The effects of cumulative forest disturbance on streamflow in a large watershed in the central interior of British Columbia, Canada

M. Zhang[1] and X. Wei[1]

[1]Department of Earth and Environmental Science, The University of British Columbia (Okanagan campus), 3333 University Way, Kelowna, British Columbia, Canada

Correspondence to: X. Wei (adam.wei@ubc.ca.)

Abstract

The Baker Creek watershed (1570 km^2) situated in the central interior of British Columbia, Canada has been severely disturbed by both ~~human-being~~ logging and natural disturbance, particularly by a recent large-scale mountain pine beetle (MPB) infestation (up to 2009, 70.2% of the watershed area was attacked by MPB) and subsequent salvage logging. The concept of equivalent clear-cut area (ECA) was used to indicate the magnitude of forest disturbance with consideration of hydrological recovery following various types of disturbances (wildfire, logging and MPB infestation) cumulated over space and time in the ~~studied~~ watershed. The cumulative ECA ~~was up to~~peaked at 62.2% in 2009. A combined approach of statistical analysis (i.e., time series analysis) ~~with~~ and graphic method (modified double mass curve~~-~~) was employed to evaluate the impacts of forest disturbance on hydrology. Our results showed that severe forest disturbance significantly increased annual mean flow. The average increment in annual mean flow caused by forest disturbance was 48.4 mm/yr, while the average decrease in annual mean flow cased by climatic variability during the same disturbance period was -35.5mm/yr. The opposite changes in directions and magnitudes clearly suggest offsetting effect between forest disturbance and climatic variability, with the absolute influential strength of forest disturbance (57.7%) overriding that from climate variability (42.3%). Forest disturbances also produced significant positive effects on low flow and dry season (fall and winter) mean flow. Implications of our findings for future forest and water resources management are discussed in the context of long-term watershed sustainability.

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Key words: forest disturbance, logging, wildfire, mountain pine beetle infestation, annual mean flow, low flow, time series analysis

1. Introduction

Forests play an important role in the water cycle ~~mainly through~~by influencing rainfall interception, evapotranspiration, and soil infiltration and storage. Forest disturbances such as logging, wildfire, and insect infestation ~~will inevitably have impacts~~can effect ~~on~~ streamflow by altering its regime (i.e., magnitude, frequency, timing, duration and rate of change). Numerous studies on the hydrological impacts of logging have been conducted on small watersheds (less than 100 km^2), using the paired-watershed experimental approach, and those studies have shown that forest ~~logging~~ harvesting can significantly increase annual mean and peak flows, and change dry season low flow (Stednick, 1996; Neary et al., 2003; Bruijnzeel, 2004; Moore and Wondzell, 2005). But the research on impacts of forest disturbances on hydrology in large watersheds (>1000 km^2) is limited (Wei and Zhang, 2010a; Vose, et al., 2011), and the results are inconsistent (Ring and Fisher, 1985; Buttle and Metcalfe, 2000; Costa et al., 2003; Tuteja et al., 2007; Wei and Zhang, 2010b). In spite of limited research, the topic ~~on~~ of the forest disturbance-hydrology relationship ~~at~~ in large watersheds has received growing attention mainly because of increasing need to support natural resources planning and management at large spatial scales.

A large watershed ~~is always featured with~~can be shown to have various types of forest disturbances that are cumulative over both space and time. These disturbances interactively affect watershed hydrology, and their effects tend to be cumulative. The interactive effects of various forest disturbances on hydrology in large watersheds are seldom examined mainly due to lack of an indicator for representing and integrating various types of forest disturbances, as well as great difficulty in separating the effects of forest disturbance from the influence of climatic variability (Wei and Zhang, 2010a).

A suitable forest disturbance indicator for a large watershed should not only represent all types of disturbances and ranges of their intensities, but also include their cumulative forest disturbance history and subsequent recovery processes following disturbance over space and time (Wei and Zhang, 2010a). ECA (equivalent clear-cut area), an indicator widely used ~~in Canada, particularly~~ in British Columbia and Alberta, is defined as the area that has been clear-cut, with a reduction factor to account for hydrological recovery due to forest regeneration after disturbances (BCMFR~~British Columbia Ministry of Forests~~, 1996). Harvest blocks, agricultural areas, residential development, and roads ~~Roads, clear-cuts, burned areas and partial cuts~~ can all be expressed as ECA. Research has established the relationships between vegetation growth (ages or tree heights) following disturbances and hydrological recovery rates so that ECA can be derived spatially and temporally in a watershed (Hudson, 2000; Talbot and Plamondon, 2002; Winkler et al., 2005; Lewis and Huggard, 2010). The ECA has already been successfully used in British Columbia, Canada to test watershed-scale forest disturbances and their effects on various watershed processes including aquatic habitat (Chen and Wei, 2008), hydrology (Lin and Wei, 2008) and aquatic biology (Whitaker et al., 2002; Jost et al., 2008). In spite of growing recognition of ECA, its utility in representing ~~all~~ various types of forest disturbances including mountain pine beetle infestation, harvesting and fire in a single large watershed for hydrological studies has not been applied as far as we know.

Another barrier for large watershed studies is the lack of a robust research methodology. Forest disturbance and climatic variability are viewed as two major drivers interactively influencing streamflow in large forested watersheds (Buttle and Metcalfe, 2000; Sharma et al., 2000; Blöschl et al., 2007; Ma et al., 2010; Wei and Zhang, 2010b). The greatest challenge is how to separate their relative contributions to hydrology (Zhang et al., 2008; Wang et al., 2009; Zheng et al., 2009; Wei and Zhang, 2010b). P~~The p~~hysically-based hydrological modeling is commonly used to assess the relative effects of climate variability and forest change on hydrology (Tuteja et al., 2007; Juckem et al., 2008; Zégre et al., 2010; Zhao et al., 2010). But this modeling approach is only suitable for the watersheds that are well monitored with extensive, long-term available data on vegetation, soil, topography, land use, hydrology and climate (Wei and Zhang, 2010a, b). Moreover, it requires time-consuming model calibration and validation. Advanced statistical methods (e.g., non-parametric tests, regression analysis and time series analysis), combined with graphical methods (double mass curves, single mass curves, and flow duration curves) ~~have been proved to be~~are promising alternatives in view of their limited data requirements and abilities to generate reliable inferences (Jones and Grant, 1996; Buttle and Metcalfe, 2000; Wei and Lin, 2008; Wei and Zhang, 2010b).

Lack of suitable watersheds can also constrain forest hydrological study at large spatial scales. In order to detect the cumulative effects of forest disturbances on hydrology, a large watershed must experience significant forest disturbances. It must also have long-term data on forest disturbance, climatic and hydrological data with a sufficient long period of no or limited forest disturbance as a comparable reference or control period. Given the fact that the majority of large watersheds are poorly monitored or regulated, ~~it's~~ it is rather challenging to find suitable study watersheds.

The Baker Creek watershed in the central interior of British Columbia, Canada has been severely disturbed by large-scale mountain pine beetle (MPB) infestation and subsequent salvage logging in ~~recent~~ the last 10 years. Up to 2009, 70.2% of the watershed area was attacked by MPB, and cumulative logged area accounted for about 41.4% of the total watershed area. The forest disturbance level in terms of ECA was up to 62.2% in 2009. The significant forest disturbances, along with long-term data on climate, hydrology and forest disturbance history provide a unique opportunity to examine the possible cumulative effects of forest disturbances on hydrology at a large spatial scale. Early work by Alila et al. (2007) used the DHSVM model to evaluate the hydrological impacts of different forest logging scenarios in the Baker Creek watershed. However, their analysis only included forest logging without addressing the cumulative hydrologic effect of various types of forests disturbances. In this study, we used ~~our well-tested~~our non-modeling methodology to study the cumulative effects of forest disturbances on the hydrology ~~in~~ of the Baker Creek watershed. The methodology combines statistical analysis (e.g. time series analysis) with graphical methods (e.g., modified double mass curves) (Wei and Zhang, 2010b). The major objectives of this study were: (1) to assess the cumulative effect of forest disturbances on annual mean and low flows; and (2) to quantify the relative contributions of forest disturbance and climatic variability to annual mean flows in the Baker Creek watershed.

2. Watershed description

The Baker Creek, about 114 km in length and with a drainage area of 1570 km^2, flows into the Fraser River in Quesnel in the central interior of B.C., Canada (Figure 1). Most of the watershed is a plateau. E~~The e~~levations for the watershed range from 475m at the river mouth to 1500 m in the headwaters, with a median elevation of 1100 m. Areas at higher elevations and the valley bottom above the canyon section are characterized by volcanic bedrock. Unconsolidated sediments are dominant at middle elevations, while the middle or canyon section of the watershed is a complex of meta sedimentary and volcanic rock.

The climate in the Baker Creek watershed is relatively cool and dry. As shown in Figure 2, December and January always have lowest temperatures while July and August ~~are featured with~~have the highest temperatures. The long-term average monthly maximum temperature can reach 20.4 ºC in July, while the average monthly minimum temperature is -14.4 ℃ in January. Annual watershed areal precipitation ranges from 360 mm (in 1987) to 738 mm (in 1982) with an average of 542 mm, of which 34% is from snow during the winter season (November to March).

According to the biogeoclimatic ecosystem classification (BEC) system, this watershed is primarily located within the Sub-Boreal-Pine-Spruce (SBPS) biogeoclimatic zone featured with lodgepole pine (*Pinus contorta*) and white spruce (*Picea glauca*) (BCMFR, 2012). The Sub-Boreal-Spruce (SBS) and the Montane-Spruce (MS) biogeoclimatic zones can also be found at middle and higher elevations, respectively.

Figure 1 Location of the study watershed in the central interior of British Columbia, Canada

Figure 2 Long-term (1964 to 2009) average monthly temperature (°C) and precipitation (mm)

3. Data and methods

3.1. Data

There is one active hydrometric station in the Baker Creek watershed (Station ID: 08KE016, Baker Creek at Quesnel), with records dating back to 1964. Hydrological data including daily flows and monthly flows from 1964 to 2009 were obtained from this station. According to the historical records, the annual streamflow hydrographs can be divided into four periods: spring (April–June), summer (July–August), fall (September - October) and winter (November–March). The annual mean flow is highly variable, ranging between 24 mm in 1988 and 179 mm in 2007 with an average of 103.3 mm. Streamflow usually reaches peaks in late April or May from snowmelt, and the streamflow during the snowmelt seasons accounted for 68% of the annual total.

Figure 3 Average monthly flows in the Baker Creek watershed

Climate data such as monthly mean, maximum and minimum temperature, and precipitation used in this study are from ClimateWNA dataset. ClimateWNA is a gridded climate dataset for Western North America, which downscales and integrates monthly and annual historical climate data (1901-2009) (Mitchell and Jones, 2005; Mbogga et al., 2009). Given large spatial variations ~~on~~ in climate and precipitation in particular due to topographic effect, ~~, precipitation in particular due to topographic effect in the watershed,~~ gridded monthly climate data ClimateWNA were derived with a resolution of 10 km*10 km and then aggregated to generate monthly climate data series for the whole watershed.

GIS based data on forest disturbances history for the study watershed were derived by use of ArcGIS 9.2 from two provincial databases: Cutblocks 2010 and VRI (Vegetation Resources Inventory) 2010, developed and maintained by the B.C. Ministry of Forests, Lands and Natural Resources Operations. The Cutblocks 2010 database combines

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logging information from both the B.C. Ministry of Forests, Lands and Natural Resources Operations and Forest Industries up to 2009. It contains complete records of cutblock sizes and logged years but detailed vegetation information has not been included. The VRI 2010 database records various disturbances information (i.e., fire, infestation, and logging) and detailed vegetation descriptions up to 2009. However, its records on logging are incomplete due to delayed submissions from ~~the industries~~forestry companies. Thus, both datasets are complementary, and were used in this study. Data from two databases were overlaid~~y~~ and analyzed in ArcGIS 9.2. to generate complete records on quantitative forest disturbance history for the study watershed.

3.2. Methods

3.2.1. Quantification of forest disturbance level

Logging, fire and MPB infestation are recognized as three major forest disturbance types in the Baker Creek watershed. Between 1960s and 1970s, forest disturbances were ~~rather~~ limited except for a large burn in 1961 occurred in the ~~long~~ Long John Creek-Wentworth Lake area, a tributary to the study watershed~~, in 1961 and by~~ and which burned about 0.3% of the watershed area~~ was burned~~. ~~And t~~The cumulative area burned by wildfire was less than 1% ~~till~~ up to 2009. The MPB disturbance was rare before 2000. Nevertheless, it has become dominating after its large-scale outbreak in 2003, with 17.3% of the watershed area affected in that year. 85% of forest stands are pine-leading and 83% of them have been attacked by MPB. Up to 2009, forests attacked by MPB came up to 70.2% of the total watershed area. ~~.~~Logging is the most dominant human-being disturbance after 1970. Large-scale logging activities occurred in two periods (1975- 1980 and 1989-2009). The most intensive logging took place between 2001 and 2009 as a result of salvage logging in response to large-scale MPB outbreak, and 23.8% of the watershed (14% salvage logged) was harvested during that period with an average clear-cut rate of 2.6% per year. From 1961 to 2009, the cumulative logged area accounted for 41.4% of the total watershed area (Figure ~~4~~5a). Thus, the Baker Creek watershed has been ~~severely~~ disturbed by severe MPB infestation and subsequent salvage logging in the recent 10 years.

~~**Figure 4 Forest disturbances histories from 1961 to 2009**~~

Since all kinds of forest disturbances are cumulative over both space and time in the study watershed, ECA was used in this study as an integrated indicator that combines all types of forest disturbances spatially and temporally with consideration of vegetation and hydrological recovery following disturbances. For example, an ECA coefficient of 100% means no hydrological recovery in a disturbed forest stand, while an ECA coefficient of 0% indicates a 100% hydrological recovery. However, the generation of ECA coefficients for each type disturbance is challenging because hydrological recovery is determined by various factors, mainly including disturbance type, climate, and tree species (Hudson, 2000; Talbot and Plamondon, 2002).

The relationship between vegetation growth represented by ages or tree heights following logging and hydrological recovery rates ~~was studied by Hudson (2000) and Talbot and Plamondon (2002) in British Columbia, Canada, which~~ was generally used to estimate ECA after logging for different tree species, mainly spruce and lodgepole pine forests in the watershed assessment (British Columbia Ministry of Forests and Rangeland,1999). Given that those two species are dominant in the study watershed, we developed a relationship between age / height and hydrological recovery for those two tree species for logging. For MPB infestation, Lewis and Huggard (2010) have developed a model to quantify the effects of MPB infestation on ECA calculation based on their monitoring in different biogeoclimatic zones. Based on their studies and inputs from local forest hydrologists, we also developed relationships between tree ages/height and hydrological recovery in SBPS, SBS and MS biogeoclimatic zones for the MPB killed forest stands. The hydrological impact of MPB infestation on forests is different from that of logging. Since dead trees remain in stands, the hydrological function of dead trees is not completely damaged as removal of trees by logging (Winkler et al., 2008). Moreover, the understory beneath MPB attacked stands and other trees not attached by MPB at overstorey can also intercept and transpire water. Thus, the alteration of hydrology due to

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MPB infestation was much lower than clear-cut, especially within 1-2 years after attacks. However, as dead trees lose their canopy over time, the hydrological effect of MPB attack is increased and then decreased with regeneration of young trees. For example, the ECA coefficient for the forest stand in SBS/SBPS zone is only about 15% one year after MPB attack and reaches the maximum of 75% in 18-20 years later and then drop to 10% after 60 years (Lewis and Huggard, 2010). Figure 4 provided time series of ECA coefficients for logging, fire and MPB, which was used to estimate ECA data series for each forest stand based on their disturbed area (i.e., annual clear-cut area) derived from historic disturbance records~~For MPB infestation, Lewis and Huggard (2010) have developed a model to quantify the effects of MPB infestation on ECA calculation based on their monitoring in different biogeoclimate zones. Based on their studies and inputs from local forest hydrologists, we also developed relationships between tree ages/height and hydrological recovery in SBPS, SBS and MS biogeoclimatic zones for the MPB killed forest stands. ~~. Figure ~~5~~ 4 provided time series of ECA coefficients for logging, fire and MPB, which was used to estimate ECA data series for each forest stand based on their disturbed area (i.e., annual clear-cut area) derived from historic disturbance records.

Figure ~~5~~ 4 Equivalent clear-cut area (ECA) coefficients for the Baker Creek watershed

Any forest stand in the study watershed could actually be disturbed by a single disturbance agent or multiple types of disturbances chronologically or simultaneously. In

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order to calculate long-term ECA for the whole watershed, disturbed forest stands in the Baker Creek watershed were classified into 5 groups according to the disturbances history from two datasets, Cutblocks 2010 and VRI 2010. They are described as below:

a) Forest stands disturbed by logging;
b) Forest stands disturbed by MPB;
c) Forest stands disturbed by fire;
d) Forest stands disturbed by both logging and fire;
e) Forest stands disturbed by both logging and MPB.

Annual ECA data series for each group was calculated individually and then ~~added~~ ~~up~~summed to derive annual ECA data for all disturbances in the watershed. As shown in Figure ~~6~~5b, cumulative ECA was about 1% in 1975, which was then slowly increased to 10.4% and jumped from 22.4% in 2002 to 62.2% in 2009 due to salvage logging after the large-scale MPB outbreak in 2003. Up to 2009, the cumulative ECA of logging and salvage logging in response to MPB attack were 24.4 % and 22.6%, respectively. The cumulative ECA of MPB attack without logging was 14.8% (Figure 6).

Figure ~~6~~ 5a,b Cumulative equivalent clear-cut area (ECA) from 1961 to 2009

3.2.2. Trend analysis

Trend analysis was conducted first to provide background information on temporal dynamics in hydrological and climatic data series over the study period for better understanding of hydrological variations caused by different factors. Hydrological variables involved in trend analysis including mean flow and 7 day low flow (lowest average flow over a 7-day period) on annual and seasonal (spring, summer, fall and winter) scales. ~~The tested climatic variables~~Precipitation trends were also viewed at ~~are~~ annual~~, spring, summer, fall and winter~~ and seasonal ~~precipitation.~~scales. Many studies show an obvious shift in the Pacific Decadal Oscillation (PDO) regimes from cool phase to warm phase around 1977 (Mantua and Hare, 2002; Fleming et al., 2007). This shift has caused a significant effect on climate in ~~the~~ Pacific North America with more precipitation and lower temperature in the cool phase (1946-1976) than the warm phase (1977-1990s) (Kiffney et al., 2002; St. Jacques et al., 2010). To exclude the effect of this climate regime shift on streamflow, trend analysis was conducted not only over the whole study period (1964-2009), but also under different PDO regimes (1964-1976 and 1977-2009). Non-parametric tests including Mann-Kendall tau and Spearman's rho ~~are most widely used for trend detection in hydrology and meteorology~~ (Berryman et al., 1988; Burn and Hag Elnur, 2002~~; González Hidalgo et al., 2003; Déry and Wood, 2005) due to their fewer assumptions than parametric tests (~~;McCabe and Wolock, 2002~~; Xu et al., 2003~~)~~). In this paper, both Mann-Kendall tau and Spearman's rho tests~~ were applied in the trend detection, and changes with a significance level of 5% for each data series during three different periods were identified.

3.2.3. Correlation analysis

Cross-correlation in time series analysis was performed to detect the relationships between hydrological variables (mean flow and 7 day low flow on annual and seasonal scales) and annual ECA series. Cross-correlation analysis is found to be an effective approach to investigate the relationships among environmental variables ~~for~~ because it can~~it can not~~ ~~only~~ address autocorrelation issue in data series ~~but also~~and identify the lagged causality between two data series (Jassby and Powell, 1990; Lin and Wei, 2008; Zhou et al., 2010). All hydrological data series along with ECA data series were pre-whitened to remove autocorrelations by fitting ARIMA (Autoregressive Integrated Moving Average) models. White noises or model residuals from ARIMA models with best performance in terms of achievements of model stationarity and coefficient of determination (R^2) were selected for cross-correlations (Lin and Wei, 2008).

3.2.4. Quantification of forest disturbance effect on annual mean flow

For a large forested watershed, climatic variability and forest disturbances are two primary drivers ~~for~~ of hydrological variation. In order to separate the effects of climate variability and forest disturbances on annual mean flow, the “modified double mass curve” developed by Wei and Zhang (2010b) was used to eliminate the influence of climatic variability on annual mean flow. According to the annual watershed water balance, streamflow is determined by the difference between precipitation and evapotranspiration because change in soil water storage over an annual scale can be assumed to be constant and minor (Zhang et al., 2001). Thus, we firstly defined an integrated climatic index named “effective precipitation (Pe)” for streamflow generation, referring to the difference between precipitation and evapotranspiration (Wei and Zhang 2010b). The annual evapotranspiration was estimated by Equation (1) (Zhang et al., 2001), a modification of Budyko’s evaporation by adding an additional vegetation factor *w*, which has been proven to be a sound solution for watershed scale evapotranspiration estimation (Donohue et al., 2007; Li et al., 2007; Oudin et al., 2008). Given the limited long-term data in this large watershed, ~~temperature-based methods~~ the Hargreaves ~~method~~ equation (Hargreaves and Samani, 1985) was applied to compute potential evapotranspiration (Equation (2)). It requires only mean, minimum and maximum air temperature, and extraterrestrial radiation (Shuttleworth, 1993; Sankarasubramanian et al., 2001), which are available in the study watershed. ~~has been recognized as the best temperature-based potential evaporation estimation method by many hydrologists (Shuttleworth, 1993; Sankarasubramanian et al., 2001).~~

$$E=P[1+w(E_0/P)]/[1+w(E_0/P)+P/E_0] \qquad (1)$$

$$E_0=0.0023*Ra*[(Tmax+Tmin)/2+17.8)]*(Tmax-Tmin)^{0.5} \qquad (2)$$

Where, Ra: extraterrestrial radiation; Tmax: mean maximum temperature in ºC; Tmin: mean minimum temperature in ºC; P: precipitation; E: actual evapotranspiration; E_0: potential evapotranspiration; *w*: plant-available water coefficient

~~Then, a~~A modified double mass curve was created then by plotting accumulated annual mean flow versus accumulated annual effective precipitation. In this way, the climatic effect on annual mean flow can be eliminated. The basic assumption underlying this modified double mass curve (MDMC) is that there is a linear relation between variation in annual mean flow and that in effective precipitation (Zheng et al., 2009; Wei and Zhang, 2010b). In the period without or with minor forest disturbances (namely the reference period), a straight line is expected, which serves as a baseline describing the linear relation between annual mean flow and annual effective precipitation, and a break in this curve indicates the change of annual mean flow caused by the factors other than climatic variability, for example, forest disturbance or land use change. In other words, a step change or regime shift occurs in the slope of the modified double mass curve and the slope before the break is different from that afterwards. Both the CUSUM control chart (the cumulative sum control chart) and the Mann-Whitney U test were applied to determine identified the breakpoint with statistical significance. The CUSUM control chart~~ (or cumulative sum control chart)~~, a widely used change point detection method was applied to identify the breakpoints of statistical significance (Barnard, 1959). Then the study period was divided into the reference period and disturbance period using the significant breakpoint. Mann-Whitney U test (Siegel, 1957) was then used to further confirm if there is~~'s~~ a step change of statistical significance in the slope of MDMC through comparison of slope in the reference period with that in the disturbance period.

Finally, the difference between the observed values and the values predicted by the baseline during the disturbance period in the MDMC ~~can be viewed as~~is the estimated cumulative effect of forest disturbances on annual mean flow as compared with undisturbed conditions. Once annual mean flow deviation attributed to forest disturbance (ΔQ_f) is estimated, the deviation resulting from climatic variability can then be computed by the following equation:

$$\Delta Q_c(t) = \Delta Q(t) - \Delta Q_f(t) \qquad (3)$$

Where, $\Delta Q(t)$, $\Delta Q_c(t)$ and $\Delta Q_f(t)$ represent annual mean flow deviation, annual mean flow deviation attributed to climate variability and annual mean flow deviation attributed to forest disturbances for the t^{th} year, respectively.

4. Results

4.1. Long-term changes in hydrological and climatic variables

Over the whole study period between 1964 and 2009, there was a significant downward trend in winter precipitation, while no statistical significant trends ~~was~~ were detected in other hydrological variables and climatic variables (Table 1). However, ~~when the whole~~separation of the study period ~~was separated~~ into different PDO periods~~,~~ revealed no significant trend in annual precipitation ~~some interesting results have been disclosed. F~~from 1977 to 2009, ~~no significant trend was identified in annual precipitation~~ but ~~the annual mean flow displayed~~ a significant upward trend for annual mean flow (Table 1). The inconsistent trends between annual precipitation and annual mean flow suggest~~ed~~ that ~~the factors~~something other than climatic variability ~~had~~ altered streamflow. Since climatic variability and forest disturbances are regarded as the two main drivers for inter-annual mean flow changes, the increment in annual mean flow during the period of 1977 to 2009 was judged to be caused by forest disturbances. This suggests that forest disturbance and climate have interactively influenced streamflow. It further highlights that the effect of climatic variability on streamflow must be removed before the effects of forest disturbance on hydrology can be quantified.

Table 1 Trends in hydrological and climatic variables from 1964 to 2009

4.2. Correlations between hydrological variables and forest disturbance level

As suggested by the cross-correlation analysis, annual, winter and fall mean flows were significantly and positively correlated with ECA (Table 2). Also, there were significantly positive correlations between annual 7-day low flow and ECA.

Table 2 Cross-correlation between hydrological variables and ECA

4.3. Forest disturbance effect on annual mean flow

Figure ~~7~~ 6 ~~displayed~~ displays the modified double mass for the study watershed, where accumulated annual mean flow ~~was~~ is plotted against accumulated annual effective precipitation. According to the CUSUM control chart change point analysis of slopes in Figure 7, a significant breakpoint in 1999 was detected at α=0.05. ~~And~~ The Mann-Whitney U test further confirmed the statistical significance of this breakpoint by comparing the median of slopes in the period from 1964 to 1998 with that from 1999 to 2009. Thus, we defined the reference period as between 1964 and 1998, while the disturbance period was from 1999 to 2009. As shown in Figure 7, a straight line (linear relationship) was observed between accumulated annual mean flow and accumulated annual effective precipitation in the period from1964 to 1998. After 1999, the observed line started to deviate from the original line (predicted line), suggesting that more annual streamflow was generated than predicted. The differences between observed accumulated annual mean flow and predicted values from 1999 to 2009 are referred to as accumulated annual mean flow deviations attributed to forest disturbances. Annual mean flow deviations attributed to forest disturbance ~~was~~ were then calculated accordingly. As ~~described~~ shown in Figure ~~8~~ 7 (a, b), annual mean flow deviations attributed to forest disturbances ranged from 9 mm (8.9% of long-term annual mean flow) to 91 mm (87.6% of long-term annual mean flow), with an average of 48.4 mm (46.9% of long-term annual mean flow). Meanwhile, ECA experienced a significant increase from 19.2% in 1999 to 62.2% in 2009.

Figure ~~7~~ 6 Modified Double mass curve

Table 3 Statistical tests of changes in the slope of MDMC

Figure ~~8~~ 7 a) Annual mean flow deviation attributed to forest disturbance in mm; b) Annual mean flow deviation attributed to forest disturbance in percentage

4.4. Relative contributions of climatic variability and forest disturbance on annual mean flow

In order to explore the temporal dynamic of the hydrological impact of forest disturbances, the whole study period was divided into three phases according to forest disturbance level: 1964 to 1989 (Phase 1, ECA ≤10 %), 1990 to 1998 (Phase 2, 10 %≤ECA ≤20 %), and 1999 to 2009 (Phase 3, ECA≥20%). Table 4 ~~summarized~~ summarizes the average annual mean flow deviation and its components in different phases. In phase 1, with an average ECA of 3.7%, average annual mean flow deviation attributed to forest disturbances was -0.8 mm/yr, which rose to 9.2mm/yr in phase 2 and sharply increased to 48.4mm (equivalent to 46.9% of average annual mean flow) in phase 3. Meanwhile, the average annual mean flow deviations attributed to climate variability in phase 1, phase 2 and phase3 were -4.8, -13.3 and -35.5 mm, respectively. As shown in Table 4, forest disturbance and climatic variability affected streamflow in opposite directions. Forest disturbance increased streamflow, while climatic variability decreased it over the study period.

Table 4 Annual mean flow deviation and its components in different phases

Table 5 ~~demonstrated~~ demonstrates the relative contributions of forest disturbances and climatic variability on annual mean flow variation. The impacts of forest disturbances and climate variability on annual mean flow were dynamic. The influence of forest disturbances on annual mean flow went upwards with increasing ECA, while that of climate variability declined over time. In phase 1, 84.9% of the variation in annual mean flow was explained by climate variability and only 15.1% of that was accounted by forest disturbances. During phase 2, the relative contribution of forest disturbances on annual mean flow variation (R_f) climbed to 40.9%, compared with 59.1% of variation explained by climate variability. ~~And in~~In phase 3, the relative contribution of forest disturbances went up to 57.7%, while that of climate variability dropped to 42.3%. In short, climate variability produced greater impact on annual mean flow than forest disturbances in phases 1 and 2, while forest disturbances became more influencing in phase 3.

Table 5 The relative contributions of forest disturbance and climate variability on annual mean flow variation

5. Discussion

5.1. Thresholds of forest disturbance for significant hydrological changes

Since watersheds always have ability to buffer changes caused by disturbances, there must be a theoretical threshold ~~on~~ of forest disturbances level, below which significant change on hydrology may not be detected. Identification of forest disturbance thresholds is useful for guiding forest management practices to protect water resources and public safety. Efforts have already been made to determine the thresholds of forest logging in small watersheds. Such thresholds tend to be ~~various~~ variable due to ~~the~~ differences in topography, vegetation, geology, hydrological regime and climate. For examples, in the Appalachian Mountains, USA, only 10% reduction in forest cover can produce a detectable response in annual mean flow (Swank et al., 1988), while in the Central Plains of the Unite States, 50% harvest might be required for significant change on flows (Stednick, 1996). Generally, it’s believed that more than 20% of the watershed area must be changed or disturbed to detect significant change in streamflow in small watersheds (Bosch and Hewlett, 1982; Hetherington, 1987).

In comparison with small watersheds, the forest disturbance~~s~~ threshold for significant streamflow responses in large watersheds is likely more variable and difficult to be generalized due to the greater complexity of topographies, land forms and spatial patterns. For examples, In the Baker Creek watershed (this study), with about 62.2% ~~of~~ ECA, a significant change in annual mean flow was detected. Similarly, in the Willow River watershed, adjacent to our study watershed, ~~about a~~ logging ~~rate~~ of about 30% of the watershed (watershed area: 2,860 km2) caused a significant increase in annual mean flow (Lin and Wei, 2008; Wei and Zhang, 2010b). ~~And~~ Costa et al (2003) found that in the Tocaintins River watershed (175,360 km^2)~~ from ~~, Brazil~~a tropical region~~, only 19% reduction in forest cover produced a significant increase in annual mean flow. In contrast, Wei and Davidson (1998) did not detect significant change ~~on~~ in annual mean flows in the Bowron River watershed (3,420 km^2), the watershed adjacent to the Willow River watershed mentioned above, although 30% of the watershed was harvested. The study from Buttle and Metcalfe (2000) failed to find definitive changes in annual mean flow with disturbance levels ranging from 5 to 25% of watersheds (from 401 to11900 km^2) in Canadian boreal forests. Additionally, even with forest cover reduced by 53%, no significant hydrological change was identified in the Nam Pong River Basin (12,100 km^2) , Northeast Thailand (Wilk et al., 2001). Those ~~contrasted~~ contrasting results clearly suggest that forest disturbance threshold is likely watershed specific~~ in large watersheds~~.

It also demonstrates a need for more case studies in large watersheds before generalized conclusions can be derived.

5.2. Forest disturbance effect on mean flows

~~Not surprisingly, with~~ With ECA over 60%, annual mean flow was significantly increased by 46.9% on average after forest disturbances as suggested by both correlation analysis and MDMC. This is consistent with the previous modeling work by Alila et al. (2007) in the Baker Creek watershed where with 34% of the watershed harvested, annual mean flows were ~~predicted~~ estimated to be increased by 31%. However, the change magnitudes are different. The difference in hydrological responses between two studies may be explained by their different research approaches and different disturbance levels.

Our analysis shows that during the severe disturbance period from 1999-2009, with ECA increased from 19.2% to 62.2%, average increment in annual mean flow caused by forest disturbances is 48.4 mm, which is about 12 mm increment in annual mean flow for each 10% increase in ECA. The change magnitude is lower than that from an adjacent watershed, the Willow River watershed (watershed size: 2860 km^2) where each 10% increase in ECA can result in about a 23 mm increment in annual mean flow (Wei and Zhang 2010b). The positive responses of annual mean flows to forest disturbance in both the Baker and Willow watersheds are within the range of responses in the small watershed studies in the Pacific Northwest (2.5 to 30 mm increment in annual mean flow for each 10% increase in harvested area) (Moore and Wondzell~~er~~, 2005). However, the relative change in long-term annual mean flow in the Baker Creek watershed is much higher than that in the Willow River watershed. On average, with an ECA of 62.2%, annual mean flow is increased by 46.9% in the Baker Creek watershed, while the increment in the Willow River watershed is only 9.8% with an ECA of 29.4% (Wei and Zhang 2010b). This suggests that the hydrological response to forest disturbances in the Baker Creek watershed is more sensitive than that in the Willow River watershed. The difference in the magnitude of annual mean flow may be responsible for different hydrological responses between two neighbouring watersheds. The ~~difference in climate and forest disturbance intensity may be responsible for different hydrological responses between two neighbouring watersheds. The long-term average annual precipitation and mean flow in the Baker Creek watershed were 542 mm and~~ annual mean flow in the Baker Creek watershed was only 103 mm, ~~respectively,~~ while ~~those values are 820 mm and~~it is 435 mm~~, respectively~~ in the Willow River watershed~~,~~. For example, 20 mm increment can increase the annual mean flow in the Baker Creek watershed by about 20% while it can only cause less than 5% change in annual mean flow in the Willow River watershed.

~~revealing that the Baker Creek watershed is much drier with very low runoff coefficient (0.19). Besides, the forest disturbances in the Baker Creek watershed are more severe, with ECA as twice as that of the Willow River watershed.~~

There are limited large watershed studies on quantification of the hydrological impacts of forest disturbance, and change magnitude in annual mean flow is highly variable, ranging from 4% to 136%. The study from the interior Columbia River basin (567,000km^2) disclosed that 27% of land cover change ~~resulted~~ resulting in only 4.2-10.5% increment in annual mean flow (Matheussen et al., 2000), while in the Great Lakes basin (494,000km^2), annual mean flow was augmented by up to 136% resulted from only 17% of land cover change (Mao and Cherkauer, 2009). Clearly, more large watershed studies are needed to draw any reliable conclusions on the annual mean flow change magnitude caused by forest disturbances or land cover change.

5.3. Forest disturbance effect on low flows

The correlation analysis showed that forest disturbances significantly increased annual low flow and dry season (fall and winter) mean flow. This is in accordance with some small-scale studies from snowmelt dominated watersheds (Van Haveren, 1988; Swanson *et al.,* 1986; Gottfried, 1991) and the majority of studies from rainfall dominated watersheds (Bari et al., 1996; Bent, 2001; Robinson and Dupeyrat, 2005; Webb et al., 2007). Since removal or death of forests can decrease evapotranspiration and interception in disturbed sites, it ultimately increases soil moisture and groundwater recharge (Bosch and Hewlett, 1982). Hence, discharges to the streams from groundwater and channel banks tend to increase in dry/low flow seasons.

However, no changes or decreases in dry season flow or low flow have also been reported after forest disturbances (Bruijnzeel, 2004; Calder, 2005). Many factors such as soil infiltration characteristics, regional aquifer characteristics, vegetation distribution, climate, and human activities control low flow generation (Smakhtin, 2001). The degree of soil disturbances after logging or wildfire is regarded as an important indicator for low flow response. When the soil characteristics is severely affected by forest disturbances, for example~~,~~ soil compaction by heavy machinery of logging or soil hydrophobization after fire, soil infiltration capacity can be severely impaired ~~,~~and lead to more surface runoff and consequently less recharge to deep soil and groundwater systems. As a result, dry season flows or low flows are expected to be less or unchanged. Moreover, removal of cloud forests in some coastal watersheds, where fog drips intercepted by forests serve~~s~~ as an important precipitation input, is likely to reduce low flows. This is because decreased fog drips after forest disturbances can lead to reduction of water input for streamflow and consequently declined low flows in summers (Harr, 1982).

Our study watershed is a snowmelt dominated watershed with low flows typically occurring from late summer through the winter until spring snowmelt. Forest logging in the interior of B.C.~~, Canada~~ normally occurs in winter ~~seasons~~ when soils are completely frozen, which may cause minor or insignificant damage to soils. Therefore, dry season flows or low flows are expected to increase as removal of forests reduces evapotranspiration and interception, resulting in more water available in the soils to promote soil infiltration and groundwater recharge. This may explain why there are significant changes ~~on~~ in hydrology during low flow seasons in our study watershed.

5.4. Off-setting effect of forest disturbance and climate variability on annual mean flow variation

According to our analysis, forest disturbances and climatic variability produced opposite impacts on streamflow: forest disturbance increased streamflow while climatic variability decreased it. For example, during the severely disturbed period from 1999 to 2009 with ECA greater than 20%, forest disturbances boosted annual mean flow, ~~averagely~~on average, by about 48.4 mm/yr, while climate variability reduced it by 35.5 mm/yr. Not surprisingly, their counteracting or cancelling effects ~~made~~ meant that annual mean flow displayed a stable trend over the study period. These counteracting effects of forest disturbances and climate variability have also been identified by Jones et al's (2012) through analyses of long-term records in 35 headwater basins in the United States and

Canada. Both of our studies imply that forest ecosystems have the ability of adjusting their water uses to compensate for climate variability.

Interestingly, the interactive influences of climatic variability and forest disturbances are dynamic over time with significantly increased forest disturbances. Prior to 1999 with ECA less than 20%, climate variability was more influential than forest disturbances. Before 1990, about 84.9% of variation in annual mean flow was accounted by climate variability, and this percentage greatly declined to 42.3% during the severe disturbance period (1999-2009) with an average ECA of 35%. In contrast, the contributions from forest disturbances on annual mean flow variation was minor during the early period when ECA was less than 10%, and then ~~was on a significant increase~~increased significantly after 1998. Clearly, between 1999 and 2009, the influence on streamflow from forest disturbances ~~overrode~~ exceeded that from climatic variability ~~and became dominating~~. This finding is different from a similar study in the Willow River watershed where climatic variability generally played a slightly more important role than forest disturbances did (Wei and Zhang, 2010b). The Willow River watershed was mainly disturbed by logging activities with ECA less than 30%, while the Baker Creek watershed was attacked by large-scale MPB infestation and subsequent salvage logging with an

ECA of 62%. This ~~incredible~~ high level of forest disturbances made it ~~as~~ the major contributor to annual mean flow variation instead of climate variability. As a matter of fact, in many other large watersheds experienced significant land use changes, the influence of climate variability on streamflow appeared to be weaker. For example~~s~~, ~~research by Zheng et al. (2009)~~ in the headwaters of the Yellow River Basin, China ~~disclosed that~~ only 30% of the streamflow reduction in the 1990s was caused by climate variability while land use change was responsible for 70% of the reduction (Zheng et al., 2009). A similar result was also reported in the Chaobai River watershed, China by Wang et al. (2009) and Zhang et al. (2008). -Moreover, small watershed studies yielded similar findings too. Land use changes or forest disturbances are believed to mitigate or even overwhelm climatic effects on streamflow. For example, in three long-term experimental forests (Andrews, Coweeta and Hubbard Brook), increments of daily streamflow in the late summer and early fall caused by forest harvest can be up to 300% in early years after disturbance while climate induced changes in streamflow can be 10-50%(Jones and Post, 2004).

In forest dominant watersheds, forest changes and climatic variability are commonly recognized as two major drivers for hydrological changes. Understanding their interactive, dynamic effects is important for sustainable water management and protection of ecosystem functions and public safety. In our study watershed, the effects of climatic variability and forest disturbance were offsetting over the study period because the dry climate trend reduced streamflow while forest disturbances increased it. This offsetting effect can help buffer hydrological alteration. In some dry small watershed in the United States, no trends in streamflow have been identified with global warming (Jones et al, 2012)However, the effects of climatic variability and forest disturbances can be cumulatively added if their effects are on the same direction. For example, if climate displayed a wetting trend, then increasing streamflow resulting from climatic variability could further augment higher river discharge from more forest disturbance, and consequently led to higher risks of floods. To maintain a healthy watershed, the level of forest disturbances or land use change should be carefully designed so that their negative impacts on aquatic functions can be minimized.

5.5. Implication for watershed management

Severe forest disturbances have produced significant hydrological impact in the Baker Creek watershed. Annual mean flow has been increased by 47.6%, and dry season mean flow has also been significantly augmented. From the water supply perspective, these increases can be positive and substantial, particularly for this relatively dry watershed. The average annual mean flow in our study watershed is only 103.3 mm with great inter-annual variability, suggesting that water supply is likely constrained or stressed, especially in the dry seasons from late summers to winters. The positive effect of forest disturbances on streamflow will certainly help alleviate the water supply stress within the watershed and downstream of the watershed. But such a positive effect will be gradually diminished with forest regeneration over time. Resource managers must recognize this dynamic, positive effect and incorporate it into designing of sustainable water management.

Forest disturbances and climate variability have counteracting effect on streamflow, which helps maintain a stable water supply system. However, as forest disturbances become more severe, the impact of forest disturbances on hydrology tends to override the influence from climate variability, which possibly breaks the inherent balance of aquatic system. For example, severe forest disturbance can dramatically increase soil erosion and impose negative impacts on aquatic habitat due to increased water temperature and sediments. Under this circumstance, forest disturbance may cause irreversible change in aquatic ecosystems and eventually damage watershed ecological functions. Therefore, it’s critical to constrain forest disturbance to a safe level so that their negative effects can be minimized.

Our analysis suggests that dry season flows or low flows have been significantly increased by forest disturbance. This finding is important for water allocation and fish habitat conservation. As mentioned before, increased dry season flows or low flows may reduce drought risks and enhance water supply from late summers through winters. On the other hand, these changes may affect aquatic habitat. For example, salmon~~s always~~ migrate from the Pacific Ocean to the upper reaches and tributaries of Fraser River to spawn in dry seasons. Significantly increased flow in dry seasons may affect salmon migration and spawning due to alteration of flow magnitude and associated water quality. More research is needed to further explore the potential impacts of low flow change on aquatic ecosystems.

6. Conclusion

Severe forest disturbances such as large-scale MPB infestation and subsequent salvage logging have significantly increased annual mean and low flows in the Baker Creek watershed. The influence of forest disturbances on hydrology exceeded that from climatic variability when forest disturbances level in terms of ECA was up to 62.2% in the watershed. These findings are of great importance to water resource planning and aquatic habitats protection. Although the increment in annual mean flow and dry season flows has positive effects on water supply and can alleviate water stress in this dry watershed, their impacts on aquatic habitat and other aquatic functions remain uncertain. This result can be useful for hydrological modeling studies.

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Tables

Table 1 Trends in hydrological and climatic variables from 1964 to 2009

Variables	1954-2009		1954-1976		1977-2009	
	Mann-Kendal tau	Spearman rho	Mann-Kendal tau	Spearman rho	Mann-Kendal tau	Spearman rho
Annual Q	0.01	0.05	-0.23	-0.25	**0.25***	**0.39***
	(p=0.89)	(p=0.70)	(p=0.08)	(p=0.20)	**(p=0.04)**	**(p=0.03)**
Winter Q	0.08	0.14	-0.10	-0.15	0.12	0.19
	(p=0.48)	(p=0.18)	(p=0.45)	(p=0.55)	(p=0.14)	(p=0.30)
Spring Q	-0.02	-0.01	0.10	0.17	0.19	0.30
	(p=0.82)	(p=0.89)	(p=0.45)	(p=0.42)	(p=0.20)	(p=0.15)
Summer Q	-0.04	-0.06	-0.21	-0.26	0.04	0.05
	(p=0.75)	(p=0.65)	(p=0.10)	(p=0.18)	(p=0.83)	(p=0.82)
Fall Q	0.02	0.03	-0.10	-0.21	0.05	0.08
	(p=0.82)	(p=0.78)	(p=0.45)	(p=0.25)	(p=0.62)	(p=0.65)
Annual P	-0.15	-0.20	-0.08	-0.11	0.03	0.05
	(p=0.15)	(p=0.18)	(p=0.58)	(p=0.70)	(p=0.88)	(p=0.89)
Winter P	**-0.19***	**-0.30***	0.21	0.29	0.17	0.2
	(p=0.04)	**(p=0.02)**	(p=0.10)	(p=0.15)	(p=0.28)	(p=0.23)
Spring P	-0.03	-0.05	-0.07	-0.12	-0.05	-0.07
	(p=0.78)	(p=0.70)	(p=0.65)	(p=0.64)	(p=0.62)	(p=0.70)
Summer P	-0.05	-0.09	-0.13	-0.15	0	-0.03
	(p=0.72)	(p=0.55)	(p=0.32)	(p=0.55)	(p=0.99)	(p=0.98)
Fall P	-0.05	-0.09	**-0.36***	**-0.55***	0.03	-0.04
	(p=0.72)	(p=0.55)	**(p=0.01)**	**(p<0.01)**	(p=0.88)	(p=0.85)
Annual E	-0.03	-0.04	-0.21	-0.28	0.08	0.10
	(p=0.78)	(p=0.72)	(p=0.10)	(p=0.16)	(p=0.48)	(p=0.50)
Annual Pe	-0.13	-0.20	-0.13	-0.16	0.02	0
	(p=0.17)	(p=0.18)	(p=0.32)	(p=0.48)	(p=0.88)	(p=0.99)
Annual 7day low flow	0.15	0.20	-0.09	-0.18	0.21	0.24
	(p=0.15)	(p=0.18)	(p=0.50)	(p=0.35)	(p=0.10)	(p=0.22)

* Significant at α=0.05

Table 2 Cross-correlation between hydrological variables and ECA

Hydrological variables	Lag		
	0	-1	-2
Annual mean flow	0.19($p=0.25$)	**0.34***($p=0.05$)	0.19($p=0.25$)
Winter mean flow	0.20($p=0.26$)	**0.38***($p=0.03$)	**0.47***($p<0.01$)
Spring mean flow	0.20($p=0.26$)	0.22($p=0.20$)	0.12($p=0.39$)
Summer mean flow	0.17($p=0.36$)	0.05($p=0.60$)	0.10($p=0.46$)
Fall mean flow	0.24($p=0.16$)	**0.47***($p<0.01$)	0.09($p=0.50$)
Annual 7 day low flow	0.10($p=0.46$)	**0.50***($p<0.01$)	0.08($p=0.56$)

* Significant at $\alpha=0.05$; ARIMA model for ECA (1,1,1) non-constant

Table 3 Statistical tests of changes in the slope of MDMC

CUSUM Control Chart		Mann-Whitney U test	
change point	Bootstrap times	Step change	Statistics Z
1999 * ($p=0.04$)	5000	1999*	-3.03 ($p<0.01$)

*Significant at $\alpha=0.05$

Table 4 Annual mean flow deviation and its components in different phases

Period	ΔQ (mm)	ΔQ_f (mm)	ΔQ_c (mm)	$\Delta Q/Q$ (%)	$\Delta Q_f/Q$ (%)	$\Delta Q_c/Q$ (%)	ECA (%)
Phase1:1964-1989	-5.7	-0.8±5.3	-4.8±5.3	-5.5	-0.8±5.2	-4.7±5.2	3.7
Phase2:1990-1998	-4.2	9.2±4.8	-13.3±4.8	-4.0	8.9±4.7	-12.9±4.7	15%
Phase3:1999-2009	9.7	48.4±4.3	-35.5±3.9	0.4	46.9±4.1	-34.4±3.8	35%

Q: Average annual mean flow from 1964 to 2009 (103.3 mm)

Table 5 The relative contributions of forest disturbance and climate variability on annual mean flow variation

Period	ΔQ (mm)	Rf (%)	Rc (%)	ECA (%)
Phase1:1964-1989	-4.1	15.1	84.9	3.7
Phase2:1990-1998	-4.2	40.9	59.1	15%
Phase3:1999-2009	9.7	57.7	42.3	35%

$R_f=100*|\Delta Q_f|/(|\Delta Q_f|+|\Delta Q_c|)$; $R_c=100*|\Delta Q_c|/(|\Delta Q_f|+|\Delta Q_c|)$

Figures

Figure 1 Location of the study watershed in the central interior of British Columbia, Canada

Figure 2 Long-term (1964 to 2009) mean monthly temperature (ºC) and precipitation (mm)

Figure 3 Average monthly flow in the Baker Creek watershed

Figure 4 Equivalent clear-cut area (ECA) coefficients for the Baker Creek watershed

Figure 5 a) annual area disturbed by different forest disturbances from 1961 to 2009; b) Cumulative equivalent clear-cut area (ECA) from 1961 to 2009

Figure 6 Modified Double mass curve of accumulated annual mean flow (Q_a) and accumulated annual effective precipitation (P_{ae})

Figure 7 a) Annual mean flow deviation attributed to forest disturbance in mm(ΔQ_f); b) Annual mean flow deviation attributed to forest disturbance in percentage($\Delta Q_f/Q$)

Figure 1 Location of the study watershed in the central interior of British Columbia, Canada (See the attached figure)

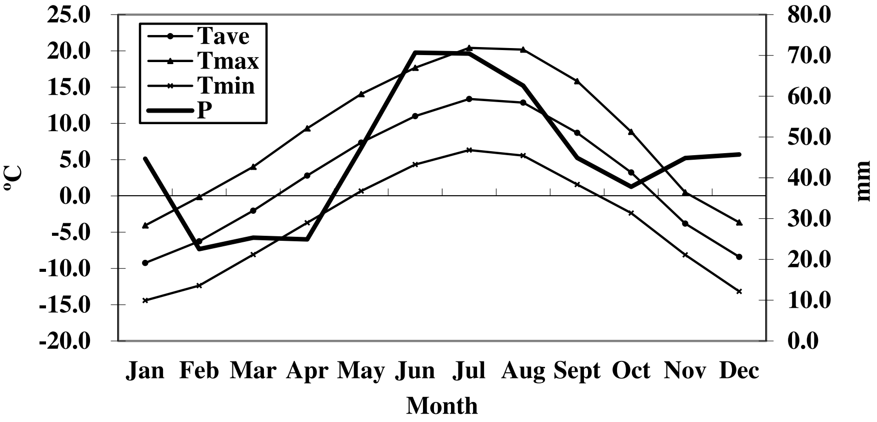


Figure 2 Long-term (1964 to 2009) mean monthly temperature (ºC) and precipitation (mm)

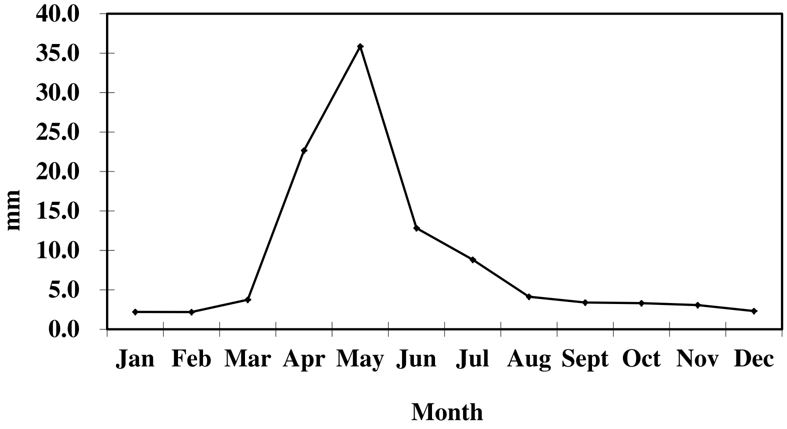
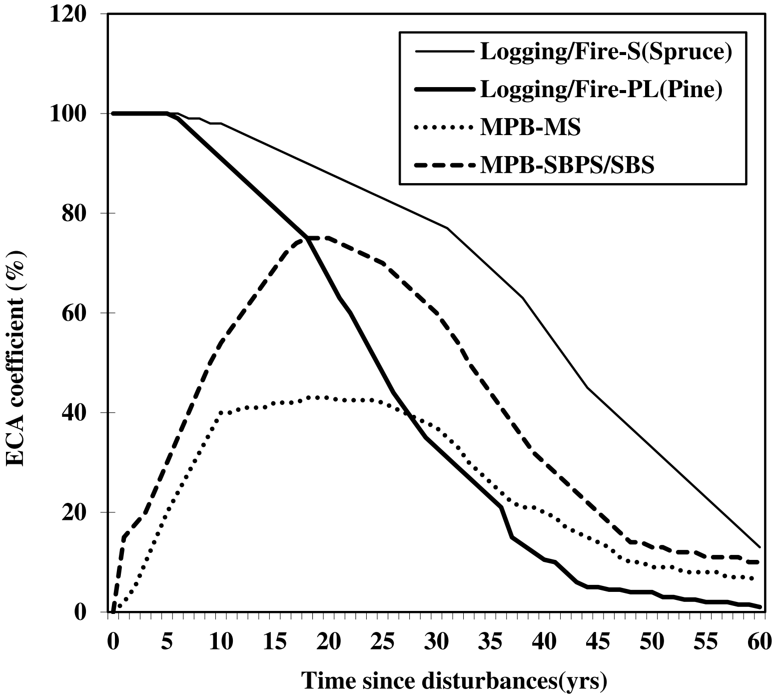


Figure 3 Average monthly flow in the Baker Creek watershed



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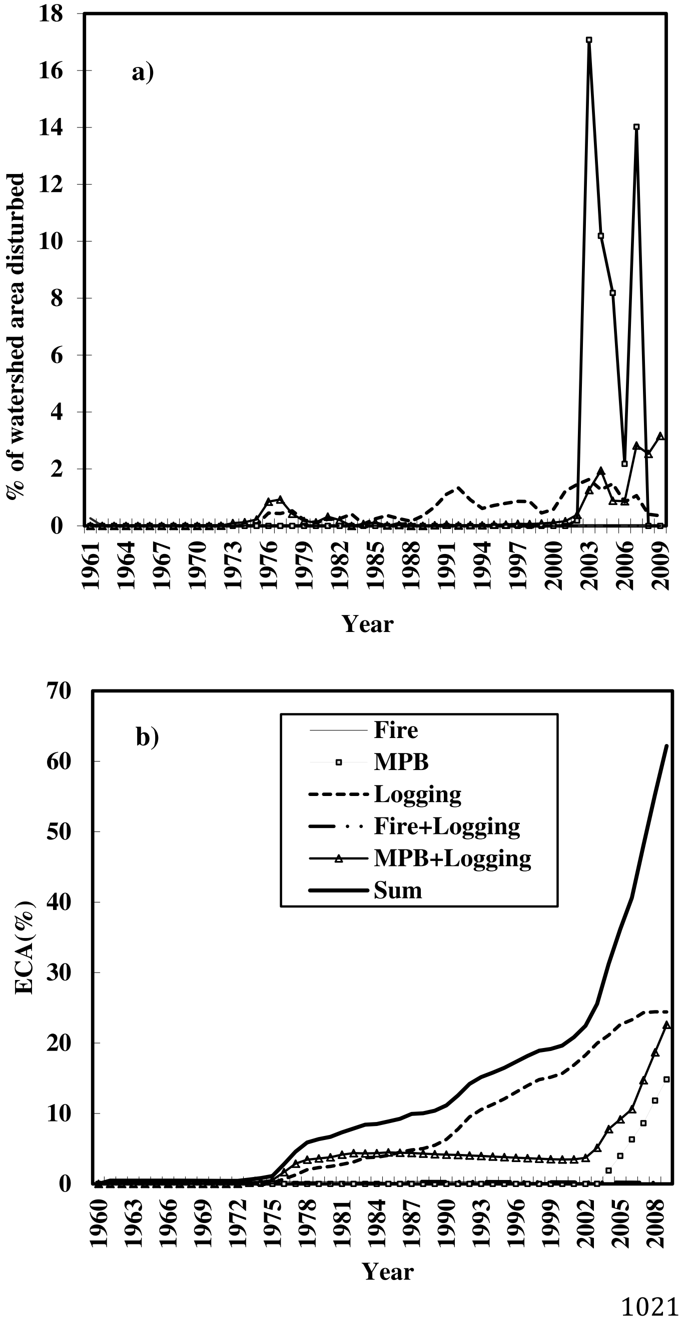

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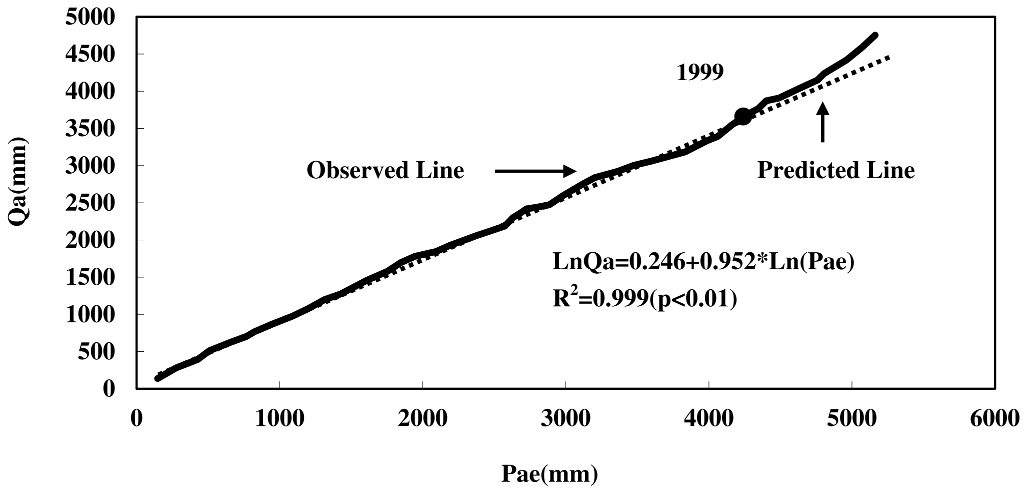
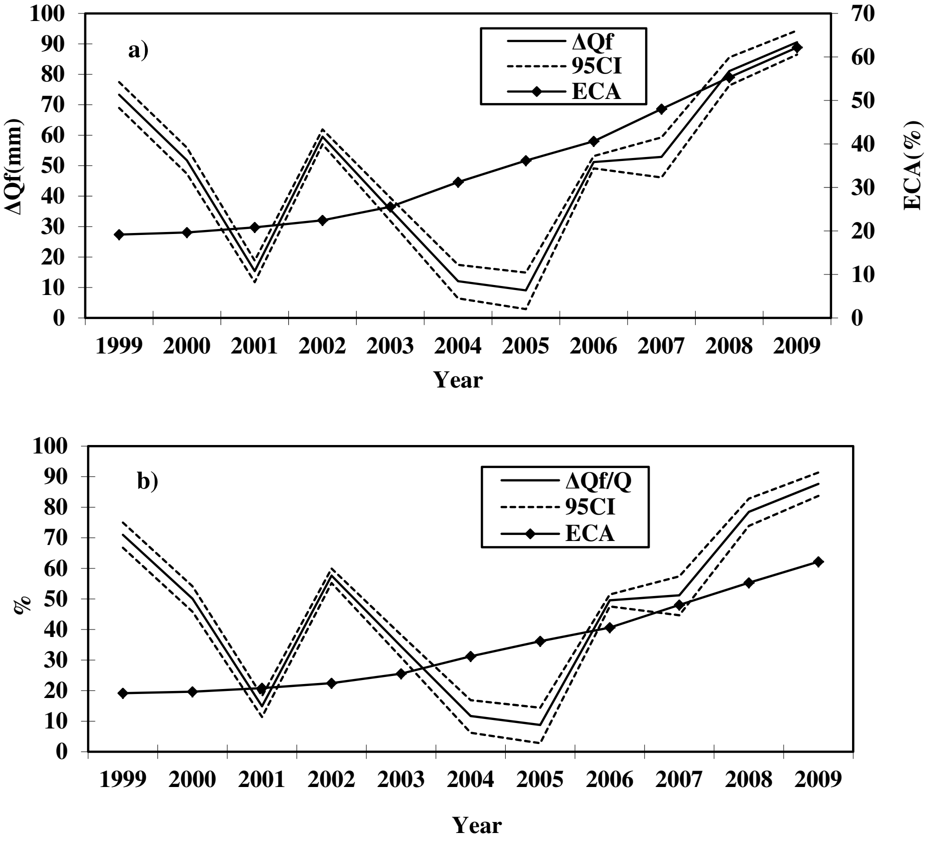


Figure 6 Modified Double mass curve of accumulated annual mean flow (Q_a) and accumulated annual effective precipitation (P_{ae})



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