Timber Harvest Impacts on Water Yield in the Continental/Maritime Hydroclimatic Region of the United States

Jason A. Hubbart, Timothy E. Link, John A. Gravelle, and William J. Elliot

Abstract: The inland Pacific Northwest of the United States is influenced by both maritime and continental hydrometeorological conditions. To date there are limited studies of hydrologic impacts resulting from contemporary timber harvest in this region. Streamflow data were collected since 1991 at the Mica Creek Experimental Watershed (MCEW) in northern Idaho. Treatments were designed to isolate the effects of road construction and two different harvest practices (50% clearcut, 50% partial cut). The change in water yield was assessed using linear regression and analysis of covariance (ANCOVA). Water yield increased in excess of 270 mm/yr ($P < 0.01$) after clearcut harvesting, and by more than 140 mm/yr ($P < 0.01$) after partial cut harvesting. Monthly and seasonal analyses revealed the largest impacts of harvest practices on water yield during the snow deposition and melt season from November through June. Dry season analyses (July through October) indicated negligible water yield increases after treatments. Estimates of evapotranspiration (ET) as the residual of the catchment water balance suggest that ET was reduced by 35% and 14% after clearcut and partial cut harvest, respectively. These results establish a base on which to develop tools for effective watershed management in the northern Idaho continental/maritime hydroclimatic region. FOR. SCI. 53(2):169–180.

Keywords: forest hydrology, timber harvest, stream discharge, Mica Creek, Pacific Northwest

THE RELATIONSHIP BETWEEN timber harvest and water yield has long been of interest (Bates and Henry 1928). Worldwide studies showed that water yield usually increases immediately after timber harvest (Bosch and Hewlett 1982, Douglass 1983, Harr 1983, Hibbert 1983, Kattelmann et al. 1983, Troendle 1983, Troendle and King 1985, Stednick 1996). The relative amount of increase depends on climate regime and forest type and tends to diminish as forests regenerate (Bosch and Hewlett 1982, Whitehead and Robinson 1993, Bari et al. 1996, Lesch and Scott 1997). Reductions in evaporation and transpiration are the primary effects of the removal of forest vegetation resulting in increased water yields (Bosch and Hewlett 1982, Hicks et al. 1991, Sun et al. 2005). During the winter months, increases in snow accumulation were shown to result from reduced canopy interception and canopy sublimation losses (Wallace 1997, Troendle and King 1987, Whitaker et al. 2002). Increases in water yield also depend on the percentage of the land area that is harvested, and harvest patterns (Trimble and Weirich 1987). Roads can affect local soil infiltration and exfiltration processes, and may increase flow routing efficiency and function as conduits between small headwater catchments, depending on pattern and construction practices. Although primarily of concern from a peak flow perspective, roads could have a small impact on water yield since clearing for roads eliminates canopy over a small part of a watershed. In general, increases in water yield are assumed to be positively correlated to the percentage of area harvested. In the case of partial cuts or canopy thinning, removal of vegetation may result in smaller yield increases than predicted by area alone because of increased use of available moisture by retained vegetation and vegetation in surrounding uncut areas (Hibbert 1966).

From a total annual water yield perspective, Hibbert (1966) and Bosch and Hewlett (1982) examined 39 and 55 paired catchment studies, respectively. They concluded that (1) a reduction in forest cover increases water yield, (2) afforestation decreases water yield, and (3) response to treatment is "highly variable and unpredictable." Stednick (1996) extended this work by examining 95 catchment studies within the United States and developed regional statistical relationships between vegetation removal and annual yield. His findings agreed with Bosch and Hewlett (1982) in that increased water yield is detectable after 20% to 30% of a watershed has been harvested. In almost every hydroclimatic region of the United States, clearcutting resulted in increases of total water yield (Bosch and Hewlett 1982, Stednick 1996). However, in the Rocky Mountain and inland intermountain region of Oregon, decreased to no increases in water yield were observed after logging (Stednick 1996). It was suggested that higher wind speeds after

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clearcutting increased sublimation from the snowpack, offsetting transpiration reductions. In areas with higher precipitation, increases in water yield were found to be much greater relative to areas with lower precipitation. In snow-dominated systems in British Columbia (continental/maritime climate) and Colorado (continental climate), small increases in yield were likewise reported (Hibbert 1966, Cheng 1989). When Stednick (1996) grouped studies based on eight hydroclimatic regions to assess climate and water yield, studies were limited in the continental/maritime region of the United States, where hydrologic responses to timber harvest may be distinct. The one exception is the Horse Creek Study, which was conducted in northern central Idaho to assess the effects of road construction and patch clearcutting on forested headwater catchments. Following 21 to 33% patch harvest units in four subwatersheds with areas ranging from 3.6 to 14.2 ha, annual water yield was significantly increased by a range of 13 to 29%, or an average 358 mm/yr (King 1994). Other than this study, most studies in the Pacific Northwest (PNW) were conducted in more maritime climatic regimes west of the Cascade crest. Thus, knowledge of the impacts on water yield subsequent to timber harvest within the continental maritime climate region of the PNW is limited.

The continental/maritime region includes the northeast corner of Washington, the Idaho panhandle, and the northwestern tip of Montana (US Environmental Protection Agency 1980, Stednick 1996), and is a transitional climate influenced by both maritime and continental weather patterns. Continental climates are characterized by large seasonal variations in air temperature and strong influences by relatively dry polar air masses. Maritime climates are generally wetter and influenced by the prevailing westerly winds, with cool summers and mild winters.

In light of the general lack of information in the continental/maritime region of northern Idaho, studies assessing impacts to water yield due to timber harvest are greatly needed in this region if watersheds are to be optimally managed (Beschta 1998). To meet this need, the Mica Creek study was initiated in northern Idaho to better understand how forest roads and current timber harvest practices (e.g., clearcut and partial cut) affect water yield and efficacy of best management practices (BMP) in this complex hydroclimatic region.

The objectives of this study were to assess the changes in annual water yield due to contemporary timber harvest practices. Additionally, since annual water yield changes may bear little relation to summer flow changes when there can be water deficits coupled with vegetative regrowth (Hicks et al. 1991), monthly and seasonal water yields were also assessed. This work has not been undertaken previously in this portion of the continental/maritime region in the United States.

Methods

Study Site and Data Collection

The Mica Creek Experimental Watershed (MCEW) is a paired and nested research watershed that drains into the St. Joe River in northern Idaho and is located approximately at 47.17°N latitude and 116.25°W longitude (Figure 1). Both continental and maritime weather systems control the hydroclimatic regime at the MCEW. Summers are generally warm and dry, and winter months are generally wet and cold, with occasional rain-on-snow events produced by warmer Pacific air masses (maritime climate influence). The Mica Creek Experimental Watershed encompasses the Mica Creek and West Fork Mica Creek subcatchments, totaling approximately 2,700 ha. The watershed ranges in elevation from approximately 1,000 to 1,600 m asl, and receives approximately 1,450 mm of annual precipitation. The average annual temperature is approximately 4.5°C. The majority of precipitation falls from November to May, with greater than 70% of all precipitation falling as snow. Rain-on-snow events are common in the lower elevations.

Geology of the MCEW consists primarily of the metamorphic Prichard and Wallace Formations of the Belt Super group (Griggs 1973). The dominant rock is the Wallace gneiss, with some areas of Prichard quartzites. The primary soils are the Boulder Creek Soil Series and the Marble Creek Soil Series. The upper 10 inches of both soil types are composed of silt loam (USGS 2003).

Vegetation on the site consists of 65- to 75-year-old naturally regenerated conifer stands, while remnant old-growth western redcedar (*Thuja plicata*) remains along the upper tributaries of the West Fork of Mica Creek. The current vegetation community status is the result of extensive logging that took place during the 1920s and 1930s. Since that time there were no major anthropogenic disturbances in the watershed. Dominant canopy vegetation within the watershed includes western larch (*Larix occidentalis*), grand fir (*Abies grandis*), western redcedar (*Thuja plicata*), western white pine (*Pinus monticola*), western hemlock (*Tsuga heterophylla*), and Engelmann spruce (*Picea engelmannii*). Understory vegetation is largely composed of grasses, forbs, and shrubs. Stream riparian zones tend to be dominated by alder (*Alnus* spp.) and dogwood

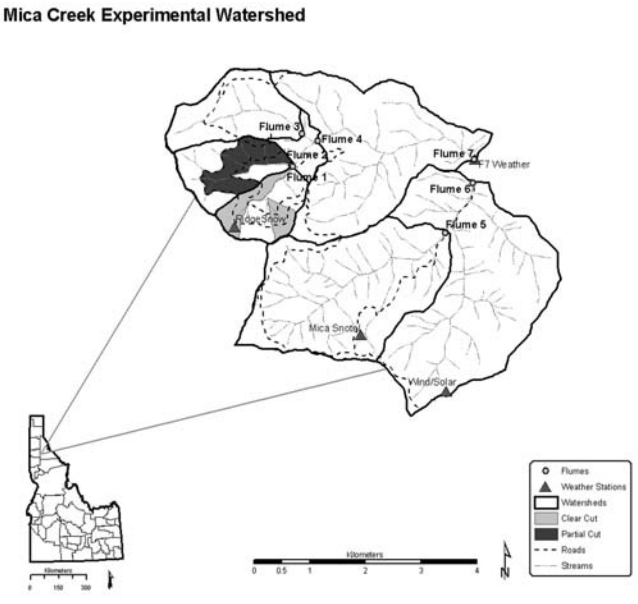

Figure 1. The Mica Creek Experimental Watershed (MCEW) in northern Idaho.

(*Cornus* spp.), and many stream reaches are well populated with bracken fern (*Pteridium acquilinum*) undergrowth.

The study was designed such that comparative paired and nested catchments would have similar land area, elevation, and physiography (Table 1). Seven gauge stations consisting of Parshall flumes designed to accommodate 50-year return interval flow events were installed in the Mica Creek catchment in 1990 and 1991 (Figure 1). Stations 3, 5, and 6 are used to monitor streamflows in untreated control catchments, and stations 1 and 2 monitor flow from the clearcut and partial cut catchments, respectively. Station 4 monitors the cumulative effects of treatments in catchments 1 through 3, and station 5 is the compliment for station 4. Station 7 monitors the flows from the larger catchment, including catchments 1 through 4, and station 6 is the complement for station 7.

Contributing land area for the small experimental catchments ranges from 139 to 227 ha, with elevations ranging from 1,193 m to 1,612 m asl (Table 1). Contributing land area for the intermediate catchments 4 and 5 are 597 and 667 ha, respectively, with elevations ranging from 1,055 to 1,612 m asl. Contributing land areas for catchments 6 and 7 are 1,456 and 1,226 ha, respectively, with elevations ranging from 1,008 to 1,612 m asl, respectively.

The steel Parshall flumes were installed to provide a consistent channel cross-section for greater streamflow measurement accuracy than natural channel conditions. Flume sites were installed using an excavator for site preparation. Construction included extending the Parshall wingwalls by attaching steel I-beams or using solid cedar logs from the nearby forest. Bedrock was not always reached when digging the locations, and treated railroad ties were leveled and anchored with steel rebar as bases for the flumes. To minimize under-flume leakage, the front of the flumes as well as the wingwall extensions had polyethylene geomembrane attached and extended below the surface of the stream bed. This material was extended upstream and was topped with welded wire mesh gabions filled with rock. The gabions were used to assure the channel upstream of the flumes remained stable over time. Soil was used to backfill the sides of the flumes, and soil and heavy riprap were placed at the front of the wingwalls.

Stream stages were measured at 30-minute intervals using a nitrogen bubbler pressure transducer system (Riverside Technology Inc.). The system consists of three lines bubbling regulated low-pressure nitrogen. Two lines are used by the transducer to calibrate for varying atmospheric pressures by measuring resistance in an ethylene glycol/water-filled reference cylinder. The remaining line slowly bubbles out nitrogen at the bottom of the Parshall flumes, and the transducer calculates resistance to produce water level measurements at ±3 mm accuracy. Data were recorded on Campbell Scientific CR10 data loggers. Specific rating curves for each flume were determined from measured stage-discharge relationships. The automated transducer and manually measured staff gauge relationship was assessed when data were downloaded (approximately every 3 months) for data quality control. In addition, surveys of the flume corners and centers using standard survey equipment were performed approximately annually since the mid-1990s to check for flume shifting over time. Slight shifting was observed at some flumes, and where necessary rating curves were adjusted to account for these changes. Accuracy for the largest catchments is estimated to be within 5% at mid to high flows, with ~10% error at the lowest flows, while the flumes at catchments 1, 2, and 3 seem to exhibit slightly higher measurement errors of 10% at midflows, with ~20% at the lowest flows (including transducer error), based on manual flow measurements.

Six years of pretreatment (calibration) flow data were collected from 1991 to 1997, and roads were constructed in the fall of 1997. The only existing roads in the watershed before timber harvest were old railroad beds near the study area divide, several overgrown forest access roads, and a light duty, outsloped road with no stream crossings used to access the flume stations. In September 1997, the existing primary road, which was an old railroad bed first used during timber harvest in the early 1930s, was improved for heavy truck traffic by grading and slightly widening the road surface, removing trees and brush from the cut and fill slopes, and installing new culverts. Mid-slope harvest access roads designed to accommodate truck traffic associated with log hauling were also constructed through catchments 1 and 2. Timber was removed during road construction, and residual slash was used as material for filter windrows along fill slopes. Roads were surfaced with native material, outsloped, and steel relief culverts were installed near stream crossings. Steel culverts were also installed at all stream crossings.

Flow data collected from 1997 to 2001 were used to isolate effects of road building from subsequent vegetation removal. From approximately July to October 2001, harvesting of timber took place with a combination of line and tractor skidding. Clearcut harvest took place on north (~23 ha) and southeast (~43 ha) facing slopes, while partial cut harvest (50% canopy removal) took place on northeast

Table 1. Physical characteristics and treatments for all catchments within the MCEW for the period 1991 to 2005

Catchment #	Harvest type	% Area cut	Area (ha)	Elev. range (m)	Mean aspect (0-360)	Mean degree slope	% Area in roads (pre-calib)	Total % area in roads
1	CC	48	139	1205-1528	174	19	1.4	2.8
2	PC	24	177	1201-1612	135	18	1.5	2.5
3	C	0	227	1193-1612	122	17	1.3	1.3
4	CC/CP/C	18	597	1169-1612	146	18	1.4	2.0
5	C	0	667	1055-1528	166	18	1.3	1.3
6	C	0	1456	1017-1594	178	18	0.7	0.7
7	CC/PC/C	9	1226	1008-1612	153	18	1.0	1.3

CC = clearcut (goal, 50% removal of canopy in watershed). PC = partial cut (goal, 50% canopy removal in 50% of watershed); C = control.

Table 2. Average annual (water year) precipitation (mm), residual (R) (mm) ($R = ET = Q - P$), and average percentage R from seven study catchments within the confines of the Mica Creek Experimental Watershed (MCEW)

Period	C1	C2	C3	C4	C5	C6	C7	Average
Average water yield (mm)								Avg. precip.
Calibration	571	563	556	570	547	567	521	1513
Roads	548	539	468	541	524	503	473	1337
Harvest	755	628	475	645	483	461	485	1401
Average ET (mm) based on residual (R)								Avg R
Calibration	943	950	957	943	967	947	993	957
Roads	789	797	869	796	813	833	864	823
Harvest	646	773	926	756	918	940	916	839
Average percentage ET (mm based on residual (R)								Avg. % R
Calibration	62	63	63	62	64	63	66	63
Roads	59	60	65	60	61	62	65	62
Harvest	46	55	66	54	66	67	65	60

R = residual (assumes $ETR = P - Q$); C = catchment.

(~34 ha) and southeast (~49 ha) facing slopes (Figure 1). In late May 2003, after harvest, the two clearcut harvest units were broadcast-burned as a site preparation measure. Within a week after the burning, a mixture of tree species was replanted in the clearcut units. Four years of posttreatment data were collected from 2001 to 2005.

Data Analysis

Paired catchment studies are the optimal design for determining the relationships between change in hydrologic processes and water yield in relatively small catchments (Loftis et al. 2001). A number of methods have been used to analyze paired catchment data over various time scales. The most commonly used method is to develop a linear regression between the control and the treated catchment for annual data collected during the calibration period (Keppeler and Ziemer 1990, Brooks et al. 1991, Hicks et al. 1991, Hornbeck and Adams 1993, Stednick 1996). The regression equation is then used to predict the water yield that would have occurred in the treated catchment in the absence of hydrologic change. Therefore, any difference in the observed and the predicted streamflow is assumed to be due to change in canopy density, as the method provides a control over climatic variability (Bari et al. 1996).

Regression analysis is actually an analysis of covariance (ANCOVA) where two variables are compared for a linear relationship (i.e., pretreatment calibration, post roads, and post roads + harvest). The result is a much stronger analysis than analysis of variance (ANOVA) or *t*-test, as it adjusts for changes that may have occurred during the study because of processes other than treatments (Thomas and Megahan 1998). In this work, change as a result of treatments was assessed using a reduced ANCOVA model that assumed that changes were effected by reduced ET resulting from land cover alteration (recognizing that ET may also be influenced by temperature, interception, and changes in storage). The model assumed no slope change in the regression relationships, thereby allowing for clearer interpretation of treatment response. This approach was used to assess annual, monthly, and seasonal changes in water flow data collected at the MCEW since 1991. Data collected at the MCEW since 1991 were reduced to three time periods for each catchment pair by water year: (1) the calibration period (1992–97); (2) the period after road construction (1998–2001); and (3) the period after harvest treatments (2002–05), to assess cumulative road and harvest effects on water yield.

Results

Annual Water Yield

Figure 2 shows the annual water yield trends for all gauged catchments for water years 1992 through 2005. During the calibration period average water yield from the higher-elevation catchments (i.e., 1–4) ranged from 547 to 571 mm/yr (computed on a water-year basis), whereas catchments with lower elevations (i.e., 6–7) ranged from 521 to 567 mm/yr, respectively (Table 2). After road construction, water yield ranged from 468 to 548 mm/yr in catchments with higher elevations, and from 473 to 503 mm/yr in catchments with lower elevations. After harvest treatments, water yield ranged from 475 to 755 mm/yr in catchments with higher elevations to 461 to 485 mm/yr in catchments with lower elevations. Double mass plots of water yield, shown in Figure 3, reflect the relative change between catchments pre and posttreatment. Road construction carried out in 1997 in C1 (C = catchment) resulted in a statistically significant ($P < 0.01$) increase in water yield of 12%, or 68 mm/yr (Table 3). As a result of clearcut timber harvest in C1, annual water yield increased 36%, or 272 mm/yr ($P < 0.01$) (Table 3, Figures 3 and 4).

Road construction in 1997 in C2 resulted in a marginal statistically significant difference between the calibration and road construction periods in terms of water yield, as indicated by a P value exceeding 0.05. Response to partial cut harvest in C2 resulted in a statistically significant difference in intercept values between the calibration and road plus harvest period ($P < 0.01$). Based on these results, partial cutting resulted in an average increase in annual water yield of 23%, or 145 mm/yr.

Statistical analysis of annual (water year) streamflow data from C4 and C5, where C4 includes C1, C2, and C3, and C5 functions as a control of similar size and topography as C4, resulted in a statistically insignificant difference in water yield ($P > 0.86$) after road construction in C1 and C2. After harvest, a significant change ($P < 0.01$) was detected

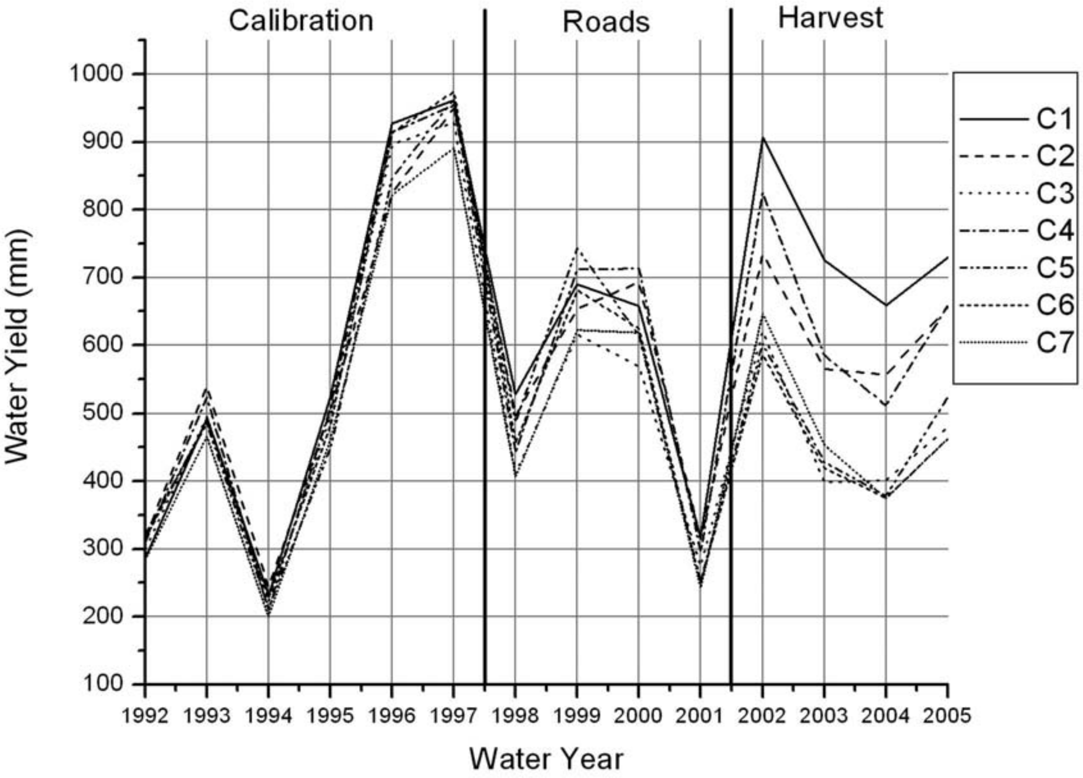

Figure 2. Hydrographs reflecting water yield for 7 catchments before and after road construction and harvest treatments within the Mica Creek Experimental Watershed located in northern Idaho. C1 = clearcut, C2 = partial cut, post roads monitoring = 1998–2001, postharvest monitoring = 2002–2005.

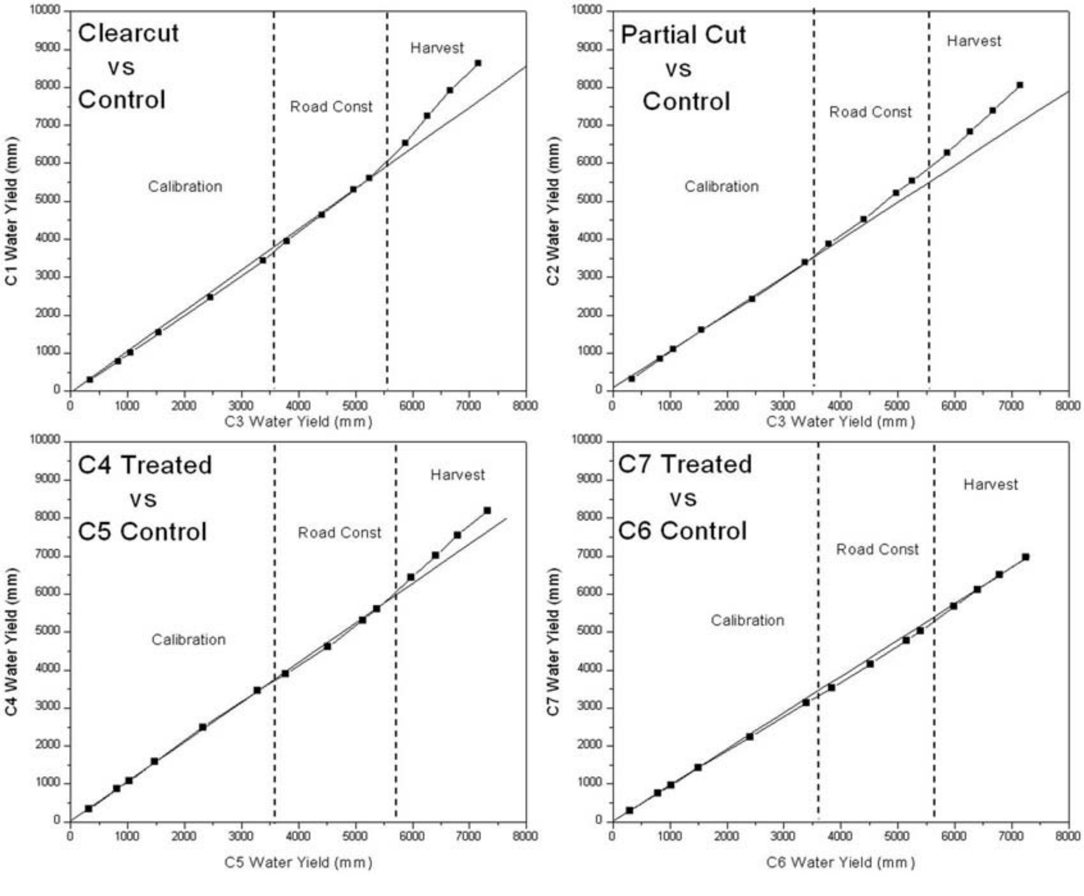

Figure 3. Double mass plots of water yield after road construction and harvest treatments in the Mica Creek Experimental Watershed, located in northern Idaho; C = catchment.

Table 3. Results of regression analysis of annual (water year) water yield before and after road construction and harvest treatments applied within the confines of the Mica Creek Experimental Watershed (MCEW) in northern Idaho

				Model results			
Catchment comparison	Time period	Control	Treatment	Intercept	Intercept *P* value	Change in water yield (mm)	Percentage change
C3/C1 Mean water yield (mm)	A	556	571	−11	—	—	—
	B	468	548	57	<0.01	68	12
	C	475	765	260	<0.01	272	36
C3/C2 Mean water yield (mm)	A	556	563	47	—	—	—
	B	468	539	96	0.06	48	9
	C	475	628	2	<0.01	145	23
C5/C4 Mean water yield (mm)	A	547	570	9	—	—	—
	B	524	541	14	0.86	5	1
	C	483	645	140	<0.01	131	20
C6/C7 Mean water yield (mm)	A	567	521	7	—	—	—
	B	503	473	14	0.49	6	1
	C	461	485	59	0.01	52	11

Time period A is calibration period (1992-97), B is road construction (1998-2001), and C is harvest (2002-05); C = catchment.

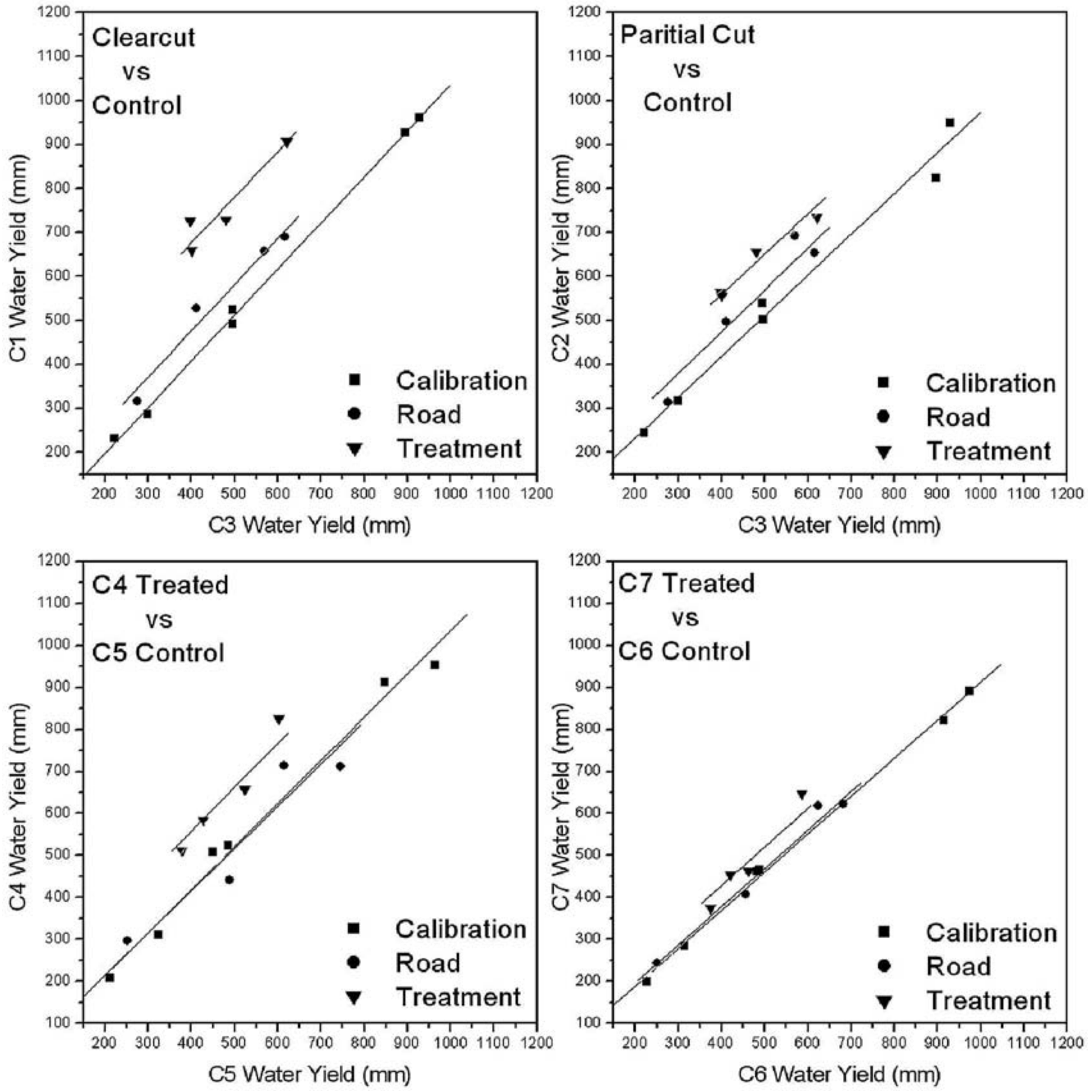

Figure 4. Regression relationships between catchments at the MCEW during the calibration period, after road construction and timber harvest; C = catchment.

between intercepts of the regression models, with an increase in water yield of 20%, or 131 mm/yr. Finally, after road construction, analysis of annual flow data between paired catchments 6 and 7, where C7 includes C1, C2, C3, and C4, and C6 acts as a control of similar size and topography as C7, resulted in a statistically insignificant difference ($P > 0.49$). After harvest practices, however, analyses indicated a significant increase ($P = 0.01$) in water yield of 11%, or 52 mm/yr.

Monthly and Seasonal Water Yield Results

Monthly precipitation and flow differences relative to the control for the pre and postharvest periods are shown in Figure 5. Tables are not included for monthly analyses due to the large data volume, and relatively few significant results. After all treatments (i.e., roads and roads plus harvest), there were no significant changes detected in water yield for each of the individual months of July through October, for either clearcut (C1), or partial cut (C2) catchments. In C1, the month of April showed a significant ($P = 0.03$) increase in water yield after road construction, with an increase of approximately 12 mm (11%). After clearcut timber harvest, monthly water yield in C1 was significantly increased for the months of December through June, with water yield increases ranging from 35 to 54%, or 11 to 57 mm, during those months, with the largest increases in April and May (Table 4, Figure 5).

In these analyses, seasons are defined as the months of March through June, July through October, and November through February, which correspond to the snowmelt, dry, and snow deposition seasons, respectively. Seasonal analyses of water yield (Table 4) in C1 showed the greatest increases during the melt season of March through June, with a 7% (7 mm) increase after road construction and a 35% (44 mm) increase in water yield after clearcut harvest, with P values less than 0.02. Dry season analysis during the months of July through October indicated no significant changes due to road construction ($P > 0.16$). During this season, there was a significant increase ($P = 0.01$) of approximately 1 mm (5%) detected after harvest; however, this result should be considered negligible, if measurable. During the snow deposition months of November through February, clearcut harvest resulted in a significant increase of water yield ($P < 0.01$) of as much as 14 mm, or 38%.

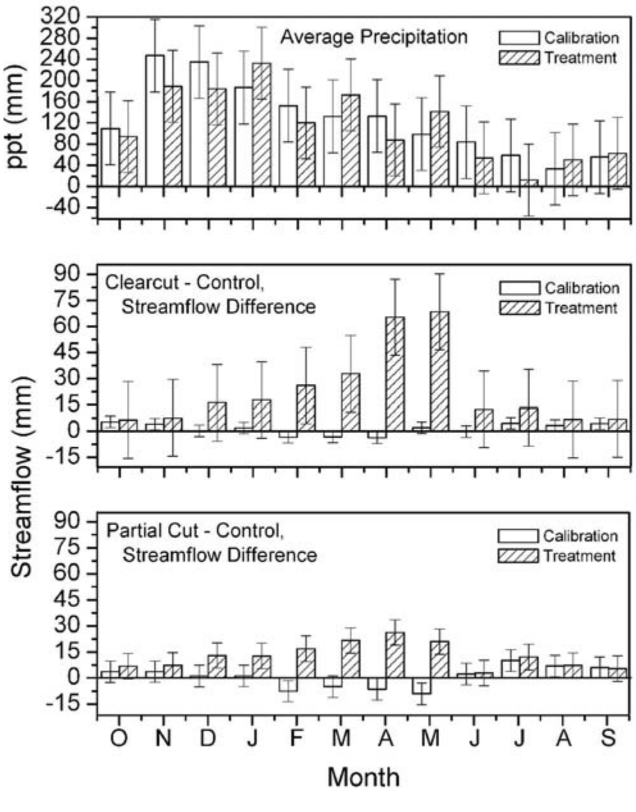

Figure 5. Average monthly precipitation and streamflow relationships during calibration (1992–97), and following treatments (50% clearcut and 50% partial cut timber harvest) (2002–05) relative to the control catchment at the Mica Creek Experimental Watershed. Error bars indicate 1 SD.

Monthly analysis of streamflow from the partial cut catchment (C2) indicated significant changes after road construction ($P \leq 0.03$) during the months of December, January, and March ranging from 4 to 7 mm (average increases of ~8%). In C2, significant changes in water yield were detected after partial cut timber harvest for the months of November through June, with increases in water yield ranging from a 9% increase in June to a 37% increase in December, or 8 to 13 mm, respectively. Similar to catchment 1, seasonal analyses of catchment 2 indicated the greatest increases in water yield ($P < 0.01$) were during the melt season of March through June with an average overall increase of 22% or approximately 22 mm in water yield after partial cut harvest (Table 4). Dry season analysis during the months of July through October indicated significant increases in water yield resulting from road construction of as much as 28% ($P = 0.05$), or 7 mm (Table 4). Partial cut timber harvest (C2) did not significantly alter water yield during the dry season months ($P > 0.69$). During the snow deposition months of November through February, a significant increase ($P < 0.01$) in water yield was detected after road construction of 4 mm, or 22%. Partial cut harvest in C2 during this same period of time resulted in a significant increase of water yield ($P < 0.01$) of as much as 10 mm (Table 4).

Evapotranspiration

Approximate annual evapotranspiration (ET) was estimated from the residual (R) of the catchment mass-balance equation, where $ET \cong R = P - Q$, where P is precipitation and Q is streamflow. This estimate assumes that deep drainage and change in catchment storage are negligible between years and that the annual precipitation recorded at the SNOTEL (Natural Resources Conservation Service (NRCS)) site is a reasonable estimate of spatially distributed precipitation over the watershed. The SNOTEL site is located at 1,448 m asl (Figure 1), near the median elevation of catchments 1–5, therefore this site is assumed to provide a reasonable proxy measurement for these catchments. However, it will likely overestimate the areal precipitation for catchments 6 and 7. The SNOTEL site is located in a 50-m wide clearing on the lee side of prevailing winds, and includes a large-volume, alter-shielded precipitation gauge that is 3.7 m high, with a

Table 4. Results of regression analysis of seasonal water yield before and after road construction and clearcut (WS1) or patch-cut (WS2) harvest treatments applied within the confines of the Mica Creek Experimental Watershed (MCEW) in northern Idaho

Month(s)–Season		Control mean water yield (mm)	Treatment mean water yield (mm)	Intercept	Intercept *P* value	Change in water yield (mm)	Percentage change
Catchment 1—Road & clearcut harvest							
March–June	A	97	96	−1.47	—	—	—
	B	92	100	5.87	0.01	7	7
	C	82	127	42.30	<0.01	44	35
July–Oct	A	15	19	4.72	—	—	—
	B	14	20	8.75	0.16	4	20
	C	17	25	5.99	0.01	1	5
Nov–Feb	A	27	28	3.43	—	—	—
	B	11	16	6.12	0.07	3	16
	C	20	37	17.57	<0.01	14	38
Catchment 2—Road & Partial Cut Harvest							
March–June	A	97	92	1.63	—	—	—
	B	92	91	6.81	0.13	5	6
	C	82	100	23.19	<0.01	22	22
July–Oct	A	15	21	1.74	—	—	—
	B	14	24	8.36	0.05	7	28
	C	17	24	3.30	0.69	2	6
Nov—Feb	A	27	27	6.82	—	—	—
	B	11	20	11.14	<0.01	4	22
	C	20	33	16.37	<0.01	10	29

Time period A is calibration period (1992–97), B is road construction (1998–2001), and C is harvest (2002–05).

30.5 cm diameter orifice. Corresponding average precipitation during calibration, road, and harvest periods was 1,513 mm, 1,337 mm, and 1,401 mm, respectively (see Table 2).

Based on the basic mass balance approach, ET in C1 dropped from 62% of the annual P to 46% of P after roads and clearcut harvesting, for a total drop in ET of almost 35% with 50% canopy removal (Table 2). ET in catchment 2 dropped from 63% of the annual P to 55% after road construction and harvesting, for a total drop in ET of 14% after 25% canopy removal by partial cutting (i.e., thinning).

Discussion

Annual Water Yield

Increases in annual water yield were shown to be one of the immediate results of timber harvest, and water yield increased after logging in C1 and C2 after clearcut and partial cut harvesting, respectively. Generally, there were minimal impacts on water yield due to road construction. However, there was a significant increase ($P < 0.01$) of approximately 68 mm/yr in C1 after road construction. The magnitude of change in this instance may be unreasonable even if the entire 2.8% of roaded area yielded 100% runoff (i.e., 0 mm ET), which is highly unlikely. However, studies have shown that roaded catchments (particularly midslope roads) tend to exhibit increased runoff efficiency due to compacted surfaces, road cutslope interception of subsurface flow paths, and road networks that re-route and channel flow to the stream network (King and Tennyson 1984, King 1994, Thomas and Megahan 1998). Furthermore, ditches may function as intercatchment transfer conduits. King (1994) suggested that the location of the road and its relative effects on these phenomena on altering subsurface flow paths can be variable between catchments. Based on these possible mechanisms, the relatively large increase in water yield observed in C1 after road construction suggests that some yield increase may not be completely due to canopy reductions. Catchment 2 did not change significantly in water yield due to road construction. This may be due to local topography, road length (Table 1), location and type of timber harvest practice, and/or antecedent conditions and response to roads in snow-dominated systems (MacDonald and Stednick 2003). Although these data do not lead to the conclusion that roads are causing these increases, elucidating the mechanisms that produced these changes is beyond the scope of this manuscript, but provides direction for future research.

Increases in water yield at the MCEW generally appear largest in wettest years, as evidenced by the regression residuals in the first 4 years of postharvest data. This is also when there is theoretically little demand for additional water relative to the amount of precipitation. This is consistent with previous work that found that in dry years more precipitation is required to recharge soil, and there may be greater soil moisture depletion due to evapotranspiration (Harr 1983, MacDonald and Stednick 2003). This trend also exists at the MCEW, where there were increased water yields and larger differences in water yield between catchments in wetter years (Figure 2) after treatments. At the MCEW, clearcut harvesting increased water yield from C1 an average of 36% or 272 mm/yr in the first 4 years after harvest (Table 3). Previous studies indicated that winter precipitation losses due to interception can be quite large, and clearcutting can reduce such losses, resulting in higher snow water equivalent (SWE) (Troendle and Meiman 1984, Gary and Watkins 1985). Haupt (1979) found that clearcutting at the nearby Priest River Experimental Forest increased SWE by 47% on average, because of decreased interception losses. Recent work at the MCEW indicates that peak SWE is approximately 50% higher in the clearcut areas relative to the forested areas. This, along with preferential snow deposition and redistribution in the clearcut catchments, helps to explain the large increases in annual water yield at the MCEW, where the majority of increases were observed during the snowmelt months of March through June. Exacting these relationships will be accomplished through future work in the watershed.

After partial cut harvest, annual water yield from C2 increased significantly ($P < 0.01$) by 23%, or 145 mm. It is recognized that catchment characteristics, instrument detection limitations, and ET variability may force these results near the threshold of detectability, and the 20% harvested area detectability limitations discussed in previous work (i.e., Bosch and Hewlett 1982, Stednick 1996). Despite these constraints, this response is reasonable since partial cutting decreases individual competition for available resources (i.e., soil moisture), potentially leading to increased transpiration by individuals, and thus partially compensates for transpiration reduction from harvested trees. This response is also expected because partial cutting, where trees were individually marked for removal or thinning, has consistently been shown to result in increases in snowpack water equivalent and thus increased soil water availability (Gary and Troendle 1982). This may be particularly true for relatively young second-growth stands such as those at the MCEW (65–75 years), where snow deposition accounts for >70% of precipitation. Finally, although the loss of canopy may reduce precipitation interception and related canopy snow sublimation losses, stand thinning can increase surface snow sublimation processes via increased turbulent flow (Troendle and King 1987, Whitaker et al. 2002). The relative importance of these physical processes are unknown based on these data alone, but will be identified in future work.

The water yield relationship between paired catchments 5 and 4 did not change significantly due to road construction. After clearcut and partial cut harvest, a statistically significant increase of 20%, or 131 mm/yr, was detected. The results appear reasonable for C4, since it encompasses the streamflow from C1, C2, and C3; however, the results between C4 and C5 may be confounded by catchment elevation differences. Catchment 5 has approximately 100 ha of land that ranges between 1,025 and 1,175 m, all of which is below the lowest elevations of C4, while C4 has approximately 60 ha of land, or 8% of its land area, that exceeds the maximum elevation at C5. These differences likely lead to variations in precipitation deposition (e.g., higher incidence of rain-on-snow events in C5), evaporation, and transpiration rates.

The water yield relationships between C6 and C7 is not unexpected, since water yield increases due to road construction and timber harvest should only be slight, if not negligible at a distance of approximately 2.5 km from the treatment catchments (i.e., impact on relative area declines as the watershed size increases). Results indicate that there was no change observed due to road construction between C6 and C7; however, there was a significant increase ($P = 0.01$) detected in water yield in excess of 50 mm/yr or an 11% increase in water yield after harvest treatments. The downstream cumulative effects from timber harvest will be affected by stream morphology, length, and the greater watershed drainage area at downstream observation points. In this study, no other timber harvest or other anthropogenic disturbance occurred to confound downstream cumulative results, so the impacts of harvest were effectively diminished by hydrologic contributions from the greater unaffected drainage area. In other watersheds, where more disturbances (timber harvest or road construction) have occurred, downstream cumulative effects from one upstream harvest area may be compounded by the extent and location of these disturbances, as well as the timing (hydrologic recovery) of these disturbances.

Subannual Water Yield

Results from this work, based on best measurement technology, show that streamflow was insignificantly altered during the summer dry season after road construction and clearcut timber harvest. In contrast, previous studies in wetter regions showed increased streamflow after timber harvest during the summer season (Ziemer et al. 1996, Keppeler 1998). Figure 5 illustrates the average monthly precipitation and streamflow relationships during calibration and after treatments (50% clearcut and 50% partial cut timber harvest) (2002–2005) relative to the control catchment. The greatest increases in water yield at the MCEW were detected from March through June, with a 7% increase after road construction and a 35% increase in water yield after clearcut harvest in catchment 1. During the months of July through October, there was a significant increase detected of over 1 mm (5%) after clearcut harvest. This quantity falls well within detectability and measurement limitations and should therefore be considered suspect. There were no other significant changes during the months of July through October. During the snow deposition months (November through February), clearcut harvest resulted in a significant increase of water yield ($P < 0.01$) of as much as 14 mm (Table 4). Increases or decreases in water yield at these low levels should be considered negligible, if measurable (e.g., flume transducer error ±3 mm), given that the flow through the flumes may be ±15% for low flows.

Partial cutting in C2 showed similar results to C1 in that monthly water yields were not significantly affected by timber harvest during the months of July through October. On a monthly basis, the greatest increases in water yield were seen through the deposition and melt seasons of November through June, ranging from 14% and 37%, or 4 and 32 mm per month, respectively. Analyses indicated significant changes after road construction ($P < 0.03$) during the months of December, January, and March ranging from 4 to 7 mm per month. Seasonal analyses showed the greatest increases during the snowmelt season of March through June, with a 6% increase in water yield after road construction equating to approximately 6 mm, and an average increase of 22% or approximately 22 mm in water yield after partial cut harvest. Dry season analysis indicated a significant ($P = 0.05$) increase as a result of road construction in C2 by as much as 28%, or 7 mm (Table 4). Partial cut harvest in C2 did not alter the water yield regime during the dry season months, as evidenced by a P value exceeding 0.69. During the rain and snow deposition months of November through February, road construction appeared to increase water yield by as much as 4 mm (22%), while partial cutting resulted in a significant increase in water yield by as much as 10 mm, or 29% (Table 4).

There are difficulties associated with the detection of low flow effects in Mica Creek. During low flow periods it takes relatively little change in measured water level to significantly affect treatment results. Slight shifting of the Parshall flumes, algae growth, substrate movement through the flume, and macroinvertebrate activity at the bubbler orifice can contribute to potential low flow errors at Mica Creek. Efforts were taken to minimize these effects by routine maintenance of the flumes and monitoring the observed water level/discharge relationships, but at low water levels variation in measurement is unavoidable. Furthermore, results might fall within accuracy limitations of the flume transducer bubblers (±3 mm) and/or low flow measurement accuracy limitations (±15%). A final caution should be given to the error associated with low flow detection during winter low flows, and long periods of ice formation in the stream channel, which has been shown to result in flow path alteration and instrument failure. These are similar challenges to other studies in snow-dominated study areas, where long periods of ice formation in the winter have affected streamflow measurements (Troendle and King 1987, Moore and Wondzell 2005).

A great deal of information has been collected on the effects of timber harvesting on snowpack accumulation. Harr (1983) identified the months of October to March as being when most of the increase in annual water yield after logging will occur in the coastal Pacific Northwest because of the largely snowmelt-driven hydrologic regime and related antecedent soil moisture conditions. The MCEW only differs from this region in that the timing of increase appears to be delayed to the spring months. At the MCEW, most increases in water yield are observed from the months of November through June, with largest increases observed during the months of March through June. The MCEW appears to exhibit a shorter fall wet season, going from dry to cold and wet fairly quickly, as opposed to the relatively long fall warm and wet season west of the Cascades that exhibit a more extended wet season and tend to produce increased streamflows from cleared (i.e., relatively wet) areas. Thus, because of this difference, antecedent soil moisture effects are generally not seen at the MCEW until the winter-spring soil recharge period, except for unusually rainy fall seasons. Future research needs to address how antecedent soil moisture conditions affect seasonal water yields in this region. This clearly illustrates the need for more mechanistic studies focused on internal watershed processes.

Evapotranspiration

Using the residual of the catchment water balance as a rough approximation of annual ET timber harvest led to a drop in ET of approximately 35% in the clearcut catchment, and a drop of approximately 14% in the partial cut relative to the calibration period (see Table 2). In terms of ET, these are the expected responses, as similar reductions were found for similar harvest treatments (i.e., reductions of ET by as much as 50 to 55% or less depending on harvest practice) (Stednick 1996, Troendle and Reuss 1997). To better elucidate the effects of harvest on ET, it would be useful to separate the ET term into its primary components of evaporation, sublimation, and transpiration to understand the dominant hydrologic processes that produced the observed yield changes. Ultimately, there are a number of hydrologic processes that may be altered as a result of the effects of timber harvest in the MCEW. To improve our understanding of how the magnitudes of the specific components of the water balance are altered, additional empirical work focused on canopy interception, snowpack dynamics, soil moisture depletion, and transpiration is ongoing in the watershed. These data will also be used to parameterize physically based, spatially distributed hydrologic models to further analyze impacts of treatment and to control for variations between the watershed pairs, and extend these results to other catchments in the region.

Conclusions

This work is the first study focused on contemporary timber harvest practices in the continental/maritime climate region of the western United States. In one treated catchment (C1) water yield was observed to increase significantly ($P < 0.01$) by nearly 70 mm after road construction, and by more than 270 mm/yr after subsequent 50% clearcut timber harvest. In the second experimental catchment (C2), changes in water yield were insignificant after road construction, but increased significantly ($P < 0.01$) in excess of 140 mm/yr after 50% partial cut harvests with a 50% canopy removal. Paired catchment analysis indicated that cumulative effects of timber harvest practices were minimal approximately 2.5 km downstream from the headwaters and harvest treatments, yet were still significant ($P = 0.01$), with an increase of approximately 50 mm (11%). Monthly and seasonal analysis revealed that in the snow-dominated system of the MCEW the largest effects of harvest practices were observed during the snow deposition and melt months from November to June, resulting in average water yield increases of 31% (range 22–38%). Studies on the effects of timber harvest practices in the continental maritime region have not reported reductions in water yield during base flow seasons. After harvest, water yield did not change significantly in the MCEW during the dry season months. ET, estimated as the residual of the catchment mass balance, was reduced by 35% and 14% after clearcut and partial cut harvest, respectively. Since the largest increases in water yield observed at the MCEW after clearcut timber harvest occurred during wet and snowmelt seasons, future management decisions regarding timber harvest extent within watersheds of this region need to take this into account. Integrating knowledge of water yield effects with land use planning will lead to sound and sustainable forest management, which will help ensure that the health of stream channels and stream biota are maintained, as well as addressing downstream water quantity concerns.

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