The effect of climate and land cover change on water resource sustainability in the Similkameen River Watershed (Progress Report)

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Executive summary

The Regional District of Okanagan Similkameen (RDOS) contracted UBC Okanagan to conduct the above-mentioned project (Jan. 2013-Jan. 2017). This progress report summarized what we have done up to now.

Land cover or forest change and climatic variability are the two main drivers influencing hydrology in forest-dominated watersheds. However, it is challenging to separate their relative contributions to hydrology. The Similkameen River watershed provides vital water resource for development of communities and aquatic needs. However, it is undergoing the significant alteration caused by the combination of climate change and various forest disturbances. Based on our results, the cumulative equivalent clear-cut area (CECA) was 42% for the whole Similkameen River watershed in 2011, which indicates that the watershed was significantly disturbed by forest disturbances.

We have successfully separated the relative contributions of forest disturbance and climate variability to annual mean flow in the Tulameen River watershed, a major

tributary of the Similkameen River watershed. Our result showed that the forest disturbance and climatic variability contributed 60.3 ± 29.8 mm and -63.2 ± 38.5 mm (or 50.4 ± 10.5 % and 49.6 ± 10.5 %) to annual mean flow in the period of 1984 to 2009. It indicates that the forest disturbance and climatic variability played an offsetting effect on annual mean flow. It also suggested that forest disturbance and climatic variability are equally important to annual water yield in the Tulameen River watershed.

Our next steps are: 1) to quantitatively assess the impacts of forest disturbance and climatic variability in other identified tributaries as well as the whole Similkameen River watershed; 2) assess the possible hydrological response to future scenarios of climate and forest or land cover changes; and 3) link the results to future water and watershed management plans. In addition, in November 2014, we submitted a NESRC proposal to study the cumulative effects of forest disturbance on hydrology in the Similkameen River watershed. In this proposal, a combination of statistical methods with hydrological modelling will be used to achieve our objective. We believe that successful implementation of the contracted and proposed studies will allow us gain a full understanding of water resources and their responses to climate and forest disturbances, and provide critical data to support water managers to make suitable decision on water and watershed management in the Similkameen River watershed.

1. Introduction

Land cover or forest change and climatic variability are commonly recognized as the two main drivers influencing hydrology in forest-dominated watersheds (Wei and Zhang 2010a, b; Zhang, 2013). However, separating their relative contributions is challenging, and relatively little research has addressed this subject (Stednick 1999; Moore, 2005; Tuteja 2007; Wei and Zhang, 2010b). Recently, we have developed a research methodology for quantifying relative contributions of forest disturbance and climatic variability to hydrology in large watersheds (>1000 km^2). The methodology involves the combination of time series analysis and modified double mass curves (Wei and Zhang 2010b; Zhang, 2013). The method has been successfully applied to several large basins in the central interior of British Columbia (Zhang, 2013).

Many communities, particularly in the semi-arid regions of Canada, are heavily dependent on water availability. In BC, over 75% of the population relies upon water supply from community-based watersheds. With population increasing, intensifying land use change and climate change impacts, water availability is becoming a limiting factor for future economic wellbeing and environmental protection. The growing dependency of our economic and social development on water resource highlights a critical need to understand future water demand and supply under various key drivers such as climate change, forest disturbance or land use change, and increasing water demand.

The objectives of this 4-year project (2013-2017) include: (1) development of equivalent clear-cut area (ECA) for the whole Similkameen River watersheds and its sub-watersheds (e.g. Tulameen River watershed) considering hydrological recovery following the mountain pine beetle infestation and other forest disturbance; (2) application of our well established methodology in sub-watersheds to assess relative contributions of climate variability and forest disturbance (in Tulameen River watershed) or land cover change (in the whole Similkameen River watershed) to hydrology; and (3) interpretation of the results for designing future water and watershed management plans.

2. Methodology

2.1. Quantification of cumulative forest disturbance levels

Logging, fire and Mountain Pine Beetle infestation (MPB) are considered as the three major forest disturbance types in the Similkameen River watershed. These forest disturbances, however, are cumulative over space and time (Gluns, 2001). Equivalent Clear-cut Area (ECA) was used as an integrated indicator that combines all types of forest disturbance, spatially and temporally, with consideration of vegetation recovery following disturbance (BC Ministry of Forests, 1999). Cumulative Equivalent Clear-cut Area (CECA) is the sum of the annual ECA over space and time (IWAP, 2006). However, hydrological recovery of forest stand is determined by various factors, mainly including disturbance type, climate, and tree species (BC Ministry of Forests, 1999; BC Ministry of Forests, 2012). Here are some details of ECA calculation.

2.1.1. Biogeoclimatic ecosystem classification in the Similkameen River watershed

According to the biogeoclimatic ecosystem classification (BEC) system, the most of the Similkameen River watershed locates in the Interior Douglas Fir (IDF), Engelmann Spruce Subalpine Fir (ESSF) and Montane Spruce (MS) biogeoclimatic zones. 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 elevation of the Simikameen River watershed. With the elevation increasing, the areas are featured with MS dry mild (MSdm), MS moist warm (MSmw), ESSF dry cold (ESSFdc) and ESSF very dry cold (ESSFxc).

The dominant tree species in this watershed include lodgepole pine (Pinus contorta) and interior Douglas fir (Pseudotsuga menziesiiinterior). 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 landscape in the driest regions due to 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 the higher elevations. Trembling aspen (Populus tremuloides) is also a widely distributed seral species (BC Ministry of Forests, Lands and Natural Resource Operations, 2012).

2.1.2. H60 calculation

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

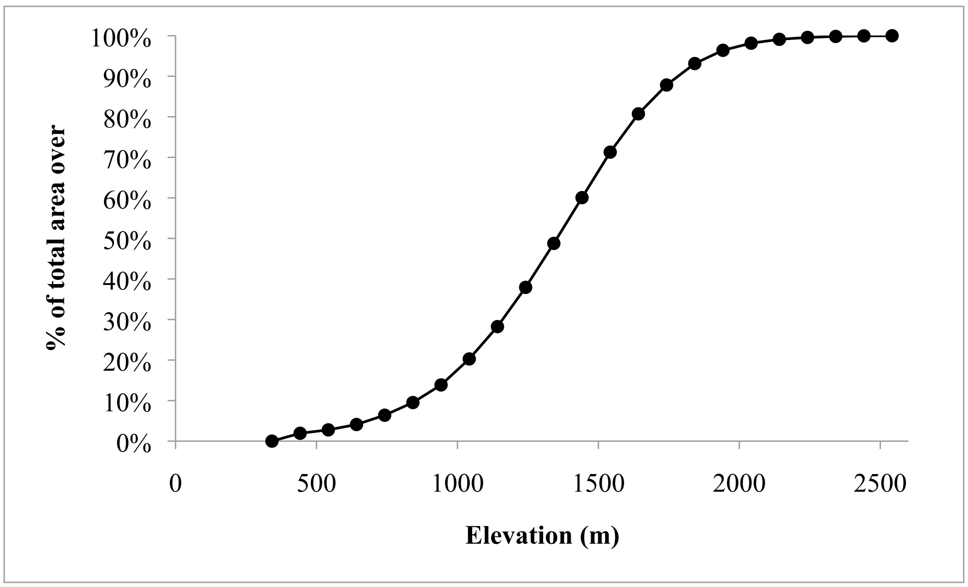


Figure 1 Hypsometric curve in the Similkameen River watershed

2.1.3. Hydrological recovery and ECA coefficient

Equivalent clear-cut area (ECA) is defined as the area that has been clear-cut, fire-killed or infested by MPB, with a reduction factor (ECA coefficient) to account for hydrological recovery due to forest regeneration. ECA coefficient of 100% means no hydrological recovery in a disturbed area while an ECA coefficient of 0% indicates a full hydrological recovery. The cumulative clear-cut area (CECA) is the sum of the annual ECA. However, hydrological recovery of forest stand is determined by various factors, mainly including disturbance type, climate, and tree species. Site index is the most common measure of forest site productivity and forest growth used in British Columbia. The relationship between vegetation growth (expressed by ages and tree height) and hydrological recovery rate was generally used to estimate ECA after logging for different tree species, mainly spruce, lodgepole pine, and Douglas fir forests in the watershed assessment (BC Ministry of Forests and Rangeland, 1999). Thus, the relationship of the hydrological recovery according to age and 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 1 to 3). Then, the ECA coefficients time series for different tree species after logging or fire disturbance and MPB infestation were estimated based on the IWAP (2006) (Figure 2).

Table 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
9-11	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 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
9-11	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. 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	9-19	30
5-<7	17-27	50
7-<9	23-33	70
9-11	28-40	80
11-13	34-51	90
13-15	41-62	95
>15	>63	100

Note: Based on the site index of 13

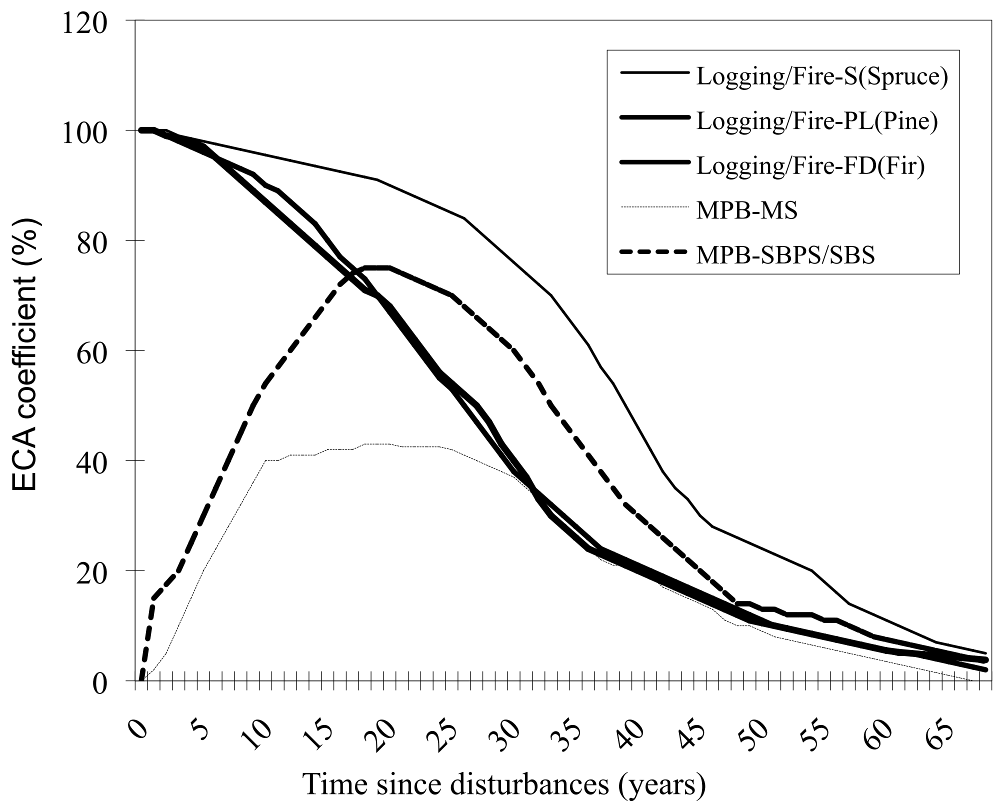


Figure 2. ECA coefficients of different forest disturbance types for Similkameen River watershed

2.2. Separating the relative contributions of forest disturbance and climatic variability to annual mean flow

For a large watershed, climatic variability and forest disturbance are two primary drivers of hydrological variation. In order to quantitatively separate the effects of climate variability and forest disturbance on annual mean flow, the influence of climatic variability on annual mean flow should be eliminated. The modified double mass curve (MDMC), developed by the Wei and Zhang (2010 b), was an effective method to eliminate the influence of the climatic variability on annual mean flow. The MDMC was created by plotting the accumulated annual mean flow versus accumulated annual effective precipitation (i.e. residue between precipitation and evapotranspiration) under the assumption of linear relationship between variations in two variables. In the periods of without or with limited forest disturbance (reference period), a straight line is expected and serve as the baseline. A break in this curve indicates that the changes of annual mean flow caused by the factors other than climatic variables, for example, forest disturbance or land use change. Also, the ARIMA (autoregressive integrated moving average) model was introduced to validate the breaking point on the MDMC to make the robust conclusion on the breaking point (Zhang, 2013).

3. Results

3.1. Cumulative forest disturbance levels

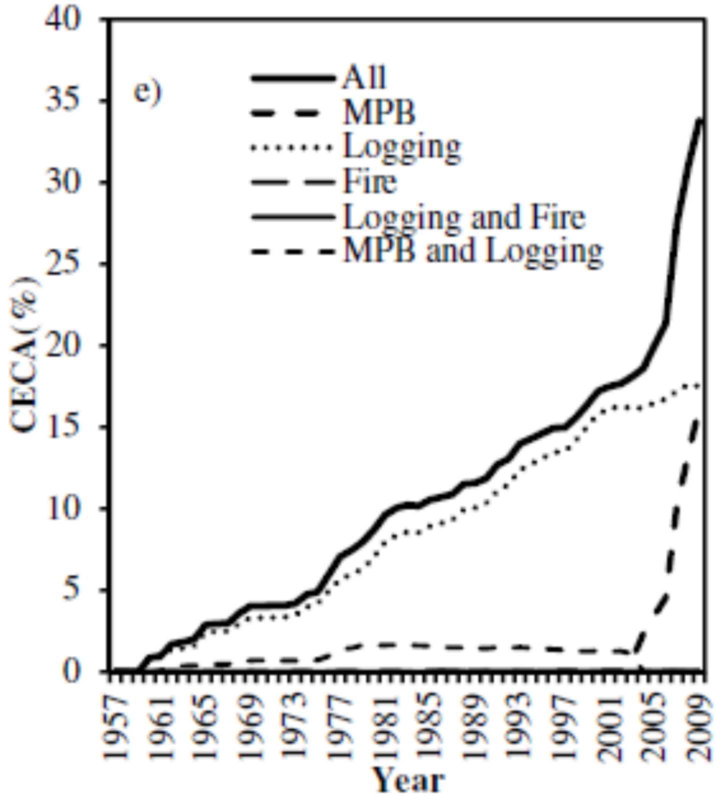


Figure 3 Cumulative equivalent clear-cut area (CECA) in the Tulameen River watershed from 1957 to 2009.

Logging, MPB infestation, and fire are recognized as three major forest disturbance types in the Tulameen River watershed. Based on the VRI data, a forest stand in this watershed was disturbed by either one type of disturbance (logging, fire or MPB) or two types of disturbances (logging + fire or logging +MPB) (Figure 3). Logging activities, the leading forest disturbance type, dated back to 1957 but on a small scale before 1961. Since 1962, logging activities were on a steady increase and the watershed was progressively logged with an average clear-cut rate of 0.42% per year (7.5 km^2). Particularly, about 1% of the total watershed area (18 km^2) was logged in 1976, 1977, 1991, and 1993. Up to 2009, cumulative clear-cut area came up to 457.5 km^2 (25.7% of the total watershed area). MPB infestation is the second leading disturbance type. MPB infestation was limited before 2003, except in 1986 with a small area infested. Between 2003 and 2007, forests attacked by MPB were on an increase with 356 km^2 forests infested (20% of the total watershed area) during that period. Fires occurred occasionally on a small scale in 1985, 1986, 2001, 2004, and 2006. Up to 2009, cumulative disturbed area was up to 817 km^2 (45.9% of the total watershed area) in the Tulameen River watershed. The Tulameen River watershed has experienced substantial forest disturbances, particularly logging since 1957.

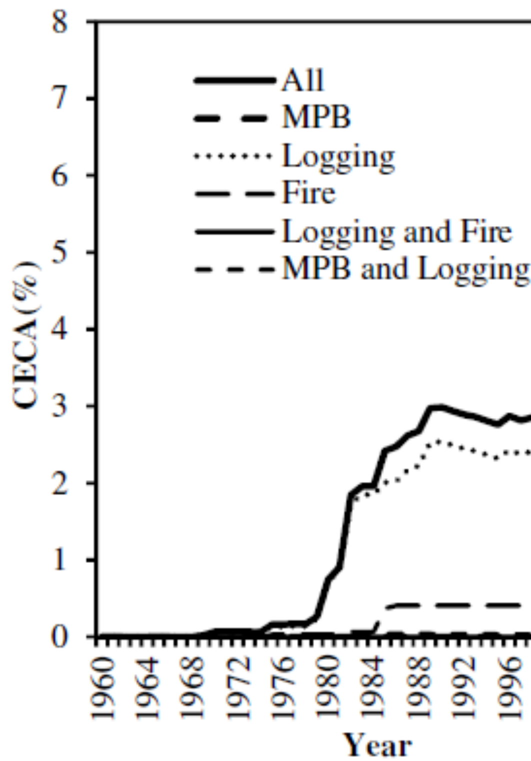


Figure 4 Cumulative equivalent clear-cut area (CECA) in the Ashnola River watershed from 1957 to 2009.

Logging, MPB (Mountain Pine Beetle) infestation, and fire are recognized as three major forest disturbance types in the Ashnola River watershed. Based on the VRI data, a forest stand in this watershed was disturbed by either one type of disturbance (logging, fire, or MPB) or two types of disturbances (logging +fire or logging +MPB) (Figure 4). Logging activities were limited before 1980 and slightly on an increase but with low levels (Figure 4). Up to 2009, cumulative clear-cut area was only 50 km^2 (4.8% of the total watershed area). MPB infestation was limited before 2003. Between 2003 and 2007, forests attacked by MPB were on an increase with 190.4 km2 infested (18.1% of the total watershed area) during that period. Fires occurred occasionally in 1975, 1982, 1985, and 1986. The largest fire in 1985 burned an area of about 3.2 km^2. Up to 2009, cumulative disturbed area was 247 km^2 (23.5% of the total watershed area). The Ashnola River watershed has experienced limited forest disturbances over the study period.

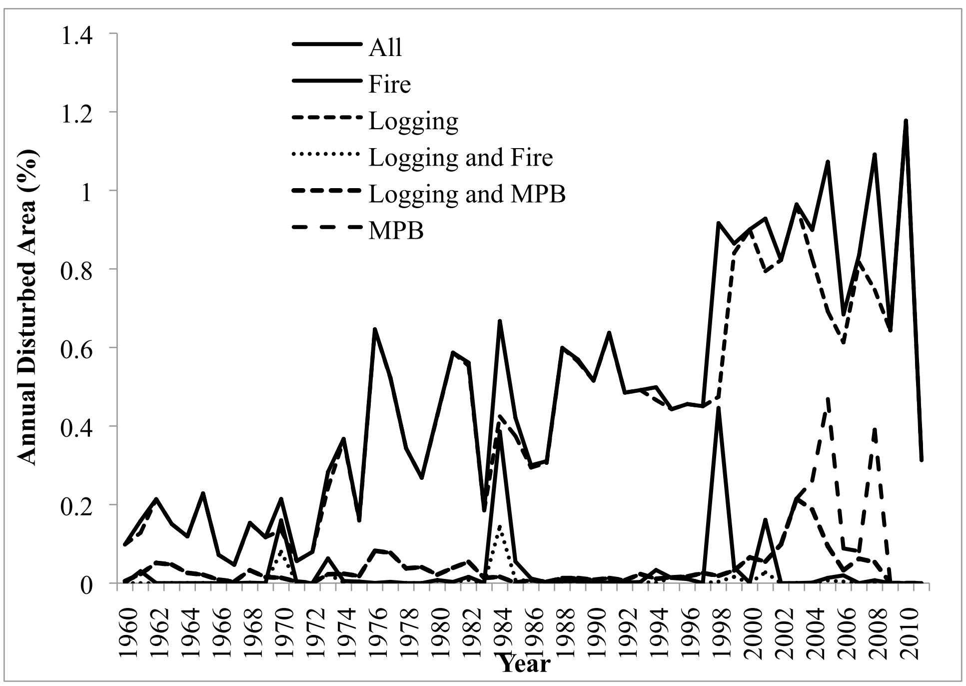


Figure 5. Annual disturbed area (%) of the Similkameen River watershed from 1960 to 2011.

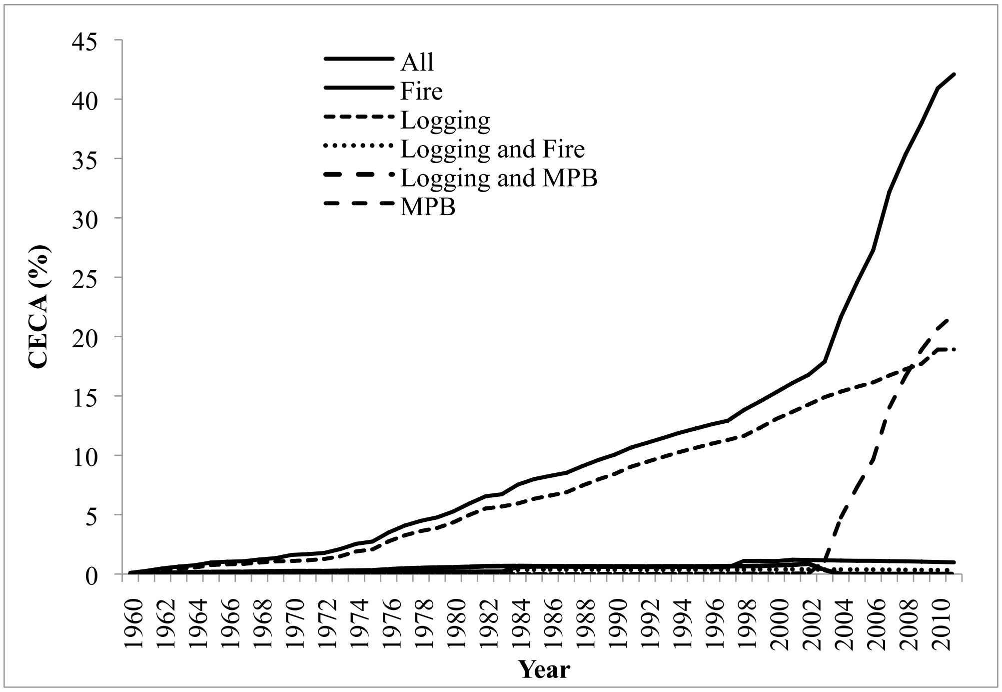


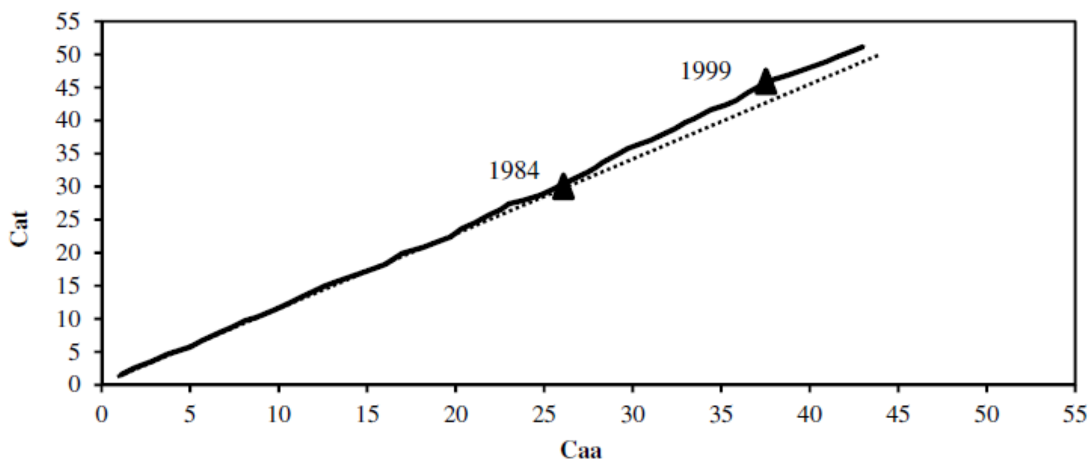
Figure 6 Cumulative equivalent clear-cut area (CECA) in the Similkameen River watershed from 1960 to 2011.

Table 4. Summary of CECA in 2011 (% of total watershed area) for the Similkameen River watershed.

	Fire	Logging	MPB	Logging + Fire	Logging+ MPB	All
CECA	0.98	18.92	21.87	0.32	0.00	42.09
CECA above H60	0.62	10.51	16.86	0.23	0.00	27.61
CECA above H60/Total (%)	63.37	55.58	77.09	72.71	-	65.59

As shown in Figure 6 and Table 4, the cumulative equivalent clear-cut area (CECA) of all disturbance types was 42.1% (3185 km^2) in 2011 in the Similkameen River watershed. The logging is the leading disturbance type before 2009. Until 2011, the CECA of logging in the Similkameen River watershed was 1431 km^2 (18.9% of the whole watershed area). The average CECA of fire was 0.52% from 1960 to 2011. The major three fire events made the CECA jumping from 0.21% in 1980 to 1.21% in 2002. The average CECA of MPB was 2.2% from 1986 to 2011. The large intensive MPB infestation broke out in 2003 with the CECA of 0.05%, and then became the dominant disturbance type after 2009 with the CECA of 18.8%. Up to the 2011, the CECA of MPB was 1655 km^2, which is about 21.9% of the total watershed area. The CECA of two types of disturbances (i.e., logging + fire and logging + MPB) are relative small with the CECA of 0.32% and 0 for logging + fire and logging + MPB, respectively until 2011.

3.2. Impacts of forest disturbance and climate change on the annual mean flow in the Tulameen River watershed



C_{at} and C_{aa} are the accumulated annual effective runoff coefficient of the Tulameen River watershed and the Ashnola River watershed, respectively.

Figure 7 The modified double mass curve for the Ashnola-Tulameen quasi-paired watershed study

Figure 7 presents the modified double mass curve for the Ashnola-Tulameen quasi-paired watershed study using the original values of variables, where the accumulated annual effective runoff coefficient of the Tulameen River watershed is plotted against the accumulated annual effective runoff coefficient of the Ashnola River watershed. According to the ARIMA Intervention model of the slope in Figure 7, two significant breakpoints at 1984 and 1999 were identified at a=0.05 (Table 5). Thus, we defined the reference period as between 1954 and 1983 and the disturbance period from 1984 to 2009. The disturbed period was further divided into two phases: phase 1 from 1984 to 1998 and phase 2 from 1999 to 2009. The differences between the observed line and the predicted line were ascribed to forest disturbances. By use of log-transformed values of variables, the linear model with autoregressive errors that relates the accumulated annual effective runoff coefficient of the Tulameen River watershed with the accumulated annual effective runoff coefficient of the Ashnola River watershed was used to predict the accumulated annual effective runoff coefficient of the Tulameen River watershed without disturbances in the disturbed period (Table 6). Then the annual mean flow variations attributed to forest disturbances were estimated accordingly. The accumulated annual mean flow variations attributed to climate variability were also calculated.

Table 5 The ARIMA Intervention model of slope in the MDMC for the Ashnola- Tulameen quasi-paired watershed study

AR part	Int part	MA part	Intervention Part			Model Structure	MS
			CP1 (1984)	CP2 (1999)	Change Type		
p(1)	d(1)	q(1)	ω(1)	ω(2)			
-0.76 (p<0.001)	3	0.89 (p<0.001)	0.86* (p=0.009)	-0.61* (p=0.05)	AP	ln(x),(1,3,1)	0.2

Note: *, Significant change point at α=0.05; p(1), d(1), and q(1) are parameters for autoregression, differencing, and moving average; ω(1) and ω(2) are parameters for intervention; AR part, Int part, and MA part refer to autoregressive part, integrated part, and moving average part, respectively; CP1, CP2, AP, and MS refer to the first change point, the second change point, abrupt permanent change, and model residual, respectively; The slope is the ratio of annual mean flow to annual effective precipitation.

Table 6 The autoregressive model for MDMC for the Tulameen River watershed.

PE method	Parameter estimates			DW statistics	AC(1) coefficient	R^2	RMSE
	β_0 (constant)	β_1 ($\ln(C_{at})$)	φ_1 (AR1)				
ML	0.322 (p<0.001)	0.945 (p<0.001)	-0.555 (p=0.006)	2.06	-0.03	0.999	0.02

Note: PE is parameter estimation method; ML is maximum likelihood; RMSE is rooted mean squared error; C_{at} (t) and C_{aa} (t) are the accumulated annual effective runoff coefficient of the Tulameen River watershed and the Ashnola River watershed at year t, respectively; γ(t) is regression model error; ε(t) is autoregressive model(AR1) error; DW is Durbin-Watson statistics; AC(1) coefficient is lag 1 autocorrelation coefficient of model errors; Regression model: $\ln(C_{at}(t))=0.322+0.935\ln(C_{aa}(t))+\gamma(t)$, $\gamma(t)=0.555\gamma(t-1)+\varepsilon(t)$ (See Figure A-5 for its regression plot).

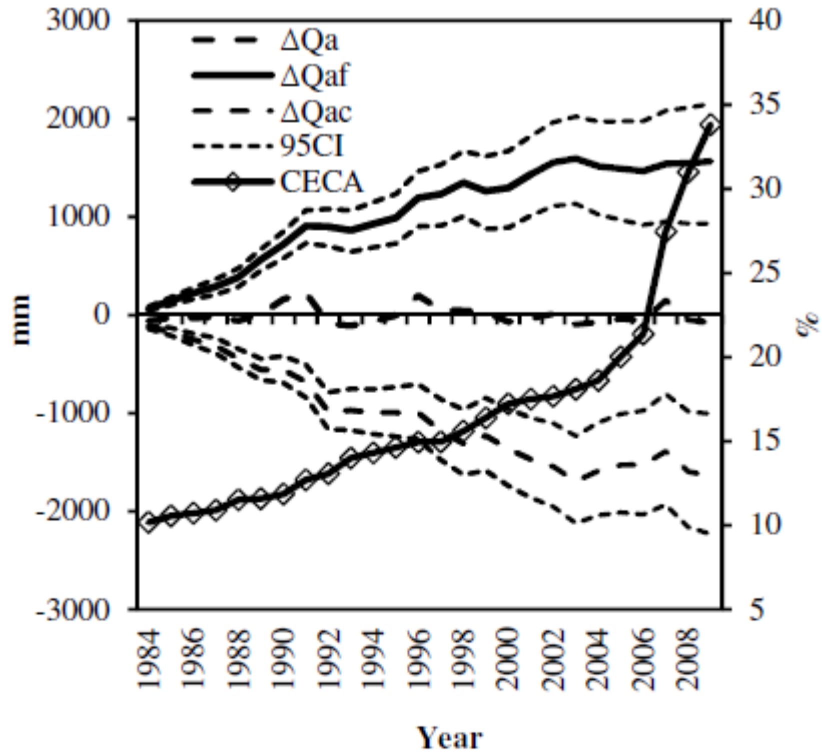


Figure 8 The accumulated annual mean flow variation (ΔQa), accumulated annual mean flow variation attributed to forest disturbances (ΔQaf), and the accumulated annual mean flow variation attributed to climate variability (ΔQac) in the Tulameen River watershed

As seen in Figure 8, up to 2009, the accumulated annual mean flow variation attributed to forest disturbances was 1566.6 mm, while its variation attributed to climate variability was -1644.3 mm. This cumulatively resulted in a 77.7 mm decrease in annual mean flow by 2009. The annual mean flow variations attributed to forest disturbances ranged from -86.7 mm (22.5% of the average annual mean flow from 1954 to 2009) to 202.9 mm (52.6% of the average annual mean flow from 1954 to 2009), with an average of 60.3 mm (15.6% of the average annual mean flow from 1954 to 2009) (Figure 9, Table 7). The annual mean flow variations attributed to climate variability varied from -303.3 mm to 134.0 mm with an average of 63.2 mm (Table 7). Meanwhile, during the disturbed period, the CECA of the Tulameen River watershed experienced a substantial increase from 10.6% in 1985 to 33.8% in 2009, whereas the CECA of the Ashnola River increased slightly from 2.0% to 6.8%.

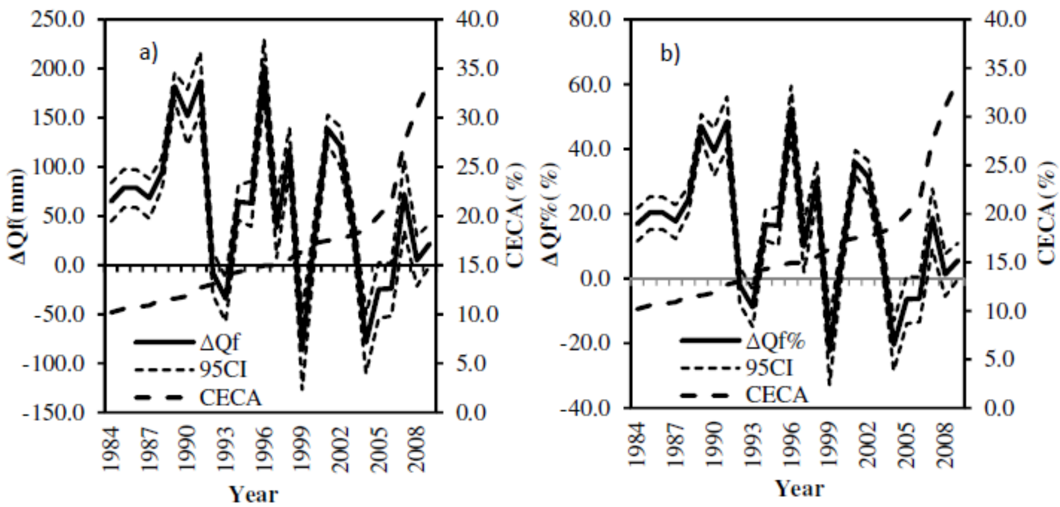


Figure 9 The annual mean flow variation attributed to forest disturbances (ΔQf); and b) the relative annual mean flow variation attributed to forest disturbances (ΔQf%) in the Tulameen River watershed

As suggested in Figure 9 (a, b), the normalized annual mean flow variations attributed to forest disturbances varied from -5.3 mm/% to 15.7 mm/%, with an average of 4.6 m/%. That means, during the disturbed period, per 10% CECA caused a -53 mm (13.7% of the average annual mean flow from 1954 to 2009) to 157 mm (40.7% of the average annual mean flow from 1954 to 2009) change in annual mean flows, with an average of 44 mm (11.4% of the average annual mean flow from 1954 to 2009).

Table 7 Forest disturbance effects on annual mean flows in the Tulameen River watershed in the different phases (1984-2009)

Phase	ΔQ (mm)	ΔQ_f (mm)	Q_f/CECA	$\Delta Q_{f\%}$	$\Delta Q_{f\%}$/CECA	ΔQ_c (mm)	$\Delta Q_{c\%}$	CECA (%)
1:1984-1998	2.8	90.0±33.6	7.2±2.6	23.3±8.7	1.9±0.7	-87.2±41.5	-22.6±10.8	12.8
2:1999-2009	-10.8	19.7±43	0.9±2.4	5.1±11.1	0.2±0.6	-30.5±67.2	-7.9±17.4	21.7
Average	-3.0	60.3±29.8	4.6±2.2	15.6±7.7	1.2±0.6	-63.2±38.5	-16.4±10.0	16.6

Note: CECA is cumulative equivalent clear cut area; ΔQ and ΔQ% are annual mean flow variation and relative annual mean flow variation (ΔQ%= ΔQ/Q, and Q is average annual mean flow from 1954 to 2009), respectively; ΔQ_f and ΔQ_f% are annual mean flow variation attributed to forest disturbances and relative annual mean flow variation attributed to forest disturbances (ΔQ_f%= ΔQ_f/Q), respectively; ΔQ_f/CECA and ΔQ_f%/CECA are normalized annual mean flow variation attributed to forest disturbances and normalized relative annual mean flow variation attributed to forest disturbances by CECA, respectively. ΔQ_c and ΔQ_c% are annual mean flow variation attributed to climate variability and relative annual mean flow variation attributed to climate variability (ΔQ_c%=ΔQ_c/Q, and Q is average annual mean flow from 1954 to 2009).

Table 7 summarizes forest disturbance effects on annual mean flows in different phases, which helps us explore the temporal dynamic of hydrological impacts of forest disturbances. In phase 1, with an average CECA of 12.8%, the average annual mean flow variation attributed to forest disturbances was 90.0 mm/yr (equivalent to 23.3% of the average annual mean flow from 1954 to 2009), but it greatly declined to 19.7 mm/yr (equivalent to 5.1% of the average annual mean flow from 1954 to 2009) in phase 2, the most intensively disturbed phase. The normalized annual mean flow variations attributed to forest disturbances displayed a similar pattern. In phase 1, per 10% CECA resulted in a 72 mm increment in annual mean flow while in phase 2, this number declined to 9 mm.

Unlike forest disturbances, climate variability impacted annual mean flows in a negative way. The average annual mean flow variations attributed to climate variability in phase 1 and phase 2 were -87.2 mm and -30.5mm, respectively.

Table 8 The relative contributions of forest disturbances and climate variability on annual mean flow variations in the Tulameen River watershed (1984-2009)

Phase	ΔQ (mm)	R_f (%)	R_c (%)	CECA(%)
1: 1984-1998	2.8	58.3±13.9	41.7±13.9	12.8
2: 1999-2009	-10.8	39.6±13.5	60.4±13.5	21.7
Average	-3.0	50.4±10.5	49.6±10.5	16.6

Note: CECA is cumulative equivalent clear cut area; ΔQ is annual mean flow variation; R_f and R_c are relative contributions of forest disturbances and climate variability, respectively ($R_f=100*|\Delta Q_f|/(|\Delta Q_f|+|\Delta Q_c|)$; $R_c=100*|\Delta Q_c|/(|\Delta Q_f|+|\Delta Q_c|)$).

Table 8 demonstrates the relative contributions of forest disturbances and climatic variability to annual mean flow variations. Forest disturbances and climate variability produced offsetting effects on annual mean flows, and their strength of influences is almost equal. The relative contribution of forest disturbances on annual mean flows was averaged 50.4% and similarly, the relative contribution of climate variability was 49.6%. But their relative contributions on annual mean flow variations were dynamic over time. In phase 1, forest disturbances produced greater impact on annual mean flows and 58.3% of the variation in annual mean flows was explained by forest disturbances and 41.7% of that was accounted by climate variability. During phase 2, the relative contribution of forest disturbances on annual mean flow variations greatly dropped to 39.6%, compared with 60.4% of variation explained by climate variability.

4. Next steps

Our next steps are: 1) to quantitatively assess the impacts of forest disturbance and climatic variability in other identified tributaries as well as the whole Similkameen River watershed; 2) assess the possible hydrological response to future scenarios of climate and forest or land cover changes; and 3) link the results to future water and watershed management plans.

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