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Hydrological response to timber harvest in northern Idaho: implications for channel scour and persistence of salmonids

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Abstract:

The potential for forest harvest to increase snowmelt rates in maritime snow climates is well recognized. However, questions still exist about the magnitude of peak flow increases in basins larger than 10 km^2 and the geomorphic and biological consequences of these changes. In this study, we used observations from two nearly adjacent small basins (13 and 30 km^2) in the Coeur d'Alene River basin, one with recent, relatively extensive, timber harvest, and the other with little disturbance in the last 50 years to explore changes in peak flows due to timber harvest and their potential effects on fish. Peak discharge was computed for a specific rain-on-snow event using a series of physical models that linked predicted values of snowmelt input to a runoff-routing model. Predictions indicate that timber harvest caused a 25% increase in the peak flow of the modelled event and increased the frequency of events of this magnitude from a 9-year recurrence interval to a 3·6-year event. These changes in hydrologic regime, with larger discharges at shorter recurrence intervals, are predicted to increase the depth and frequency of streambed scour, causing up to 15% added mortality of bull trout (*Salvelinus confluentus*) embryos. Mortality from increased scour, although not catastrophic, may have contributed to the extirpation of this species from the Coeur d'Alene basin, given the widespread timber harvest that occurred in this region. Copyright © 2008 John Wiley & Sons, Ltd.

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INTRODUCTION

Increases in peak flows during rain-on-snow events have been attributed to forest harvest in maritime snow climates (Christner and Harr, 1982; Beaudry and Golding, 1983; Harr, 1986; Berris and Harr, 1987; MacDonald and Hoffman, 1995; Jones and Grant, 1996; Marks *et al.*, 1998; Storck *et al.*, 1998, 1999; Bowling *et al.*, 2000). Much of the work has focused on plot scales, demonstrating that there may be large increases in local water input for some events (e.g. Harr, 1986; Berris and Harr, 1987; Marks *et al.*, 1998; Storck *et al.*, 1999). However, notable spatial variability in water inputs occurs during rain-on-snow events (Storck *et al.*, 1998; Miller *et al.*, 2003), and the effect at basin scales is less clear and less well documented. Adding to the complexity at basin scales, multiple mechanisms exist for increased peak flow due to forest management, and some investigators have noted the potential for forest roads to intercept subsurface flow and increase peak flows, confounding statistical analysis of peak flow changes in small basins (Jones and Grant, 1996, 2001; Wemple *et al.*, 1996; Thomas and Megahan, 1998, 2001; Lamarche and Lettenmaier, 2001; Luce, 2002; Wemple and Jones, 2003).

Additional problems arise when examining larger floods that may have important effects on geomorphic and biological processes. A key issue is that there are fewer observations of large events and greater variability, making analysis less tractable by statistical methods than for smaller and more common events. Furthermore, at the scale of basins greater than 10 km^2, there are few paired watershed data sets, and very few of these have strongly contrasting treatments (Bowling *et al.*, 2000). Rain-on-snow is associated with the largest (rarest) peak flows and, consequently, the effects of changing canopy on rain-on-snow floods in basins greater than 10 km^2 have not been well documented *statistically*.

One way to address this problem is to examine individual events using a physically based model to estimate the contribution of snowmelt to changes in flow. For example, after calibration to existing conditions, one can alter the modelled forest canopy to estimate flows under changed conditions. In essence, this is a 'virtual paired-watershed experiment' for different basin treatments (*sensu* Storck *et al.*, 1998). Using flow data from

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similar basins with strongly contrasting treatments can strengthen inferences from this approach because the data allow for validation of the forest cover parameterization, e.g. to demonstrate that the effect is not just a model effect but reflects observed discharge patterns. We have adopted this latter approach, a 'model-assisted paired watershed analysis', because the pretreatment data for developing a *statistical* runoff model such as would be used in a classic paired watershed analysis were not available.

We examined runoff from two watersheds, Big Elk Creek and Halsey Creek, in the Coeur d'Alene River basin of northern Idaho to investigate the effect of timber harvest on the magnitude of peak discharge. These basins were selected for their proximity, physiographic similarities, and strong contrast in land management. The Halsey basin is nearly undisturbed, whereas extensive clearcutting occurred in the Big Elk basin (USDA Soil Conservation Service, 1994). A striking difference in unit area peak flow was recorded in 1990 during a regional rain-on-snow event, providing an opportunity to examine how differences in flow could be related to differences in melt-water input due to changes in forest cover.

These two watersheds also provided the opportunity to assess whether any hydrologic changes were geomorphically and biologically significant. Both watersheds are within the historic range of bull trout (*Salvelinus confluentus*), a threatened species under the Endangered Species Act, and may have contained important spawning habitat in the past. Bull trout are believed to be extinct throughout the Coeur d'Alene basin, and one hypothesis is that widespread changes in the hydrology of managed basins might have contributed to their extinction (Rieman and McIntyre, 1993). Bull trout are fall-spawning fish that bury their eggs in streambed gravel where embryos incubate over winter; and increases in peak winter flows due to timber harvest might have increased the frequency and depth of bed scour and, consequently, the vulnerability of incubating embryos (Montgomery *et al*., 1996; Shellberg, 2002). Montgomery *et al.* (1999) predicted that fall-spawning salmonids should be very sensitive to changes in bed scour depths resulting from increased discharge, and scour associated with winter floods has been implicated in the losses of other fall-spawning salmonids, including brook trout (*Salvelinus fontinalis*) (Seegist and Gard, 1972) and chum salmon (*Oncorhynchus keta*) (Schuett-Hames *et al*., 2000).

If egg pocket scour is rare or limited in extent, then the population might absorb the additional mortality, but if the situation becomes frequent and widespread, then a population could decline or be driven to local extinction through this additional mortality (Rieman and McIntyre, 1993). Even if these changes do not occur in all tributary watersheds of a basin, the loss of key tributary populations could lead to a general collapse across the basin (Schlosser and Angermeier, 1995; Rieman and Allendorf, 2003).

Our study examined whether differences in snowmelt rate could explain differences in peak flows between disturbed (harvested) and undisturbed (no recent timber harvest) basins, and whether the changes in flow from canopy loss could have changed scour regime and survival of bull trout embryos. Although some streams, like Halsey Creek, were not directly influenced by timber harvest, their lack of bull trout may reflect larger scale indirect effects of logging within the Coeur d'Alene basin. Widespread timber harvest throughout the basin (USDA Soil Conservation Service, 1994; Idaho Department of Environmental Quality, 2001) and associated hydrologic changes might have precipitated a general extirpation through disruption of large-scale demographic support among bull trout populations (e.g. Dunham and Rieman, 1999). Part of our interest here is to see whether such a hypothesis is plausible.

STUDY AREA

The study watersheds are located in the Coeur d'Alene River basin, about 40 km northeast of the town of Coeur d'Alene (Figure 1). The area is part of the Coeur d'Alene metasedimentary zone (McGrath *et al*., 2002), within the Northern Rockies ecoregion, ranging in elevation from 700 to 2000 m. Climate and vegetation are 'maritime influenced' with Douglas fir (*Pseudotsuga menziesii*), white pine (*Pinus strobus*), grand fir (*Abies grandis*), western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), and at higher elevations, mountain hemlock (*Tsuga mertensiana*), subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmanni*), and white bark pine (*Pinus albicaulis*). Fractured quartzite and argillaceous rocks of Precambrian origin characterize the underlying geology (McGrath *et al*., 2002).

The mouths of the two study basins are about 2 km apart, and the furthest points in the two watersheds are less than 18 km apart. Big Elk and Halsey Creeks are gravel-bed rivers with median grain sizes of about 30 mm and 20 mm respectively near their outlets. Both streams are tributaries to Teepee Creek, which is in the North Fork Coeur d'Alene River watershed. The closest US Geological Survey (USGS) stream gauge is North Fork Coeur d'Alene River above Shoshone Creek near Prichard, Idaho (#12 411 000). Extensive logging occurred in the Big Elk basin during the 1970s and 1980s, with most of the harvest occurring in the 15 years prior to the 1990 rain-on-snow event analysed in this study; logging reduced the mature forest cover to 74% of the basin area (Figure 2). In contrast, the Halsey watershed has had no timber harvest or other disturbance since the fires in 1910, 1919, 1926, and 1931, which spread throughout much of the northern Coeur d'Alene basin (USDA Soil Conservation Service, 1994). The Halsey basin has a 95% forest cover, representing a nearly pristine condition (Figure 2); virtually all of the open area in the basin is natural, with the exception of a

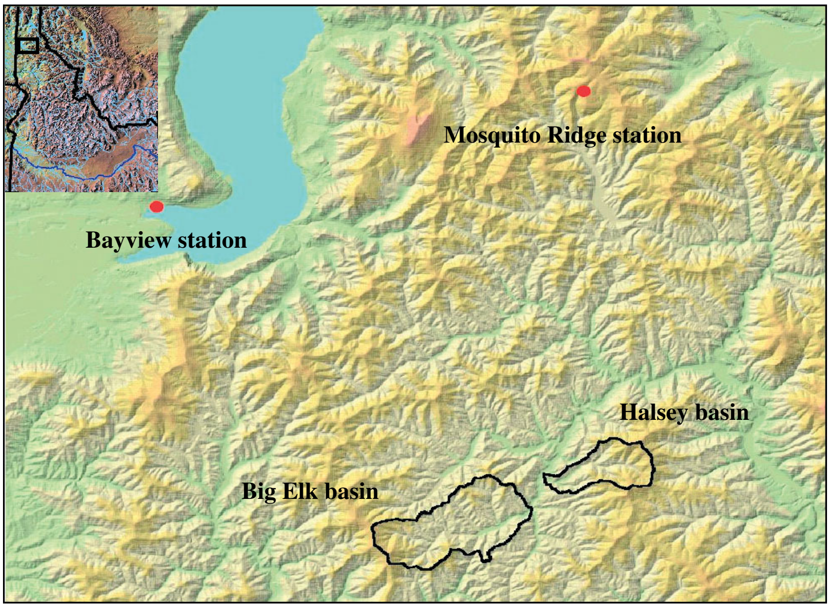

Figure 1. Shaded relief map, showing the locations of the study basins and weather stations (solid dots)

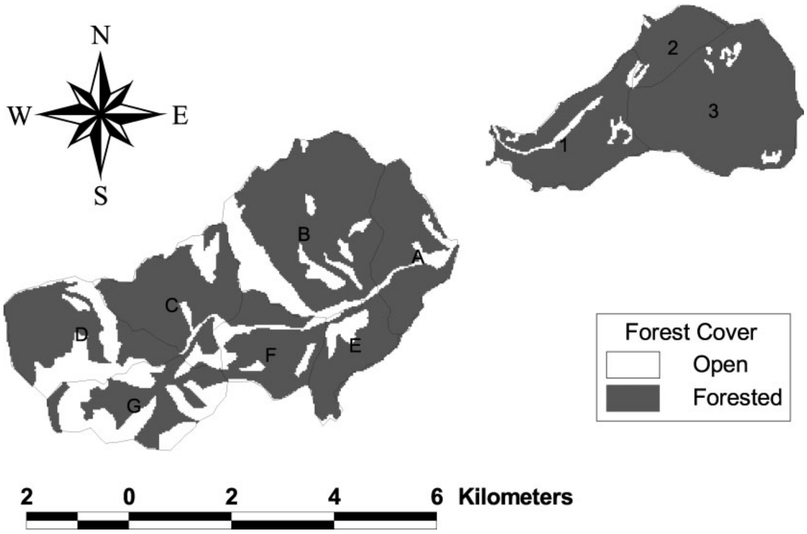

Figure 2. Sub-basin divisions and forest cover for the Big Elk (left) and Halsey (right) basins (Idaho Panhandle National Forests stand records and 1991 aerial photography)

small road corridor about 0·5 km long near the catchment mouth.

Some forest regeneration occurred in the Big Elk basin between the initial logging and the 1990 rain-on-snow event. This may introduce a degree of non-stationarity in the flow record. However, regeneration is slow at higher elevations, and effects of harvest can last more than 20 years, even in productive forests (e.g. see Jones and Grant (1996: table III)). Furthermore, shrubs and small trees initially colonizing open sites after logging tend to have minor impacts on snowmelt because they bow under the weight of deep snowpacks. Snowfall is high in this area, with an average peak annual snow water equivalent of 0·9 m at the Mosquito Ridge SNOTEL station (Figure 1).

Both streams currently support cutthroat trout (*Oncorhynchus clarki*) and are similar to streams supporting bull trout in other surrounding basins (e.g. Rich *et al*., 2003). Bull trout were widely reported in the Coeur d'Alene basin in 1940 (Maclay, 1940), but have not been observed in extensive sampling conducted in the last two decades (Abbott, 2000; McGrath, 2003).

METHODS

The hypothesis that timber harvest has increased the magnitude of peak flows for winter rain-on-snow events was tested by modelling snowmelt changes, runoff generation, and routing. Predicted snowmelt for the 1990 rain-on-snow event was routed through each basin to compare predicted and observed hydrographs at the mouths of each watershed. Calibration was only done for the runoff generation parameter of the model to match the observed

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hydrograph. The snowmelt model did not require calibration, so we could compare basin-averaged snowmelt rates directly. After calibration of the runoff model to the 1990 rain-on-snow event, we modelled the potential change in flow due to forest harvest in Big Elk by predicting snowmelt for the 1990 event with 95% forest cover (undisturbed conditions based on those of Halsey Creek) versus 74% forest cover (1990 conditions).

Besides the numerical model, we also assessed the utility of a simplified basin comparison using an empirical peak-flow model (Berenbrock, 2002), which allows extension of the analysis to the full flow record (1984–1999) from the two basins to estimate the runoff for Big Elk under undisturbed (95% cover) conditions.

Watershed characteristics

We extracted stream orders, slopes, and aspects of the two basins from digital elevation models (DEMs, 30 m grid) in ArcView 3·2 by applying TARDEM (Tarboton, 2000). The D-8 method (Tarboton, 2000) was used to estimate the contributing area, the maximum flow path length, and stream order for each point along the stream. Reach lengths were calculated by TARDEM for link–node topology (i.e. between tributary junctions).

Basin topography and drainage density were also characterized because they are primary controls on runoff generation and routing, and it is important to separate these natural physical effects on peak flow from anthropogenic ones (logging) within and between study sites. The topography of each watershed was summarized in hypsometric curves that describe the cumulative relationship between elevation and area among elevation intervals. Drainage density, which is the ratio of the total length of the streams within a watershed to the total basin area, can be used as an index for stream network complexity and runoff efficiency. Large drainage density may generate a faster hydrological response because more water is routed through channels than across hillslopes.

To distinguish the effect of natural physical characteristics from the effect of timber harvest on peak flows, we used a physically based snowmelt model coupled to an empirical runoff model. The primary physical factors affecting snowmelt are the elevation range, aspect distribution, and canopy cover, with the effects of timber harvest quantified through this last factor. Runoff generation is controlled by topographic and soil conditions, which we assumed were similar in the two basins. We tested this assumption by comparing the calibrated curve number (e.g. McCuen, 1998) for the two basins. Logging roads can influence drainage density by intercepting subsurface flow and acting as stream channels, increasing the speed of basin response and increasing peak flows, particularly for small floods (Jones and Grant, 1996, 2001; Wemple *et al.*, 1996; Thomas and Megahan, 1998, 2001; Lamarche and Lettenmaier, 2001; Luce, 2002; Wemple and Jones, 2003). However, sensitivity testing for the 1990 event in these basins showed almost no sensitivity to roughness parameter changes in our model when using a 6 h time step; so we did not model routing differences in the basins.

Snowmelt model

During the winter and early spring, snowmelt governs the hydrology and runoff in these basins. Snowmelt is primarily a function of solar radiation, temperature, humidity, vapour pressure, and wind speed, which govern the radiant and turbulent energy exchanges at the snow–air interface. Forest canopies limit wind speeds and turbulent transfers of latent or sensible heat to the snowpack, reduce snow accumulation, reduce shortwave energy input substantially, and increase longwave energy input. So-called rain-on-snow events are primarily a result of strong condensation, which occurs with warm, moist air and strong turbulence associated with high winds (Harr, 1986, Marks *et al.*, 1998). Precipitation, which is only a few degrees above freezing during the cold season, does not melt snow because it adds very little heat. Instead, precipitation adds to the mass of the snowpack and contributes to the total event output.

To model the snowmelt process, we used the physically based UEB model (Tarboton *et al.*, 1995; Tarboton and Luce, 1996), which has been applied and tested in a variety of environments (Koivasulo and Heikinheimo, 1999; Luce *et al.*, 1999; Knowles and Cayan, 2004; Luce and Tarboton, 2004; Schulz and de Jong, 2004; Zanotti *et al.*, 2004; Singh and Gan, 2005). Recognizing the need to represent spatial variability in snowmelt processes (Luce *et al.*, 1998), we chose to distribute snowmelt across the basin using a probability distributed approach (Moore, 1985), breaking the watershed into three elevation bands and three aspect classes. For each basin, three representative elevations were selected, corresponding to the 16th, 50th, and 84th percentiles of the elevation distribution. Because the hypsometric curves for the two watersheds were so similar (discussed further in the Results section), one set of elevation values representing the average elevation of the three respective percentiles, was applied to both watersheds: 1062 m (16th), 1198 m (50th), and 1358 m (84th). The three aspect classes were south, ranging from an azimuth of 135° to 225°, north, between 315° and 45° degrees, and east–west, covering both 225° to 315° and 45° to 135°. Central aspects of 180°, 0°, and 90° were used as representative hillslopes in each case. We used basin-average slope in conjunction with aspect to estimate solar radiation. The UEB model was run on 18 scenarios created by combinations of three elevations, three aspects, and two cover types within each basin (forested, 95% cover, and open, 0% cover). Each basin was divided into a series of sub-basins, three in the Halsey Creek watershed and seven in Big Elk (Figure 2). For each sub-basin, soil water inputs calculated from the snowmelt model were weighted by the fraction of the sub-basin in each of the 18 classes (Table I).

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Table I. Percentage of total watershed area in each aspect, elevation, and cover type

Aspect (°)		Elevation			
		Lower (Elev < 1131 m)	Middle (1131 ≤ Elev < 1264 m)	Upper (Elev ≥ 1264 m)	Total
Halsey					
North (≥315 or <45)	Forested	9·4	7·2	11·6	28·2
	Open	0·5	0·0	0·5	1·0
East (≥45 to <135) and west (≥225 to <315)	Forested	8·9	11·6	19·5	40·0
	Open	0·9	0·4	0·2	1·5
South (≥135 to <225)	Forested	9·8	7·3	9·8	26·8
	Open	1·1	0·5	0·9	2·5
Total		30·6	27·0	42·4	100·0
Big Elk					
North (≥315 or <45)	Forested	5·6	5·6	1·9	13·1
	Open	2·7	2·9	2·7	8·3
East (≥45 to <135) and west (≥225 to <315)	Forested	14·3	17·6	8·1	40·0
	Open	4·3	4·1	4·5	12·9
South (≥135 to <225)	Forested	8·1	9·6	3·7	21·3
	Open	1·7	1·6	1·2	4·4
Total		36·7	41·4	21·9	100·0

Weather records

Three weather stations (Bayview COOP (NWS#100 667), Mosquito Ridge SNOTEL (NRCS#16A04S), and Spokane Airport COOP (NWS#457 938)) provided the meteorological data for the snowmelt modelling. The Bayview station is located approximately 30 km northwest of the study watersheds near Lake Pend Oreille at an elevation of about 650 m, and the Mosquito Ridge station is located approximately 30 km north of the study basins at an elevation of 1585 m (Figure 1). Daily precipitation, maximum temperature and minimum temperature were available at these stations. Daily wind speed was acquired from the Spokane Airport station, on a plateau about 75 km west of the sites at an elevation of 720 m. We interpolated the daily information to the location and elevation bands for each watershed, and then disaggregated the data into 6 h time steps for input to the snowmelt model. The following assumptions were used for disaggregating the daily data to a 6 h time-step meteorological input file: constant average wind speed for each day; constant average precipitation rate for each day; sinusoidal approximation of daily temperature variations; and identical dew point and daily minimum temperatures. Daily maximum and minimum temperatures were estimated at the study watersheds based upon the lapse rates evaluated between Bayview and Mosquito Ridge. The lapse rate describes the change in temperature with elevation and has units of degrees Celsius per kilometre. Daily minimum and maximum temperatures were used to model daily sinusoidal temperature variation for 6 h intervals for each elevation band.

Humidity and vapour pressure were assumed to be functions of the daily minimum temperature $T_{\min}$, which was adopted as a surrogate for the dew point temperature T_{dew}. This allowed vapour pressure to be modelled as a function of minimum temperature: $e_s = \mathrm{funct}(T_{\mathrm{dew}}) \approx \mathrm{funct}(T_{\min})$ (where e_s is the water vapour pressure at saturation temperature). The ratio of the actual vapor pressure e to the saturated vapour pressure $e_s(T)$ defines the relative humidity R_h:

$$R_h = \frac{e}{e_s(T)} \tag{1}$$

which was simplified to

$$R_h = \frac{e_s(T_{\min})}{e_s(\tilde{T}_i)} \tag{2}$$

where the denominator corresponds to the saturated pressure at $\tilde{T}_i$, the average temperature for the time step.

Wind speed or turbulence, in interaction with temperature and humidity, influences the rate of exchange of warm moist air at the interface between snow and air; the faster this layer exchanges, the more quickly snow melts. Although the wind station is too distant for confident estimation of small wind speeds at the study basins, higher wind speeds associated with large frontal systems result from pressure differences across larger areas, so the weather station data should be a reasonable approximation for a daily average.

Precipitation data were extrapolated from observed values at Mosquito Ridge. Daily precipitation measured at Mosquito Ridge was adjusted based on the ratio of the mean monthly precipitation at Mosquito Ridge to that of each elevation band in each watershed according to the PRISM database (National Water and Climate Center, 2000). Precipitation in each elevation band was estimated based on the area-weighted average of the monthly ratio calculated at each of the 4 km^2 PRISM cells. Because no timing information was available for the precipitation data, we assumed it fell uniformly throughout the day.

Runoff generation

Soil water input was computed as the average of the unit area rate of snowmelt from the UEB model for each elevation and cover class weighted by the area of each elevation/cover class combination in each sub-basin. The largest rain-on-snow event in water year 1990 was selected for detailed analysis. The event produced peak discharges in both watersheds on 10 January 1990, representing the second largest flood event of record (Table II). Meteorological data were processed for water year 1990 and input to the UEB model to determine the soil water input rate for the runoff routing model (HEC-1; Hydrologic Engineering Center, 1981).

Runoff generation during the event was estimated using the Soil Conservation Service (SCS) unit hydrograph method in HEC-1. The following simplifying assumptions were made: (1) channel roughness was constant (Manning's $n = 0{\cdot}03$) at all stages and in all channel types; (2) both watersheds were represented by the same curve number (CN; McCuen, 1998) because of physiographic similarities. Additionally, the initial abstraction, which is the volume of precipitation lost at the beginning of the event, was assumed near zero because of antecedent precipitation that moistened soils. The catchment lag time t_l (h) used in the SCS unit hydrograph was calculated as

$$t_l = \frac{(L/0{\cdot}3048)^{0{\cdot}8}(1000 - 9\mathrm{CN})^{0{\cdot}7}}{1900\mathrm{CN}^{0{\cdot}7}Y^{0{\cdot}5}} \qquad (3)$$

where L (m) is the hydraulic length (the distance between the most distant point in the watershed and the watershed outlet, measured along the principal watercourse) and Y (%) is the average watershed slope. Hydraulic routing along the channel was modelled using a kinematic wave approximation.

The effects of timber harvest on peak runoff for the 1990 rain-on-snow event were investigated by repeating the modelling analysis holding all factors (e.g. elevation, aspect, and CN) constant except for forest cover, which was changed from 74% (disturbed) to 95% (undisturbed) in the Big Elk basin.

Flood frequency analysis

Stream flow data from US Forest Service stream gauges at the mouths of each watershed have a period of record from 1984 to 1999 for Halsey Creek and from 1988 to 1999 for Big Elk (Table II). This is a relatively short record, and the data from Big Elk were from a period after most harvest was complete. Thus, these data do not represent a traditional paired-watershed experiment where a calibration period is used to develop a statistical model relating the two basins before treatment begins. Rather, in this study we used the observed flow data to validate our model predictions for the 1990 rain-on-snow event and then used our model to predict the flood frequency distribution in Big Elk that would have occurred without logging. Table III summarizes the observed flood frequencies for each watershed fit by a log Pearson type III distribution (USGS, 1982) (Figure 3).

We could alternatively estimate peak flows for Big Elk under undisturbed conditions using regionalized peak flow relationships. From the empirical formulae of Berenbrock (2002), the peak flow from two basins can be related for a given recurrence interval Rt:

$$Q^a_{\mathrm{Rt}} = Q^b_{\mathrm{Rt}}\left(\frac{A_a}{A_b}\right)^m\left(\frac{\mathrm{Elev}_a}{\mathrm{Elev}_b}\right)^n\left(\frac{p_a}{p_b}\right)^o \qquad (4)$$

where a and b signify the paired basins, Q, A, Elev, and p are the annual peak discharge, contributing area, mean elevation and mean annual precipitation respectively,

Table II. Observed instantaneous annual peak flows at the outlets of the Halsey and Big Elk watersheds

Water year	Discharge ($m^3\ s^{-1}$)		Big Elk/Halsey ratio
	Big Elk Creek	Halsey Creek	
1984	—	1·5	—
1985	—	1·9	—
1986	—	1·4	—
1987	—	1·2	—
1988	12·5	2·4	5·2
1989	8·9	1·9	4·6
1990	13·2	4·0	3·3
1991	13·1	3·4	3·9
1992	2·2	0·4	5·1
1993	6·3	2·0	3·1
1994	4·2	1·3	3·3
1995	11·5	3·9	2·9
1996	19·4	4·5	4·3
1997	12·5	1·9	6·6
1998	8·7	1·5	5·8
1999	8·9	2·0	4·5

Table III. Observed and predicted annual peak discharges Q for various return periods at the outlets of the Big Elk and Halsey basins

Return time (years)	Observed $Q_{\mathrm{Big\ Elk}}$ ($m^3\ s^{-1}$)	Observed Q_{Halsey} ($m^3\ s^{-1}$)	Q ratio	Predicted undisturbed $Q_{\mathrm{Big\ Elk}}$ ($m^3\ s^{-1}$)[a],Eqn.(5)[a]	Predicted undisturbed $Q_{\mathrm{Big\ Elk}}$ ($m^3\ s^{-1}$), model[b]
2	10·4	2·1	4·84	4.6 (2.9–7.4)	8·32
5	14·4	3·1	4·72	6.7 (4.2–10.9)	11·52
10	16·8	3·7	4·61	8 (5–12.9)	13·44
20	19·1	4·2	4·51	9 (5.5–14.9)[c]	15·28
50	21·7	5·0	4·38	10.8 (6.5–18)	17·36

[a] Based on rescaled peak flows from Halsey Creek, using Equation (5), with +/− standard error shown in parentheses.

[b] Based on a 20% reduction of observed peak flow as indicated by the physical model (see Discussion).

[c] Using standard error for 25-year return interval.

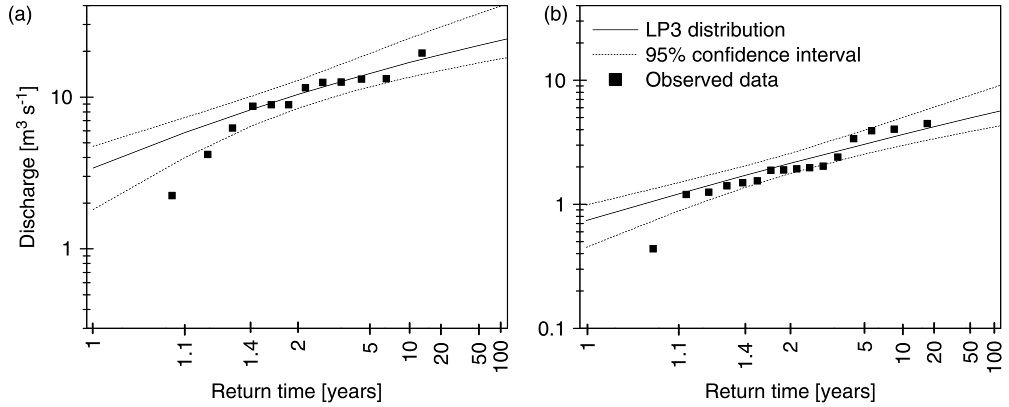

Figure 3. Log Pearson type III analysis for annual floods in (a) Big Elk Creek and (b) Halsey Creek

and m, n and o are empirical exponents estimated in the regressions and vary by return interval. Halsey and Big Elk have nearly identical mean elevation and precipitation, simplifying Equation (4) to

$$Q^a_{\mathrm{Rt}} = Q^b_{\mathrm{Rt}} \left(\frac{A_a}{A_b}\right)^m \tag{5}$$

where m takes values of 0·9 and 0·89 for the 2- and 5-year flood events respectively, and 0·88 for the 10-, 25- and 50-year return periods for northern Idaho (see Berenbrock (2002: table VII, region 2)). Applying Equation (5) estimates the undisturbed peak flow in Big Elk Creek as between 2·20 (for common events) and 2·16 (for rare events) times the flow in Halsey Creek. This model has a substantial uncertainty with a standard error of +60% to −38%, which gives the multiplier a range of 1·36 to 3·52 for common events.

RESULTS

Watershed characteristics

Morphological analysis shows that the Halsey and Big Elk watersheds are similar in most physical characteristics, except area; Halsey is less than half the drainage area of Big Elk (Table IV). Both support third-order streams and share similar elevation ranges, aspect distributions, basin-average slopes, and slope distributions (Figure 4). The Big Elk basin has slightly less area above 1100 m than Halsey, which is approximately 100 m higher than Big Elk across the 60–90th percentiles of the elevation distribution (Figure 4a). The cumulative distributions of basin slope are nearly identical for the two watersheds (Figure 4b), and the aspect distributions are similar for north-northeast-facing slopes (Figure 4c). However, Halsey has fewer east-facing slopes and more southwest-facing slopes than Big Elk. Normalized hypsometric curves (McCuen, 1998) indicate that watershed area is relatively uniformly distributed across the elevation range of both watersheds (Figure 4d, 1 : 1 line indicates uniform distribution). However, 45% of the total area of the Big Elk basin occurs within a narrow elevation range of 1075–1200 m, whereas only 25% of the total area falls under the same elevation range in the Halsey basin (Figure 4a).

Predicted drainage densities for the two basins are reported in Table IV. The results show that the drainage density in Big Elk is 30% greater than that of Halsey. Large values of drainage density may suggest more efficient runoff and, thus, a more rapid and higher peaked (i.e. flashy) response to storms. The Big Elk basin contains 50 first-order streams, whereas Halsey has only 14. Logging roads in the Big Elk basin may further increase drainage density (Wemple *et al.*, 1996). Mainstem channels (defined as third-order streams) also differ in length and slope. Big Elk is somewhat elongated relative to Halsey, and Big Elk's mainstem channel (7631 m) is more than twice as long as Halsey's (3635 m).

Most of the notable differences in physical characteristics of the watersheds relate to flow routing (i.e.

Table IV. Physical characteristics of the study sites

Basin	Area (km^2)	Elevation (m)		Basin average slope[a] (°)	No. first-order streams[b]	Length of mainstem stream (m)	Slope of mainstem stream (m m^{-1})	Drainage density[b] (km^{-1})	Watershed precipitation[c] (mm)
		Range	Mean						
Halsey	12·6	929–1620	1236	22·6	14	3635	0·0052	1·2	990
Big Elk	30·2	946–1612	1185	22·3	50	7631	0·0115	1·6	1048

[a] Average slope is computed from the slopes of each 30 m grid. The slope of each cell is derived from the maximum rate of change from each cell to its neighbours.

[b] The resolution of the digital elevation model and the threshold values selected in defining contributing area influence the calculations of stream order and drainage density (Tarboton, 2000).

[c] Average annual precipitation from PRISM.

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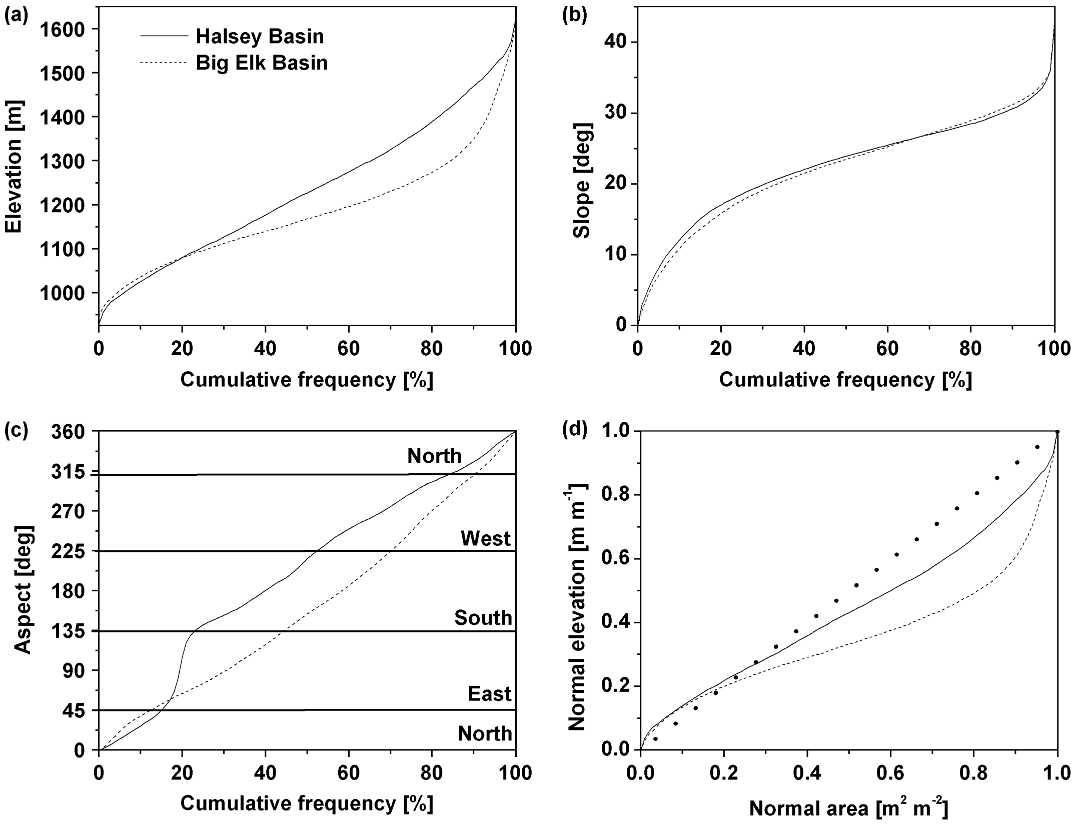

Figure 4. Comparison of cumulative distributions of (a) elevation, (b) slope, (c) aspect, and (d) normalized hypsometric curves for the two study basins

differences in natural drainage density and that due to forest roads), but flow was relatively insensitive to variations in routing parameters in initial testing of the model for the 1990 storm. This lack of sensitivity is partially a function of the 6 h time steps used in the analysis and the assumption of uniform water input during each 6 h period. Models for basins this small would need to use shorter time steps (with matched time-scales for input data) to describe the effects of routing differences on a flood the size of the 1990 rain-on-snow event. Furthermore, widespread saturated conditions during major floods can make routing differences relatively insignificant (Jones and Grant, 1996, 2001; Thomas and Megahan, 1998, 2001). Differences in routing in basins of this scale probably affect the daily average flows very little, which were the data to which the runoff model was calibrated.

Flood frequency analysis

Observed differences in flow peaks (Table II) were greater than would be expected due solely to differences in drainage areas corrected by physiographic region (Equation (5)). The empirical area-based discharge ratio (2·2) is less than half the observed ratio of the 2-year flood event (4·84, Table III), a surrogate for the bankfull and dominant discharge (Wolman and Leopold, 1957; Wolman and Miller, 1960; Williams, 1978; Andrews and Nankervis, 1995), suggesting that Big Elk Creek produces much more runoff relative to Halsey Creek than could be explained by the size difference alone, especially at frequent recurrence intervals.

Snowmelt from the UEB model

Figure 5 shows the modelled snowmelt response per unit area for each of the 18 landscape classes (Table I). Melt per unit area was larger at low elevations than at high elevations, and open areas consistently produced a higher soil water input than forested areas. During the simulated 1990 rain-on-snow event, the upper elevation open areas with north aspect produced the lowest soil water input (Figure 5b, U0), and the lower elevation open areas with east–west aspect showed the two highest peak flows (Figure 5a, L90). South-facing, low-elevation slopes had less snow water equivalent available for the peak events. Figure 6 shows that the peaks in the observed hydrograph are largely tied to major snowmelt inputs.

Hydrographs from HEC-1

To distinguish between natural and anthropogenic influences on runoff, we calibrated the runoff generation model by changing the CN (McCuen, 1998). Figure 7 shows the observed and calibrated hydrographs for Big Elk and Halsey Creeks. We were able to calibrate both basins well using the same CN (76), supporting the idea that differences in snowmelt rate were the primary differences between the basins during the 1990 rain-on-snow event.

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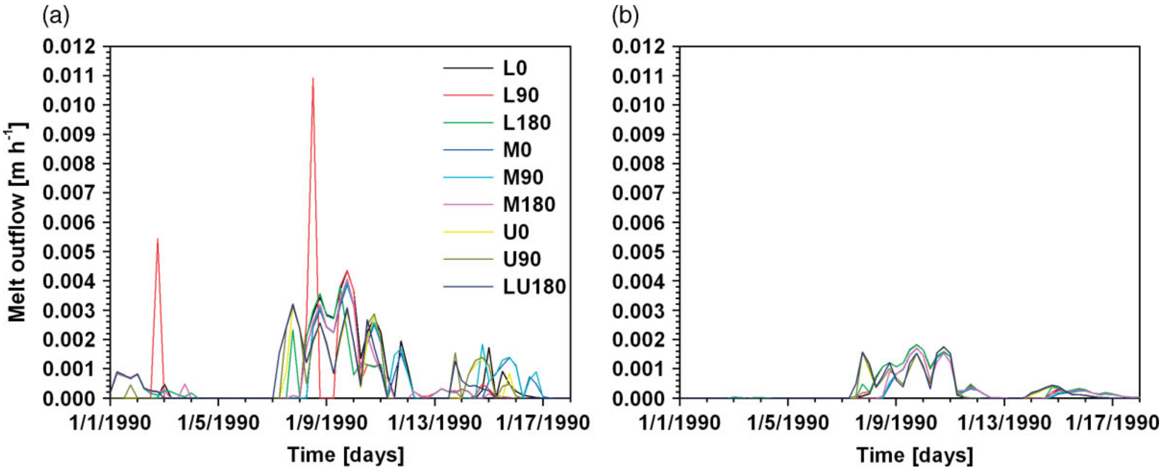

Figure 5. Snowmelt outflow for the 18 landscape classes (Table I) (independent of the area of each class within the basin) for (a) open and (b) forested areas. L, M, and U stand for lower, middle, and upper elevations; 0, 90, and 180 indicate north, east–west, and south aspects; and Fr and Op stand for forested and open

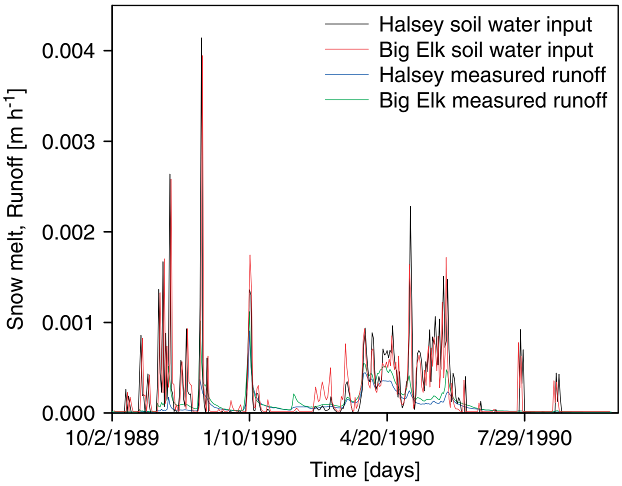

Figure 6. Basin-average soil water input and measured runoff for the two basins over the 1990 water year. Note that large flows are tied to large soil water inputs

The modelled hydrographs in Figure 7 are daily-averaged values, and Figure 8 shows the results every 8 min, for comparison with the observed instantaneous peak discharges. We predicted a peak discharge of 4·3 $m^3 s^{-1}$ for Halsey Creek during the 1990 rain-on-snow event; since the observed peak was 4·0 $m^3 s^{-1}$ (Table II), this is a 7% overestimation. The predicted peak discharge for Big Elk Creek was 12·9 $m^3 s^{-1}$, compared with an observation of 13·2 $m^3 s^{-1}$; a 2% under-prediction (Table I). The peak discharge predicted for Big Elk under natural (undisturbed) conditions, considering a scenario of 95% forest cover (similar to the unmanaged Halsey basin), was 10·3 $m^3 s^{-1}$.

DISCUSSION

Timber harvest effects on snowmelt and peak discharge

Rain-on-snow events can generate some of the most substantial floods in the Northern Rockies because of high, sustained snowmelt rates. Both snow accumulation and turbulent energy exchange are greater in open areas than under a forest canopy. The difference in water input between forested and open areas can change strongly with elevation and aspect, which control both the energy exchange during the event and the total accumulation of snow preceding the event. Rain on snow from open areas at lower elevations (within the range of snow-covered areas affected by the storm) may constitute the majority of runoff during such events, whereas differences between forested and open areas at high elevations can be minimal because the air temperature and absolute humidity are lower and some or all of the precipitation is in the form of snow.

Our model results show that peak flow is strongly influenced by timber harvest, causing larger floods to occur more frequently. We predict that a reduction in forest cover from 95% to 74% in the Big Elk basin caused a 25% increase in the peak flow (10·3 to 12·9 $m^3 s^{-1}$) for the January 1990 storm. This is consistent with order of magnitude differences seen in other storms comparing unit area discharges for the two basins (USDA Soil Conservation Service, 1994). To consider the effects of logging on the hydrologic regime of Big Elk from a frequency perspective, we rescaled the basin's annual peak flows using the above results. Effectively, this meant that we estimated undisturbed peak flows as a 20% decrease from observed values. Assuming a uniform 20% reduction in peak flows for undisturbed conditions (95% forest cover) (Figure 9), the 1990 rain-on-snow event in Big Elk (13·2 $m^3 s^{-1}$) would have had a 9-year recurrence for undisturbed conditions, but was a 3·6-year event after logging (Figure 9). We recognize that there is some uncertainty in this analysis; in particular, a uniform 25% increase in peak flow is a simplistic assumption, and the range on the estimate of the return interval of a 13·2 $m^3 s^{-1}$ event as defined by the 95% confidence band is substantial for these data (Figure 3), but the regressed estimate used in the above result gives a sense of the order of magnitude of effects.

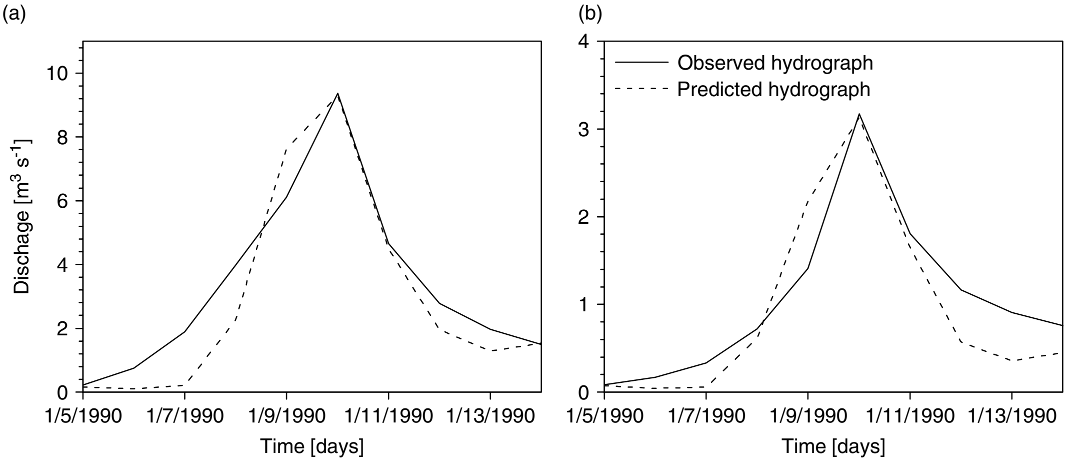

Figure 7. Comparison of observed and predicted daily average hydrographs for (a) Big Elk Creek and (b) Halsey Creek. Predictions are simulated with the same CN (76) in both watersheds

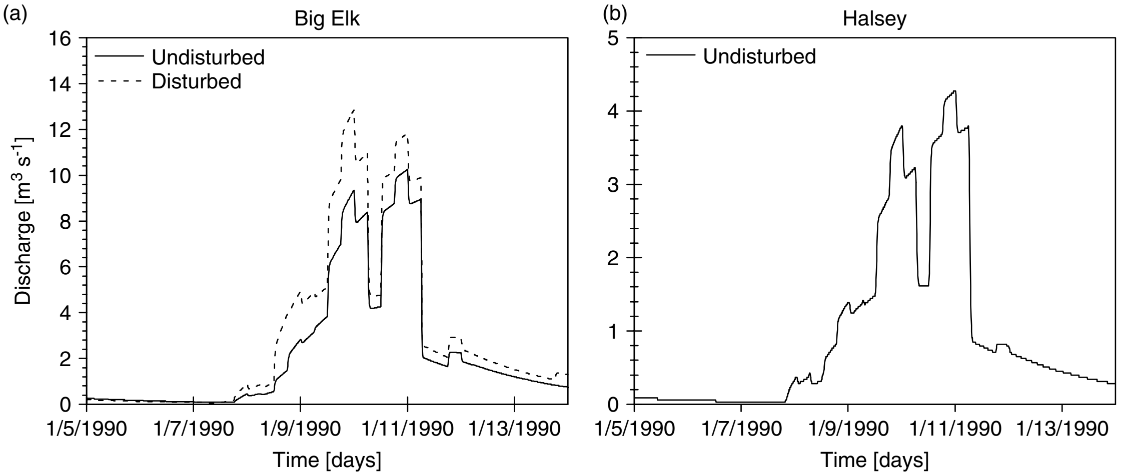

Figure 8. Modelled instantaneous hydrographs for undisturbed versus existing, disturbed conditions for (a) Big Elk Creek and (b) Halsey Creek

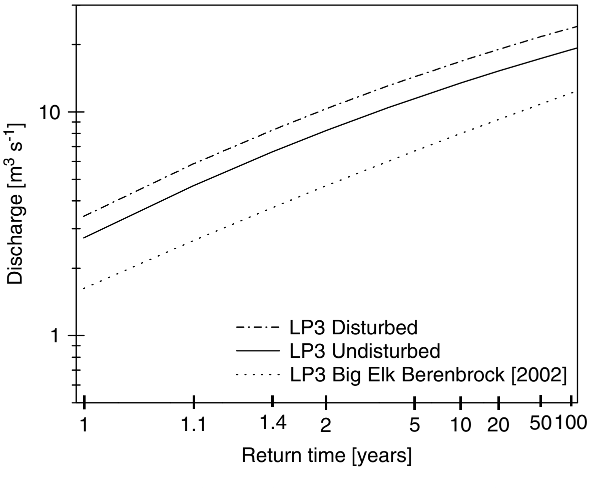

Figure 9. Annual flood frequencies in Big Elk Creek for disturbed (logged) and undisturbed conditions. Undisturbed discharges are based on a 20% reduction of disturbed values (see text). Big Elk Berenbrock is a second prediction of undisturbed peak flows based on rescaled values from Halsey Creek using Equation (5), which represent a possible flow distribution for undisturbed conditions

The analysis shows the potential of this tool to predict hydrologic impacts of timber harvest, and could be applied to evaluate different harvesting practices and undisturbed conditions of a watershed using stochastically generated weather sequences. By comparing the results of the different harvest scenarios, it may be possible to find the harvest strategy that affects the catchment the least. For example, most of the harvest in Big Elk occurred at lower elevations, which contributed more melt water than did higher elevation areas during the 1990 rain-on-snow event.

Berenbrock's (2002) model (Equation (5)) provides an alternative method to predict the annual peak flows of Big Elk for undisturbed conditions (Figure 9). This approach predicts that the observed 1990 flood (13·2 $\mathrm{m}^3\ \mathrm{s}^{-1}$) would exceed a 100-year event under undisturbed conditions (Figure 9). The approach also implies a 100% increase in annual peak floods following timber harvest (Table III compare columns 2 and 5), which is much higher than the physical model predicts and is well outside expectations from the literature (e.g., Thomas and Megahan, 1998). Furthermore, the standard errors of this method are substantial (Table III). Because this approach seems to greatly overestimate flow changes, we used the modeled increase of 25% (Figure 8a) for further geomorphic and ecological analysis.

Bed scour and bull trout mortality

Changes in flow regime can influence boundary shear stress and channel morphology, with consequent changes in scour and deposition. Bed scour, in turn, is related to survival of fish embryos incubating within stream gravels (e.g. Montgomery *et al.*, 1996). Scour events more frequent than the life span of bull trout (~8 years on average) have the greatest ecological influence. Here, we use a scour model to explore changes in the probability of bull trout embryo mortality due to predicted changes in flow magnitude and frequency resulting from timber harvest in the Big Elk basin.

The reach-average mean scour depth $\overline{d}_s$ (cm) can be predicted from Haschenburger's (1999) empirical scour equation for gravel-bed rivers:

$$\overline{d}_s = (3{\cdot}33e^{-1{\cdot}52\theta/\theta_c})^{-1} \tag{6}$$

where $\theta = \tau_0/[(\rho_s - \rho_w)gD_{50}]$ is the applied Shields stress and θ_c is the critical Shields stress for incipient motion of the streambed, which we set equal to 0·045 to be consistent with Haschenburger's (1999) formulation of Equation (6). For calculation of the Shields stress, g is acceleration due to gravity, ρ_s and ρ_w are sediment and water densities respectively, and D_{50} is the median surface grain size. τ_0 is the total boundary shear stress defined from the reach-average depth–slope product as $\tau_0 = \rho_w gRS$, where R is the hydraulic radius and S is the water surface slope.

Local scour can be substantially different from the mean value (Hassan, 1990; Haschenburger, 1999; Bigelow, 2005) and depends on a variety of factors, including local sediment supply, local shear stress as modified by channel topography and flow obstructions, particle size and density, degree of channel armouring, bed material packing and interparticle friction angles, and the magnitude and duration of sediment transport (Buffington *et al.*, 2002), all of which are difficult to represent in numerical models. Nevertheless, the local scour depth d_s can be treated as a stochastic variable, whose probability density function (pdf) describes the spatial variability of scour within the reach. Haschenburger (1999) showed that, in gravel-bed rivers, local scour and fill depths closely follow an exponential distribution, with the distribution parameter λ equal to the inverse of the mean scour depth $(1/\overline{d}_s)$. Consequently, the probability to have a scour depth $d_s = z$ can be predicted as

$$\mathrm{pdf}(z) = \lambda \mathrm{e}^{-\lambda z} = \frac{\mathrm{e}^{-z/\overline{d}_s}}{\overline{d}_s} \tag{7}$$

which together with Equation (6) allows assessment of the effects of altered flow regime on scour depth.

The depth of the egg pocket within a salmonid nest or 'redd' depends on many factors: fish size, sediment size, water depth, alluvium depth, and flow velocity (Bjornn and Reiser, 1991). Bull trout embryos are typically buried only 10–20 cm below the original streambed level (DeVries, 1997). If we assume complete embryo mortality for eggs of resident bull trout when scour depths exceed 10 cm and for eggs of migratory bull trout when scour depths exceed 20 cm, then we can estimate changes in mortality with changes in streamflow.

In Figure 10, we report the probability of exceeding 10 and 20 cm deep scour as a function of peak flow return time at two characteristic cross-sections in Big Elk Creek for disturbed (logged) and undisturbed conditions. These predictions indicate that timber harvest causes higher probability of scour for both 10 and 20 cm burial depths and that the probability of scour generally increases at a faster rate with greater flood size compared with undisturbed conditions. For example, greater scour depths due to larger 2-year floods following timber harvest might have produced an added mortality of 7–15% for shallow egg pockets (10 cm) and 1–10% for deeper ones (20 cm). Overall, the probability of embryo mortality

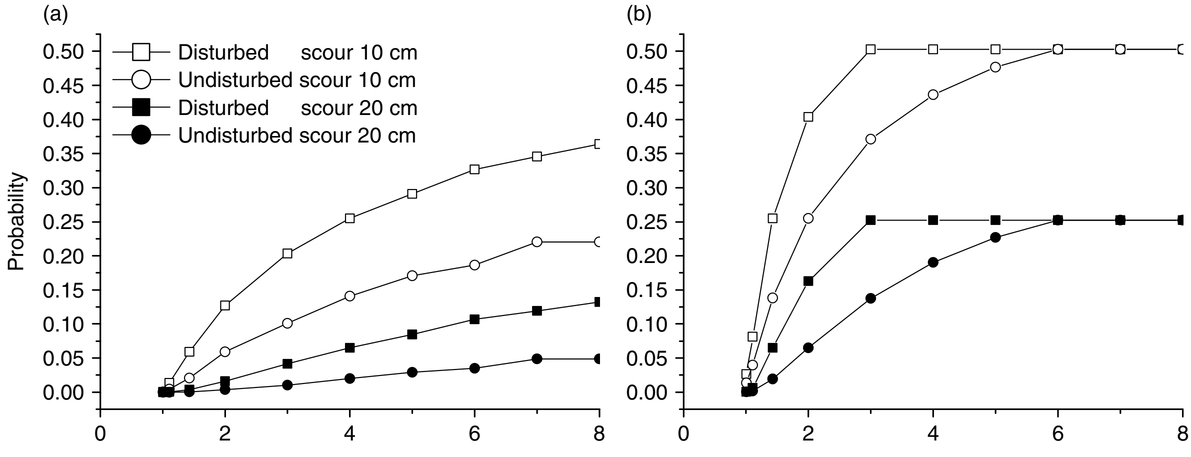

Figure 10. Probability of exceeding 10 and 20 cm scour depths for different return periods at two characteristic cross-sections (panels (a) and (b) respectively) near the mouth of Big Elk Creek. Predictions for undisturbed (95% forest cover which was represented by 20% reduction of annual flow discharge) and disturbed conditions are shown

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for post-harvest flow regimes ranges from essentially nothing to 35–50%, depending on the flood, cross-section characteristics, and the depth of the egg pocket. The asymptotic nature of the curves resulting from overbank flow shows that very large floods may not produce substantially greater mortality than those expected with 3- to 8-year return intervals. The above results suggest that mortality of embryos could have varied substantially among cross-sections and stream channel segments, but mortality linked to flood events with return intervals less than 6 to 8 years probably did increase with forest harvest.

Loss of bull trout from the Coeur d'Alene basin

Our results suggest that incubation mortality for bull trout embryos could have been aggravated by extensive timber harvest. The estimated, absolute increase was relatively modest (i.e. up to 15% additional mortality) and never exceeded about 50% total mortality in the worst case. Results also show that some scour mortality already existed and that greater flooding due to timber harvest would not produce catastrophic mortality (i.e. >50%). But changes of the magnitude we estimated during a critical early life stage could make the difference between stability and long-term decline in some populations, especially if those populations were already depressed by other changes in their environments (Rieman and McIntyre, 1993). The loss of migratory life histories has been common throughout the bull trout range (Rieman and McIntyre, 1993). If that were the case, then the population would have been limited to resident forms with limited egg burial depths and a higher vulnerability to the hydrologic changes.

Although our predictions suggest that timber harvest increased scour depth and frequency, the magnitude of the changes we estimated are not exceptionally large, and could be absorbed by relatively resilient populations (Rieman and McIntyre, 1993). In addition, it appears that flood-induced scour might vary widely across different channels and among years. The magnitude of the estimated increase in scour is biologically important, but it is unlikely that changes in scour were the sole cause explaining the disappearance of bull trout from watersheds like Big Elk throughout the Coeur d'Alene basin. It could well have been a factor, however, which influenced or accelerated the process.

CONCLUSIONS

Timber harvest of about 20% of the forest cover in the Big Elk basin probably increased the peak flow magnitude for the January 1990 rain-on-snow event by 25% relative to undisturbed conditions. That change equates to a shift in the frequency of a $13{\cdot}2\ \mathrm{m}^3\ \mathrm{s}^{-1}$ peak flow from a 9-year event for undisturbed conditions to a 3·6-year event after harvest. The increased frequency of deeper scour associated with these hydrologic changes is unlikely have produced a catastrophic loss of bull trout from a given basin, but the magnitude is sufficient to effectively reduce the escapement of bull trout from harvested basins. If the widespread clearcutting that occurred throughout the Coeur d'Alene area reduced production from enough basins, then the cumulative effect of increased scour mortality may have contributed to the extirpation of bull trout from the region, but was unlikely the sole cause. Further work is necessary to understand the full biophysical implications of timber harvest across the Coeur d'Alene region, but this study shows the potential for modelling cascading effects of timber harvest on the hydrologic, geomorphic, and biological responses of mountain basins.

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