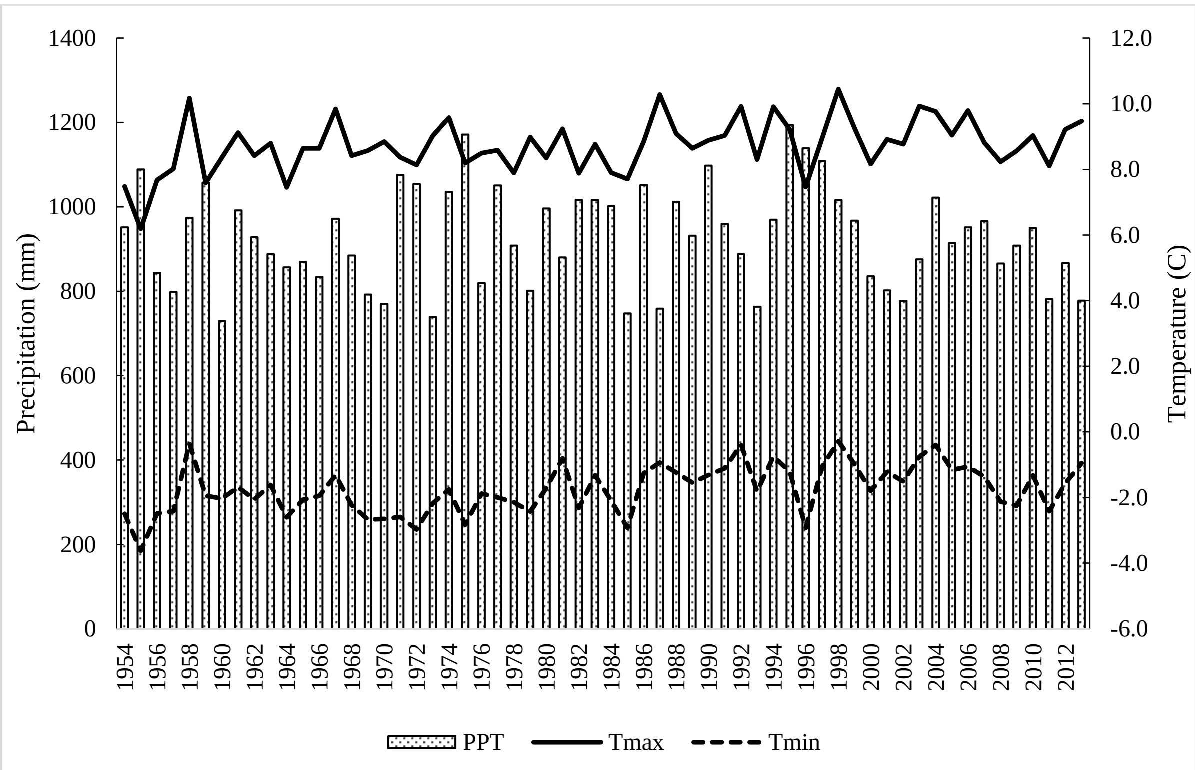

Figure 2.5 Annual precipitation (PPT), maximum (T_{max}) and minimum (T_{min}) temperatures from 1954 to 2013 in the Tulameen River at Princeton

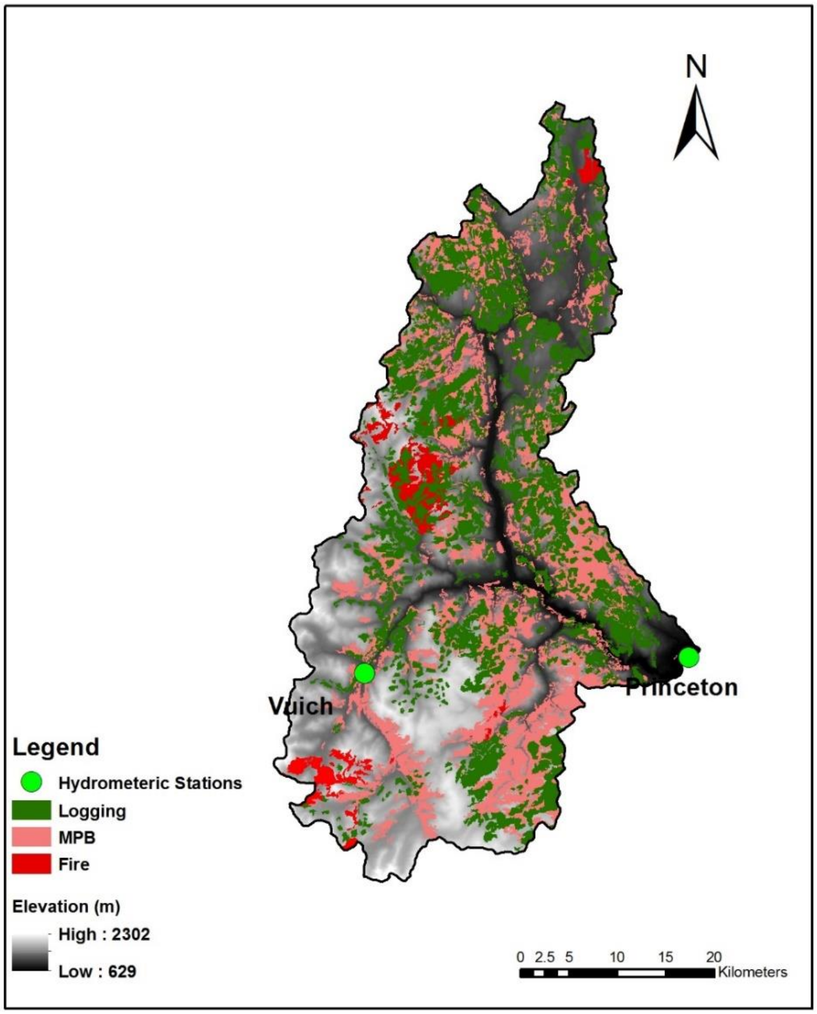

Figure 2.6 Hydrometric stations, elevations, and spatial distributions of forest disturbance (logging, fire, and MPB infestation) in the Tulameen River at Princeton.

2.3 Similkameen River near Hedley

The catchment area of the Similkameen River near Hedley (SRH) is 5580 km^2, of which 540 km^2 is located in the USA. The hydrometric station (Station number: 08NL038) is the last monitoring station on Similkameen River before it flows into the USA. Elevation ranges from 534 to 2400 meters above sea level (Figure 2.8). The average slope is 13.82 degrees. The flow density is about 0.83 km/km^2. Average annual precipitation was 806 mm from 1967 to 2013 (Figure 2.7).

Maximum, minimum, and mean temperatures are 8.6, -1.8, and 3.4 ºC, respectively (Figure 2.7). Average annual runoff depth was 275 mm from 1967 to 2013. The highest and lowest monthly flows are 242.1 m^3/s in June and 16.6 m^3/s in September. The licensed off-streamflow water volume is roughly about 5.8% of total volume measured at the hydrometric station.

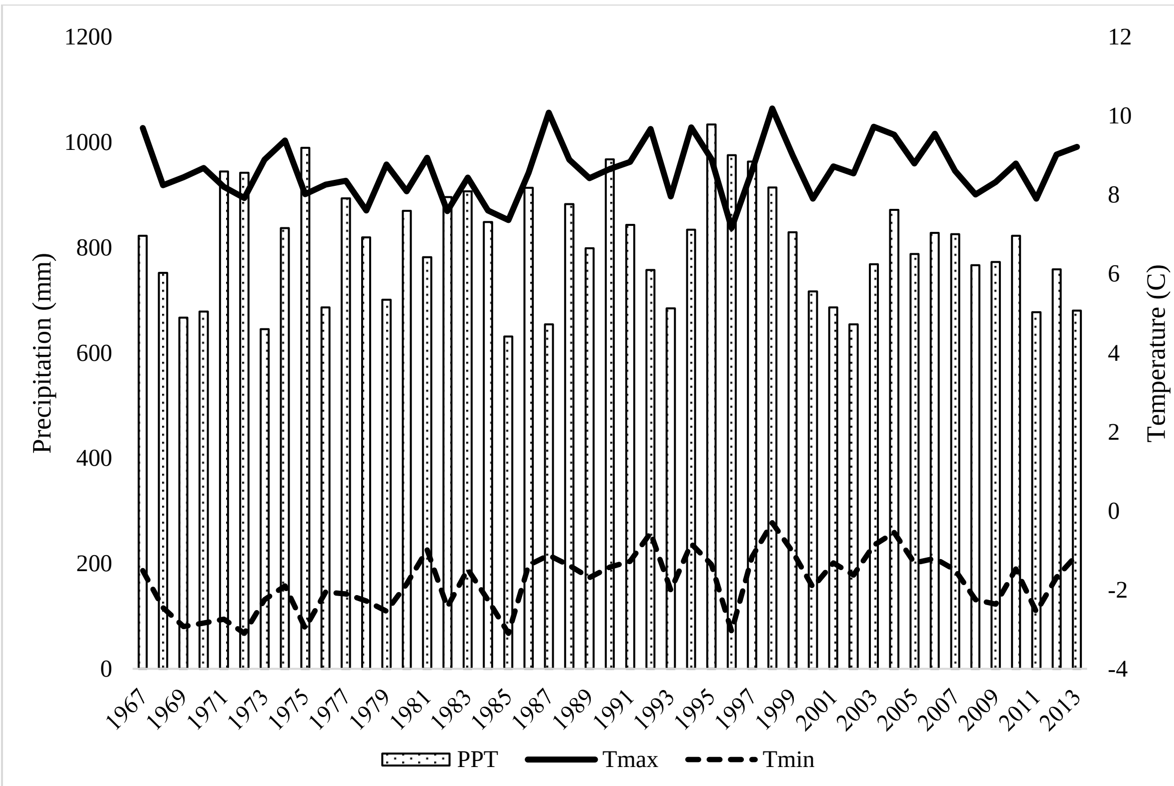

Figure 2.7 Annual precipitation (PPT), maximum (T_{max}) and minimum (T_{min}) temperatures from 1967 to 2013 in the Similkameen River near Hedley

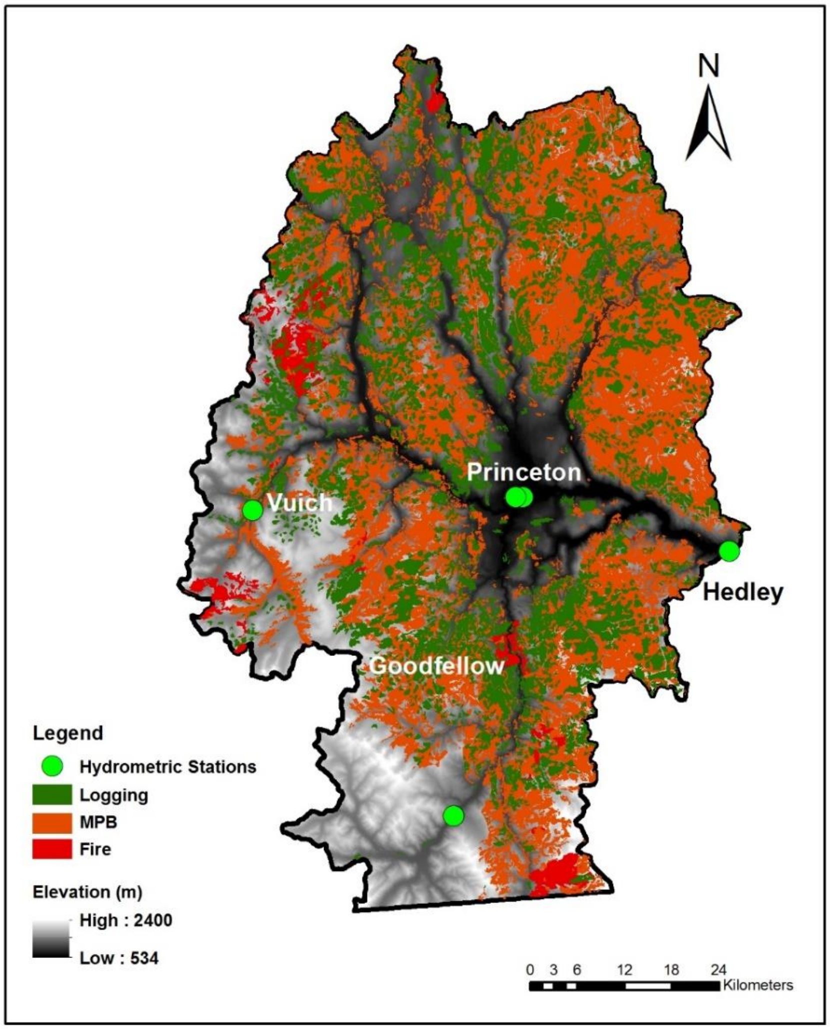

Figure 2.8 Hydrometric stations, elevations and spatial distributions of forest disturbance (logging, fire, and MPB infestation) in the Similkameen River near Hedley

3. Methods

3.1 Quantification of forest disturbance levels

3.1.1 H60 calculation

In the interior of British Columbia, H60 elevation is defined as the elevation of snowline where the upper 60% of a watershed is covered with snow. It has been applied to evaluate the hydrological impacts of forest harvesting (IWAP, 2006). Snow cover above the H60 elevation contributes significantly to high flows in the late spring. As such, forest harvesting in the area above H60 is normally recognized to have more influential impacts on high flows in the British Columbia interior (Gluns, 2011; Whitaker et al., 2002). As suggested from Interior Watershed Assessment Procedure (IWAP), the disturbed area above H60 is multiplied by a weighted factor of 1.5 for CECA calculation (IWAP, 2006).

3.1.2 Hydrological recovery and ECA coefficients

Logging, fire, and MPB infestation are recognized as three major forest disturbance types in the Similkameen River watershed. Since forest disturbances are cumulative over both space and time, cumulative equivalent clear-cut area (CECA) was used in this study as an integrated indicator that combines all types of forest disturbances spatially and temporally with a consideration of vegetation and hydrological recovery following disturbances. Equivalent clear-cut area (ECA) is defined as the area that has been clear-cut, fire-killed or infested by insects, with a reduction factor (ECA coefficient) to account for hydrological recovery due to forest regeneration. An ECA coefficient of 100% means that there is no hydrological recovery in a recently disturbed area, while an ECA coefficient of 0% indicates a full hydrological recovery. The CECA is the sum of annual ECA values. However, hydrological recovery of a forest stand is determined by various factors, including disturbance types, climate, and tree species. Site index is the most common measure of forest site productivity and forest growth used in British Columbia. The relationships between tree growth (expressed by age and tree height) and hydrological recovery rates were generally used to estimate CECA after logging for different tree species, mainly spruce, lodgepole pine, and Douglas fir in the IWAP guidelines (BC Ministry of Forests and Rangeland, 1999). Thus, the relationships of hydrological recovery with ages or height of major tree species were developed based on the site index for the Similkameen River watershed with the dominant site index of 13 (Tables 3.1 to 3.3). Then, the ECA coefficient time series for different tree species after logging or fire and MPB infestation were established based on the IWAP guidelines (Figure 3.1).

Table 3.1 Hydrological recovery according to age (year) and height (m) of main tree species (Lodgepole pine)

Average height of the main canopy (m)	Corresponding age (years)	Hydrological Recovery (%)
0-<3	0-13	15
3-<5	14-19	30
5-<7	20-26	50
7-<9	27-34	70
09-11	35-41	80
11-13	42-51	90
13-15	52-61	95
>15	>72	100

Note: The heights of lodgepole pine are 3, 5, 7 and 9.1m at ages of 5, 13, 20 and 25 years (based on the site index of 13), respectively.

Table 3.2 Hydrological recovery according to age (year) and height (m) of main tree species (Spruce)

Average height of the main canopy (m)	Corresponding age (years)	Hydrological Recovery (%)
0-<3	0-25	15
3-<5	26-33	30
5-<7	34-39	50
7-<9	40-45	70
09-11	46-54	80
11-13	55-61	90
13-15	62-70	95
>15	>70	100

Note: (based on the site index of 13)

Table 3.3 Hydrological recovery according to age (year) and height (m) of main tree species (Douglas fir)

Average height of the main canopy (m)	Corresponding age (years)	Hydrological Recovery (%)
0-<3	0-11	15
3-<5	11-19	30
5-<7	17-27	50
7-<9	23-33	70
09-11	28-40	80
11-13	34-51	90
13-15	41-62	95
>15	>63	100

Note: Based on the site index of 13

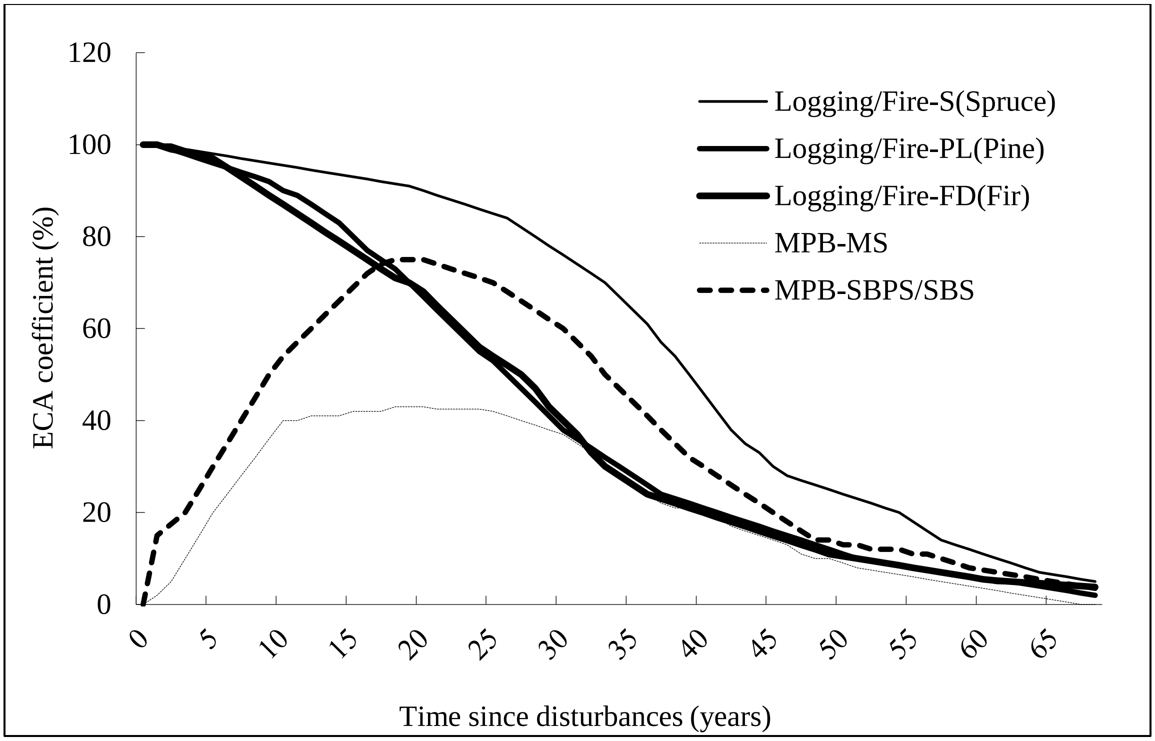

Figure 3.1 ECA coefficients of different forest disturbance types in the Similkameen River watershed

3.1.3 Annual disturbed areas in the Similkameen River watershed

GIS-based data for forest disturbance history of the Similkameen River watershed were obtained from two provincial databases: Cutblocks and Vegetation Resource Inventory (VRI). Both are developed and maintained by the BC Ministry of Forests, Lands and Natural Resource Operations. The Cutblock dataset includes spatial records of cut block sizes and logged years, but detailed vegetation information are not recorded. The VRI database records various disturbance information (e.g. fire and MPB infestation) and provides detailed vegetation descriptions. However, logging records are incomplete due to delayed submissions by forestry industries. As a result, the combination of two datasets are complementary to generate complete records of quantitative forest disturbance history in the Similkameen River watershed. It is also noted that because the detailed forest inventory data in the USA are not available, our calculations were for the watershed areas only located in Canada.

Logging, MPB infestation, and wildfire are three major forest disturbance types in the Similkameen River watershed. A forest stand in the Similkameen River watershed disturbed by either one type (i.e. logging, fire or MPB) or two types of disturbances (logging + fire or logging+ MPB) was considered in the CECA calculations. A stand affected by two types of disturbance is defined as a forest stand which is firstly disturbed by one type and then disturbed by another type (e.g. fire first and then by salvage logging). In this report, the CECA of the entire Similkameen River watershed and its sub-watersheds, including SRP, Tulameen River, Wolfe Creek, Hedley Creek, SRP, and Ashnola River watersheds were calculated in order to get a whole picture of spatial distributions of forest disturbance in the entire Similkameen River watershed (Figure 2.1).

3.2 Statistical methods for assessing relationships between forest disturbance and hydrological variables

3.2.1 Mann-Kendall Trend test

The Mann-Kendall rank correlation coefficient is widely used to detect the significance of trends existing in hydrometeorological time series (Zhang et al., 2008; Zhang et al., 2011). The Mann-Kendall test statistic (*S*) is calculated by

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \qquad (3\text{-}1)$$

$$\text{if } \theta > 0,\ \text{sgn}(\theta) = 1$$

$$\text{if } \theta = 0,\ \text{sgn}(\theta) = 0$$

$$\text{if } \theta < 0,\ \text{sgn}(\theta) = -1$$

where n is the record length of data; x_j and x_k are the sequential data value.

The Mann-Kendall test has two critical parameters for trend detection. The null hypothesis of the trend test is that there is no trend existing in the data and the distribution of *S* is then expected to have a mean of zero and a variance of:

$$\text{var} = \frac{n(n-1)(2n+5)}{18} \tag{3-2}$$

The normal Z-test statistic is calculated by Equation (3-3):

$$z = \frac{S-1}{\sqrt{Var\,(S)}} \qquad \text{if } S \neq 0; \tag{3-3}$$

$$z = 0 \qquad \text{if } S = 0$$

The null hypothesis is rejected at the chosen significance level of α if $|Z| > Z_{(1-\alpha/2)}$, where $Z_{(1-\alpha/2)}$ is the value of the standard normal distribution with a probability of exceedance of α/2. A positive value of *Z* indicates an increasing trend, while a negative value represents a decreasing trend.

3.2.2 Time series cross-correlation analysis

For a large forested watershed, forest disturbance and climatic variability are two primary drivers of hydrological variations. The time series cross-correlation was performed to detect statistical significance of the cause-effect relationships between forest disturbance and hydrological variables (e.g., annual mean flow, high and low flows) for each study watershed (Zhang and Wei, 2014a). This method has been found to be an effective approach to investigate causality among environmental variables since it can not only address autocorrelation issues in data series but also identify lagged causality between two data series with a plausible causal relation (Chatfield, 1989; Jassby and Powell, 1990; Lin and Wei, 2008; Zhou et al., 2010). All hydrological data series along with CECA data series were pre-whitened first to remove autocorrelations by fitting Autoregressive Integrated Moving Average (ARIMA) models (Box and Jenkins, 1976). The white noises or model residuals of selected ARIMA models with the best performance in terms of their achievements of model stationarity were used in time series cross-correlation analysis to test statistical significance of causal relationships between the CECA data series and each hydrological variable.

3.3 Quantification of relative contributions of forest disturbance and climate variability to annual mean flows

3.3.1 Modified Double Mass Curves

The influence of climate variability must be removed or excluded in order to assess the effects of forest disturbance on annual mean flows. The modified double mass curves (MDMC) are used to quantify the relative contributions of forest disturbance and climatic variability to annual mean flows (Wei and Zhang, 2010; Zhang and Wei, 2012; Liu et al., 2015a). According to water balance of a watershed, streamflow is determined by the difference between precipitation (*PPT*), evapotranspiration (*ET*), and changes in soil water storage. The inter-annual changes in soil water storage can be generally assumed to be a constant. Therefore, streamflow variations are mainly affected by precipitation and evapotranspiration. Effective precipitation (P_e) is defined as the difference between precipitation and evapotranspiration (Wei and Zhang, 2010). In the MDMC method, cumulative annual streamflow (Q_a) is plotted against cumulative effective precipitation (P_{ae}) for a large forested watershed (Wei and Zhang, 2010; Zhang and Wei, 2012a; Zhang et al., 2012b). In a period of no or little forest disturbance (reference period), a straight line is expected, describing the linear relation between annual mean flows and annual effective precipitations. Break points can be identified on MDMC if there are significant influences from non-climatic variables, which can be attributed to forest disturbance. Once a break point is identified, a study period can be subsequently divided into reference and disturbance periods.

In this study, the MDMC method was used to detect any break points for each watershed. The Pettitt breaking point test was further used to test statistical significance of each breaking point on MDMC. The Pettitt test has been widely used for detecting abrupt changes in the hydrometeorological data series (Zhang et al., 2008). Before implementation of the Pettitt test, possible autocorrelations and trends existing in the slope of MDMC were removed by the method suggested by Yue et al. (2002). The baseline relationship in each watershed was therefore employed to project cumulative annual mean flows for the disturbance period. The differences between the observed and projected values were treated as annual mean flow deviations caused by forest disturbance (ΔQ_f). Thus, annual mean flow deviations caused by climate variability can be determined as:

$$\Delta Q_c = \Delta Q - \Delta Q_f \tag{3-4}$$

Where, ΔQ, ΔQ_f and ΔQ_c are the total deviations of annual mean flows, annual mean flow deviations caused by forest disturbance and climate variability, respectively.

In this study, monthly potential evapotranspiration (*PET*) was estimated by averaging of Hargreaves and Hamon methods. It was then used to calculate actual evapotranspiration (*ET*) by both Budyko and Zhang's equations (Eqns. (3-8) and (3-9)). The final monthly *ET* estimates were averaged from those two methods or equations.

$$PET_{Hargreaves} = 0.0023 R_a \left[\frac{T_{\max} + T_{\min}}{2} + 17.8 \right] (T_{\max} - T_{\min})^{0.5} \tag{3-5}$$

$$PET_{Hamon} = 0.1651 \times D \times K \times 216.7 \times \frac{V_s}{(T + 273.3)} \tag{3-6}$$

$$V_s = 6.108 \times \exp(17.27 \times \frac{T}{T + 237.3}) \tag{3-7}$$

$$ET_B = \{P[1 - \exp(-PET / P)] \times PET \times \tanh(P / PET)\}^{0.5} \tag{3-8}$$

$$ET_z = P \frac{1 + \omega(PET / P)}{1 + \omega(PET / P) + P / PET} \tag{3-9}$$

where, Eqns. (3-5), (3-6 and 3-7), (3-8), and (3-9) are Hargreaves (Hargreaves and Allen, 2003), Hamon (Zhou et al., 2015), Budyko (Budyko, 1974), and Zhang (Zhang et al., 2001), respectively. R_a is extraterrestrial radiation (mm); *PET* is potential evapotranspiration (mm); T_{max} and T_{min} are maximum and minimum temperatures (ºC); *P* is precipitation (mm); *ET* is actual evapotranspiration (mm); *w* is plant-available water coefficient (*w* =2 used for this study).

3.3.2 Sensitivity based method

The Sensitivity based method has been successfully applied to assess the effects of land cover changes and climate variability on water resource variations (e.g., Jones et al., 2006; Zhao et al., 2010; Liu et al., 2015a). The changes in annual mean runoff attributed to climate variability can be calculated through the following equations:

$$\Delta Q_c = \beta \Delta P + \gamma \Delta PET \tag{3-10}$$

$$\beta = \frac{1 + 2x + 3wx^2}{(1 + 2x + wx^2)^2} \tag{3-11}$$

$$\gamma = -\frac{1 + 2wx}{(1 + x + wx^2)^2} \tag{3-12}$$

where, ΔQ_c, ΔP, and ΔPET are the changes in streamflow attributed to climate variability, precipitation, and potential evapotranspiration, respectively. The parameters β and γ are the sensitive coefficients of streamflow to precipitation and potential evapotranspiration, respectively. The parameter x is the dryness index of a watershed, which is the ratio of potential evapotranspiration and precipitation (PET/P) and w is the plant-available water coefficient (Zhang et al., 2001). Once the streamflow attributed to climate variability is estimated, the streamflow caused by forest disturbance can be estimated through Eqn. (3-10).

3.3.3 Quantification of relative contributions of forest disturbance and climate variability to annual mean flows

The relative contributions of forest disturbance and climatic variability to annual mean flows can be quantified and calculated as:

$$R_f = \frac{\left|\Delta Q_f\right|}{\left|\Delta Q_f\right| + \left|\Delta Qc\right|} \times 100\% \tag{3-13}$$

$$R_c = \frac{\left|\Delta Q_c\right|}{\left|\Delta Q_f\right| + \left|\Delta Qc\right|} \times 100\% \tag{3-14}$$

where, R_f and R_c are relative contributions of forest disturbance and climate variability to annual mean flows, respectively. ΔQ_f and ΔQ_f are the changes in annual mean flows attributed to forest disturbance and climate variability, respectively.

3.4 Quantification of the effects of forest disturbance on high and low flows

3.4.1 High and low flow definitions

The flow duration curve (FDC) is a cumulative distribution function of daily flows over a time interval of interest (Zhang et al., 2014a). It shows the percentage of time that streamflow equals or exceeds a given amount. In this study, flow duration curves for each year were generated using daily flows, with which flows at a given percentile (denoted as *Qp*) were derived. In this study, high flows are defined as the flows that are equal to or are greater than *Q5* (*Q5*: flows exceed 5% of the time in a year), while low flows refer to the flows that are equal to or less than *Q95* (*Q95*: flows exceed 95% of the time in a year) (Liu et al., 2015b; Zhang et al., 2015). Thus, annual high and low flows of the three watersheds were generated for this study. The 7-day minimum flows were also selected to investigate how forest disturbance might affect minimum flows, which are defined as the smallest values of daily mean discharges over any 7-consecutive days during an annual period.

3.4.2 Quantification of the effects of agriculture irrigation on high and low flows

In the Similkameen River watershed, agriculture is an important sector for social, economic and development of communities. Cattle-ranching and fruit growing are two major agriculture activities and water consumers during the growing seasons (from April to September) (Summit, 2013). However, the detailed daily irrigation data were not available. In this report, the licensed off-stream watering was assumed to occur every day from April to September with the same daily irrigation rate. This allows us estimate how much of streamflow was consumed by agriculture irrigation and what the hydrological effects might be.

3.4.3 Quantitative assessment of the impacts of forest disturbance on high and low flows

Time series cross-correlation was firstly adopted to detect significant relationships between forest disturbance and hydrological variables. Once significant relationships between forest disturbance and hydrological variables were found in study watersheds, quantitative assessments were conducted for the selected hydrological variables to evaluate the impacts of forest disturbance on high and low flows. To quantify the impacts of forest disturbances on hydrological variables, the effects of climate variability must be excluded first. The paired-year approach has been applied to numerous watersheds with dramatic forest change (Zhang et al., 2014a; Liu et al., 2015b; Liu et al., 2016), and was applied for this study. In the paired-year approach, a year in a reference period was paired with its comparable year in a disturbed period based on similarities in climate conditions.

In selecting paired climate variables, the first step was to determine the climate variables that are closely related to high and low flows in each watershed. The Pearson, Kendall tau, and Spearman's correlation analyses were used to test the correlations between hydrological variables and possible relevant climatic variables. Using those tests, climate variables that were significantly correlated with hydrological variables were identified. Thus, similar climate conditions between reference and disturbance periods were determined, and consequently the comparable flows were selected for further analysis.

3.5 Predictions of future water resource sustainability under forest and climate changes scenarios

The climate data (precipitation and temperature) for the future period (from 2020 to 2050) were generated from General Circulation Models (GCMs) of the Coupled Model Intercomparison Project Phrase 5 (CMIP5) included in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC, 2015). Two greenhouse gas (GHG) emission scenarios (RCP 4.5 and RCP 8.5) were selected to represent future climate change scenarios in this study. The RCP 4.5 describes the scenario when GHG emissions reach the highest level around 2040. GHG emissions in the RCP 8.5 scenario is assumed to rise throughout the 21st century (IPCC, 2015). The average climate conditions of future climate data from six GCMs (i.e., ACCESS1-0, CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3, and INM-CM4) outputs were generated and applied to predict future water resources in the study watersheds. Time-series data of future annual climate were from ClimateBC for the years between 2011 and 2050 for RCP 4.5 and RCP 8.5 of six GCMs (Wang et al., 2012).

Only two forest disturbance scenarios were adopted to predict future water resources using the relationships established in the MDMCs. The first scenario was to assume that the historic forest disturbance continues for the period of 2020 to 2050. As such, the relationships established between cumulative annual mean flows and cumulative effective precipitations in the disturbance periods were employed for this scenario. The second one was to assume that no or limited forest disturbance would occur in the future in study watersheds. For this scenario, the relationships between cumulative annual mean flows and cumulative effective precipitations in the reference periods were adopted. Two climate scenarios (RCP 4.5 and RCP 8.5) were conducted for each forest disturbance simulation scenario.

4. Results and discussion

4.1 Cumulative equivalent clear-cut areas (CECA)

4.1.1 Forest disturbance in the Tulameen River watershed

The H60 of the Tulameen River watershed is 1300 m. Among three identified forest disturbance types, logging was the leading forest disturbance type. Since 1962, logging activity has steadily increased with an average annual clear-cut rate of 0.42% of the watershed area (Figure 4.1). Logging was accelerated in 1976, 1977, 1991, and 1993, with about 1% annual cutting rate in these years (Figure 4.2). Up until year 2011, the CECA from logging reached 19.9% of the watershed area (Figure 4.1). The MPB infestation is the second dominant disturbance type, which was limited before 2003. Between 2003 and 2007, forests attacked by MPB increased to 20% of the total watershed area. Fires occurred occasionally on small scales. Overall, the Tulameen River watershed has experienced significant disturbance since 1954.

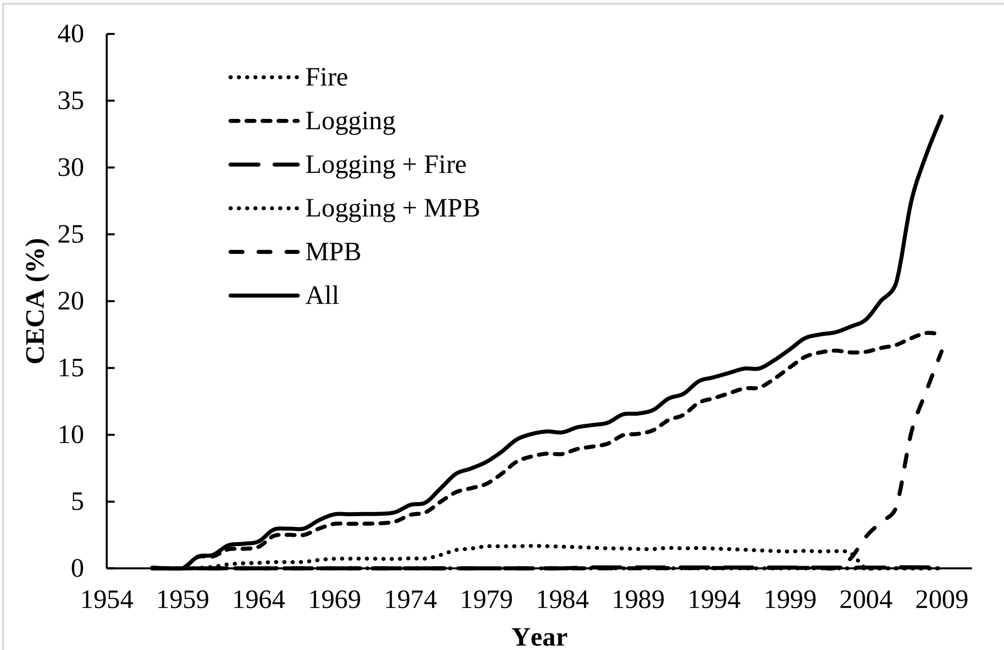

Figure 4.1 Cumulative equivalent clear-cut areas (%) of the Tulameen River watershed from 1954 to 2011

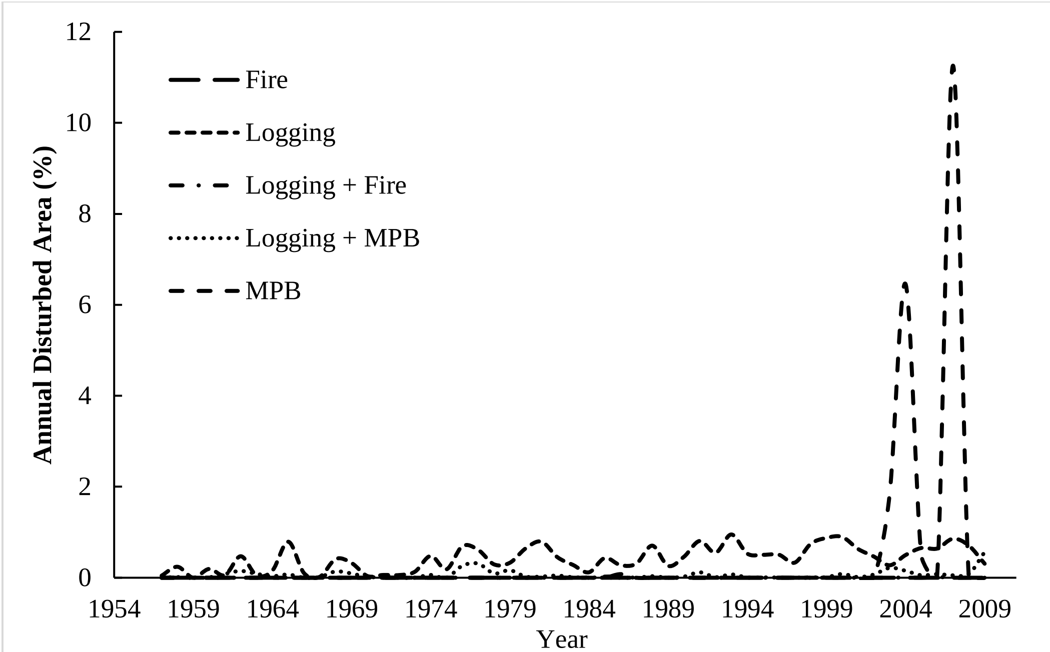

Figure 4.2 Annual disturbed areas (%) of the Tulameen River watershed from 1954 to 2011

4.1.2 Forest disturbance in the Similkameen River at Princeton

The H60 of the SRP is about 1360 m. Logging or post-disturbance salvage logging was the dominant disturbance types in the Similkameen River at Princeton. The upper reaches of the watershed are located in the E.C. Manning Provincial Park where logging is prohibited. The annual area logged is about 0.38% of the watershed area (Figure 4.3). Up until 2011, the CECA from logging was 17.5% of the watershed area. Forest fires happened occasionally throughout the time period with the largest forest fire occurred in 1984. On average, about 1% of the watershed area was burnt (Figure 4.4). MPB was not a significant disturbance type until 2003. About 1.4% and 2.3% of the watershed area were affected by MPB in 2004 and 2007, respectively. The CECA from MPB reached 15.7% of the watershed area in 2011 and the CECA from all disturbance types was 37.1% of the total watershed area in the Similkameen River at Princeton watershed (Figure 4.3).

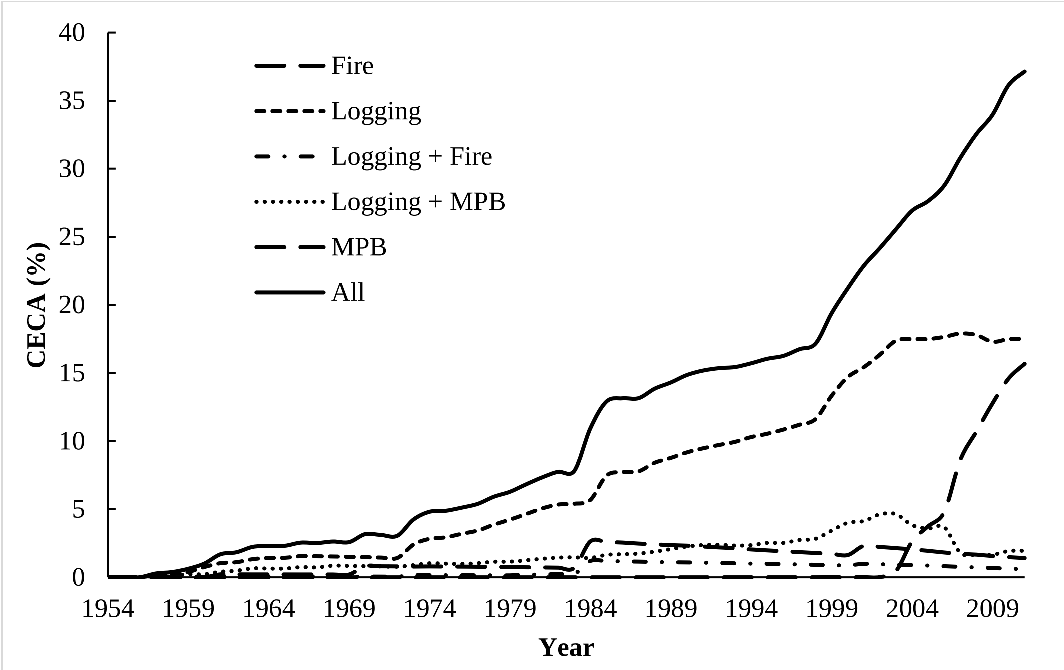

Figure 4.3 Cumulative equivalent clear-cut areas (%) of Similkameen River at Princeton from 1954 to 2011

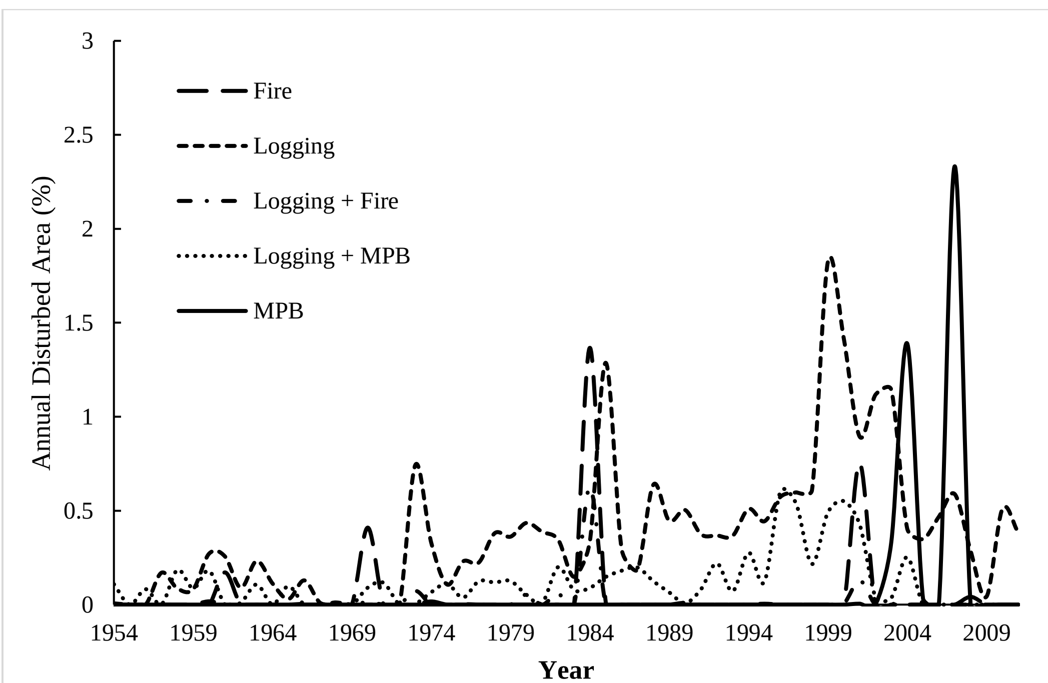

Figure 4.4 Annual disturbed areas (%) of Similkameen River at Princeton from 1954 to 2011

4.1.3 Forest disturbance in the Wolfe Creek watershed

The H60 is 1260 m of the Wolfe Creek watershed (1610 km^2) (Figure 2.1). Logging and MPB infestation were the dominant disturbance types. Logging was the leading forest disturbance type with logging activity steadily increasing over time. The annual logging rate was 0.6% of the watershed area between 1954 and 2011 (Figure 4.5). Up until 2011, the CECA from logging was 33.2% of the watershed area. The CECA from MPB dramatically increased since 2003, and exceeded that from logging in 2007 (Figure 4.6). In 2011, the CECA from MPB was 43.6%. Forest fire rarely occurred in the watershed and the CECA from forest fire was only 0.04% of the watershed area in 2011. In summary, the Wolfe creek watershed was heavily disturbed with the CECA being 79.3% of the total watershed area in 2011.

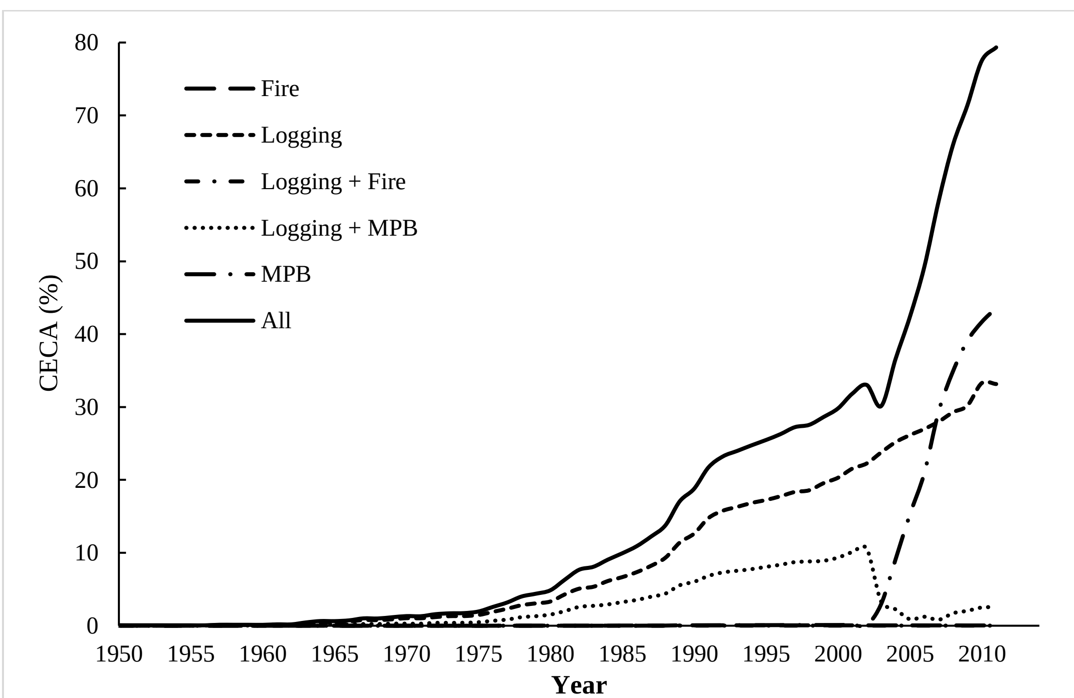

Figure 4.5 Cumulative equivalent clear-cut areas (%) of the Wolfe Creek watershed from 1950 to 2011

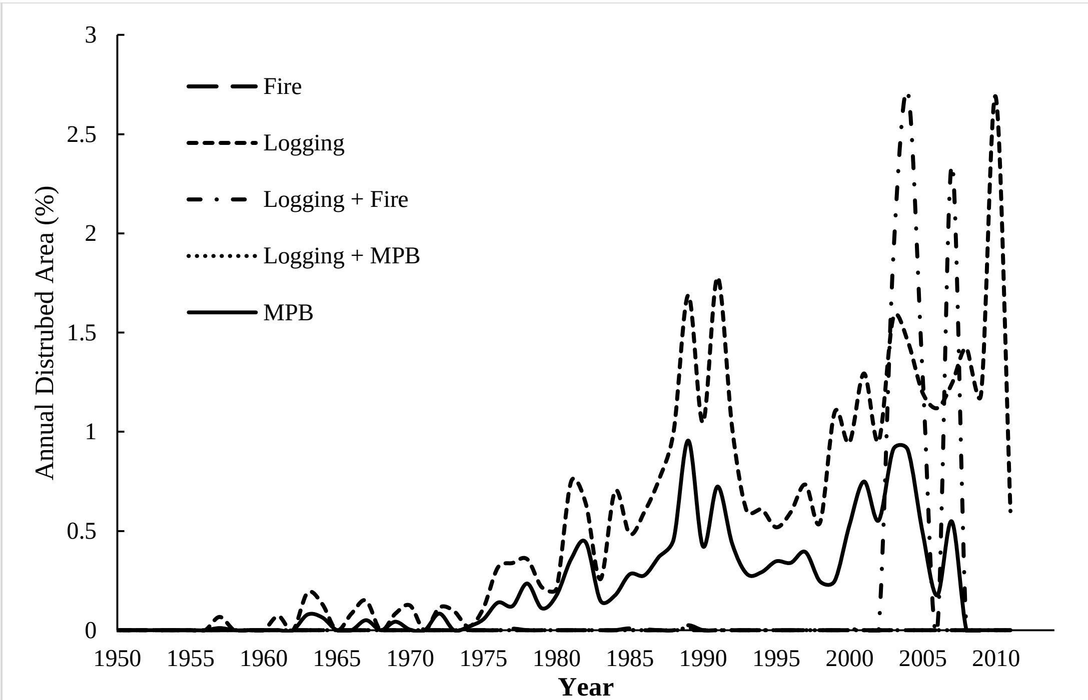

Figure 4.6 Annual disturbed areas (%) of the Wolfe Creek watershed from 1950 to 2011

4.1.4 Forest disturbance in the Similkameen River near Hedley watershed

The H60 of Similkameen River near Hedley (SRH) is about 1305 m. The SRP, the Tulameen River, and the Wolfe Creek watershed are the three major sub-watersheds of the SRH watershed. The Wolfe Creek watershed contributed significantly to the CECA of the SRH watershed. Logging and MPB infestation were the major forest disturbance types in the SRH watershed (Figure 4.7). Logging was the dominant forest disturbance type with the CECA from logging at 24.4% of the SRH watershed area in 2011. The CECA from MPB began to exceed the CECA of logging in 2011 with the CECA from MPB at 25.7% in 2011. Overall, due to the severe forest disturbance in the Wolfe creek watershed, the CECA of the SRH watershed was about 55.7% of the watershed area in 2011.

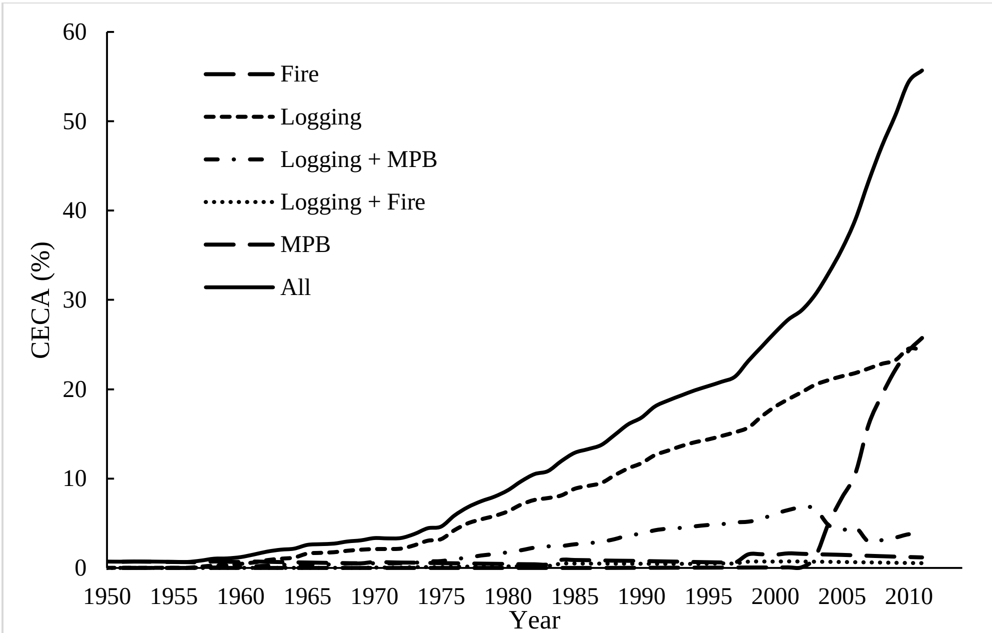

Figure 4.7 Cumulative equivalent clear-cut areas (%) of the Similkameen River near Hedley from 1950 to 2011

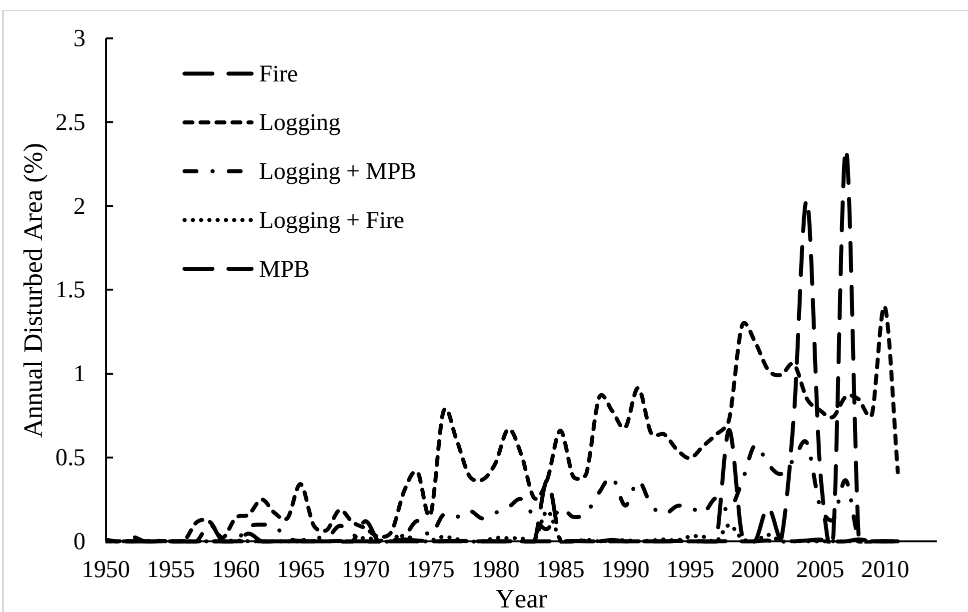

Figure 4.8 Annual disturbed areas (%) of the Similkameen River near Hedley from 1950 to 2011

4.1.5 Forest disturbance in the Hedley Creek watershed

The H60 in the Hedley Creek watershed (388 km^2) is about 1600 m. Logging and MPB infestation were the dominant disturbance types. Logging was the leading forest disturbance type before 2004. Logging started since 1976 with an annual logging rate of 11.4% between 1976 and 2011. The largest logged areas were logged in 1981, 1995, and 2003, which were 1.4%, 1.5%, and 1.9% of the watershed area, respectively (Figure 4.10). In 2011, the CECA from logging was about 21.3%. The CECA from MPB dramatically increased since 2003, with 4.1% in 2003 and 8.9% in 2004 (Figure 4.10). The CECA from MPB was 44.7% of the watershed area (Figure 4.9). The CECA from forest fire was only 0.2% of the watershed area in 2011. In conclusion, the Hedley Creek watershed was heavily disturbed with its CECA being 66.9% of the total watershed area in 2011.

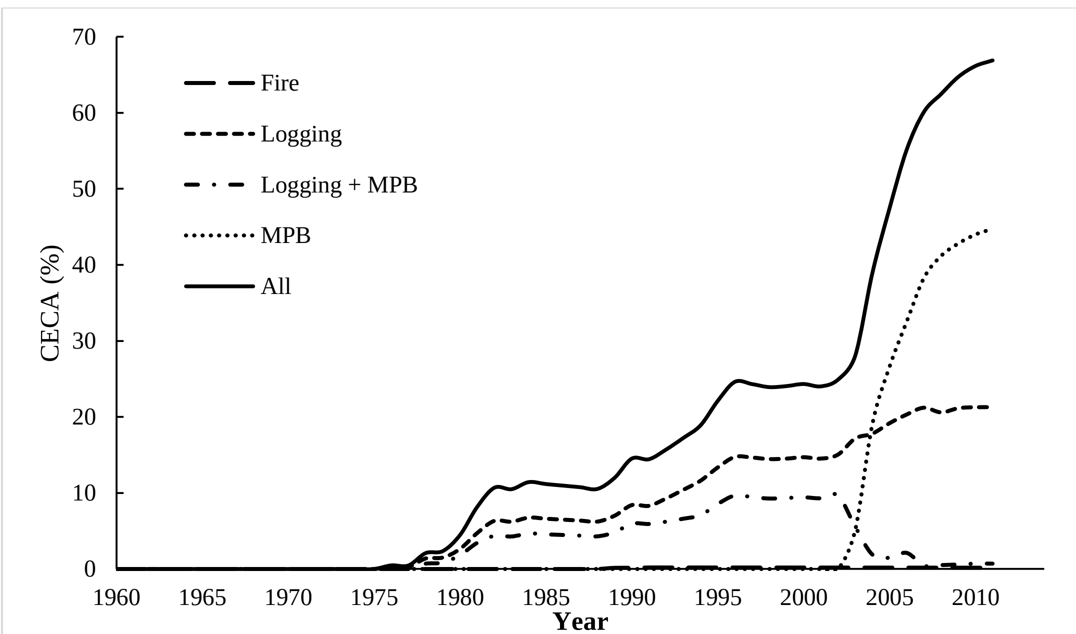

Figure 4.9 Cumulative equivalent clear-cut areas (%) of the Hedley Creek watershed from 1960 to 2011

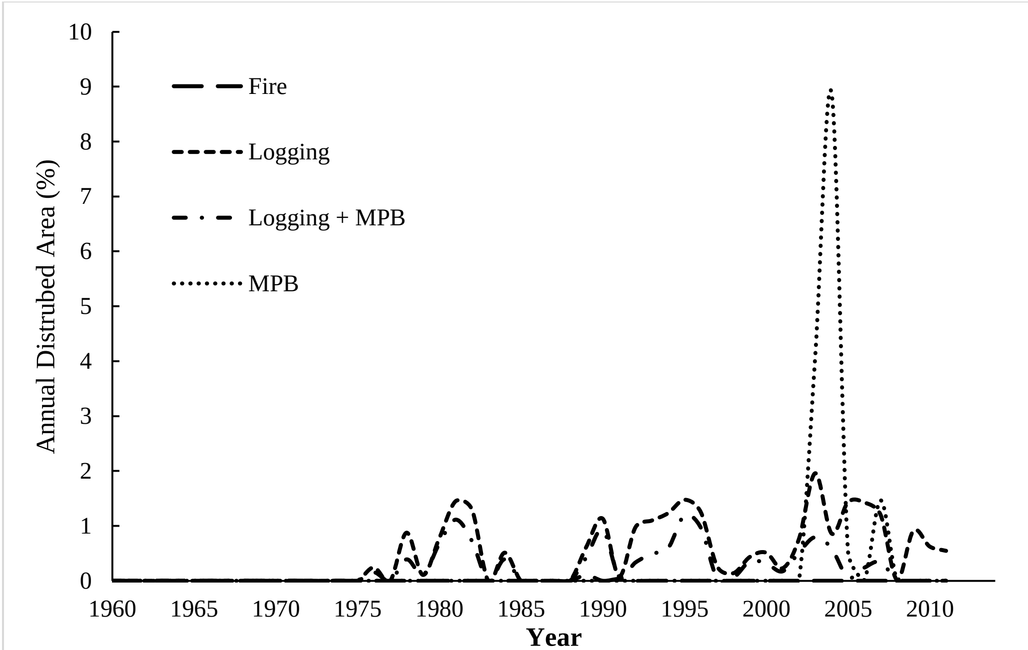

Figure 4.10 Annual disturbed areas (%) of the Hedley Creek watershed from 1960 to 2011

4.1.6 Forest disturbance in the Ashnola River watershed

The H60 of the Ashnola River watershed (1050 km^2) is about 1840 m. The Ashnola River watershed was the least disturbed sub-watershed in the Similkameen River watershed between 1950 and 2011. The CECA from all disturbance types of the Ashnola River watershed was 9.0% in 2011 (Figure 4.11). The largest logging activity took place in 1983 (0.6% of the watershed area), 2007 (0.8%), and 2010 (0.5%). The CECA from MPB infestation was only 3.0% of the watershed area up to 2011. The largest MPB infestation occurred in 2007 with 9.2% of the watershed being infested. Overall, the Ashnola River watershed has limited forest disturbance during the study period as compared with other watersheds.

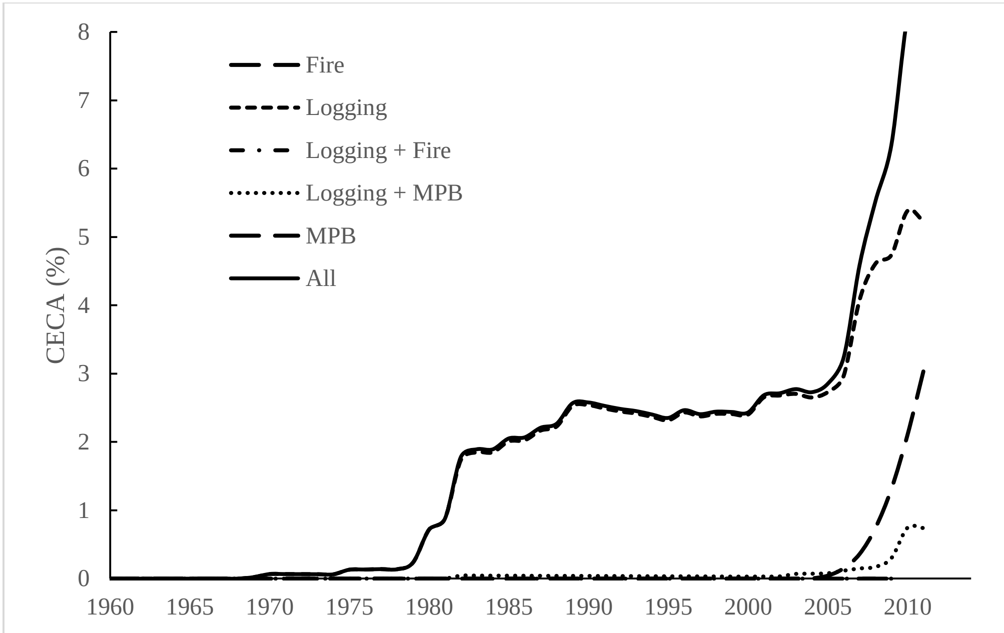

Figure 4.11 Cumulative equivalent clear-cut areas (%) of the Ashnola River watershed from 1960 to 2011

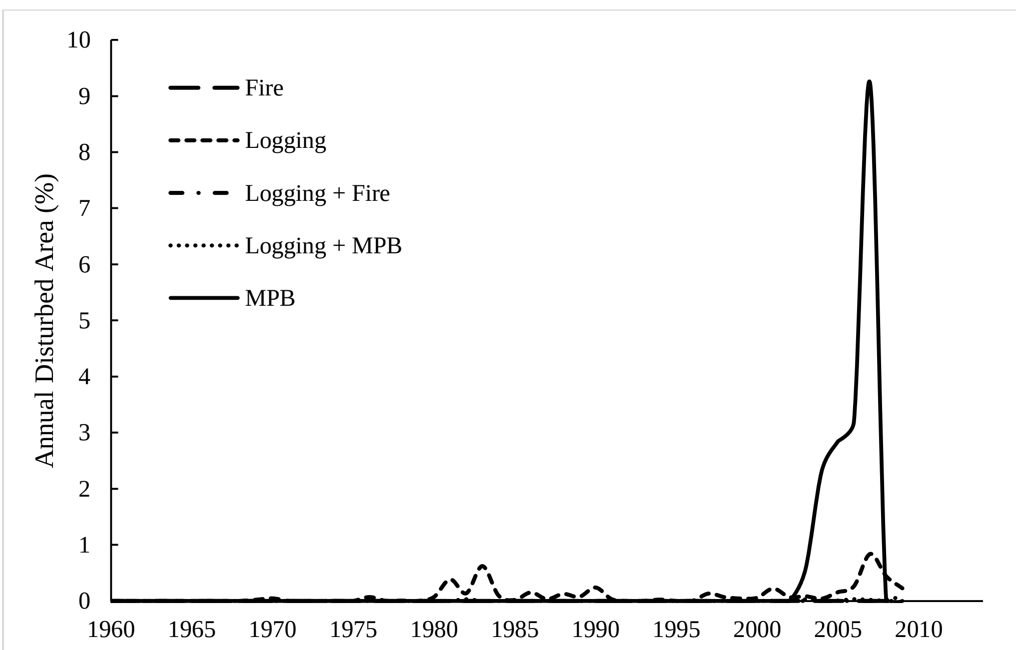

Figure 4.12 Annual disturbed areas (%) of the Ashnola River watershed from 1960 to 2011

4.1.7 Forest disturbance in the whole Similkameen River watershed

The H60 of the whole Similkameen River watershed in Canada is 1340 m. Logging was the dominant disturbance type in the whole Similkameen River watershed. The largest logging year occurred in 2010 with 1.2% of the total watershed being harvested. The annual average logged area was 0.44% of the total watershed area from 1960 to 2011 (Figure 4.14). The large-scale MPB infestation occurred in 2003 and dramatically increased the CECA. The peak of the MPB infestation was in 2005 with 0.47% of the watershed area affected. Fires took place occasionally in the Similkameen River watershed with limited contribution to CECA.

In 2011, the CECA for all disturbance types was at 45.5% of the total Similkameen River watershed area with 18.6% from logging and 22.6% from MPB (Figure 4.13). The CECA from MPB was relatively small before 2003 with an average annual disturbance area of 0.02% from 1986 to 2002 and then increased to an average annual disturbance area of 12.7% for the period from 2003 to 2011 (Figure 4.13). The CECA from fires was relatively small with 0.98% of the watershed area in 2011.

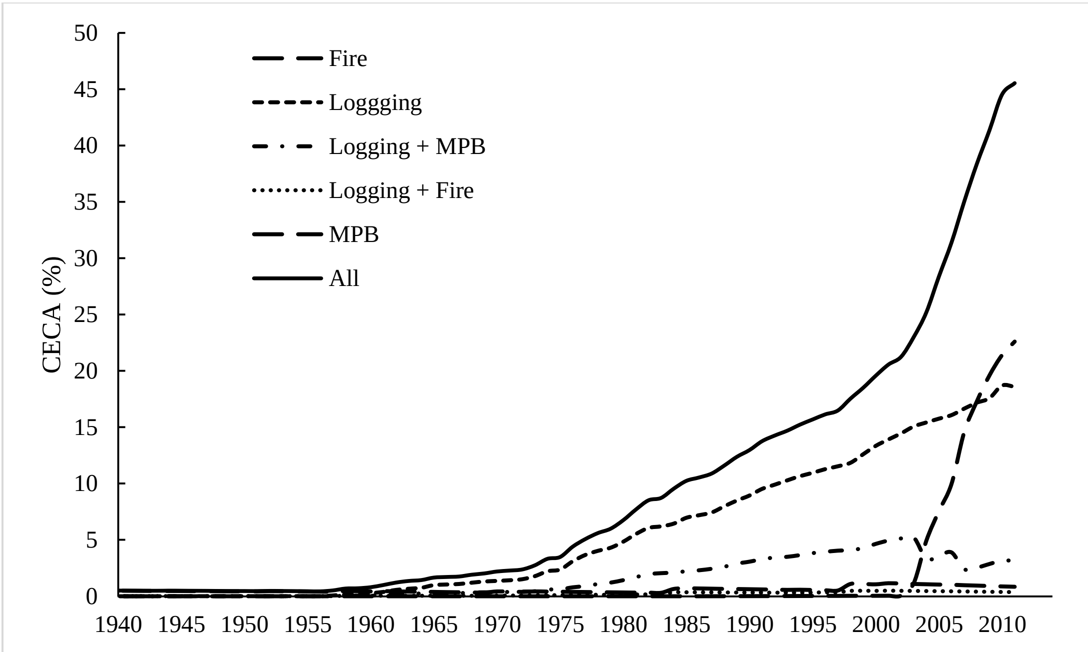

Figure 4.13 Cumulative equivalent clear-cut areas (%) of the whole Similkameen River watershed from 1940 to 2011

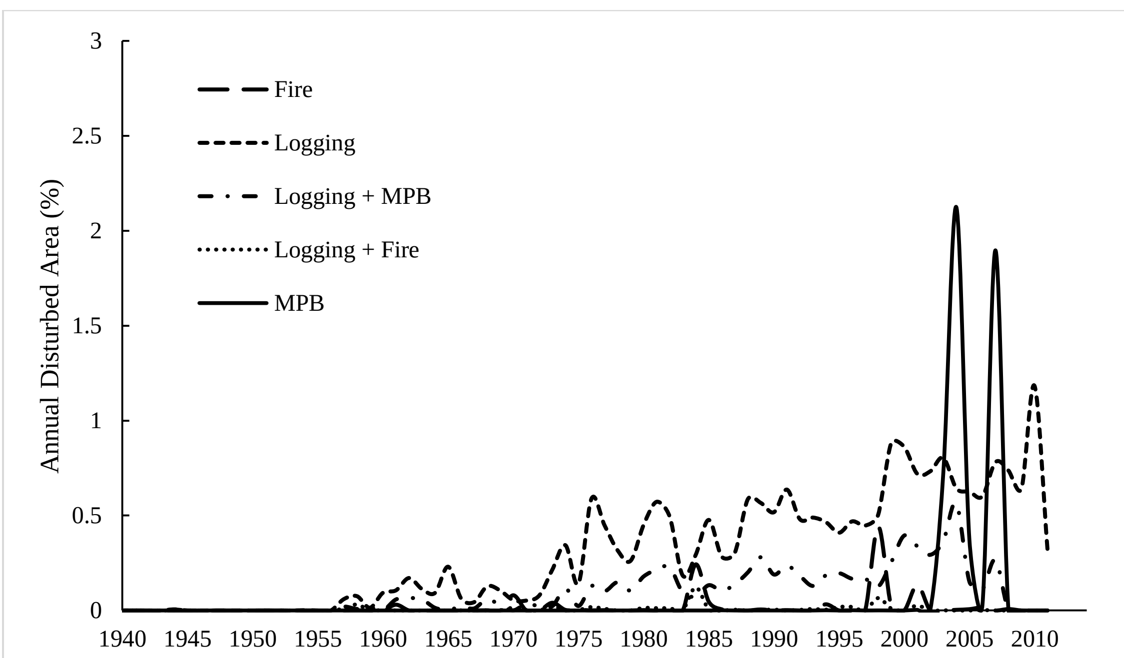

Figure 4.14 Annual disturbed areas (%) of the whole Similkameen River watershed from 1940 to 2011

Table 4.1 Summary of the cumulative equivalent clear-cut areas (CECA) by disturbance type (%) in the whole Similkameen River watershed and its sub-watersheds in 2011

Watersheds in Canada	Watershed Area (km^2) in Canada	Logging (%)	MPB (%)	Fire (%)	CECA (%)
Similkameen River at Princeton	1270	17.5	15.7	1.4	37.1
Tulameen River	1780	19.9	16.7	0	36.7
Wolfe Creek	1610	33.2	43.6	0.04	79.3
Similkameen River near Hedley	5040	24.4	24.3	1.2	55.7
Hedley Creek	388	21.3	44.7	0.2	66.9
Ashnola River	1050	5.2	3	0	9
Similkameen River	7566	18.6	22.6	0.8	45.5

As of 2011, the CECA of the whole Similkameen River watershed was 45.5%. Among the sub-watersheds, the Ashnola River watershed and Wolfe Creek watershed experienced the lowest and highest levels of forest disturbance, respectively. The Wolfe Creek watershed had the highest proportions of both logging and MPB among other sub-watersheds. Among the disturbance types, the MPB infestation was the largest forest disturbance type with 22.6% of the watershed area being infested. Forest logging steadily increased from 1950 and reached 18.6% of the watershed area in 2011. The Similkameen River watershed showed the large spatial distributions in forest disturbance. The upper reaches of the Similkameen River watershed (from Manning Provincial Park to Princeton) and Tulameen River watershed had a moderate forest disturbance level. Due to large forest disturbance in the Wolfe creek watershed, the CECA in the middle reach (Similkameen River near Hedley) of the watershed increased dramatically. With lower levels of forest disturbance in the lower reaches of the Similkameen River (from Hedley to the International border), the CECA showed a decreasing trend (Figure 2.1 and Table 4.1).

4.2 Trend analyses of hydrometeorological variables

4.2.1 Trend analyses of climate and hydrological variables

For annual hydrometeorological variables over the study period, annual mean and minimum temperatures exhibited a significant increasing trend in the three study watersheds (Table 4.2 to 4.4). The annual maximum temperature in the SRP and Tulameen River watersheds also showed a significantly upward trend. In contrast, no significant trend was found in the SRH. Annual precipitation in the three watersheds did not show any significant trend. The Tulameen River watershed is the only one that showed significantly increasing trends in annual potential and actual evapotranspiration, which, consequently, led to a significant deduction in annual streamflow.

For seasonal hydrometeorological variables in the SRP and Tulameen River watershed, all tested seasonal temperature variables showed significantly increasing trends except spring maximum temperature. In the SRH, seasonal minimum temperature showed a significant upward trend, while no significant trends were found in other seasonal variables (Table 4.4). Spring precipitation in the SRP and Tulameen River showed a significant increasing trend (Tables 4.2 and 4.3), while no such trend was found in the SRH. Spring evapotranspiration in all three watersheds showed a significantly increasing trend. Summer streamflow exhibited a significant decreasing trend in the SRP and Tulameen River watersheds, while no trend was found in this variable in the SRH watershed.

Table 4.2 Results of Mann-Kendall trend test for the Similkameen River at Princeton for the period of 1954-2013

Mann-Kendall Trend Test		T_{max}	T_{min}	T_{mean}	P	PET	ET	Q
Annual	Z	**2.5**	**3.9**	**3.4**	-0.4	2.1	1.6	-1.8
	P	**0.01**	**0.0001**	**<0.001**	0.707	0.04	0.11	0.07
Spring	Z	1.4	**2.9**	**2.4**	**2.1**	1.1	**2.8**	-0.2
	P	0.154	**0.004**	**0.02**	**0.03**	0.264	**0.005**	0.853
Summer	Z	**2**	**4.1**	**2.9**	0.4	1.8	0.3	**-2**
	P	**0.05**	**<0.001**	**0.004**	0.71	0.07	0.77	**0.04**
Fall-Winter	Z	**1.7**	**2.3**	**2**	-1.1	1.8	1.5	-0.3
	P	**0.08**	**0.02**	**0.05**	0.26	0.07	0.12	0.79

Note: Spring: March to May; Summer: June to September; Fall-Winter: January, February, and October to December.

Table 4.3 Results of Mann-Kendall trend test for the Tulameen River watershed for the period of 1954-2013

Mann-Kendall Trend Test		T_{max}	T_{min}	T_{mean}	P	PET	ET	Q
Annual	Z	**2.9**	**3.6**	**3.5**	-0.4	**2.4**	**2.3**	**-2.1**
	P	**0.004**	**<0.001**	**<0.001**	0.67	**0.02**	**0.02**	**0.03**
Spring	Z	1.7	**2.9**	**2.5**	**2.9**	1.8	**3.6**	-0.8
	P	0.1	**0.004**	**0.01**	**0.004**	0.07	**<0.001**	0.45
Summer	Z	**2.1**	**3.5**	**2.8**	1	**2**	0.8	**-2.5**
	P	**0.04**	**<0.001**	**0.006**	0.31	**0.05**	0.43	**0.01**
Fall-Winter	Z	**2.2**	**2.3**	**2.2**	-1.4	1.8	1.7	-0.7
	P	**0.03**	**0.02**	**0.03**	0.15	0.07	0.09	0.46

Note: Spring: March to May; Summer: June to September; Fall-Winter: January, February, and October to December.

Table 4.4 Results of Mann-Kendall trend test for the Similkameen River near Hedley for the period of 1967-2013

Mann-Kendall Trend		T_{max}	T_{min}	T_{mean}	P	PET	ET	Q
Annual	Z	1.3	**3.1**	**2.2**	-0.6	0.7	1.4	-0.2
	P	0.2	**0.002**	**0.03**	0.53	0.46	0.16	0.88
Spring	Z	0.4	**2.4**	1.5	1.4	1	**2.5**	0.8
	P	0.72	**0.02**	0.12	0.15	0.33	**0.01**	0.4
Summer	Z	0.7	**2.8**	1.4	0.7	0.7	0.7	-0.9
	P	0.5	**0.005**	0.15	0.47	0.47	0.46	0.39
Fall-Winter	Z	1.3	**2.3**	1.8	-1.1	1.1	1.5	1.4
	P	0.2	**0.02**	0.08	0.28	0.27	0.14	0.15

Note: Spring: March to May; Summer: June to September; Fall-Winter: January, February, and October to December.

4.2.2 Trend analyses for future climatic data (2020-2050)

Annual precipitation and temperature data for the period of 2020-2050 were generated for three study watersheds for the RCP 4.5 and RCP 8.5 scenarios, respectively (Figures 4.15-4.20; Table 4.5). Since three watersheds show consistent trends in precipitation and temperature, we use the larger SRH watershed as an example to explain future climate trends. The average annual precipitations for RCP 4.5 and RCP 8.5 scenarios are 816 mm and 802 mm, respectively in the SRH watershed. There is no big distinction in average annual precipitation between the two scenarios for the period of 2020-2050. Whereas annual precipitation shows large temporal variation between two scenarios in the three watersheds in as much as the differences in the GHG emission scenarios (Figure 4.15, 4.17, and 4.19).

Overall, temperature shows a significantly increasing trend in both scenarios. The average annual temperatures for RCP 4.5 and RCP 8.5 scenarios are 5.0 ºC and 5.4 ºC, respectively in the SRH watershed. The annual mean temperature in the RCP 8.5 scenario shows a steady increasing trend over the period of 2020-2050, while the temperature in the RCP 4.5 scenarios shows a sharp decrease around 2040 and then a gradually increasing trend after 2040 (Figures 4.16, 4.18, and 4.20). This is because the RCP 4.5 scenario is based on the assumption that GHG emission reaches the peak in 2040.

The Mann-Kendall trend analyses were conducted to test the trend of future precipitation and temperature data for the period of 2020-2050 (Tables 4.6 and 4.7). Both precipitation and temperature of the RCP 4.5 and RCP 8.5 scenarios showed consistent results. No significant trend was detected for precipitation (Table 4.6), while a significantly increasing trend was detected for temperature in all three watersheds (Table 4.7). We further calculated the rate of temperature increase for the period of 2020 to 2050. In the SRH, for example, the RCP 4.5 and RCP 8.5 scenarios are increasing by 0.037 and 0.045 ºC $year^{-1}$ between 2020 and 2050 (Table 4.5). As indicated by Mann-Kendall trend tests, the Similkameen River watershed is likely to become drier for the period of 2020 to 2050.

Table 4.5 Comparisons between historical and future precipitation and temperature by watersheds and climate scenarios

Watersheds	Climatic Variables	RCP 4.5		RCP 8.5		1960-2013	
		Average	SD	Average	SD	Average	SD
SRP	P (mm)	854.0	43.4	839.0	41.8	889.0	126.8
	T (ºC)	4.9	0.4	5.3	0.5	3.1	0.7
Tulameen	P (mm)	852.2	40.8	836.8	41.9	925.8	118.0
	T (ºC)	5.4	0.4	5.8	0.5	3.5	0.7
SRH	P (mm)	816.4	40.2	801.5	39.9	806.1	106.0
	T (ºC)	5.0	0.4	5.4	0.5	3.4	0.7

Table 4.6 Mann-Kendall trend tests of future climatic variables in the study watersheds for the period of 2020 to 2050 under the RCP 4.5 and RCP 8.5 scenarios

Period 2020-2050		RCP4.5		RCP 8.5	
		Z	P	Z	P
P	SRP	-0.1	1.9	1.9	0.06
	Tulameen	-0.1	1.7	1.7	0.08
	SRH	-0.2	1.9	1.9	0.06
T	SRP	**5.3**	**5.1**	**5.1**	**<0.001**
	Tulameen	**5.1**	**5.2**	**5.2**	**<0.001**
	SRH	**5.2**	**5.1**	**5.1**	**<0.001**

Table 4.7 Annual increasing rate of future temperature in the study watersheds for the period of 2020 to 2050 under the RCP 4.5 and RCP 8.5 scenarios

Watersheds	Scenarios	Slope (ºC $year^{-1}$)
SRP	RCP 4.5	0.0377
	RCP 8.5	0.0448
Tulameen	RCP 4.5	0.0365
	RCP 8.5	0.0452
SRH	RCP 4.5	0.0371
	RCP 8.5	0.0454

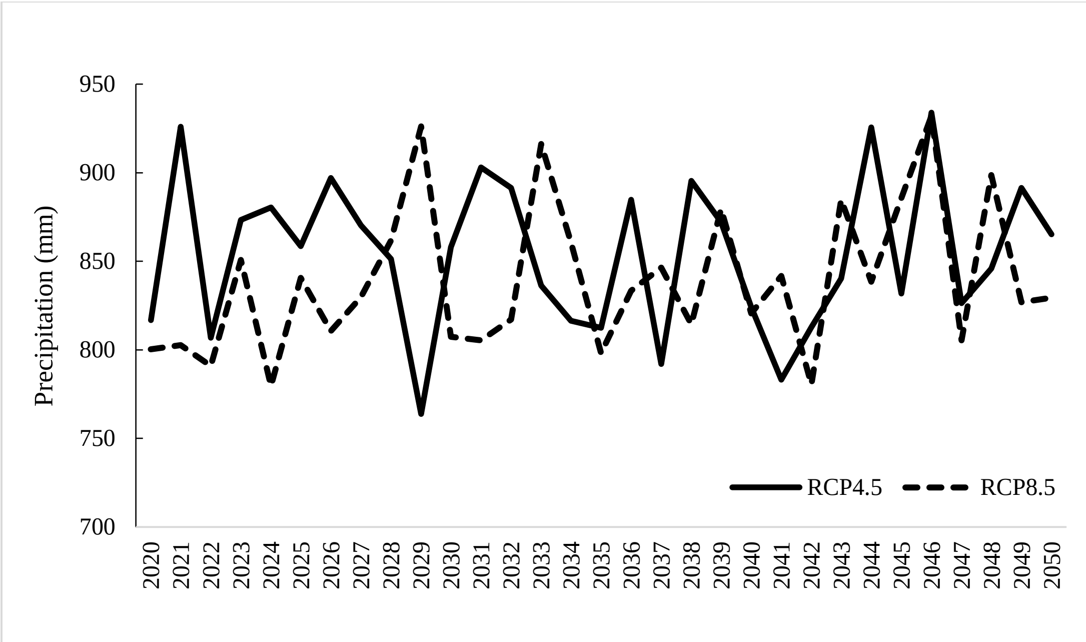

Figure 4.15 Two future precipitation scenarios (RCP 4.5 and RCP 8.5) in the Similkameen River at Princeton for the period 2020 to 2050

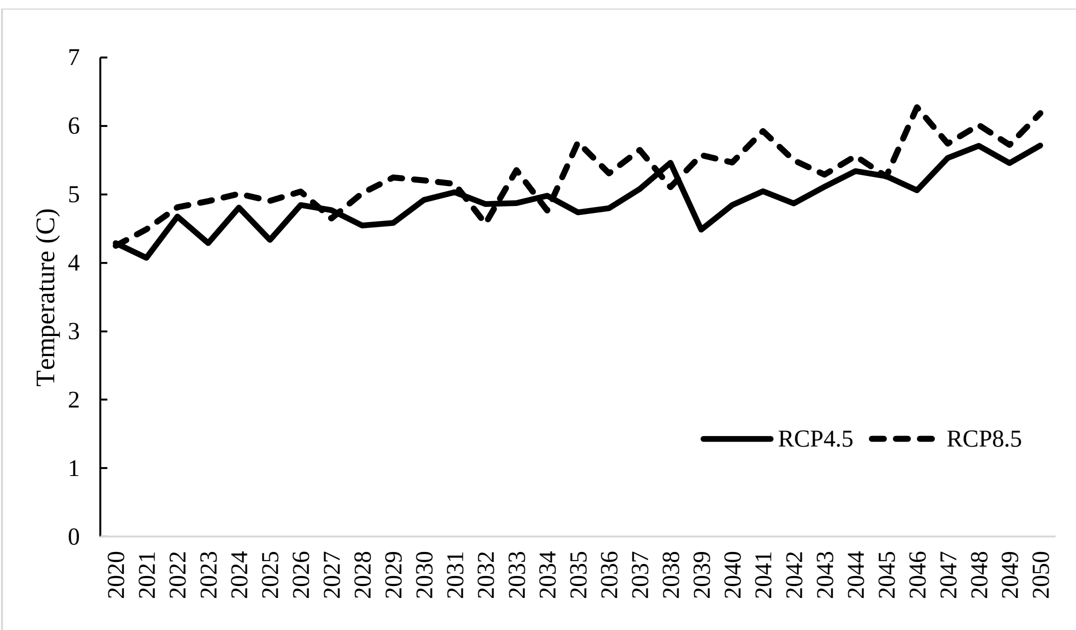

Figure 4.16 Two future temperature scenarios (RCP4.5 and RCP 8.5) in the Similkameen River at Princeton for the period 2020 to 2050

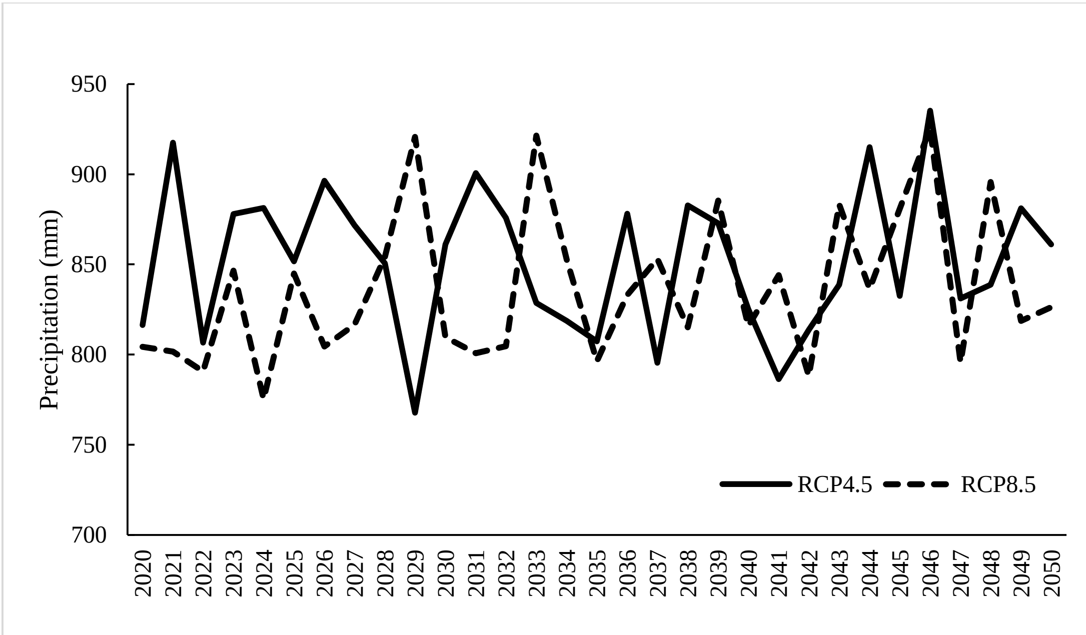

Figure 4.17 Two future precipitation scenarios (RCP 4.5 and RCP 8.5) in the Tulameen River watershed for the period 2020 to 2050

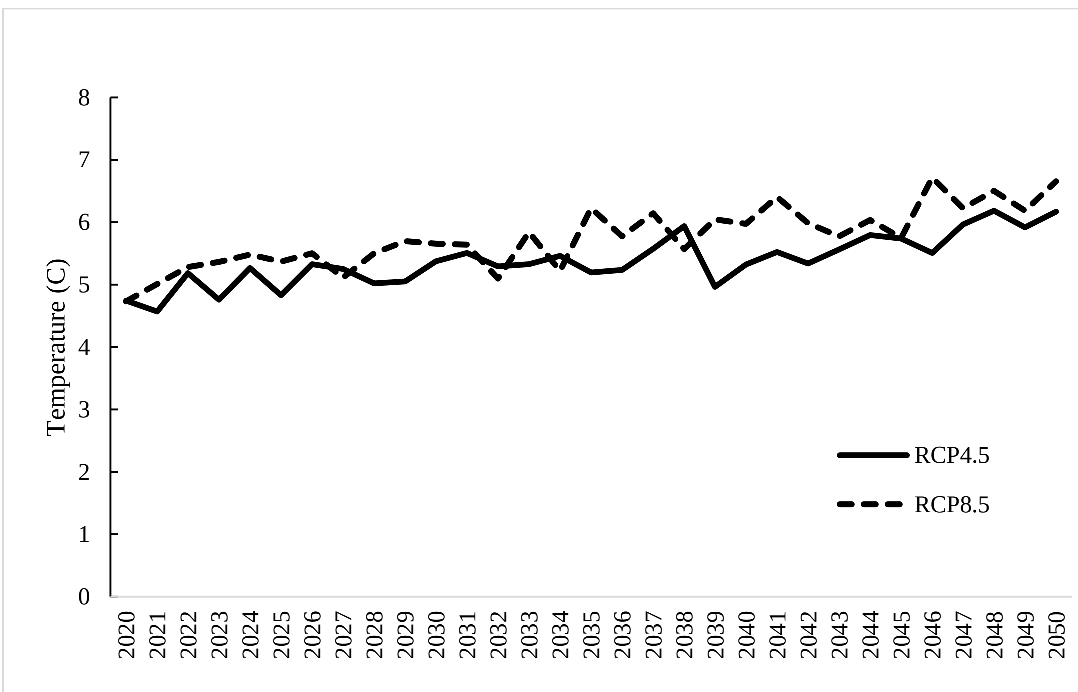

Figure 4.18 Two future temperature scenarios (RCP4.5 and RCP 8.5) in the Tulameen River watershed for the period 2020 to 2050

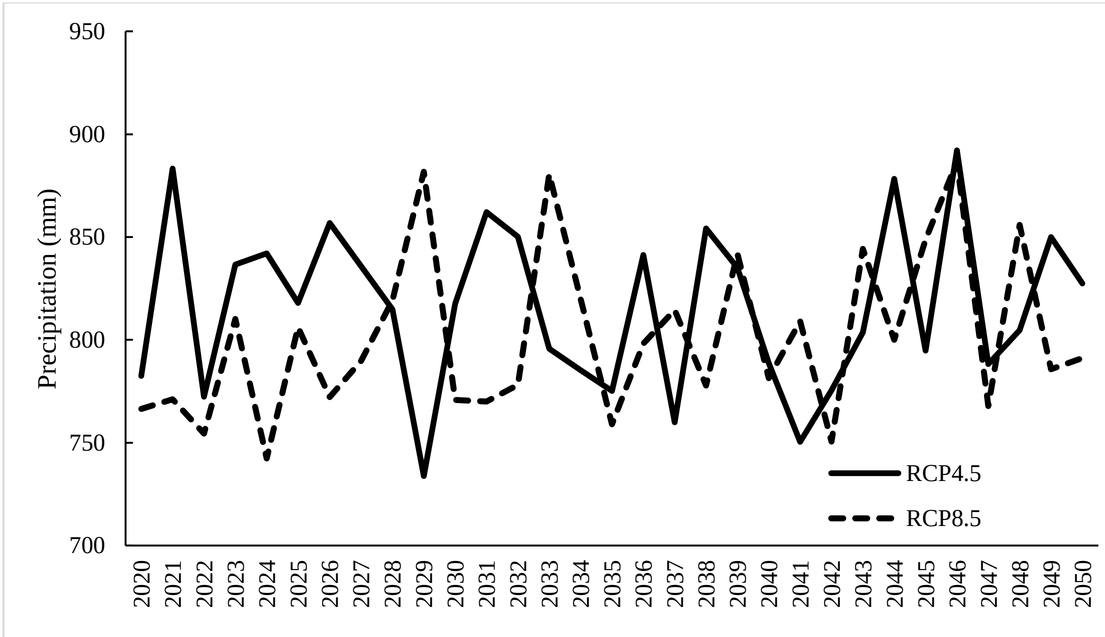

Figure 4.19 Two future precipitation scenarios (RCP 4.5 and RCP 8.5) in the Similkameen River near Hedley for the period 2020 to 2050

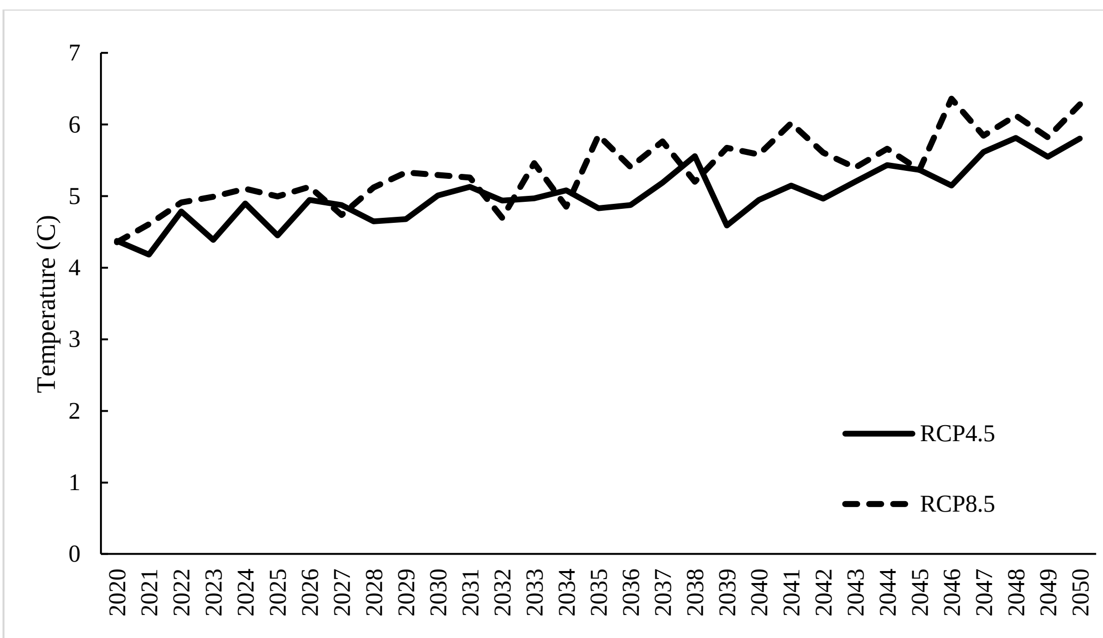

Figure 4.20 Two future temperature scenarios (RCP 4.5 and RCP 8.5) in the Similkameen River near Hedley for the period 2020 to 2050

4.3 Quantification of relative contributions of forest disturbance and climate variability to annual mean flows

4.3.1 Time series cross-correlation between forest disturbance and hydrological variables

As shown in Tables 4.8 to 4.10, significant and positive correlations were detected between forest disturbance (CECA) and annual mean flows in all three study watersheds. This suggests that forest disturbance has significantly increased the annual mean flows in three watersheds. However, due to the differences in landscape characteristics, forest disturbance levels, and watershed sizes, consistent correlations between the forest disturbance and seasonal mean flows were not shown. In the SRP watershed, positive correlations between CECA and seasonal flows were found in spring and summer, indicating the forest disturbance increased the spring and summer mean flows. In contrast, no significant relationship between forest disturbance and summer mean flows was detected in the Tulameen River watershed although significant correlations of spring and winter were found. In the larger SRH watershed, no significant correlation was detected in the spring mean flows, whereas the summer and winter mean flows were increased by forest disturbance. As indicated by the cross-correlation tests between CECA and high flows (Table 4.11), forest disturbance increased high flows in the SRP and SRH watersheds, while no significant relationship between forest disturbance and high flow was detected in the Tulameen River watershed.

Table 4.8 Time series cross-correlations between CECA and hydrological variables in the Similkameen River at Princeton

Hydrological Variables	Cross-correlations		
	ARIMA Model	Coefficients	Lag
Annual Streamflow	(0, 1, 1)	**0.298***	**0**
Spring Streamflow	(0, 0, 0)	**0.362***	**-6**
Summer Streamflow	(3, 1, 0)	**0.291***	**0**
Fall-Winter Streamflow	(0, 1, 1)	0.325	-4
ARIMA model for ECA (0, 2, 1)			

Note: Spring: March to May; Summer: June to September; Fall-winter: January, February, and October to December.

Table 4.9 Time series cross-correlations between CECA and hydrological variables in the Tulameen River

Hydrological Variables	Cross-correlations		
	ARIMA Model	Coefficients	Lag
Annual Streamflow	(0, 2, 1)	**0.317***	**5**
Spring Streamflow	(0, 0, 0)	**0.323***	**0**
Summer Streamflow	(2, 1, 0)	0.226	4
Fall-Winter Streamflow	(0, 1, 1)	**0.332***	**12**
ARIMA model for ECA (0, 2, 1)			

Note: Spring: March to May; Summer: June to September; Fall-winter: January, February, and October to December.

Table 4.10 Time series cross-correlations between CECA and hydrological variables in the Similkameen River near Hedley

Hydrological Variables	Cross-correlations		
	ARIMA Model	Coefficients	Lag
Annual Streamflow	(0, 1, 1)	**0.353***	**8**
Spring Streamflow	(0, 1, 1)	0.165	1
Summer Streamflow	(2, 1, 0)	**0.386***	**15**
Fall-Winter Streamflow	(0, 1, 1)	**0.406***	**7**
ARIMA model for ECA (0, 2, 1)			

Note: Spring: March to May; Summer: June to September; Fall-winter: January, February, and October to December.

Table 4.11 Cross-correlations between cumulative clear-cut area and high flows in the three study watersheds

Watershed	Flow	ARIMA Model	Coefficient	Lags
SRP	Q5	(3, 1, 0)	**0.305***	**2**
Tulameen	Q5	(3, 1, 0)	0.174	1
SRH	Q5	(0, 0, 0)	**0.559***	**2**

4.3.2 Assessing the cumulative effects of forest disturbance on annual mean flows

As shown in Figures 4.21 to 4.23, modified double mass curves (MDMC) have been generated for all three study watersheds, in which cumulative annual mean flow was plotted against the cumulative effective precipitation. As indicated by the Pettitt tests, significant break points in 1983, 1982, and 1990 were detected on the slopes of MDMC in the SRP, Tulameen, and SRH watersheds, respectively. The study period was then divided into reference and disturbance periods by those break points. The reference periods of three study watersheds are 1954-1983 for the SRP watershed, 1954-1982 for the Tulameen River watershed, and 1967-1990 for the SRH watershed. The forest disturbance increased annual mean flows approximately 24.03 ± 17.82 mm in the SRP watershed; 32.96 ± 25.29 mm in the Tulameen River watershed; and 19.70 ± 21.22 mm the SRH watershed by MDMC analysis. In contrast, climate variability decreased the annual mean flows of -26.14 ± 17.82 mm in the SRP watershed, -30.27 ± 25.29 mm in the Tulameen River watershed, and -22.13 ± 21.22 mm the SRH watershed (Tables 4.12 to 4.14). The sensitivity-based method generated consistent results as the MDMC (Tables 4.15 to 4.17). The forest disturbance increased annual mean flows by 20.26 mm in the SRP, 10.10 mm in the Tulameen River, and 15.04 mm in the SRH watersheds, while climate variability decreased the annual mean flows by -22.37 mm in the SRP, -7.42 mm in the Tulameen River, and -17.47 mm in the SRH watersheds. In summary, climate variability played a larger role in annual mean flow variations in the SRP and SRH watersheds, while forest disturbance had larger effects on them in the Tulammen River watershed.

More details on the effect of cumulative forest disturbance on annual mean flows in each watershed are presented below. For the SRP watershed, the break point is in the year 1983 with the CECA of 7.8% of the watershed area (Figure 4.21). Over the disturbance period of 1984-2013, annual mean flows decreased by 2.12 mm (Table 4.12). Annual mean flow deviation attributed to forest disturbance ranged from -128 mm to 305 mm with the average of 24 mm or 6.18% of the annual mean flow (Figure 4.24). In contrast, annual mean flow deviation attributed to climate variability ranged from -406 mm to 194 mm with the average of -26 mm or 6.72% of the average mean flow (Figure 4. 25).

In the Tulameen River watershed, the cumulative effects of forest disturbance on annual mean flows started in the break point of the year 1982 with the CECA of 8.4% of the watershed area (Figure 4.22). In the disturbance period of 1983-2013, annual mean flows increased by 2.69 mm (Table 4.13). Annual mean flow deviation attributed to forest disturbance ranges from -133 mm to 264 mm with an average of 33 mm or 6.18% of the annual mean flow (Figure 4.26). In contrast, the annual mean flow deviation attributed to climate variability ranged from -298 mm to 194 mm with an average of -30 mm or 9.18% of the annual mean flow (Figure 4. 27).

In the SRH watershed, the cumulative effects of forest disturbance on annual mean flows emerged in the break point of the year 1990 with the CECA of 16.8% of the watershed area (Figure 4.23).

In the disturbance period of 1999-2013, annual mean flows decreased by 2.43 mm (Table 4.14). Forest disturbance increased annual mean flows by 19.70 mm while climate variability decreased them by 22.13 mm. Annual mean flow deviation attributed to forest disturbance ranged from -102 mm to 252 mm with the average of 6.70% of the annual mean flow (Figure 4.28). On the other hand, annual mean flow deviation attributed to climate variability ranged from -290 mm to 187 mm with the average of 7.52% of the annual mean flow (Figure 4.29).

Our study indicated that forest disturbance increases annual mean flows. This result is consistent with many other studies (Matheussen et al., 2000; Wilk et al., 2001; Fohrer et al., 2005; Moore et al., 2005; Siriwardena et al., 2006; Tuteja et al., 2008; Yao et al., 2012; Zhang and Wei, 2012a; Creed et al., 2014; Liu et al., 2015a). For example, annual mean flows were found to be increased by 61 mm with the forest disturbance level of 23.6% of the watershed area in the Willow River watershed located in the central interior of British Columbia (Wei and Zhang, 2010). With the CECA over 60%, annual streamflow was increased by 46.9% in the Baker River watershed also located in the central interior of British Columbia (Zhang and Wei, 2012). In our study watersheds, the CECA levels of 37.1%, 36.7%, and 55.7% increased the annual mean flow by 22.15 mm (6.18%), 21.53 mm (10%), and 17.37 mm (6.7%) in the SRP, Tulameen River, and SRH watersheds, respectively. The SRP and Tulameen River watersheds had a similar forest disturbance level, and climatic conditions and thus had the similar annual hydrological responses. With a higher forest disturbance level in the larger SRH watershed, the impacts of forest disturbance were actually lowered. This may be due to the larger watershed's capacity of buffering the effects of the forest disturbance on annual mean flows in this large sized watershed (Shuttleworth, 1988; Shaman et al., 2004).

For any watersheds, there may be a forest change threshold over which hydrological changes can be detected. Existing studies have demonstrated large variations on thresholds in different watersheds. For example, a CECA of 30% in the Willow River watershed significantly increased annual mean flows, while no significant changes in annual mean flows were detected in the Bowron River watershed for the same level of forest disturbance (Zhang and Wei, 2014b). No detectable changes in annual mean flows have been found with forest disturbance ranging from 5% to 25% in watersheds in the Canadian boreal forest (Buttle and Metcalfe, 2000). Thus, a commonly accepted threshold has not been concluded. However, the common perception is that more than 20% of forest change would cause significant hydrological responses (Stednick, 1996; Andreassian, 2004) based on small watershed studies. To our surprise, the cumulative disturbance levels of (CECA) of 7.8 %, 8.4%, and 16.8% in the SRP, Tulameen River, and SRH watersheds have caused significant hydrological changes. We judge that the disturbance levels (e.g. 5% to 10%) in the reference periods may play an important role in this surprising response because disturbance levels act as bases so that any further forest disturbance could trigger dramatic hydrological responses. Nevertheless, more researchers are needed to study forest change thresholds at which significant hydrological responses are introduced.

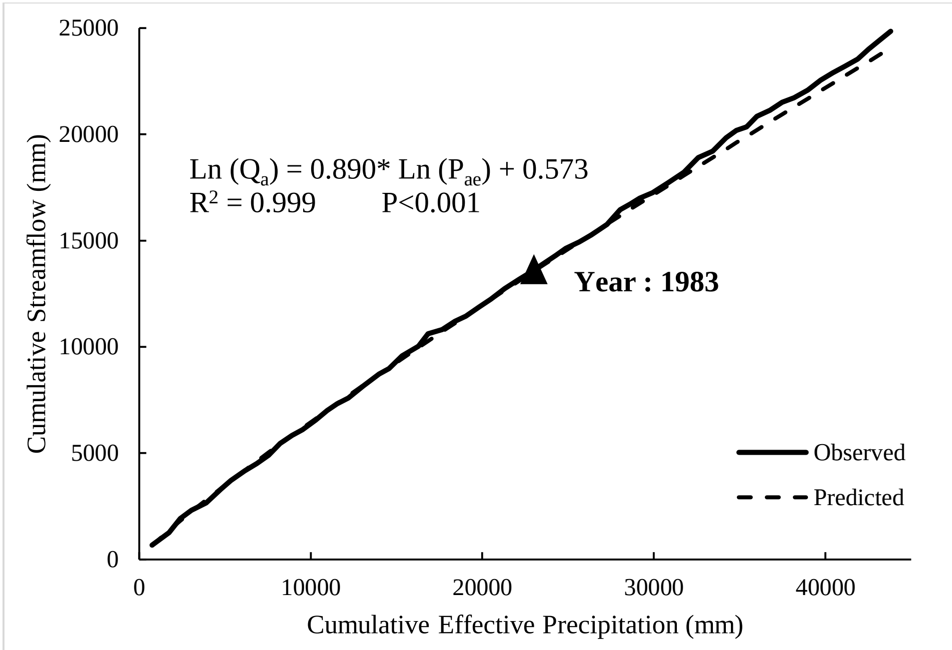

Figure 4.21 The modified double mass curves for the Similkameen River at Princeton watershed for the period of 1954 to 2013 (Q_a: cumulative annual mean flow; P_{ae}: cumulative effective precipitation)

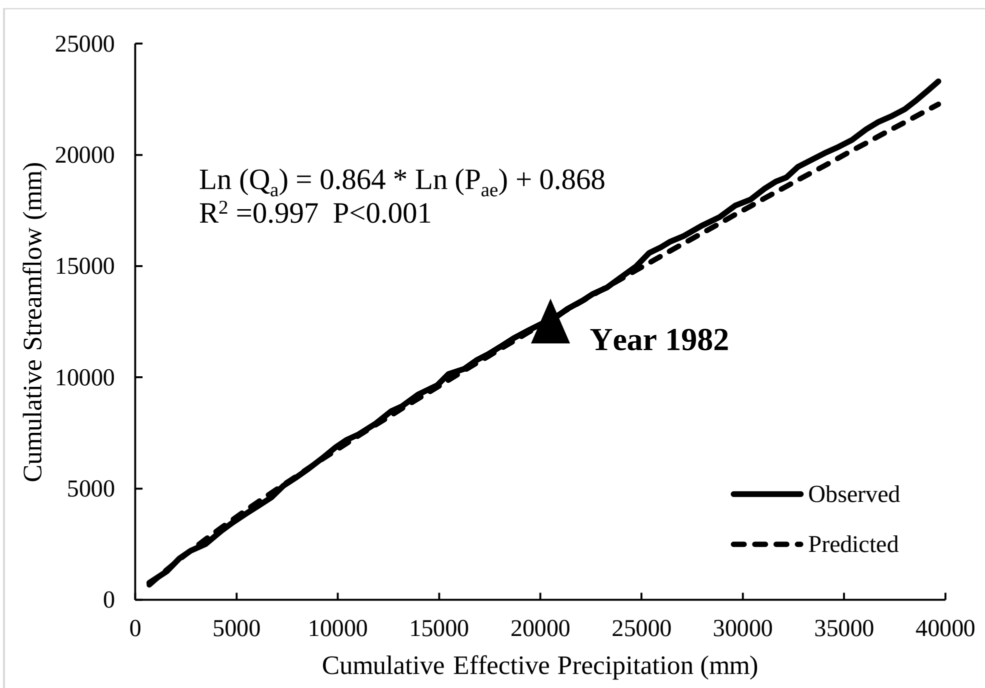

Figure 4.22 The modified double mass curves for the Tulameen River watershed for the period of 1954 to 2013 (Q_a: cumulative annual mean flow; P_{ae}: cumulative effective precipitation)

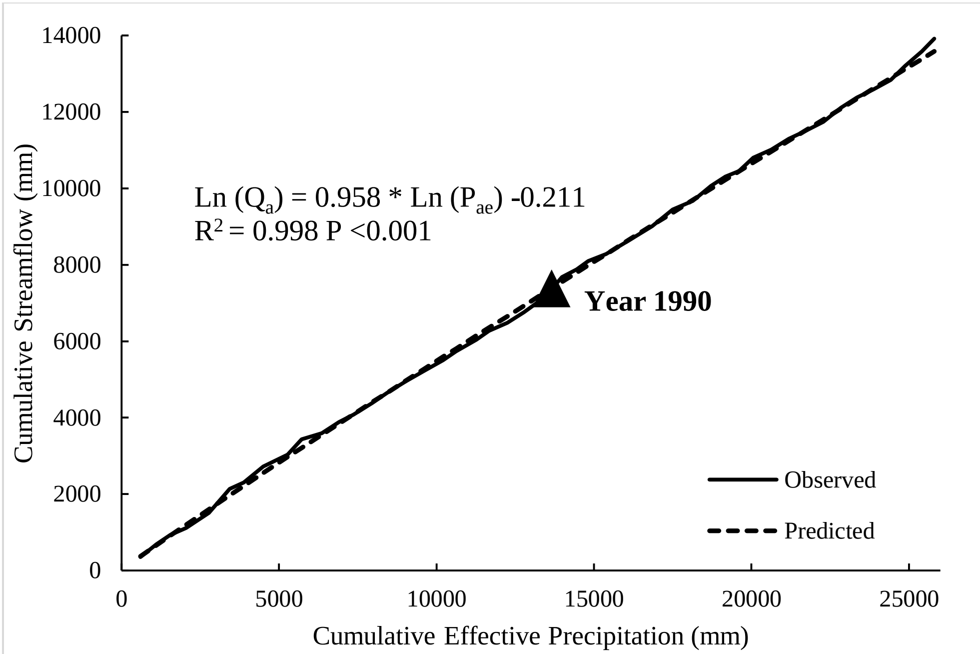

Figure 4.23 The modified double mass curves for the Similkameen River near Hedley watershed for the period of 1967 to 2013 (Q_a: cumulative annual mean flow; P_{ae}: cumulative effective precipitation)

Table 4.12 Annual mean flow variations and relative contributions of forest disturbance and climate variability to annual mean flows in the Similkameen River at Princeton (1984-2013)

Streamflow	ΔQ (mm)	ΔQ_f (mm)	ΔQ_c (mm)	$\Delta Q_f/Q$ (%)	$\Delta Q_c/Q$ (%)	R_f (%)	R_c (%)	CECA (%)
1984-1993	-17.43	16.62 ± 17.82	-34.04 ± 17.82	4.35	-8.92	32.80 ± 23.62	67.20 ± 23.62	6.71
1994-2003	1.95	31.1 ± 18.72	-29.15 ± 18.72	7.50	-7.03	51.61 ± 24.62	48.39 ± 24.62	14.77
2004-2013	9.13	24.37 ± 16.93	-15.24 ± 16.93	6.57	-4.10	61.53 ± 33.95	38.47 ± 33.95	26.58
1984-2013	-2.12	24.03 ± 17.82	-26.14 ± 17.82	6.18	-6.72	47.89 ± 28.01	52.11 ± 28.01	17.12

Table 4.13 Annual mean flow variations and relative contributions of forest disturbance and climate variability to annual mean flows in the Tulameen River watershed (1983-2013)

Streamflow	ΔQ	ΔQ_f (mm)	ΔQ_c (mm)	$\Delta Q_f/Q$ (%)	$\Delta Q_c/Q$ (%)	R_f (%)	R_c (%)	CECA (%)
1983-1993	-9.06	30.31 ± 25.24	-39.37 ± 25.24	9.21	-11.97	43.50 ± 22.50	56.50 ± 22.50	11.71
1994-2003	3.92	13.91 ± 26.99	-9.99 ± 26.99	3.95	-2.84	58.21 ± 33.34	41.79 ± 33.34	16.13
2004-2013	9.54	45.98 ± 23.65	-36.44 ± 23.65	14.91	-11.82	55.79 ± 31.13	55.79 ± 31.13	28.13
1984-2013	2.69	32.96 ± 25.29	-30.27 ± 25.29	10.00	-9.18	52.12 ± 28.41	47.88 ± 28.41	17.98

Table 4.14 Annual mean flow variations and relative contributions of forest disturbance and climate variability to annual mean flows in the Similkameen River near Hedley (1991-2013)

Streamflow	ΔQ	ΔQ_f (mm)	ΔQ_c (mm)	$\Delta Q_f/Q$ (%)	$\Delta Q_c/Q$ (%)	R_f (%)	R_c (%)	CECA (%)
1991-1997	6.6	29.01 ± 23.10	-22.41 ± 23.09	8.85	-6.83	47.73 ± 28.63	52.27 ± 28.63	14.81
1998-2004	-21.96	-4.00 ± 20.77	-17.96 ± 20.77	-1.51	-6.78	42.91 ± 27.03	57.09 ± 27.03	21.72
2006-2013	5.75	30.90 ± 20.10	-25.15 ± 20.10	10.62	-8.64	54.02 ± 30.20	45.98 ± 30.20	39.64
1991-2013	-2.43	19.70 ± 21.22	-22.13 ± 21.22	6.70	-7.52	48.72 ± 27.88	51.28 ± 27.88	24.68

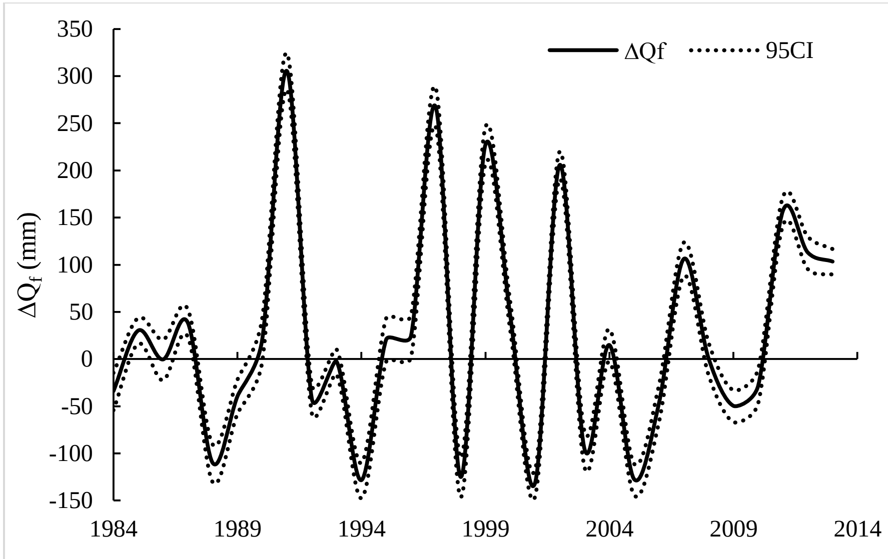

Figure 4.24 The annual mean flow variations attributed to forest disturbances (ΔQ_f) and 95% confidence interval (95CI) in the Similkameen River at Princeton for the period of 1984 to 2013

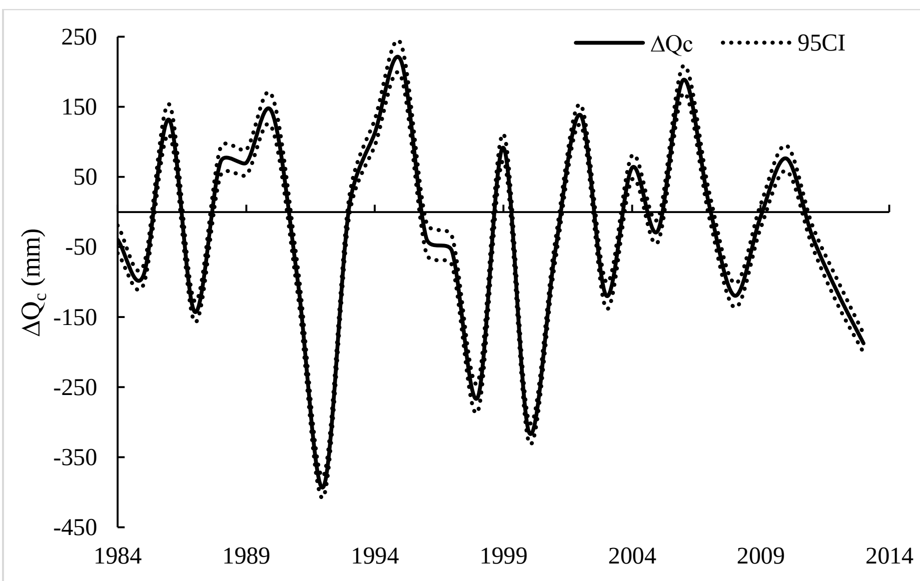

Figure 4.25 The annual mean flow variations attributed to climate variability (ΔQ_c) and 95% confidence interval (95CI) in the Similkameen River at Princeton for the period of 1984 to 2013

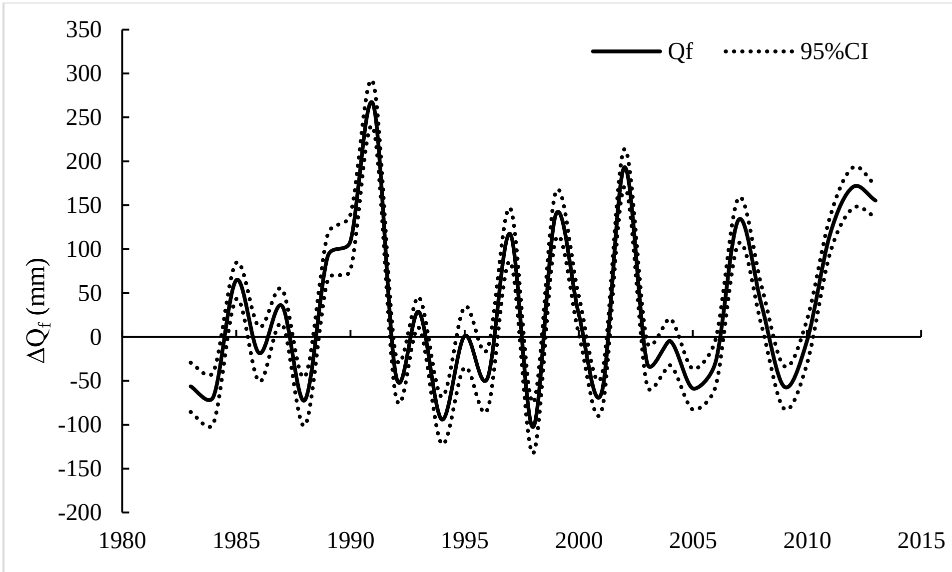

Figure 4.26 The annual mean flow variations attributed to forest disturbances (ΔQ_f) and 95% confidence interval (95CI) in the Tulameen River watershed for the period of 1983 to 2013

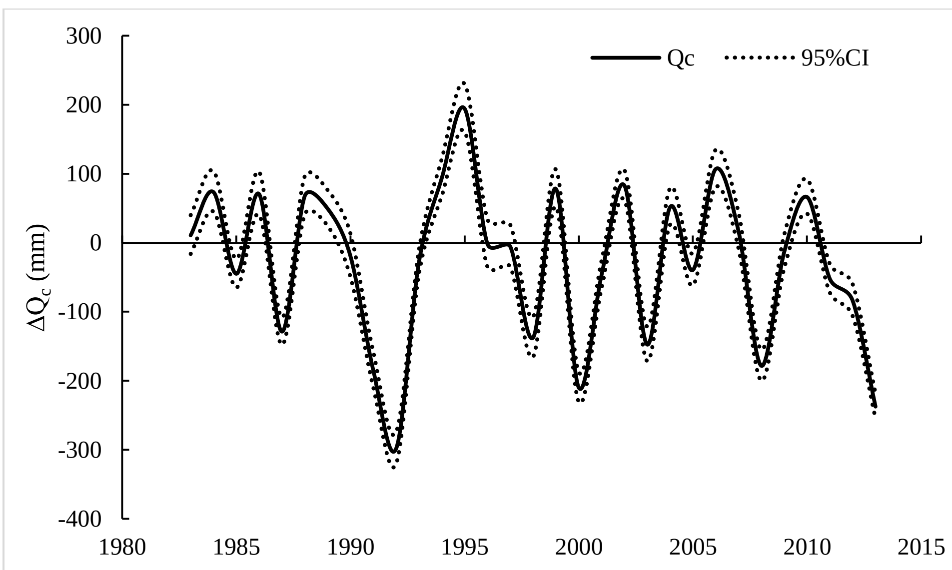

Figure 4.27 The annual mean flow variations attributed to climate variability (ΔQ_c) and 95% confidence interval (95CI) in the Tulameen River watershed for the period of 1983 to 2013

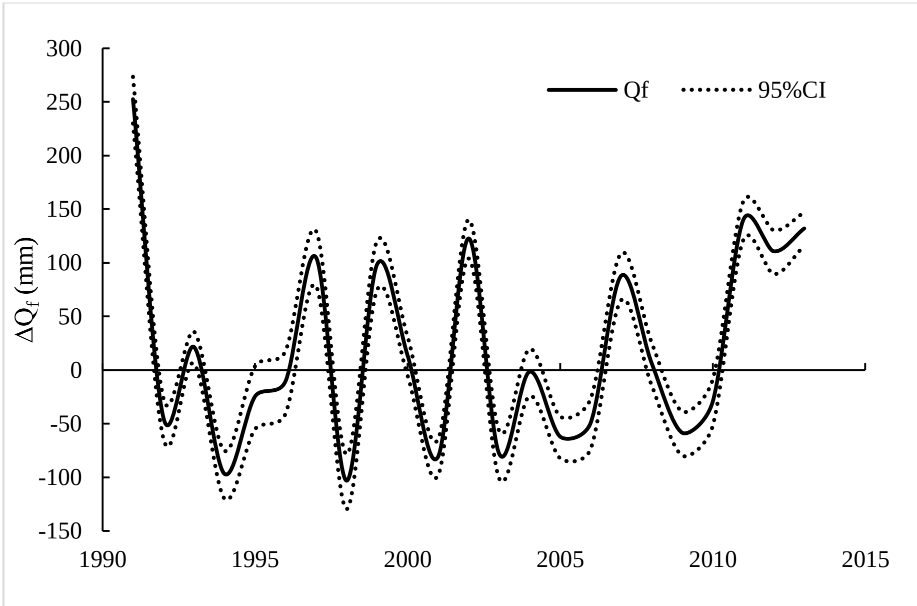

Figure 4.28 The annual mean flow variations attributed to forest disturbances (ΔQ_f) and 95% confidence interval (95CI) in the Similkameen River near Hedley for the period of 1991 to 2013

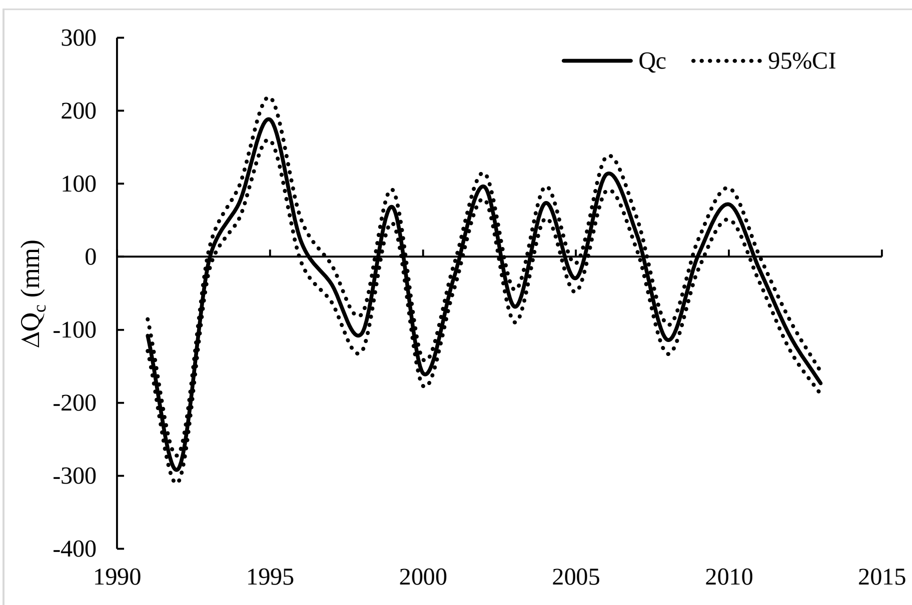

Figure 4.29 The annual mean flow variations attributed to climate variability (ΔQ_c) and 95% confidence interval (95CI) in the Similkameen River near Hedley for the period of 1983 to 2013

4.3.3 Relative contributions of forest disturbance and climate variability to annual mean flows

The relative contributions of forest disturbance (R_f) and climate variability (R_c) to annual mean flows were calculated based on the results from two methods (sensitivity-based and MDMC methods) in the three watersheds (Tables 4.15 to 4.17). In the larger SRH watershed, climate variability played a more dominant role than forest disturbance in annual mean flow variation. The average values of R_f and R_c were 47.49% and 52.51%, respectively (Table 4.17). In the SRP watershed, climate variability had larger effects (R_c: 52.30%) than forest disturbance ($R_{f:}$: 47.70%) on annual mean flows (Table 4.15), while forest disturbance (R_f: 54.89%) played a more dominant role than climate variability (R_c: 45.11%) to annual mean flows in the Tulameen River watershed (Table 4.16).

We further examined the temporal variations of R_f and R_c in the three watersheds. Our tables (Tables 4.12-4.14) showed that the impact of forest disturbance and climate variability on annual mean flow variations were dynamic. R_f showed a consistent upward trend with increasing CECA, while R_c declined over time in all three watersheds. In the SRP watershed, only 32.8% of the annual mean flow variation was explained by forest disturbance with the average CECA of 6.71% of the watershed area from 1984 to 1993. With a CECA increase to 26.58% in the period of 2004 to 2013, the impacts of forest disturbance (61.53%) were larger than climate variability (38.47%) in this period. In the Tulameen River watershed, R_f increased from 43.50% with the CECA of 11.71% in the period of 1983-1993 to 55.79% between 2004-2013 with the CECA of 28.13%, indicating that the impacts of forest disturbance were larger than climate variability. In the SRH watershed, the average CECA value increased from 14.81% in the period of 1991-1997 to 39.64%

in the period of 2006-2013, which resulted in the R_f increasing from 47.73% to 54.02%. In short, the impacts of forest disturbance and climate variability are directional and dynamic. Climate variability produced larger impacts on annual mean flows when the levels of forest disturbance were lower. With increasing forest disturbance, the impacts of forest disturbance exceeded the impacts of climate variability.

Our results clearly demonstrated that the forest disturbance and climate variability played a similar role in annual mean flow variations or changing magnitudes, but in opposite directions. Forest disturbance increased annual mean flows, while climate variability decreased them. Similar findings are also reported by other studies (Liu et al., 2009; Wei and Zhang, 2010; Zhang and Wei, 2012; Liu et al., 2015a). For example, Zhang and Wei (2013) found that the relative contributions of forest disturbance were 43% and 40% with average values of CECA of 23.8% and 35% in the Baker and Willow River watersheds in British Columbia, respectively. Zheng et al. (2009) showed that about 70% of streamflow reduction was attributed to land cover change in the headwaters of Yellow River in China. Clearly, there were offsetting effects on annual mean flows between forest disturbance and climate variability in those studies. However, the effects of forest disturbance and climate variability can be additive. For example, Zhang et al. (2011) found that plantation forestry accounted for 28% to 106% of the total streamflow deductions, while climate variability accounted for 5% to 80% of the total streamflow deductions in the 15 catchments in Australia with areas of watersheds ranging from 0.6 to 1136 km^2. Thus, the interactions between forest disturbance and climate variability in terms of both magnitudes and directions are critical for determining annual mean flow change. Understanding those interactions would have important implications for managing water resources and protecting public safety and ecosystem services.

Table 4.15 Comparisons of relative contributions of forest disturbance (R_f) and climate variability (R_c) to annual mean flows in the Similkameen River at Princeton watershed

Method	ΔQ_c (mm)	ΔQ_f (mm)	R_f (%)	R_c (%)
Sensitivity-based method	-22.37	20.26	47.52	52.48
MDMC	-26.14 ± 17.82	24.03 ± 17.82	47.89 ± 28.01	52.11 ± 28.01
Average	-24.26	22.15	47.70	52.30

Table 4.16 Comparisons of relative contributions of forest disturbance (R_f) and climate variability (R_c) to annual mean flows in the Tulameen River watershed

Method	ΔQ_c (mm)	ΔQ_f (mm)	R_f (%)	R_c (%)
Sensitivity-based method	-7.42	10.10	57.66	42.34
MDMC	-30.27 ± 25.29	32.96 ± 25.29	52.12 ± 28.41	47.88 ± 28.41
Average	-18.85	21.53	54.89	45.11

Table 4.17 Comparisons of relative contributions of forest disturbance (R_f) and climate variability (R_c) to annual mean flows in the Similkameen River near Hedley

Method	ΔQ_c (mm)	ΔQ_f (mm)	R_f (%)	R_c (%)
Sensitivity-based method	-17.47	15.04	46.26	53.74
MDMC	-22.13 ± 21.22	19.70 ± 21.22	48.72 ± 27.88	51.28 ± 27.88
Average	19.80	17.37	47.49	52.51

4.4 Quantification of the cumulative effects of forest disturbance on high and low flows

4.4.1 Quantification the effects of agriculture irrigation on the high and low flows

As shown in Table 4.18, the agriculture irrigation has limited or even no effect on high flows in the Similkameen River and its tributaries. The irrigation amount only accounts for less than 3% of the measured high flows. However, the effects of irrigation may be significant on low flows and 7-day minimum flows. The agriculture irrigation consumed more than 20% of the measured low and 7-day minimum flows. For the whole Similkameen River, the agriculture irrigation is almost equivalent to the measured 7-day minimum flow (from Manning Provincial Park to Nighthawk). It should be noted that our assumptions on the irrigation rates are conservative as more intensive irrigation usually occurs in drier periods (e.g. July or August). Therefore, our calculation is somewhat underestimating the impacts of irrigation on streamflow. Due to our assumptions and possible large uncertainties, our assessment on the effects of agriculture irrigation on low flows are preliminary and a more detailed study is needed in the future.

Table 4.18 The effects of agriculture irrigation on the high and low flows in the Similkameen River watershed in Canada

Sub-basins	Licensed off-stream		% in Apr	% in May	% in Jun	% in Jul	% in Aug	% in Sept	% of Q5	% of Q95	% of 7-day low
	ML/year	Apr-Sep (m^3/s)									
Similkameen River, from Manning Park to Princeton	15792	1.0	5.1	1.2	1.1	3.0	11.2	17.7	0.7	34.9	38.0
Tulameen River at Princeton	6628	0.4	1.6	0.5	0.6	2.2	9.3	11.2	0.3	19.7	21.2
Similkameen River, from Manning Park to Hedley	30050	1.9	3.7	1.1	1.2	3.7	13.2	19.6	0.7	31.1	35.5
Similkameen River, from Maning Park to Nighthawk	115930	7.3	12.5	3.3	3.1	8.9	29.1	44.1	2.1	78.2	98.7

Note: Data on licensed off-stream water volume data are from Summit, (2011).

4.4.2 Correlation tests for selecting climatic variables

Our cross-correlation tests indicated that forest disturbance had no significant impacts on high flows in the Tulameen River watershed. Thus, the Pearson, Kendall's tau, and Spearman's rho correlation tests were only conducted in SRP and SRH watersheds to select the most significant climatic variables in the respective watersheds (Table 4.19 and 4.20). For the SRP watershed, annual maximum, minimum, and mean temperatures were significantly negatively related to the high flows, indicating that higher temperature lowers high flows. Annual precipitation was also significantly related to high flows. Spring temperatures are significantly related to high flows, but no statistically significant relationship was detected between spring precipitation and high flows as high flows usually occur in the spring due to snow-melting. To select comparable high flows between the reference and disturbance periods, we selected precipitation (named as PPTWS) in the period of October to December in antecedent year and the period of January to February in the current year, and maximum and average temperatures in spring since those climatic variables are closely associated with snow accumulation and melting processes. For the SRH watershed, no significant correlations were found for annual maximum and average temperature. However, PPTWS and spring temperatures were significantly related to the high flows. As a result, the PPTWS, spring maximum and average temperatures were selected for the SRH watershed.

4.4.3 Assessing the cumulative impacts of forest disturbance on high flows

As shown in Tables 4.21 and 4.22, similar climate conditions between the reference and disturbance periods in the SRP and SRH watersheds were selected. In the SRP watershed, the averaged high flows (Q5) was about 124 m^3/s in the reference period (1954-1983), whereas it was 141 m^3/s in the disturbance period (1984-2013), which was an increase of 13.7%. Similarly, the Q5 in the reference period (1967-1990) was 254 m^3/s in the SRH, while it was 282 m^3/s, an increase of 11% in the disturbance period (1991-2013). We further conducted the non-parametric Mann-Whitney U test to examine if there are significant differences of the selected climatic variables (Zhang and Wei, 2014b). The results indicated that there were no statistical differences of the selected climatic variables between reference period and disturbance period in either SRP or SRH watersheds. Therefore, the increased high flows were mainly due to the forest disturbance in these two study watersheds. Our above results showing that forest disturbance increased high flows are consistent with other studies (Buttle and Metcalfe, 2000; Whitaker et al., 2002; Neary et al., 2003; Moore and Wondnell, 2005; Liu et al., 2015b; Liu et al., 2016). For example, in the interior of British Columbia, forest disturbance increased high flows by 31.4% in the Baker River watershed (1570 km^2) with a CECA of 62.2% (Zhang and Wei, 2014). In the Willow River watershed (2860 km^2), with the CECA of 35.4% of the watershed area, forest disturbance increased the high flows by 36.2% (Zhang and Wei, 2013).

In this study, non-consistent results were found on the impacts of forest disturbance on high flows in the three study watersheds. Although levels of forest disturbance in the SRP and Tulameen River watersheds were similar, their effects on high flows were contrasting. No significant results were detected between forest disturbance and high flows in the Tulameen River watershed. This might be due to the differences in the watershed properties, such as topography, soil, landforms, and watershed sizes, which suggests that the impacts of forest disturbance on high flows are likely watershed specific in large watersheds. A similar study by Zhang and Wei (2014a) also showed contrasting hydrological responses to similar forest disturbance levels in two neighboring watersheds in the central interior of British Columbia. In the subtropical region of China, similar forest cover change also resulted in different effects on high flows in two nearby large forested watersheds (Liu et al., 2016). Interestingly, the SRH watershed experienced larger forest disturbance levels than the SRP watershed did, but the increment of high flows in the SRH watershed was lower than that in the SRP watershed. A similar study in Ontario indicated that no definitive changes in annual mean flow were detected with the forest disturbance levels ranging from 5% to 25%. They further concluded that larger watershed had a greater capacity of buffering hydrological responses caused by forest disturbance (Buttle and Metcalfe, 2000).

Table 4.19 Correlation tests between high flows and climatic variables in the Similkameen River at Princeton

Q5		Annual					Spring				Summer				Fall-Winter			
		Tmax	Tmin	Tave	P	PPTWS	Tmax	Tmin	Tave	P	Tmax	Tmin	Tave	P	Tmax	Tmin	Tave	P
Pearson Correlation	Coefficient	**-.323***	**-.280***	**-.318***	**.284***	**.328***	**-.497****	**-.433****	**-.501****	-0.028	-0.174	**-.273***	-0.232	0.055	-0.060	-0.079	-0.072	**.286***
	P	**0.013**	**0.032**	**0.014**	**0.029**	**0.011**	**0.000**	**0.001**	**0.000**	0.831	0.188	**0.037**	0.077	0.679	0.653	0.552	0.588	**0.028**
Kendall's tau	Coefficient	**-.218***	**-.200***	**-.236****	**.195***	0.171	**-.334****	**-.285****	**-.350****	-0.066	-0.109	**-.207***	-0.137	-0.004	-0.019	-0.087	-0.056	**.196***
	P	**0.015**	**0.026**	**0.008**	**0.029**	0.055	**0.000**	**0.001**	**0.000**	0.460	0.224	**0.021**	0.124	0.963	0.829	0.333	0.534	**0.028**
Spearman's rho	Coefficient	**-.311***	**-.287***	**-.317***	**.308***	**.261***	**-.499****	**-.409****	**-.512****	-0.090	-0.161	**-.291***	-0.200	-0.009	-0.029	-0.118	-0.071	**.299***
	P	**0.016**	**0.027**	**0.015**	**0.018**	**0.046**	**0.000**	**0.001**	**0.000**	0.498	0.223	**0.025**	0.128	0.946	0.827	0.372	0.594	**0.022**

Note: PPTWS is the sum of precipitation from October to December in antecedent year and precipitation in January and February in current year.

Table 4.20 Correlation tests between high flows and climatic variables in the Similkameen River near Hedley

Q5		Annual					Spring				Summer				Winter			
		Tmax	Tmin	Tave	P	PWS	Tmax	Tmin	Tave	P	Tmax	Tmin	Tave	P	Tmax	Tmin	Tave	P
Pearson Correlation	Coefficient	-0.166	**-.289***	-0.243	**.289***	**.469****	**-.445****	**-.406****	**-.460****	0.223	0.002	-0.216	0.003	-0.086	0.023	-0.153	-0.073	0.197
	P	0.258	**0.046**	0.096	**0.046**	**0.001**	**0.002**	**0.004**	**0.001**	0.127	0.988	0.140	0.983	0.559	0.877	0.299	0.621	0.181
Kendall's tau	Coefficient	-0.124	-0.163	-0.163	0.151	**.289****	**-.363****	**-.349****	**-.378****	0.090	0.012	-0.119	-0.005	-0.023	0.048	-0.067	-0.002	0.117
	P	0.213	0.102	0.102	0.131	**0.004**	**0.000**	**0.000**	**0.000**	0.365	0.901	0.234	0.957	0.817	0.631	0.499	0.986	0.241
Spearman's rho	Coefficient	-0.192	-0.235	-0.228	0.218	**.427****	**-.540****	**-.479****	**-.554****	0.133	0.006	-0.175	-0.014	-0.041	0.063	-0.112	-0.009	0.168
	P	0.191	0.108	0.120	0.137	**0.002**	**0.000**	**0.001**	**0.000**	0.368	0.968	0.233	0.927	0.780	0.669	0.448	0.952	0.254

Note: PPTWS is the sum of precipitation from October to December in antecedent year and precipitation in January and February in current year.

Table 4.21 Selected pairs of high flows for the Similkameen River at Princeton watershed

Pair Number	Periods	Year	PPTWS	Tmax Spring	Tave Spring	Q5	CECA
1	Reference	1979	552.0	8.3	2.2	85.3	6.3
1	Disturbance	1986	558.1	7.5	2.6	196.9	13.1
1	Disturbance	2012	562.0	7.4	2.0	121.1	37.1
2	Reference	1966	635.0	8.1	2.0	85.1	2.5
2	Disturbance	2006	639.9	8.2	2.6	137.7	28.8
3	Reference	1977	628.1	7.8	2.3	62.5	5.4
3	Disturbance	2001	610.7	7.7	2.2	63.9	22.9
4	Reference	1957	706.4	8.6	3.1	150.9	0.3
4	Disturbance	1990	710.4	8.0	2.9	111.3	14.9
5	Reference	1981	741.3	7.9	2.5	101.9	7.3
5	Disturbance	1988	738.4	8.1	2.8	98.3	13.9
5	Disturbance	1995	739.5	8.8	2.9	145.8	16.0
6	Reference	1960	838.0	6.6	1.3	122.7	1.0
6	Disturbance	2011	838.2	5.8	0.7	148.9	37.1
7	Reference	1962	824.3	6.2	1.0	100.9	1.8
7	Disturbance	1999	825.8	7.0	1.5	189.3	19.4
7	Disturbance	2000	822.6	7.4	2.2	93.6	21.2
8	Reference	1956	941.6	7.6	1.7	281.3	0.0
8	Disturbance	1997	988.3	7.1	2.0	248.9	16.7
9	Reference	1976	954.0	6.7	1.1	155.8	5.1
9	Disturbance	1996	932.3	6.2	1.3	133.6	16.3
10	Reference	1973	689.2	9.1	2.9	93.3	4.2
10	Disturbance	2008	693.6	6.4	1.3	148.4	32.6

Table 4.22 Selected pairs of high flows for the Similkameen River near Hedley watershed

Pair Number	Periods	Year	PWS	T_{max} Spring	T_{ave} Spring	Q5	CECA
1	Reference	1990	587.0	8.5	3.4	254.1	18.0
1	Disturbance	2006	592.9	8.7	3.1	258.0	41.7
2	Reference	1971	561.8	7.7	1.9	383.9	3.5
2	Disturbance	1991	558.1	7.7	2.3	393.1	19.3
3	Reference	1968	480.1	8.1	2.5	287.6	3.2
3	Disturbance	2012	475.8	8.0	2.6	275.9	59.5
4	Reference	1983	477.8	9.6	3.7	275.1	11.6
4	Disturbance	2011	476.9	6.4	1.2	329.2	59.5
5	Reference	1979	404.9	8.8	2.7	182.2	8.5
5	Disturbance	1993	406.8	9.5	4.0	236.5	20.7
6	Reference	1977	303.5	8.2	2.8	122.2	7.3
6	Disturbance	2001	315.8	8.2	2.8	140.1	29.7
7	Reference	1979	404.9	8.8	2.7	182.2	8.5
7	Disturbance	1993	406.8	9.5	4.0	236.5	20.7
8	Reference	1976	393.0	7.2	1.5	307.4	6.3
8	Disturbance	2002	403.6	5.6	1.0	355.4	30.9
9	Reference	1985	442.7	8.2	2.5	291.7	13.8
9	Disturbance	2008	468.9	7.0	1.9	318.3	50.5

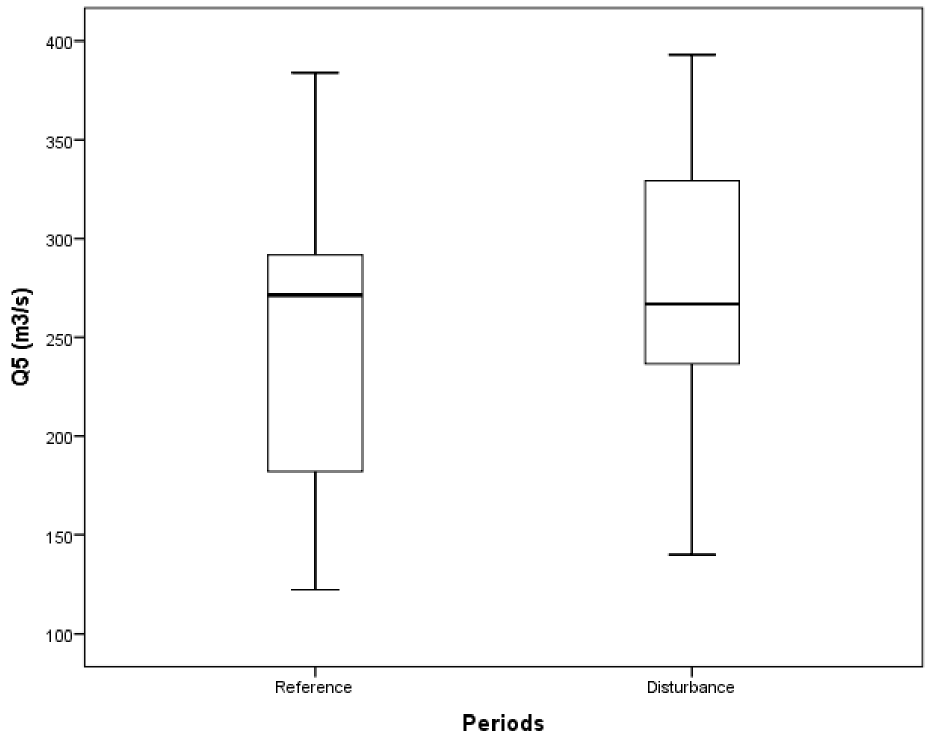

Figure 4.30 Comparisons of high flows in Similkameen River at Princeton between the reference and disturbance years (averages in the reference and disturbance periods are 124 and 141 m^3/s, respectively)

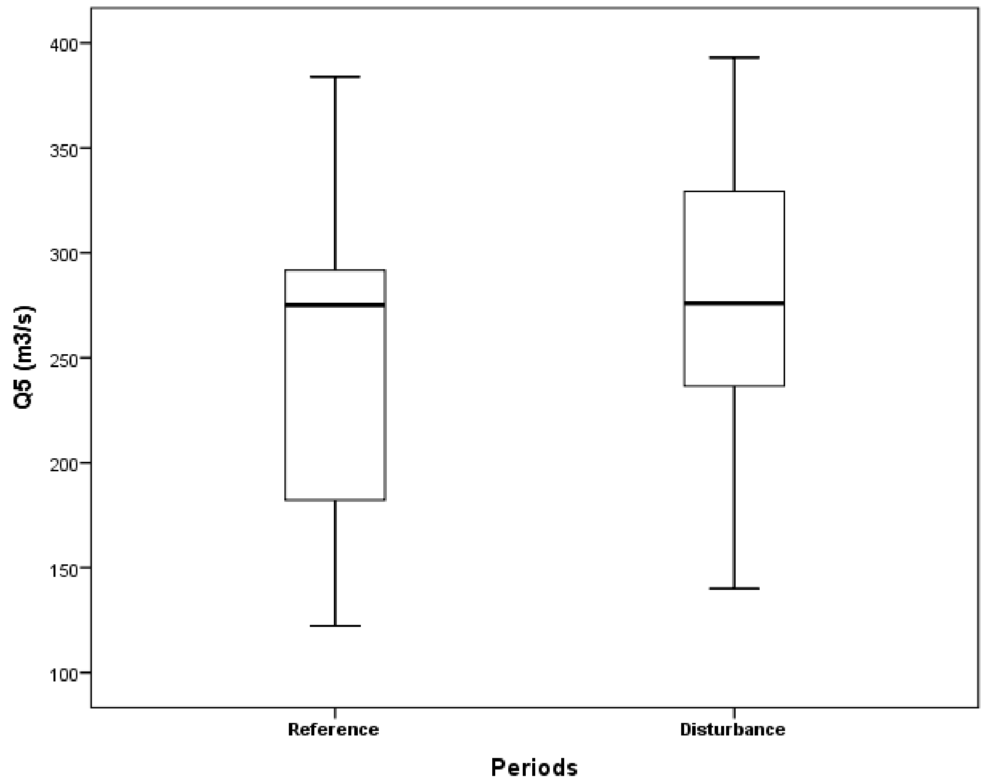

Figure 4.31 Comparisons of high flows in Similkameen River near Hedley between the reference and disturbance years (average in the reference and disturbance are 254 and 282 m^3/s, respectively)

4.5 Predictions of water resource availability under future forest disturbance and climate change scenarios

As indicated by the Mann-Kendall trend test (Table 4.6), no significant trend in precipitation were detected under the RCP 4.5 and RCP 8.5 scenarios, whereas a significant upward trend was found for the annual mean temperature in the three study watersheds. This indicated that the Similkameen River watershed is likely to experience drier conditions in the near future. In this study, annual mean flows in the three watersheds were estimated under the future climate change and forest disturbance scenarios. Our preliminary predictions show that both climate change scenarios would decrease annual mean flows. Forest disturbance is likely to increase annual mean flow in all watersheds, but different changes in magnitudes showed across three watersheds. For instance, the forest disturbance increased annual mean flows by about 15 mm (8% of the predicted annual mean flows) and 15.5 mm (10%) in the SRP and Tulameen River watershed, respectively in the RCP 4.5 scenario. However, only 1 mm (0.6% of the predicted annual mean flow) increment of the annual mean flows attributed to forest disturbance would be likely to occur in the SRH watershed (Table 4.22). This may be due to the greater buffering capacity associated with larger watershed size. In addition, there are important temporal patterns on annual mean flows between defined scenarios (Figures 4.32 to 4.37). For example, in the Tulameen River watershed, the annual mean flows reach the highest values in the year of 2030 in the RCP 4.5 scenario, while the lowest annual mean flow is expected in 2030 in the RCP 8.5 scenario.

The Similkameen River watershed is experiencing intensive forest disturbance. In our estimations, forest disturbance can increase water availability in terms of annual mean flows. Under a future drier climate, forest disturbance could alleviate water stress to some extents. However, this benefit can be overshadowed by its negative effects (e.g. increasing flood and droughts potentials due to its possible negative effects on flow regimes, causing soil erosion, decreasing biodiversity). Therefore, management decisions must be carefully balanced among various processes and functions.

Table 4.23 Predicted (2020 to 2050) annual mean flows under future climate and forest disturbance scenarios in the three watersheds

Annual mean flow (mm)		RCP 4.5		RCP 8.5		Disturbance Period
Watershed	Streamflow	Average	SD	Average	SD	Average
SRP	No forest disturbance	179.5	18.4	170.1	15.9	365.1
	With forest disturbance	194.5	19.8	184.3	17.2	389.1
	ΔQ_f	15	1.5	14.3	1.4	24
Tulameen	No forest disturbance	152.9	16.5	144.5	14.9	329.7
	With forest disturbance	168.4	15.5	160	16.6	362.7
	ΔQ_f	15.5	1.6	15.4	1.7	33
SRH	No forest disturbance	175.6	20.7	181.4	15	274.5
	With forest disturbance	176.6	21	182.4	15.1	294.2
	ΔQ_f	1.0	1.0	1.0	0.3	19.7

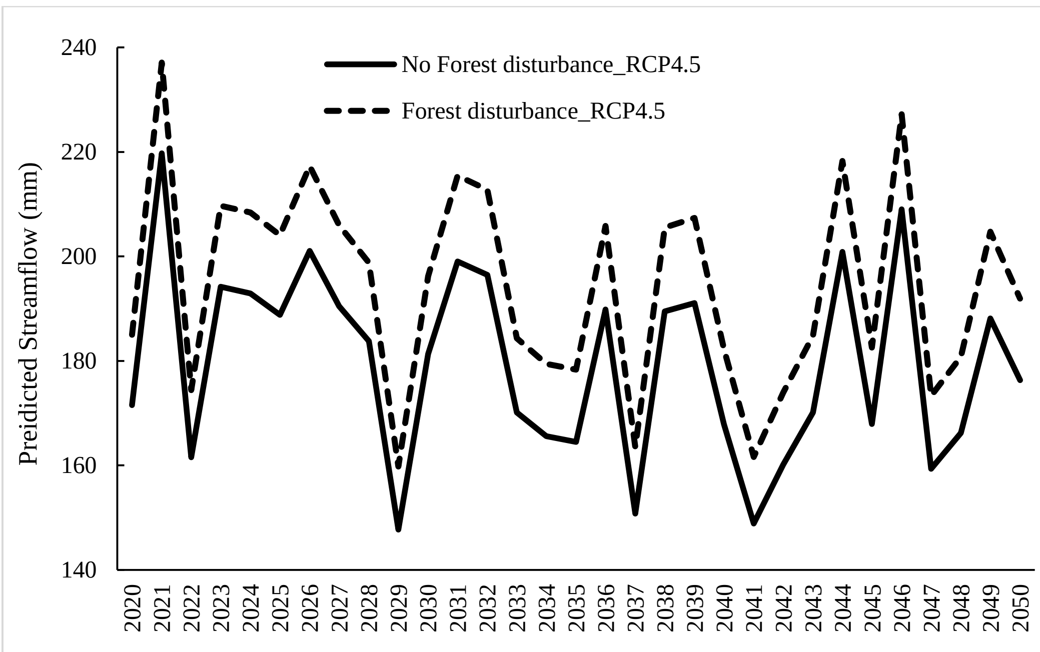

Figure 4.32 Predicted annual mean flows with and without forest disturbance in the period of 2020 to 2050 under the future climate scenarios of RCP 4.5 in the Similkameen River at Princeton watershed

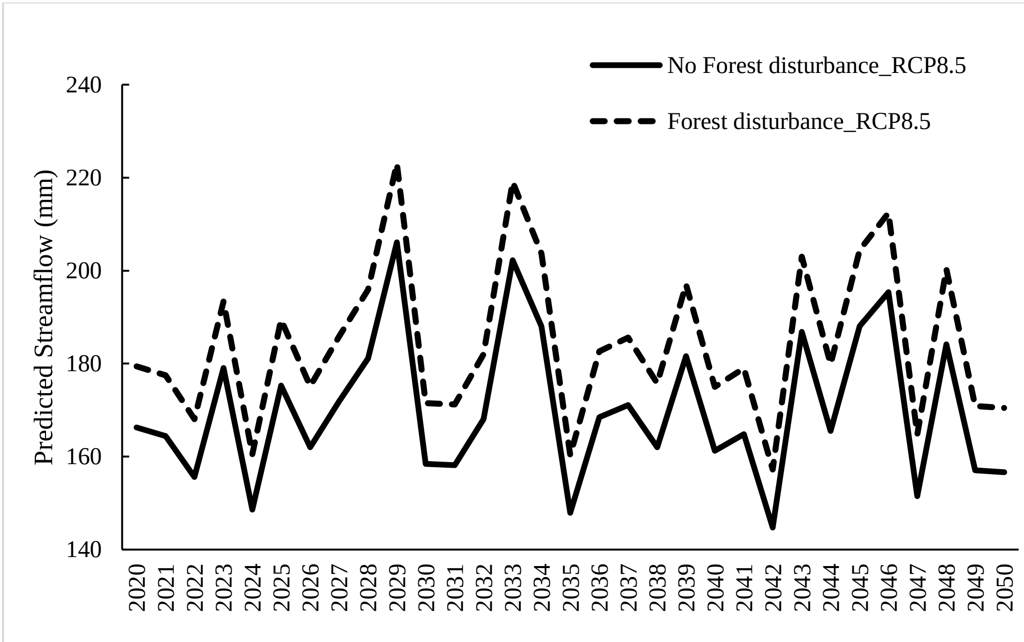

Figure 4.33 Predicted annual mean flows with and without forest disturbance in the period of 2020 to 2050 under the climate scenarios of RCP 8.5 in the Similkameen River at Princeton watershed

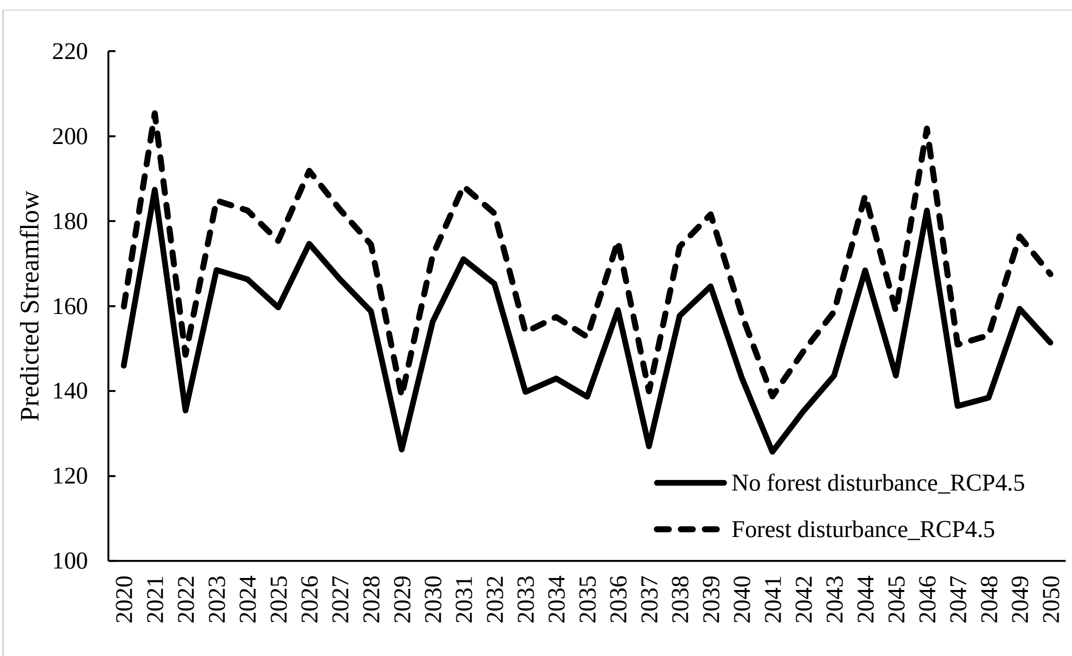

Figure 4.34 Predicted annual mean flows with and without forest disturbance in the period of 2020 to 2050 under the climate scenarios of RCP 4.5 in the Tulameen River watershed

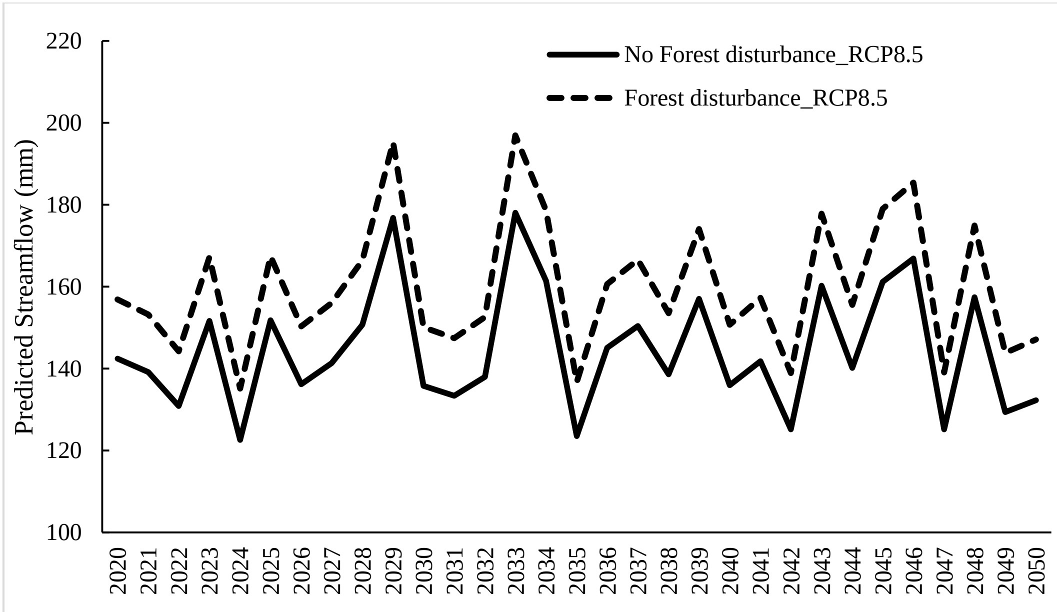

Figure 4.35 Predicted annual mean flows with and without forest disturbance in the period of 2020 to 2050 under the climate scenarios of RCP 8.5 in the Tulameen River watershed

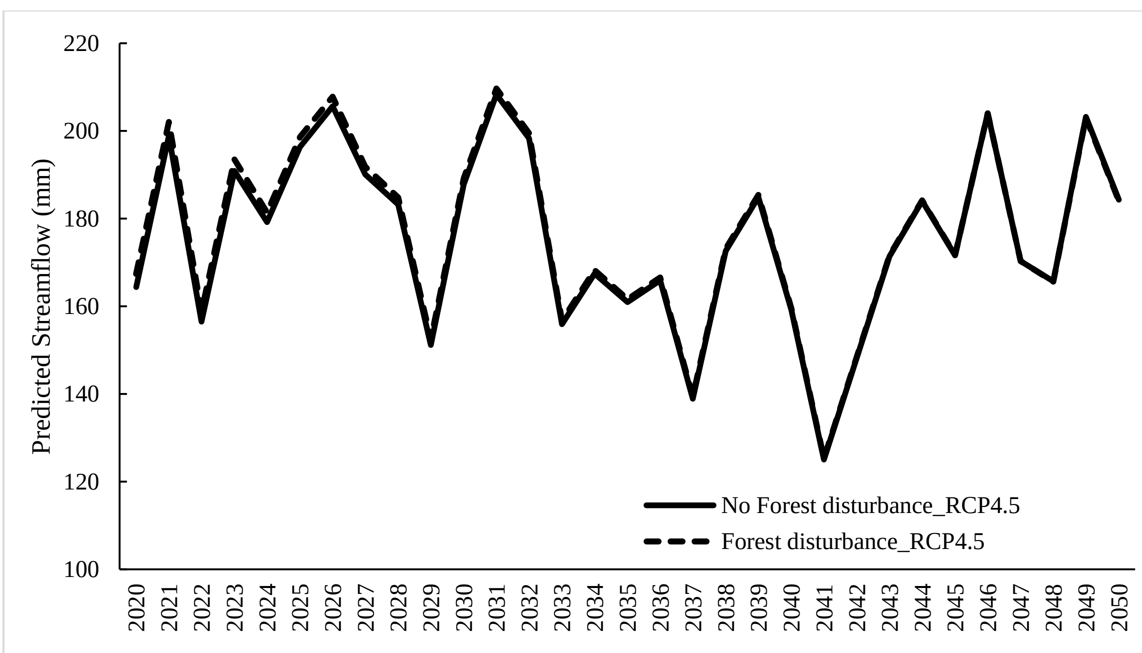

Figure 4.36 Predicted annual mean flows with and without forest disturbance in the period of 2020 to 2050 under the climate scenarios of RCP 4.5 in the Similkameen River near Hedley watershed

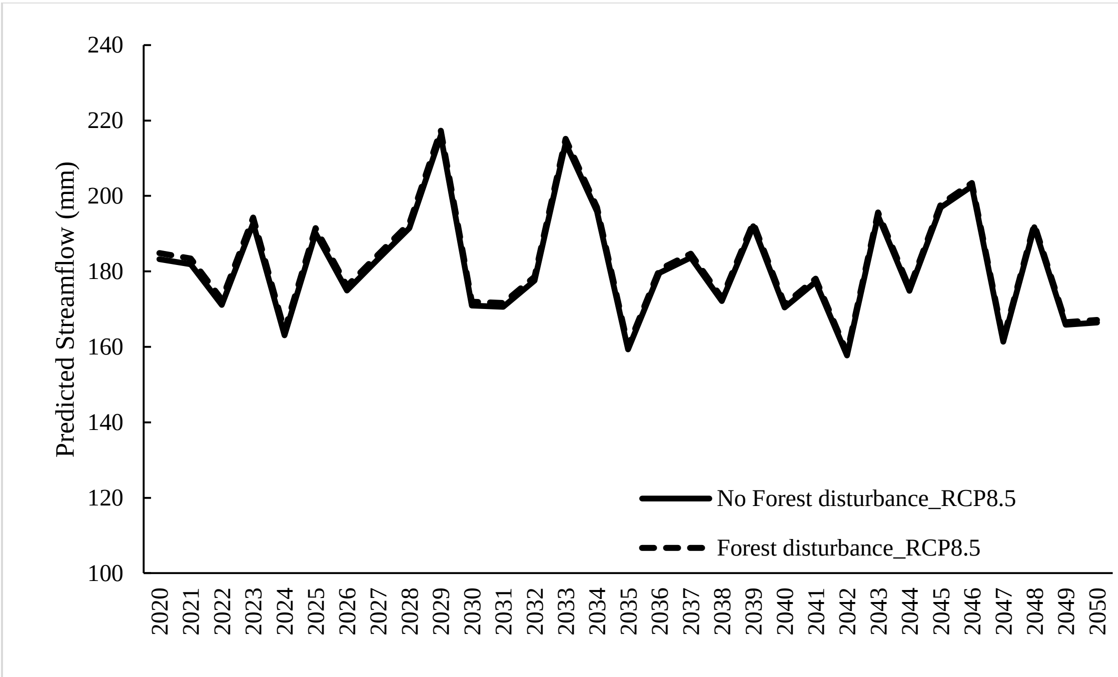

Figure 4.37 Predicted annual mean flows with and without forest disturbance in the period of 2020 to 2050 under the climate scenarios of RCP 8.5 in the Similkameen River near Hedley watershed

5. Key conclusions and recommendations

We have the following key conclusions from this study. We found that all three study watersheds experienced significant forest disturbance with the cumulative disturbance levels ranging from 37.1% to 55.7% in 2011. Those disturbances significantly increased annual mean flows in all three watersheds and high flows in both the SRP and SRH watersheds. We also found that the effects of forest disturbance on annual mean flow change magnitudes are similar to those from climatic variability, but in opposite directions, demonstrating that forest disturbance and climate played a co-equal role in annual mean flow changes. Based on our preliminary analysis, water resource supplies in terms of annual mean flows in all three watersheds are predicted to be reduced under the defined future and forest change scenarios. Our general conclusion is that both forest change and climate must be considered together in predicting and managing future water resources in the study region.

We also have several recommendations. Firstly, low flow is an important hydrological variable in our study region as it critically affects water supply and aquatic functions in dry seasons. Unfortunately, we were not able to assess how forest disturbance and climatic variability affect low flows due to the confounding factor of un-quantified but significant irrigation consumptions in all three study watersheds. Clearly, there is a need to collect data on actual water consumptions from irrigation and possible other water users before a robust analysis on low flows can be conducted. Secondly, we provided a preliminary assessment on future water resources under future forest disturbance and climate change scenarios using a modified double mass curves method. We recommend a more detailed study employing a process-based hydrological model for those study objectives. Finally, our methods applied in this study are statistical approaches, which provided valid inferences about the relationships between forest disturbance or climate and hydrological variables of interest. However, statistical approaches would not normally lead to understanding of underlying mechanisms. Thus, to fully understand water resource availability and its variations, more processed-based studies such as groundwater and surface water interactions are needed.

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