WATER RESOURCES RESEARCH, VOL. 48, W10503, doi:10.1029/2012WR012449, 2012

A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments

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Received 25 May 2012; accepted 23 August 2012; published 2 October 2012.

[1] A well-established precept in forest hydrology is that any reduction of forest cover will always have a progressively smaller effect on floods with increasing return period. The underlying logic in snow environments is that during the largest snowmelt events the soils and vegetation canopy have little additional storage capacity and under these conditions much of the snowmelt will be converted to runoff regardless of the amount or type of vegetation cover. Here we show how this preconceived physical understanding, reinforced by the outcomes of numerous paired watershed studies, is indefensible because it is rationalized outside the flood frequency distribution framework. We conduct a meta-analysis of postharvest data at four catchments (3–37 km^2) with moderate level of harvesting (33%–40%) to demonstrate how harvesting increases the magnitude and frequency of all floods on record (19–99 years) and how such effects can increase unchecked with increasing return period as a consequence of changes to both the mean (+11% to +35%) and standard deviation (−12% to +19%) of the flood frequency distribution. We illustrate how forest harvesting has substantially increased the frequency of the largest floods in all study sites regardless of record length and this also runs counter to the prevailing wisdom in hydrological science. The dominant process responsible for these newly emerging insights is the increase in net radiation associated with the conversion from longwave-dominated snowmelt beneath the canopy to shortwave-dominated snowmelt in harvested areas, further amplified or mitigated by basin characteristics such as aspect distribution, elevation range, slope gradient, amount of alpine area, canopy closure, and drainage density. Investigating first order environmental controls on flood frequency distributions, a standard research method in stochastic hydrology, represents a paradigm shift in the way harvesting effects are physically explained and quantified in forest hydrology literature.

Citation: Green, K. C., and Y. Alila (2012), A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments, *Water Resour. Res.*, *48*, W10503, doi:10.1029/2012WR012449.

1. Introduction

[2] Understanding the influence of land cover changes on flood response in forested catchments is critical to ensure forest management is undertaken in a way that minimizes the risk of negative effects to the environment and to humans dependent on surface water ecosystems. A response by *Calder et al.* [2007] published in Nature summarizing the current state of knowledge in the study of forest hydrology reports that "Now forest hydrologists generally agree that, although forests mitigate floods at the local scale and for small to medium-sized flood events, there is no evidence of significant benefit at larger scales and for larger events." The lack of an influence of forest harvesting on large floods at all spatial scales is a preconception [*DeWalle*, 2003] reinforced by a century of paired watershed studies undertaken using inappropriate experimental design and leading to scientifically indefensible conclusions regarding the relationship between land cover changes and flood response [*Alila et al.*, 2009, 2010; *Schultz*, 2012]. Over the past five decades such a preconception has also been taught to students as an established precept in forest hydrology textbooks [e.g., *Jeffrey*, 1970; *Lee*, 1980; *Brooks et al.*, 2003; *Calder*, 2005; *Chang*, 2006] creating a bias in the understanding of the influence of forests on floods at the very core of the science.

[3] In the early 1900s the American Society of Civil Engineers Special Committee on Floods and Flood prevention rejected the opinion of many of its members that forests reduce the frequency and severity of large floods in its final report commissioned by the US Government on the practical benefits of reforestation because of the lack of quantitative data [*Hoyt and Troxell*, 1932; *Dodds*, 1969]. In response to an obvious need for scientific studies the first experimental watershed in North America, Wagon Wheel Gap, Colorado, was established in 1910 specifically

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0043-1397/12/2012WR012449

to address the lack of quantitative data on the influence of forests on the frequency and magnitude of floods. Since the early 1900s at least half a dozen subsequent studies have been undertaken in snowmelt-dominated watersheds in western North America to investigate the influence of forest harvesting on streamflow metrics including maximum annual peak flows (a.k.a. maximum annual flood peak or flood flow) [*Bates and Henry*, 1928; *van Haveren*, 1988; *Troendle and King*, 1985, 1987; *King*, 1989; *Burton*, 1997; *Cheng*, 1989; *Troendle et al.* 2001; *Moore and Scott*, 2005; *Moore and Wondzell*, 2005; Table 1].

[4] Despite the original call to investigate the influence of forest removal on flood frequency and magnitude the research questions of these past studies overlooked the dimension of flood frequency and focused only on quantifying a change in magnitude between preharvest and postharvest floods paired by equal meteorology or storm input (i.e., chronological pairing or CP). Recently, *Alila et al.* [2009] revealed that this traditional experimental design that measures treatment effect through chronological event pairing is flawed because it does not account for physical changes in frequency of peak flows following harvesting. By ignoring changes in frequency the reported changes in magnitude for events larger and smaller than the mean flood are deceptive [*Alila et al.*, 2009], even if they were correct it would be for the wrong reason [*Alila et al.*, 2010]. Changes in flood response, regardless of whether the cause is land cover or climate change, must be investigated within the context of a frequency distribution that reveals changes in magnitude of floods with equal frequency (i.e., frequency pairing or FP), consistent with the methods employed by climatologists to evaluate the effects of changing climate on weather extremes [*Wigley*, 1985; *Katz*, 1993; *Wigley*, 2009]. *Alila et al.* [2009] illustrated using two long term paired watershed data sets from contrasting hydroclimate regimes how investigations of flood response conducted using CP-based analyses actually mask the effects of forest harvesting practices on the larger floods.

[5] In the three years since the publication by *Alila et al.* [2009] numerous studies and literature syntheses have been published that report or rereport the results of CP-based investigations on the influence of forest and land cover changes on floods [*Buttle*, 2011; *Sibert and McDonnell*, 2010; *Bathurst et al.*, 2011a, 2011b; *Birkinshaw et al.*, 2010; *Jones and Perkins*, 2010; *Schleppi*, 2011; *Troendle et al.*, 2010; *Zégre et al.*, 2010; *Zhao et al.*, 2010]. The reluctance of the forest hydrology community to abandon CP-based analysis is surprising considering years of inconsistencies between study results and the repeated call by researchers to adopt new analytical approaches to provide a more consistent and uniform understanding of watershed scale hydrological response to forest harvesting [e.g., *DeWalle*, 2003; *Jones*, 2005; *Moore and Wondzell*, 2005; *McDonnell et al.*, 2007; *Alila et al.*, 2009, 2010].

[6] This study is a response to the recommendation by *Jones* [2005, 2009] and *Lewis et al.* [2010] to adopt a meta-analysis approach to investigate watershed hydrological response to forest harvesting. Our meta-analysis is an intersite comparison using four previously published flow data sets from snowmelt-dominated headwater catchments of the western North America Cordillera with which we investigate the influence of forest harvesting on both flood magnitude and frequency of annual maximum daily peak flows (i.e., flood events with return periods larger than one year). We use this intersite comparison, investigated within the framework of a frequency distribution to provide new insights on catchment-scale flood response to forest harvesting not revealed previously in studies using CP-based analyses. We contrast the outcome of FP and CP analyses to further reveal how the results and interpretations of traditional CP-based analyses have misled us in our understanding of the physics of the forests and floods relation in snowmelt-dominated watersheds. Our meta-analysis uses both moderate-length (19 to 48 years) observed peak flows (*Qp*) from paired catchment studies as well as long-term (95 to 99 years) simulated peak flows from modeled catchment studies. The use of both observed and simulated flows allows us to address uncertainties associated with post-treatment sample size and nonstationarity due to changing land cover associated with forest regeneration, both of which may affect the estimated change in frequency and magnitude of the floods [*Lewis et al.*, 2010; *Alila et al.*, 2010].

[7] The results of numerous stand level investigations on the influence of physical characteristics including aspect, elevation, slope gradient, and canopy density on hydrological response to forest removal are drawn on to assist us in our understanding of watershed-scale peak flow response. Similarities and/or differences in peak flow response to forest harvesting identified using the meta-analysis approach allow us to link the basin physical characteristics to hydrological response and thus develop a conceptual model of the first order controls of the relation between forest harvesting and the peak flow frequency distribution.

2. Background

[8] By ignoring the question of changes in flood frequency at the outset of the investigation of forest removal on floods [e.g., *Bates and Henry*, 1928] the stochastic nature of floods was forgotten. Most of the studies undertaken over the past century in snowmelt-dominated hydroclimate regions of North America (Table 1) have applied the traditional CP-based analysis in the investigation of forest harvesting effects on streamflow. Chronological pairing utilizes the paired before – after impact (BACI) design to isolate a treatment response that is measured in nival regimes as the difference between maximum flood magnitude of the same snowmelt season in control and treatment watersheds (i.e., paired by year). The results of these studies vary widely. However, most report that harvesting can increase peak flows and that increases are largest for small and moderate magnitude floods but generally insignificant or nonexistent for larger floods, contributing to the current perception that larger floods are not influenced by forest removal [*van Haveren*, 1988; *Troendle and Olsen*, 1994; *Troendle and Stednick*, 1999; *Troendle et al.*, 2001; *King*, 1989; *MacDonald and Stednick*, 2003; *Moore and Scott*, 2005; *Moore and Wondzell*, 2005].

[9] It is, in part, the incorrect definition (or indexing) of a "large" flood, based solely on the ranking of the peak flows in the control catchment, which leads to misleading study outcomes in CP-based analyses. In CP-based studies, when the largest control catchment floods are not affected by harvesting it is mistakenly concluded that harvesting has no effects on the large floods in the treatment catchment.

Table 1. Summary of Paired Watershed Studies That Have Investigated the Influence of Forest Harvesting on Streamflow in Snow-Dominated Regions of Western North America

Study or Catchment	Location	Size	Treatment	Method of Analysis	Peak Flow Response	Citation
Wagon Wheel Gap-Watershed B	Colorado	81 ha	100% clear-cut	CP[a]/Change in mean *Q*peak	Elevated and advanced	*Bates and Henry* [1928]
				Avg. pre- and post-treatment flow duration curves/ ANCOVA	Increased on average by 50%. Large floods not affected	*van Haveren* [1988]
Deadhorse Creek – North Fork Subbasin	Colorado FEF	40 ha	36% cut in small circular openings	CP/ANCOVA	Increased on average by 50%	*Troendle and King* [1987]
				Avg. pre- and post-treatment flow duration curves/ ANCOVA	Flows increased. Largest not affected	*Troendle and Olsen* [1994]
Fool Creek	Colorado FEF	289 ha	40% cut in strips of 1 to 7 tree heights wide	CP/ANCOVA	Increased on average by 23%	*Troendle and King* [1985]
Fool Creek	Colorado FEF	289 ha	40% cut in strips of 1 to 7 tree heights wide	CP/ANCOVA	Increased on average by 23%. Large floods not affected	*Moore and Wondzell* [2005]
Horse Creek Basins 12, 14, 16, 18	Idaho	22–86 ha	25% to 36% clear-cut in patches	CP/ANCOVA	Average increases from 34% to 87%	*King* [1989]
Brownie Creek	Utah	2145	Clear cut of 25% of catchment all in upper 1/3	CP/ANCOVA	Increased on average by 66%	*Burton* [1997]
Coon Creek	Wyoming	1673 ha	Clear cut of 24% of catchment	Annual flow duration curves/ANCOVA	No significant increase	*Troendle et al.* [2001]
Camp Creek	BC	3390 ha	27% clear cut of catchment area	CP/ANOVA	21% increase	*Cheng* [1989]
				CP/ANCOVA	No significant increase for larger floods	*Moore and Scott* [2005]

[a]CP = chronological pairing.

Alila et al. [2009] illustrated how this line of reasoning is a logical fallacy because some small and medium control catchment floods may be amplified enough to become some of the largest flood events on record in the treatment catchment, consequently increasing the frequency, and by association magnitude, of postharvest large floods. This adjustment in the ranking (frequency) of flood events caused by harvesting changes what should be designated as a large flood in the treatment watershed. Several studies listed in Table 1 investigated harvesting effects on floods larger than the mean flood without recognizing this change in frequency, which could not be done because harvesting effects were measured as the difference between the chronologically paired control and treatment catchment flood magnitudes [e.g., *Troendle and Olsen*, 1994; *Moore and Scott*, 2005].

[10] Floods, as with most hydrological and meteorological variables, are randomly occurring events so that their prediction is probabilistic (or stochastic) rather than deterministic [*Yevjevich*, 1972]; that is, while it is not possible to predict exactly when a given flood of some magnitude will occur, we can predict the likelihood that it will occur in a specific period of time according to its frequency distribution. As a stochastic process, floods are described in part by two inextricably linked attributes: magnitude and frequency. Investigating changes in magnitude without controlling for frequency, as conducted in CP-based studies, leads to an "apples to oranges" type of comparison. A frequency distribution is the only framework that allows for the investigation of one attribute while controlling the other and is the only correct method of addressing the research question: What is the change in magnitude (frequency) for an event of a specific frequency (magnitude) of interest [*Alila et al.*, 2010]?

[11] Another critical flaw of traditional CP-based paired watershed investigations that seek to measure treatment effect by comparing chronologically paired peak flows in control and treatment catchments is that it is assumed that peak flow response in the treatment catchment can be predicted based on peak flows in the control catchment. This premise of a strong deterministic association between the peak flow responses is true for physically identical basins subject to identical meteorological inputs and identical runoff processes and is often used by engineers to fill-in missing peak flow data in two neighboring gauged catchments [e.g., *Dalrymple*, 1960]. Such premise, however, is no longer valid during the post-treatment period because following harvesting, the hydrometeorological processes largely responsible for the stochastic nature of the peak flow (*Qp*) response [*Yevjevich*, 1972] differ between treatment and control catchments. In snowmelt-dominated regions the difference in pre- and post-treatment runoff generating processes is commonly observed as peak flows that are separated in time by days or weeks [*van Haveren*, 1988; *Troendle and Olsen*, 1994; *Troendle and Stednick*, 1999; *Troendle et al.*, 2001; *Troendle and King*, 1987; *Moore and Scott*, 2005; *Moore and Wondzell*, 2005; *Troendle and King*, 1985].

[12] The independence of hydrometeorological processes in treatment and control catchments following logging is often observed as a decrease in the statistical strength of the post-treatment *Qp* response regression relation. This unexplained variability caused by forest harvesting has often been viewed as a nuisance and suppressed by logarithmic

transformations of *Qp* but only to satisfy the basic assumptions of normality and homogeneity of variance in traditional peak flow investigations by ANOVA and ANCOVA analyses [e.g., *Jones and Grant*, 1996; *Thomas and Megahan*, 1998, 2001; *Jones*, 2000]. However, these efforts to rectify increased variability in the post-treatment regression relation do not remedy the most fundamental problem: Measuring treatment effects as the difference between chronologically paired peak flows ignores a critical aspect of the physics of the relation between forests and floods, namely a change in frequency. Since the frequency and magnitude are two linked attributes of a flood event, a logging induced change in one causes a change in the other. A regression fit as used in CP-based analysis does not account for this simultaneous change in magnitude and frequency, nor does it preserve the all-important relation between these two attributes, but a frequency distribution does. Since we must invoke the dimension of frequency, and the frequency of an event depends not only on its own magnitude but also on the magnitude of all other events in the historic sample, the flood response of interest at the outlet of a watershed cannot be a single event as done in CP via a regression equation: It must be the entire flood frequency distribution. Therefore, the question that must be answered first is how has harvesting changed the entire frequency distribution? Only by answering this question can we answer our question of primary interest and the question that was first asked but never answered a century ago: How has harvesting affected the frequency and magnitude of large flood events?

[13] Treatment effects measured as changes in the mean, variability, and possibly the form of the frequency distribution of peak flows can provide insights into how the frequency and magnitude of both smaller and larger floods have changed, but also an original framework for understanding the physics of the relation between forests and floods. The ability to observe how the full frequency distribution has changed is important because of the inverse and highly nonlinear relation between magnitude and frequency that makes small changes in the mean and variability translate into surprisingly large changes in the upper tail of the frequency distribution (i.e., the frequency and magnitude of larger events) [*Alila et al.*, 2009]. Our paper addresses therefore a critical facet of extreme value theory of fundamental construct long recognized by climatologists [*Wigley*, 1985; *Wigley*, 2009] but, for too long, overlooked in decades of literature on forests and floods.

3. Study Sites and Harvest Scenarios

3.1. Overview

[14] A meta-analysis employs the simultaneous examination of physically different catchments to expose similarities and/or differences in catchment response that can be used to reveal the influence of physical basin characteristics on peak flow response [*Jones*, 2005; *McDonnell et al.*, 2007]. We limit this investigation to snowmelt-dominated headwater catchments to eliminate variability in hydrological response associated with different runoff-generating processes. The four study sites are typical of interior continental snow environments where flood hydrology is dominated by annual snow melt and where rainfall plays a much less important role either during the freshet or in the remainder of the year. During the snowmelt period between the beginning of March and the end of July the annual hydrograph for each of the four study watersheds typically displays between two to five independent peak discharge events in response to variability in annual spring meteorology. The four snowmelt-only headwater catchments in our meta-analysis include two large (25 and 37 km^2) and two small (<5 km^2) basins (Figure 1). For contrast, both large and small basin pairs include one basin that contains a component of alpine area (Fool and Redfish Creeks) and one fully forested basin (Camp and 240 Creeks). Two of the hydrometric data sets are from long-term paired watersheds (Camp and Fool Creeks), and two are simulated data sets (240 and Redfish Creeks). The use of simulated flows is appealing because of the length of years of simulated discharges (95 and 99 years, respectively) for the modeled catchments compared to 19 and 48 years of post-treatment hydrometric data for Camp and Fool Creeks and because simulated discharges represent static land cover conditions without forest regeneration that can obscure treatment effects on larger floods. The use of simulated discharges allows us to estimate changes in frequency and magnitude of flood events during the most critical period after logging before any substantial recovery has occurred.

[15] The paired watersheds have been subject to moderate levels of harvest accounting for 38% and 40% of Camp and Fool Creek watersheds, respectively (Table 2). In both cases harvesting is situated at the midelevations of the watershed and conventional ground skidding methods were used to transport the logged timber to haul roads. In Fool Creek most of the roads used to access cut blocks were deactivated following harvesting to re-establish natural drainage patterns. An extensive network of roads and old skid trails is apparent on air photographs of Camp Creek, however, it is not known if any of these roads or trails were deactivated to restore natural drainage patterns. Harvesting scenarios selected for the modeled catchments were chosen to most closely resemble the level of harvest and location of openings in the observed paired watersheds (Table 2). Modeled catchments do not include the effect of roads on hydrological response.

3.2. Fool Creek

[16] Fool Creek is a 289 ha, north flowing treatment drainage in a paired watershed experiment at the Fraser Experimental Forest (FEF), located about 100 km northwest of Denver, Colorado. The watershed is characterized by moderate gradient slopes with predominantly northern aspects, ranging in elevation from 2896 to 3505 m (Table 2). Mean annual precipitation at the site is around 595 mm, 60%–80% of which occurs as snow. The geology of the watershed is metamorphic, consisting of schist and gneiss derived from granite, subjected in the past to extensive glaciation. Soils are gravelly except for deep alluvial soils adjacent to stream courses. Vegetation in the watershed consists of a dense mature stand (aged 250–350 years) of lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*). The upper 25% of the watershed consists of alpine terrain and open krumholtz forest [*Troendle and Kaufmann*, 1987].

[17] Calibration of the Fool Creek watershed began in 1943 and ended in 1954. The contiguous East St. Louis watershed (803 ha) was used as a control. Logging began

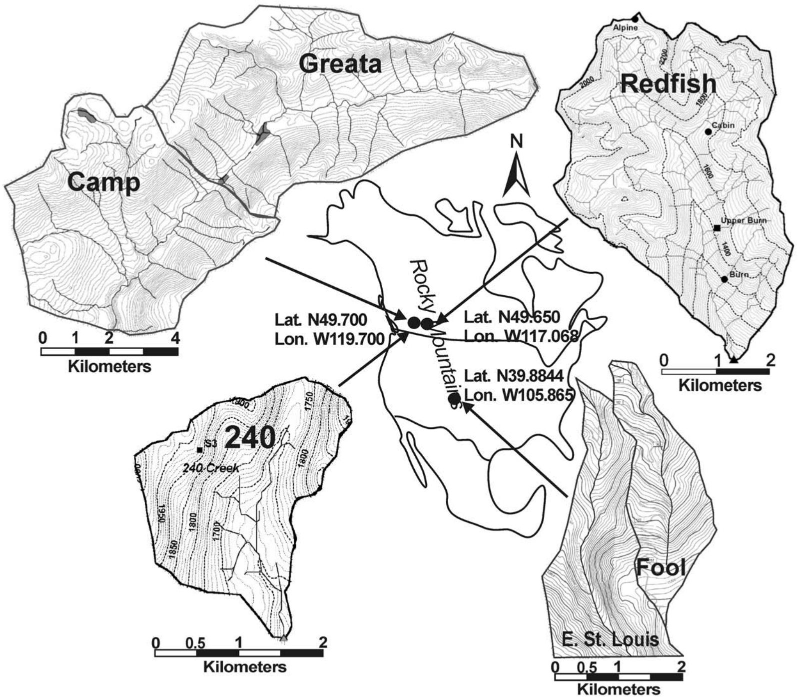

Figure 1. Location and topography of study areas.

in 1954 and was completed in 1956. The harvesting pattern consisted of alternating cut and leave strips of varying width (one, two, three, and six chains, where a chain equals 20.12 m) running normal to contours between 2950 and 3300 m, with 40% of the watershed harvested (50% of the timbered area) and the forest left to regenerate naturally. Spur roads (14.2 km) built along contours were decommissioned after logging; culverts were removed on alternate roads, and all roads were grass seeded. The main haul road (5.3 km), however, is still open and subject to regular maintenance [*Alexander and Watkins*, 1977]. For more details, the reader is referred to *Goodell* [1958], *Alexander and Watkins* [1977], and *Troendle and King* [1985].

3.3. Camp Creek

[18] Camp Creek (37 km^2) is located along the western side of the Okanagan Valley approximately 20 km west of Peachland, British Columbia (BC). Camp Creek together with Greata Creek (41 km^2) comprise an opportunistic treatment–control catchment pair with long term streamflow gauging by Environment Canada. Mean annual precipitation measured 12 km north of Camp Creek at the Brenda Mine climate station (1500 m asl) is approximately 600 mm, 60% of which falls as snow between the months of November and March. Both catchments display dominantly south slope aspects and similar average slope gradients of 20% (Table 2). Elevation in Camp Creek ranges from 1900 to 1050 m at the hydrometric gauging site. Both catchments are forested to the headwaters and are underlain by coarse textured bedrock and surficial materials. Forest cover varies from Lodgepole Pine (*Pinus contorta Dougl*) leading stands with lesser Douglas fir (*Pseudotsuga menziesii*) at lower elevations to mixed Douglas fir and Lodgepole pine stands at intermediate elevations and spruce (*Picea Engelmannii Parry*) and subalpine fir (*Abies lasiocarpa*) at higher elevations.

[19] Concurrent daily discharge gauging of Greata and Camp Creeks began in 1971. Logging commenced in Camp

Table 2. Physical Watershed Characteristics and Harvest Description

	Modeled Catchments		Observed Catchments	
Basin Characteristics	Redfish (100U)	240 (40T)	Fool	Camp
Years of Post-treatment Data	99	96	48	19
Size (km^2)	25	5	3	37
Avg. Slope (%)	50	24	23	20
Elevation Range (m)	700 to 2300	1600 to 2000	2896 to 3505	1900 to 1050
% Alpine (+ Open Subalpine)	40	0	23	0
Aspect Distribution[a]	E = W/S	E/W/S	N/NW/NE	S/SE/E/W
Stand Composition[a]	Sp/Bf/Lp/Cw	Lp	Sp/Bf/Lp	Lp/Df/Sp/Bf
Crown Closure (%)	50–80	44(avg.)	>50%	55–70
Harvest area (%)	33	40	40	37
Elevation of Harvesting (m)	1520 to 1880	1750 to 1950	2950 to 3300	1200 to 1700
Aspect Dist. of Harvesting[a]	E = W/S	E/W/S	NE/NW/N	SE/S/E/W

[a] Listed in order of abundance.

in 1976 in response to a Mountain Pine Beetle (MPB) outbreak and by the end of 1977 over 29% of the 37 km^2 watershed had been harvested. A number of blocks accounting for an additional 8% of the watershed were harvested between 1977 and 1990. By 1991 a total of 37% of the Camp Creek watershed was in a clear cut state. Most of the harvesting occurred in stands consisting of lodgepole pine with lesser amounts of spruce and Douglas fir at elevations between 1300 and 1700 m. Digital forest inventory information available from the B.C. Ministry of Forests (http://geobc.gov.bc.ca) indicates that the blocks harvested in 1977 contain regenerating juvenile pine stands averaging 22 years in age and ranging in height from 4.4 to 7 m (5.5 m avg.). Crown closure in these regenerating stands averages 35%. In contrast, the unharvested mature forest in Camp Creek consists of greater than 100-year-old lodgepole pine (120 year avg.), balsam fir, and Douglas fir stands averaging 25 m in height and 55% to 70% crown closure (Table 2). A small amount of logging, less than approximately 9% of the 41 km^2 area has occurred over the past 30 years at the western headwaters of Greata Creek control catchment. The logging in Greata Creek is thought to have occurred in part before 1980 with the remainder occurring sometime before 1990 [*Moore and Scott*, 2005]. Although it may affect our study outcomes, we ignore this small amount of logging in Greata Creek. If anything, it would cause an underestimation of our predicted effects of forest harvesting on peak flows [*Moore and Scott*, 2005]. It is not known if the numerous roads and skid trails constructed to access the cut blocks in Camp Creek have been deactivated to restore natural drainage patterns.

3.4. Redfish Creek

[20] Redfish Creek is a 26 km^2 catchment located in the Selkirk Mountains of BC, approximately 20 km northeast of Nelson. Redfish Creek ranges in elevation from 700 to 2300 m. Mean annual precipitation is estimated at between 1400 and 1800 mm with precipitation occurring throughout the year but falling as snow from October to May. Basin slopes are moderately steep, with a median gradient of 50% and primarily east and west aspects (Table 2). Bedrock underlying Redfish Creek is dominantly coarse crystalline granodiorite. Soils are derived from rapidly drained sandy gravelly glacial till and colluvium. Slopes below approximately 2000 m are densely forested with a mixed coniferous stand including western redcedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), Douglas fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), spruce (*Picea glauca x engelmannii*), and subalpine fir (*Abies lasiocarpa*). Above an approximate elevation of 2000 m the forest stands transition into subalpine parkland, which is a sparsely vegetated subzone that occupies approximately 40% of the basin area and does not hold any operable forest.

[21] The distributed hydrology, soils, vegetation model (DHSVM) has been used by *Schnorbus and Alila* [2004] to generate 99 years of simulated flows for a fully forested control scenario plus nine other different harvest scenarios in Redfish Creek. Only two of the 10 (Control and 100U) simulated scenarios of *Schnorbus and Alila* [2004] were used in this study. For the Control scenario the watershed is fully forested which required trees to be re-established over approximately 250 ha (10% of the watershed) on lower and midelevation slopes. For the 100U scenario, all merchantable forest is removed from the middle and upper forested slopes between the elevations of 1520 and 1880 m, which accounts for roughly 33% of the total watershed. For a detailed description of forest cover distribution and harvest scenarios the reader is referred to *Schnorbus and Alila* [2004].

3.5. 240 Creek

[22] 240 Creek is a 5 km^2 fully forested catchment located in the Okanagan Highlands roughly 25 km northeast of Penticton, BC. 240 Creek is one of three heavily instrumented catchments in the Upper Penticton Creek Experimental Watershed (UPC) that is maintained by the BC Ministry of Forests. Mean annual precipitation is 750 mm, of which about half falls as snow from November to April. Elevation ranges from 1600 to 2000 m (Table 2). Slopes are of moderate gradient and have predominantly east and west aspects (Table 2). The catchment is underlain by coarse crystalline granodiorite and metamorphic orthogneiss overlain by veneers of sandy soil derived from glacial till and colluvium. 240 Creek has a relatively open forest canopy containing predominantly mature lodgepole pine (*Pinus contorta*) with small amounts of Engelmann spruce (*Picea Engelmannii*) and subalpine fir (*Abies lasiocarpa*) [*Thyer et al.*, 2004].

[23] DHSVM has been used by M. Schnorbus and Y. Alila (Peak flow changes following harvesting in a snow-dominated basin: Effects of harvest area, elevation and channel connectivity, submitted to *Water Resources Research*, 2012, hereinafter referred to as Schnorbus and Alila, submitted manuscript, 2012) to generate 95 years of simulated flows for a fully forested control scenario plus 11 other different harvest scenarios in 240 Creek. Only two of the 12 (Control and 40T) simulated scenarios of Schnorbus and Alila (submitted manuscript, 2012) were used in this study. In the 40T scenario, 40% of the watershed is removed uniformly in a band that extends across the mid and upper slopes between the elevations of 1750 and 1950 m. For the Control scenario forest cover exists over the full catchment area. For a detailed description of forest cover distribution and harvest scenarios the reader is referred to Schnorbus and Alila (submitted manuscript, 2012).

3.6. Simulation of Harvesting Scenarios by DHSVM

[24] DHSVM is a spatially distributed model that approximates catchment-scale precipitation inputs and outputs through multiparameter algorithms that account for changes in the energy and water balance associated with forest cover removal [*Wigmosta et al.*, 1994]. As with all physically distributed models, DHSVM may introduce uncertainties in the estimation of large peak flows due to the low number of extreme events represented during the calibration period. However, in both Redfish and 240 Creeks rigorous testing and calibration of DHSVM included reproducing multiple years of observed flows at the basin outlets as well as numerous internal catchment processes and meteorological variables. At Redfish, DHSVM was initially calibrated and tested by *Whitaker et al.* [2003]. Model calibration incorporated an extensive network of field based meteorological and hydrological parameters. A multipass approach to calibration, in which potentially correlated parameters were

excluded from the same calibration exercise, reduced the potential for equifinality in model output. *Whitaker et al.* [2003] found that the calibrated model provided good approximation of measured hydrometeorological parameters including streamflow, and snow accumulation and melt at multiple sites throughout the catchment. Details regarding the calibration and parameterization of the DHSVM model for Redfish Creek are presented by *Whitaker et al.* [2003]. At UPC (240 and 241 Creeks), DHSVM was also extensively calibrated and evaluated by *Thyer et al.* [2004] who found that the model successfully simulated streamflows as well as other spatially distributed hydrometeorological parameters including forest and clear-cut SWE, tree transpiration, and clear-cut snowmelt rates. Further testing and validation of the UPC DHSVM model output was undertaken by *Kuraś et al.* [2011] who determined that the model realistically simulated the spatiotemporal variability of road and stream network flows, and subsurface responses in the watershed. The DHSVM applications at Redfish and 240 Creeks are believed to be reliable enough tools for contributing to the ongoing debate on the effects of forest harvesting on the peak flow regimes of snow-dominated watersheds [*Schnorbus and Alila*, 2004; *Kuraś et al.*, 2012].

4. Methods

4.1. Overview

[25] At each of the four study sites we assess treatment effects on the magnitude of peak flows using both frequency pairing and chronological pairing frameworks. In the frequency pairing framework we assess treatment effects on the magnitude of peak flows by examining the difference between control and treatment catchment peak flows of the same historic probability of occurrence. In the chronological pairing framework, on the other hand, we assess treatment effects on the magnitude of peak flows by examining the difference between treatment and control catchment peak flows generated by the same snowmelt freshet every year. At Camp and Fool, the effect of forest harvesting on peak flow regimes was assessed by comparing the observed peak flow sample following harvest (post-treatment sample) with a sample of peak flows expected to occur during the same period in the absence of harvesting (expected post-treatment sample). The expected peak flows are therefore not observed and must be modeled in some fashion. At each of these two sites, expected post-treatment peak flows in both CP and FP frameworks are predicted using the pretreatment calibration regression established from each study site (treatment peak flow regressed on paired control peak flow). Confidence intervals for the chronologically paired assessment (not shown in Figure 3) were derived directly from the predictive uncertainty of the calibration equation. Confidence intervals for the frequency-paired assessment are a combination of this predictive uncertainty and quantile sampling uncertainty, both estimated via Monte Carlo simulation. At Fool Creek we adjusted the observed post-treatment peak flows to remove the effects of forest regrowth by including a recovery trend with time to a regression fit applied to chronologically paired observed and expected post-treatment discharges, however such adjustment was found unnecessary at Camp Creek. This adjustment is conducted for two reasons: (1) justify the basic assumption of stationarity in frequency analysis; and (2) allow the effects of harvesting during the most critical period prior to any substantial forest regrowth to be evaluated, as well as the effects of other longer-lasting forest land-use changes such as deforestation. At each of Redfish and 240 Creeks, the DHSVM model was used to simulate two time series of peak flows with and without forest cover generated by the same long-term proxy climate data, with no forest regrowth. Therefore, direct comparison of the two time series in FP and CP frameworks was conducted without need to adjust for recovery.

4.2. Adjusting for Nonstationarity Due to Forest Regeneration

[26] A multiple regression analysis that included the variable "time since harvest" (T since Hv) indicated that no time trend is present ($F = 1.71$, $p = 0.2$) in the post-treatment annual daily peak flow data set of chronologically paired observed and expected post-treatment discharges (Camp Qp and Greata Qp).

$$\text{Camp } Qp = 1.13 + 1.00 * \text{Greata}\,Qp - 0.01 * T \text{ since } Hv. \tag{1}$$

[27] The variable T since Hv is also not a predictor of "treatment effect" measured as the difference between Camp Creek observed and predicted (control) maximum daily discharge [treatment effect $\Delta Q = Q\text{obs} - Q\text{cntrl} = 0.66 - 0.01 * T\,\text{since}\,Hv\,(F = 1.92,\ p = 0.18)$]. *Hence, the 19 year post-treatment annual maximum daily peak flow data set from Camp Creek has not been adjusted to remove the effects of forest regrowth.*

[28] A time trend is present in the Fool Creek data set but only when the entire 48 year data set is included in the analysis (FC = Fool Creek, ESLC = East Saint Louis Creek):

$$\begin{aligned}\text{FC } Qp = 37.2 + 0.35 * \text{ESLC}\,Qp - 1.12 * T\\ \text{since}\,Hv\,(F = 7.39,\ p < 0.001).\end{aligned} \tag{2}$$

[29] Further investigation determined that a time trend is not present when the 48 year data set is subdivided into three contiguous subsets of 30 years each, however, the trend is statistically significant in a data set consisting of the first 20 years and last 10 years of data. This finding suggests that forest regeneration only started to influence stand level processes in the last decade of recorded data. To remove the time trend the correction factor was applied to the data starting with the last 10 years and moving back in time until the T since Hv variable was no longer a significant predictor of discharge in the regression analysis. Using this method of adjusting for recovery only the last 12 years of the Fool Creek data needed to be adjusted for the effects forest regeneration. Limiting the time adjustment to the last 12 years addresses a previous concern that adjusting for recovery in the entire post-treatment data set may contribute to additional increases in the estimated treatment effect between the pretreatment and post-treatment frequency distributions [*Lewis et al.*, 2010].

4.3. Estimation of Expected Post-Treatment Discharges

[30] Analysis of the Camp (treatment) – Greata (control) and Fool (treatment) – East St. Louis (control) paired

watershed data sets requires the development of a pretreatment regression model from which an expected post-treatment data set is derived during the post-treatment period. Typically the regression relation is developed through simple linear regression derived by relating chronologically paired annual peak flow data:

$$\widehat{Y}_i = b_o + b_1 X_i, \qquad (3)$$

where X_i is the peak flow of the control watershed and $\widehat{Y}_i$ is the expected untreated peak flow for the treated watershed. Due to the relatively short pretreatment calibration period for Camp and Greata Creeks the pretreatment regression is derived using the method of multiple, chronologically paired peaks (analogous to the method of peaks over threshold or PoT). This method extends the pretreatment data set from 6 to 16 paired peak flow events from which the pretreatment regression relation is defined, and is appropriate because snowmelt-dominated hydrographs of the semiarid BC Okanagan region typically display multiple (3 or more) independent peak events (separated in time by at least 5 days [*U.S. Water Resources Council*, 1976]) during most freshets. Improving the regression relation for the pretreatment calibration period between control and treatment catchments by including additional paired peaks from a single freshet can be used to extend the pretreatment data set where peak flows are driven by a single meteorologic process (e.g., snowmelt) [*Waylen and Woo*, 1982]. Depending on the development of meteorology through the snowmelt season any one of the independent multiple peaks during the freshet could be the annual maximum peak. Regardless of whether a given peak is the maximum annual peak or not it provides additional chronologically matched regression points that further define the relationship between the two catchments. Independence of the 16 pretreatment peak flow events at Camp and Greata Creeks was further confirmed through the nonparametric Spearman rank order serial correlation test which indicates that both time series can be considered a set of independent observations ($\alpha = 0.05$).

4.4. Flow Duration Curve Analysis

[31] The comparison of pre- and post-treatment flow duration curves, also known as empirical cumulative distribution functions (CDFs), enables the assessment of the change in magnitude for a given probability (or return period) flood, or conversely, the change in probability for a given magnitude flood. We decided to use an empirical approach without fitting a frequency distribution model to the data to avoid introducing other sources of uncertainty in our estimation of the effects of harvesting on the peak flow regime. However, for presentation purposes and without loss of generality we have plotted our CDFs in probability space defined using the generalized extreme value function.

[32] The process of assigning a probability (p) to a given flood (Y) from a time series of peak flows involves ranking the floods in descending order of magnitude from 1 to n such that $Y_{(1)}$ is the largest value and $Y_{(m)}$ is the mth largest value in the sample of n values, where $Y_{(1)} > Y_{(2)} > \cdots Y_{(m)} > Y_{(n)}$.

[33] An estimate of the probability p for ranked event $Y_{(m)}$ is obtained using the cumulative distribution function Fy as

$$p = F_Y[Y_{(m)}]. \qquad (4)$$

[34] An estimate of the exceedence probability $1 - p$ for ranked event $Y_{(m)}$ is obtained by

$$1 - F_Y[Y_{(m)}] = \frac{m - 0.40}{n + 0.2}, \qquad (5)$$

where the right-hand side of equation (5) is the approximately quantile-unbiased Cunnane plotting position [*Stedinger et al.*, 1993]. From equation (5) the discharge event of rank m (Y_m) is an empirical estimate of the pth quantile y_p, and identical estimates exist for the paired expected sample ($\widehat{Y}_m$) derived from the regression relation (equation (3)) with the control catchment.

[35] The predicted discharge ($\widehat{Y}_m$) is corrected for loss of variance from the regression model in equation (3) by reintroducing a random error, sampled from a t distribution with $n - 2$ degrees of freedom, to the expected discharge [*Alila et al.*, 2009]. This is done through a Monte Carlo simulation that adds the random error to the expected discharges ($\widehat{Y} + e$), ranks the corrected expected data set ($\tilde{Y}_m = \widehat{Y}_m + e_m$), and repeats this for 10,000 iterations to provide an estimate of the mean, corrected, ranked expected discharge ($\overline{\tilde{Y}}_m$).

4.5. Statistical Versus Physical Significance

[36] For a sample of flood flows the uncertainties associated with the estimation of probability increases with event size so that the probability of the largest flood event in a sample of any size cannot be determined accurately by an empirical plotting position equation. Large errors in plotting position for the largest floods can cause a premature convergence (or divergence) of the pretreatment/control and post-treatment/observed CDFs. An apparent negative change in the magnitude of the largest few events, where the upper tail of the observed CDF dips below the upper tail of the control CDF, could be real but could also be an artifact of a mismatch in event return periods and/or uncertainties in estimated expected discharges by regression models, which are often based on a short sample of peak flows (e.g., Camp and Fool Creeks).

[37] The lack of statistical power has always been a hindrance to detecting changes in larger flood events. *Lewis et al.* [2010] suggest that a prudent course of action when faced with nonsignificant results is (1) to note the apparent direction of change, regardless of statistical significance, and (2) to conduct metastudies to investigate whether analogous changes have repeatedly been measured but declared insignificant in the absence of sufficient statistical power. In our meta-analysis, therefore, we are looking for trends in the direction of the peak flow response to harvesting, irrespective of its statistical significance. By investigating several catchments concurrently we determine if the treatment effects on the few largest floods display similar trends regardless of post-treatment sample length. In this way we

are able to identify physically meaningful treatment effects even if they are not statistically significant. Since we are using a meta-analysis approach we do not report our study results in terms of null hypothesis statistical tests of significance [e.g., *Alila et al.*, 2010, p. 4]. The upper confidence intervals (95%) on the expected CDFs from the paired catchment data sets and on the control CDFs from the two DHSVM modeled catchments are included for general information only.

[38] Confidence intervals about the expected CDFs are approximated as normally distributed errors about the estimated mean corrected, ranked discharge that are a combination of the predictive uncertainty of the calibration equation and quantile sampling uncertainty [*Alila et al.*, 2009]. Confidence intervals about the control CDFs from the modeled data sets are only a function of the quantile sampling uncertainty. To facilitate sampling of empirical quantile values at the sample extremes for the observed hydrometric data sets the generalized extreme value (GEV) frequency distribution is fit to the ($\bar{Y}_m$) series [*Alila et al.*, 2009]. For a comprehensive explanation of the generation of the control empirical CDFs and the associated confidence limits the reader is referred to *Alila et al.* [2009].

5. Results

5.1. Meta-analysis and the Frequency Pairing Framework

[39] Moderate levels of harvesting changed both the mean and the variability (as measured by the standard deviation) of post-treatment peak flows compared to the pretreatment (control) sample in the four catchments (Figure 2). In Camp Creek (Figure 2a), a 37% clear-cut harvest results in a 35% increase in the mean and almost no change (1% increase) in the standard deviation of post-treatment compared to the pretreatment peak flows. Harvesting of 40% of the watershed area in 240 Creek (Figure 2c) has resulted in a 15% increase in the mean and a 19% increase in the standard deviation of the post-treatment sample of peak flows compared to the pretreatment sample. Redfish Creek (Figure 2d), with a harvest level of 33%, displays the smallest increase in the mean (11%) but one of the largest increase in standard deviation (18%) of post-treatment peak flows compared to the pretreatment sample. For all three catchments, these changes in mean and standard deviation of post-treatment peak flows have the effect of shifting the post-treatment probability density function (PDF) to the right toward the larger magnitude floods combined with a widening of the PDF so that the probability of occurrence of the larger floods increases (see insets in Figure 2). Relative to the pretreatment PDF, Camp Creek displays the largest rightward shift in the upper tail of the PDF followed by 240 and Redfish Creeks. Perhaps one of the most interesting results of this meta-analysis is the different treatment response observed in Fool Creek (Figure 2b) where a 40% level of harvest has resulted in a 23% increase in the mean but a 12% decrease in the standard deviation of post-treatment peak flows relative to the pretreatment sample. An increase in the mean coupled with a decrease in the standard deviation of post-treatment peak flows is observed as a larger rightward shift of the lower tail of the PDF compared to the upper tail.

[40] Interestingly, the upward shift in the mean and the negative, zero, or positive change in variability of post-treatment peak flows at the four study sites results in an upward shift of all post-treatment peak flows, save the largest event, irrespective of sample size. In all four catchments even small increases in the magnitude of larger floods translate to substantial increases in flood frequency and, remarkably, in one of the four study sites the largest increases in frequency occurred for the largest flood events. The 40% level of cut in 240 Creek has resulted in nearly a fourfold increase in the frequency of the 50 year flood while the 20 year flood has doubled in frequency. Similarly, the 33% level of cut in Redfish Creek resulted in a doubling of the frequency of the 10, 20, and 50 year pretreatment floods. For the observed data sets of Camp and Fool Creeks the 5, 10, and 20 year floods had also all doubled in frequency. These findings represent a new insight in the relation between forests and floods; in all cases we observed increases in frequency of all floods, including the largest on record, regardless of whether the CDFs are diverging, as in the case of 240 and Redfish Creeks, running nearly parallel as in the case of Camp, or converging as in the case of Fool.

[41] Considered collectively the four paired frequency analyses suggest there is no clear upper limit to the influence of forest harvesting on flood response in snowmelt-dominated regimes. As post-treatment sample size increases the apparent "no-effect" threshold signposted by the intersection of the pre- and post-treatment CDFs in Figures 2a–2d shifts toward the right from the 20 year for Camp to the 50 year for Fool and to beyond the 100 year flood for 240 and Redfish Creeks. Furthermore, the divergence of the pre- and post-treatment CDFs in two of the four study catchments (240 and Redfish) implies that treatment effects on the magnitude of peak flows in snowmelt dominated catchments in absolute terms actually increases with increasing return period. The exception being Fool Creek, where the standard deviation of the post-treatment peak flows decreases causing such effects on the magnitude of peak flows to decrease with increasing return period. It is important to note that the decreasing treatment effects expressed in relative terms as suggested by the rapidly decreasing percent increase for the flood quantiles (Q2, Q10, Q20, and Q50) given in Figures 2a–2d is deceptive and must not be interpreted to mean that forest harvesting is not substantially affecting the magnitude and frequency of larger floods. While the relative change in flood magnitude may be decreasing (where relative change is measured as (Q_T post-treatment − Q_T pretreatment)/Q_T pretreatment) with increasing return period, the absolute change (Q_T post-treatment − Q_T pretreatment) is increasing in the case of 240 and Redfish Creeks, remaining nearly unchanged for Camp or, in the case of Fool, is decreasing albeit with a slow rate.

5.2. Chronological Pairing and the Missing Dimension of Frequency

[42] By comparing Figures 2a–2d with Figures 3a–3d we reveal the flaw in an analysis that measures treatment effects solely as changes in flood magnitude without controlling for changes in flood frequency. In all four snowmelt-dominated catchments, the CP-based analysis suggests that the largest floods are either not affected much or are reduced relative to the control catchment (Figures 3a–3d).

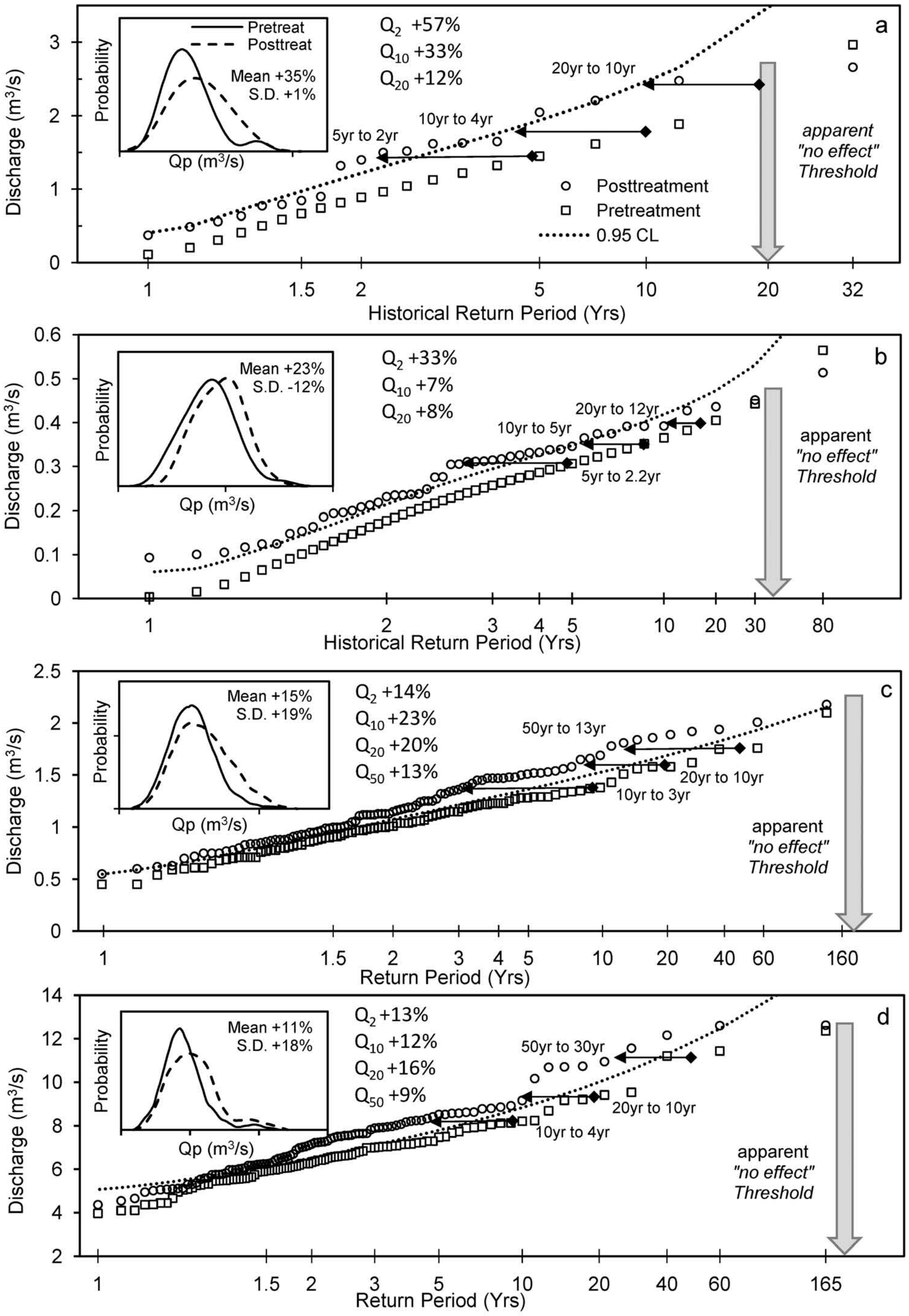

Figure 2. Flow duration curve analysis for pre- and post-treatment daily peak flows at (a) Camp Creek (19 years), (b) Fool Creek (48 years), (c) 240 Creek (95 years), and (d) Redfish Creek (99 years). The point at which the two CDFs intersect, marked by the vertical arrow, increases with record length suggesting a no clear upper threshold to the effects of forest harvesting on floods in snowmelt-dominated hydroclimate regimes.

In the CP framework, the deception that the largest floods are reduced or not affected much occurs because the largest floods in the treatment catchment are not occurring at the same time as the largest floods in the control catchment, and there lies the incorrect definition (or indexing) of a “large” flood event. We also observe an increase in variability around the post-treatment regression in the CP-based analysis, which is best illustrated by the simulated flows in Figures 3c and 3d. In these two graphs the control and treatment catchments are the same so the pretreatment regression is a perfect line with R^2 equal to 1. The increased variability about the post-treatment regression line, observed as a decrease in the R^2, is strictly an artifact of the wrong type of pairing and is caused by year to year variability between pre- and post-treatment

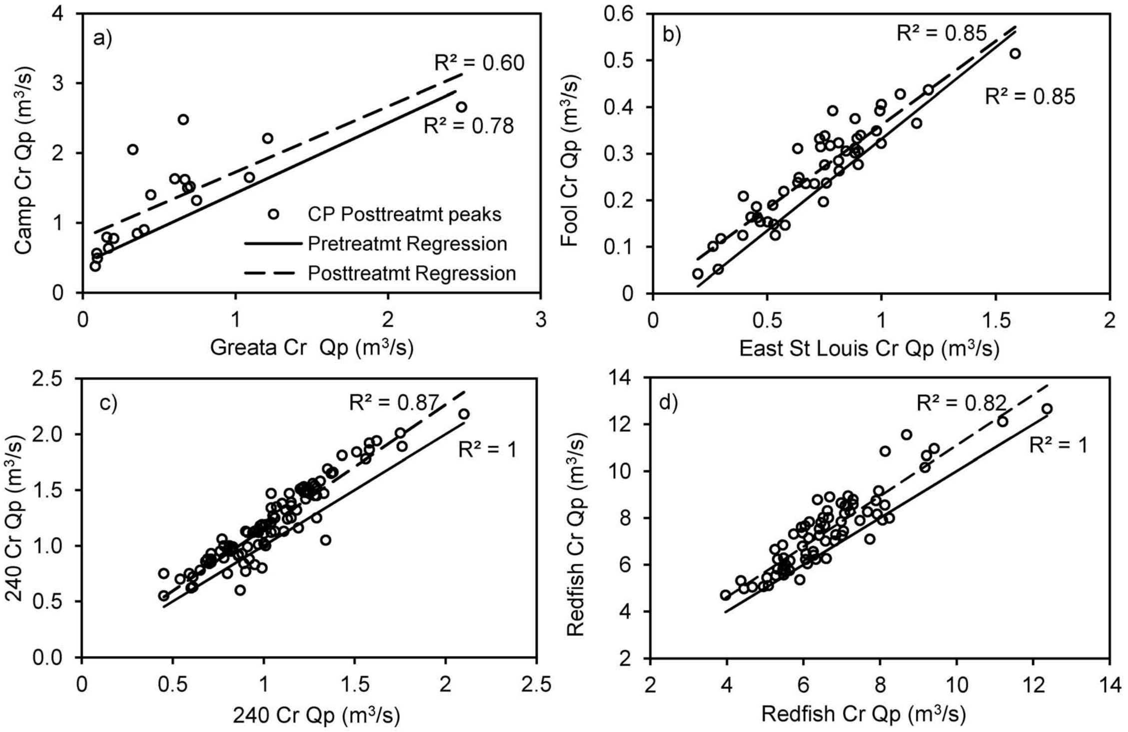

Figure 3. The chronologically paired analysis of pre- and post-treatment daily peak flows at (a) Camp Creek (19 years), (b) Fool Creek (48 years), (c) 240 Creek (95 years), and (d) Redfish Creek (99 years).

peak flows. In contrast, the change in variability observed in the post-treatment PDF in Figures 2a–2d (insets), as measured by the change in the standard deviation, reflects the influence of forest harvesting on the variability of the full sample of post-treatment peak flows and can substantially affect the magnitude and frequency of larger floods.

[43] As stated in section 2, the incorrect estimate of the change in flood magnitude that results from pairing flood events of different frequencies is one of the major failings of CP-based analyses. In all four catchments pairing flood events chronologically rather than by equal frequency produces the repeatedly cited CP-based outcomes that (1) treatment effects rapidly diminish with increasing control basin flood magnitude (e.g., decreasing trend of percent change in Qp with increasing control catchment flood magnitude, Figure 4), and (2) that forest harvesting can cause peak flow magnitude to increase, decrease or remain the same (e.g., the positive, zero or negative percent change in Qp, Figure 4) [e.g., *Thomas and Megahan*, 1998; *Brath and Montanari*, 2000; *Calder*, 2005; *Moore and Scott*, 2005; *Moore and Wondzell*, 2005; *Brath et al.*, 2006; *NRC*, 2008]. However, both outcomes are deceptive because of the missing element of flood frequency. Although FP analysis may also reveal decreasing relative treatment effect trends with increasing flood magnitude as well as positive, zero, or negative relative changes in Q_T, these are not the same relative changes observed in the CP analysis. By ignoring flood frequency, the CP-based analysis does not reveal the correct change in flood magnitude of small, medium, and large events, or, how the frequency of small, medium, and large events have changed relative to the control catchment.

[44] An investigation of the changes in the frequency of chronologically paired floods reveals consistent changes in flood return period in the treatment catchment relative to the control catchment following harvesting for both modeled and observed data sets (Figure 5). Fool and Redfish Creeks, the two basins selected to illustrate this trend, both reveal that post-treatment large magnitude floods have increased in frequency (decrease in return period, Figures 5a and 5c) and moderate floods have decreased in frequency (increased in return period, Figures 5a and 5c).

[45] The corresponding change in the rank order of floods (floods are ranked from 1 to "n" with 1 being the largest and "n" the smallest) associated with the change in return period for large and moderate flood years is illustrated in the adjacent CDFs for both the observed (Fool) and modeled (Redfish) data sets (Figures 5b and 5d). In a cumulative distribution function the flood of rank n is the smallest event located at the extreme left and the flood of rank 1 is the largest event located at the extreme right. One of the largest decreases in flood rank (i.e., rank moving up toward 1) for Fool occurred in 1958. In the accompanying CDF curve it can be seen that while the 1958 flood had a historical return period of approximately 3 years in the control catchment, the flood in the treatment catchment for the same year was nearly doubled in magnitude and had a corresponding return period of approximately 10 years. Conversely, the 1971 flood which was one of the largest floods in the control catchment for the post-treatment period with a return period of approximately 20 years decreased slightly in magnitude in the treatment catchment but the post-treatment frequency increased to a 7 year return period. This same pattern is also illustrated in the simulated data for Redfish for the flow years 2037 and 2060.

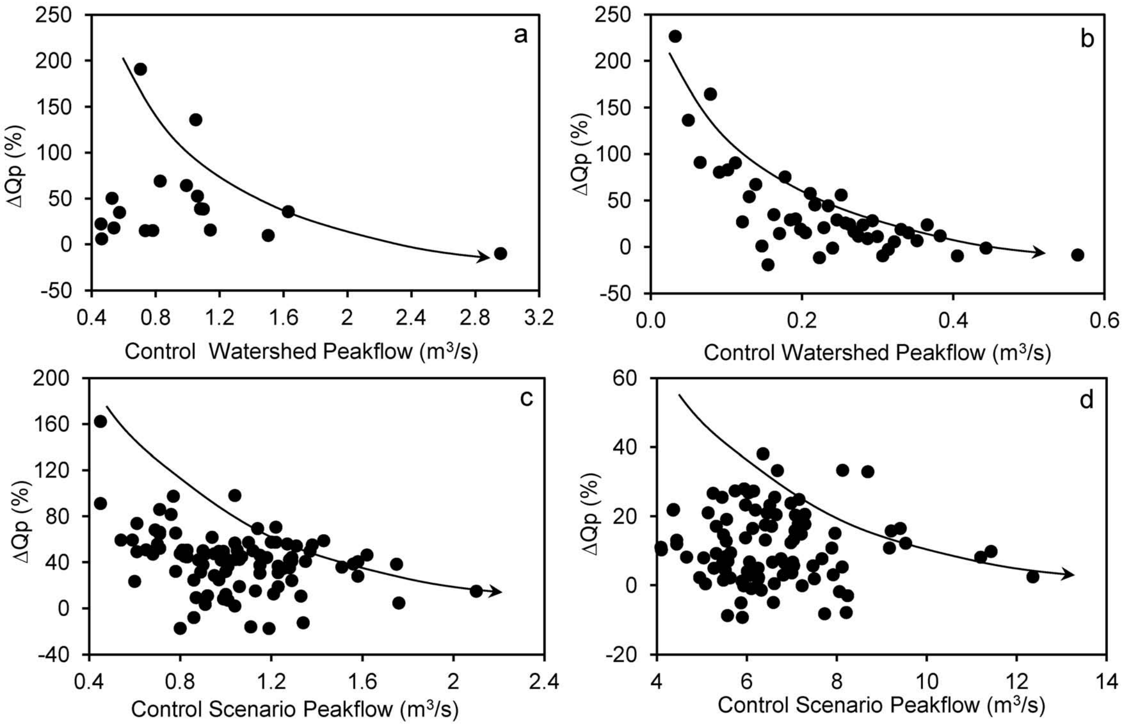

Figure 4. The misleading trend of decreased treatment effects for increased control catchment flood magnitude, apparent in all four data sets when CP-based analysis methods are applied (panel designation as in Figure 3).

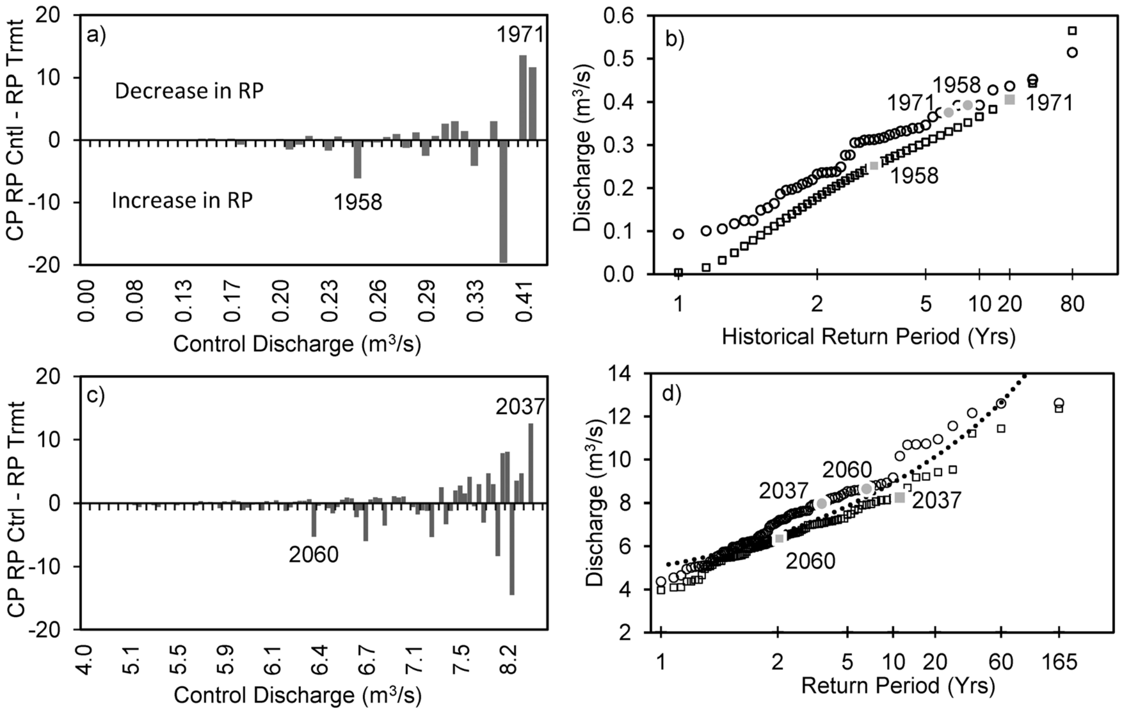

Figure 5. Difference between chronologically paired treatment and control catchment return periods as a function of control discharge at: (a) Fool Creek (48 years) and (c) Redfish Creek (99 years). How these changes in return period correspond to absolute changes in magnitude and frequency is shown on the adjacent CDFs: (b) Fool Creek (48 years) and (d) Redfish Creek (99 years).

[46] The pattern in the change of rank order of floods between treatment and control catchments observed in both the simulated and observed data sets suggests that there has been some consistent change in the physical processes generating peak flows in the treatment catchments relative to the control catchments. More specifically, it appears that, at least in some years, the seasonal meteorology that is producing medium events in the control watershed is now contributing to the generation of much larger events in the treatment watershed and, consequently, a decrease in the rank (increase in return period) of these floods in the treatment watershed. However, this is not always the case as some larger floods in the control watershed are not changed substantially in magnitude and remain large in the treatment watershed. These unchanged, and at times even slightly reduced, large events end up dropping in rank as they compete with the amplified flood events for the rank positions of larger floods in the treatment watershed.

5.3. Physical Processes Investigation

[47] We have undertaken regression analysis using both observed and simulated hydrometric and meteorologic data to explore possible factors contributing to peak flows. Meteorological data including snow water equivalent (SWE) for Camp Creek is from the Environment Canada climate station (#1126077) located 7 km north at an elevation of 1520 m. Increased snow accumulation and increased rates of snow melt are most often implicated as processes contributing to peak flow increases following harvesting [*Troendle and Leaf*, 1980; *Troendle*, 1987; *Schmidt and Troendle*, 1992]. For the four catchments we observe that peak flows and peak SWE are positively related in all four treatment watersheds (i.e., during the post-treatment period) in this study. However, low R^2 values indicate that peak SWE only accounts for 38% to 50% of the variability for the observed catchments and less than 30% of the variability in the modeled catchments (Table 3).

[48] Our regressions of simulated catchment-average daily snowmelt from the DSHVM studies indicate that peak discharge is more strongly determined by catchment-average 3 day total snowmelt preceding peak flows [$R^2 = 0.90$ for 240 and 0.58 for Redfish ($p < 0.001$)], however, daily snowmelt data were not available for Camp or Fool Creek. For these catchments observed daily air temperature is used as a proxy for snowmelt [*Hock*, 2003]. We found that annual peak discharge is moderately determined ($R^2 = 0.48$, $p < 0.001$) by 3 day average temperature preceding peak flows in Camp but in Fool neither 24 h, 3 day, or 7 day average temperature preceding peak flows were found to be significant predictors of the magnitude of the annual peak flow (3 day average temperature versus Qp, $R^2 = 0.01$, $p > 0.05$). However, the daily discharge (daily Q), for the two week period preceding and including the peak discharge, is strongly determined by the preceding average 7 day air temperature in both Camp and Fool Creeks ($R^2 = 0.67$ to 0.94 for period of record, $p < 0.05$) suggesting that the increases in daily net radiation in the days preceding peak flows is the primary factor in catchment scale flood response rather than the measure of total energy (i.e., maximum daily temperature or average 3 day temperature) at the time of peak flow.

[49] To help us understand how changes in shortwave radiation related to forest harvesting affect flood response in watersheds with different physical characteristics we use a frequency analysis to investigate changes in catchment-average total 3 day snowmelt preceding peak flow between forested and harvested scenarios following 40% and 33% harvest in 240 and Redfish Creeks, respectively (Figure 6). These two watersheds represent physiographic opposites; 240 is a small, fully forested, moderate gradient watershed, whereas Redfish is a much larger, steeper basin containing 40% alpine area. The results for both 240 and Redfish reveal similar increases in the mean of the total 3 day snowmelt (increases of 7% in 240 versus 8% in Redfish) with moderate levels of harvest but larger increases in the variability of 3 day melt in 240 (23%) compared to Redfish (18%). As snowmelt is the dominant process in generating peak flows we expect that changes in mean and variability of basin average snowmelt preceding peak flows will transmit to changes in the mean and variability of peak flow response at the outlet of the watershed but that this response could be amplified or mitigated by the location of harvested openings and routing of surface and subsurface runoff.

6. Discussion

6.1. Meta-analysis Investigation

[50] A frequency based meta-analysis reveals that moderate levels of forest harvesting (33% to 40%) has affected the entire flood frequency distribution including the largest floods on record in all four study catchments, irrespective of sample size. In two of the four study catchments (240 and Redfish) harvesting has resulted in increases in both the mean and the standard deviation of the post-treatment series of flood peaks compared to the pretreatment or

Table 3. Linear Regression Analysis of Meteorological Variables With Discharge

Regression[a]	R^2	P Value
Fool (Qp) = 6.9442(Max SWE) + 32.501	$R^2 = 0.511$	$p < 0.001$
Camp (Qp) = 0.0056(Max SWE) − 0.2481	$R^2 = 0.381$	$p < 0.001$
240 (Qp) = 0.0019(Max SWE) + 0.6933	$R^2 = 0.076$	$p < 0.01$
Redfish (Qp)= 0.0072(Max SWE) + 1.251	$R^2 = 0.269$	$p < 0.001$
Redfish (Qp) = 0.0705(3 day melt) + 1.3132	$R^2 = 0.582$	$p < 0.001$
240 (Qp) = 0.0184(3 day melt) − 0.0022	$R^2 = 0.902$	$p < 0.001$
Fool Creek (Qp) = 4.5179(3 day avg. T) + 206.9	$R^2 = 0.014$	$p < 0.05$
Camp Creek (Qp) = 0.107(3 day avg. T) + 0.5125	$R^2 = 0.475$	$p < 0.001$
Camp(Daily Q) = 0.115 (7 day avg. T) − 0.0094 (1981)	$R^2 = 0.812$	$p < 0.001$
Fool (Daily Q) = 16.67 (7 day avg. T) − 14.31 (1976)	$R^2 = 0.813$	$p < 0.001$

[a] Units: Qp ($m^3 s^{-1}$) except Fool Creek (l/s), Max SWE (mm), 3 day melt (mm), Avg. T (°C).

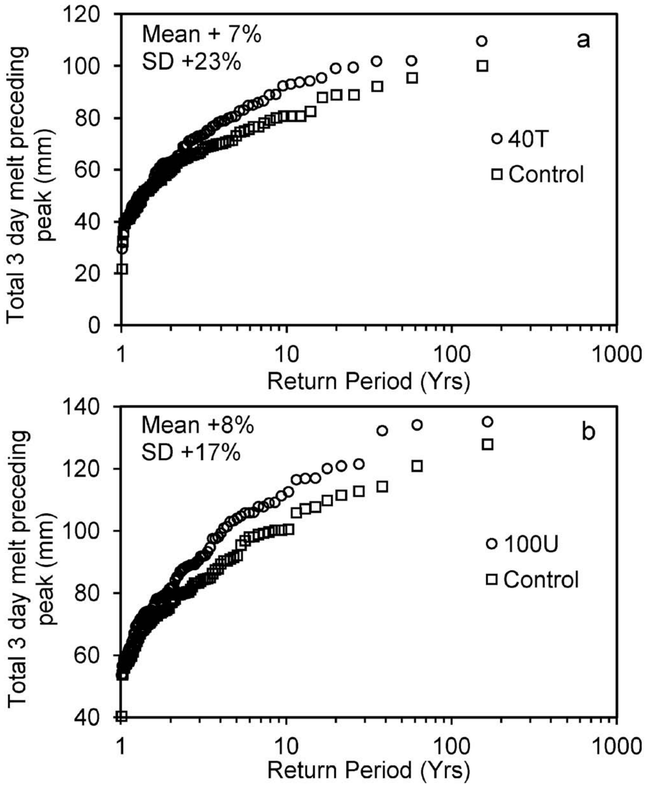

Figure 6. Flow duration curve analysis of catchment average 3 day snowmelt preceding the annual maximum peak flow for: (a) 40% clear-cut and control scenarios in 240 Creek and (b) 33% clear-cut and control scenarios for Redfish Creek.

control series. In the third catchment (Camp) harvesting has increased only the mean with almost no change in the standard deviation, while in the fourth catchment (Fool) harvesting has increased the mean but decreased the variability of post-treatment floods.

[51] Investigating changes to the mean and variability of post-treatment flood peaks represents a paradigm shift with respect to the way treatment effects are physically explained and quantified [*Alila et al.*, 2009] in the study of forest hydrology. Past investigations using CP-based analysis, with associated ANOVA or ANCOVA methods, attempted to quantify changes in the mean of the post-treatment sample while controlling for changes in variability, most often through log transformation of flood magnitudes or categorical parsing of data sets [e.g., *Jones and Grant*, 1996; *Thomas and Megahan*, 1998; *Jones*, 2000]. However, this traditional approach fails to recognize the importance of changes in variability in quantifying changes in extreme events [*Katz and Brown*, 1992]. By investigating treatment effects in terms of changes in both the mean and variability of the post-treatment frequency distribution we reveal how, in snowmelt-dominated regions, harvesting has influenced floods across a much wider range of magnitude including the largest floods on record.

[52] The increase in the mean and variability of post-treatment peak flows at Camp, 240, and Redfish Creeks and the upward shift of all post-treatment peak flows, save the largest event, translate into a divergence of the empirical post-treatment CDFs with increasing return period relative to the pretreatment CDFs. The sudden disappearance of the vertical difference between the pre- and post-treatment CDFs at the largest flood for these three catchments cannot be touted with any physical meaning without considering the error in the plotting position for the largest one or two floods [e.g., *Alila et al.*, 2009]. In fact, we consider the dip in the last point that gives the impression of no effect on the largest flood to be inconsistent with the physical outcome of an increase in the mean and standard deviation which is that the post-treatment curve is shifted upward and becomes steeper than the pretreatment curve and therefore the two curves should diverge (or run parallel in case of a no change in standard deviation), at least within the range of observed or simulated peak flows. The intersection between pre- and post-treatment CDFs, imposed by the dipping of the largest flood event, shifts to a higher return period from about 20 year at Camp to beyond 100 year at 240 and Redfish Creeks. Our meta-analysis therefore clearly illustrates that this dipping of the largest flood event is not real and is an artifact of sample size.

[53] Within a frequency distribution framework we observe consistent changes in flood frequency in the four study catchments regardless of the changes in the variability of the post-treatment peak flows (i.e., whether the CDFs are converging, diverging, or running parallel). The upward shift in the post-treatment CDF associated with the increase in the mean of the distribution causes the frequency of all floods in all four catchments to increase despite the deceptive rapid decrease in the relative increase in the magnitude of the 2, 10, 20, and 50 year return period floods (Figure 2). In general, we observed that events up to approximately the 20 year flood double in frequency (e.g., 10 year becomes a 5 year and 20 year becomes a 10 year flood) while larger floods tend to increase in frequency by 2 to 4 times (e.g., 50 year may become a 30 or 13 year flood). The larger increase in frequency for the larger magnitude floods is due to the highly nonlinear relation between flood frequency and magnitude which creates large increases in frequency for floods in the upper tail of the distribution even if the increase in magnitude is below statistically significant levels. The effect of larger increases in frequency for larger floods appears to be particularly evident in these snowmelt-dominated catchments where the slopes of the CDFs are relatively gentle so that small changes in magnitude translate into surprisingly large changes in return periods. We therefore illustrate for the first time how the occurrence of more frequent events of same magnitude, or higher magnitude events of same frequency, are amplified in watersheds with milder sloping flood frequency curves as a consequence of forest harvesting. In a century of CP-based literature that rarely invoked the dimension of frequency only *Berris and Harr* [1987; p. 141] hinted to such a scientifically and practically profound generalizing percept that the peak flow regimes of watersheds with milder slope flood frequency curves should be more sensitive to forest harvesting.

[54] In all four catchments forest harvest appears to have increased flood magnitude over a wide range of return periods including the 5, 10, and 20 year events in Camp and Fool Creeks, and up to the 50 year events in 240 and Redfish Creeks. Most intriguing perhaps is that the outcome of our meta-analysis suggests there is no clear upper threshold

to the effects of forest harvesting on floods in snowmelt-dominated hydroclimate regimes. As post-treatment sample length increases between our four study catchments the threshold return period beyond which forest harvesting has no effect shifts toward the right. The rightward shift of the no-effect threshold with increasing post-treatment sample length was also demonstrated by *Alila et al.* [2009] when they extended the post-treatment sample length for Fool Creek from 29 years to 48 years. *Kuraś et al.* [2012] came to the same conclusion of a no clear upper threshold to the effects of forest harvesting on floods in snow environments using 100 years of model simulated postharvest peak flows. Our findings are inconsistent with the claim reported and rereported in the literature from snowmelt-dominated regimes, that forests have no or minimal effects on larger return period floods [e.g., *MacDonald and Stednick*, 2003; *Moore and Wondzell*, 2005; *NRC*, 2008; *Bathurst et al.*, 2011a].

[55] The results of our physical process investigation do not support the assertion that larger floods are not affected by harvesting due to an "overwhelming" of the interception capacity of the forest canopy and storage capacity of the forest soils that has been used to explain the relative decrease in treatment effects with increasing flood magnitude [*MacDonald and Stednick*, 2003; *Brooks et al.*, 2003; *Lee*, 1980; *Jeffrey*, 1970; *Chang*, 2006; *NRC*, 2008]. To the contrary, regardless of the relative role of forests on evapotranspiration, our findings suggest that the mitigating effects of the forest canopy on snowmelt, the primary process controlling peak flows, are maintained over the full post-treatment sample, which is consistent with multiyear stand level investigations that have found melt rates to be consistently higher in cut blocks relative to the forest regardless of the seasonal variability in meteorology during the study period [*Golding and Swanson*, 1978; *Kattelmann*, 1991; *Toews and Gluns*, 1986; *Winkler et al.*, 2005; *Jost et al.*, 2007].

[56] Our finding that the effect of forests on floods has no clear upper no-effect threshold return period in four snowmelt catchments, at least within the range of observed or simulated records, challenges a precept at the very core of forest hydrology. Such a precept is reinforced by decades of paired watershed studies guided by the inappropriate hypothesis that treatment effects can be measured as the difference between chronologically paired peak flow magnitudes. By ignoring changes in the frequency of floods the traditional CP-based analysis fails to reveal that while the largest floods may or may not be increasing in magnitude relative to the chronologically paired control catchment floods, the small and moderate floods are being elevated in magnitude as a result of harvesting to become some of the largest floods on the observed or simulated peak flow records of the treatment watershed. Additionally, while harvesting may or may not be resulting in statistically significant increases in the magnitude of the largest floods, the frequency of these floods has tripled or quadrupled resulting in what appear to be physically real and potentially damaging treatment effects within the fluvial ecosystem.

6.2. Linking Meta-analysis Results With Stand Level Process Understanding

[57] The main objective of a meta-analysis is to gain an understanding of influence of physical characteristics on the treatment response by observing the differences and/or similarities in treatment response in multiple basins. Our meta-analysis revealed that the mean of the frequency distribution of post-treatment peaks increased in all four catchments while the variability of post-treatment peak flows increased in two catchments, remained unchanged in the third, and decreased in the fourth catchment. We also observed consistent changes in flood frequency between control and treatment catchments. The upward shift of the post-treatment CDF causes the frequency of all floods to increase relative to their pretreatment return periods. These treatment effects hint at consistent physical changes in the processes governing peak flows in snowmelt dominated hydroclimatic regimes.

[58] Previous forest hydrology studies have attributed stand level changes in snow accumulation and melt rates following harvesting to peak streamflow increases at the basin scale [*MacDonald and Stednick*, 2003; *NRC*, 2008]. The role of reduced evapotranspiration in harvested areas has also been conjectured in explaining increases in peak flows in snow environments [*MacDonald and Stednick*, 2003]. However, a recent basin-scale process investigation indicates that reductions in evapotranspiration account for a minor component of peak flow increases in snow environments (Schnorbus and Alila, submitted manuscript, 2012). Our regression analysis determined that streamflow magnitudes are poorly correlated to maximum annual snow accumulation but strongly correlated to 3 day total basin average snowmelt (modeled catchments) and to 7 day average air temperature (observed catchments), both of which point to changes in the energy balance as the primary process driving peak streamflow. *Winkler et al.* [2008] also recognized the greater importance of changes in snowmelt associated with increased short wave radiation as the primary mechanism generating peak streamflows based on observed data in the Upper Penticton Creek study.

[59] A frequency analysis of basin average total 3 day melt preceding peak flows using simulated snowmelt output for 240 and Redfish Creeks indicates that in both catchments moderate levels of forest removal increases the mean and variability of basin average total 3 day snowmelt preceding peak flows but despite physical differences between the two catchments only the change in variability displays any substantial difference (standard deviation shows a 23% increase in 240 versus 17% increase in Redfish). We interpret this result to indicate that differences in basin physiography (size, aspect, slope gradient, etc.) has a greater influence on the behavior of extreme melt events which influence the standard deviation of the sample than on the mean melt event. In both 240 and Redfish Creeks, similar increases in the mean of the total 3 day melt (7% and 8%, respectively) reflects similar average increases in snowmelt with similar levels of forest removal. In both catchments increases in total 3 day melt is maintained over the full range of meteorological conditions included in the model.

[60] Increases in catchment-average total 3 day snowmelt observed in 240 and Redfish Creeks using simulated output are much lower than increases in seasonal average melt rate reported in multiyear stand-level investigations [*Golding and Swanson*, 1978; *Kattelmann*, 1991; *Toews and Gluns*, 1986; *Teti*, 2004; *Winkler et al.*, 2005; *Jost et al.*, 2007], which is not surprising when basin averaged

melt rates, averaged across multiple aspects and elevations, are compared to melt rates of a single stand site. Stand-level increases in seasonal average melt rates range from two to three times the melt rate in the adjacent forest stands [*Kattlelmann*, 1991; *Winkler et al.*, 2005]. In these detailed stand level studies melt rate increases vary as a function of slope gradient, aspect, elevation, and forest cover characteristics [*Winkler et al.*, 2005; *Jost et al.*, 2007; *Ellis et al.*, 2010; *Varhola et al.*, 2010]. Melt rate increases associated with forest removal have been found to be much lower on north aspect slopes than on west and south aspect slopes due to natural shading that limits potential increases in shortwave radiation [*Jost et al.*, 2007; *Ellis et al.*, 2010] and are also comparatively lower in gentle gradient terrain due to a greater influence of shade-related long wave radiation on snowmelt [*Ellis et al.*, 2010]. Smaller increases in net radiation and snowmelt rate have also been documented for open pine stands and adjacent clear-cuts than compared to nearby denser spruce stands and adjacent clear-cuts due to the relatively higher net radiation and higher melt rates in the open pine stands [*Winkler et al.*, 2005; *Ellis et al.*, 2010].

[61] If we make use of the collective outcomes of the above stand-level energy balance studies to assess the potential for catchment-scale flood response we would expect the largest harvesting related increases in the mean and variability of post-treatment peak flows to occur in catchments that most directly reflect the largest increase in energy due to the change from longwave to shortwave-dominated snowmelt. The stand level studies cited above suggest basin characteristics of aspect distribution, elevation distribution, canopy density, and slope gradient should all influence catchment scale flood response to harvesting. More specifically, larger increases in basin-average melt rates and resulting peak flows reflecting the increase in net radiation related to the change from longwave to shortwave-dominated melt should occur in catchments where aspect distribution and elevation range are minimal, forest canopy density is high, and slope gradient maximizes absorption of incoming shortwave radiation (insolation). The largest increases in post-treatment peak flow variability should occur where increased snowmelt is most effectively and synchronously delivered to the stream channel. That is, the physical basin characteristics contributing to the largest increases in post-treatment peak flow mean and variability should minimize the potential for desynchronization of melt due to shading on contrasting aspects or differences in the timing of maximum snowmelt across a large range of elevation. In addition, drainage density should also influence the change in the mean and variability of post-treatment peak flows because it reflects the efficiency of the delivery of runoff to the mainstream channel [*Alila et al.*, 2009; *Pallard et al.*, 2009]. The influence of basin characteristics with respect to synchronization of snowmelt runoff and delivery of runoff to stream networks consistent with the conjectures presented above has recently been confirmed using detailed DHSVM model output for the upper 50% and bottom 50% harvest scenarios in 240 Creek Schnorbus and Alila (submitted manuscript, 2012). The results of their physical process investigation using simulated model outputs indicate that harvesting in the upper 50% increases peak flow response through the synchronization of melt between upper and lower elevation slopes. However, in the case of 240 Creek the timing of delivery of meltwater from upper elevation slopes is influenced more by low drainage density in the upper half of the drainage than by elevation range (Schnorbus and Alila, submitted manuscript, 2012).

[62] Decades of literature on hydrologic processes have intensively studied, using a deterministic approach, the complex idiosyncrasies of single plots, hillslopes, and catchments in isolation [*McDonnell et al.*, 2007] that have added "another brick to the temple of science" [*Platt*, 1964, p. 351] but making it difficult to derive generalizing principles of how forests may be affecting the flood frequency regime across scales and locations. Here we combine our intersite comparison of flood response to forest harvesting across our four study watersheds with related stand-level energy balance studies to hypothesize the conceptual model of Figure 7. This original model illuminates some of the first order controls of the relation between forest cover and the flood frequency curve in snow environments.

[63] The results of our meta-analysis are generally consistent with our proposed conceptual understanding of the potential for flood basin response to forest harvesting outlined in Figure 7. Camp Creek, the largest of our four catchments, is a fully forested, dominantly south aspect, catchment with moderate gradient slopes that displays the largest increase in the mean (35%) and almost no change in the variability (1%) of post-treatment peak flows. According to our proposed conceptual understanding, the large increase in the mean stems from the combination of dominantly south aspect slopes and relatively high preharvest canopy density but the lack of synchronization during snowmelt due to the large elevation range of the harvested area (Table 2) limits the increase in variability. 240 Creek, which is a much smaller catchment than Camp Creek with a more open canopy, a more variable aspect distribution, and a less variable elevation distribution, displays smaller increases in the mean (15%) but a large increase in variability (19%) of post-treatment peak flows. This response suggests that harvesting is not elevating peaks to the same degree as in Camp but that runoff is being delivered to the stream channel in a more synchronized way than in Camp. Redfish Creek, our steepest gradient catchment, displays the smallest increase in the mean (11%) but also larger increases in variability (18%). The small increase in the mean in Redfish suggests that one or more basin characteristics including large alpine area, steep gradient slopes, multiple aspects, and a large elevation range limit increases in peak flows, however, the larger increase in variability indicates that harvest related increases in runoff from a relatively concentrated elevation band are effectively delivered to the stream network, which is not surprising in a steep, well drained catchment. Finally, Fool Creek, a predominantly north aspect drainage with an upper alpine area and high canopy density displays the most unique response to forest harvesting of the four catchments investigated in this study with the second largest increase in the mean (23%) but a decrease in the variability (−12%) of peak flows compared to the control catchment. In Fool Creek the increase in the mean of the post-treatment peak flows reflects relatively large increases in snowmelt runoff following harvesting of densely forested slopes but the decreased variability suggests increased de-synchronization of runoff between upper elevation alpine areas and lower

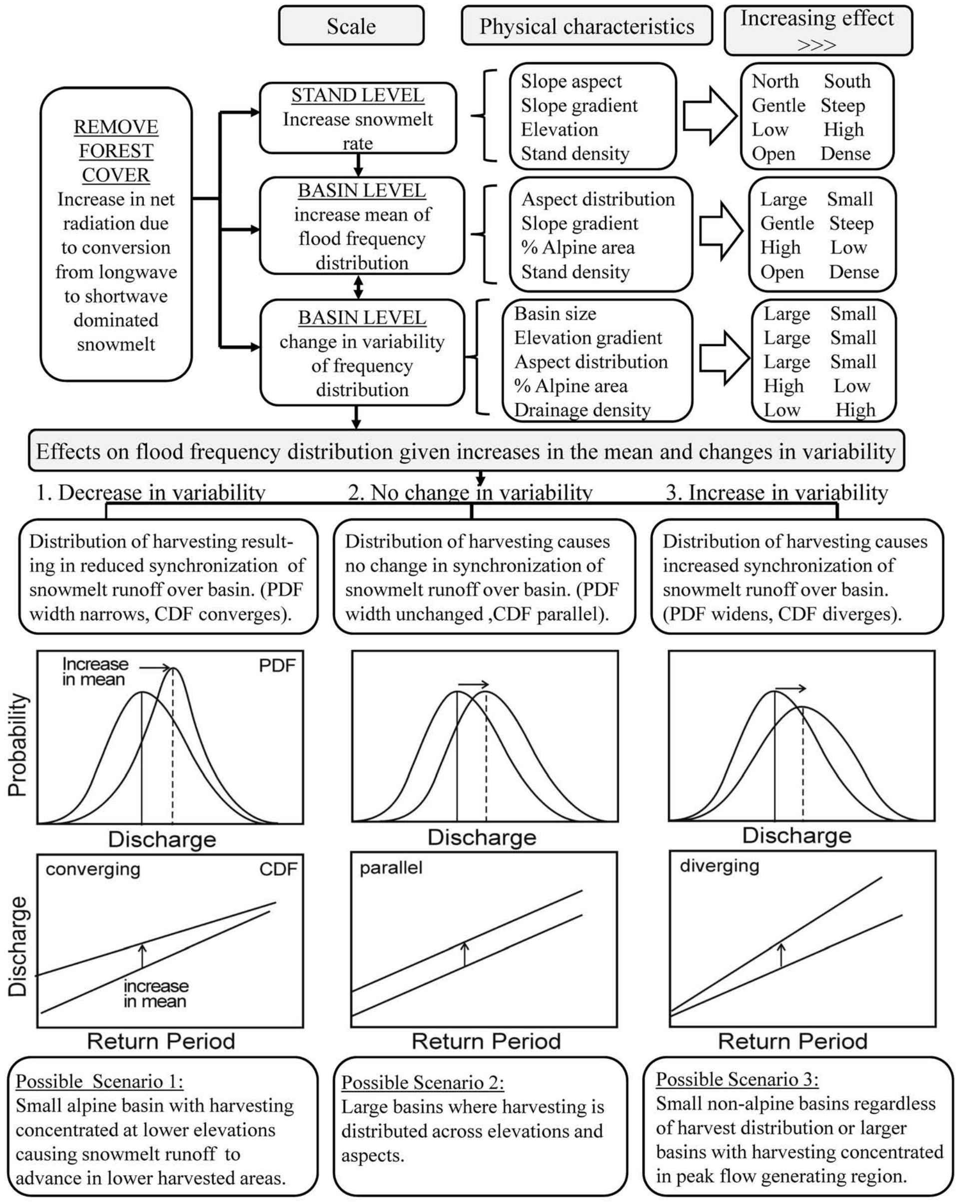

Figure 7. Conceptual model of the influence of basin characteristics on daily annual peak flow maxima response following harvesting. Harvesting may also influence the form (skew) of the distribution but our conceptual model considers only changes in the mean and variability. Harvesting induced changes to evapotranspiration and runoff routing may also play a role in peak flow response but to a much lesser extent than the conversion from longwave to shortwave radiation.

elevation slopes where harvesting was concentrated. Our conceptual understanding of the influence of harvesting on runoff in Fool Creek is consistent with an earlier detailed investigation of snowmelt timing at the same site, which found that prior to forest harvesting, peak flows were generated by snowmelt occurring concurrently from both the alpine and forested areas. Following harvesting however, snowmelt from the forested area was advanced so that runoff from forested areas preceded that from upper elevation areas and the annual peak flow was shifted by up to an average of a week earlier and driven primarily by lower elevation melt compared to the unharvested basin [*Troendle and Kaufmann*, 1987].

7. Conclusions

[64] Our meta-analysis of four snowmelt-dominated catchments identifies harvesting related increases in the magnitude of peak flows over a wide range of event sizes, including the larger floods of the approximate 10, 20, and 50 year return periods. In addition to observing increases in flood magnitude we also observe that forest harvesting results in two- to fourfold increase in the frequency of these large floods. In all four treatment watersheds preharvest small and moderate floods become larger and decrease in frequency while the largest floods increase in frequency following harvesting regardless of whether they show

statistically significant increases in magnitude. In two of our four study sites taken collectively, and inconsistent with the prevalent perception among scientists, the effects of harvesting on peak flows increase with increasing return period with no apparent no-effect threshold. Our estimated effects of forest harvesting on floods are representative of the most critical period after logging before any substantial recovery has occurred. However, the fact that no time trend was observed in the 19 year post-treatment data set for Camp Creek and only the last 12 years of the 48 year data set in Fool Creek required adjustment to correct for a time trend suggests that hydrological recovery occurs slowly in snowmelt-dominated hydroclimate regimes. This is consistent with previous analyses at Fool Creek which speculated that full hydrologic recovery of the flow regime may take as long as 80 years after logging [*Troendle and King*, 1985].

[65] The outcome of our meta-analysis, that the largest floods on record are increased in frequency for all four catchments should be acknowledged as a real effect of forest harvesting irrespective of statistical significance because it represents a repetitive, physically explainable pattern in magnitude and direction among the four study sites [*Lewis et al.*, 2010]. Harvest induced changes in the mean and variability of peak flows responsible for such surprising increases in the frequency and magnitude of larger floods in our four snowmelt-dominated watersheds can be explained by applying an understanding of the influence of forest removal on changes in the energy balance at the stand and watershed scales. We find that the dominant physical process associated with increases in peak flows is the increase in net radiation associated with the conversion from longwave-dominated snowmelt beneath the forest canopy to shortwave-dominated snowmelt in harvested areas. At the stand level, physical factors including slope aspect, slope gradient, and canopy density combine to influence the increase in net radiation. At the catchment level we propose that basin characteristics including aspect distribution, elevation range, slope gradient, the amount of alpine area, and drainage density can all influence the magnitude of changes in the mean and variability of peak flows following harvesting. We observe that the greatest increase in the mean of the post-treatment flood frequency distribution occurs in a fully forested, predominantly south aspect catchment and the smallest increase occurs in the steep east–west aspect, alpine catchment. The increase in variability of the post-treatment frequency distribution appears to reflect the efficiency (synchronization) of delivery of increased snowmelt to the stream channel.

[66] The consequences of dismissing an effect based on statistical significance with no consideration for either physical or practical significance can be far reaching, an argument continuously emphasized across disciplines [*Alila et al.*, 2009]. Our study outcome, that the largest floods experience the largest increase in frequency, has implications with respect to the lifespan of engineered structures, the safety of human settlement as well as the sustainability of fluvial ecosystems. The potential for increased frequency of damaging floods due to upstream forest harvesting was conjectured by engineers in the early 1900s [*Hoyt and Troxell*, 1932]. The results of our meta-analysis, undertaken a century later, support their original concerns that harvesting in upstream headwater forests can increase the occurrence of damaging floods. In addition to the concerns for impacts to human infrastructure, the role of flood frequency in maintaining fluvial and riparian ecosystems has garnered substantial attention in recent decades [*Resh et al.*, 1988; *Naiman et al.*, 2005]. While flood disturbance is important for maintaining habitat diversity and sediment and nutrient flux between terrestrial and aquatic environments [*Naiman et al.* 2005] the form and function of a fluvial system is adjusted to a flood regime consisting of infrequent channel-forming floods and more frequent channel maintaining bankfull floods [*Wolman and Miller*, 1960; *Schmidt and Potyondy*, 2004]. Increases in the frequency of large channel forming floods has the potential to destabilize fluvial stream channels beyond the natural range of variability causing long term changes to channel form and function [*Schmidt and Potyondy*, 2004].

[67] Although the flaw in CP-based analytical methods has recently been brought to the attention of the forest science community [*Alila et al.*, 2009; 2010] and consequently acknowledged by regulatory agencies [*United States Department of Agriculture, Forest Service*, 2010; *Bunnell et al.*, 2011] traditional CP-based analyses continue to be used in the investigation of forest and floods. Numerous literature syntheses reporting that there is no clear relationship between level of harvest and changes in peak flows but that the largest peak flows appear unaffected by logging are the consequence of an old paradigm that misguided research for a century and misled land managers and policy makers for decades [*Hewlett*, 1982; *Scherer and Pike*, 2003; *Calder*, 2005; *Grant et al.*, 2008; *NRC*, 2008; *Redding et al.*, 2008; *Winkler et al.*, 2009; *Bathurst et al.*, 2011a, 2011b]. The rapid decrease in relative treatment effect with increasing flood size either in FP domain, as illustrated in this study, or in CP domain, as reported in past studies [e.g., *Beschta et al.*, 2000; *Thomas and Megahan*, 1998; *Calder*, 2005; *Birkinshaw et al.*, 2010; *Bathurst et al.*, 2011a, 2011b] is irrelevant and does not translate physically to larger floods not affected by harvesting. In the analysis of forest effects on floods the primary changes of interest are: (1) a change in magnitude for an event of a specific frequency and, most importantly (2) a change in return period for an event of a specific magnitude; and this evaluation can only be made through direct comparison, in absolute and not relative terms, of frequency distributions of the pretreatment expected or control and post-treatment flood series.

[68] The outcomes of our FP-based meta-analysis have brought to light some fundamental but critical aspects of extreme value theory applied to the forests and floods relation in snow environments namely:

[69] 1. There is a strong nonlinear relation between changes in the mean of a flood frequency distribution and changes in the probability of larger floods, where small changes in mean or in flood events larger than the mean can translate to large changes in their return period.

[70] 2. In an evaluation of the relation between forests and floods changes in variability could be as important as changes in averages. Changes in variability could be an essential aspect of the investigation and may be a keystone to any physical understanding and prediction of the effects of forests on the magnitude and frequency of larger floods.

[71] 3. Larger flood events are more sensitive to a simultaneous increase in the mean and variance of the flood frequency distribution than in its mean alone.

[72] 4. Irrespective whether forests harvesting has increased the mean and variance, increased the mean alone or increased the mean and decreased the variance, the larger the flood the more frequent it may become.

[73] 5. While the effects of forest clearing on the magnitude of large floods may, in some cases, decrease with increasing return period, the more important and still open question is, however, where "large" begins or how rare must floods be [*Sturdevant-Rees et al.*, 2001, p. 2161] for the consequential increase in net radiation causing the melt to have no effects on floods?

[74] These are some of the same tenets which have long been recognized by climatologists since the mid-1980s [e.g., *Mearns et al.*, 1984; *Wigley*, 1985] and which brought clarity of perspective to the approach guiding the scientific investigation of the relation between climate change and weather extremes [e.g., *Katz*, 1993; *Katz and Brown*, 1992; *Allen and Ingram*, 2002; *Schaeffer et al.*, 2005]. In decades of CP-based often contradictory literature on forest harvesting effects on peak flows, lip service is often paid to the effect of forests on flood frequency [e.g., *Rothacher*, 1973; *Beschta*, 1978; *Hess*, 1984; *Troendle and King*, 1985; *Wright et al.*, 1990; *Jones and Grant*, 1996; *Thomas and Megahan*, 1998; *Beschta et al.*, 2000; *Jones*, 2000; *Jones and Perkins*, 2010; *Birkinshaw et al.*, 2010; *Bathurst et al.*, 2011a, 2011b]. But just how will a small change in mean and/or variability affect the frequency of larger flood events? "Quantitative discussions of this subject are rare, and, surprisingly, there are some extremely simple analyses that have not yet been carried out" [*Wigley*, 2009, p. 68]. One of the implicit objectives of this paper was to remedy this deficiency.

[75] By overlooking the dimension of frequency at the outset of the investigation of forest influence on floods nearly a century ago the forest science community took the wrong research path which resulted in dozens of studies that were guided by irrelevant research hypotheses and therefore produced misleading outcomes. To emerge from this long-enduring period of contradictory and confusing study results forest hydrologists must abandon CP-based analysis and accept that the influence of forest removal on floods cannot be quantified without simultaneously investigating changes in both the magnitude and frequency of floods. To move forward toward a more comprehensive understanding of the connection between forests and floods we must retrace our path and reanalyze existing hydrometric data using FP-based methods. Similar observational studies of existing data could further corroborate our hypothesized physical explanations of the environmental controls on the forests and floods relation but could also lead to interesting new hypotheses that should be tested using the derived flood frequency approach [e.g., *Eagleson*, 1972]. Although common in the wider hydrology literature, such approach is relatively unexplored when it comes to advancing the understanding of the relation between forests and floods.

[76] Future research fundamental to improving our understanding of (a) forests influence on floods and (b) the extent to which current land use policies may have been misguided by past CP-based studies must begin with applying frequency based analysis in other hydroclimate regimes, especially rain-dominated environments that have been the focus of the majority of past CP-based studies. In addition, to establish sustainable annual harvest volumes and long-term timber supply rates, the influence of basin size and hydrological recovery must both be reinvestigated within a frequency distribution framework especially in light of a changing climate and wide spread mountain pine beetle infestation which have affected the North American Cordillera from Northern BC to southern Mexico [*Alila et al.*, 2009].

[77] **Acknowledgments.** We thank three anonymous referees for their especially detailed and helpful comments on an earlier draft. We gratefully acknowledge the guidance provided by Markus Schnorbus, Georg Jost, and Charles Luo in various aspects of data analysis. Thanks also to Rob Hudson and Andrés Varhola for their helpful editorial comments. We are grateful to Kelly Elder and the USFS for access to the Fool Creek hydrometric and climate data sets. A special thanks to W. Halleran for his unfailing support and enthusiasm throughout this hydrological journey. This work was partially funded by the National Science and Engineering Research Council of Canada Discovery Grant RGPIN 194388-11 to Y. Alila and Forest Investment Account Forest Science Program project funding Y051294 (Y. Alila) and Y081214 (D. Moore). We would like to thank our industry partners Tembec and Kalesnikoff Logging Company Ltd. for their ongoing support and for asking the questions that needed answering.

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