REVEALING FOREST HARVESTING EFFECTS ON LARGE PEAKFLOWS IN RAIN-ON-SNOW ENVIRONMENT WITH NEW STOCHASTIC PHYSICS

by

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Abstract

Using nine pairs of control-treatment watersheds with varying climate, physiography, and harvesting practices in the Rain-On-Snow (ROS) environment of the Pacific Northwest region, this thesis demonstrates the linkage between environmental control and the sensitivity of peakflow response to harvesting effects. Compared to previous paired watershed studies in ROS environment, this study, for the first time, employed an experimental design of Frequency Pairing to isolate the effects of disturbances on systems' response. The use of frequency distributions for evaluating the relation between forest harvesting and peakflows is a well-established framework outside forest hydrology literature. The results show how harvesting can dramatically increase the magnitude of all peakflows on record and how such effects can increase with increasing return periods, as a consequence of substantial increases to the mean and variance of the peakflow frequency distribution. Most critically, peakflows with return period larger than 10 years can increase in frequency, where the larger the peakflow event the more frequent it may become. The sensitivity of the upper tail of the frequency distribution of peakflows was found to be linked to the physiographic and climatic characteristics via a unifying synchronization / desynchronization spatial scaling mechanism that controls the generation of rain-on-snow runoff. This new physically-based stochastic hydrology understanding on the response of watersheds in ROS environments runs counter the deterministic prevailing wisdom of forest hydrology, which presumes a limited and diminishing role of forest cover as the magnitude of the peakflow event increases. By demonstrating the need for invoking the dimension of frequency in the understanding and prediction of the effects of harvesting on peakflows, this study added another brick to the pile of evidence in calling for the abandonment of the outdated pure deterministic hypotheses and

experimental designs that have misguided forest hydrology research for over a century on this topic.

Lay Summary

This study has found that large floods can be affected by forest logging in area where rain-on-snow (ROS) commonly occur. However, not all watersheds are affected by logging in the same manner, some are more sensitive and some are less sensitive depending on the environmental characteristics of the watersheds. This study found flatter landscapes and drier and warmer environment in the ROS region to be effective indicators of conditions that are sensitive to logging practices. The new understanding in the effects of logging also emphasized the aspect of changing occurrence frequency. Even if large floods may not be significantly bigger in terms of volume of water, these large floods could occur much more frequently under logged conditions in ROS environment.

Preface

I collaborated with my supervisor in identifying and designing the research program and I conceived the research questions under the consultation of my supervisory committee. I conducted all tasks related to the research which includes: data collection, data analysis, interpretation, and drafting of the manuscript. No part of this dissertation has been submitted for journal publication yet.

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List of Abbreviations

AMC	Antecedent Soil Moisture Condition
ANCOVA	Analysis of covariance
ANOVA	Analysis of variance
CC	Coyote Creek in the South Umpqua National Forest (CC1, CC2, CC3, CC4 refer to the specific watersheds within Coyote Creek)
CDF	Cumulative Distribution Function
CP	Chronological Pairing (equivalent to paired by storm input)
FOX	Fox Creek in the Mt. Hood National Forest (FOX1, FOX2, FOX3 refer to the specific watersheds within Fox Creek)
FP	Frequency Pairing
HJA	H.J. Andrews Experimental Forest (HJA1, HJA2 …, HJA10 refer to the specific watersheds within HJA)
LTER	Long Term Ecological Research Network
PDF	Probability Distribution Function
PDS	Partial Duration Series
POT	Peak-Over-Threshold
Qp	Peakflow
ROS	Rain-On-Snow
STZ	Snow Transient Zone
SWE	Snow Water Equivalent
WAR	Water-Available-for-Infiltration-or-Runoff

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This dissertation is dedicated to families

and friends who never stop believing in me

Chapter 1: Introduction

"*Perhaps because of difficulties experienced in forecasting flood flows during warm storms, rain-on-snow events seem to have been regarded as somewhat mysterious and have generated considerable folklore*" [*Kattelmann*, 1997, p.59]. This statement, arguably still valid today, not only highlights the challenge of predicting floods related to Rain-On-Snow (ROS) events but also how much confusion are there among hydrologists when it comes to understanding its runoff mechanism. The significance of ROS in relation to landslides and large floods led to worldwide public attention and scientific research efforts since the early 20th century. It is peculiar that decades of research in ROS environment had failed to resolve this mysterious nature of watershed scale ROS hydrology, especially after the significant advancement of physical processes understanding gained from detailed stand level investigations. While recognizing that the research effort so far has been concentrating on small scale stand level snow mass and energy balance, *Jennings and Jones* [2015, p.7649] echoed how *"[s]ixty years of research on rain-on-snow floods has provided limited insights into the internal dynamics of snowpack during storm events."* One has to wonder why inferring insights into watershed level response from stand level understanding has turned into such a daunting task? Is our dominantly reductionist, small scale, and deterministic approach to research in part to blame for the lack of progress on the science of ROS hydrology at the more relevant larger scales? The next two sub-sections in this introduction report on the two major challenges that have impeded progress in the science of ROS at the watershed scale:

1.1 Failure to Bridge the Gap between the Observable and Operational Scales

Concurrent to the research on stand level ROS runoff mechanism, scientists of the wider hydrology community noticed that small scale processes cannot be simply extrapolated to explain larger scale phenomenon [e.g. *Dunne*, 1998; *Sivapalan*, 2003; *McDonnell et al.*, 2007]. This scaling challenge is inevitably imposed by the gap between the scales of observable processes (stand and hillslope levels) and the scale of operational processes (basin level) relevant for management and regulation. Bridging this gap has evolved as a seemingly unsurmountable task, which is why this scaling challenge "*is seen as one of the important reasons for the slow progress of hydrological science on basin scale…*" [*Klemeš*, 1983, p.1]. For decades, hydrologists are being reminded repeatedly that "*scaling issues are at the heart of most, if not all, hydrologic problems* [*Blöschl*, 2001, p.710]" and "*focusing on small-scale processes often precludes seeing the 'big picture', that is, the emergence of patterns and processes unseen at small scales* [*Benda et al.*, 2001, p.7]." Forest hydrologists, nonetheless, have followed and continue to follow the reductionist approach to explaining the relation between forest cover and the flow regime at the outlet of a watershed using processes derived from stand level studies without fully considering the spatial and temporal variability of the processes involved [*Alila et al.*, 2009 and references therein]. "*Fieldwork and scaling theory, apparently, are too widely divergent for a single individual to excel in both* [*Blöschl*, 2001, p.709]" and this is perhaps one of the reasons why forest hydrologists, who traditionally are known for their field expertise, have difficulty recognizing the fact that temporal and spatial extrapolations of the physical processes beyond their observable scale require more than just "arm waving" [as characterized by *Benda et al.*, 2001]. Outside traditional forest hydrology literature, there has been a growing amount of research work in the area of spatial-time heterogeneity of processes related to snowpack dynamics and runoff generation in ROS environments [e.g. *Liston*, 2004; *Brunengo*, 2012; *Garvelmann et al.*, 2015; *Dickerson-Lange et al.*, 2017]. This thesis draws heavily on these new developments and bring them to bear in original ways on the understanding and prediction of hydrologic system response at the larger watershed scales.

1.2 The Pairing that Strips Hydrology from its Stochastic Nature

Although hydrologists have long been aware of the importance of stochastic aspect of hydrology, such statement of "*determinism has taken the form of response hydrology and is in full progress at present* [*Yevjevich*, 1974, p.225]" is more valid than ever today. A case in point are the ways forest hydrologists evaluate the effects of harvesting practices on the peakflow regime, which have led to outcomes that continue to be characterized as "*highly variable, and for the most part unpredictable*" [*Hibbert*, 1967, p.535; *Leopold*, 1970; *Harr and McCorison*, 1979; *Hewlett*, 1982; *Jones*, 2000; *Eisenbies et al.*, 2007]. *Eisenbies et al.* [2007, p.81] characterized the state of science on this topic as "enigmatic." *Alila et al.* [2009] and *Alila and Green* [2014a, 2014b] attributed such a state to the dominantly deterministic thinking that strips hydrology from its stochastic nature in related research investigations.

For close to a century, research on this topic has been guided by the following question: What is the difference in the magnitude of peakflow when the forested (control) and harvested (treatment) watersheds are subject to the same storm input. A more thorough historical review of the origin of such prevailing research question will be provided in the following Background chapter to illustrate how this deterministic thinking of hydrologic system response has misguided scientists on the effects of forests, especially on larger floods. *Alila and Green* [2014a, 2014b] argued that the answers to such question which pairs peakflows in control and treatment watersheds by equal storm input (termed as the Chronological Pairing method or CP) are irrelevant to whether forest harvesting affects floods. In all science disciplines, pairing is critical to the design of controlled experiments and is used to isolate the effects of a disturbance on a system's response. At a first glance, it may be counter-intuitive, but CP does not fully isolate the effects of harvesting on the magnitude of floods and, hence, the experimental design that guided for so long research work on this topic is uncontrolled, leading to an incorrect and outright misleading change in the magnitude of floods [*Alila and Green*, 2014a, 2014b].

Alila et al. [2009] maintain that the pairing must be by equal frequency (termed as the Frequency Pairing method or FP). While FP is a well-established "statistical paradigm" [as labeled by *Katz*, 1993] in the wider hydrology and climatology communities, some in forest hydrology do not recognize the method of pairing by storm input as erroneous [e.g. *Lewis et al.*, 2010; *Bathurst*, 2014; *Birkinshaw*, 2014]. Therefore, in what follows this thesis illustrates, through pedagogical thought experiments in rain, snow, and ROS environments, how and why pairing by equal storm input leads to an uncontrolled experimental design and hence irrelevant conclusions.

In a rain environment, the same peakflow event of a certain magnitude of interest could be generated by a wide range of scenario combinations of storm input and antecedent soil moisture conditions (AMC). Testing the hypothesis that the magnitude of such peakflow event has changed as a result of harvesting ought to be conducted, and simultaneously, for all possible scenario combinations of these two hydro-meteorological factors (i.e. storm input and AMC). There lies the need to invoke the frequency in any research hypothesis or question investigating the effects of harvesting on the magnitude of peakflows. Therefore, the question that must guide research on this topic should be: What is the difference in magnitude when the peakflows of the control and treatment watersheds are of the same frequency. The pairing that fully and properly isolates the effects of harvesting on peakflows must be of equal frequency and not equal storm input. Pairing by equal storm input leaves uncontrolled the AMC, which is known to have a significant effect on the magnitude of peakflows with or without the forest cover [*Sklash and Farvolden*, 1979; *Buttle and Sami*, 1990].

With the argument of CP-based research question or hypothesis being flawed in rain dominated environment due to the inability to consider the full range of storm input and AMC combination scenarios that could generate a flood of the same magnitude, the additional effects of snow mass and energy balance on peakflow generation only further strengthen such argument and makes it all the more interesting and convincing in the snow and ROS environments. Although the detailed physics will be presented later in this thesis' Discussion chapter, in general snowpack can contribute to peakflow as melt water and it can also attenuate precipitation as cold content, regulating the relationship between precipitation input and streamflow just as soil water storage and release. Not only such snowpack response to storm input is energy-related, the response of snowpack also propagates downstream to affect soil moisture. The randomness in the pre-event energy balance (e.g. air temperature, wind, and radiation) and the nonlinear process interactions between the weather, snowpack, and soil moisture conditions make it impossible to isolate the effects of logging on the response of peakflow magnitude by controlling only the amount of precipitation input. Again, testing the hypothesis that the magnitude of a peakflow event has changed as a result of harvesting ought to be conducted, and simultaneously, for all possible scenario combinations of the three hydro-metrological factors: weather, snowpack, and soil moisture conditions. Stated differently, the question guiding a research investigation on forest harvesting effects on peakflows must take the following form: What is the change in the magnitude of a peakflow with a specific frequency or return period? On the significance of asking the right questions in scientific investigation, *Leopold and Langbein* [1963, p.192] state:

> *"The measure of a research man is the kind of question he poses. So, also, the vitality of a branch of science is a reflection of the magnitude or importance of the questions on which its students are applying their effort. Geomorphology* [forest hydrology in our case] *is an example of a field of inquiry rejuvenated not so much by new methods as by recognition of the great and interesting questions that confront the geologist* [forest hydrologist in our case]*."*

As a preface disclaimer to this thesis, the author's take on CP and CP-based studies in decades of literature on this topic should not be viewed as an overall condemnation of deterministic hydrology itself; because deterministic process understanding certainly has its place in hydrological research. As exemplified above, however, certain research questions in hydrology can only be investigated via a stochastic approach. CP (the pairing of peakflows by time or equal storm input) as an experimental design, which confines the investigation of the harvesting effects to pure deterministic approach, is the one being opposed in this thesis. Since the experimental design required for isolating the effects of harvesting on peakflows imposes on us the pairing of peakflow events by equal frequency, the use of a stochastic approach becomes a necessity, and is not a matter of subjective choice as some continue to claim [*Perry et al.*, 2016, p.18 and 21].

1.3 Need for Stochastic Physics in Understanding ROS Peakflow Generation

Reanalyses of existing long term observed and simulated flows in snow environment using FP by Alila and co-workers have so far revealed outcomes that run counter the prevalent wisdom on how forest harvesting affects peakflows, especially larger peakflows [*Schnorbus and Alila*, 2004, 2013; *Green and Alila*, 2012; *Kuraś et al.*, 2012]. FP analysis by others, in rain environment, has also yielded conclusions that run counter the prevalent wisdom in forest hydrology [e.g.

Birkinshaw et al., 2011]. In their Figure 8 of a modelled FP analysis result, the frequency of the one in 100-year peakflow has been increased to one in 25-year event following logging. Traditionally, when new research outcomes challenge the status quo of the existing understanding, others would attempt to replicate the experiment to refute or corroborate the new findings. For example, soon after *Jones and Grant* [1996] claimed logging and roads have larger effects than other CP-based studies have concluded, a series of re-analyses of the same dataset attempting to refute such claims were published [*Thomas and Megahan*, 1998, 2001; *Beschta et al.*, 2000; *Jones and Grant*, 2001]. Given the critical role of ROS events in large regional flood generation and given *Alila et al.* [2009] has demonstrated how CP stems from an uncontrolled experiment, one would expect a quick and swift movement of re-analyzing existing paired watershed data under the new probability framework. Challenging on methodological grounds an entire body of literature related to perhaps one of the most controversial and policy laden topic in hydrology and claiming it is all based on logical fallacies of irrelevant conclusions is after all serious [*Alila et al.*, 2009]. Almost eight years have gone by since 2009, and although several FP-based studies done in rain and snow dominated regimes have continuously added more support to the abandonment of the CP research method and its conclusions on watershed scale physical processes, there has not been a single attempt to sort out the confusion lurking in the scientific understanding of how ROS environment is affected by logging using FP.

This study contributes to the new era of research for advancing the physics and predictions of the effects of forests on peakflows (or floods) guided by the research questions that invoke the dimension of frequency. Unfortunately, the concept of frequency or probability is not immediately intuitive to many forest hydrologists, especially the very idea of understanding the physics of floods in a probabilistic framework (i.e. stochastic physics or statistical physics). Investigating the environmental controls of flood frequency distributions, an area of research pioneered by *Eagleson* [1972], is however a standard research method in the wider hydrology literature, but it represents a paradigm shift in the way harvesting effects are physically explained and quantified in forest hydrology [*Green and Alila*, 2012]. This study draws heavily on such stochastic hydrology literature to advance the science of forests and floods. To preserve the inverse and highly non-linear relation between magnitude and frequency, the research questions on the effects of logging are investigated using the flood frequency distribution framework. How the magnitude of a specific T-year peakflow event changes, or how the return period of a peakflow event of a specific magnitude changes, as a result of logging, must necessarily pass through the understanding and prediction of how logging affects the mean, variance, and potentially the form of the peakflow frequency distribution.

1.4 Overarching Objective of the Study and Research Hypotheses

In summary, the overarching objective of this study is to use long term flow data at nine pairs of control-treatment watersheds with varying physiographic characteristics to advance the physical understanding and prediction of the effects of various forest harvesting practices on particularly larger peakflows in the ROS environment of the State of Oregon (U.S.A) using the FP framework. Through understanding the physical processes at play, the goal is to understand how the environmental conditions (climate and physiographic) affect the peakflow response of watersheds to harvesting, especially on the more infrequent peakflows. The understanding of the environmental controls will assist in future predictions of the peakflow response to harvesting in different times or regions, but more importantly it also provides the basis for continuous scaling of processes and the prediction of the peakflow response at an even larger scale. In this study, the various environmental controls and treatments are linked to peakflow generation via a novel unifying synchronization/de-synchronization framework that combines the two realms of stochastic and deterministic hydrology, where a high synchronization means runoff generated at different parts of the watershed arrives at the outlet in a relative small window of time (hence higher probability of a flashier and larger peakflow at the outlet), and vice versa.

To fill the knowledge gaps of current understanding of the environmental controls on the relation between harvesting practices and the peakflow regime, the following hypotheses are offered:

1. Watershed elevation range controls the extent of synchronization of runoff generation through snow mass and energy balance; higher synchronization effects lead to larger increase in the mean and variability around the mean of the peakflows following harvesting.
2. Road network increases the routing efficiency of the watershed and the resulting increased runoff, reduced response timing, and enhanced synchronization lead to higher mean and higher variability around the mean of the peakflows.
3. Tree removal suppresses fog interception in certain humid environments, which in turn increases the mean and variability around the mean of the peakflows as a consequence of an increase in baseflow and an intensification of the ROS phenomenon; making the peakflow regime of such humid environment with the presence of fog interception one of the most sensitive to forest harvesting.
4. In the Snow Transient Zone of Pacific Northwest (STZ, roughly defined as elevation 450 ~ 1100 m above sea level), with snow being more important in peakflow generation,

peakflows in watersheds with drier climate are more sensitive to tree removal as manifested by larger increases in the mean and variability around the mean of the peakflows.

5. The magnitude of infrequent peakflows (defined as events with return period larger than 10 years) can be substantively affected by tree removal and road building, as a direct consequence of the increase in the mean and/or variability around the mean of the peakflows articulated in hypotheses 1 through 4 above.
6. Tree removal and forest road effects on the magnitude and frequency of peakflows can increase unchecked with event size, i.e. with no apparent 'no-effect' threshold to the influence of forest harvesting on peakflow response, again as a direct consequence of such increase in the mean and/or variability around the mean of peakflows articulated in hypotheses 1 through 4 above.

Before transitioning into the Method chapter 3, the ROS literature will be reviewed in the Background chapter 2 with emphasis on the line of work from R. Dennis Harr who spent significant portion of his career on investigating the effects of harvesting on both stand and watershed scale hydrologic response in ROS environment. Harr was drawn to ROS research in the 1970's not just because ROS is responsible for most of the large runoff events in the Pacific Northwest region where he lives and worked but also because of how his "*field observations appeared to conflict with current hydrologic perceptions* [*Harr and Coffin*, 1992, p.457]." After the Results chapter 4, the Discussion chapter 5 will open with a preamble laying out the base of spatial and temporal upscaling of runoff generation that links the physiographic characteristics to the sensitivity of the peakflow regime to harvesting practices. The rest of the Discussion chapter 5 will be contrasting the sensitivity of the peakflow regime to harvesting practices in the nine pairs of control-treatment study watersheds. The emphasis in the Discussion chapter 5 will be on how the differences in the peakflow regime response could be explained by the proposed unifying synchronization/de-synchronization framework, as well as local climatic conditions of the watersheds. The Extended Discussion chapter 6 will compare the results and conclusions of this FP study to the previously published CP study of *Jones* [2000] on the same topic with similar dataset. The emphases of this comparison chapter 6 focus on the similarities (or lack thereof) between the outcomes of both CP and FP studies and most importantly the differences in the physical understandings of how forest harvesting affects the peakflow regime between both studies. The Conclusion Chapter 7, before ending the discussion with the implications and the proposed future research direction, provides the readers an opportunity to reflect on some of the thought provoking philosophical issues of research and scientific inquiry in relation to forests and peakflows.

Chapter 2: Background

Even before the dawn of the forest hydrology research, the role of the forest in peakflow generation has long been conceptualized around a CP-based century old "sponge theory" in which the forest is imagined to soak up water during storm and releases it later on [*Pinchot*, 1905, p.68]. A simple extension of logic from this sponge theory suggests that given a large enough storm the watershed can be "overwhelmed" since any sponge should have a finite storage capacity:

> *"We have long believed that forest cover by itself only can play a limited role in controlling peakflows due to extreme events. That is, an extreme rain event, spawned perhaps by a hurricane, would produce the same peakflows with or without forest cover, assuming all other conditions, especially soil conditions, were maintained."* [*DeWalle*, 2003, p.1255]

What turned into a literally "overwhelming" hypothesis was later extrapolated to explain the effects of forest cover on peakflows in snow environments:

> *"...during the largest rain or snowmelt events the soils and vegetative canopy will have little additional storage capacity, and under these conditions much of the rainfall or snowmelt will be converted to runoff regardless of the amount or type of vegetative cover."* [*Macdonald and Stednick*, 2003, p.13]

Decades of research in forest harvesting effects on peakflows in ROS environment have since been faithfully adhering to this line of reasoning as to why the often vaguely defined large peakflows should not be affected, at least not 'significantly' as often reported in the literature [*Rothacher*, 1973; *Jones and Grant*, 1996; *Thomas and Megahan*, 1998; *Beschta et al.*, 2000]. Specific attention has not been given to extreme events in the literature on forests and floods [*DeWalle*, 2003], which explains why most remained vague on the very definition of a large flood (i.e. how large is large?). Nonetheless, the "no-effect" threshold return period beyond which forest harvesting has no effect on peakflows have been reported to be as small as 2-year [*Thomas and Megahan*, 1998; *Macdonald and Stednick*, 2003], 5-year [*Beschta et al.*, 2000], and 10-year [*Calder et al.*, 2007; *Bathurst et al.*, 2011a, 2011b].

Perhaps based on his field experiences and his observation that snowpack could contribute significant amount of water to generate some largest peakflows, R. Dennis Harr disagrees with his U.S. Forest Service colleague Jack Rothacher's physical explanation of the limited role of forest cover as it neglects the aspect of snow mass and energy dynamics. *Harr* [1986, p.1099] states:

> *"Rothacher [1973] inclusion of rain-caused runoff events…seriously restricted observations about how snow accumulation and melt in the transient snow zone might be altered by clearcut logging as is reflected in higher storm flows."*

Following his scientific intuition, Harr's work in the 1970's and 80's on the snow mass and energy balance during ROS events in the Pacific Northwest region pointed out how water contributed by ROS melt could be substantial. In certain scenarios, smaller storm events combining with suitable conditions for snowmelt could actually lead to large peakflows [*Harr*, 1981]. This early theoretical and modelling work of snowpack physics also suggests that logging may increase meltwater input to soil by some 25% during certain conditions.

Subsequent stand level field experiments in the region by *Beaudry* [1984] and *Berris and Harr* [1987] confirmed the hypothesis of Harr's previous modelling exercises that water output of snowpack under an open stand is significantly increased compared to a forested stand. Because the wet season in Pacific Northwest coincides with dormant season, the relatively high soil moisture condition irrespective of the vegetation cover has been frequently used as a physical explanation to further reinforce the argument of vegetation cover having minimal impact on the magnitude of peakflows in this region [*Rothacher*, 1973; *Thomas and Megahan*, 1998; *Beschta et al.*, 2000; *Jones*, 2000]. However, Harr hypothesized that if the soil moisture condition is mostly wet during the winter season as the CP physics explained, the increased input of meltwater to the system, found in stand level experiments, should translate into larger peaks at the outlet. "*Despite a fairly strong physical basis,* (this) *hypothesis seems to be contradicted by published results of two case studies* (referring to *Rothacher* [1973] and *Harr and McCorison* [1979]) *conducted in the western Cascade Range in Oregon"* [*Harr*, 1986, p.1095]. Harr therefore questioned the watershed level research method, not Chronological Pairing itself but the use of regression curves as an indication of harvesting effects.

Regression analysis has been for decades the *modus operandi* for the analysis of pre- and post-harvest paired watershed observed peakflow data for evaluating the effects of harvesting on peakflows. For two adjacent watersheds with similar conditions (climate, geomorphology, and vegetation), regression analysis can be used to develop a relationship between peakflow (Qp) observations of the two watersheds. With this relationship (calibration or pre-treatment regression), one can predict the Qp of a watershed using Qp of the other watershed should the observation of Qp for the former be no longer available. If one of the watersheds is logged or has road construction (treated watershed) while the other watershed remains intact (control watershed), a new relationship (post-treatment regression) is developed. The two regression curves (pre- and post-treatment regressions) are compared and the vertical distance between these two curves has always been interpreted to be the measure of the effects of treatment on the magnitude of peakflows. As briefly explained in the Introduction, the peakflows in control and treatment watersheds have always been paired chronologically (or by equal storm input) for both pre- and post-treatment regressions.

As will be described in the Method chapter, the use of CP to develop a calibration regression equation relating treatment to control Qp in the pre-harvesting period is scientifically defensible because all four hydro-meteorological conditions (precipitation, antecedent soil moisture condition, snowpack conditions, and snowmelt energy) are similar between the control and treatment watersheds. Such CP-based regression equation is commonly developed and used by scientists and engineers alike, for instance, to fill-in missing data gaps of neighbouring watersheds [e.g. *Dalrymple*, 1960; *Howe et al.*, 1967]. However, the use of CP to develop a regression relation in the post-harvesting period as an attempt to quantify the effects of harvesting on the magnitude of peakflows is indefensible [*Alila et al.*, 2009, 2010; *Green and Alila*, 2012; *Schnorbus and Alila*, 2013]. As explained in the Introduction, this is because CP stems from an experimental design that does not allow for the simultaneous control of the combined effects of all four hydro-meteorological conditions acting on the magnitude of the peakflows of the unharvested and harvested watersheds, and hence the effects of forest cover removal on the magnitude of Qp are neither properly nor fully isolated. Hence, the use of CP-based regression equation relating treatment to control Qp **in the post-harvest period** leads to an incorrect change in the magnitude of peakflows [*Alila and Green*, 2014a, 2014b].

In addition, this kind of prediction of the effects of harvesting on the magnitude of Qp using CP-based regression analysis is an unfortunate misuse of the analysis of variance (ANOVA) and analysis of covariance (ANCOVA) [*Alila et al.*, 2009 and references therein]. ANOVA and ANCOVA were originally designed to quantify the effects of harvesting on the *mean* Qp response. The comparison of the pre- and post-treatment regression curves as described above extends the application of ANOVA/ANCOVA to evaluate treatment effects on Qp smaller and larger than the mean. This extended application of ANOVA/ANCOVA was indoctrinated by *Beschta* [1978], but has since became common practice in forest hydrology worldwide. The statistical inference from using ANOVA/ANCOVA for evaluating the effects on the mean Qp response comes with stringent requirements and assumptions, such as homoscedasticity and normality of the observations. Because the distribution of peakflows is often skewed positively, the untransformed Qp often violates these assumptions.

As a first common observation in CP forest hydrology literature, the post-treatment regression curve has a higher intercept and lower slope than the pre-treatment curve [e.g. *Alila et al.*, 2009, fig.3a], which means the two curves will eventually intersect. Such convergence of the two regression curves was then mistakenly used to support the hypothesis of diminishing role of forest cover with increasing peakflow sizes [*Alila et al.*, 2009]. The point of intersection associated with the two converging regression curves was then interpreted as the quantification of a "no effect" Qp threshold and reinforcing the preconceived dogma of the vaguely defined larger Qp not being affected by logging. While revisiting some of the CP studies with conflicting conclusions drawn from stand level experiments, *Harr* [1986, p.1096] referred to the convergence of regression curves and the associated "no effect" threshold as being categorically "irrelevant" to whether forest harvesting affects larger Qp. He argued that such convergence is a mere statistical artifact due to mixing of rain-induced smaller Qp with more variable ROS-induced larger Qp in the same regression analysis. Not only such mixing violates the fundamental homoscedasticity assumption of ANOVA/ANCOVA, the larger relative increases of the smaller Qp, as relative change always decline with increasing size, "tilted" the post-treatment regression line, producing an illusion of diminishing treatment effect. The log-transformation technique commonly employed to satisfy the homoscedasticity assumption further exaggerates the influence of the smaller Qp by suppressing the influence of the larger Qp in the regression analysis [*Jones and Grant*, 2001]. With log-transformation, the intercept and slope of the post-treatment regression became even more influenced by the comparisons of smaller rain-induced Qp. Therefore, on the basis of a homogenous runoff mechanism and in his attempt to alleviate the regression prediction error with an increase in the size of Qp, Harr separated ROS-induced Qp from rain-induced Qp. However, as himself noted:

> *"Including only snow-related peakflows in my reanalysis eliminated some but by no means all of the variance in size of post logging peakflows. Considerable variance remains unaccounted for because of wide ranges of antecedent snow conditions, snow storm characteristics, and climatological variables that combined to produce a range of melt situations and a variety of runoff events."* [*Harr*, 1986, p.1099] ,

Harr believes such excess unexplained variance among post-treatment ROS Qp is intrinsically a consequence of the natural variability of ROS physical processes [*Harr*, 1986]. It is true that peakflows generated by ROS are often more variable than rain-induced peakflows, however, this is neither the dominant nor the only cause of the large unexplained variance in post-treatment regression [*Alila et al.*, 2009]. At this pivotal moment in history, Harr incorrectly attributed the unexplained variance exhibited in the post-harvest regression analysis to the natural variability around the mean of ROS Qp instead of the inappropriate type of pairing of the control and treatment Qp. By pairing Qp chronologically (or by storm input), the response of Qp can be increased, decreased, or remain unchanged by logging compared to the control as Harr himself noted in the same publication of *Harr* [1986], inducing large uncertainty in the prediction of the post-treatment regression curve. This relates to a second common observation in CP forest hydrology literatures, namely the post-treatment regression curve most often had a higher unexplained variance than the pre-treatment regression curve [*Green and Alila*, 2012]. This is a direct consequence of harvesting in the treatment watershed changing the hydro-meteorological processes largely responsible for the stochastic nature of the peakflow response in comparison to the control watershed. This in turn changes not only the magnitude of peakflows but their frequencies and the intricate inverse and highly non-linear magnitude-frequency relation referred to by the wider hydrology community as the frequency distribution.

The other solution considered by Harr to solve the excessive unexplained variance is to subset pairs of Qp into arbitrarily defined magnitude category or season groups and the changes in the mean of each sub-class groups are assessed for significance of treatment effect. With this sub-setting method, the heteroscedasticity problem is less obvious since Harr assumed it came from mixing of event sizes. However, the core of the problem, namely the incorrect pairing, remains unresolved. In fact, by sub-setting Qp into different groups and disassociating Qp responses between groups leads to a "logical fallacy of decomposition" [*Alila et al.*, 2009]. "*If we are interested in identifying extremes in a collection of parameters, the focus of statistical analysis must shift from individual values to the group as a whole* [i.e. the entire frequency distribution]" [*Link and Sauer*, 1996, p.1633]. Nonetheless, this sub-setting method was later adopted by other researchers investigating forest harvesting effects on peakflows [e.g. *Jones and Grant*, 1996; *Jones*, 2000].

Naturally, the practice of dividing events into sub-class groups also led to a conclusion that changes in the mean of extreme large events are difficult to assess and low statistical power of smaller sample size of 'extremes' is to be blamed [*Harr and Coffin*, 1992; *Jones and Grant*, 1996; *Thomas and Megahan*, 1998; *Jones*, 2000]. However, such blame of small sample size is again trivial compared to the real problem of incorrect pairing. Sample size is definitely a hindrance [*Link and Sauer*, 1996], but the signal of an effect is further blurred by the large uncertainty introduced by the inappropriate type of pairing in the significance tests of changing mean Qp response [*Alila et al.*, 2009, 2010]. Through detailed comparisons of CP versus FP analysis results, *Alila et al.* [2009], *Green and Alila* [2012], and *Schnorbus and Alila* [2013] demonstrated how this large uncertainty is indeed an artifact of the CP method; and this is yet another reason why the treatment effects must be properly isolated using Frequency Pairing (FP).

The deterministic CP-based framework started gaining momentum in forest hydrology research since the early twentieth century and soon after the few first years of flow data collected at paired watershed study sites became available [e.g. *Engler*, 1919; *Bates and Henry*, 1928]. It continues to be the dominant approach to investigating forest harvesting effects on the peakflow regime in the forest hydrology literature worldwide [*Robinson et al.*, 2003 (Europe); *Guillemette et al.*, 2005 (Asia and Australia); *Grant et al.*, 2008 (North America); *Bathurst et al.*, 2011a, 2011b (Latin America); and citations therein]. Outside forest hydrology, however, independent progress continues to be made in the development of stochastic hydrology, a field of investigation pioneered by hydrologists such as Peter Eagleson, Vit Klemeš, and Vujica Yevjevich [e.g. *Eagleson*, 1972; *Yevjevich*, 1974; *Klemeš*, 1978]. Near the end of the series of Harr publications, through several of his physical reasoning and arguments, it is fascinating that Harr started to suspect the importance of changing frequency by logging:

1. *"Cutting trees could cause water input to soil of a magnitude that would occur, on the average, only every 25 yr. under forest whereas the same weather conditions after cutting would result in water input to soil that would occur on the average every 12 yr. under forest."* [*Harr*, 1981, p.297] – suggesting logging could double the frequency of an event;

2. *"…Rothacher concluded that extremely high peakflows may be no greater after logging... His conclusion, however, does not consider changes in size of moderate-sized peakflows that, because of logging, may have been greater after clear-cut logging."* [*Harr*, 1986, p.1096] – suggesting that the effects logging is not on the increasing magnitude of the largest few peaks but the number (or frequency) of medium peaks turning into larger peaks;

3. *"Although it seems clear that the combination of greater accumulation of snow and energy inputs to snow packs in clear-cut areas can cause greater rates of water input to soil, we need to know* ***how often*** *this situation occurs."* [*Berris and Harr*, 1987, p.141, boldface added for emphasis].

Recall that CP as a quantitative experimental design strips away the aspect of frequency when comparing Qp by equal storm input, one can only assume that it was perplexing for Harr to further associate his stochastic thinking of physical processes to any of the deterministic watershed analysis conducted using CP. *Alila et al.* [2009] and *Alila et al.* [2010] see no linkages between the CP and FP-based study outcomes because CP-based methods do not preserve the nonlinear and inverse relation between the magnitude and frequency of peakflows, which can only be maintained through the use of a frequency distribution framework.

Harr is certainly not the only scientist whose cues about the significance of the frequency dimension in evaluating forest harvesting effects on peakflows went unnoticed for decades. More than 40 years ago, *Hewlett and Helvey* [1970] pointed out how the frequency dimension is critical to the understanding and prediction of the effects of harvesting on peakflow responses at the outlet, but they did not explicitly point out the flaws of CP in its early stage of development as a research method.

Recognizing the challenge of switching between deterministic and stochastic thinking, *Hewlett* [1982, p.546] dropped yet another overlooked hint about the importance of probability theory (or the probabilistic framework) in investigating the ***causal*** relation between forests and floods:

> *"Hydrologists have understandably been confused by the difficulties inherent in describing the nature and frequency of floods to laymen, who are apt to have little patience with probability statements…But among ourselves we must drop back to rigorous language in order to discuss and trade information about land-use causes and flood effects."*

Historically, a few occasional deployments of frequency analysis alongside CP analysis in a handful of studies, such as *Christner and Harr* [1982], *Birkinshaw et al.* [2011], and *Du et al.* [2014], have yielded conflicting conclusions regarding whether larger floods are affected by logging. The apparent contradictions have been dismissed and attributed to trivial methodological issues on the side of frequency analysis, either because of the confusion and lack of rigor referred to in the above quote of J. D. Hewlett, one of the most luminous in the forest hydrology science community, is persisting to date; or possibly due to the "confirmatory bias" of some scientists [*Nickerson*, 1998]. After close to a century of CP dominance and the associated incorrect statistical inference reinforcing the century-old preconceived bias of forests effects on peakflows, it is rather not surprising *Alila et al.* [2009] and *Green and Alila* [2012] were welcomed with reticence by the forest hydrology community [*Barber*, 1961].

Although the physics and the conclusions of Chronological Pairing research have been contradicted by FP-based findings by Alila and co-workers in recent years, the legitimacy of CP as an experimental design was never seriously questioned until *Alila et al.* [2009] (refer to the way *Burt and McDonnell* [2015] cites *Alila et al.* [2009]). Recognized as a "seminal" paper by *Perry et al.* [2016], *Alila et al.* [2009] has provided irrefutable evidence to why CP must be completely abandoned as research method on evaluating peakflows, along with the prevailing 'wisdom' that larger peakflows are not affected by forest harvesting, which have been reinforced by decades of

CP research and continues to be regurgitated in highly influential science journals [e.g. *Calder et al.*, 2007; *Laurance*, 2007; *van Dijk et al.*, 2009] and literature syntheses and policy oriented documents [e.g. *Eaton and Church*, 2001; *Macdonald and Stednick*, 2003; *Food and Agriculture Organization (FAO) of the United Nations*, 2005; *Moore and Wondzell*, 2005; *Grant et al.*, 2008; *Winkler et al.*, 2010; *Perry et al.*, 2016]. Since then, several FP-based articles by Alila and co-workers in snow dominated environment have further demonstrated that the core problem in a century of forest hydrology literature on this topic is the pairing by equal storm input; and the consequential irrelevancy of research outcomes introduced by the uncontrolled experimental designs [*Green and Alila*, 2012; *Kuraś et al.*, 2012; *Schnorbus and Alila*, 2013].

In summary, the frequency framework advocated in this thesis, although not commonly used by the forest hydrology community, has long been a common practice in the wider hydrology community for evaluating the effects of land use and climate change on water resources where the watershed response to disturbance needs to be isolated from complex interactions of stochastic processes. In fact, some of the early hydrology papers published in *Science* and *Nature* have used the FP framework [e.g. *Howe et al.*, 1966; *Wigley*, 1985; and references therein]. The FP framework has also been a well-established "paradigm" guiding climatologists in their quest for understanding and predicting the effects of a changing climate on weather extremes [*Katz*, 1993]. Ecologists appear to have only recently being lobbied to join the campaign in their scientific enquiries related to the understanding and prediction of the effects of ecological disturbances on extremes [*Katz et al.*, 2005]. Isn't it about time the forest hydrology community follow suit?

This study on the effects of logging in ROS environment will further illustrate the need for FP in evaluating the peakflow response to logging in such hydroclimate regime. The complex nature of the ROS mechanism amplifies the problem of equal storm input leading to a distorted account of what could be the most sensitive peakflow regime to forest harvesting practices, as will be demonstrated in this thesis. Therefore, the persistent "*folklore*" [*Kattelmann*, 1997, p.59], "*limited insights*" [*Jennings and Jones*, 2015, p.7649], and "*enigma*" [*Eisenbies et al.*, 2007, p.81] in predicting peakflows and their responses to harvesting in ROS environments will not go away if scientists working on forests and peakflows or floods continue to resist the need for drastic change to the course of research direction [*Barber*, 1961; *Kiang*, 1995].

Chapter 3: Method

3.1 Study Sites

This study uses nine pairs of control-treatment watersheds from three study sites: Coyote Creek (CC), Fox Creek (FOX), and H.J. Andrew Experimental Forest (HJA). In Coyote Creek, the treatment watersheds are CC1, CC2, and CC3; all with CC4 as control. In Fox Creek, FOX1 and FOX3 are treated and both use FOX2 as control. In H.J. Andrews, treatment watersheds HJA1 and HJA3 use HJA2 as control, HJA6 uses HJA8 as control, and HJA10 uses HJA9 as control (Table 1). Although all three sites are located within the state of Oregon (U.S.A.), and subject to similar larger scale climate patterns, the local climate and vegetation conditions at the three study sites are hydrologically distinctive. Fox Creek is at the Northern end of Oregon close to Washington and Coyote Creek is at the Southern part of Oregon closer to California; H.J. Andrews is located in the middle, about 130 to 150 km distance to the other two sites (Figure 1). Detail environmental conditions of the three sites are discussed below.

3.1.1 Climate

All three sites are characterized by a distinctive dry hot summer and wet cool winter [*Kottek et al.*, 2006]. The long term normal climate statistics (1961-1990) of the three sites output from ClimateWNA (v.5.3, *Wang et al.* [2012]) show that Coyote Creek, being at the southern part of Oregon, is warmer and receives significantly less amount of precipitation than the other two sites all year around (Figure 1). The average annual precipitation is about 2600 mm, 2300 mm, and 1100 mm for Fox Creek, H.J. Andrews, and Coyote Creek, respectively. Fox Creek and H.J. Andrews receive comparable amount of precipitation in fall and winter but Fox Creek receives noticeably more precipitation than H.J. Andrews in spring and summer (Figure 2). Also, a stand-level water balance experiment at Fox Creek found that the area underneath forest canopy receives 20~30% more water annually due to the fog interception phenomenon compared to the nearby open area [*Harr*, 1982]. In the winter months (December to February), the average monthly precipitation is about 340 mm in Fox Creek, 341 mm in H.J. Andrews, and about 144 mm in Coyote Creek. In terms of monthly average air temperature, Coyote Creek is about 2 to 4°C warmer than Fox Creek and H.J. Andrews throughout a normal year. In the winter months, the monthly average air temperature is about 2.4 ~ 2.8°C for Fox Creek and H.J. Andrews and it is about 5°C for Coyote Creek. Even with the same precipitation amount, the warmer temperature in Coyote Creek likely contributed to the dry condition via stronger evaporation and sublimation. Detailed annual water balance calculations demonstrated that Coyote Creek has a lower net moisture input than the other two sites [*Jones*, 2000].

Precipitation and temperature normally change with elevation. Such variation is reasonably controlled by the experimental design of paired watershed study (control and treatment watersheds are adjacent and have similar elevation ranges). However, elevation control on precipitation and temperature is potentially a confounding factor in inter-pair comparisons of the sensitivity of peakflow response to treatment if the two pairs are sitting at different elevations. Unlike Fox Creek and Coyote Creek where there is only one control watershed, H.J. Andrews site has three control watersheds: HJA2 (outlet at 545 m), HJA8 (outlet at 962 m), and HJA9 (outlet at 426 m). The pair of HJA6/HJA8 is at higher altitude than the other three pairs of HJA watersheds. Long term normal climate data (1961-1990) output from ClimateWNA (v.5.3) is used to estimate the lapse rates of precipitation in the region of H.J. Andrews. The winter monthly precipitation is normally about 287 mm at elevation 500 m and is about 354 mm at elevation 1000 m (equivalent to a lapse rate of 0.13 mm precipitation increase per meter in elevation). Across the H.J. Andrews Experimental Forest, air temperature decreases with increasing elevation at a rate of about 2.5 ~ 6.3 °C/km [*Rosentrater*, 1997]. Since temperature and precipitation are affected by factors other than elevation, the actual lapse rates could vary significantly from event to event.

Controlled by different combinations of local climate, elevation, and aspect; snow accumulation and melting are different between watershed pairs. Being higher up in elevation, with outlet above 800 m, the two pairs of watersheds in Fox Creek and HJA6/HJA8 have snow depth sometimes exceeding 1.5 m and may persist for up to half a year [*Harr*, 1982]. Although watersheds in Coyote Creek have similar elevation range as watersheds in Fox Creek and HJA6/HJA8, the snowpack in Coyote Creek normally melts away within 1-2 weeks due to the drier and warmer local climate [*Harr et al.*, 1979]. In H.J. Andrews, snowpack development in HJA10/HJA9 is weak and normally melts away within 1-2 days due to their lower elevation (outlet at around 460 m) [*Harr and McCorison*, 1979; *Harr et al.*, 1982]. With the melting time changing from days to half a year between HJA10/HJA9 and HJA6/HJA8, snowpack within the Snow Transient Zone (STZ) exhibited high sensitivity to small elevation changes. Watersheds HJA1, HJA2, and HJA3 have much larger elevation ranges than other watersheds in this study (Table 1) and almost completely cover the entire elevation range of STZ which is roughly around 450 ~ 1100 m in this region of Pacific Northwest. The outlet elevations of HJA1 and HJA3 are similar to the 460 m outlet elevation of HJA9 and HJA10 and the upper elevations are all above 1000 m like those higher elevation watersheds.

3.1.2 Rocks and Soils

Overland runoff rarely occurs in the western Cascadia range of Oregon due to high soil infiltration rate which exceeds 2000 mm/h [*Jones*, 2000]. Prolonged water input increases the pore-water pressure between soil particles and therefore the risk of landslide and mass movement, especially on slopes with a poorly developed external drainage pattern [*Swanson and Swanston*, 1977; *Harr et al.*, 1979]. A study in H.J. Andrews found that the number of soil mass movement increases on slopes steeper than 40% and situated at elevations between 600 – 800 m [*Dyrness*, 1967, fig.10]. Among the watersheds in this study, average slope gradient increases from watersheds in Fox Creek (<10%), to watersheds in Coyote Creek and HJA6/HJA8 (30%), to HJA1/HJA2/HJA3/HJA9/HJA10 (>60%) [*Jones*, 2000].

3.1.3 Vegetation and Treatments

Vegetation in these three sites were each dominated by high Leaf Area Index (LAI) old-growth coniferous trees before any logging activities. Common species include: Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), mountain hemlock (*Tsuga mertensiana*), and Pacific silver fir (*Abies amabilis*) [*Jones*, 2000]. Treatment (logging and road building) varies between watersheds. In terms of harvesting, logging rate increases from 25%-35% patch-cut in FOX1, FOX3, CC2, and HJA3, to 50% selection cut in CC1, to 100% clear-cut in CC3, HJA1, HJA6, and HJA10 (Table 1). All treated watersheds except HJA1 and HJA10 have forest roads, with road density varying from 1.3 to 4.6 km/km^2.

3.2 Data Collection and Analysis

The long term normal climate statistics came from the PRISM data [*PRISM Climate Group*, 2004] and were extracted and spatially disaggregated by the ClimateWNA software [*Wang et al.*, 2012]. The discharge data analyzed in this study were obtained from the data bank of H.J. Andrews Experimental Forest, a member of the U.S. Long Term Ecological Research (LTER) network. The calibration period of paired watershed studies varies from two to ten years. The post treatment period also varies among studied watersheds, with watersheds in H.J. Andrews having longer post-treatment record of 38 to 50 years and with watersheds in Fox Creek and Coyote Creek having shorter post-treatment record of 17 to 22 years. The post-treatment record in Coyote Creek consists of two segments due to interruption of the monitoring program (segment one started in 1972 and ended in 1981; segment two started in 2000 and ended in 2013). As a result, there is a gap in the time series of discharge measurements. With the linearity assumption in the relationship between time and hydrological recovery (described below), the effect of this interruption in the time series should be small if the linearity assumption holds.

The selection of peakflows from the long term flow measurements are done according to the method described in *Jones* [2000], which involves several steps. First, the hourly peak discharge data in each watershed are filtered with a watershed-specific minimal threshold which is set to produce an initial dataset of 10-15 events per year on average. Second, the selected peaks in treated and control watersheds are paired. Peakflows in the treated and control watersheds are paired when occurring within 12 hours of each other. The resulting final dataset contains 9-12 matched events per year on average in each pair of watersheds. Occasionally, due to gauge malfunction or other reasons, a few flow records are missing in the discharge dataset and the gaps were filled by estimated values based on the knowledge of the stream gauge manager. Although the error in estimation values varies depending on the conditions and information from nearby watersheds, estimation errors could be large when extrapolating for extreme events (low or high) [*USDA-NRCS*, 2007]. Since exclusion of the estimated peakflows is not an uncommon practice [e.g. *Beschta et al.*, 2000], peakflows with an "estimated" flag in the dataset are eliminated to reduce uncertainty in the subsequent frequency analysis.

The frequency analysis of observed (representing post-harvest) and expected (representing pre-harvest) peakflows is done according to the method described in *Alila et al.* [2009] and *Green and Alila* [2012], which involves three major steps: estimation of the expected discharge, peakflow frequency analysis, and adjustment for non-stationarity caused by forest regrowth. Before treatment is applied (the calibration period), the treated and control watersheds have similar conditions and therefore have close to identical response to storm input. A linear regression developed from selected peaks in the calibration period is used to predict the expected peakflow magnitudes of treated watershed in the post-treatment period as if the treatment was never applied:

$$\widehat{Y_i} = b_0 + b_1 X_i \,, \tag{1}$$

where $\widehat{Y}_i$ is the expected peakflow in the treatment watershed and X_i is the peakflow in the control watershed. The use of linear regression in developing calibration equation is scientifically defensible because the conditions of the two watersheds as well as meteorological forcings are tightly controlled [*Green and Alila*, 2012]. However, linear regression should not be used in the post-treatment period because the pre-event and event conditions between the two watersheds (for example: AMC, snow, and meteorology) are no longer the same, as discussed in detail in the Introduction section. It is well known in the modelling community that offset in the initial condition of complex systems would produce drastically different behaviour and response even if the subsequent forcings are identical (see literatures related to chaos theory in hydrology such as *Sivakumar* [2017]).

For peakflow frequency analysis, this study follows the Partial Duration Series (PDS) frequency analysis described in *Alila et al.* [2009]. The peakflow (Qp) of the treated watershed in the post-treatment period is the *observed peakflow* with treatment effects. With a sample size of n, the observed peakflows Y_i (i.e. chorological event i = 1, 2, 3, …, n) are then ranked from largest to smallest and the return period of the j^{th} largest event Y_j is estimated by the approximately quantile-unbiased Cunnane plotting position [*Stedinger et al.*, 1993]:

$$1 - F_Y[Y_j] = \frac{j-0.40}{n+0.20}, \tag{2}$$

where F_Y is the cumulative distribution function (CDF). The frequency curve of the observed peakflow is then plotted as return period versus peakflow magnitude. The same ranking and return period calculation procedure is then applied to produce a series of ranked expected peakflows $\hat{Y}_j$. To correct the loss of variance from the use of regression in equation (1), an error term e randomly sampled from a t-distribution with n-2 degrees of freedom is introduced to each of the ranked expected peakflow $\hat{Y}_j$ to produce a ranked and corrected expected peakflow $\tilde{Y}_j$ with $\tilde{Y}_j = \hat{Y}_j + e$. This procedure is iterated 10,000 times in a Monte Carlo simulation to provide a mean of the ranked and corrected expected peakflow $\bar{\tilde{Y}}_j$. Following the method described in *Alila et al.* [2009], confidence limits on the expected peakflow frequency curve are estimated to account for a combination of predictive uncertainty in the calibration equation (1) and the quantile sampling variability, assuming the overall uncertainty is normally distributed. Although confidence limits on the frequency curves were estimated and plotted, the discussion of analysis outcome does not report the effects of harvesting on the magnitude of Qp as being important only if they are statistically significant, because what is statistically insignificant could be physically and practically significant [*Kirk*, 1996; *Johnson*, 1999]. Since nine pairs of watersheds are being investigated concurrently (i.e. meta-analysis), the analysis focus rather on whether the upper tails of the frequency distributions of peakflows are displaying similar patterns regardless of post-harvest sample size. This will assist in identifying physically meaningful treatment effects even if they are not necessarily statistically significant, as suggested by *Lewis et al.* [2010] and adopted by *Green and Alila* [2012].

The observed peakflows are adjusted to remove the effect of hydrologic recovery to meet the stationarity assumption of the peakflow frequency analysis. Using the chronologically paired Qp, the "time since end of treatment" $t_{harvest}$ is introduced into the linear regression as a covariate to represent the recovery effect:

$$\widehat{Y_i} = b_0 + b_1 X_i + b_2 * t_{harvest}\ , \qquad (3)$$

This de-trending procedure, which involves subtracting the time component from the observed peakflows has been used in *Alila et al.* [2009] and *Green and Alila* [2012] to produce a stationary peakflow series in the post-treatment period for the frequency analysis. Because the use of chronologically paired events and the assumption of linear recovery effect are potentially concerning, nonstationary frequency analysis would be a more ideal method to isolate the recovery effect but this method is not yet established.

Chapter 4: Results

In this section, the treatment effects (from harvesting and/or roads) are first reported in the form of changes to sample statistics (mean and variance) of peakflow (Qp) (Table 2). Because the analysis of peakflow response in the form of changes to event frequency is important to the understanding of the physical processes, treatment effects on the Qp magnitude and frequency are reported as changes in the Cumulative Distribution Function (CDF) and Probability Distribution Functions (PDF). In terms of observed peakflow in either CDF or PDF, we presented both curves with and without adjustment for recovery effects due to forest regrowth. Because we are interested in the treatment effect under an assumed stationary condition, any discussion related to treatment effect will be referred to the observed peakflow with adjustment for recovery. The implications of hydrological recovery effect will be discussed separately in section 5.6. Overall, watersheds in Coyote Creek and Fox Creek illustrate higher treatment impact than watersheds in Fox Creek and H.J Andrews with similar treatments (logging cut rate and road density).

4.1 Coyote Creek and Fox Creek

At Coyote Creek watersheds, the impact of treatment on mean of Qp increases with logging rate: 30% patch-cut in Coyote Creek watershed 2 (CC2) causes 35.4% increase in the mean, 50% selection cut in CC1 causes 50.3% increase in the mean, and 100% clear-cut in CC3 causes 85.5% increase in the mean. The effect of logging on the variance of Qp in Coyote Creek also increases with cut rate: 52%, 135.9%, and 154% increase in the variability around the mean in CC2, CC1, and CC3, respectively. Although treatments at Coyote watersheds were designed with different road densities, the experimental design within site does not allow the isolation of the effect of roads from the effect of tree removal. At Fox Creek sites, however, the two watersheds (FOX1 and FOX3) have similar logging rates (25% patch-cut) but different road density (2.1 km/km^2 in FOX1 and 1.3 km/km^2 in FOX3). The increase in mean of Qp is 20.9% in FOX1 and 4.7% in FOX3. The increase in Qp variability around the mean is 82.9% in FOX1 and 34% in FOX3.

CDFs and PDFs of Coyote Creek and Fox Creek watersheds are plotted in Figure 3 and Figure 4 for the assessment of changing event magnitude and frequency. At Coyote and Fox Creek sites, logging increased the magnitude of all Qp regardless of size (illustrated by the entire observed Qp CDFs shifting upward compared to the expected Qp CDFs). Remarkably, the effect of logging on the magnitude of Qp increases with event size (illustrated by vertical differences between the observed and the expected CDFs increasing with return period). Logging in Coyote and Fox Creek watersheds also increased the frequency of all peakflow, irrespective of magnitude (See insets of Figure 3 and Figure 4). In Coyote Creek, for instance, 100% clear-cut with roads have caused a four to five times increase in Qp frequency in CC3 (e.g. 50-year event becoming ~11-year event), 50% selection cut with roads caused a four times increase in Qp frequency in CC1 (e.g. 50-year event becoming ~13-year event), and 30% patch cut with roads caused up to two times increase in Qp frequency in CC2 (e.g. 30-year event becoming 18-year event). In Fox Creek, interestingly the relatively lower cut rate (25% patch-cut) has resulted in two to eleven times increases in the peakflow frequency with the larger events showing even larger increase in frequency (10-year events turning into 2 to 3-year events; 40-year events turning into 4 to 5-year events).

The split season analysis (ROS dominant months versus non-ROS dominant months) in Fox Creek and Coyote Creek reveals that the watershed sensitivity to treatments (either change in sample statistics or the vertical difference between observed and expected CDFs) is higher during months of when ROS events more commonly occur (Figure 5). For CC3 (100% cut rate with roads), the increase in the mean is 107% during ROS dominant months and 58% during non-ROS dominant months; and the change in the variability around the mean is 223% and 22%, respectively. In the case of FOX3 (25% cut rate with roads), changes in the mean Qp between ROS and non-ROS dominant months are similar, 3% and 3.5%, respectively. However, the response in terms of the variability around the mean is drastically different between the two: 28.5% during ROS dominant months and -6.6% during non-ROS dominant months. In CDF comparisons of both CC3 and FOX3, the vertical difference between observed and expected CDF of the non-ROS dominant months is relatively smaller compared to ROS dominant months. The vertical difference also remains relatively constant with increasing return period for the non-ROS dominant months but shows strong increasing trend in ROS dominant months.

4.2 H.J. Andrews

At H.J. Andrews site, there are four treatment watersheds with HJA1, HJA3, HJA10 being adjacent to each other and sitting at the southwest corner of the Experimental Forest; and with HJA6 sitting across the Experimental Forest at the higher up northeast corner. Although HJA10 is adjacent to HJA1 and HJA3, HJA10 is different because it is about 10 times smaller and has a lower elevation range. For HJA1 (100% clear-cut, no roads) and HJA3 (25% patch-cut, with roads), differences in treatments resulted in different increases in the mean (39% in HJA1 and 12% in HJA3) and different change in the variability around the mean (3.3% in HJA1 and -8.5% in HJA3). Frequency analysis (CDFs and PDFs in Figure 6) illustrates that peakflow magnitude of smaller peakflows (with return period < 10-year) have increased in these two H.J. Andrews watersheds. For peakflows larger than 10-year, notably overlapping observed and expected CDFs of HJA1 and HJA3 suggests that larger events are not affected by treatments in these two H.J.

Andrews watersheds. In terms of change in the peakflow frequency, smaller peakflows in HJA1 are doubled in frequency (10-year becoming ~4-year event) and no change in frequency for events larger than 10-year. Similarly, in HJA3, frequency of smaller peakflows is increased by 30% with no change in frequency of the larger peakflows.

In terms of treatment level, HJA6 and HJA10 have the same cut rate compared to HJA1 (all 100% clear-cut) with HJA6 having additional treatment effects from forest roads. The increases in the Qp mean are 35% for HJA6 and 9% for HJA10; and the increases in the variability around the mean are 25.4% for HJA6 and 9.3% for HJA10. The vertical difference between CDFs in the frequency analysis shows that magnitudes of Qp are increased for all return periods in HJA6 and HJA10 (Figure 7) and, unlike HJA1 and HJA3, such vertical difference increases with return period without a no-effect threshold, suggesting larger treatment effects on events larger than 10-year. The increasing vertical difference of CDFs with return period can also be translated into larger increasing Qp frequency with larger events. In HJA6, the 10-year and 60-year events become 1.3 and 2.7 times more frequent, respectively (10-year and 60-year becoming ~7-year and ~22-year events, respectively). In HJA10, the change in frequency for 10-year event is 1.6 times and 2.8 times for 70-year event (10-year and 70-year becoming ~6-year and ~25-year events, respectively). Since the general climate conditions are the same for the four watersheds of H.J. Andrews, judging by the responses of post-treatment peakflow frequency curves between watersheds, the contrasting treatment sensitivity of the large events (either low sensitivity as in the case of HJA1 and HJA3 or high sensitivity as in the case of HJA6 and HJA10) needs to be understood through the physical processes of how watershed physiographic characteristics influence treatment effects.

Chapter 5: Discussion

This section starts with the issue of elevation control on runoff generation mechanism in Rain-on-Snow environment and how stand level runoff production at different elevation bands aggregates spatially, in synchronized or de-synchronized ways, to produce watershed level response. We then focus on the discussion of treatment effects from past stand level field observations, namely the mass and energy balance of snowpack change by harvesting and the runoff routing efficiency increases by roads. The inter-site comparisons of the sensitivity of the peakflow regime to treatment between Coyote Creek, Fox Creek, and H.J. Andrews are then explored by combining understanding of treatment effects at stand level and the spatial aggregation mechanism (synchronization/de-synchronization of runoff).

5.1 Elevation Control on Runoff Generation

Among all the stand level physiographic characteristics, elevation is the most important factor in controlling snowpack mass and energy balance [*Jost et al.*, 2007; *Brunengo*, 2012; *Wayand et al.*, 2015]. Although elevation is the single most important factor, the interaction between elevation and other factors such as aspect and vegetation cover were found to be significant [*Winstral and Marks*, 2014], which makes the investigation of elevation's control on ROS events a nonlinear complex problem. By investigating the elevation control on ROS runoff generation in a probabilistic framework, *Brunengo* [2012] found that, although ROS can occur in a wide range of elevations (even at sea level), there is a narrow elevation range termed peak-ROS elevation where Water-Available-for-Infiltration-or-Runoff (WAR) is most likely larger than precipitation (P). The author noted that although the probability of [WAR>P] with changing elevation properly isolates the effects of elevation on runoff generation, discussion of physical processes is difficult since common understanding of soil water equivalent (SWE) and mass and energy balance is mostly deterministic and on stand-level. Brunengo therefore explained how different pre-event mass and energy balance processes can influence runoff generation through a generalized scenario of changing elevation without involving the dynamic interactions of other factors such as aspect and vegetation. At elevations lower than the peak-ROS elevation, he ascertained that the thin and patchy snowpack leads to a lower probability of the snowpack contributing significant amount of water for infiltration or runoff compared to the event input received from ROS precipitation. On the other hand, at elevations higher than the peak-ROS elevation, he determined that the thick and cold snowpack tends to retain event rainfall input and lead to a smaller WAR than ROS precipitation. Therefore, during any ROS event, the response to a precipitation input between areas at different elevations is different and the watershed cannot be treated as a homogenous entity when discussing ROS runoff at the watershed outlet (an analogy not previously invoked in the hydrology literature on this ROS topic would be the Variable Source Area concept [*Hewlett and Hibbert*, 1967] in rain-dominated environment). Field observations related to this peak-ROS elevation were reported a few decades ago in *Christner and Harr* [1982, fig.2] as a nonlinear relationship between mean basin elevation and the unit-area specific magnitude of the 10-year peakflow event. They found that the specific magnitude of the 10-year peakflow is highest for watersheds with mean elevation of around 850 m in the Pacific Northwest. However, there was significant variation in the reported correlation and they shied away from making any inference from such correlation. Recent advances in the understanding of snow process heterogeneity (caused by elevation range) as discussed above seem to have provided the missing puzzle piece of why the early attempt to relate mean basin elevation to peakflow generation was clouded with variation.

Although the stochastic approach of inter-event comparisons employed in *Brunengo* [2012] is the way to isolate the effects of elevation from other environmental factors, communicating this stochastic physics understanding of runoff generation in ROS environment remains a challenge due to the natural intuition of deterministic process thinking. For that, the hypothetical and simplified scenarios of how elevation changes snow dynamics described above can also be checked by findings from deterministic and process-based studies. A recent study focusing on the within-event deterministic processes in the ROS regime provided support to the conclusions from the above stochastic analysis of *Brunengo* [2012]. Within any single event, the term "activation period (hours)" represents the time lag between the beginning of rainfall and snowpack contributing runoff and it is found to vary significantly with relatively small change in elevation [*Garvelmann et al.*, 2015]. Findings of *Garvelmann et al.* [2015] suggest that in a watershed with a large elevation gradient, parts of the watershed higher in elevation have snowpack contributing to WAR later than lower elevations. From the perspective of the outlet, lags in the arrival time of water from different parts of the watershed translate into smaller peakflows. Such de-synchronized runoff production leading to reduction in the magnitude of peakflows have been hypothesized in snowmelt dominated environments [e.g. *Hendrick et al.*, 1971; *Kattelmann*, 1991; *Schnorbus and Alila*, 2004; *Green and Alila*, 2012] but has not yet been discussed in Rain-on-Snow environments. We hypothesize that a similar de-synchronized/synchronization runoff generation process is also governing how stand level runoff production is aggregated spatially to a watershed level response at the outlet.

5.2 Other Physiographic Controls on Synchronization/De-synchronization

There are other physical characteristics of the watershed that can also lead to such synchronization or de-synchronization of the peakflow generation. First, the size of the catchment matters. When all other environmental controls are constant (or, *ceteris paribus*), larger watersheds' peakflow generation is de-synchronized due to more varying travel time of water from the source of input to the outlet and non-uniform precipitation input across the landscape. Such de-synchronization in larger basin size is known to reduce the size as well as the variability of peakflows [*Blöschl and Sivapalan*, 1995] and it forms the bases of scaling parameters with basin area in regional analysis for the estimation of peakflows for ungauged watersheds. Second, the aspect distribution also influences the mass and energy balance of the snowpack and large aspect distribution has a similar de-synchronization effect as large elevation range on the peakflow generation [*Green and Alila*, 2012]. However, as mentioned previously that there is a complex interaction between elevation and aspect and the quantification of such aspect-induced de-synchronization will be difficult if not impossible outside of a stochastic framework. For example, the de-synchronization caused by contrasting aspects would be more prominent with steep terrain than a subdued terrain. Third, the shape and geometry of the drainage network are also known to affect the runoff generation processes [general review in section 10.1 of *Dingman*, 2015]. In general (when all other environmental controls remain constant), watersheds with more elongated shape tend to produce smaller peakflows than circular shaped watersheds due to a higher de-synchronization of water arrival time at the outlet from across the landscape [*Strahler*, 1964; *Ayalew and Krajewski*, 2017]. Again, the assumption of *ceteris paribus* is unrealistic and this de-synchronization effect by drainage network geometry could be mitigated by longer storm duration [*Ayalew and Krajewski*, 2017]. Such interaction between physiographic conditions and storm characteristics further suggest the use of a stochastic approach in understanding the influence of environmental control on peakflows generation, best illustrated by *Ayalew and Krajewski* [2017].

From the discussions above, the concept of synchronization/de-synchronization has been commonly used in hydrology to explain spatial and temporal aggregation of processes (elevation range, watershed size, aspect distribution and drainage network geometry) and their influences on the peakflow generation. The presence or lack of vegetation cover will further complicate the discussion of interactions between various environmental controls on the peakflow generation. Although the experimental design of a paired watershed study is thought to have tightly controlled all these environmental conditions between treatment and control watersheds, it is the interaction between these conditions and vegetation cover in the post-harvesting period that complicates the discussion. For example, the previous discussion on elevation control with vegetation cover based on the findings of *Garvelmann et al.* [2015] has shown that the elevation-induced de-synchronization can be amplified by certain harvesting practices (e.g.: clear-cut). In snowmelt environments, the aspect-induced de-synchronization is also found to interact with the removal of forest cover [*Green and Alila*, 2012]. This interaction between aspect and harvesting on the de-synchronization of peakflow generation appears to be more complicated in ROS environment due to the uncertain influence of forest cover during the pre-event snow accumulation phase and the during-event melting phase of peakflow generation.

5.3 Canopy Removal's Effects on Stand-level Processes

5.3.1 Snow Accumulation Processes Prior to ROS Event

It was once hypothesized that canopy removal should reduce snow accumulation due to the lack of shielding from short wave radiation input. This hypothesis was contradicted by some field observations; and the lower snow accumulation in forested stands was explained by an increase in the canopy interception and sublimation loss [*Schmidt*, 1991; *Lundberg et al.*, 1998] and an increase in the longwave radiation input to the snowpack by vegetation cover (known as the "radiative paradox") [*Ambach*, 1974; *Sicart et al.*, 2004]. Recent global multi-site analysis suggests that at warmer locations where mean winter temperature is above -1°C the reduction in the longwave radiation could be greater than the increase in the shortwave radiation as a result of forest canopy removal, which leads to a net increase in the snow accumulation in the open site [*Lundquist et al.*, 2013]. Coincidentally (or not?) that ROS also occurs at regions with winter temperatures hovering around or above 0°C. The elimination of energy inputs to the snowpack from canopy dripped water, which comes from either intercepted snowmelt and/or fog interception was also found to contribute to a higher snow accumulation in the open site [*Beaudry*, 1984; *Berris and Harr*, 1987]. Although fog interception could lead to 20 to 30% more precipitation under the forest canopy than open stand [*Isaac*, 1946; *Azevedo and Morgan*, 1974; *Harr*, 1982], we are not aware of any investigation on the direct influence of fog interception on the energy balance of snowpack. The effect of dripped water on the amount of snow available for ROS runoff is likely a dynamic process as it should depend on the energy state and the associated water retention capacity of the snowpack.

5.3.2 Melting During ROS Events

During ROS events, additional energy input from wind and turbulence is considered as the main driving force of faster melting in the open site, with advective energy in the rain drops being a secondary source [*Beaudry and Golding*, 1983; *Harr and Coffin*, 1992; *van Heeswijk et al.*, 1996]. The increase in the during-event melt energy input in the open site leads to faster response of snowpack (shorter activation time). However, such shorter activation time in the open stand appears to be confined to only lower elevation comparisons of open and forested stands [*Garvelmann et al.*, 2015]. At higher elevation, the increase in the melt energy input in open stands is counteracted by an increase in the faster increasing snowpack depth with elevation and hence more energy would be required to activate the snowpack. Therefore, the difference in activation time between elevation bands would be larger if the entire slope is clear-cut.

5.4 Road Effects on Watershed Runoff Routing and Synchronization

Forest roads are known to act as an extension of the natural drainage system to increase the watershed's drainage efficiency [*Harr et al.*, 1975; *Jones et al.*, 2000; *Tague and Band*, 2001; *Luce*, 2002; *Wemple and Jones*, 2003; *Pallard et al.*, 2009]. Roads increase the drainage efficiency of a watershed by: 1) increasing the impervious area of the watershed, 2) altering the runoff generation process of the watershed by intercepting surface and sub-surface runoff, and 3) re-routing runoff through roadside ditches that connect directly to existing streams or gullies. Because the intercepted water can originate from a larger contributing area than the induced road surface impervious area, the interception and re-routing effect is suspected to have larger effect on the peakflow generation [*Wemple and Jones*, 2003]. The drainage density is found to be sensitive to road density when taking the road-induced gullies into consideration and 4.2 km/km^2 of roads could increase the drainage density by some 40% [*Wemple et al.*, 1996]. Although the level of runoff generation synchronization across the watershed is also influenced by other physiographic conditions (such as elevation, aspect, and basin geometry as discussed previously) and/or precipitation input (in the case of larger watersheds), on the basis of higher routing efficiency alone, it is reasonable to expect increased synchronization by roads can lead to higher peak discharges at the outlet due to reduction in the de-synchronization effects [*Jones and Grant*, 1996]. Because flashiness and peakflow variability are inter-related measures of watershed level responses [*Archer*, 2007], changing routing efficiency of the watershed may more profoundly affect the peakflow frequency distribution. Given FOX1 and FOX3 are physically similar and have the same logging rate, we find that the higher increase in the mean and variability around the mean of Qp in FOX1 compared to FOX3 can be attributed to the higher road density in FOX1 based on the reasoning above. The deterministic physics of roads and how they manifested in a probabilistic framework can be drawn from a paralleled and well-established mechanism of the drainage density-increasing effect of ditching in agricultural and afforestation practices [*Howe et al.*, 1966; *Robinson*, 1986].

5.5 Process Control of Sensitivity of Peakflow to Treatment: Inter-site Comparison

Within each group of the three sites (Coyote Creek, Fox Creek, and H.J. Andrews), there appears to be a general correlation of higher cut rate/road density and larger increase in the mean and variability around the mean of Qp. It gets interesting when results are compared between the three sites. At first glance, the treatment sensitivity appears to be erratic. Among all watersheds observed across the three sites, the four treatment watersheds that have received 100% clear-cut experienced increases in the mean of Qp ranging from 9% to 86% and in the variability of Qp around the mean from 3% to 154%. The four treatment watersheds that were subject to moderate level of cut rates (25 and 30% harvesting) experienced increases in the mean of Qp by 5% to 35% and changes of the variability of Qp around the mean of -9% to 52%. The immediate following observation indicates that the increase in the mean and variability around the mean appear to be larger in Coyote Creek and Fox Creek compared to watersheds in H.J. Andrews when the treatment is similar. For example, the treatment effect in HJA1 (100% clear-cut, no roads) is smaller when compared to CC3 (100% clear-cut, with roads), even though roads in CC3 might be a confounding factor. HJA3 has similar treatment as the two Fox Creek watersheds (25% patch-cut, with roads) but the treatment effects on the larger events (>10 year) are drastically different: no effect in HJA3 but some 10 to 30% increase in peakflow magnitude in FOX1 and FOX2.

In terms of physiographic characteristics, what makes HJA1 and HJA3 distinctive compared to other experimental treatment watersheds is their larger elevation range. We hypothesize that, with large elevation gradient (roughly ranging from 450 m to 1050 m) in HJA1 and HJA3, the runoff generation is de-synchronized due to differences in the pre-event snowpack conditions at different elevations, with or without the treatment effects. After the clear-cut treatment in HJA1, a larger difference in the melt rates between elevation bands further de-synchronized the runoff generation. Therefore, although harvesting increases snow accumulation and melt rates of snowpack of stands at the same elevation, the stronger de-synchronization across elevation gradient in HJA likely mitigated the possibility of an increase in the peakflow at the outlet. HJA3 is used here to further illustrate such de-synchronization effect in the runoff generation process: There are three discrete cut blocks, each about 8% of the total watershed area. Two of these cut blocks are at the mid-elevation range while the third is near the outlet. The runoff generation is de-synchronized between 1) the cut blocks and their nearby forested area, 2) the three cut blocks situated at different elevation, and 3) forested area at different elevation. Forest roads in HJA3 have a density of 2.7 km/km^2, which should introduce synchronization to the runoff generation process. A reduction in the variability around the mean of observed peakflow in HJA3 appears to suggest that the de-synchronization caused by its elevation gradient and harvesting is more dominant than the roads' synchronization effects in this particular watershed.

Contrary to high elevation ranges in steep HJA1 and HJA3 watersheds that are hypothesized to have caused the de-synchronized peakflow generation, the topography in Coyote Creek and Fox Creek are relatively subdued. In snowmelt dominated regions of British Columbia, peakflows in subdued watersheds are found to have higher variability than steep mountainous watersheds, hypothesized to be caused by synchronized melting [*Beckers et al.*, 2002]. Similar processes could also be at play in the ROS environment since spatial homogeneity of pre-event snowpack condition also leads to synchronized melting. Comparison of the Coefficient of Variation (CV) of Peak-Over-Threshold (POT) series of the control watersheds (CC4, FOX2, HJA2, HJA8, and HJA9) yielded head scratching findings as the behaviour of CVs in Coyote Creek and Fox Creek are unexpectedly different. First, the 1.08 CV of CC4 (control watershed of CC1, CC2, and CC3) is higher than the CVs of steep mountainous control watersheds in H.J. Andrews (ranging from 0.42 to 0.81). This is as expected not only because of the synchronized runoff generation in a subdued watershed [*Hendrick et al.*, 1971] but also the drier hydroclimatology in Coyote Creek compared to the other two sites (Figure 2), as meteorological conditions themselves tends to be more variable in drier environment [*Merz and Blöschl*, 2009]. The head scratching part comes from Fox Creek. We expected a higher CV in Fox Creek than H.J. Andrews since watersheds in Fox Creek are subdued and the lack of de-synchronization should have resulted in a higher CV, although it may not be as high as Coyote Creek due to a more humid climate in Fox Creek. Surprisingly, the CV of the Fox Creek's control watershed is lowest (0.38) among control watersheds in this analysis.

Why the peakflow variability is surprisingly low in Fox Creek's control? Perhaps an even more important question is how such low CV in the control is associated with the larger increase in the variability around the mean in FOX1 and FOX3 following treatments compared to other pairs of experimental watersheds analyzed in this study. Given the more elongated shape of watersheds in Fox Creek compared to others [*Jones*, 2000, fig.4], the peakflow generation process could be de-synchronized by the drainage network geometry. However, as a holistic observation, the much lower CV of FOX2 (control) compared to other control watersheds does not seem to be fully explained by this additional de-synchronization effect of elongated drainage network. More importantly, such drainage network geometry-induced synchronization should not be significantly affected by harvesting practices and therefore does not fully explain the large increase of variability around the mean following harvesting practices. It is therefore hypothesized that additional process mechanisms are acting to reduce the peakflow variability around the mean in this region. The 30% more annual water input to forested stands compared to clear-cut stands in Fox Creek [*Harr*, 1980, 1982] could contribute to both observations, namely the low peakflow variability in the control and the substantial increase in variability around the mean following treatment. First, fog interception increases water input (mass balance effect) to the control watershed which raises baseflow and as a consequence reduces CV [*Blöschl and Sivapalan*, 1997]. This moisture recharging effect is no doubt more predominant during early season as the soil is drier [*Jones*, 2000]. Secondly, water from fog interception during winter could potentially further reduce CV through increasing snowpack energy input (energy balance effect), preventing the snowpack from developing underneath the canopy and as a consequence contributing less to ROS runoff. An analogy to this mechanism would be drip water from intercepted snow which is known to add more energy to the snowpack underneath the forest canopy [*Bewley et al.*, 2010]. There is a lack of quantification on the energy input caused by the extra drip water of fog interception. Nonetheless, it appears that the hypothesis of such energy effect of drip water from fog interception is logical based on the extrapolation of physics from intercepted snow to intercepted fog drip. An unusual behaviour in the comparison of flood frequency curves in FOX1 and FOX2 seems to support this hypothesis. The treatment effect (illustrated as vertical difference between CDFs) on the small Qp events (return period < 0.7 years) are distinctively smaller than treatment effects on the larger Qp events for Fox Creek (Figure 4). In the case of FOX2, there is no treatment effect for such small events. Since the energy balance effect of dripped water from fog interception is likely negligible during the more rain-dominated seasons of the year, the reduction in the fog interception following harvesting would likely reduce rain-only runoff events mainly by its mass balance effect (ie: less water input to the watershed). This physical reasoning is echoed in the observation of the split analysis of FOX2 in which there is no significant treatment effect during non-ROS dominant months (Figure 5). The energy balance effect of the extra dripped water becomes increasingly more important as the contribution of snowpack melt water becomes more influential on the runoff generation processes in mid-winter. The reduction in pre-event energy input following harvesting could therefore lead to higher snow accumulation and subsequently higher WAR. This energy balance effect appears to be only significant at the peak of ROS season as seen in the FOX3 split analysis where large treatment effects appear to be experienced by only the largest a few events.

Holistically, the high treatment sensitivity of watersheds in Coyote Creek and Fox Creek compared to H.J. Andrews are mainly the consequences of their subdued topography due to a lack of de-synchronization in the runoff process. The presence of roads in all Coyote Creek and Fox Creek but not all H.J. Andrews watersheds further exaggerates the treatment effect discrepancy in the comparison of Coyote Creek/Fox Creek versus H.J. Andrews due to the synchronization effect of roads. Within the four H.J. Andrews pairs, HJA6 has the most subdued topography and a mean elevation right at the peak-ROS elevation. Therefore, the observation of HJA6 showing the biggest treatment sensitivity compared to other H.J. Andrews watersheds is consistent with the proposed physical framework. On the other hand, the HJA10 shows the smallest treatment sensitivity in H.J. Andrews, which it too can be explained by HJA10's physical characteristics such as its steepest topography, lowest mean elevation, and lack of roads.

In addition to the physical characteristics of the watersheds, deeper process control investigation also suggests that local hydroclimatic conditions are important to the sensitivity of peakflow variability around the mean to treatment. In Coyote Creek, the results suggest the larger increase in the peakflow variability around the mean following treatments may be contributed to by the drier and more variable hydroclimatic condition. The splitting by season into ROS versus non-ROS dominated months, reveals that such sensitivity stems from altering the snowpack dynamics in mid-winter following harvesting. The presence of fog interception in Fox Creek is hypothesized to lower the Qp variability, which means watersheds in this region are exceptionally vulnerable to harvesting. This is because the reduction of return period is relatively faster in watersheds with lower pre-harvesting Qp variability (gentler CDF slope) than watersheds with higher pre-harvesting Qp variability (steeper CDF slope). It is important to point out that watersheds with milder slope pre-harvest peakflow frequency curves being most sensitive to harvesting is perhaps the most fundamentally critical dictum related to harvesting effects on peakflows, which can only be revealed by a FP-based framework. This explains why such dictum is being repeatedly echoed and emphasized more in recent studies [*Berris and Harr*, 1987; *Bewley et al.*, 2010; *Green and Alila*, 2012]. Therefore, although both Coyote Creek and Fox Creek are displaying high sensitivity to harvesting practices, they displayed *different types of sensitivity*.

In Coyote Creek, the lack of de-synchronization in the snow mass and energy balance made the peakflow generation process sensitive to harvesting in the form of changing peakflow magnitude (shown as the larger increase in the Qp mean and variability around the mean, as well as the larger vertical distance between the flood frequency curves in Figure 3). In Fox Creek, the high sensitivity is manifested in the large reduction in the return period caused by the milder slope of the flood frequency curve. Therefore, the two types of sensitivity (magnitude versus frequency) are not necessarily equivalent in terms of how watersheds respond to harvesting effects. This observation of differential treatment sensitivity seems counter-intuitive at first but it serves as an excellent example to illustrate the esotericism of stochastic understanding.

5.6 Hydrological Recovery

The discussion so far on watershed treatment sensitivity with the assumption of stationarity potentially limits the practical implications of the findings to the period of immediately following treatments. The pace of hydrological recovery determines the length of heighten risk exposure and has tremendous influence on how professionals assess overall risk and reliability over a longer term. Although the experimental design of this study (namely the stationary frequency analysis coupled with a CP-based de-trending technique) was not designed to investigate recovery specifically, we offer some of the observations from our de-trending exercise to illustrate the contradiction in the conclusions of the pace of hydrological recovery between FP framework and the full CP-based ANOVA/ANCOVA framework.

The exercise reported in Table 2 purposefully reduces the record length of some longer records in H.J Andrews to match the record sample size of other studied watersheds. The differences in the amount of recovery adjustment (which is the vertical difference between adjusted and unadjusted series) between the shorter sample set and longer sample set could be considered as an indirect representation of the hydrological recovery in the four H.J. Andrews. First, adjustment for recovery in HJA1 with a shorter record length of 23 years shows no significant difference in either change of the mean or variability around the mean of Qp relative to the expected. Then, with the full record of 50 years of observations, the change in the mean and variability around the mean of Qp relative to the expected are significantly different between adjusted and unadjusted for recovery. Because the adjustment for recovery is only significant for a record length of 50 years but not for 23 years, it is reasoned that significant hydrological recovery does not occur until some 20 years after the initial treatment effects. This conclusion contradicts the conclusion drawn from a CP-based analysis by *Thomas and Megahan* [1998] who claimed significant hydrological recovery in the first, third, and fourth decades in the post-treatment period with the first decade showing the fastest recovery, and for no apparent physical reasons there is no recovery in the second decade. Consider the vegetation recovery rate in this region which is about 60% in 30 years for canopy cover and LAI [*Jones and Grant*, 1996], we postulate that there is little if not zero hydrological recovery in the first two decades following clear-cutting of the watershed. A similar conclusion of no significant recovery for the first two decades after treatments is also found in HJA6 where no significant recovery is found by the recovery adjustment exercise for the shorter record length (22 years post-treatment) but for the longer record length (39 years post-treatment) for both changes in the mean and variability around the mean of Qp relative to the expected. The same exercise for HJA3 is inconclusive possibly due to several confounding factors such as time-sensitive de-synchronization caused by scattered cut-blocks and time-independent synchronization caused by roads. The record of 17 years at Fox Creek also requires almost no recovery adjustment which is consistent with the hypothesis that little recovery happens in the first two decades following treatment. Therefore, from our observations in the H.J. Andrews, we find no support to the notion of fast hydrological recovery proposed in the traditional CP-based analyses of *Thomas and Megahan* [1998].

In Coyote Creek, due to a gap in the discharge time series, although the sample size for post-treatment frequency analysis is only 22 years, the effective recovery period for the three Coyote Creek treatment watersheds is in fact 41 years (1972 to 2013) and the recovery is noticeable. Nevertheless, the amount of hydrological recovery over a period of four decades does not appear to be on the same magnitude as the treatment effects. Stationarity assumption aside, if the unadjusted observed peakflow frequency curve, which confounds treatment effects with hydrological recovery effects, is to be compared to the expected flood frequency curve, the increase in Qp magnitudes is still large. This suggests that the hydrological response to logging and roads could be slow to recover in this region, which echos previous studies by R.D. Harr and colleagues whose stand level outflow experiment observed significant increase of water outflow at the 40-year old plantation stand compared to the fully forested stand [*Harr et al.*, 1989; *Harr and Coffin*, 1992]. That led them to conclude hydrological recovery by vegetation regrowth in Rain-on-Snow environment is slow. Unfortunately, such findings from a stand level experiment were mostly dismissed by the forest hydrology community perhaps because they are inconveniently incompatible with the research outcomes of few available watershed-level CP-based recovery studies [e.g. *Beschta et al.*, 2000].

On the physical processes related to hydrological recovery, resilient ecosystem is often being used to support why hydrological recovery should be fast in the region of Pacific Northwest. Often studies on the topic of hydrological recovery focus on one of the many aspects of such ecosystem resilience, either fast recovered vegetation and soil conditions or how snow dynamics changed following regrowth. However, since vegetation regrowth or snow dynamics are hard to be assessed on a larger scale, the discussion of hydrological recovery often relies on an understanding of stand level processes. Similar to treatment effects, discussion of spatial aggregation and cumulative effects between processes are often missing when in fact the hydrological recovery is occurring on a watershed scale. In this study, we demonstrate how runoff generation can be synchronized or de-synchronized by physical characteristics of the watershed, such as elevation range and aspect distribution and/or the treatment itself. How differential vegetation regrowth rate at lower and upper elevations might influence hydrological recovery through altering such synchronization/de-synchronization process is still an open question. For the above spatial, temporal, and process complex interactions, it is the opinion of the author of this thesis that the experimental design of watershed-scaled hydrological recovery needs to be understood under a frequency-based nonstationary framework [*Green and Alila*, 2012] and that stochastic methods developed in other disciplines, such as climate science and analytical finance, could potentially free hydrologists from the linear up-scaling of processes.

5.7 Synthesis of Hydrological Thinking

No doubt that some observations and findings in this study may not be freely transferable to other watersheds or regions due to different hydroclimate conditions. It is the thought process and hydrological thinking that need to be emphasized. Perhaps forest hydrologists knew the system cannot be understood just based on the stand level scale but upscaling using watershed scale simulation models, until recently, was not part of their tool box for investigating forest hydrology. In addition, most experimental designs are often constrained to one level of processes and one study site at a time, due to feasibility issues. The cross-scale thinking therefore should have been a priority for professionals in the field of hydrology and yet it has been largely missing in previous literatures published under the topic of forest hydrology [*McDonnell et al.*, 2007]. Perhaps because hydrologists do recognize the problem of scaling issues and this is why efforts and funding are being swiftly funnelled into computational and modelling works in hydrology, especially in the field of complex and parameter-driven deterministic modelling [*Burt and McDonnell*, 2015]. Deterministic modelling on one hand allows scientists to scale up or down processes easily, at least in theory, but it is also known to perform poorly when simulating or predicting extreme phenomenon due to the inherent nature of process approximation. Although stochastic methods are wonderful at displaying extreme phenomenon, they heavily rely on historical information and it is difficult to extrapolate beyond observations (for example, how system will response to unprecedented disturbance). Therefore, we strongly agree with the idea that the best practice of hydrology should be about bridging the gap between scales and the gap between deterministic thinking and stochastic thinking (e.g. *Klemeš* [1986] and the closing statement of *Yevjevich* [1974, p.238]:

> *"There seems to be no real meaning in sharpening controversies between the deterministic and probabilistic approaches to investigation of time-space hydrologic processes, because in most cases the realistic, combined deterministic-stochastic approach gives the most rewarding results, leading to reliable understanding and descriptions of input, state, and output processes of natural, man-made, or combined natural and man-made water resources systems.")*

In this thesis, we demonstrated how we cross the two realms of thinking with deterministic processes at the stand level and stochastic analysis of extreme events at the larger watershed scale (Figure 8) through a hypothesized framework of synchronization/de-synchronization in the peakflow runoff generation process. It is never the intention of this thesis to favour either deterministic or stochastic physical understanding, as put forward in the Introduction chapter. The emphasis of introducing a stochastic framework into the understanding of forests and peakflows is solely driven by the fact that, in order to isolate the effects of harvesting practices, too many interacting hydroclimatic conditions need to be simultaneously controlled which can only be done through the proxy of equal frequency.

Chapter 6: Extended Discussion on CP versus FP Physical Understanding

Jones [2000] analyzed ten pairs of treatment-control watersheds and proposed a conceptual model based on the relative importance of water balance components to explain and predict the effects of harvesting in ROS environment. This study uses nine out of the ten pairs of selected watersheds in *Jones* [2000] (due to one pair's post-treatment length being too short for frequency analysis) and the same peak selection procedures were applied to the discharge data. The most critical difference between this study and *Jones* [2000] is in the pairing of peakflows between treatment and control watersheds. This study uses Frequency Pairing (FP) instead of the Chronological Pairing (CP) in *Jones* [2000]. In *Jones* [2000], the treatment effect between the chronologically paired peakflows was assessed based on whether the means of Qp were significantly different. Such ANOVA test was applied to different compositions of observations: 1) all selected Qp observations, 2) subset of only small Qp of Fall season, 3) subset of only small Qp of Spring season, and 4) subset of only larger events (defined as control Qp > 1-year). In the Background section of this thesis, it was mentioned that such sub-setting of observations based on the magnitude of Qp in the control watershed leads to a logical fallacy of decomposition. Understanding this statement requires a thorough understanding of the uncontrolled nature of CP experimental design which was discussed in length in the Introduction section of this thesis (refer to the thought experiment in section 1.2).

Between this study and *Jones* [2000], the only possible direct quantitative comparison of research outcomes is through the analysis of treatment effects on the mean of all selected Qp. This comparison yielded comparable conclusions: 1) increase in the mean of Qp is larger in Coyote Creek compared to H.J. Andrews and Fox Creek given similar treatments and 2) within each study site, increase in the mean of Qp seems to increase with higher logging rate between watershed pairs.

The rest of *Jones* [2000]'s analysis is incomparable to the analysis of this study since her analysis is CP based and the ANOVA test concerns only the mean of Qp. *Jones* [2000]'s analysis does not reveal, or make any attempt to physically explain, changes in the variability of Qp. By log transforming the peakflows to meet the fundamental assumption of homoscedasticity of ANOVA, *Jones* [2000] further suppressed the variability of Qp which is particularly important for the understanding of extreme Qp. In this study, the interpretation of harvesting effects under a FP framework, changing variability around the mean of Qp are considered as important as changing mean of Qp if not more important. This is because, borrowed from the climate change and ecology research communities, extreme events are known to be more sensitive to changing variability [*Katz and Brown*, 1992; *Gaines and Denny*, 1993; *Katz*, 1993; *Katz et al.*, 2005]. More importantly, many problems in forest hydrology concern the extremes of a hydrologic response variable (e.g. peakflows, lowflows, landslides, etc.). Those extremes cannot be adequately evaluated by the standard statistics of means and variances in isolation and outside of the frequency distribution framework; hence the need for statistics of extremes or extreme value theory [*Gaines and Denny*, 1993].

Nonetheless, between this study and *Jones* [2000], there are many overlapping discussions on issues such as harvesting effects on ROS snowmelt, fog interception, and how large Qp is affected differently compared to other Qp. In what follows, we offer comparisons **on the understanding of physical process** between this study and *Jones* [2000] in order to illustrate how effects of harvesting on peakflows can only be advanced in a stochastic framework.

6.1 Harvesting Effects on Peakflow Through Changing Snow Dynamics

On the issue of ROS runoff and the role of forest canopy, *Jones* [2000, section 5.2] reiterated two deterministic physical process understanding that were originally proposed by R.D. Harr [*Harr and McCorison*, 1979; *Harr*, 1986]. In one scenario, "[i]f *forest canopy removal increases snowpacks and snowmelt in these gaps is synchronized with the peak precipitation, forest canopy removal may increase peak discharges*" [*Jones*, 2000, p.2636]. The "synchronization" in the context of *Jones* [2000] refers to whether peak-melting coincides with peak-precipitation and has no connection to the spatial and temporal aggregation (the "synchronization/de-synchronization") framework proposed in this study. This hypothesis of peak-melting coinciding with peak-precipitation of *Jones* [2000] was established based on the **stand-level** mass and energy balance understanding of how snowmelt is faster in the absence of forest canopy during ROS events due to higher energy exchange. For simplicity, this first scenario will be referred to as the "coincide-timing scenario". In a second scenario, a similar but different explanation on how a thicker snowpack following harvesting requires more melting energy is used to explain how forest canopy removal can, contrarily, reduce the peakflow as *Jones* [2000, p.2636] stated "*increases in snowpack depth without synchronized melting might not affect peak discharges, and precipitation absorbed by the snowpack along with delayed melting could even decrease peak discharges*." This second scenario will be referred to as the "time-lag scenario".

In this study, we have demonstrated that the difficulty of understanding the physics is confounded by two problems. First, the two quotes from *Jones* [2000] mentioned above considered the entire watershed as a homogeneous entity (when in fact those mass and energy balance understanding were drawn from stand-level experiments). In Section 5.1 of this study, it was demonstrated that, pre-event snowpack conditions vary significantly with elevation and therefore the snowpack response to event-precipitation is heterogeneous across different elevation bands (see the discussion related to the concept of "activation period" (of the snowpack) which was originally reported by *Garvelmann et al.* [2015]). The two stand-level scenarios could very likely co-exist in a single ROS event but at different locations of the watershed. For example, the "coincide-timing scenario" might be dominating at lower elevation bands but "time-lag scenario" is dominating at higher elevation bands. Other than elevation, how these two scenarios are distributed across the watershed would depend on many different physiographic and climatic conditions (for example, slope aspect and event wind direction). This is directly related to the review in the Introduction section 1.1 of this study about how stand level processes are often inappropriately extrapolated to watershed level response without considering the spatial scaling of processes.

If recall, following the Introduction section 1.1, the subsequent section 1.2 pointed out the pairing design of CP failed to isolate the treatment effects due to a lack of consideration of probability. Here, the two scenarios from *Jones* [2000] mentioned above provided the perfect example for demonstration. For a moment, assume there is no spatial scaling issue and the entire watershed's snowpack respond simultaneously and arrive at the outlet at the same time (like a single stand). The two scenarios of how snowpack affects Qp, namely 1) timing of snowmelt coincides with precipitation producing larger Qp or 2) timing of snowmelt lags behind precipitation producing smaller Qp, can both be observed over multiple ROS events regardless of the presence or lack of tree removal [*Harr*, 1986; *Harr and Coffin*, 1992]. Therefore, tree removal does not **cause** either of these two scenarios as how *Jones* [2000] has articulated. By changing the snow dynamics, tree removal however does change the probability of occurrence of these two scenarios (for example, probability of coincide-timing scenario increases while the probability of time-lag scenario decreases following harvesting, or vice versa). Recall the quote mentioned in the Background section regarding R.D. Harr who was thinking exactly along the same line:

> *"Although it seems clear that the combination of greater accumulation of snow and energy inputs to snow packs in clear-cut areas can cause greater rates of water input to soil, we need to know **how often** this situation occurs." [Berris and Harr, 1987, p.141, boldface added for emphasis].*

Such intuitive stochastic understanding serves to emphasize that, even at the stand-level, sometimes the physics must be understood through a stochastic framework. Without the element of frequency in the tool box, *Jones* [2000] hypothesized the harvesting effects on snow dynamics as either one of these two scenarios when trying to establish a causal relationship between forest canopy and the magnitude of Qp. Such causal relationship cannot be established because the intermediate process of snowmelt and precipitation timing which links forest canopy effects to the magnitude of Qp is stochastic and cannot be understood without invoking the dimension of frequency.

Understanding the two problems mentioned above, one would understand why *Jones* [2000] remained vague on the discussion of physical understanding related to how forest canopy removal affects the snowpack mass and energy balance:

> *"…when old-growth conifer forests in the Pacific Northwest were removed, the snowpack dynamics effect produced moderate increase in peak discharges of rain-on-snow events. **However, the snowpack dynamics effect varied according to the susceptibility to melting of the snowpack and the relative volumes of the***

> ***snowmelt, the precipitation event, and the soil moisture reservoir.****"* [*Jones*, 2000, p.2636, bolded text for emphasis of ambiguity]

Although vague on the discussion of physics, *Jones* [2000, p.2636] did mention several peakflow forming hydro-meteorological conditions, namely the "*melting of the snowpack and the relative volumes of the snowmelt, the precipitation event, and the soil moisture reservoir*". Recall that in the Introduction section of this thesis, it has been mentioned that, using rain dominated environment as thought experiment example, the same magnitude of Qp can be produced by many different combinations of hydro-meteorological conditions. Conversely, the same precipitation event can produce varying magnitudes of Qp depends on other hydro-meteorological conditions. Each combination of hydro-meteorological conditions has its own probability of occurrence (for example, the probability of a combination of an extremely large precipitation occurring on an extremely large isothermal snowpack sitting on a saturated soil is much smaller than the probability of a combination of a medium size precipitation occurring on a thin snowpack with saturated soil). The effects of harvesting can easily be understood as how the probability of occurrence of each one of these combinations of hydro-meteorological conditions have changed and therefore the consequential change of Qp magnitude given a specific probability of occurrence. We therefore agree with *Jones* [2000, p.2636] that the afore-mentioned hydro-meteorological conditions are critical to the generation of peakflow in ROS environment. However, *Jones* [2000] was not able to further diagnose the influences of harvesting on peakflow because *Jones* [2000] was working outside of a stochastic framework. Without invoking the dimension of frequency to control all hydro-meteorological conditions simultaneously, the deterministic process thinking would require anyone to consider the simultaneous influences of all those hydro-meteorological conditions in a time-varying high dimensional space, which can easily overwhelm even the smartest scientist if it is not entirely impossible.

Perhaps more critically important than just being equivocal on the discussion of physics, *Jones* [2000] seems to have concluded that the harvesting effects have caused the "coincide-timing scenario": *"[t]his result indicates, …, that snowpack volume, or at least the amount of snowmelt coinciding with the peak discharge, was increased after forest canopy removal*" [*Jones*, 2000, p.2637]. If the conclusions of the two scenarios are contradicting, in terms of whether peakflows have been increased or decreased by forest canopy removal, does it mean *Jones* [2000, p.2637] accepting the "coincide-timing scenario" should logically lead to the invalidation of the other "time-lag scenario" for the effects of harvesting? If it is the case, the physical understanding (harvesting leads to timing of peak-precipitation coincides with peak-snowmelt) advocated by *Jones* [2000] could be misleading future research direction since harvesting does not cause either of the two scenarios but merely changing the probability of occurrences. At the root of the problem, this statement of *Jones* [2000, p.2637] illustrates that the deterministic and reductionist (one event at a time) approach and the use of chronological pairing method (CP) not only lead to an incomplete but also untestable physical understanding of how forest harvesting affects stand-level snowpack dynamics and consequently the peakflows at the outlet of a watershed. Hence, it is for this reason, *Alila and Green* [2014a, p.2760] concluded "*throwing out the baby (CP) with the bathwater (CP-based study outcomes)*" is the only way moving forward. Without throwing both the baby and the bathwater, the forest hydrology community risks the danger of testing untestable hypotheses and letting personal or institutional bias to influence the interpretation of research outcomes stemming from an uncontrolled experimental design.

6.2 Fog Interception: Deterministic versus Stochastic Understanding

The same fog interception mechanism being explained differently between CP-deterministic framework and FP-stochastic framework provides another rather interesting comparison of physical processes understanding. From a stand-level water balance perspective, it has been hypothesized that the fog interception mechanism counteracts evapotranspiration (ET). In *Jones* [2000, p.2635], the author stated:

> *"[t]he greater the role of cloud water interception in the water balance prior to canopy removal, the greater is the reduction in moisture inputs after forest removal, offsetting the evapotranspiration effect. ... small, fall peak discharge events did not increase significantly after 25% patch cutting…"*

The stochastic physics on fog interception mechanism in this study on the other hand explains its effect is in the lowering of variability around the mean of peakflow. The important revelation of a lowered variability around the mean lies in how the return period of some larger Qp is reduced extraordinarily after harvesting. Such observation of how fog interception influences the effects of harvesting on changing the frequency of Qp can only be acquired through FP framework and not CP framework since CP does not invoke the dimension of frequency. It is important to emphasize that frequency is invoked in the analysis of harvesting effects because a hypothesis testing regarding whether harvesting has change the magnitude of Qp need to be conducted through comparing treatment-Qp and control-Qp with equal frequency. Without controlling the frequency, the same magnitude of Qp can be produced by many different combinations of hydro-meteorological conditions (as discussed in the previous section). Therefore, although the assessment of changing return period stemming from conducting frequency analysis provides insightful physical understanding, it is not the reason for invoking frequency in the experimental design. Nonetheless, the comparison between CP and FP physics regarding the fog interception mechanism, as well as the observation of how the frequency of large Qp has increased dramatically in Fox Creek, illustrated how harvesting effects on extreme events cannot be fully understood outside of a frequency distribution framework.

6.3 Deterministic "Sponge Theory" of CP Studies

Related to the above discussion about the CP analysis of *Jones* [2000] being uncontrolled in nature and does not reveal the important changes in the frequency of large Qp, a summary quote in *Jones* [2000, p.2638] demonstrates that the deterministic and reductionist approach of CP analysis is a direct descendant of the prevailing wisdom of "sponge theory":

> *"Although small sample size precluded statistical tests of rain-on-snow events by event size, percent increases of large rain-on-snow events appeared to be smaller than for rain-on-snow events of all sizes in the three 100%-clear-cut basins in the Andrews basins. If so, this indicates that the influences of snowmelt and changes in snowpack dynamics decline with increasing size of peak discharge event, as precipitation inputs and stored soil moisture increase."*

First, the interpretation of smaller "*percent increases***"** of large events as indication of smaller influences of snowmelt is not physically meaningful. This is in part because (i) percentage change tends to decline rapidly with increasing magnitude of Qp regardless of the absolute change, and (ii) "*smaller increases*" when expressed in relative terms do not necessarily translate to larger Qp being affected less by harvesting in magnitude and certainly not in frequency, as illustrated in this study with several control-treatment pairs. Therefore, it should be reiterated that in any investigation of the effects of harvesting on peakflows the only relevant measures of such effects are: (1) change in magnitude for an event of a frequency of interest, and most importantly (2) a change in frequency for an event of a magnitude of interest; and this evaluation can only be done through direct comparison, in absolute and not in relative terms, of the frequency distributions of pre- and post-harvest peakflows.

The second half of the above *Jones* [2000] quote is a more literal re-interpretation of the "sponge theory", in which the effects of forest cover declines with increasing peakflow magnitude. In the beginning of the Background section of this thesis, two similar "sponge" quotes were provided from studies in rain-dominated [*DeWalle*, 2003, p.1255] and snow-dominated environment [*Macdonald and Stednick*, 2003, p.13]. This quote of *Jones* [2000, p.2638] in Rain-on-Snow environment shows such deterministic and reductionist thinking of sponge theory is universal and not necessarily confined to the storage capacity of forest soil. The FP analysis in this thesis has demonstrated that the harvesting effects on Qp magnitude can only be properly isolated through controlling the frequency of Qp. By pairing treatment-Qp and control-Qp by equal storm input, the comparison of magnitude cannot properly isolate the harvesting effects due to the uncontrolled hydro-meteorological conditions in each pairs of comparison. Therefore, even when ignoring the misleading percent changes of Qp, whether *Jones* [2000] finds a statistically significant increase in the mean magnitude of large-Qp subset after harvesting is irrelevant to whether large Qp is affected by harvesting. More importantly, such investigation on the mean of extreme events provided little advancement on the understanding of physical process regarding the effects of harvesting practices and only served to reinforce a century old deterministic "sponge theory".

In summary, this extended discussion section compared the hydrological physics between the deterministic CP framework and the stochastic FP framework. Although *Jones* [2000] and this thesis analyzed almost identical datasets, the conclusions and physical understanding are rather different and in most cases diametrically opposite (for example, on how large Qp is affected by harvesting). If CP and FP analysis yielded contradicting conclusions, accepting one must lead to the rejection of the other. Therefore, accepting the FP stochastic physical understanding and its conclusions on the harvesting effects, in terms of sequence of writing, must come after explanations of why CP and its conclusions are flawed. Without explaining the difference in understanding beforehand, since CP physics and conclusions are part of the established paradigm of forest hydrology, writing of the Result and Discussion sections of this thesis outlining research outcomes under a new FP paradigm would have been perceived as "agree to disagree". In what follows in the Conclusion chapter, through discussing a series of quotes from research concerning the philosophy of science, it will be explained why such attitude of "agree to disagree" does not serve the best interest of science and professional practice.

Chapter 7: Conclusion

In *Harr* [1981, p.302], the forest hydrology community was being reminded that *"[a]t this point, we have little chance of predicting whether or not increased melt would increase channel erosion without knowing more about snowmelt during rainfall, how it might be affected by timber harvest, and how physiographic characteristics interact."* Almost four decades later, not only ROS is still being viewed as mysterious and "folklore" [*Kattelmann*, 1997], the understanding of the environmental control of watershed hydrologic response to harvesting practices have also not advanced much since the golden age of stand level experiments [*Burt and McDonnell*, 2015]. In order to draw confident predictions on the response of peakflow generation to harvesting practices, this study reviewed and addressed two of the most fundamental problems that have been impeding the progress of understanding and prediction of forests effects on peakflows: upscaling challenges and the deterministic approach to pairing that striped hydrology from its stochastic nature. Findings from the multi-site peakflow frequency analysis not only offer new insights into the relationship of forests and peakflows, they also effectively renounce the old hydrological thinking of the 'sponge' forest theory.

From the nine pairs of small headwater watersheds, the predicted effects of harvesting and road network on peakflows in ROS environments appear to be more pronounced but remarkably more predictable than portrayed in previously published literatures on this topic. The most critical question related to this topic is whether infrequent peakflows of return periods larger than 10 years can be affected by harvesting practices. The age-old conventional wisdom in forests and floods literature suggested, due to the finite watershed storage capacity ("the sponge") being overwhelmed, forest cover exerted a limited role in controlling the magnitude of large peakflow events. The conventional wisdom always reasoned around event magnitude and not frequency (recall frequency dimension cannot be invoked in CP-based mode of thinking), but since the forest cover was not meant to affect the magnitude of larger peakflows it is presumed that their frequency would also not be affected. Obviously, floods cannot become less (more) frequent unless they increase (reduce) in magnitude. Conclusions drawn from the observations in this study challenge this conventional wisdom by demonstrating that large peakflows can be affected, and in most cases rather substantially. Depending on the environmental controls, the logging effects on large peakflows can be small, such as in the case of HJA1 and HJA3 but it can also be large, such as in the case of HJA6, watersheds in Coyote Creek, and watersheds in Fox Creek. In two of the Coyote Creek watersheds, as revealed by the large increase in the mean and variability around the mean of the peakflow frequency distribution, the harvesting effects on the magnitude of peakflows appear to increase unchecked with increasing peakflow size. Such prediction on the effects of forest cover on large peakflow events is therefore diametrically opposite to the diminishing effects of forest cover proposed in the "sponge theory." Related but previously unrecognized in ROS environment, this FP analysis also reveals surprisingly dramatic increases in the frequency of large peakflows, where the larger the peakflow event the more frequent it may become. In summary, not only large peakflows are increased in magnitude and frequency, they can increase in magnitude and frequency more so than the smaller and medium peakflows under the effects of harvesting practices.

This study demonstrated that the response of larger peakflows to harvesting practices can be linked to the physiographic characteristics and climatic conditions, which control the spatial and temporal variability of runoff generation and routing. Watersheds with large elevation ranges, large aspect distribution, and elongated shape of drainage network are thought to experience a de-synchronization of runoff generation across the watershed landscape and, therefore, are less likely to produce large and flashy peakflow responses. For the de-synchronization induced by elevation range, due to snow accumulation and ROS melt responding differently to logging at different elevation bands, logging could further de-synchronize the peakflow generation. The additional de-synchronization effect due to harvesting is therefore hypothesized to mitigate some of the increasing effects of logging on the mean and variability around the mean of the peakflow frequency distribution. Such hypothesis on the physics of synchronization / de-synchronization can simultaneously explain the appearance of large peakflow response to harvesting practices in subdued watersheds (such as HJA6 and those in Coyote Creek and Fox Creek) and the appearance of small peakflow response in steep watersheds (such as HJA1, HJA3, and HJA10). It is important to point out that the elegance of this synchronization / de-synchronization framework on the peakflow generation lies in its simplicity ("it makes sense!").

To the readers who are interested in the thought processes of scientific inquiry that have led to what one might consider as breakthroughs related to the stochastic physics of forest harvesting and larger peakflows, the unifying synchronization / de-synchronization framework in ROS environment was inspired from a similar but original framework of de-synchronized melting on the sensitivity of the peakflow regime to harvesting practices in the snow environment proposed by *Green and Alila* [2012], and from the hypothesis of de-synchronized peakflow at a confluence of two creeks proposed in *Harr* [1981, p.302]. Since peakflow generation in both continental snow and maritime ROS environments are tied to the energy balance of the snowpack, our guiding principle has been if the magnitude of the freshet hydrographic response at the outlet of a watershed in snow environment is attenuated due to de-synchronized melting across elevations, there should be a similar hypothesis for the ROS events, especially when ROS as a mechanism is even more sensitive to elevation range.

Another intriguing physical understanding drawn from this FP-based study is how the fog interception mechanism is perceived in regulating peakflows of a watershed. It has always been deterministically argued that since tree removal suppresses fog interception, logging in humid environments such as Fox Creek is supposed to mitigate any potential increase in the magnitude of peakflow as a result of suppressed evapotranspiration. The stochastic physics related to fog interception proposed in this thesis, however, perceives fog interception as a mechanism that reduces the natural peakflow variability around the mean of the peakflow frequency distribution by 1) compensating soil moisture deficit during early period of the wet season and 2) preventing the development of snowpack underneath the forest canopy through dripped water introducing extra melting energy. Such intriguing phenomenon makes the peakflow regime of watersheds in this kind of environment one of the most sensitive to forest harvesting practices, especially for the larger peakflow events. Some of the largest increases in the frequency of larger peakflows occurred in Fox Creek treatment watersheds. This occurs as a consequence of the surprisingly large increase in the variability around the mean of the peakflow frequency distribution following logging, which was explained by the removal of such variability-suppressing fog interception mechanism. This new stochastic physics of fog interception, together with the de-synchronization hypothesis on the control of the mean and variability around the mean of the peakflow frequency distribution, could be viewed as good examples of the so called "outrageous hypotheses" and how scientists in the hydrology community must "*seek new fundamental understanding, new mechanistic explanations…to challenge existing ideas and process complacency, and to confront old theories with new data*" [*Burt and McDonnell*, 2015, p.5919, 5921]. Since in the case of this study the old theories were confronted with only old data, in our opinion it is our distinctive approach to scientific research, referred to by John R. Platt as "Strong Inference", which led to our "outrageous hypotheses" and our challenging of the age-old hydrologic wisdom. In an inspirational paper published in *Science* and entitled "*Strong Inference*" *Platt* [1964, p.347, 351] stated:

> *"Why should there be such rapid advances in some fields and not in others? I think the usual explanations that we tend to think of – such as the tractability of the subject, or the quality or education of the men drawn into it, or the size of research contracts – are important but inadequate. I have begun to believe that the primary factor in scientific advance is an intellectual one. These rapidly moving fields where a particular method of doing scientific research is systematically used and taught, an accumulative method of inductive inference that is so effective that I think it should be given the name of "strong inference." …To paraphrase an old saying, Beware of the man of one method or one instrument, either experimental or theoretical. He tends to become method-oriented rather than problem-oriented. The method-oriented-man is shackled; the problem-oriented man is at least reaching freely towards most important. Strong inference redirects to problem-orientation, but it requires to be willing repeatedly to put aside his last methods and teach himself new ones."*

The strength of this study at hand comes from three major factors that are in fact inter-related. First, the treatment effects are properly isolated through pairing the peakflows by equal frequency. The isolation of the treatment effects allows for the analysis of the environmental controls on peakflow generation and their interactions with the treatment effects. Second, the wide range of watershed characteristics in the nine pairs of studies, especially the difference in elevation range, were key to discovering the linkage between sensitivity to harvesting practices and elevation control. Lastly, and perhaps a hypothesis most proud of by the author of this thesis, the proposal of a simple but elegant synchronization/de-synchronization mechanism to scale up stand level runoff production to watershed level response (spatial aggregation processes). The presence of (or lack thereof) de-synchronization is sufficient to relate and explain how each of the forest management practices, might affect the processes of the peakflow generation using pieces of the deterministic physical process understanding from past studies. This analysis along with *Green and Alila* [2012] illustrated how sound physical understanding can only deepen and widen if the treatment effects were properly isolated in the first place.

Based on a deterministic physics of "sponge" theory, forest hydrologists have been for so long attempting to test the hypotheses regarding the effects of harvesting on large floods using CP-based experimental design. Two hypotheses of this study (hypothesis number 5 regarding larger Qp is affected and hypothesis number 6 regarding the non-existence of the no-effect threshold) were supported by the evidence from the analysis of the nine pairs of watersheds in this study. Recall the "sponge" theory intrinsically imposes a "no-effect" threshold requirement and larger peakflow must be affected less due to diminishing role of the sponge in peakflow. Following the logic of "[i]f you have a hypothesis and I have another hypothesis, evidently one of them must be eliminated" [*Platt*, 1964, p. 350], together the two hypotheses of this study are disarming the foundational "sponge" theory of CP framework. Through discussion of the missing element of changing frequency following harvesting, this study along with other FP-based studies (*Alila et al* [2009], *Green and Alila* [2012], and *Alila and Green* [2014a, 2014b]), reiterate that CP leads to non-testable hypotheses and uncontrolled experimental designs because the foundational physics of the CP framework is not supported. Therefore, CP-based research outcomes are irrelevant to whether forest harvesting practices affect peakflows of any size, let alone the larger events. It appears that for so long in forest hydrology we have not been abiding to the single most important touchstone of the method of *Strong Inference*, namely "The Question", as John R. Platt likes to call it. At the risk of boredom, the reader is exposed to yet another quote from *Platt* [1964, p.352] where he state:

> *"Obviously it [The Question] should be applied as much to one's own thinking as to others'. It consists of asking in your own mind, on hearing any scientific explanation of theory put forward, "But sir, what experiment could disprove your hypothesis?"' or on hearing a scientific experiment described, "But sir, what hypothesis does your experiment disprove?"…This goes straight to the heart of the matter. It forces everyone to refocus on the central question of whether there is or there not a testable scientific step forward…if such a question were asked aloud, many a supposedly great scientist would sputter and turn livid and would want to throw the questioner out, as a hostile witness! Such a man is less than he appears, for he is obviously not accustomed to think in terms of alternative hypotheses and crucial experiment for himself; and one might also wonder about the state of science in the field he is in. But who knows? – the question might educate him, and his field too!"*

Alila and co-workers repeatedly called for abandoning CP and the century worth of CP-based study outcomes in archival forest hydrology literature, which continue to unduly influence regulations and land use policy worldwide [*Alila et al.*, 2009; *Bewley et al.*, 2010; *Green and Alila*, 2012; *Alila and Green*, 2014a, 2014b]. To this day, CP-based methods continue to be used in the analysis of old and new data [e.g. *Bathurst et al.*, 2011a, 2011b, 2017; *Birkinshaw et al.*, 2011; *Dung et al.*, 2012; *Kelly et al.*, 2016], and historic CP-based studies and their outcomes continue to be reported business as usual, as if there is nothing wrong with them [e.g. *Jones and Perkins*, 2010; *Seibert and McDonnell*, 2010; *Troendle et al.*, 2010; *Zégre et al.*, 2010; *Zhao et al.*, 2010; *Buttle*, 2011; *Schleppi*, 2011; *Perry et al.*, 2016]. Although it would be naïve to think that misconceptions in archival science can easily or quickly be corrected [*Kiang*, 1995], we must constantly remind ourselves that:

> *"The only ethical principle which has made science possible is that the truth shall be told all the time. If we do not penalize false statements made in error, we open up the way for false statements by intention. And a false statement of fact, made deliberately, is the most serious crime a scientist can commit."* [*Sayers*, 2016]

In closing, the outcomes of this study could find implications in engineering and fluvial ecology. The increase in the flood frequency following treatment can easily be translated into increasing risk posed to existing engineering infrastructures such as stream crossing or levees. Large shifts found in the frequency distribution of peakflows means a different hydrologic regime for sediment and nutrient environments for the aquatic ecosystems. Hydrological recovery in ROS environment is also slow and no significant recovery was detected in the first two decades of post-treatment period. Even after the watershed had subsequently fully recovered in terms of vegetation cover and hydrological functions, the large increase especially in the frequency of small, medium, and large peakflows in the few decades following treatment could be enough to disturb the long-term ecosystem equilibrium and irreversibly alter the channel's form and function [*Schmidt and Potyondy*, 2004].

The interactions between the effects of forest harvesting practices, physiographic characteristics of the watershed, and climatic conditions could be better quantified if a larger sample of unique watersheds with various combinations of conditions is observed. There are other long term paired watershed sites in the U.S. and other parts of the world that could be potentially useful in corroborating or refuting the proposed physical model of synchronization/de-synchronization of ROS runoff generation. On top of understanding processes from small headwater watershed studies, there is an even higher urgency for the understanding of the effects of harvesting and roads in larger watersheds due to greater concerns from the public and stakeholders. We can envision that the spatial and temporal aggregation processes would be even more critical in the physical understanding of runoff generation in larger watersheds but more work needs to be done to relate forest harvesting effects and hydrologic system response. Combining with the forecasted changes in the climate system, the analysis of harvesting and the effect of roads under a nonstationary setting could lead to revolutionary changes in policies concerning the management of the hydrological syste

Tables

Table 1 Watershed characteristics and history of harvesting practices.

Sites	Pair (Treatment - Control)	Treatment		Available Record (Water Year)		Size (km^2)	Elevation (m)		Elevation Range (m)	Aspect (degree)
		Logging (%)	Road (km/km^2)	Pre-treatment period	Post-treatment period		Lower Bound	Upper Bound		
Coyote	CC1-CC4	50	2.2	WY63-70	WY72-81 & WY00-13	0.69	750	1065	315	45-90 NE-E
Coyote	CC2-CC4	30	4.1	WY63-70	WY72-81 & WY00-13	0.68	760	1020	260	45 NE
Coyote	CC3-CC4	100	3.2	WY63-70	WY72-81 & WY00-13	0.50	730	960	230	0-45 N-NE
Fox	FOX1-FOX2	25	2.1	WY58-64	WY70-87	0.59	840	925	85	270 W
Fox	FOX3-FOX2	25	1.3	WY58-64	WY70-87	0.71	840	950	110	315 NW
HJA	HJA1-HJA2	100	0	WY56-61	WY67-14	0.96	439	1027	588	286 W-NW
HJA	HJA3-HJA2	25	2.7	WY56-58	WY64-14	1.01	471	1080	609	313 NW
HJA	HJA6-HJA8	100	4.6	WY63-73	WY75-14	0.13	878	1029	151	165 S-SE
HJA	HJA10-HJA9	100	0	WY68-74	WY76-14	0.10	461	679	218	250 W-SW

Table 2 Relative change in sample statistics with full record length and similar record length comparison.

Sites	Pair (Treatment - Control)	Full available Record Length: Relative Change of Qp Mean (%) With Recovery	Full available Record Length: Relative Change of Qp Mean (%) Recovery Adjusted	Full available Record Length: Relative Change of Qp Variance (%) With Recovery	Full available Record Length: Relative Change of Qp Variance (%) Recovery Adjusted	Full available Record Length: Post-Treatment Record Size (Year)	Similar Cross-site Record Length: Relative Change of Qp Mean (%) With Recovery	Similar Cross-site Record Length: Relative Change of Qp Mean (%) Recovery Adjusted	Similar Cross-site Record Length: Relative Change of Qp Variance (%) With Recovery	Similar Cross-site Record Length: Relative Change of Qp Variance (%) Recovery Adjusted	Similar Cross-site Record Length: Post-Treatment Record Size (Year)
Coyote	CC1-CC4	35.4	50.3	116.2	135.9	22	35.4	50.3	116.2	135.9	22
Coyote	CC2-CC4	23.4	35.4	35.7	52	22	23.4	35.4	35.7	52	22
Coyote	CC3-CC4	55	85.5	121.2	154	22	55	85.5	121.2	154	22
Fox	FOX1-FOX2	19.2	20.9	59.9	82.9	17	19.2	20.9	59.9	82.9	17
Fox	FOX3-FOX2	4.6	4.7	33.8	34	17	4.6	4.7	33.8	34	17
HJA	HJA1-HJA2	30.2	38.7	-10.1	3.3	47	27.6	28.4	-19.4	-18.7	23
HJA	HJA3-HJA2	12.3	12.2	-8.4	-8.5	50	17.5	22.3	-11.6	-4.4	25
HJA	HJA6-HJA8	21.1	35.2	7.2	25.4	39	16.5	16.5	17.1	17.1	22
HJA	HJA10-HJA9	8.9	8.9	7.2	9.3	38	5.2	4.6	-0.5	-7.1	21

Figures

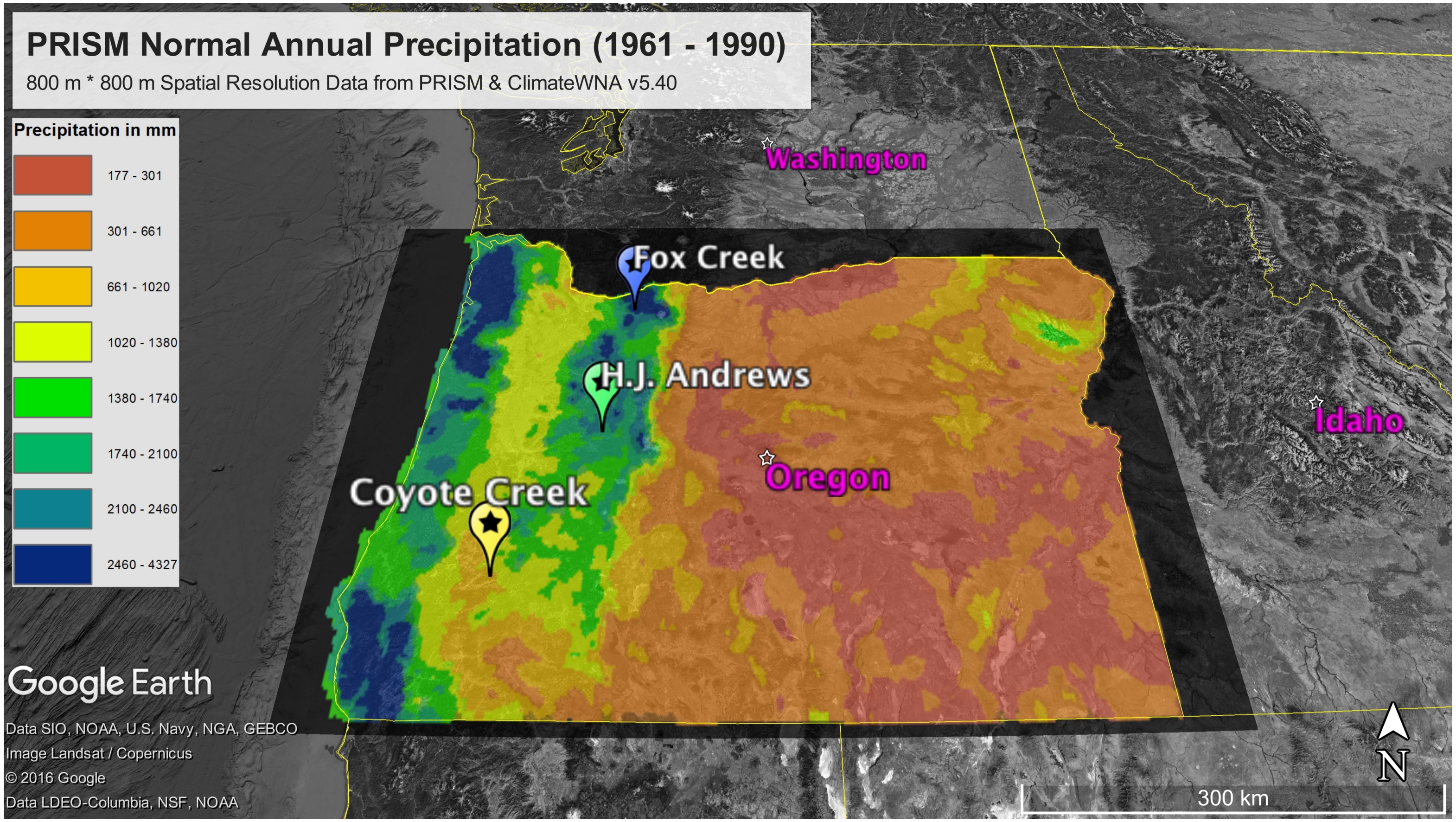


Figure 1 Locations of the three study sites and the distribution of long term average annual precipitation map of the state of Oregon. The three sites presented a smooth gradient of climatic conditions with the Fox Creek being more humid and Coyote Creek being more arid. The data are generated using PRISM long term climate statistics [*PRISM Climate Group*, 2004] **and downscaled by ClimateWNA model** [*Wang et al.*, 2012] **with an assumed 900 m elevation**

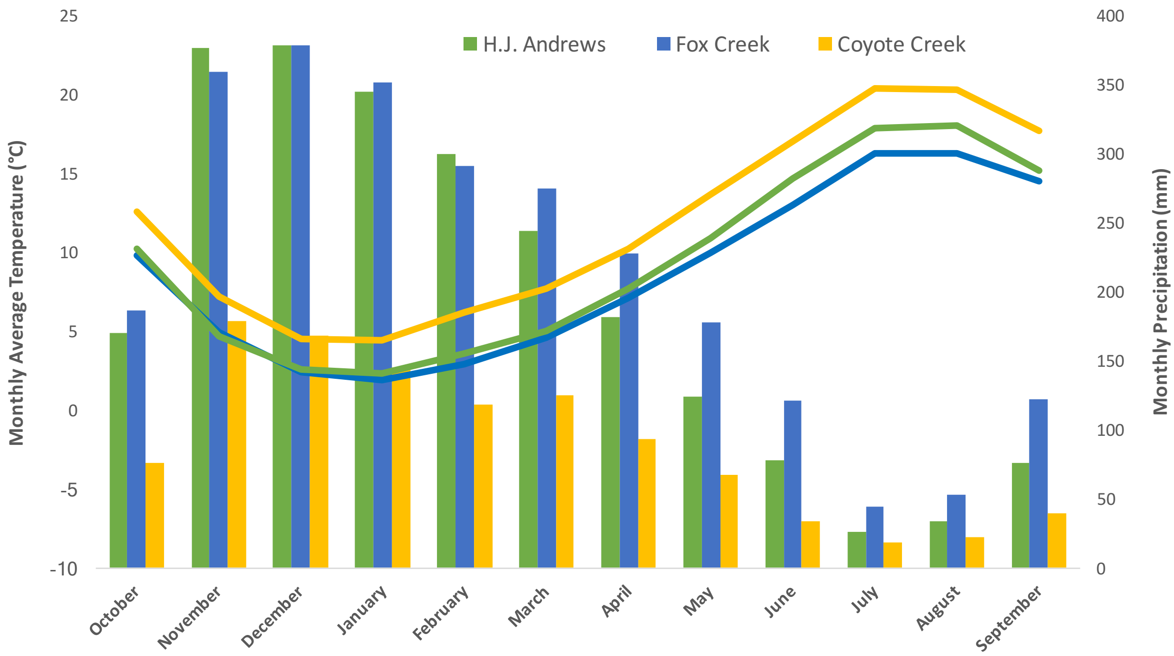
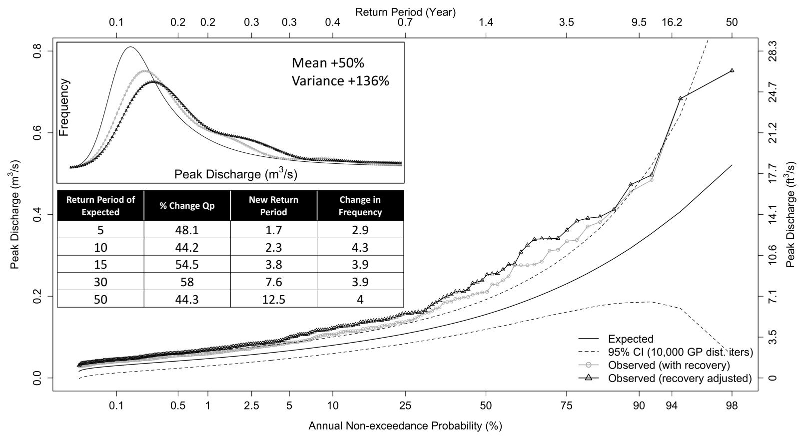
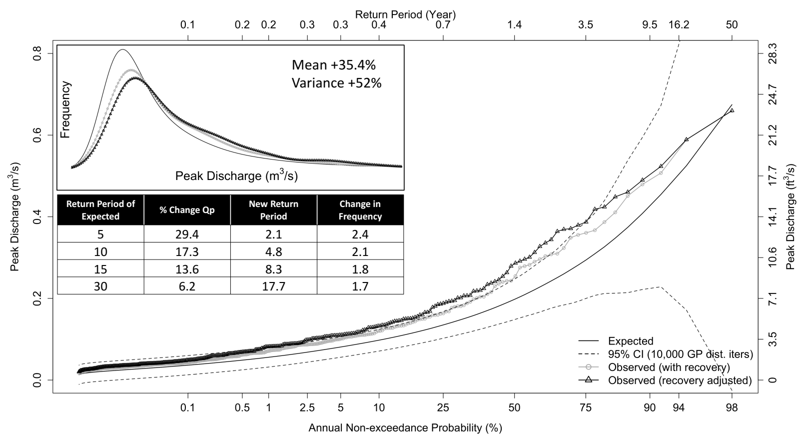


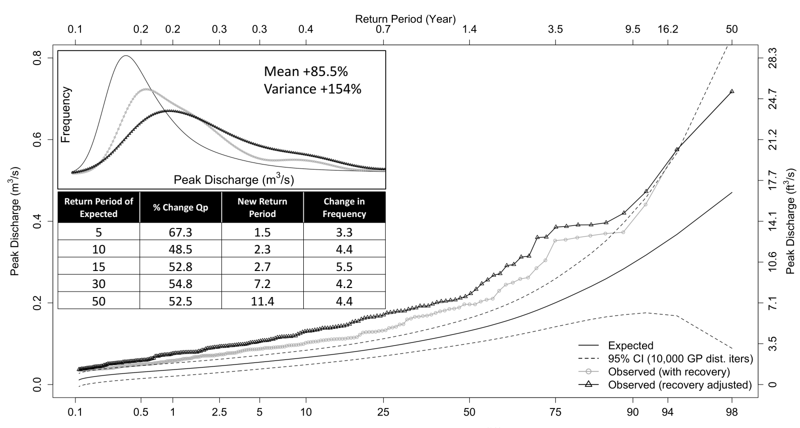
Figure 2 Long term normal climate (1961-1990) of H.J. Andrews (green), Fox Creek (blue) and Coyote Creek (yellow). Average air temperatures (˚C) are shown in solid lines and monthly accumulated precipitations (mm) are shown in bars, both follow the colour scheme of the three sites described above. The data are generated using PRISM long term climate statistics [*PRISM Climate Group*, 2004] **and downscaled by ClimateWNA model** [*Wang et al.*, 2012] **with an assumed 900 m elevation.**



Return Period of Expected	% Change Qp	New Return Period	Change in Frequency
5	48.1	1.7	2.9
10	44.2	2.3	4.3
15	54.5	3.8	3.9
30	58	7.6	3.9
50	44.3	12.5	4



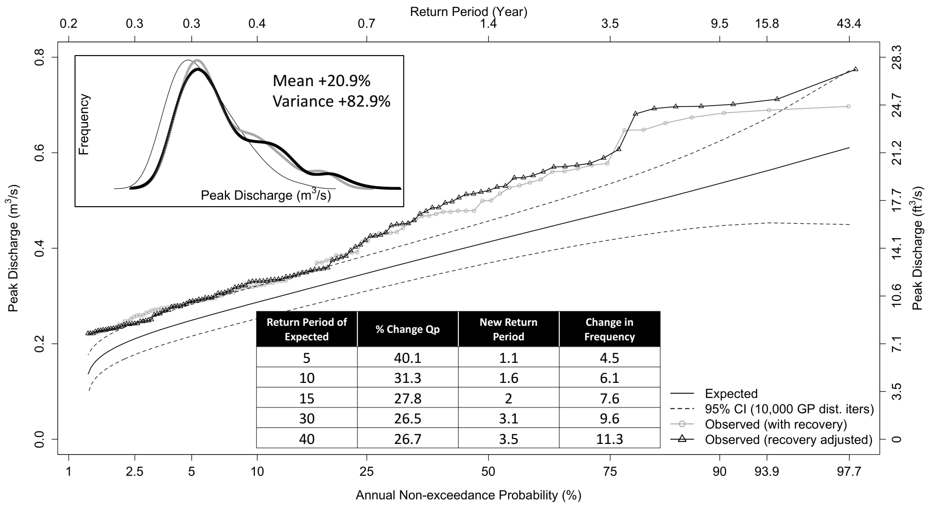
Return Period of Expected	% Change Qp	New Return Period	Change in Frequency
5	29.4	2.1	2.4
10	17.3	4.8	2.1
15	13.6	8.3	1.8
30	6.2	17.7	1.7



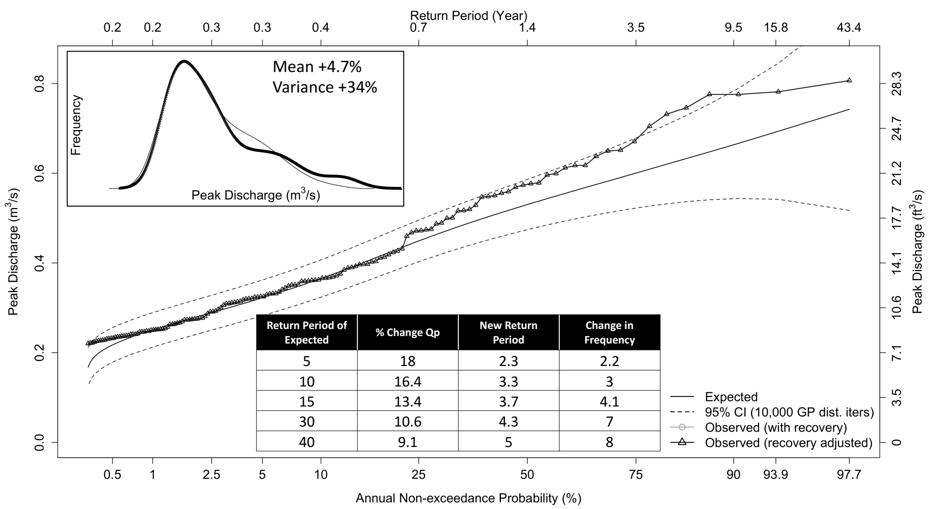
Return Period of Expected	% Change Qp	New Return Period	Change in Frequency
5	67.3	1.5	3.3
10	48.5	2.3	4.4
15	52.8	2.7	5.5
30	54.8	7.2	4.2
50	52.5	11.4	4.4

Figure 3 Cumulative Distribution Function (CDF) of post-treatment peakflows. Top panel: Coyote Creek CC1 (with CC4 as control). Middle panel: Coyote Creek CC2 (with CC4 as control). Bottom panel: Coyote Creek CC3 (with CC4 as control). Inset graphs are the Probability Distribution Function (PDF) of post-treatment

peakflows for the two respective watersheds. The thinner solid lines without any symbol in CDF and PDF graphs represent the expected peakflows, calculated using the calibration function developed with pre-treatment peakflows. The grey lines with circles represent raw observed peakflows in the treatment watersheds and are affected by hydrological nonlinearity caused by the vegetation regrowth after logging. The darker lines with triangles represent observed peakflows with the hydrological recovery effects adjusted. The inset tables show changes in magnitude (% change) and return period of some larger peakflows. The change in frequency is interpreted as, for example, the treatment changed the 50-year event of CC1 into a 13-year event (4 times more frequent).



Return Period of Expected	% Change Qp	New Return Period	Change in Frequency
5	40.1	1.1	4.5
10	31.3	1.6	6.1
15	27.8	2	7.6
30	26.5	3.1	9.6
40	26.7	3.5	11.3



Return Period of Expected	% Change Qp	New Return Period	Change in Frequency
5	18	2.3	2.2
10	16.4	3.3	3
15	13.4	3.7	4.1
30	10.6	4.3	7
40	9.1	5	8

Figure 4 Similar to Figure 3. Cumulative Distribution Function (CDF) of post-treatment peakflows. Top panel: Fox Creek Fox1 (with FOX2 as control). Bottom panel: Fox Creek FOX3 (with FOX2 as control). There is a distinct change of variability between peakflows smaller and larger than the return period of around 4-year (show as changes in the CDF slope) for both FOX1 and FOX3. Increase of peakflow frequency (reduction of return period) increases with peakflow size.

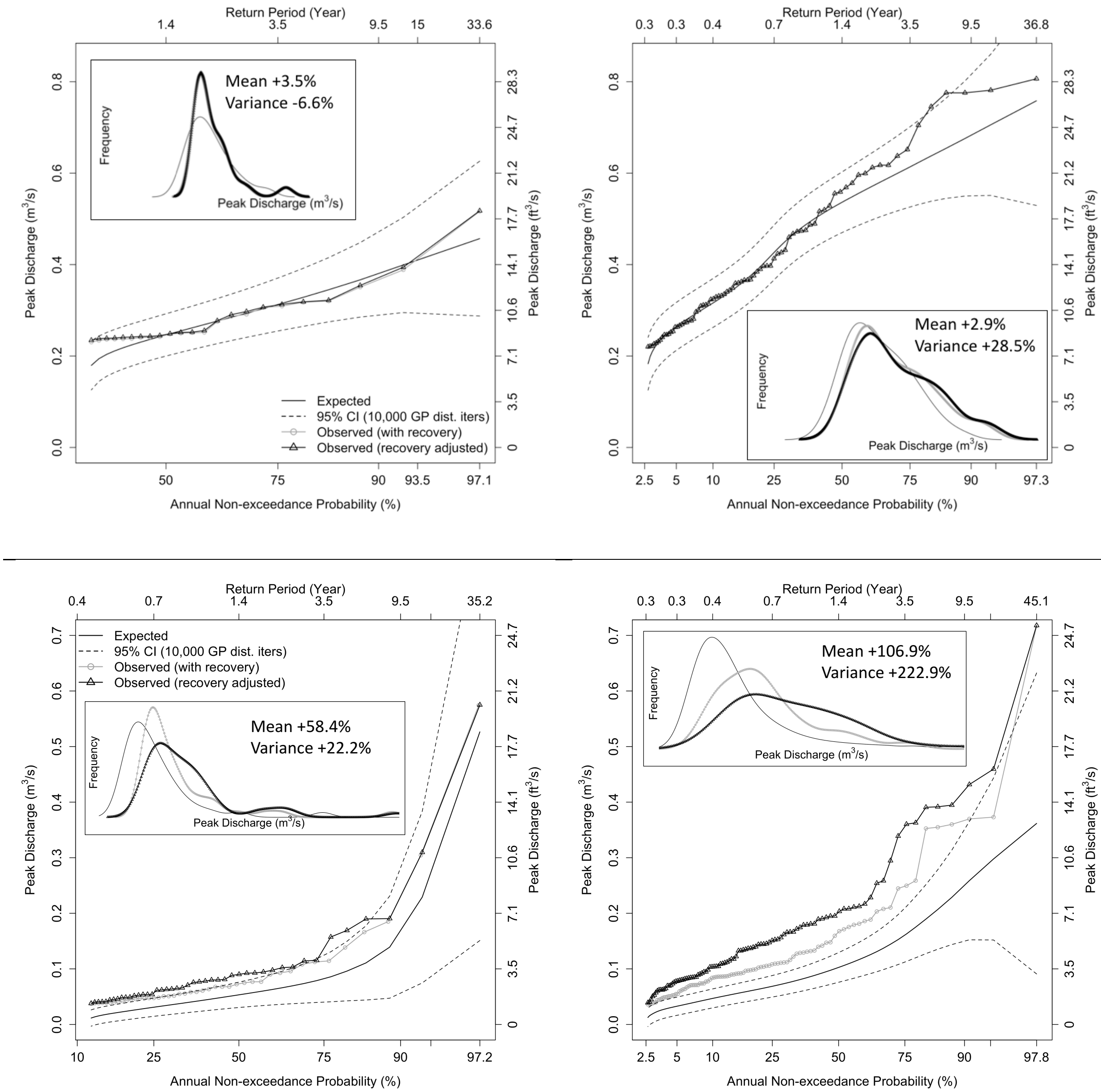
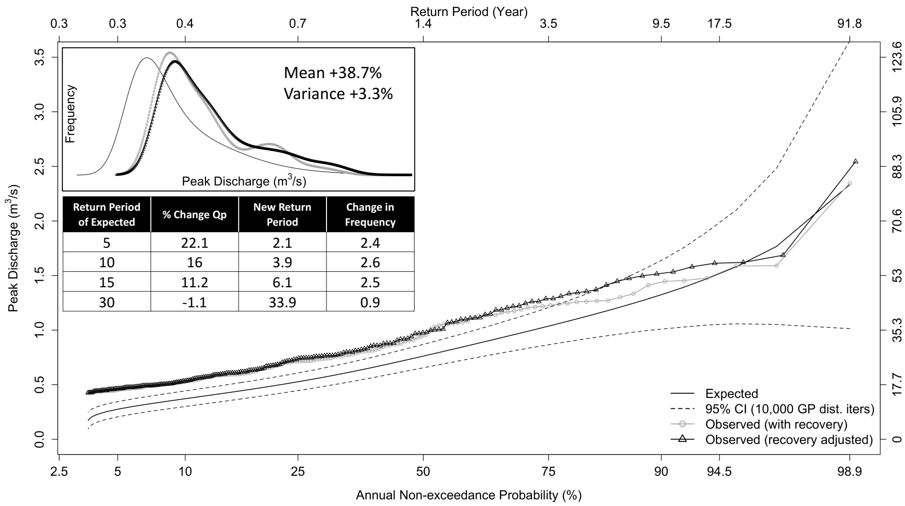
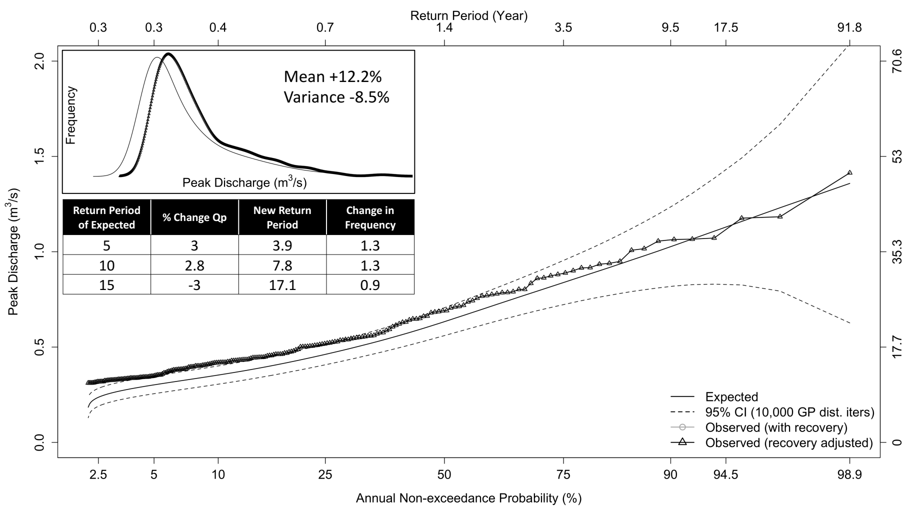


Figure 5 Cumulative Distribution Function (CDF) of post-treatment peakflows with split samples. The samples are split into non-Rain-on-Snow (non-ROS) dominant months of the wet season (September, October, March, April and May, show on the left) and Rain-on-Snow (ROS) dominant months (December and January, show on the right). Top panel: Fox Creek FOX3. Bottom panel: Coyote Creek CC3. The insets show the PDFs and changing sample statistics of the recovery-adjusted peakflows.

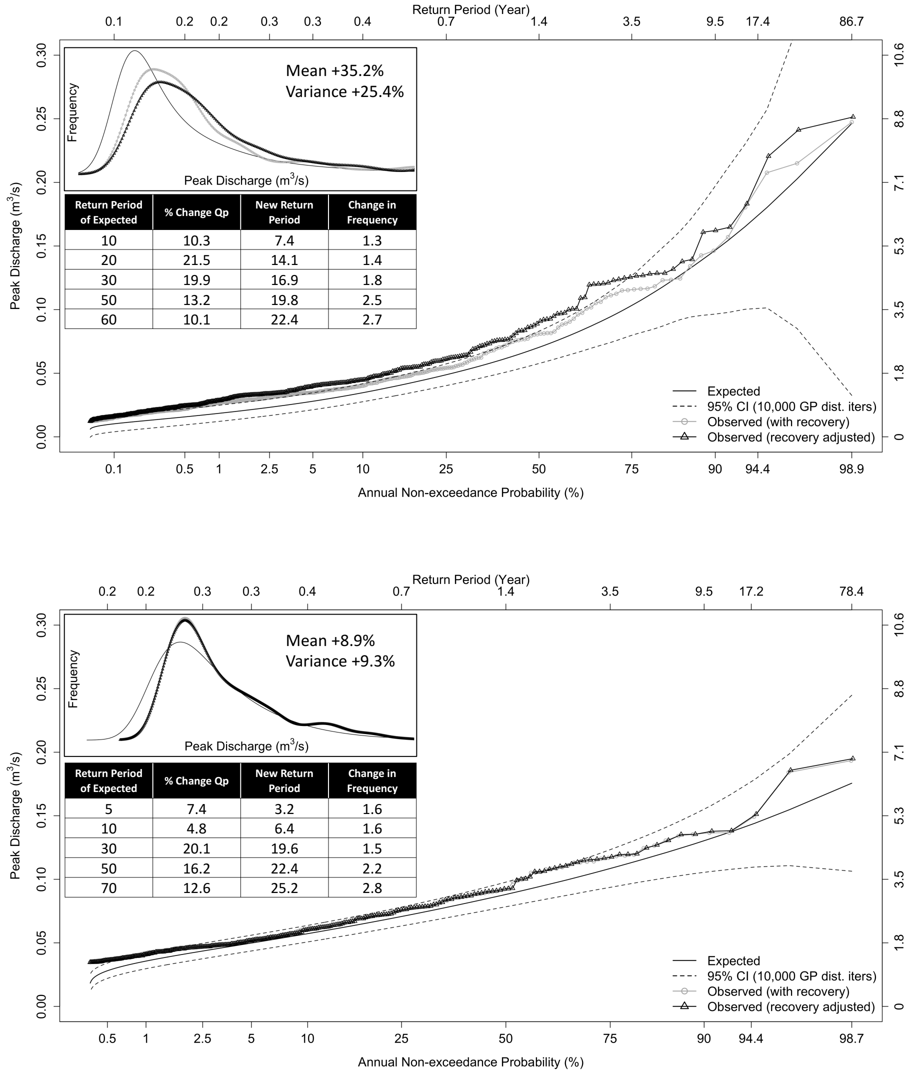


Return Period of Expected	% Change Qp	New Return Period	Change in Frequency
5	22.1	2.1	2.4
10	16	3.9	2.6
15	11.2	6.1	2.5
30	-1.1	33.9	0.9



Return Period of Expected	% Change Qp	New Return Period	Change in Frequency
5	3	3.9	1.3
10	2.8	7.8	1.3
15	-3	17.1	0.9

Figure 6 Similar to Figure 3. Cumulative Distribution Function (CDF) of post-treatment peakflows. Top panel: H.J. Andrews HJA1 (with HJA2 as control). Bottom panel: H.J. Andrews HJA3 (with HJA2 as control). The post-treatment CDF converges with expected CDF, resulted in a non-significant increase of peakflow magnitude for large peakflows (Return period > 10 year).



Return Period of Expected	% Change Qp	New Return Period	Change in Frequency
10	10.3	7.4	1.3
20	21.5	14.1	1.4
30	19.9	16.9	1.8
50	13.2	19.8	2.5
60	10.1	22.4	2.7

Return Period of Expected	% Change Qp	New Return Period	Change in Frequency
5	7.4	3.2	1.6
10	4.8	6.4	1.6
30	20.1	19.6	1.5
50	16.2	22.4	2.2
70	12.6	25.2	2.8

Figure 7 Similar to Figure 3. Cumulative Distribution Function (CDF) of post-treatment peakflows. Top panel: H.J. Andrews HJA6 (with HJA8 as control). Bottom panel: H.J. Andrews HJA10 (with HJA9 as control).

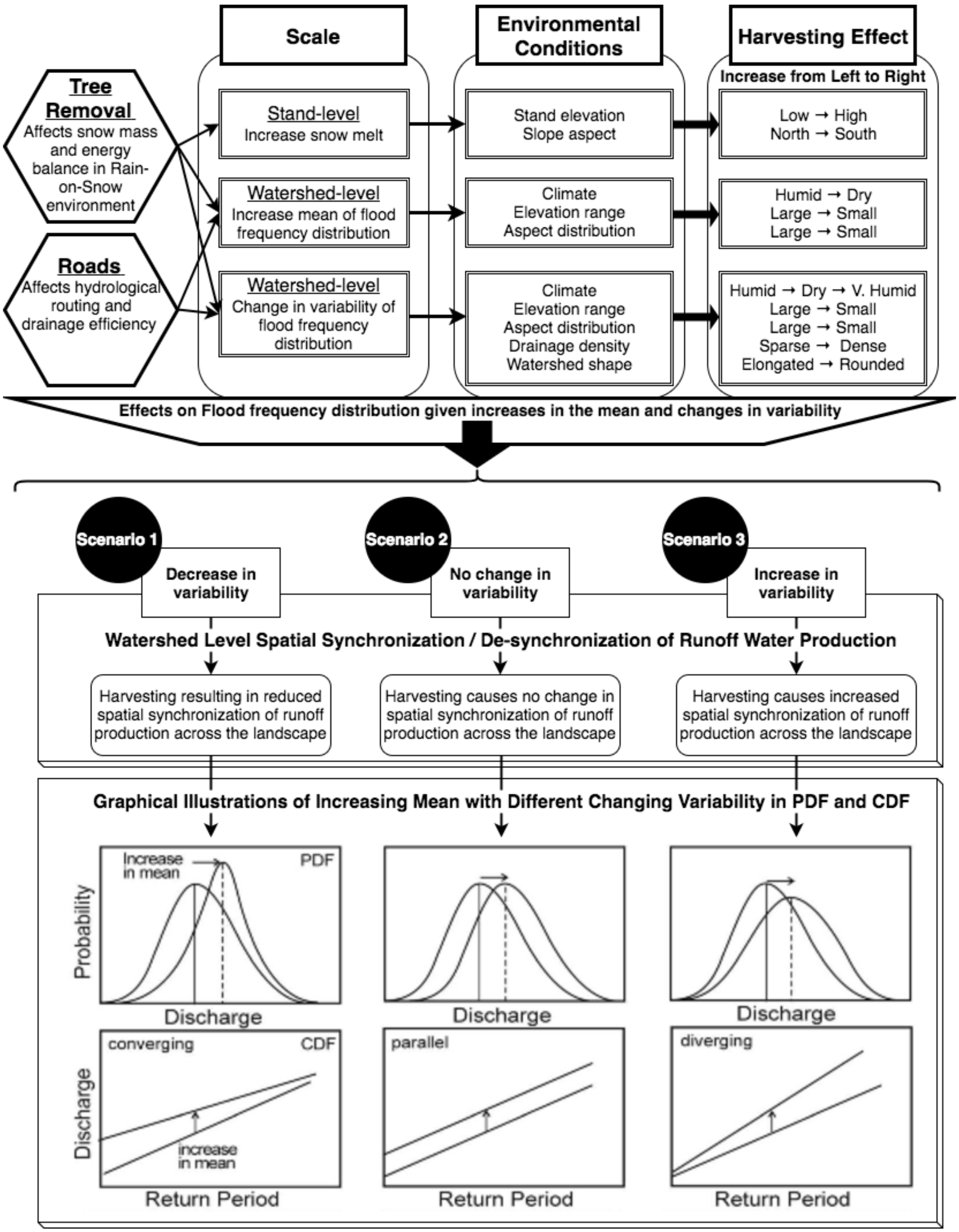


Figure 8 Conceptual diagram of processes relating the influence of environmental conditions to the effects of harvesting practices on peakflow discharge in ROS environment. The form of the distribution (skew) can also be affected by harvesting practices but the conceptual diagram here considers only changes in the mean and variability around the mean.

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