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Effects of Forest Practices on Peak Flows and Consequent Channel Response: A State-of-Science Report for Western Oregon and Washington

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Abstract

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This is a state-of-the-science synthesis of the effects of forest harvest activities on peak flows and channel morphology in the Pacific Northwest, with a specific focus on western Oregon and Washington. We develop a database of relevant studies reporting peak flow data across rain-, transient-, and snow-dominated hydrologic zones, and provide a quantitative comparison of changes in peak flow across both a range of flows and forest practices. Increases in peak flows generally diminish with decreasing intensity of percentage of watershed harvested and lengthening recurrence intervals of flow. Watersheds located in the rain-dominated zone appear to be less sensitive to peak flow changes than those in the transient snow zone; insufficient data limit interpretations for the snow zone. Where present, peak flow effects on channel morphology should be confined to stream reaches where channel gradients are less than approximately 0.02 and streambeds are composed of gravel and finer material. We provide guidance as to how managers might evaluate the potential risk of peak flow increases based on factors such as presence of roads, watershed drainage efficiency, and specific management treatments employed. The magnitude of effects of forest harvest on peak flows in the Pacific Northwest, as represented by the data reported here, are relatively minor in comparison to other anthropogenic changes to streams and watersheds.

Keywords: Peak flow, forest harvest, channel morphology, Pacific Northwest.

Summary

This paper presents a state-of-the-science synthesis of the effects of forest harvest activities on peak flows and channel morphology in the Pacific Northwest (PNW), with a specific focus on western Oregon and Washington. Findings are broadly applicable to additional areas in the PNW and other regions with similar physical characteristics. The primary intent is to provide technical guidance to land managers in distinguishing potential major from minor effects. We develop a database of relevant studies reporting peak flow data across rain-, transient-, and snow-dominated hydrologic zones, and provide a quantitative comparison of changes in peak flow across a range of flows and forest treatments. We consider treatments that are implemented at the scale of individual harvest units and small catchments (<10 km^2). We also suggest an approach for evaluating potential risk from peak flow increases in larger basins (>10 km^2) with complex management histories. We provide a qualitative analysis for interpreting likely magnitude of peak flow changes on channels of different geomorphic types.

The primary research studies used to evaluate effects of forest practices on peak flows come from long-term, experimental watersheds and, to a lesser extent, modeling and process studies. We organized studies from the literature based on hydrologic zones and intensity of management activities conducted. Next, we analyzed the data for peak flow trends across the range of flows and intensity of management treatments represented, ultimately focusing on geomorphically effective events (recurrence interval greater than 1 year) that have the potential to influence channel morphology. We constructed response lines representing the maximum and mean reported peak flow increases (expressed as percentage increase) from small watershed studies, and evaluated these increases against the limits of detectable change from flow measurements alone (approximately 10 percent change). We then expanded our scale of investigation to look at how other factors such as roads, patterns of cuts, and riparian buffers potentially influence peak flows at larger watershed scales, and suggest means of interpreting the envelope lines from the small watershed studies in larger basins. Finally, we fold considerations of channel type and morphology, as defined primarily by channel gradient, into the analysis to provide a first-order prediction of whether peak flow increases of a particular magnitude might affect channel structure in a particular basin.

The site-scale data support the interpretation that watersheds located in the rain-dominated region are less sensitive to peak flow changes than those in the transient snow region. The data further support the interpretation that if peak flow increases

do occur, they can be detected only in flows with a return period of 6 years or less. Effects of forest harvest on extreme flows cannot be detected using current technologies and data record lengths, but hydrologic theory suggests that such effects are likely to be small. Small watershed studies (particularly those involving clearcuts) likely represent the maximum effect of forest harvest on the landscape, and we suggest that such effects should diminish, or at most remain constant, with increasing watershed size.

Moreover, the data support the inference that when present, peak flow effects on channels should be confined to a relatively discrete portion of the stream network: stream reaches where channel gradients are less than approximately 0.02 and streambed and banks are gravel and finer material. Peak flow effects on channel morphology can be confidently excluded in high-gradient (slopes >0.10) and bedrock reaches, and are likely to be minor in most step-pool systems. On the other hand, if channels are gravel or sand-bedded, a more detailed hydrologic and geomorphic analysis seems warranted.

The magnitude of effects of forest harvest on peak flows in the Pacific Northwest, as represented by the data reported here, are relatively minor in comparison to other anthropogenic changes to streams and watersheds. The impact of forest harvest in the Pacific Northwest on peak flows is substantially less than that of dams, urbanization, and other direct modification of channels.

Introduction

This paper presents a state-of-the-science synthesis of the effects of forest harvest activities on peak flows and channel morphology in the Pacific Northwest, with a particular focus on western Oregon and Washington. In this paper, we suggest reasonable ranges of interpretation for existing studies and provide a framework for extrapolation of the findings to modern applications. We use published and peer-reviewed scientific literature including both primary studies and syntheses in our analysis. This work draws on recent literature reviews (e.g., Guillemette et al. 2005, Moore and Wondzell 2005), which examine a full suite of hydrological changes attributed to forest management across a large geographic region. Here we adopt a narrower geographic and topical focus because of the prominence of the peak flows issue in current management and regulatory discussions throughout western Oregon and Washington.

Our focus is exclusively on hydrologic changes to peak flows and consequent effects on stream channels. We recognize that there are many other hydrologic effects relevant to managers, including changes to low flows, water yield, etc. In the interests of providing focus, and also because the peak flow issue remains one of the most contentious in terms of land management decisions, we restrict our analysis to changes in peak flow. Further, we do not examine other well-researched geomorphic responses to land management (e.g., landslides) even though hydrologic processes are often involved. Finally, in interpreting potential effects of peak flow changes on channels we emphasize changes that have biological implications, i.e., changes to aquatic habitat and sediment transport, but do not consider biological or water quality effects directly.

Our intent is to help land managers distinguish potential major from minor effects in evaluating impacts of forest harvest on peak flows. We maintain that, despite some controversy in the interpretation of study results, there is actually a substantial amount of agreement among scientists as to the likely magnitude and consequence of peak flow changes. Moreover, we recognize important variation in peak flow response across hydrologic regions and forest harvest treatment types and suggest ways that this variation can be acknowledged in forest planning. Because of the changing nature of land use practices and large gaps in data for various treatment types, this study must inevitably rely on extrapolation of well-established results into areas with much less data, hence less certainty. We have tried to do this by using clear logic and assumptions that can provide useful sideboards to constrain uncertainty, and guide management decisions.

Beginning with some background perspectives on the peak flow issue, we lay out an approach that we believe offers a consistent train of logic to help guide management direction in this area. We develop a database of relevant studies reporting peak flow data, and provide a quantitative comparison of change in peak flow across a range of flows and forest treatments, and among hydrologic zones. We also consider how treatments that are implemented at the scale of individual harvest units might also affect peak flows at the scale of larger drainage basins, where the pattern and age of management units, presence of roads, and condition of riparian areas are all factors. Finally, we provide a qualitative analysis for interpreting likely magnitude of peak flow changes on different channel types. Taken together, these findings are intended to help managers understand the likely magnitude of forest management effects on peak flows and channel morphology in western Oregon and Washington.

Context

Understanding the approach taken here requires appreciation of the broader context of peak flows and the changing nature of forest management practices.

Motivating Issues

The relationship between forest practices and streamflow has been with us for millennia. Plato wrote of the connection between forests and streamflow in the *Critias*, and an ancient Chinese proverb reads: “To rule the mountain is to rule the river.” The first “protection forest” was established in Switzerland in 1342 to control torrents in the Alps, and such forests were common by the 16th century in Switzerland, Austria, and Germany. In the United States, establishment of federal forest reserves in 1891 was motivated by securing “favorable conditions of flow” as well as providing for timber supply. Widespread concern over the relationship between forest cutting and floods provided the impetus for laws establishing the National Forest System in 1905, and this concern is renewed following all major floods when it becomes fashionable to damn forestry as a primary cause of flooding. In the view of the public, and even among trained professionals, the relationship between deforestation and floods is well-established and self-evident (FAO 2005).

The long history of scientific research examining the effects of forests and forest practices on hydrology reveals a much more complex story. Beginning in 1910 with the first paired-watershed experiments at Wagon Wheel Gap, Colorado, hydrologists have sought to establish the relationship between timber harvest, road construction, and related activities, and streamflow in a wide range of climatic, geographic, vegetative, and management settings. The published results of these studies provide a voluminous, dense, and often contradictory literature. With reference only to the effects of forest harvest on peak flows—the focus of this paper—results differ from study to study, watershed to watershed, and region to region. Consensus views have been difficult to achieve, however, perhaps because of the wide range of experimental locales, statistical approaches, treatment types and intensities, and watershed histories represented in the technical literature.

Despite this lack of consensus from the scientific community, land managers and regulatory agencies are in the position of having to plan forest land management in a manner that addresses the peak flow issue. Forest land managers in the Western United States have developed strategies intended to minimize the potential effect of forest activities on streamflow, particularly peak flows. Such strategies are often identified as a means of addressing potential cumulative watershed effects and have included a wide range of approaches, including scheduling constraints on timber harvest (i.e., aggregate recovery percentage [ARP]), and procedures to represent land use activities in a common currency of disturbance (i.e., equivalent clearcut area [ECA], equivalent roaded area [ERA]) (reviewed by Reid 1993). More recently, regulatory agencies in the Pacific Northwest charged with implementing the Endangered Species Act (ESA) must reconcile the scientific literature on peak flows with the potential effects on fish species and critical habitat as a result of activities designed under the Aquatic Conservation Strategy of the Northwest Forest Plan (Reeves et al. 2006, Tuchmann et al. 1996). In particular, the peak flow issue has most commonly surfaced as part of the ESA consultation process associated with specific land management projects proposed by federal agencies. Regulatory agencies and land managers must resolve uncertainties associated with this issue, and reasonably assess the relationship between any potential peak flow changes and consequences to channel morphology and fish viability. Moreover, there has been continuing litigation regarding cumulative effect analyses within National Environmental Policy Act (NEPA) documents.

With both the Bureau of Land Management (BLM) and Forest Service facing major revisions of their regional-scale forest plans in the next few years in the Pacific Northwest, there is a clear need to revisit the issue of peak flows as it applies to forest management. This study and report were initiated by the BLM to provide a venue for technical analysis and guidance toward development and implementation of their new resource management plans (RMPs). This is particularly timely, as many of the forest management practices that were represented in small watershed studies in the past are changing in response to societal and ecological factors. Interpreting and extrapolating the results of this historical science in light of new management treatments is clearly necessary to bridge gaps in our understanding, and requires the perspectives of research scientists, field practitioners, and forest planners. This project is intended to begin to fill that gap.

To ensure that a broad range of both management and scientific views were considered in the development of this document, we held two 1-day workshops for external comment and review. The first, held in Corvallis, Oregon, in November 2005, included land managers and resource specialists (primarily hydrologists) from the BLM, Forest Service, and National Oceanic and Atmospheric Administration (NOAA) Fisheries. This workshop somewhat paralleled a similar one encompassing a broader set of hydrologic issues held at the H.J. Andrews Experimental Forest in May 2004 and funded by the Focused Science Delivery Program of the USDA Forest Service, Pacific Northwest (PNW) Research Station. At the 2005 workshop, the discussion focused on introducing our overall approach to this issue, including the hydrologic zone and management treatment framework, and soliciting input and suggestions on how to improve our analysis. The second workshop, held in Corvallis in March 2006, included scientists from across the Pacific Northwest whose work is relevant to aspects of the peak flow issue. Here we looked for an oral review and critique of the ideas contained in this paper and attempted to identify areas of common agreement and disagreement within the research community. Results of all three workshops have been incorporated into the document as best we could, but the paper does not necessarily reflect agreement or consensus among all workshop participants. Results from this study were also presented at the BLM State of the Science Conference in Corvallis in June 2006.

Historical Changes in Management Practices

Forest management practices on federal lands have changed a great deal in the last 50 years in response to changing markets, technology, social values, legal context, and scientific understanding of ecosystem responses. Intensive stand-level silviculture for timber production dominated federal forestry in the 1950s, 1960s, and 1970s. Although there was variation throughout the region and over time, typical practices included dispersed patch clearcutting, broadcast burning, and artificial regeneration. In some places, usually on sites that were more difficult to regenerate, shelterwood cuts were used instead of clearcuts. Shelterwoods typically left 30 to 40 percent of the basal area of the stand after the first harvest; a second harvest then removed these trees after regeneration was established, commonly 10 years later. Sometimes the second cut was never implemented and the shelter trees were left as a component of the stand, such as in Coyote Creek watershed 1. The majority of paired watershed studies in the region examine these early types of regeneration harvests.

In the late 1980s, changing science and changing values created an urgent need to modify these practices to reduce risks to species, habitats, and ecological processes, including peak streamflows. Integrating the lessons learned from long-term ecological studies into management practices resulted in the retention of large green trees, snags, and logs when regeneration harvests occurred, although the level of live tree retention differed greatly among sites. This practice of leaving green trees became known as "variable-retention harvesting" and encompassed practices where as few as 2 trees per acre (tpa) and as many as 30 to 40 tpa were left.

Regeneration harvests were dramatically reduced in the 1990s and post 2000 because of the need to conserve and recover populations of listed species, including northern spotted owls (*Strix occidentalis caurina*), marbled murrelets (*Brachyramphus marmoratus*), and several species of anadromous salmonids. Emphasis shifted to commercially thinning plantations established after clearcutting in the 1950s and 1960s. Although some commercial thinning was implemented prior to the 1990s, it was limited in extent. Initial native forest thins and precommercial thins were conservative and had little impact on stand development. However, as more information regarding the development of late-successional habitat emerged, thinning practices removed more material, sometimes leaving as few as 40 tpa. Thus the range of practices now described as thinning is as broad as (in terms of material retained), and potentially overlaps with, variable-retention harvesting.

The spatial pattern of forest harvests has also changed over time. In the 1950s, 1960s, and 1970s, clearcuts were dispersed across the landscape to help establish a road network, to intersperse areas of forage and cover for large game animals, and to distribute the hydrologic effects of forest cuttings. This began to change in the 1980s as the wildlife value of the remaining but increasingly scarce patches of intact older forest increased. Harvests were often aggregated to minimize fragmentation of the remaining old forest.

From a hydrological standpoint, a treatment that retains an extremely low percentage of live trees (e.g., 2 tpa, 100- to 80-percent harvested) can be assumed to be functionally equivalent to a clearcut. At the other end of the range (30 to 40 tpa, 30-percent harvested to lightly thinned), the challenge is to detect when hydrologic functions of a harvested watershed become significantly modified from uncut forest.

Influences on Peak Flows

It is well documented that intensive forest harvest, including clearcutting, broadcast burning, road building, and riparian disturbance, have the potential to dramatically change the biophysical processes in watersheds. Changes in annual water and sediment yield, low flows, peak flows, and water quality metrics (e.g., temperature, chemical composition) have all been observed after forest harvest, and tied to resultant ecological effects. These interactions have become an important feature of assessments of proposed forestry operations, although some aspects of these interactions are scientifically well understood, and some are not. We now have long records from experimental watershed studies (some exceeding 50 years) and maturing capability of simulation modeling to allow us to better test hypotheses of these complex linkages.

Forest management practices are not the only causes of historical variations in peak flow and other pertinent hydrologic parameters. Urbanization, agriculture, and grazing can all influence drainage efficiency, defined as the routing and timing of water delivery to the channel and through a stream network (Tague and Grant 2004). At the larger basin scale, dam and reservoir operations typically also alter the natural hydrograph, thus complicating the interpretation of direct effects of forest management to peak flows and channels. Natural disturbances such as stand-replacing wildfires, or landslides and debris flows, can also dramatically alter hydrologic and geomorphic systems.

A wide array of components factor into hydrologic and geomorphic behavior, including climate, biotic and geophysical processes, natural disturbances, and management practices; storage and fluxes of water, sediment, and wood; and resulting channel and water column habitat for aquatic organisms. This review focuses on a subset of these components: forest management effects on peak flow and channel structure (fig. 1). We recognize that this wider array of components and management practices may influence peak flow and channel structure independently and interactively, rather than directly. For example, peak flows redistribute sediment and pieces of large wood that, in turn, trap additional sediment, thereby creating

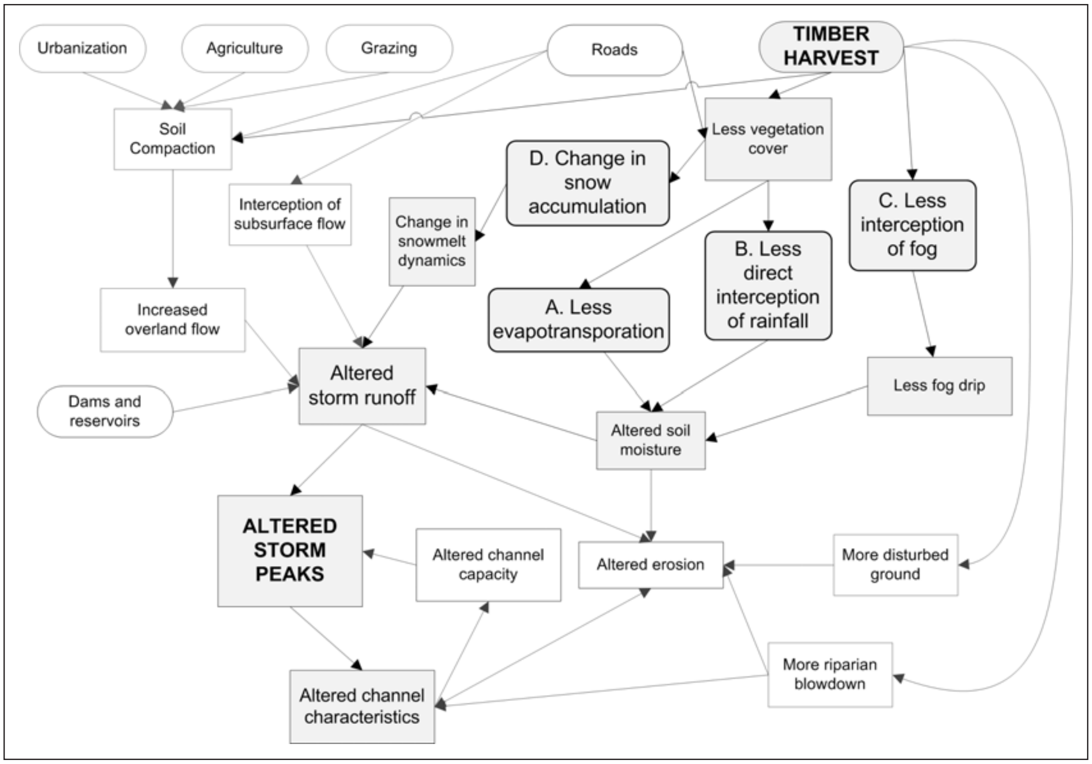

Figure 1—A process model of the relation between land use practices and altered storm peaks (after Ziemer 1998). Shading indicates processes considered in this report; A through D indicate boxes shown in figure 2.

channel habitat. We also recognize that in addition to our interest in changes in the magnitude of peak flow for the purposes of channel-changing sediment transport, changes in the timing and duration of peak flow events and the magnitude of peaks with recurrence intervals less than 1 year may have important ecological ramifications not discussed here. Although it is challenging to disentangle the complex effects of forest management on peak flows and channel morphology, we strive to keep our emphasis on the direct effects of forest management.

Technical Background

An extensive literature on a variety of mechanisms addresses the effects of forestry practices on peak flows (e.g., Beschta et al. 2000, Harr 1980, Jones and Grant 1996, Moore and Wondzell 2005, Reid and Lewis 2007, Ziemer and Lisle 1998). We begin by defining some hydrologic terminology and summarizing findings about key processes affected by forest harvest. We then explore the history, interpretations, and limitations of the paired watershed and modeling studies that have addressed changes in peak flow.

Defining Peak Flows

In the Pacific Northwest, natural fluctuations in stream discharge are controlled by seasonal precipitation and snowmelt patterns. With the majority of precipitation falling in the winter months, the annual hydrograph of a stream has a characteristic shape, reaching its highest levels during intense rain events or spring snowmelt, and receding to its lowest levels in the late summer. Overlain on this seasonal pattern are numerous hydrograph peaks that are because of individual precipitation events. Depending on the type of information desired, different populations of hydrograph peaks are used to perform statistical analyses that explore characteristics of, and changes to, peak flows. For this synthesis, we are primarily concerned with two of these populations: annual peak flow series, and partial-duration series. Dunne and Leopold (1978) presented a detailed discussion of the relation between the two types of series. Annual instantaneous peak flows are used in flood-frequency analysis to determine recurrence intervals (see below), whereas most peak flow investigations compare pre- and posttreatment partial-duration series, composed of a larger population of hydrograph peaks above a specified magnitude (see “Methods” section).

The **recurrence interval** (RI) or return period of a flow is the average number of years over the period of record that an annual peak flow equals or exceeds a specified discharge. This metric may also be reported as the annual exceedence probability, which is calculated as the inverse of the recurrence interval, e.g. the probability that the flow will be equaled or exceeded in any given year. For example, a flow with a 5-year RI has a 0.2 probability (20 percent chance) of being equaled or exceeded in any given year. Recurrence interval is based on the statistical characterization of a time series of annual peak flow values, often by fitting these values to an assumed probability distribution (i.e., Log Pearson). The highest instantaneous discharge of a stream each water year is considered the annual peak streamflow. The length of the data series determines the largest recurrence interval that can be calculated. For example, extracting the highest annual instantaneous peak flow from each of 10 years of measured streamflow allows the determination of the 1-, 2-, 5-, and up to the 10-year RI, but calculating the 20- or 50-year RI requires a longer record. Recurrence intervals of flows are commonly reported in peak flow studies and are used here to facilitate flow comparisons among watersheds.

Recurrence interval should not be confused with flow-duration analysis. Flow-duration curves are derived from daily streamflow values, and describe the percentage of time that flow is above or below a certain magnitude. Flow-duration analysis is useful for characterizing flows with recurrence intervals of 1 year or less.

The annual sequencing of flows and the inter-annual variation in discharge influences both the geomorphology of the stream channel and the ecology of aquatic and riparian habitats. This natural variation supports a complex relationship between channel morphology and ecosystem function. Flows that have the capacity to initiate bedload sediment transport, and thus channel change, are called geomorphically effective flows (Pickup and Warner 1976). In the coarse-grained streams typical of the Pacific Northwest, these flows generally occur at or above bankfull discharge, at recurrence intervals greater than 1 year (Andrews 1983, 1984), and are often captured by the analysis of an annual peak flow series. Flows with recurrence intervals of less than 1 year may transport sediment in fine-grained channels, and are more commonly analyzed with flow-duration statistics (e.g., Topping et al. 2000a, 2000b).

Hydrologic Processes Affecting Peak Flows

In general, changes in site-level conditions accompanying forest harvest are predicted to change local hydrologic processes such that peak flows generally increase (fig. 1). The strong seasonality of many of these effects can determine which processes are dominant at any given time. Our analysis involved interpreting how the change to each process is likely to scale with the intensity of treatment, and is summarized below and in figure 2.

Evapotranspiration—

Removal of trees and leaf area decreases evapotranspiration rates, leading to increased soil moisture in harvested areas; this reduces the subsurface saturation deficit that needs to be made up before direct runoff can occur, thereby increasing peak flows for the same volume storm. This effect is most pronounced in autumn when forest soils are driest. Once the soil mantle wets up, this effect largely disappears. This effect is expected to scale more or less linearly with the amount of vegetation removed by forest harvest (Harr 1976, Rothacher 1973).

Interception—

Canopy removal decreases the amount of water intercepted by vegetation during precipitation events allowing a greater proportion of total precipitation to reach the forest floor. Decreases in direct interception because of canopy removal therefore have the potential to increase soil moisture levels, thereby increasing peak flows (Reid and Lewis 2007). This effect should scale linearly with amount of canopy removed and can occur in any season.

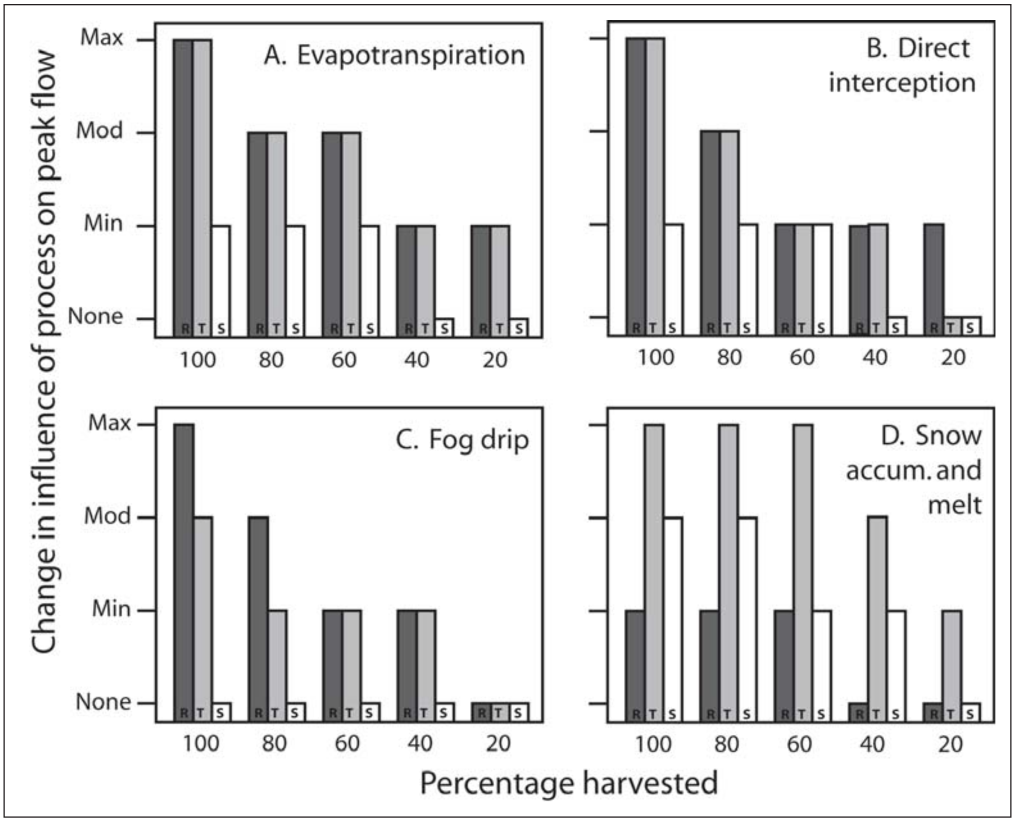

Figure 2—Conceptual change in influence of process on peak flow because of forest harvest for (A) evapotranspiration, (B) direct interception, (C) fog drip, and (D) snow accumulation and melt. The maximum possible change occurs at 100-percent harvest, and decreases with harvest as indicated by bar height for each of the three hydroregions: rain-dominated (R-dark grey), transient snow zone (T-light grey) and snow-dominated (S-white). The absolute value of the maximum effect is different among processes and hydrologic zones.

Cloud water interception—

Cloud water interception by the canopy (sometimes referred to as fog drip [Harr 1982]) can be a major source of water input in some watersheds. In this case, canopy removal has the potential to decrease cloud water interception, decreasing peak flows. As this process is strongly influenced by wind bringing moist air masses through canopies, the largest effects should be in harvested areas on upper hillslopes and ridges facing in the direction of the prevailing wind. Harvesting leeward slopes and valley bottoms should have less effect.

Snow accumulation and melt rates—

Changes to snow accumulation and melt rates may result in peak flow changes during both rain-on-snow (ROS) events and spring flows. Snow tends to accumulate in canopy openings and melt faster during warm ROS events, primarily as the result of energy released by moisture condensing on the snow surface; this effect is predicted to scale with the opening size (Harr and McCorison 1979). Large canopy openings, especially at higher elevations, are also subject to increased sublimation from wind, thereby reducing snow cover over time (Storck et al. 2002). Scaling this process is complex because of this nonlinear response.

Soil compaction—

Roads also play a key role in altering peak flow dynamics (fig. 1). Compaction of soils from construction of new access or skid roads results in less infiltration and greater overland flow. When this increased flow is intercepted by road networks that cross subsurface flowpaths and change flow routing, both the peak magnitude and time of peak concentration may change in a watershed. Because these mechanisms directly involve flow routing, the actual effect on peak flows depends on how increased flow and accelerated timing of runoff from road surfaces interact with other water delivery processes (Luce 2002). This effect should roughly scale with percentage of area compacted or length of road network that is directly connected to streams or both (Wemple et al. 1996) but is highly dependent on the location of roads in the landscape (Wemple and Jones 2003). It is difficult to disentangle road effects from harvest effects because most harvested basins have roads. Instead we draw upon modeling studies that estimate the magnitude of peak flow increase likely because of road construction alone (Bowling and Lettenmaier 2001).

Paired Watershed Studies

Experimental watershed research in the Pacific Northwest began more than 50 years ago with the establishment of three small watersheds in the H.J. Andrews Experimental Forest in the western Cascades of Oregon, and grew to include multiple sets of watersheds in British Columbia, Washington, coastal and southern Oregon, and northern California. The studies were performed over small areas (0.1 to 10 km^2), and originally were intended to assess initial effects of management practices. In several cases, the gage records were terminated 5 to 10 years after treatments, but in others the watershed records have been sustained or, in some cases, reactivated after a break in record of several decades.

Small watershed studies predominantly use control-treatment comparisons in adjacent watershed pairs, although some experimental studies (e.g., Casper Creek) use a nested approach with multiple gages measuring streamflow and other watershed products at several scales within the same watershed. Comparisons among sets of experimental watersheds arrayed longitudinally or along environmental gradients provide important information as well.

The experimental design in paired-watershed studies is typically based on comparison of metrics extracted from hydrographs between treated and untreated watersheds following a pretreatment period during which streamflows from the two watersheds are calibrated against each other. The difference between the pre- and posttreatment relation for the pair is then interpreted as the treatment effect, although other statistical comparisons are possible depending on objective (see Jones 2005 for review).

Although the paired-watershed approach is well-established in the literature, it has a number of limitations.

- The pretreatment period may not include the same range of flows as observed in the posttreatment period, leading to some uncertainty about what the predicted flow would have been based on the treated/control relationship. This is primarily a problem for extreme high and low flows.
- The relationship between the treated and control watersheds may change over time for reasons other than the treatment, for example: (a) forests are aging in both cases, but are at different points in succession, hence type and rate of change of forest stand condition differ; (b) one or both watersheds may be affected by natural disturbances, such as fire, defoliating insects, or windthrow; or (c) both control and treated watersheds may be affected by adjacent treatments.
- Extreme floods are very important, but by definition occur rarely, so the sample size of these events is always small, and it is difficult to move beyond anecdotal predictions to robust statistical analysis.
- Disentangling the effects of multiple treatments (e.g., forest cutting and roads) within the same watershed is problematic, especially when treatments overlap in both time and space.
- The timescales over which these experiments are typically run often include climatic variation that can influence the outcome of the experiment in unknown ways. For example, the measured treatment effect might be different if it occurred at the beginning of a dry or wet cycle as driven by the Pacific Decadal Oscillation. Progressive global warming over the past and into future decades introduces additional uncertainty in interpreting results.
- Local variability in precipitation and difficulty in accurately measuring precipitation means that there can be different but unmeasurable inputs to paired watersheds during the same event, leading to different flow responses.

- Small watershed studies are inherently expensive and difficult to maintain, and therefore represent case studies without even pseudoreplication. In the absence of true replication, it is difficult to make strong statistical inferences.
- Small watershed studies are limited by the accuracy of the instruments and techniques used to measure streamflow, and accuracy varies over the distribution of flows, ranging from a few percent for low flows measured with an accurately calibrated weir, to 10 to 15 percent or more for high flows measured by standard stage-to-discharge techniques and calibrated against periodic wading discharge measurements (see Sauer and Meyer 1992, for discussion of error).

Modeling Studies

Increasingly, researchers are using process-based models to formulate hypotheses that are tested against available measured data. Some models employ detailed understanding of hydrologic and geomorphic processes to inform the statistical analysis of long-term data sets (Lewis et al. 2001). Other models, such as the Distributed Hydrology Soil Vegetation Model (DHSVM) (Bowling and Lettenmaier 2001), and the Regional Hydro-Ecologic Simulation System (RHESSys) (Tague and Band 2001) use spatially distributed data sets to investigate complex linkages between management treatments and hydrologic response. Modeling efforts are increasingly relied upon to fill both data gaps and process-linkages that are not addressed by the traditional paired watershed literature, and are therefore included in this synthesis.

Study Design and Elements

To synthesize the available data from a wide variety of studies, we developed a framework to maximize the correlation of findings, and explore process-based explanations for the results of paired-watershed and modeling studies of forest harvest effects on peak flows. The following sections explain the definitions we used to explore the data set and introduce our approach to distilling the results of our analysis in a rigorous and useful fashion.

Geographic and Spatial Scales

We develop our analysis at two spatial scales. The site scale refers to studies that examine hydrologic response for management practices conducted on hillslopes, plots, or within small experimental watersheds (area <10 km^2). This scale is generally synonymous with the terms drainage and catchment, and includes headwater (zero- and first-order) streams, and is significantly smaller than the management units defined by the hydrologic unit code (HUC). Management treatments at this scale typically involve one or several management activities with or without the presence of roads; we focus on the hydrologic impact of specific forest harvest activities. Most experimental watershed studies have been conducted at the site scale (area <10 km^2), and therefore most of our data synthesis and analysis occurs at this scale.

At the basin scale (> 10 km^2 to < 500 km^2), we consider ways of evaluating the composite effects of roads, along with the size, age, and spatial distribution of harvested units, together with the effects of riparian buffers or reserves. We use this broader spatial scale to examine likely geomorphic response to peak flow increases in terms of bedload sediment transport and channel morphology. Our basin scale is larger than the site scale and generally synonymous with the terms subwatershed and watershed employed by other classification schemes. Our basins include second- to fifth-order streams, and may be applied to HUC management units up to fifth-field watersheds.

At both scales of analysis, we exclusively employ the term “watershed” when referring to a topographic area bounded by drainage divides where surface waters drain to a common point (usually a gage station). This is not to be confused with the U.S. Geological Survey’s HUC watershed class, which denotes a drainage basin of a particular size. Our watersheds have no implied scale.

Although our results are focused on western Oregon and Washington, we draw on studies beyond this area to provide context and a broader range of climatic zones and forest and treatment types. The study sites forming the basis for our analysis are typically located in steep (slopes range from 30 to greater than 60 percent), mountainous terrain with varying geology and soils but usually supporting mature to old-growth coniferous forests with pretreatment ages greater than 100 years. In general, initial management treatments occurred less than 50 years ago.

Management Treatments

The long timescales involved in implementing and following a paired watershed design means that land management practices have evolved since the original treatments were imposed. For example, in the Pacific Northwest, small experiments in the 1960s and 1970s typically used complete clearcutting without riparian buffers and hot, broadcast burning of slash. Such treatments are not generally employed today on public lands. No paired watershed studies provide data on practices commonly used today including green-tree, standing dead, and downed wood retention; extensive riparian buffers; limited-ground-disturbance logging methods; and less intense slash reduction methods. Although this might be viewed as a serious limitation on interpreting peak flow effects of contemporary forest practices, we maintain that the clearcut treatments and untreated control watersheds neatly bracket the intensity of today's treatments, providing a reasonable frame of reference for interpreting the potential effects of today's practices.

Because contemporary forest practices are so varied and unlike some of the practices used in experimental watersheds in the past, it is necessary to describe classes of practices by using a common frame of reference (fig. 3). We elected to use the percentage of watershed area harvested (hereafter referred to as percentage harvested) as the metric to compare studies and treatments, because it can be interpreted from the description of the harvest practice for each study. This classification only represents a general magnitude of harvest, and because of small sample sizes, ignores both type and spatial pattern of harvest. Under this scheme, the same percentage harvested generally can represent a range of basal area cut or canopy removed, and does not distinguish among patch sizes. For example, clearcutting a single patch equal to 50 percent of an area, cutting small patches totaling 50 percent of an area, and thinning 50 percent of the trees over 100 percent of an area all

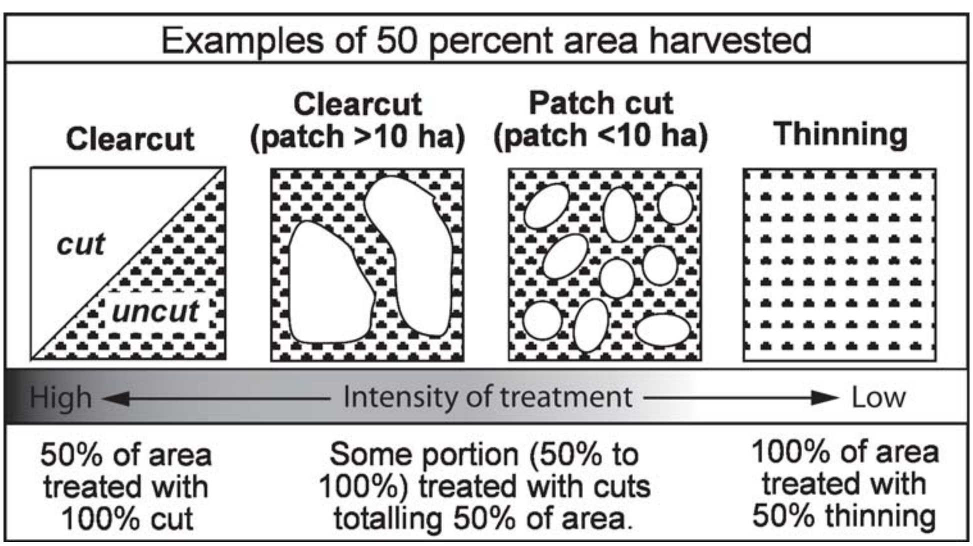

Figure 3—Forest harvest treatments that result in a reported value of 50 percent of area harvested. Theoretical intensity of treatment and predicted influence on peak flow changes decreases from left to right.

represent 50 percent harvested. However, we recognize that hydrologic effects may not be the same. In the above example, we would predict that hydrologic impacts would decrease in the presented order of diminishing intensity of treatment (fig. 3).

Hydrologic Zones

Hydrologic zones represent landscapes sharing the common hydrologic processes of precipitation type and seasonality, hydraulic conductivity and residence times, and partitioning of surface and subsurface flow (Winter 2001). These factors involve interactions among climate, geology, soils, and vegetation. Because historical weather data and seasonal observations of precipitation type are easily coupled with elevation data for a watershed, we adopt the widely used definition of three hydrologic zones based on dominant precipitation type: rain-dominated, snow-dominated, and the transient snow zone that lies between them.

The transient snow zone (TSZ) is of particular interest because it represents the geographic region where ROS events are particularly common during winter months, and such events are potentially affected by timber harvest (Berris and Harr 1987, Christner and Harr 1982, Harr 1986, Jones and Grant 1996). For example, in western Oregon, the lower boundary of the TSZ falls between 350 and 450 m, and the upper boundary falls between 1100 and 1200 m (Christner and Harr 1982, Harr 1986). For southern Oregon, the TSZ falls at the relatively higher elevational band between 760 to 1050 m and 1200 to 1700 m.

Recent studies have further partitioned the landscape on the basis of temperature (Nolin and Daly 2006) and geology (Tague et al. 2007). No commonly accepted hydrologic zone classification for the Pacific Northwest satisfactorily incorporates these factors for our purposes, although several candidates have been proposed (Winter 2001, Wolock et al. 2004). In the absence of a commonly accepted, detailed classification, we use site-specific information to guide data interpretation within each broadly defined hydrologic zone.

Scaling Hydrologic Processes and Effects

We evaluated the relative magnitude and general trend of forest treatment effect by hydrologic zone and peak flow generating mechanism (fig. 2). We considered process-based scaling issues for four key factors: (A) evapotranspiration, (B) direct interception, (C) cloud water interception, and (D) snow accumulation and melt rates. We expect the relative dominance of the four processes to range from most to least important within each hydrologic zone as follows: rain zone–ABCD, transient snow zone–DABC, and snow zone–DBAC. For example, the influence of snow dynamics is likely to be maximally expressed in the transient snow zone, where ROS events are common, moderately expressed in the snow zone, and minimally expressed in the rain zone, where snow is rare. For each process and hydroregion, the relative trend presented is a broad interpretation of the degree to which the process under consideration scales with percentage harvested. This is a conceptual scaling only, and is not tied to quantitative data. The approach presented (fig. 2) sets sideboards on the potential relative magnitude of peak flow increases as a function of hydrologic mechanisms, flow magnitude, and geography.

Limitations of Analysis

The studies reported in this document paint a reasonably consistent picture of forest management effects on peak flows. There are some outliers, however, and additional factors that may create real and apparent discrepancies among studies:

- Even within a somewhat homogeneous region such as the Pacific Northwest, existing studies represent a range of geology, topography, climate, and vegetation types, each of which gives rise to differences in hydrologic process domains and responses to the same treatment.
- The treatments differ, ranging from clearcutting with broadcast burning and roads to small patch cuts with no roads or burning. The location of treatments with respect to other important features (e.g., roads, streams, sources of groundwater, mass movements, soils of different depths) is highly variable and typically not described or replicated.
- Studies employ different statistical techniques involving different sets of assumption and sensitivities to change (Jones 2005). Furthermore, different standards of statistical significance contribute to varying interpretations.
- Definitions and uses of specific hydrologic metrics differ among studies, including what constitutes a peak flow (e.g., any hydrograph rise, flows above a threshold, only geomorphically effective flows).
- Different studies may employ or compare different lengths of record or calibration periods, and these may span different climatic periods.
- Hydrologic modeling studies employ a range of models with varying sensitivities to key hydrologic processes, spatial and temporal resolution, and accuracy of the data sets used.

Despite these limitations, small watershed studies represent the best and in many cases only means of quantifying the effects of forest practices on streamflow, particularly when combined with modeling or field-based process studies.

Methods

We first organized published studies based on hydrologic zone and intensity of management activities (percentage harvested). Next, we analyzed the data for peak flow trends across the range of flows and percentage harvested, ultimately focusing on geomorphically effective flows (recurrence interval greater than 1 year) that have the potential to influence channel morphology. Then we constructed envelope curves representing the maximum reported peak flow increases, as supported by our site scale analysis (area < 10 km^2).

We next expanded our investigation to the basin scale (area >10 km^2) to look at how other factors such as roads, patterns of cuts, treatment type, and riparian buffers potentially influence peak flows at larger watershed scales, and suggest a method to interpret the envelope curves from the site-scale studies in larger basins. Finally, we considered how channel type and morphology, as defined primarily by channel gradient, could be used to provide a first-order prediction of whether peak flow increases of a particular magnitude might affect channel structure in a particular watershed.

Literature Review and Distribution of Relevant Studies

A broad literature review was performed to compile research linking forest practices in the Pacific Northwest with changes to peak flow. We surveyed the literature with standard computer-based search engines using keyword searches for combinations of relevant terms (e.g., peak streamflow, flood, forest harvest, logging, etc.). Search criteria limited our geographic focus to western North America, except in the case of broad topical review papers. We also compiled references by cross-checking citations in relevant articles (most notably Moore and Wondzell 2005) and through personal communication with researchers in the field. The resulting bibliography includes literature on relevant general hydrologic processes, as well as experimental and modeling studies that specifically investigate forest harvest effects on peak flow (app. 1).

Our subsequent synthesis efforts focused on identifying studies that specifically report changes in peak flow attributed to forest harvest and on distilling the data to provide a transparent summary that facilitates comparison among studies. Figure 4 illustrates the range of experimental sites where research has been conducted on

	Small watersheds (<10 km^2) by area harvested (percent)						Large basins
	100-80%	80-60%	60-40%	40-20%	20-0%	Control (0%)	(>10 km^2 to <500 km^2)
SNOW: cold, persistent snowpack		Umatilla NF (2) (Fowler et al. 1987)	Umatilla NF (1) (Fowler et al. 1987)	Umatilla NF (4) (Fowler et al. 1987)		Umatilla NF (3) (Fowler et al. 1987)	Redfish Creek, BC (*Whitaker et al. 2002, Schnorbus and Alila 2004*)
				Horse Creek, ID (12,14,16,18) (King 1989)		Horse Creek, ID (King 1989)	Camp Creek, BC (Cheng 1989, Moore and Scott, 2005)
	Wagon Wheel Gap, CO (B) (Van Haveren 1988)					Wagon Wheel Gap, CO (A) (Van Haveren 1988)	Fool Creek, CO (Troendle and King 1985)
				Deadhorse Sub-basin CO (Troendle and King 1987)	Deadhorse Creek CO (Troendle and King 1987)		Deadhorse Creek, CO (Troendle and King 1987)
TRANSIENT: transient snow, near melting point	HJ Andrews (1) (Rothacher 1973, Harr 1986, Jones and Grant 1996, Thomas and Megahan 1998, Beschta et al. 2000, Jones 2000)			HJ Andrews (3) (Jones and Grant 1996, Thomas and Megahan 1998, Beschta et al. 2000, Jones 2000)		HJ Andrews (2) (Rothacher 1973, Harr 1986, Jones and Grant 1996, Thomas and Megahan 1998, Beschta et al. 2000, Jones 2000)	Lookout Creek paired with Blue River (Christner and Harr 1982, Jones and Grant 1996, Thomas and Megahan 1998, Beschta et al. 2000)
	HJ Andrews (6,7) (Harr et al. 1982, Jones 2000)		HJ Andrews (7) (Harr et al. 1982)			HJ Andrews (8) (Harr et al. 1982, Jones 2000)	Salmon Creek paired with NF MF Willamette River (Christner and Harr 1982, Lyons and Beschta 1983, Jones and Grant 1996, Thomas and Megahan 1998, Beschta et al. 2000)
	HJ Andrews (10) (Harr and McCorison 1979, Harr 1986, Jones 2000)					HJ Andrews (9) (Harr and McCorison 1979, Harr 1986, Jones 2000)	
				Bull Run, Fox Creek (1,3) (Harr 1980, Jones 2000)		Bull Run, Fox Creek (2) (Harr 1980, Jones 2000)	Breitenbush paired with North Santaim (Christner and Harr 1982, Jones and Grant 1996, Thomas and Megahan 1998, Beschta et al. 2000)
	Coyote Creek (3) (Harr et al. 1979, Jones 2000)		Coyote Creek (1) (Harr et al. 1979, Jones 2000)	Coyote Creek (2) (Harr et al. 1979, Jones 2000)		Coyote Creek (4) (Harr et al. 1979, Jones 2000)	
			Deschutes, WA (Ware) (*Bowling and Lettenmaier 2001, Lamarche and Lettenmaier 2001*)	Deschutes, WA (Hard) (*Bowling and Lettenmaier 2001, Lamarche and Lettenmaier 2001*)			HJ Andrews (Lookout Creek) (*Connelly and Cundy 1992*)
		Malcolm Knapp, BC (1) (Cheng et al. 1975)				Malcolm Knapp, BC (2) (Cheng et al. 1975)	Deschutes River paired with Naselle River, WA (Duncan 1986, *Lamarche and Lettenmaier 2001*)
				Flume Creek, BC (4) (Hudson 2001)	Flume Creek, BC (5) (Hudson 2001)	Flume Creek, BC (6) (Hudson 2001)	Western Washington basins (*Storck et al. 1998, Bowling et al. 2000*)
					Jamieson Creek, BC (Golding 1987)	Elbow Creek, BC (Golding 1987)	
RAIN: rare snow events, dominated by rain	Alsea (Needle) (Harr et al. 1975, Harris 1977)			Alsea (Deer) (Harr et al. 1975, Harris 1977)		Alsea (Flynn) (Harr et al. 1975, Harris 1977)	
	Alsea (Deer 4) (Harr et al. 1975)	Alsea (Deer 3) (Harr et al. 1975)		Alsea (Deer 2) (Harr et al. 1975)			
		Caspar South, CA (Ziemer 1981, 1998, Wright et al. 1990)				Caspar North, CA (Ziemer 1981, 1998, Wright et al. 1990)	
	Caspar Creek, CA (BAN,CAR,EAG,GIB, KJE) (Ziemer 1998, *Lewis et al. 2001*)		Caspar Creek, CA (ARF, FLY) (Ziemer 1998, *Lewis et al. 2001*)	Caspar Creek, CA (DOL, JOH, LAN) (Ziemer 1998, *Lewis et al. 2001*)	Caspar Creek, CA (NFC) (Ziemer 1998, *Lewis et al. 2001*)	Caspar Creek, CA (HEN, IVE, MUN) (Ziemer 1998, *Lewis et al. 2001*)	
	Carnation Creek, BC (H) (Hetherington 1982)			Carnation Creek, BC (B) (Hetherington 1982)		Carnation Creek, BC (C,E) (Hetherington 1982)	

Figure 4—Experimental watersheds in the Northwestern United States. Watersheds are arranged by percentage of area harvested and hydrologic zone. Each box includes applicable studies reporting peak flow data; italics indicate modeling studies. White background indicates Oregon studies; light gray shading indicates studies of watersheds outside of Oregon.

the effects of forest harvest on peak flow. The sites (area <10 km^2) are arrayed by hydrologic zone (defined by dominant precipitation type) and management treatment (represented as percentage area harvested). Each box includes the name of the experimental site and the relevant studies that analyzed peak flow data from that site. The right-hand column represents larger basins (area >10 km^2), which typically have a more complex history of forest management. Modeling studies included here may also report general findings from multiple sites (e.g., Bowling et al. 2000) when information on forest treatment and watershed characteristics are not reported for individual sites.

Although the Pacific Northwest has long been the geographic focus of small watershed studies, these studies were not intentionally designed to represent the full range of management treatments across all hydrologic zones (fig. 4). The snow-dominated zone is particularly poorly represented in Oregon. The combination of older paired studies from Colorado and Idaho, the emerging modeling literature out of British Columbia and Colorado, and process-based work in southern Oregon (Storck et al. 2002) give us a starting point for interpreting change in snow-dominated zones.

Early studies in the documentation of peak flow increases attributed to forest harvest include the only Oregon watersheds in the rain-dominated zone (the Alsea watersheds) along with the H.J. Andrews Forest in the TSZ. One of the best designed and well-documented long-term experimental studies, Caspar Creek in northern California, also falls into the rain zone, providing valuable modeling and empirical data. The main complication in interpreting the data set from the rain-dominated zone is the presence of roads in almost all watersheds. There has been a corresponding direct focus on road effects on hydrologic routing (e.g., Wemple and Jones 2003) and resulting changes in peak flow (Coe 2004).

Much of the research effort in Oregon is understandably focused on the TSZ, primarily because it affects much of the federal forest land in the Cascades. Treatments in these studies cluster around 100- and 30-percent harvested, and often included broadcast burning and road construction. Most larger basin studies are also situated in this hydrologic zone. General trends at the site scale are therefore best able to support larger basin issues (e.g., roads, scaling) in this hydrologic zone, particularly when combined with modeling and process studies. Our analysis is limited to studies that actually report quantitative data (as opposed to descriptive observations) on changes in peak flow (as opposed to water yield or low flow) attributed to forest harvest. Supplemental and additional literature may be found in appendix 1.

Peak Flow Data Set Compilation and Analysis

For each reference listed in the study framework, relevant information was compiled in a series of data tables (app. 2). This information includes the management history of each experimental watershed (location, climate, forest type, harvest history, etc.) and the research design and findings of each study (return interval of peak flow analyzed, length of record used, method of analysis, reported findings, etc.). Modeling and experimental studies were compiled separately, recognizing the inherent differences in study design and format of findings. These data tables represent the numbers reported by the authors; no additional analyses were performed on the data. No unpublished data are included in this analysis.

There is a wide range in analytical technique and reporting of peak flow data, even for a single site with a common data set (e.g., table 1). Partial-duration series of flow peaks above a specified magnitude from the pre- and posttreatment flow measurements are typically linearly or logarithmically regressed, or compared by using analysis of variance (ANOVA). The calculated changes in peak flow can be reported for flows grouped by season (fall, winter, spring), size (small, medium, large), type of precipitation event (rain, rain-on-snow), and posttreatment period length. Data are usually reported as a percentage change in peak flow, which facilitates comparison among sites. Some studies index findings to changes in absolute magnitude of flow in a control watershed, whereas other studies index changes to recurrence interval. Few studies report data across this entire range, and table 1 exemplifies the challenge that managers face in making sense of the scientific literature.

For this synthesis, we were interested in published results from paired watershed or modeling studies where statistical significance of the results were reported and peak flow changes could be evaluated (1) across a range of flows for a single watershed or (2) at a return period greater than 1 year or (3) both. Other criteria used to select studies included the use of a calibration period and sufficient explanation of the methods employed in analysis.

Several experimental studies do not report quantitative data that we could use for our comparison. These references were retained, however, for qualitative use in later sections of the synthesis. Some studies grouped findings by season (Harr et al. 1975) or precipitation form (Harr 1986) and did not report a combined change that was inclusive of all sizes of peak flows. Cheng et al. (1975) do not provide information on the recurrence interval of the flows, probably because of the very short posttreatment record, and the reported decrease in peak flow (-22 percent) is

Table 1—Peak flow data from H.J. Andrews Experimental Forest Watershed 1

Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change[a]	Magnitude of change years since harvest: All	0	5	10	15	20	25	30
			$m^3 \cdot s^{-1} \cdot km^{-2}$	*Years*	*Years*		*Percent*							
Rothacher 1973	Linear regression of peaks	All	0.11	Nr	5	Increase	**24**							
		Large	1.09	Nr	5	Nsc	nr							
Harr 1986	Linear regression of peaks	Rain-on-snow	0.98	2	18	Increase[d]	nr							
Jones and Grant 1996	Analysis of variance on log-transformed peaks[b]	All	0.03	Na	22	Increase		27	46	28	31	30		
		Fall	0.03	Na	22	Increase		39	68	30	23	27		
		Winter	0.03	Na	22	Increase		22	31	28	36	27		
		Spring	0.03	Na	22	Increase		21	70	32	28	46		
		Small	0.03	<0.125	22	Increase		20	**67**	38	42	43		
		Large	0.35	0.4	22	Nsc		27	20	**25**	16	16		
Thomas and Megahan 1998[c]	Linear regression of log-transformed peaks[b]	Small	0.03	<0.125	22	Increase			**90**	40	65	55		
		Medium-small	0.11	0.125	22	Increase			**38**	28	36	32		
		Medium-large	0.21	0.2	22	Increase			**28**	25	16	16		
		Large	0.35	0.4	22	Increase			**25**	25	14	14		
Beschta et al. 2000	Linear regression of log-transformed peaks[b]	Large	0.35	0.4	22	Increase[e]	**28**							
		Large	0.65	1	22	Increase[e]	**16**							
		Large	1.00	5	22	Increase[e]	**9**							
Jones 2000	Analysis of variance on log-transformed peaks	All	0.03	Na	30	Increase		22		31		26		21
		Small, fall	0.03	Na	30	Increase		38		53		33		20
		Small, spring	0.03	Na	30	Nsc		9		41		28		22
		Rain	0.03	Na	30	Nsc		22						
		Mixed	0.03	Na	30	Nsc		22						
		Rain-on-snow	0.03	Na	30	Increase	31							
		Large	0.65	>1	30	Increase	**25**							

Bold text indicates values graphed in figure 5. Na = not applicable, Nr = not reported, Nsc = no significant change.

[a] Values statistically significant at 0.05, except where noted.

[b] These three studies used the same dataset.

[c] Values estimated from Table 3a.

[d] Significance not reported.

[e] Significant at 0.1.

therefore not interpretable. Flume Creek (Hudson 2001) is the only experimental study we found testing contemporary management practices, but it calculated the percentage change to peak flow of only that population of peaks falling above the 95-percent confidence interval for the pretreatment regression (rather than the entire posttreatment population), thereby inflating the values reported.

Site-scale data are limited by the accuracy of the instruments and techniques used to measure streamflow, and accuracy varies over the distribution of flows, ranging from a few percent for low flows measured with an accurately calibrated weir, to 10 to 15 percent or more for high flows measured by standard stage-to-discharge techniques and calibrated against periodic wading discharge measurements (Sauer and Meyer 1992). Based on considerations of gage and measurement error at high-flow events, we identify a minimum detectable change in peak flow (detection limit) of ±10 percent for our site-scale analysis (e.g., figs. 5, 6, 8, 9, 11). Percentage changes in peak flow that fall in this range are within the experimental and analytical error of flow measurement and cannot be ascribed as a treatment effect.

Peak flow studies increasingly follow a format introduced by Thomas and Megahan (1998) to graph percentage change to peak flow at a single site over a range of flows. We adopt this as one format for study comparison (figs. 5, 6). Studies at seven sites and two studies reporting average values for a collection of similar and related sites reported data appropriate for this type of analysis. The data

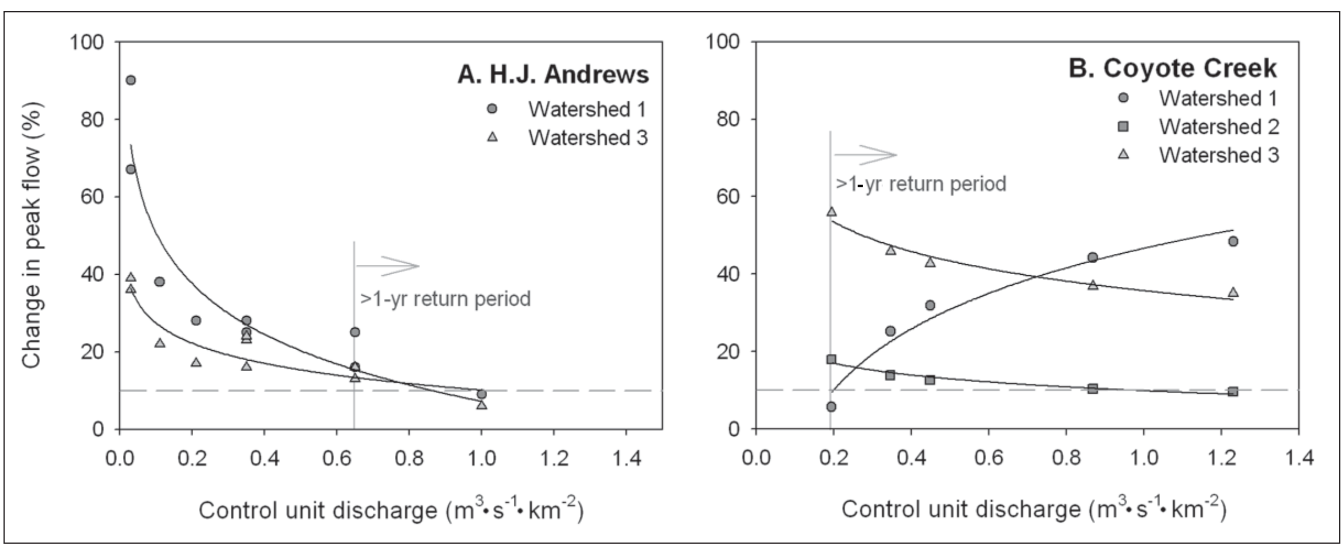

Figure 5—Reported changes in peak flow for Oregon watersheds. Each point represents a published value for percentage increase to peak flow after harvest, relative to the control flow watershed for (A) Andrews Forest and (B) Coyote Creek. Dashed vertical line indicates 1-year return period. Dashed horizontal line indicates the 10-percent detection limit.

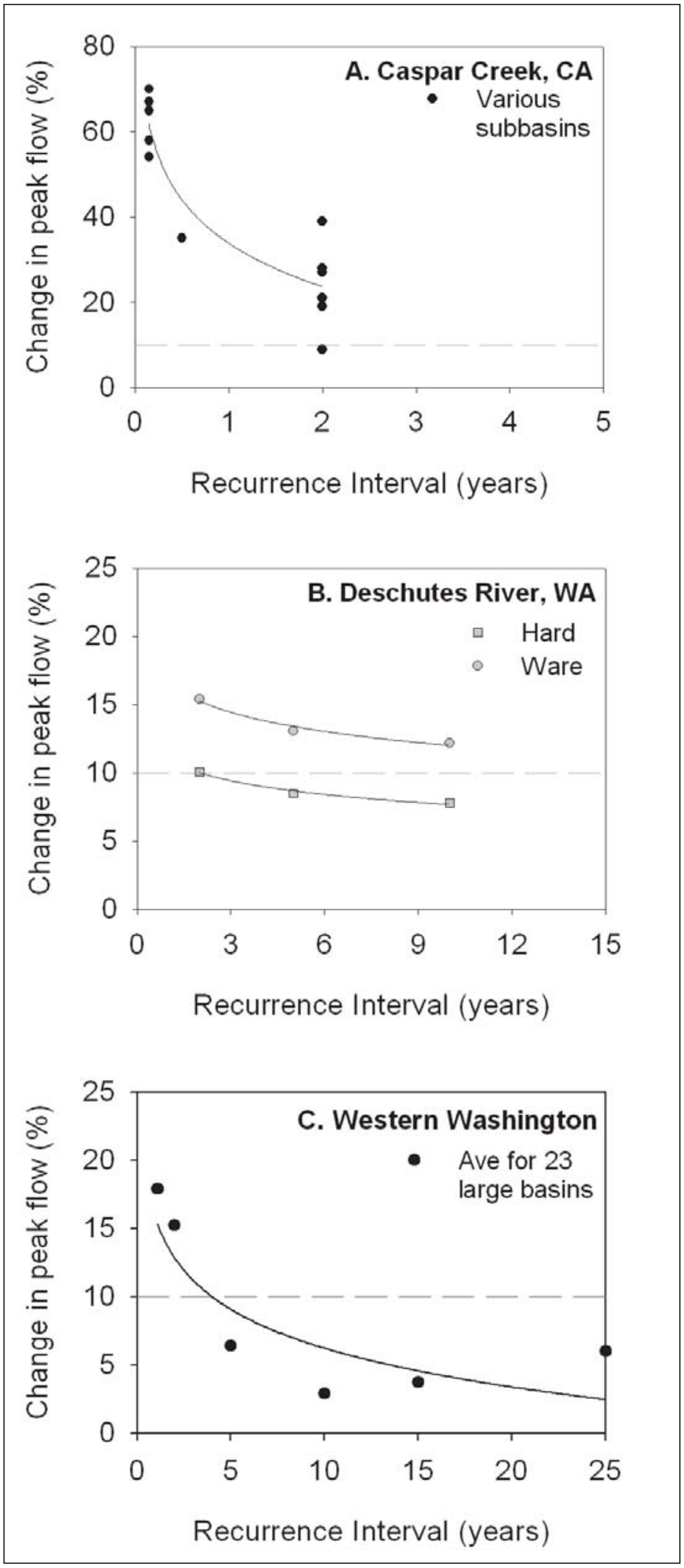

Figure 6—Reported changes in peak flow for California and Washington watersheds. Each point represents a published value for percentage increase in peak flow after harvest relative to the return period of the control watershed for (A) subbasins of Caspar Creek, California, (B) modeled basins of Deschutes River, Washington, and (C) average values of 23 large basins in western Washington. Dashed horizontal line indicates the 10-percent detection limit.

required are percentage change in peak flow keyed to a control watershed return interval or to flow across the entire wet season (e.g., bold values in table 1). The point at which the regression lines intersect the 10-percent detection limit is interpreted as the discharge (or return period) above which a change in peak flow from a watershed is not detectable (fig. 7). Watersheds from both the rain-dominated and transient-snow hydrologic zones were used in this analysis. No appropriate data are available from the snow-dominated zone.

Our second analysis explored changes in peak flow across a range of forest treatments, and incorporated a much larger subset of the compiled studies. The data criteria were percentage change in peak flow for the population of peaks with a recurrence interval of 1 year or greater (tables 2, 3, 4). Flows of this magnitude are widely recognized as geomorphically effective, defined as having the capacity to initiate bedload sediment transport (Andrews 1983, 1984). Data are presented individually for each of the three hydrologic zones: rain-dominated, transient snow, and snow-dominated (fig. 8).

Two formats are employed to display this data. First, all data from tables 2 through 4 are plotted to show the spread in values keyed to management treatment type (fig. 8a-c). Studies that reported no significant change without a percentage value, or across a larger population (e.g., all size peaks) or both subsets of the wet season (e.g., both fall and winter flows) are included as an indication of no detectable change (zero value) (see tables 2 through 4). To facilitate interpretation of this data set, representative values for each study in each watershed were then grouped by percentage harvest (fig. 8d-f). Percentage harvest group ranges (100 to 80 percent, 79 to 40 percent, and 39 to 0 percent) were determined primarily by natural data spread, but these breaks are intuitively supported by the general scaling of changes in hydrologic function with percentage harvest (fig. 2). Studies reporting no significant change (nsc) rather than a numeric value, studies reporting negative change, and multiple values for a site reported by the same study are not included in the calculation of the averages and standard deviations plotted (fig. 8d-f).

Table 2—Paired watershed studies with reported peak flow data for the rain-dominated hydrologic zone

Location	Basin name	Area	Harvest	Treatment type	Roads > 2%	Return period	Reported change	Reference
		km²	*Percent*			*Years*	*Percent*	
Carnation	H	0.12	90	Clear	Y	All	20	Hetherington 1982
Creek, BC	B	9.30	41	Mixed	Y	All	Nsc	Hetherington 1982
Alsea	Needle	0.71	82	Clear	Y	All	20	Harris 1977
River, OR	Needle	0.71	82	Clear	Y	All	Nsc	Harr et al. 1975
	Deer	3.04	25	Clear	Y	All	2	Harris 1977
	Deer	3.04	25	Clear	Y	All	Nsc	Harr et al. 1975
	Deer 2	0.56	30	Clear	Y	All	Nsc	Harr et al. 1975
	Deer 3	0.41	65	Clear	Y	All	20	Harr et al. 1975
	Deer 4	0.16	90	Clear	N	All	Nsc	Harr et al. 1975
Caspar	SFC	4.24	67	Mixed	Y	1	Nsc	Ziemer 1981
Creek, CA	SFC	4.24	67	Mixed	Y	8	Nsc	Wright et al. 1990
	SFC	4.24	67	Mixed	Y	All	Nsc	Ziemer 1998
	N_{ave}	8.89	41.4	Mixed	Y	2	15	Ziemer 1998
	N_{ave}	0.98	97.8	Clear	Y	2	27	Ziemer 1998
	BAN	0.10	95	Clear	Y	2	21	Ziemer 1998
	KJE	0.15	97.1	Clear	Y	2	28	Ziemer 1998
	GIB	0.20	99.6	Clear	Y	2	39	Ziemer 1998
	CAR	0.26	95.7	Clear	Y	2	19	Ziemer 1998
	EAG	0.27	99.9	Clear	Y	2	27	Ziemer 1998
	NFC	4.73	49.6	Mixed	Y	2	9	Ziemer 1998

Nsc = no significant change.

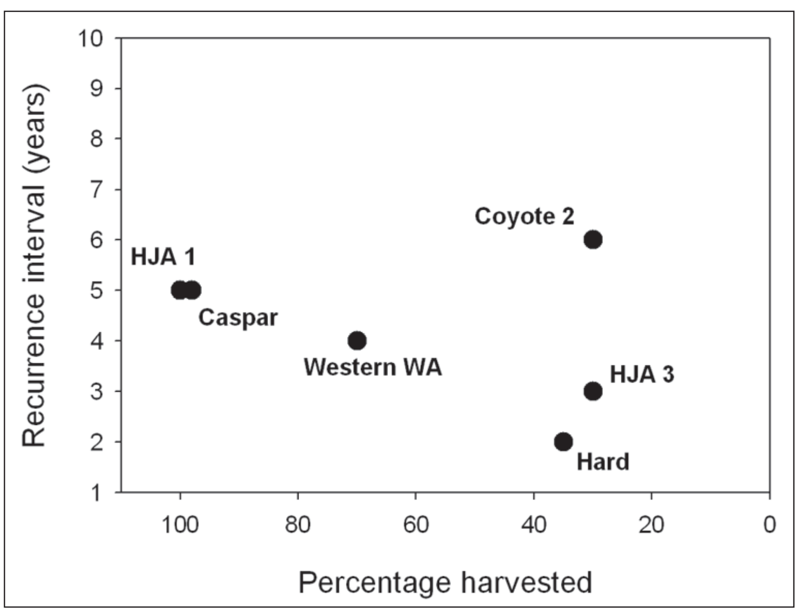

Figure 7—Maximum recurrence interval at the detection limit as a function of the percentage harvested for selected watersheds graphed in figures 5 and 6.

Table 3—Paired watershed and modeling studies with reported peak flow data for the transient snow zone

Location	Basin name	Area	Harvest	Treatment type	Roads > 2%	Return period	Reported change	Reference
		km^2	*Percent*			*Years*	*Percent*	
Deschutes River, WA	Hard	2.30	35	Modeled	N	2	10.1	Bowling and Lettenmaier 2001
	Hard	2.30	35	Modeled	Y	2	22.6	
	Ware	2.80	66	Modeled	N	2	15.4	
	Ware	2.80	66	Modeled	Y	2	29.0	
Fox Creek, Bull Run, OR	1	0.59	25	Patch	N	1	Nsc	Harr 1980
	1	0.59	25	Patch	N	1	13	Jones 2000
	3	0.71	25	Patch	N	1	Nsc	Harr 1980
	3	0.71	25	Patch	N	1	13	Jones 2000
H.J. Andrews, OR	1	0.98	100	Clear	N	1	Nsc	Rothacher 1973
	1	0.98	100	Clear	N	1	16	Beschta et al. 2000
	1	0.98	100	Clear	N	1	25	Jones 2000
	3	1.01	25	Patch	Y	1	13	Beschta et al. 2000
	3	1.01	25	Patch	Y	1	16	Jones 2000
	10	0.10	100	Clear	N	1	-8	Jones 2000
	6	0.13	100	Clear	Y	All	Nsc	Harr et al. 1982
	6	0.13	100	Clear	Y	1	16	Jones 2000
	7	0.15	60	Shelter	N	All	Nsc	Harr et al. 1982
	7	0.15	100	Shelter	N	1	27	Jones 2000
Coyote Creek, OR	1	0.69	50	Shelter	N	9	47	Harr et al. 1979
	1	0.69	50	Shelter	N	1	10	Jones 2000
	2	0.68	30	Patch	N	9	10	Harr et al. 1979
	2	0.68	30	Patch	N	1	36	Jones 2000
	3	0.59	100	Clear	N	9	36	Harr et al. 1979
	3	0.59	100	Clear	N	1	26	Jones 2000

Nsc = no significant change.

Table 4–Paired watershed, large basin and modeling studies with reported peak flow data for the snow-dominated zone

Location	Basin name	Area	Harvest	Treatment type	Roads > 2%	Return period	Reported change	Reference
		km^2	*Percent*			*Years*	*Percent*	
Umatilla National Forest, OR	ELG1	0.30	43	Patch	Y	All	Nsc	Fowler et al. 1987
	ELG2	0.24	50	Shelter	N	All	Nsc	
	ELG4	1.18	22	Patch	Y	All	Nsc	
Deadhorse Creek, CO	Dead	2.70	10	Mixed	Y	All	0	Troendle and King 1987
Wagon Wheel Gap, CO	B	0.81	100	Clear	N	All	50	Van Haveren 1988
Fool Creek, ID	Fool	2.89	40	Patch	Y	All	23	Troendle and King 1985
Horse Creek, ID	12	0.83	33	Patch	Y	All	15	King 1989
	14	0.62	27	Patch	N	All	35	
	16	0.28	21	Patch	Y	All	36	
	18	0.86	29	Patch	Y	All	34	
Camp Creek, BC	Camp	33.9	27	Mixed	Y	All	21	Cheng 1989
	Camp	33.9	27	Mixed	Y	All	Nsc	Moore and Scott 2005
Redfish Creek, BC	Curr	26.2	9.9	Modeled	N	1.9	6	Schnorbus and Alila 2004
	1/3L	26.2	11.2	Modeled	N	1.9	5	
	2/3L	26.2	18	Modeled	N	1.9	6	
	1/3M	26.2	12.3	Modeled	N	1.9	8	
	2/3M	26.2	19	Modeled	N	1.9	15	
	1/3U	26.2	15.8	Modeled	N	1.9	11	
	2/3U	26.2	22.4	Modeled	N	1.9	17	
	1/3A	26.2	19.8	Modeled	N	1.9	12	
	100L2	26.2	38.2	Modeled	N	1.9	20	
	100U2	26.2	32.8	Modeled	N	1.9	34	
	100A	26.2	52.7	Modeled	N	1.9	34	

Nsc = no significant change.

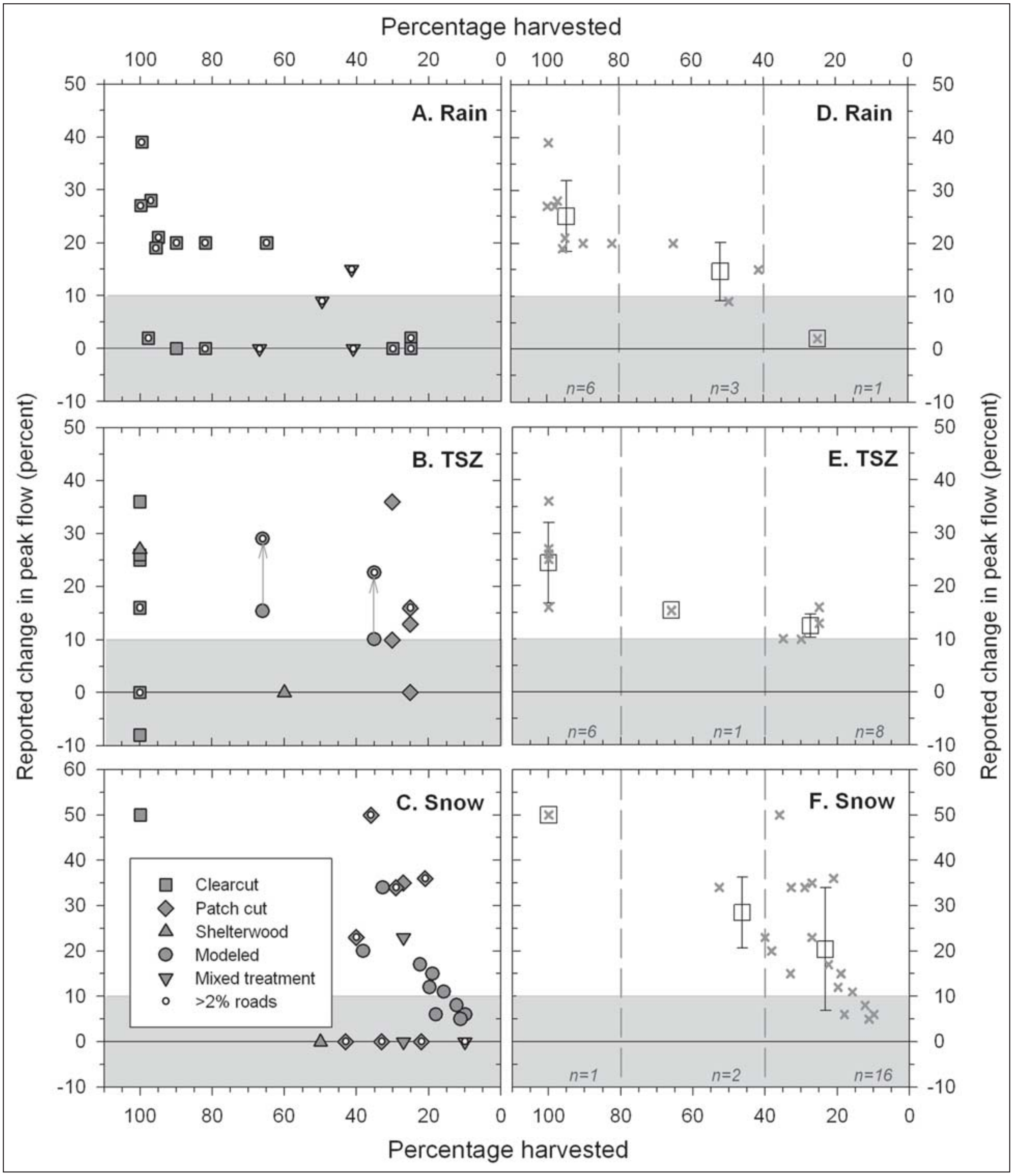

Figure 8—Reported changes in peak flow for different treatment types in (A) rain-dominated, (B) transient snow, and (C) snow-dominated zones. Dark gray symbols represent treatment type. Small white circles inside larger gray symbol indicate a basin with greater than 2 percent of the area in roads. Modeled points connected with arrows represent increases attributed to roads within a single watershed. Mean and 1 standard deviation of non-zero values plotted in (A) through (C) are grouped by percentage harvested (0 to 39 percent, 40 to 79 percent, 80 to 100 percent) in (D) rain-dominated, (E) transient snow, and (F) snow-dominated zones. For all graphs, gray shading around zero indicates limit of detection (±10 percent).

Findings

Peak Flow Changes at the Site Scale

Event magnitude—

The largest peak flow increases reported were for small storms with recurrence interval much less than 1 year (figs. 5, 6). Peak flow increases of as much as 90 percent over the control were reported for these small events. For all but one study examined, increases in peak flow diminish with increasing storm magnitude. The trend appears to be roughly an exponential decrease and was modeled as such, in both experimental watershed studies (fig. 5, 6a, 6c) and modeling studies (fig. 6b) and from the site to large basin scale (fig. 6c). For most watersheds, the decreasing trend is strongly influenced by the small number of the largest storm events. However, this trend is consistent across a wide range of studies, lending confidence to the interpretation that percentage increase in peak flow is greatest for the smallest storms. This is also consistent with studies from other regions and general hydrologic understanding (e.g., Leopold 1980).

Only one watershed (Coyote 1) (fig. 5b) did not follow the general trend of decreasing magnitude of change with event return period, but actually showed the highest percentage increases in peak flow for the largest storms. These anomalous results may reflect cross-transfer of water during the largest events as a result of road drainage, as discussed by Harr et al. (1979), and subsequently by other researchers (Wright et al. 1990). In general, results from the Coyote Creek watersheds are suspect because of the paucity of large storms during either the pre- or posttreatment periods. We report the results for both Coyote 2 and Coyote 3, however, because they fit our criteria of acceptable data, but exclude Coyote 1 from further analysis.

Peak flow increases generally approach the 10-percent detection limit (minimum detectable change in flow) at recurrence intervals less than 6 years, although this differs from watershed to watershed (figs. 5, 6). Some studies suggest the 10-percent detection limit is reached at somewhat longer recurrence intervals (e.g., Coyote 3, Ware Creek). Since experimental pre- and posttreatment periods are generally not long enough to represent these longer recurrence intervals, we cannot confidently extrapolate the curves to the corresponding percentage increase in peak flow. The field and analytical methods represented by these studies, therefore, do not provide evidence that forest harvest increases peak flows for storms with recurrence intervals longer than 6 years.

When the recurrence interval corresponding to the minimum detectable change is plotted across the range of percentage forest harvested represented by these watersheds (fig. 7), a trend of higher recurrence intervals corresponding to greater percentages of area harvested is discernable. With the exception of Coyote 2, there is a distinct linear downward trend with Y-intercept at approximately zero percent harvested. This interpretation is consistent with hydrologic theory that predicts diminishing effect of forest harvest with both increasing flow magnitude (Leopold 1980) and decreasing harvest intensity.

Management treatment—
The largest percentage increases in peak flows are expressed at 100-percent harvested (clearcut); this is true for all hydrologic zones (fig. 8). There is no consistent pattern of treatment type and reported changes in peak flow (fig. 8a-c) that would allow us to address the observed variability attributed to treatment type. Zero percent change or no significant change in peak flow is reported from 25- to 100-percent harvested in both the rain and transient zones, and from 9- to 50-percent harvested in the snow zone. Increases in peak flow range from 0 to 40 percent in the rain and transient zones, and from 0 to 50 percent in the snow zone. In all three zones, averages and standard deviations of reported increases, a conservative estimate of mean percentage change in peak flow, support the general trend of smaller changes in peak flows with lower levels of harvest (fig. 8d-f).

There is wide scatter in the data from the snow-dominated zone (fig. 8c, 8f). The scatter is indicative of the primary importance of other factors (e.g., aspect, elevation, timing and temperature of snowfall) in this hydrologic zone. Other researchers have had similar difficulty in discerning a relationship between percentage of watershed harvested and change in peak flow (Moore and Wondzell 2005, Scherer 2001). Although there is an apparent decreasing trend in the data averages (fig. 8f), similar to the other two hydrologic zones (figs. 8d, 8e), there is a lack of modeling and field studies at higher levels of harvest (>50 percent) to lend confidence to this interpretation in the snow zone. We therefore suggest that the snow zone graph should not serve as a basis for management direction, and do not include the snow-dominated zone in subsequent interpretation figures. Much of the research on this subject has been conducted in British Columbia, and we refer the manager faced with a high proportion of landscape in the snow-dominated zone to this work for further guidance (e.g., Macdonald et al. 2003, Moore and Scott 2005, Schnorbus and Alila 2004, Storck et al. 2002, Whitaker et al. 2002, Winkler et al. 2005).

Roads—

Increases in peak flows attributed to roads and associated soil disturbances complicate the interpretation of our analysis for harvested area alone. In the rain-dominated zone, all but one study site (Deer 4, Alsea) includes roads covering at least 2 percent of the treatment area (table 2, fig. 8a). Therefore, we cannot disentangle the influence of roads on the observed increases in peak flow in this hydrologic zone. In the transient zone, only two experimental sites (Watersheds 3 and 6, H.J. Andrews), and two modeling sites (Hard and Ware, Deschutes) include significant roads in the treatment (table 3, fig. 8b). Studies in Watershed 3 (25 percent harvest) report values at the upper end of the range (13 and 16 percent) for similarly harvested sites without roads, whereas values for Watershed 6 (100 percent harvest) are at the lower end of the range (nsc and 16 percent) for clearcut sites without roads. Modeling studies for Washington watersheds suggest an approximate doubling of the percentage change in peak flows attributed to harvest alone when road construction is included in the model (Bowling and Lettenmaier 2001). We cannot parse the available site-scale data to look at the effects of roads of different ages, location in the landscape, or other factors that contribute to the degree of influence of roads on change in peak flows.

Seasonality—

Although we did not do a comprehensive analysis of seasonality of peak flow increases, we observe that in most studies, percentage increases are greatest for fall storms (Beschta et al. 2000, Jones and Grant 1996, Thomas and Megahan 1998). The most consistent mechanism for producing peak flow changes appears to be related to reduced evapotranspiration following harvest resulting in higher soil moisture levels, hence increased runoff during early fall storms. The only countervailing evidence that we are aware of comes from Caspar Creek, where peak flow increases of approximately 20 percent were distributed across both season and storm intensity (Reid and Lewis 2007). The authors of this study interpret these findings as resulting from canopy interception losses that occur regardless of storm type in a redwood-dominated forest. Although intriguing, these findings have not yet been replicated in the Douglas-fir forests of western Oregon and Washington.

Riparian buffers—

During high flows, riparian water tables rise close to the soil surface, facilitating flow of water across the riparian zone (Dunne and Black 1970a, 1970b, Rivenbark and Jackson 2004). Presence of trees, roots, and woody debris on flood plains increases hydraulic resistance, and may thereby decrease velocities of both water flows and flood waves (i.e., hydrograph peaks) (Darby 1999). This effect is likely to be particularly pronounced in wide, alluvial rivers with well-developed flood plains, where flows have the opportunity to inundate valley floors and interact with vegetation (Tal et al. 2004). Most mountain rivers, however, have relatively narrow valleys with flood plains constructed by both fluvial and nonfluvial processes (Grant and Swanson 1995). Research has documented the interaction of flood flows and vegetation during floods in these systems (e.g., Johnson et al. 2000, Swanson et al. 1998). There may be some effect of riparian forests in reducing hydrologic connectivity betweens roads, compacted areas, and streams, and we therefore include it as a factor for consideration at the basin scale, but we are unaware of any research specifically linking presence, absence, or extent of riparian forests to changes in peak flows in mountain landscapes.

The evapotranspiration demands of riparian forests are likely to play only a very minor role during peak flows of the magnitude described here, as these flows typically occur during wet mantle periods when evapotranspiration is low. We have no data on whether riparian buffers are likely to mitigate or offset potential peak flow increases from harvested areas.

Forest age and recovery—

Percentage change in peak flow generally decreases with time after harvest (Jones 2000, Jones and Grant 1996, Thomas and Megahan 1998). Because of limited data availability, we use this general finding to guide our analysis by reporting peak flow increases for the first postharvest interval, generally 2 to 5 years, reported for each study if possible, and use the entire posttreatment period only when that is the only value reported, which tends to underestimate the potential increase for the first years immediately after harvest. Key questions that we are unable to address with this data set include whether thinning resets the clock at the time of second harvest, and whether the response is the same for cutting second growth and old growth.

Spatial pattern of harvest—

The specific mechanisms that drive peak flow increases are likely to be sensitive to the scale of forest patches, in terms of their horizontal and vertical dimensions, and their distribution and contiguity. In particular, rain-on-snow processes at the stand level have been shown to vary with both forest stand age and patch size (Harr and Coffin 1992), so we would expect this effect to be present for watersheds in the transitional snow zone. There is even stronger evidence for patch size and orientation affecting snow accumulation and melt processes in the snow zone (Storck et al. 2002, Troendle and King 1987, Winkler et al. 2005). We see less evidence supporting patch age and size contributing to peak flow effects for watersheds in the rain zone.

Our findings on effects of partial harvest (nonclearcuts) are limited by scant data. In general, we expect that the magnitude of peak flow increases depicted by figure 8 represent the maximum potential increases for large canopy openings because the size of opening relates directly to key hydrologic processes and figure 8 includes the largest possible opening—100-percent harvest (fig. 2). In theory, partial cutting and thinning should result in peak flow changes that are lower than those indicated for clearcutting, and may be undetectable in some watersheds.

Summary of site-scale findings—
The maximum percentage increases in peak flow can be used to construct linear envelope curves, or response lines, that encompass the full range of data reported by the studies in the rain and transient snow zones (figs. 9, 10). We also plot a mean reported change based on the averages of the data from figures 8a and 8b. Theoretically, these response lines represent conservative estimates of maximum and mean measured increases in peak flow for a given percentage harvest and can be used to evaluate the potential for hydrologic response to management treatment. By conservative, we mean that these lines are high estimates of potential forest harvest effects. Whereas the maximum line, by definition, represents the highest reported increases, the mean line is also biased toward higher values, as reported zero values are not included in the calculation.

In the rain zone, the maximum response line reaches the 10-percent detection limit at approximately 29 percent harvested (fig. 9). This suggests that if less than 29 percent of the watershed is harvested, there are no data supporting a resultant increase in peak flow; in fact, the first detectable reported value occurs at 40 percent. The response line for mean reported change crosses the detection limit at 45 percent harvest. Remembering that this data set inherently includes greater than 2 percent roads in most studies, we posit that a response line representing harvest without the construction of new roads would shift down, suggesting an even higher threshold for harvest prior to detectable change in peak flow. However, the absence of any data to support this prevents us from drawing a without-roads response line for the rain-dominated zone.

For watersheds within the TSZ, we are able to begin to disentangle the influence of road construction from peak flow increases that are attributed to harvest alone (fig. 10). We constructed a maximum response line for studies with less than 2 percent roads. This maximum no-roads response line reaches the detection limit at approximately 15 percent harvested. The mean response line, which includes a few basins with roads, crosses the detection limit at a slightly higher value of 19

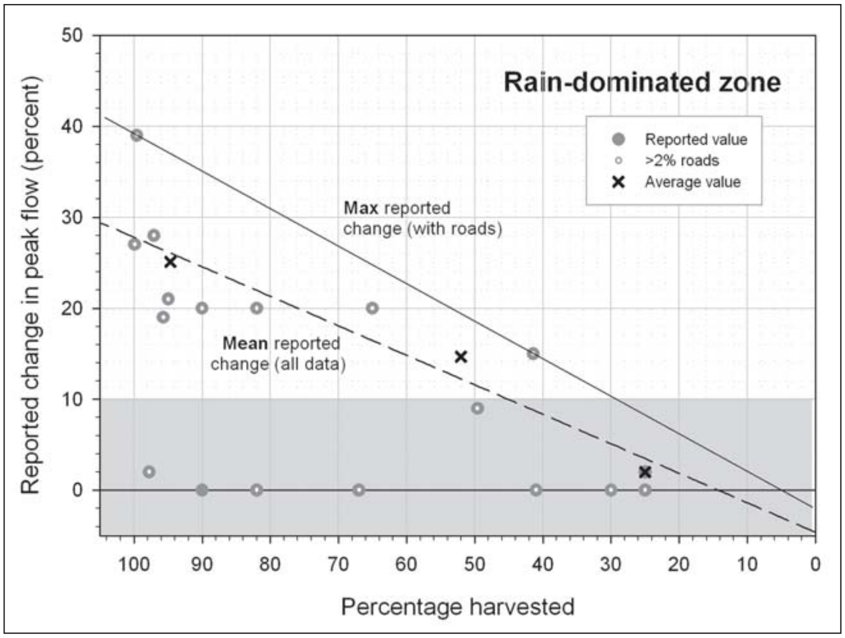

Figure 9—Peak flow response to harvest in the rain-dominated hydrologic zone. Solid line represents maximum values reported and includes the influence of roads. Dashed line is a linear fit through the average values from figure 8c, and represents the mean reported change for all data. Gray shading around zero indicates limit of detection (±10 percent).

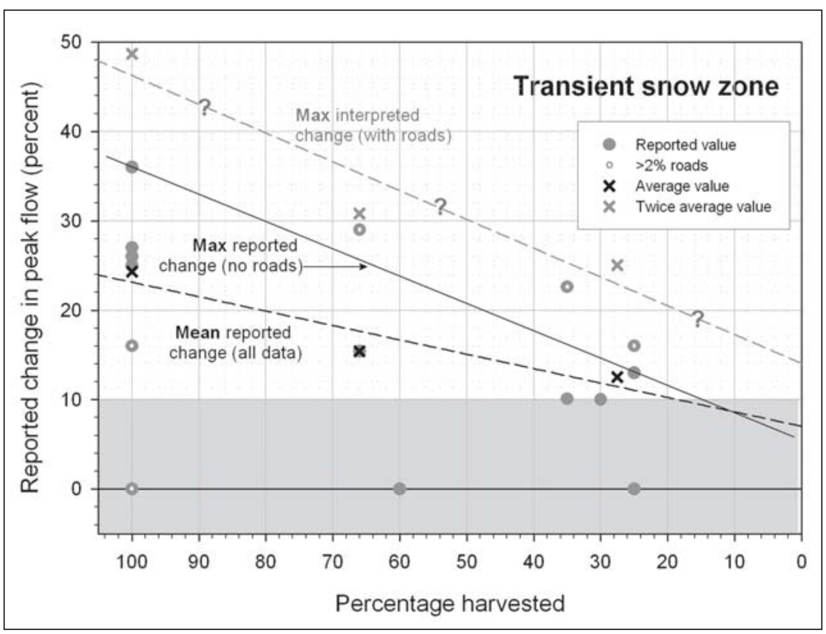

Figure 10—Peak flow response to harvest in the transient snow hydrologic zone. Solid line represents maximum values reported for basins without roads. Dashed black line is a linear fit through the average values from figure 8d, and represents the mean reported change for all data. Dashed gray line represents interpreted change with roads, and is a linear fit through a doubling of the average values. Gray shading around zero indicates limit of detection (±10 percent).

percent harvested. The Andrews Watershed 3 data point that includes roads (25 percent harvested, 16 percent increase), and the modeled points from Bowling and Lettenmaier (2001) that include roads (35 percent harvested, 23 percent increase; and 66 percent harvested, 29 percent increase) all plot above the no-roads maximum reported response line. As we lack sufficient data at the upper end of the harvest range to confidently draw a maximum with-roads response line for the TSZ as we did for the rain zone, we use the modeled 50-percent increase that was due to the presence of roads reported by Bowling and Lettenmaier (2001) to suggest an interpreted maximum response line with roads based on a doubling of the average values. This line remains above the detection limit at all values of percentage harvested.

Once we have defined the maximum and mean reported changes in peak flows that are likely at various levels of harvest, we must revisit our definition of "percentage harvested." As "50-percent harvested" represents a variety of treatment intensities (fig. 3), and our experimental and modeling data are primarily drawn from the most intense of those treatments (i.e., clearcutting), we must address the effects of less intense treatments such as partial harvest and thinning. Drawing on scaling inferences from basic understanding of hydrologic processes to identify plausible trends and magnitudes (fig. 2) we suggest that the mean response lines may provide good guidance in the prediction of likely changes in peak flow from treatments that result in lower disturbance intensities and overall reductions in basal and leaf area than clearcutting. For example, the mean response line suggests a 40-percent thinning over 100-percent of area could be predicted to result in a detectable peak flow increase of approximately 14 percent in a TSZ watershed and would be under the detection limit in rain-dominated watersheds.

Confidence in the general trends and magnitudes of peak flow increases shown in figures 8, 9 and 10 is enhanced by comparison with published global data sets for peak flow increases attributed to forest harvest (fig. 11, after Guillemette et al. 2005). The trend shows similar order of magnitude of peak flow increases as a percentage of area harvested, and our data are contained entirely within the larger data set. The correspondence between our results and these broader global data should be interpreted cautiously, as the higher peak flow increases reported by Guillemette et al. (2005) include practices that are not represented in the data sets used in this synthesis, including expansive road and skid trail networks, widespread application of herbicides, and extensive scarification.

Analysis of Peak Flow Increases in Larger Basins

A key concern in the management arena is how peak flow increases measured at the site scale (area <10 km^2) should be interpreted at the larger basin scale (>10 km^2 to <500 km^2). As we have previously discussed, changes to peak flows are influenced by factors other than harvest, including overall basin condition; the age and pattern of forest stands within a larger basin; the location, age, and extent of road networks; and the extent (both laterally and longitudinally) of riparian buffers. These factors become increasingly complex to quantify in larger basins, and therefore increasingly important in interpreting potential peak flow increases.

Unfortunately, very few studies address the response of peak flows to forest management in larger basins in this region, the papers by Jones and Grant (1996, 2001) with followup analyses by Thomas and Megahan (1998) being the exception. Some modeling studies examine larger basins (Bowling and Lettenmaier 2001). None of these studies addressed the full set of management issues that apply at larger basin scales. Thus, we cannot strictly rely on data as the basis for interpreting likely peak flow effects at the basin scale, but must draw on inferences from field and modeling studies as well. Here we present general principles for interpreting peak flow effects in larger basins, and suggest an approach consistent with data from small watersheds.

The magnitude of any peak flow increase in response to forest management diminishes with increasing basin area for several reasons, including attenuation of flood peaks because of channel resistance, flood-plain storage, and transmission losses, as well as effects of storm size and origin (Archer 1989, Garbrecht 1991, Shaman et al. 2004, Singh 1997). The magnitude of this effect differs from basin to basin and is affected by the location and timing of tributary inputs, but can typically result in reductions in unit streamflows of 50 percent or greater (Woltemade and Potter 1994).

No hydrologic mechanism exists by which peak flow increases, when measured as a percentage change, can combine to yield a higher percentage increase in peak flows in a larger basin. For example, if peak flows in two confluent subbasins each increase by 15 percent, the resultant increase downstream of the confluence can be no more than 15 percent and is likely to be less. As a consequence, the magnitude of peak flow increases for larger basins will necessarily be equal to or smaller than those reported for small watersheds.

For the few studies where increases in peak flows for large basins have been reported, the magnitude of increase is typically less than the inter-annual variability

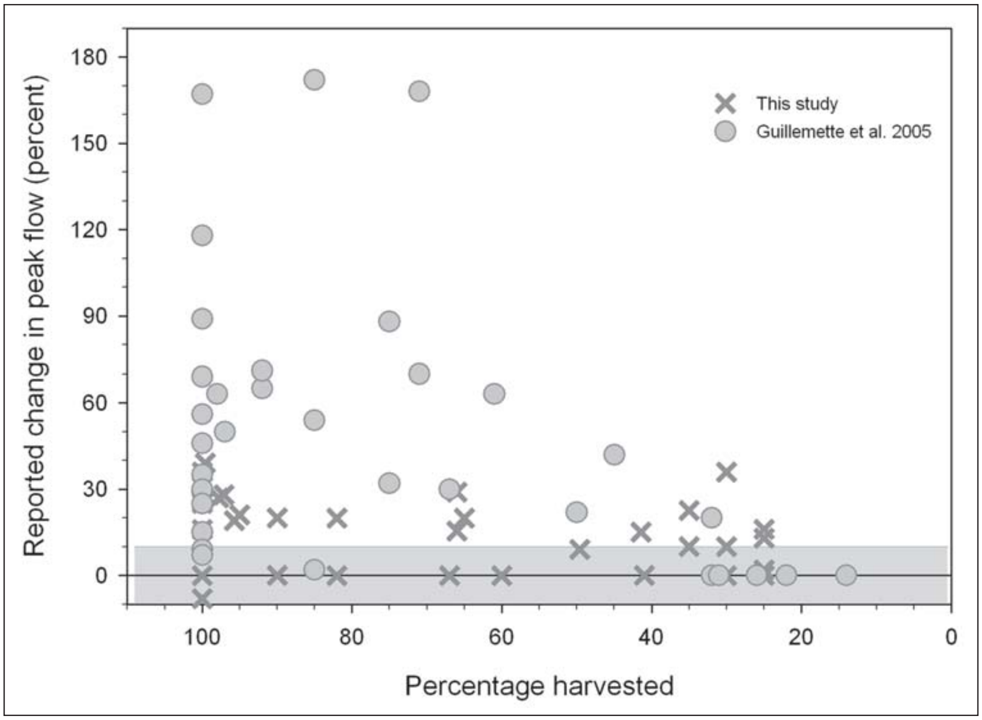

Figure 11—Reported changes to peak flow from worldwide studies, after Guillemette et al. 2005. Gray shading around zero indicates limit of detection (±10 percent).

in streamflows. For example, the range of peak flow increases for larger basins (60 to 600 km^2) as reported by Jones and Grant (1996; their fig. 7) and measured as the difference in peak flows between neighboring watersheds with different forest harvest histories, is less than the inter-annual range of streamflows as measured over the same period. This may partially explain why no studies in the Pacific Northwest have demonstrated the effect of forest harvest on peak flows by using time series of mean or instantaneous peak flow statistics–the inter-annual variance swamps the land use signal. As an aside, this has direct implications for interpreting likely effects of peak flow increases on channel morphology and aquatic habitat, when peak flow increases occurring in the landscape are less than the "natural" variability in streamflows to which channels and presumably ecosystems are adjusted.

Application

Taken together, these general principles provide strong inference that peak flow increases in large basins will almost invariably be less than those in small watersheds, suggesting that the response lines for small watersheds (fig. 9, 10) represent maximum increases for all size watersheds. The degree to which the predicted increases are less than the maximum reported response line should be based on an analysis that incorporates the manager's best evaluation of the separable effects of watershed size, roads, previous cutting history, and degree of forest recovery in establishing an overall level of acceptable "risk" or what some have termed "threshold of probable concern" (Rogers and Biggs 1999). We suggest that potential peak flow increases in large basins be interpreted from figures 9 and 10, with predicted increases falling around the mean response line in most cases. This analysis can be viewed as semi-quantitative, in the sense that it incorporates numerical analyses of key watershed conditions, but does not attempt to define a statistically rigorous solution.

A large-basin analysis should begin with standard approaches to establish the current condition of the watershed with respect to its prior forest cutting and recovery history. Such approaches can include the equivalent clearcut area (ECA) (King 1989; see Reid 1993 for review), aggregate recovery percentage or other metrics of forest regrowth (e.g., Austin 1999, Talbot and Plamondon 2002). The proposed treatment could then be added to the existing ECA or similar metric to determine the effective percentage area harvested. Locating this value on the maximum reported change line from figures 9 and 10 establishes the upper bound of potential response, with a lower bound of no response.

Determining where the proposed treatment falls within this range requires an assessment of the intrinsic basin condition and intensity of proposed management action (fig. 12). For example, the existing and proposed road network should be evaluated with respect to its degree of connectivity with the stream network (e.g., Wemple et al. 1996). Additional qualitative analyses can be performed for the extent of riparian buffers, and existing and proposed sizes of cutting units. The analysis can then be extended to include intrinsic basin factors, such as soil depth, topographic relief, stream density, permeability and porosity of bedrock, and other geologic factors influencing the drainage efficiency, or speed with which water is routed through the watershed (Tague and Grant 2004). In general, we would expect that factors contributing to faster runoff (e.g., shallower soils, low-permeability bedrock) would result in greater drainage efficiency in transmitting any potential peak flow increases to the watershed outlet. Taken together, these analyses provide a useful estimate of the extent to which proposed management actions are more or less likely to result in peak flow increases by various mechanisms.

We propose that this sort of analysis of potential peak flow increases become the basis for interpreting the response lines presented in figures 9 and 10. A greater weight of factors on the left side of figure 12 would lead to an interpretation of

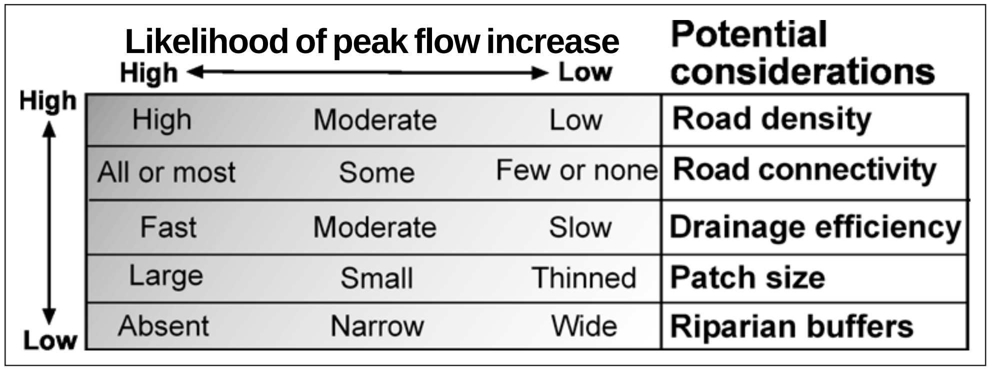

Figure 12—Site conditions and management treatment considerations that potentially influence peak flows. Considerations are listed in decreasing likelihood of effect. Grayscale represents theoretical range in impact of each factor (black = high, white = low).

peak flow increases closer to the maximum response line, whereas a greater weight on the right side would lead to an interpretation of increases at or below the mean response line. The outcome of this type of approach is not a single number for peak flow increases, but a plausible and defensible range of potential increases that is based on the preponderance of evidence and consistent with both data and inference. The following examples, beginning with simple interpretations and proceeding to more complicated analyses, suggest basic guidelines for applying the response curves and process-based understanding generated by the data synthesis to possible management scenarios. These are not meant to represent real treatments for actual watersheds, and should not be viewed as such.

Example 1—

A harvest is scheduled for a 100-year-old forest in the rain zone of the Oregon Coast Range. If the proposed cut is approximately 20 percent, both the maximum and mean response lines in figure 9 suggest it would not result in a detectable increase (i.e. greater than 10 percent) in peak flows with a return period of greater than 1 year. If the proposed cut is 35 percent of the area, figure 9 suggests the resulting increase in peak flow would not be detectable (i.e., less than 10 percent) following the mean response line, and would be approximately 13 percent based on the maximum reported response line, resulting in a range of 0 to 13-percent increase in peak flow. Figure 12 can then be used to narrow down the range of likely peak flow response. For the case of a single large clearcut on thin soils in a watershed with pre-existing dense road network that is hydrologically connected to the stream network, the predicted increase in peak flow would fall near the upper end of the range (i.e., 13 percent). If, on the other hand, the proposed treatment involved a 20-percent thinning on similar soils with the same road network, then the predicted response is more likely to fall nearer the lower end of the range, and not be detectable.

Example 2—
A patch cut involving the removal of 50 percent of basal area in small (less than 0.05 km^2) patches is proposed for a 5-km^2 watershed with no existing roads in the TSZ of the western Cascades. From figure 10, the maximum response at the smaller watershed scale is potentially a peak flow increase of 21 percent, with a mean response of 15 percent. If the treatment included construction of new, hydrologically connected roads, the peak flow increase could be higher. The larger basin (area = 100 km^2) in which this watershed falls has an ECA of 25 percent. This pre-existing basin condition corresponds to a peak flow increase of as much as 13 percent prior to any additional treatments. The proposed treatment would increase the large-basin ECA to 27.5 percent, resulting in a maximum response of 14 percent, an increase of 1 percent. In this case, the small proportion of the larger basin scheduled for harvest results in only a small increase in ECA, and a very small increase in peak flows at the larger basin scale.

Channel Response to Potential Peak Flow Increases

Despite the interest that this issue has garnered, to date no field studies explicitly link peak flow increases with changes in channel morphology. Although there is an extensive literature on forest harvest effects on stream channels, no studies that we are aware of have demonstrated a direct correlation between peak flow changes attributed to forest harvest alone and changes to the physical structure of streams. This statement refers specifically to the effect of peak flow changes directly on channels as measured by changes in channel geometry, planform, or bedload sediment transport; but not to secondary effects that could potentially be attributable to peak flow changes, such as local increases in soil water leading to increased mass movements that deliver sediment to channels and may result in changes in channel structure. Disentangling these different causal mechanisms on channel change can be problematic, as they are often confounded (Grant 1988, Lyons and Beschta 1983). We do not consider such linkages here although they clearly are a factor in some basins.

In the absence of direct studies, our approach to evaluating the likely effect of peak flow increases on channels roughly follows the train of logic suggested by Grant (1987: 143):

> A necessary condition for channel changes is that flows have sufficient force to move bed material. For a given cross-section, channel slope, and size distribution of bed material, the magnitude of flows required to move different size fractions on the bed can be estimated…

Percentage increases in peak flows can be indexed against the magnitude of flows required for bedload sediment transport while recognizing that sediment transport represents a necessary but not sufficient condition for channel change. The magnitude of flows required for bedload sediment transport, termed geomorphically effective flows, differ from channel type to channel type and even within the same channel, but some general principles apply and can be used to identify where the most likely channel responses to any peak flow changes are likely to be located in the channel network.

A detailed channel and cross-section analysis is necessary to rigorously define bedload sediment transport thresholds (e.g., Buffington and Montgomery 1997, Hicks and Gomez 2003, Rosgen 2006). We provide a more general conceptual framework relating channel types to the return period of critical flows required for sediment transport of a reference grain size, assumed here as the median grain size (D_{50}). We therefore define Q_{cr} as the flow required, on average, to move the reference grain size, and RI_{cr} as the corresponding recurrence interval of that flow. We further propose a simple classification system for channel types based on channel gradient. This scheme follows that proposed by Montgomery and Buffington (1997) but also loosely corresponds to the stream typology proposed by Rosgen (1996) and used by many federal agencies. Four broad channel types are considered: cascade, step-pool, gravel-bed, and sand-bed. These channel types generally occur within discrete slope ranges (Montgomery and Buffington 1997) (fig. 13).

In general, the frequency of bedload sediment transport increases with decreasing channel gradient. This is due to a number of factors including the correlation between gradient and bed grain size, and the dependency of critical dimensionless shear stress on gradient and channel type (e.g., fig. 8-4 in Rosgen 1996). The analytical basis for this claim is beyond the scope of this paper; see Andrews (1983) for details. But approximate ranges for RI_{cr} can be based on field evidence (fig. 13). For example, Andrews (1984) found that flows equal to or slightly less than bankfull were required for initiation of gravel transport on 24 gravel-bed streams in

Colorado; Pickup and Warner (1976) cited a range of recurrence intervals (1.15 to 1.45 years) for effective discharge on gravel-bed rivers; Wohl (2000: 106-112) gave a good summary of varying entrainment frequencies and bedload transport rates as a function of stream type. Much less frequent transport is reported for step-pool and cascade channels. Grant et al. (1990), for example, reported RI_{cr} for step-pool channels of 20 to 50 years. Topping et al. (2000a, 2000b) provided estimates of RI_{cr} for sand-bedded channels on the Colorado River. This approach is also consistent with stability analyses for channel types suggested by Rosgen (2006, table 2-4).

Following these analyses we can begin to address which channel types are most likely to be affected by potential peak flow increases. We set the lower bound on RI_{cr} as approximately 1 year and the upper bound at approximately 6 years (fig. 7 and shaded rectangle in fig. 13). The intersection of this rectangle with the labeled stability fields for each of the channel types provides a rough estimate of the likelihood of peak flow increases translating into bedload sediment transport and associated channel morphology changes. This analysis reveals that the steepest

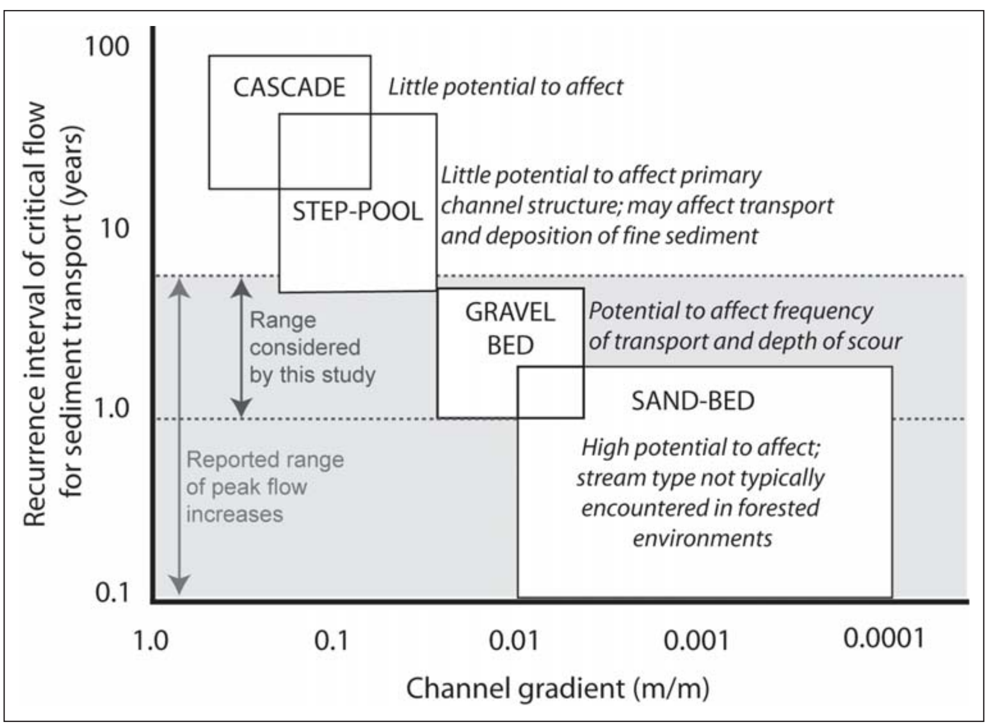

Figure 13—Domains for initiation of bedload sediment transport as a function of channel type (Grant et al. 1990, Montgomery and Buffington 1997) and recurrence interval (Andrews 1984, Grant et al. 1990, Pickup and Warner 1976, Topping et al. 2000a, 2000b, Wohl 2000).

channel types (cascade and step-pool) generally have RI_{cr} values above those likely to be affected by peak flow increases. In contrast, gravel- and sand-bed channels have RI_{cr} values where peak flow increases may be a factor. In Oregon and Washington, gravel-bed channels are the dominant stream type likely to be sensitive to any peak flow changes as sand-bed channels in forested landscapes are rare in the Pacific Northwest.

Figure 13 provides only a rough guide to where peak flow changes have the potential to be manifest–it is intended primarily to show where such changes are unlikely to occur. Moreover, local scour and fill can occur in a wide range of channels over a wide range of peak flows. For example, Faustini (2000) reported local changes of one to several grain diameters in channel cross-section area for a cobble-bed, step-pool channel from peak flows less than a 10-year recurrence interval. However, substantial changes in most cross sections of this channel type require peak flows with recurrence intervals greater than 10 years.

Field observations and more detailed analyses are called for where a high concern for potential peak flow changes exists (e.g., Rosgen 2006). Also, this analysis focuses only on sediment entrainment. Potential effects of changing hydrologic regimes on other channel processes, including changes in the frequency of wood entrainment and transport, lateral migration, or pool/riffle dynamics are not considered. However, this analysis sets the lower threshold of concern, as wood entrainment or channel geometry or planform changes generally occur at higher RI_{cr} than initiation of bedload sediment transport. This analysis is likely to be particularly useful in identifying parts of the stream network where risk of channel response to peak flow changes is relatively low. Finally, because our entire analysis is based on flood frequency analysis (recurrence interval) as opposed to flow duration data (daily flows), we cannot address the question of whether the duration of peak flows has changed, nor whether channel morphology changes because of changing flow duration are likely.

Management Implications

This analysis of the available data on forestry-induced peak flow changes and likely first-order geomorphic effects on streams raises a number of key questions with respect to management of forest lands. We have tried to frame the issue as broadly as possible while still providing our best estimates of the state of the science. We were conservative in our interpretations—the manner in which we constructed the response lines in figures 9 and 10 is an example of this. These available data do not permit an entirely rigorous and statistically valid analysis of whether or not forest harvest activities cause peak flow changes sufficient to cause geomorphic or ecological effects. The data do, however, provide a sound basis for discriminating "big" effects from "small" effects, and help to identify geographic regions and parts of watersheds where such effects are more likely to occur and result in detectable changes.

Specifically, the small-watershed data support the interpretation that watersheds located in the rain-dominated region are less sensitive to peak flow changes than those in the TSZ. This is reflected in the difference between the 29-percent (rain) versus 15-percent (transient) harvested area detection limit (figs. 9, 10). Furthermore, the data support the interpretation that if peak flow increases do occur, they can be detected only in flows of moderate frequency and magnitude. This is not to say that forest harvest has no effect on extreme events, just that we cannot detect them. Hydrologic theory, however, suggests that such effects are likely to be small.

Considerations as to how these effects might scale up in larger basins indicated that small-watershed studies likely represent the maximum effects of forest harvest present on the landscape, and that such effects will, at most, remain constant with watershed size. This finding is consistent with the observations of Jones and Grant (1996) that similar percentage harvested in small and larger basin pairs resulted in similar magnitudes of peak flow changes. In general, we would predict that harvest effects diminish as basin size increases.

Moreover, the data suggest that peak flow effects on channels, if any, should be confined to a relatively discrete portion of the network where channel gradients are less than approximately 0.02. These are primarily the domain of gravel-bed rivers and streams in forested landscapes in western Oregon and Washington. Peak flow effects on channel morphology can be confidently excluded in high-gradient (slopes >0.10) and bedrock reaches, and are likely to be minor in most step-pool systems. On the other hand, if channels have beds of fine gravel or sand, a much closer hydrologic and geomorphic analysis seems warranted.

In general, the magnitude of channel morphologic changes because of peak flow increases alone are likely to be much less significant than other impacts associated with forest harvest activities. Effects of deforestation on landslides, debris flows, and surface erosion are well documented (e.g., Reid 1993, Sakals et al. 2006, Sidle et al. 1985) and these are likely to have far more direct effects on channel structure than peak flows alone, as these processes typically involve direct introduction of sediment into stream channels. In particular, accelerated geomorphic processes associated with forest roads are likely to have some of the most pronounced effects on forest streams (e.g., Wemple et al. 2001). Although we acknowledge that there may be some synergistic effects between erosion and peak flow effects on channels, i.e., that increased surface erosion and delivery of fine sediments to channels may decrease the threshold of mobility of bed sediments because of bed fining (e.g., Curran and Wilcock 2005), we have no data from which to evaluate the magnitude of these complex responses. Instead, we look to land managers to use field evidence of such processes to guide their assessments of risk, along the lines suggested here.

The magnitude of effects of forest harvest on peak flows in the Pacific Northwest, as represented by the data reported here, are relatively minor in comparison to other anthropogenic changes to streams and watersheds. In particular, the effects of dams on hydrologic regimes, including peak flows, can be several orders of magnitude greater, particularly where the dams are large and used for flood control (Grant 1997). Urbanization similarly imposes much larger changes to peak flows than does forest harvest, although less than dams. For example, moderate amounts of urbanization in watersheds located in Puget Sound increased peak flows by factors of 1.5 to 2.75, with corresponding and measurable effects on channel incision and geometry (Booth and Henshaw 2001, Moscrip and Montgomery 1997).

The effects of global warming on hydrologic responses are only beginning to be addressed, and we know of no studies that look specifically at how warming might influence peak flow responses in forest basins. We can speculate that predictions of increased climate intensification and "storminess" in the wintertime might increase the frequency of rain and ROS events in some landscapes, and warmer summer temperatures may result in a more pronounced effect on evapotranspiration. In general, we would predict that the current estimates of global warming in the Pacific Northwest are likely to shift the boundaries of hydrologic zones upward in elevation, with zones that are currently snow-dominated becoming ROS dominated, while rain-dominated zones increase at the expense of TSZs. The identified boundaries of these regions may need to be redefined in the future (Nolin and Daly 2006).

Concerning the effects of forest harvest on the largest floods, Jones and Grant (2001: 177) noted that the peak flow issue "… cannot be resolved with statistics based on a mere handful of extreme flood events. Future physical process based modeling and field studies will improve our understanding of forest harvest effects on these rare big floods…" Ultimately the best way forward toward understanding effects of management on large peak flow events will be to illuminate the black box of forested watersheds in Oregon and the Pacific Northwest with new field-based experimental work to understand flow pathways, residence times, and stream sources. Given the extreme expense and difficulty in mounting such campaigns, modeling studies provide a key way to move beyond a singular focus on paired watershed studies (and purely statistical analysis of flow data) to seek new ways of quantifying forest harvesting and road construction influences on peak flows, particularly at the extremes of the flow frequency distribution.

The change detection modeling approach (Kundzewicz and Robson 2004) is one way to deal with the many data sets where controversy lingers, and new sites where controversy will undoubtedly rage. This is a very straightforward use of a model (Kuczera 1987), but surprisingly has had little use in interpreting peak flow issues. This modeling approach is a possible useful alternative to the paired catchment approach to evaluate the effects of a land-use or land-cover change. The approach is especially useful in cases where a suitable control basin does not exist, which is often the case for larger basins.

Using the data from decades worth of small watershed studies, we have attempted to constrain the problem of peak flow increases and likely geomorphic effects on channel systems. Although such data are incomplete, subject to interpretation, and particularly problematic for interpreting modern practices, they do provide a sound basis for setting boundaries on the likely magnitudes and directions of change. In setting these limits, we recognize the importance of site-level information and risk assessment that can only be provided by the on-the-ground manager and specialist. Work incorporating new field experiments supplemented by modeling is necessary to close some of the gaps. This analysis provides forest managers and regulators with the information needed to proceed with some measure of confidence while these newer studies take root.

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English Equivalents

When you know:	Multiply by:	To find:
Meters (m)	3.28	Feet
Hectares (ha)	2.47	Acres
Square kilometers (km^2)	0.386	Square miles
Cubic meters per second (m^3/s)	35.31	Cubic feet per second

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Appendix 2: Watershed Data Tables

Table 5—Peak flow data from Alsea Experimental Watershed, Oregon

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change: Roads	Magnitude of change: Harvest
				$m^3 \cdot s^{-1} \cdot km^{-2}$	– – – *Years*	– – –		– – – – *Percent*	– – – –
Needle Branch	Harr et al. 1975	Linear regression of peaks	Fall	Nr	Nr	<5	Increase	Nr	Nr
82% harvest			Winter	Nr	Nr	<5	Increase	Nr	Nr
5% roads	Harris 1977	Linear regression of peaks	Large	0.55	Nr	7	Nsc		
Deer Creek	Harr et al. 1975	Linear regression of peaks	Fall	Nr	Nr	<5	Nsc		
25% harvest			Winter	Nr	Nr	<5	Nsc		
4% roads	Harris 1977	Linear regression of peaks	Large	0.55	Nr	7	Nsc		2
Deer 2	Harr et al. 1975	Linear regression of peaks	Fall	Nr	Nr	<5	Nsc		
30% harvest			Winter	Nr	Nr	<5	Nsc		
3% roads	Moore and Wondzell 2005	Interpreted from Harr et al., 1975 data set	Large	0.55	Nr	7	Nsc		2
Deer 3	Harr et al. 1975	Linear regression of peaks	Fall	Nr	Nr	<5	Increase	5	Nr
65% harvest			Winter	Nr	Nr	<5	Increase	5	20
12% roads	Moore and Wondzell 2005	Interpreted from Harr et al., 1975 data set	Large	0.55	Nr	7	Increase	18	44
Deer 4	Harr et al. 1975	Linear regression of peaks	Fall	Nr	Nr	<5	Nsc		
90% harvest			Winter	Nr	Nr	<5	Nsc		
no roads	Moore and Wondzell 2005	Interpreted from Harr et al., 1975 data set	Large	0.55	Nr	7	Nsc		

Nr = not reported, Nsc = no significant change.

Table 6—Peak flow data from Carnation Creek Watershed, British Columbia

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change Roads	Magnitude of change Harvest
				$m^3 \cdot s^{-1} \cdot km^{-2}$	– – – *Years*	– – –		– – – *Percent*	– – –
Carnation H 90% harvest 6.5% roads	Hetherington 1982	Linear regression of peaks	Rain	0.55	Nr	Nr	Increase	20	20
Carnation B 41% harvest no roads	Hetherington 1982	Linear regression of peaks	Rain	0.55	Nr	Nr	Nsc	Nr	Nr

Nr = not reported, Nsc = no significant change.

Table 7—Peak flow data from Caspar Creek Experimental Watershed, California

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change: Roads	Magnitude of change: Harvest
				$m^3 \cdot s^{-1} \cdot km^{-2}$	– – – *Years* – – –			– – – – *Percent* – – – –	
South Fork	Ziemer 1981	Least squares regression of	Small	0.016	Nr	4	Increase	Nr	Nr
(SFC)		peaks	Medium	0.07	Nr	4	Nsc		
67% harvest			Large	0.16	1.01	4	Nsc		
5% roads			Very large	0.41	1.4	4	Nsc		
			All	Na	Na	4	Increase	Nr	10
		Double mass curve	All	Na	Na	4	Increase	Nr	4
	Wright et al. 1990	Least squares logarithmic	All	Nr	Na	5	Increase	Nsc	Nr
		regression of peaks	Small	<.067	Nr	5	Increase	20	111
			Large	>0.112	8	5	Nsc		
	Ziemer 1998	Least squares regression of peaks	All	>0.1	Nr	15	Nsc		
North Fork	Ziemer 1998	Linear regression of peaks	All	>.1	7x/yr	12	Nsc		2
(NFC)			Large	Nr	2	12	Increase		9
49.6% harvest			Fall	>0.125	Nr	12	Increase		300
2% roads									
BAN	Ziemer 1998	Linear regression of peaks	Large	0.8	2	12	Increase		21
95% harvest	Reid and Lewis	Analyzed by Ziemer 1998	Small	Nr	>.15	2	Increase		56
2.6% roads	2007								
CAR	Ziemer 1998	Linear regression of peaks	Large	0.8	2	12	Increase		19
95.7 % harvest	Reid and Lewis	Analyzed by Ziemer 1998	Small	Nr	>.15	2	Increase		54
2.8 % roads	2007								
EAG	Ziemer 1998	Linear regression of peaks	Large	0.8	2	12	Increase		27
99.9 % harvest	Reid and Lewis	Analyzed by Ziemer 1998	Small	Nr	>.15	2	Increase		58
4.9 % roads	2007								
GIB	Ziemer 1998	Linear regression of peaks	Large	0.8	2	12	Increase		39
99.6 % harvest	Reid and Lewis	Analyzed by Ziemer 1998	Small	Nr	>.15	2	Increase		70
4.2 % roads	2007								
KJE	Ziemer 1998	Linear regression of peaks	Large	0.8	2	12	Increase		28
97.1 % harvest	Reid and Lewis	Analyzed by Ziemer 1998	Small	Nr	>.15	2	Increase		67
6.5 % roads	2007								

Table 7—Peak flow data from Caspar Creek Experimental Watershed, California (continued)

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change	
								Roads	Harvest
				$m^3 \cdot s^{-1} \cdot km^{-2}$	– – – *Years*	– – –		– – – – *Percent*	– – – –
Average of clearcut NFC basins 97.8 % harvest	Ziemer 1998	Linear regression of peaks	Large	Nr	2	12	Increase		27
			Medium	>0.4	0.5	12	Increase		34
Average of partial cut NFC basins 41.4 % harvest	Ziemer 1998	Linear regression of peaks	Large	Nr	2	12	Increase		15
			Medium	>0.4	0.5	12	Increase		16

Na = not applicable, Nr = not reported, Nsc = no significant change.

Table 8a—Peak flow data from Watershed 3, H.J. Andrews Experimental Forest, Oregon

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change, by years since harvest							
								All	0	5	10	15	20	25	30
				$m^3 \cdot s^{-1} \cdot km^{-2}$	– – – *Years* – – –			– – – *Percent* – – –							
Watershed 3	Jones and	Analysis of	All	0.03	Na	25	Increase		11	28	22	17	14	14	
30% harvest	Grant 1996	variance on log-	Fall	0.03	Na	25	Increase		7	30	23	12	15	5	
6% roads		transformed peaks[a]	Winter	0.03	Na	25	Increase		8	23	22	21	16	23	
			Spring	0.03	Na	25	Increase		5	42	25	23	7	15	
			Small	0.03	<0.125	25	Increase		4	**36**	27	16	15	12	
			Large	0.35	0.4	25	Increase		6	**23**	22	13	13	15	
	Thomas and	Linear regression	Small	0.03	<0.125	25	Increase			**39**	23				
	Megahan 1998[b]	of log-transformed peaks[a]	Medium-small	0.11	0.125	25	Increase			**22**	18				
			Medium-large	0.21	0.2	25	Increase			**17**	17				
			Large	0.35	0.4	25	Increase			**16**	16				
	Beschta et	Linear regression of	Large	0.35	0.4	25	Increase[c]	**24**							
	al. 2000	log-transformed peaks[a]	Large	0.65	1	25	Increase[c]	**13**							
			Large	1.00	5	25	Increase[c]	**6**							
	Jones 2000	Analysis of variance on	All	0.03	Na	33	Increase		8		19		14		10
		log-transformed peaks	Small, fall	0.03	Na	33	Increase		15		31		21		12
			Small, spring	0.03	Na	33	Nsc		9		22		8		10
			Rain	0.03	Na	33	Nsc	10							
			Mixed	0.03	Na	33	Nsc	22							
			Rain-on-Snow	0.03	Na	33	Increase	26							
			Large	0.65	>1	33	Increase	**16**							

All values statistically significant at 0.05. Bold indicates values graphed in figure 5. Na = not applicable, Nsc = no significant change.

[a] These three studies used the same data set.

[b] Values estimated from table 3a.

[c] Statistical significance not reported.

Table 8b—Peak flow data from Watersheds 6, 7, and 10, HJ Andrews Experimental Forest, Oregon

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change, by years since harvest All	0	5	10	15	20	25	30
				$m^3 \cdot s^{-1} \cdot km^{-2}$	– – – *Years*	– – –		– – – – – – – – – – *Percent* – – – – – – – – – –							
Watershed 6 100% harvest 9% roads	Harr et al. 1982	Linear regression of peaks	All	0.45	1	6	Nsc	Nr							
	Jones 2000	Analysis of variance on log-transformed peaks	All	0.03	Na	23	Increase				37		20		
			Large	0.65	1	23	Increase	16							
Watershed 7 100% harvest no roads	Harr et al. 1982	Linear regression of peaks	All	0.45	1	6	Nsc	Nr							
	Jones 2000	Analysis of variance on log-transformed peaks	All	0.03	Na	12	Increase				25	36			
			Large	0.65	1	12	Increase	27							
Watershed 10 100% harvest no roads	Harr and McCorison 1979	Linear regression of peaks	All	0.22	Na	1	Decrease	-32							
	Harr 1986	Linear regression of peaks	Rain-on snow	0.55	Na	16	Nsc	Nr							
	Jones 2000	Analysis of variance on log-transformed peaks	All	0.03	Na	22	Increase				25		26		
			Large	0.65	1	22	Nsc	-8							

Na = not applicable, Nr = not reported, Nsc = no significant change.

Table 9—Peak flow data from Bull Run Watershed, Oregon

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change, by years since harvest: All	0	5	10	15	20
				$m^3 \cdot s^{-1} \cdot km^{-2}$	*Years*	*Years*		*Percent*					
Fox 1	Harr, 1980	Linear regression	All	0.56	1	Nr	Nsc	**0**					
25% harvest		of peaks											
1% roads	Jones, 2000	Analysis of	All	Nr	Na	20	Increase				12		5
		variance on log-	Small, fall	Nr	0.28	20	Nsc				7		12
		transformed peaks	Small, spring	Nr	0.28	20	Nsc				22		-5
			Large	Nr	1	20	Increase	**13**					
Fox 3	Harr, 1980	Linear regression	All	0.56	1	Nr	Nsc	**0**					
25% harvest		of peaks											
1% roads	Jones, 2000	Analysis of	Small, fall	Nr	0.28	20	Nsc				1		2
		variance on log-	All	Nr	Na	20	Nsc				2		8
		transformed peaks	Small, spring	Nr	0.28	20	Nsc				4		-8
			Large	Nr	1	20	Increase	**13**					

Bold indicates values graphed in figure 5. Na = not applicable, Nr = not reported, Nsc = no significant change.

Table 10—Peak flow data from Coyote Creek Experimental Watershed, Oregon

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change, by years since harvest: All	0	5	10	15	20
				$m^3 \cdot s^{-1} \cdot km^{-2}$	– – – – *Years*	– – – –		– – – – – – – – – – – *Percent* – – – – – – – – – – –					
Coyote 1 50% harvest 1.6% roads	Harr et al. 1979	Linear regression of peaks	Large	0.22	9	5	Increase	**47**					
	Jones 2000	Analysis of variance on log-transformed peaks	All	Nr	Na	12	Increase			36	42		
			Small, fall	Nr	0.24	12	Increase			73	63		
			Small, spring	Nr	0.24	12	Nsc			17	15		
			Large	Nr	1	12	Nsc	**10**					
	Moore and Wondzell 2005	Estimated from Harr et al. 1979 regression relationships	Large	0.19	1.1	5	Nr	**6**					
				0.35	1.5	5	Nr	**25**					
				0.45	2	5	Nr	**32**					
				0.87	5	5	Nr	**44**					
				1.23	10	5	Nr	**48**					
Coyote 2 30% harvest 1.7% roads	Harr et al. 1979	Linear regression of peaks	Large	0.22	9	5	Increase	**10**	10				
	Jones 2000	Analysis of variance on log-transformed peaks	All	Nr	Na	12	Increase			32	40		
			Small, fall	Nr	0.24	12	Increase			71	61		
			Small, spring	Nr	0.24	12	Nsc			26	36		
			Large	Nr	1	12	Increase	**36**					
	Moore and Wondzell 2005	Estimated from Harr et al. 1979 regression relationships	Large	0.19	1.1	5	Nr	**18**					
				0.35	1.5	5	Nr	**14**					
				0.45	2	5	Nr	**13**					
				0.87	5	5	Nr	**10**					
				1.23	10	5	Nr	**9.6**					
Coyote 3 100% harvest 0.3% roads	Harr et al. 1979	Linear regression of peaks	Large	0.22	9	5	Increase	**36**					
	Jones 2000	Analysis of variance on log-transformed peaks	All	Nr	Na	12	Increase			45	73		
			Small, fall	Nr	0.24	12	Increase			116	75		
			Small, spring	Nr	0.24	12	Increase			24	71		
			Large	Nr	1	12	Increase	**26**					
	Moore and Wondzell 2005	Estimated from Harr et al. 1979 regression relationships	Large	0.19	1.1	5	Nr	**56**					
				0.35	1.5	5	Nr	**46**					
				0.45	2	5	Nr	**43**					
				0.87	5	5	Nr	**37**					
				1.23	10	5	Nr	**35**					

Bold indicates values graphed in figure 5. Na = not applicable, Nr = not reported, Nsc = no significant change.

Table 11—Peak flow data from Umatilla National Forest, Oregon

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change	
								Roads	Harvest
				$m^3 \cdot s^{-1} \cdot km^{-2}$	– – – – *Years*	– – – –		– – – – *Percent*	– – – –
Elgin 1 43% harvest	Fowler et al. 1987	Nr	All	Nr	Nr	6	Nsc		0
Elgin 2 50% harvest	Fowler et al. 1987	Nr	All	Nr	Nr	6	Nsc		0
Elgin 3 22% harvest	Fowler et al. 1987	Nr	All	Nr	Nr	6	Nsc		0

Nr = not reported, Nsc = no significant change.

Table 12—Peak flow data from Deadhorse Creek, Colorado

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change: Roads	Magnitude of change: Harvest
				$m^3 \cdot s^{-1} \cdot km^{-2}$	– – – – *Years*	– – – –		– – – – *Percent*	– – – –
Deadhorse 10% harvest 3.4% roads	Troendle and King 1987	Analysis of covariance	All	Nr	Nr	Nr (<5)	Nsc		0
North Fork 36% harvest 3.1% roads	Troendle and King 1987	Analysis of covariance	All	Nr	Nr	Nr (<5)	Increase		50
Unit 8 40% harvest 4.9% roads	Troendle and King 1987	Nr	All	Nr	Nr	3	Nr		0
Upper Basin 30% harvest 3.2% roads	Troendle and King 1987	Nr	All	Nr	Nr	Nr (<5)	Nr		0

Nr = not reported, Nsc = no significant change.

Table 13—Peak flow data from Camp Creek, British Columbia

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change: Roads	Magnitude of change: Harvest
				$m^3 \cdot s^{-1} \cdot km^{-2}$	– – – –*Years*	– – – –		– – – – *Percent*	– – – –
Camp Creek 27% harvest	Cheng 1989	Comparison of annual peak flow values	Large	Nr	Nr	6	Increase		21
	Moore and Scott 2005	Analysis of covariance	Medium	>0.03	Nr	17	Nsc		Nr
			Small	<0.03	Nr	17	Increase		Nr

Nr = not reported, Nsc = no significant change.

Table 14—Peak flow data from Wagon Wheel Gap, Colorado

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change: Roads	Magnitude of change: Harvest
				$m^3 \cdot s^{-1} \cdot km^{-2}$	*– – – Years – – –*			*– – – – Percent – – – –*	
Catchment B 100% harvest no roads	Bates and Henry 1928	Comparison of mean daily flow	All	Nr	Nr	7	Increase		50
	Van Haveren 1998	Comparison of maximum daily flow	All	Nr	Nr	7	Increase		50

Nr = not reported.

Table 15—Peak flow data from Fool Creek, Colorado

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change: Roads	Magnitude of change: Harvest
				$m^3 \cdot s^{-1} \cdot km^{-2}$	*– – – – Years– – – –*			*– – – – Percent – – – –*	
Fool Creek 40% harvest 5% roads	Troendle and King 1985	Analysis of covariance	All	Nr	Nr	28	Increase		23

Nr = not reported.

Table 16—Peak flow data from Horse Creek, Idaho

Site and treatment	Reference	Method of analysis	Event type	Minimum flow	Return period	Record length	Direction of change	Magnitude of change: Roads	Magnitude of change: Harvest
				$m^3 \cdot s^{-1} \cdot km^{-2}$	*Years*	*Years*		*Percent*	*Percent*
Horse Creek no harvest 3.7% roads	King and Tennyson 1984	Linear regression of peaks	All	Nr	Nr	Nr	Nsc		Nr
Subbasin 10 no harvest 2.6% roads	King and Tennyson 1984	Linear regression of peaks	All	Nr	Nr	Nr	Nsc		Nr
Subbasin 12 33% harvest 3.9% roads	King 1989	Linear regression of peaks	All	Nr	Nr	Nr	Nsc		15
Subbasin 14 27% harvest 1.8% roads	King 1989	Linear regression of peaks	All	Nr	Nr	Nr	Increase		35
Subbasin 16 27% harvest 3% roads	King 1989	Linear regression of peaks	All	Nr	Nr	Nr	Increase		36
Subbasin 18 29% harvest 4.3% roads	King 1989	Linear regression of peaks	All	Nr	Nr	Nr	Increase		34

Nr = not reported, Nsc = no significant change.

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