The Effect of Timber Harvest on Summer Low Flows, Hinkle Creek, Oregon

Christopher G. Surfleet and Arne E. Skaugset

ABSTRACT

Changes to summer low flows from forest harvesting were measured for a gauged fourth-order stream in the Hinkle Creek Paired Watershed Study. At the gauged stream, August streamflow increased an average of 1.9 mm/year (45%) for the three summers following forest harvest of 13% of a 1,084 ha watershed. Following a second harvest of an additional 13% of the watershed the August streamflow increased by 4.5 mm (106%) the first summer and 2.0 mm (47%) the second summer. Master recession curves were fit to the gauged watersheds and the resulting recession coefficients were used to predict low flows from small watersheds nested within the gauged watersheds. The estimated low flows were used to evaluate changes in summer low flows associated with forest harvest for the small watersheds. Using recession curve analysis, the estimated range of the increase for average August streamflow for the four small watersheds in the Hinkle Creek Paired Watershed Study was 1.7 mm to 4.4 mm the first summer following forest harvest. August streamflow in the small watersheds was not distinguishable from preharvest levels within 5 years for all but one watershed, which had the highest proportion of watershed area harvested.

Keywords: low flow, recession curve, forest management, water yield, forest hydrology

The Hinkle Creek Paired Watershed Study (HCPWS) (Figure 1) was initiated in 2002 to study the impacts of contemporary forest practices on the aquatic ecology of forest streams. Stream temperature was a response variable of primary interest. The effect of timber harvest, especially the removal of riparian, shade-producing vegetation, on stream temperature is well documented (Beschta et al. 1987, Moore et al. 2005). During the Alsea Watershed Study, in the Coast Range of Oregon, the harvest of riparian conifers in conjunction with a prescribed broadcast burn resulted in an increase in the maximum daily stream temperature of 16° C and an increase in the maximum monthly stream temperature of 8° C (Brown and Krygier 1970, Ice 2008). The harvest of old-growth Douglas-fir in conjunction with slash burning in the H. J. Andrews Experimental Forest resulted in increases in the maximum daily stream temperatures of 7° C (Levno and Rothacher 1967, 1969, Johnson and Jones 2000). Clearcut timber harvest in coastal British Columbia in the Malcom Knapp Experimental Forest increased maximum daily temperatures by as much as 5° C (Moore et al. 2005).

Kibler (2007) and Otis (2007) reported the preliminary results on the effect of clearcut timber harvest adjacent to four nonfish-bearing streams on stream temperature from the HCPWS. For the four experimental streams (Figure 1; Montana Flumes mark the locations) the maximum daily stream temperature increased by as much as 1.1° C and, for one stream, the maximum daily stream temperature decreased 2.8° C. The average daily maximum temperature increased 1.1, 0.7, and 0.6° C for three of the streams and decreased 1.6° C for one stream. These results were not expected and the decreased maximum daily stream temperature result was counterintuitive. The fact that maximum stream temperatures did not increase as much as was hypothesized was attributed to the dead shade provided by logging slash lying over the streams after logging was completed (Kibler 2007). However, this could not completely explain the muted increase and the decrease in maximum stream temperatures for the one stream. It was hypothesized that the muted increase and, in one stream, decrease in maximum stream temperature may be attributed to increases in groundwater due to timber harvest in conjunction with the dead shade provided by the logging slash.

It is well established that the timber harvest, in the short term, will result in increased summer low flows. The impact of timber harvest on streamflow is well studied and it is widely accepted that the removal of forest vegetation results in increased annual water yield (Bosch and Hewlett 1982, Andreassian 2004). Rothacher (1970) reported on the seasonality of the increased annual water yield. After clearcut logging and slash burning of old-growth Douglas-fir in the H. J. Andrews Experimental Forest, 80% of the increase in annual water yield occurred during winter while the remaining 20% occurred during summer low flows. During the Alsea Watershed Study in the Oregon Coast Range, average daily flows in August were higher than predicted and the number of days less than a threshold low flow decreased after clearcut logging and burning (Harr and Krygier 1972, Stednick 2008). Significant increases in streamflow during the low-flow season and a decrease in the number of low-flow days less than a threshold discharge were also observed at Caspar Creek after selective logging of harvest regenerated redwood

Manuscript received October 18, 2011; accepted June 26, 2012. http://dx.doi.org/10.5849/wjaf.11-038.

Christopher G. Surfleet (chris.surfleet@oregonstate.edu), Oregon State University, Department of Forest Engineering, Resources, and Management, Corvallis, OR; Phone: (541) 737-4952. Arne E. Skaugset III (arne.skaugset@oregonstate.edu), Oregon State University. *This work was made possible by grants from the Fish and Wildlife Habitat in Managed Forests Research Program of the College of Forestry at Oregon State University, a Gibbet Hill Fellowship, and funds from the Watersheds Research Cooperative. We thank Kelly Kibler for summer streamflow measurements.*

This article uses metric units; the applicable conversion factors are: millimeters (mm): 1 mm = 0.039 in; meters (m): 1 m = 3.3 ft; kilometers (km): 1 km = 0.6 mi; hectares (ha): 1 ha = 2.47 ac.

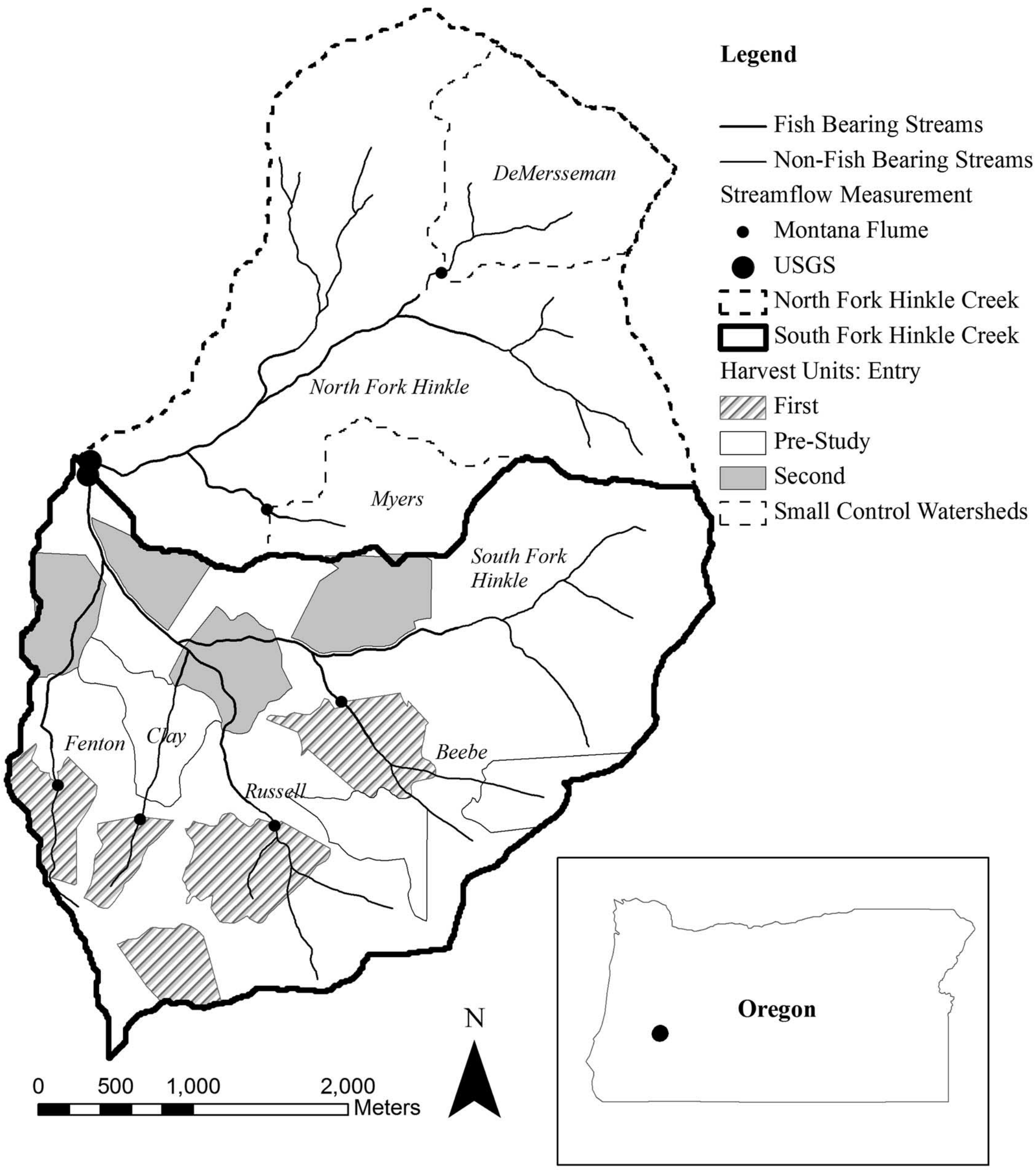

Figure 1. Hinkle Creek Paired Watershed Study.

and Douglas-fir (Keppler and Ziemer 1990). Thus, knowledge of the increases in low flows associated with the timber harvest adjacent to the nonfish-bearing streams in the HCPWS could help explain the stream temperature response for those streams.

Discharge for the HCPWS was measured for the nonfish-bearing streams with Montana flumes sized to pass the 100-year return period flow. The size of the flumes was prescribed so that winter streamflow and peak flows could be measured accurately and precisely. The tradeoff was that these structures were not designed to accommodate the lowest discharges during summer. For example, a 36-in Montana Flume is rated for a minimum discharge of 27 l/s and a 48-in Montana Flume is rated for a minimum discharge of 35 l/s[1] while low-flow discharges at these flumes were commonly below 5 l/s. An alternative technique was needed to estimate the magnitude of change in the summer low flows for the nonfish-bearing streams.

A widely used technique to analyze low flows in rivers is recession curve analysis (Hall 1968, Tallaksen 1995). The recession limb of an annual hydrograph during summer low flows is related to the drainage characteristics of the watershed (Tallaksen 1995). Summer baseflow is the portion of streamflow that comes from soil moisture storage, groundwater, and other delayed sources (Hewlett and Hibbert 1963, Hall 1968). Fedora and Beschta (1989), Bransom (1996), and Zillgens et al. (2007) used recession curve analysis to characterize the drainage of small streams and headwater swales. Martinec (1975), Bergstrom (1976), and Rees et al. (2004) used recession curve analysis to model the drainage of hillslopes and aquifers after storms. The master recession curve (MRC) method is available and has been successfully used in a variety of applications (Toebes and Strang 1964, Brutsaert and Nieber 1977, Nathan and McMahon 1990). Moore (1997) showed that fitting storage-outflow models for forest catchments was an alternative to the MRC method.

The objectives of this project were: (1) evaluate change to summer low flow in the 1,084 ha South Fork Hinkle Creek (SFH) following forest harvest; (2) estimate summer low flows in nonfish-bearing streams nested in the HCPWS using an MRC; and (3) use the estimated streamflow to evaluate the impact of timber harvest on summer low flows in the small nonfish-bearing streams of SFH.

Methods

Study Area

The HCPWS is located within the Hinkle Creek watershed in the western Cascades of southern Oregon approximately 40 km northeast of Roseburg, Oregon (Figure 1). The HCPWS is comprised of two fourth-order watersheds; the 856 ha North Fork Hinkle Creek (NFH), the control watershed, and the 1,084 ha SFH, the treatment watershed. The elevation of the study area ranges from 400 to 1,250 m and the mean annual precipitation is approximately 1,500 mm, which occurs primarily as rain between November and March. The geology of the study watersheds consists of Brown Mountain Basalts at highest elevations, volcanolithic, sandstone, conglomerate, laharic brechia, rhyolite, and dacite flows at intermediate elevations, and Holocene and Pleistocene landslide deposits at lower elevations (Wells et al. 2000). The soils of the study watersheds are Typic Ultisols, Humic Inteceptosols, and Andic Inteceptosols (Natural Resources Conservation Service (NRCS) 1994). The vegetation in Hinkle Creek is a 60-year-old harvest-regenerated forest comprised mainly of Douglas fir (*Pseudotsuga menziesii*) with minor components of western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), and red alder (*alnus rubra*). Vegetation in the riparian areas is comprised of the overstory species listed above with huckleberry (*Vaccinium parvifolium*) and sword fern (*Polystichum munitum*) in the understory. The study watersheds are owned and managed by Roseburg Forest Products for timber production.

The HCPWS was initiated in fall 2002. In 2001, prior to the initiation of the HCPWS, timber was harvested from 103 ha or 9.5% of the area of the SFH watershed in three clearcuts (Figure 1). Calibration data for streamflow were collected from fall 2002 to fall 2005. The treatments in the SFH consisted of two harvest entries. The first harvest entry occurred between August 2005 and May 2006 and consisted of four clearcuts totaling 154 ha or 14% of the SFH area located adjacent to the small, nonfish-bearing streams in SFH (Figure 1). The second harvest entry occurred between August 2008 and May 2009 and consisted of an additional 131 ha or 12% of area of the SFH, in four clearcuts, located adjacent to fish-bearing tributaries or the main stem of the SFH (Figure 1).

All timber harvesting was carried out in accordance with current Oregon Forest Practice Rules (OFPR) (Oregon Department of Forestry 2007). The OFPR require that fixed-width buffer strips that contain overstory, merchantable trees be left adjacent to fish-bearing streams; there is no similar requirement for nonfish-bearing streams. Thus, for the first harvest entry, where the clearcuts were placed adjacent to nonfish-bearing streams, while understory vegetation retention and equipment exclusions zones were retained, no overstory merchantable conifers were retained. For the second harvest entry, clearcuts were placed adjacent to fish-bearing tributaries or the main stem. For the tributaries, a 50-foot buffer strip that contained at least 40 ft^2 of conifer basal area per 1,000 ft of one side of the stream was left. For the mainstem SFH, a 70-ft-wide buffer strip that contained at least 140 ft^2 of conifer basal area per 1,000 ft of one side of the stream was left.

The trees in the clearcuts were felled by hand and yarded to the landings with a slackline, skyline cable system with a motorized, slack-pulling carriage. This yarding system allowed the trees in the vicinity of the streams to be lifted straight up into the air and be fully suspended in the vicinity of the streams. The trees were yarded whole-length and limbed and processed into logs at the landings. Site preparation activities occurred on the clearcuts during the late summer and fall after harvest occurred. These activities included burning slash piles, predominately slash piles in the vicinity of the landings, and the aerial application of herbicides. All streams, fish-bearing and nonfish-bearing, were buffered during the aerial application of herbicides. The clearcuts were replanted with plug-1, Douglas-fir seedlings at 176 trees/ha during the first winter after the clearcuts were harvested. By the end of the posttreatment period, all clearcuts were fully stocked and free to grow. Forest roads were not considered to be a factor in this study because they were present in the control and treatment watershed and this study focused on dry season, low-flow time periods when the hydrologic influences of roads are minimal.

Measurement of Streamflow

The US Geological Survey (USGS 2010) measured streamflow at rated cross sections at the outlets of the NFH and SFH (Figure 1). Mean daily discharges for the NFH and SFH were available from June 2003 to September 2010. Instantaneous streamflow was measured on five nonfish-bearing streams (Fenton, Clay, Russell, Beebe, and Meyers Creeks) with steady-state dye tracer techniques at various times during the summers of 2004 to 2006 (Otis 2007). During the summer of 2007, discharge was measured three times in late July and August at 14-day intervals. During the summer of 2010, discharge was measured three times in August at 7-day intervals. The summer low-flow measurements of discharge with the steady-state dye tracer techniques were carried out near the Montana flumes, where winter streamflow was gauged (Figure 1). Rhodamine WT fluorescent dye was injected into the stream at a steady rate and concentration. The dye concentration was measured with a Fluorometer (Model AU10 or Cyclops 7.0 by Turner Designs) approximately 25 m downstream of the dye injection to allow adequate mixing of the stream water with the dye. Once the dye concentration reached steady state at the Fluorometer, the discharge was calculated by the following equation:

$$Q_{STREAM} = Q_{DYE} \cdot \frac{(C_{DYE} - C_{TOTAL})}{(C_{TOTAL} - C_{STREAM})}$$

where Q_{STREAM} is the calculated streamflow rate, Q_{DYE} is the injection flow rate of the dye, C_{DYE} is the concentration of the dye, C_{TOTAL} is the dye concentration of the dye/stream water mixture at the fluorometer, and C_{STREAM} is a background ‘equivalent concentration’ of dye, based on the natural fluorescence of stream water prior to beginning each study (Rantz 1982).

The use of a dye tracer is more accurate than a velocity meter in low streamflow conditions, the velocity meter can be limited by the low depth of streamflow. In trials at Hinkle Creek (Otis 2007) a 13% difference in discharge was measured between the use of salt and dye tracers. Although they are different tracers, the approach is the same and the 13% difference was likely indicative of the error associated with the measurements.

Effect of Forest Harvest on August Streamflow for SFH

Total August streamflow was calculated for the SFH and NFH in mm of runoff from daily streamflow measurements. August was used to represent the baseflow or low-flow portion of the summer hydrograph. The start and stop of baseflow for each period of summer streamflow was highly variable. Streamflow during August was predominately baseflow while streamflow in July and September had varying amounts of quickflow and baseflow. The use of August to represent the summer low flow allowed for a consistent length of time over which to compare streamflow estimates. To determine the effect of timber harvest on August streamflow for the SFH, the change in August streamflow compared to preharvest conditions (2003–2005) was calculated for each year for the SFH. The August streamflow change was the ratio of August streamflow for the SFH (harvested watershed) and NFH (control watershed) for each year normalized by the average ratio for the two streams for the preharvest years.

Recession Curve Analysis and Forest Harvest Impacts

For the NFH and SFH, recession curves were fit to the August hydrographs for each water year between 2003 and 2010. The recession curve took the form:

$$Q_0 = KQ_t^{\ t}$$

where, Q_t is the discharge at time t, Q_0 the initial discharge, t is one for a daily time step, and K is a recession constant that is the exponential decay coefficient (Tallaksen 1995). MRCs were fit to NFH and SFH August low flows using the correlation method (Langbein 1938) and the matching strip method (Snyder 1939).

For the correlation method, a linear relationship is determined for discharge taken 7 days apart for each stream. For the NFH and SFH, a pair of discharge estimates taken 7 days apart was selected from the August streamflow data for each water year from 2003 to 2010. For the nonfish-bearing streams, discharge was measured during August 2007 and 2010 at 7- to 14-day intervals. The slope of the linear relationship is the recession constant or ratio of the discharges taken 7 days apart when the intercept is forced through zero. High and low values of the recession constant were developed from the high and low range of the ratios for the streamflows; this provided the minimum and maximum observed recession constants (Zecharias and Brutsaert 1988, Troch et al. 1993). Daily recession coefficients (k) were calculated from the recession constants from the correlation method.

MRCs were developed for only the NFH and SFH with the matching strip method to validate the correlation method results. For this method, the August hydrographs were ranked from high to low based on the discharge value at the end of the month. The August hydrographs were considered in pairs starting with the pair with the lowest discharges at the end of the month. The hydrograph with the lowest value was shifted in time until one of the discharges was less than the lowest discharge value in the pair with the higher value. At this point, the hydrographs were connected and the process was continued to the next hydrograph in the ranking. This process continued until all of the August hydrographs were linked. The MRC was fit through the collection of linked August recession curves.

For the NFH and SFH, the mean daily streamflow for August 1 was the Q_0 in the recession curve equation with a daily time interval used for the recession curve equation. Mean daily streamflow was estimated until August 31 for the NFH and SFH for each of the summers streamflow was measured (2003–2010). August streamflow for each stream and year was the sum of the mean daily streamflows for August estimated with the recession curve times the number of seconds in a day divided by the area of the watershed times a unit conversion constant. This resulted in total August streamflow in mm of runoff from the NFH and SFH by year. To test the accuracy of the MRC method, a linear regression was developed between the August streamflow estimated with the MRC method and the measured USGS data for each year (2003–2010) for the NFH and SFH. A perfect estimation by the MRC method would yield a relationship with measured streamflow with a slope of 1.0.

The range of recession coefficients (k) developed with the correlation method with data from the NFH, SFH, and headwater streams were used to estimate August streamflow for the headwater streams. The calculation was carried out only for years when instantaneous streamflow measurements were available. The first measured streamflow in August was Q_0 in the recession curve equation with a daily time step used for the recession curve calculation. The first measurement of streamflow in August did not occur on August 1. Thus, the streamflow was estimated back until August 1 using the inverse of the recession curve equation; which calculates increasing streamflow back in time. Mean daily streamflow was estimated from August 1 until August 31. If more than one measurement of streamflow occurred in August, the Q_0 was reset to the new streamflow measurement. The range of August streamflow for each stream and year was the sum of the mean daily streamflows estimated with the recession curves. The estimated mean daily streamflows were normalized, by the same calculation as the NFH and SFH, into total August streamflow in mm of runoff by year.

To determine the effect of forest harvest on summer low flows for the NFH and SFH, the average of the ratios between the NFH and the SFH for August low flow for the pretreatment years (2003–2005) was determined. For any given postharvest year, the difference in the ratio of the August low flow for the NFH and SFH for that year was compared to the mean pretreatment ratio. The difference in the ratio for each year was multiplied by the August low flow in the SFH to provide the change in runoff in mm from the average pretreatment August low flow.

To determine the effect of timber harvest on August streamflow for the nonfish-bearing streams, the same technique was used. However, the August streamflow for the nonfish-bearing streams was estimated using recession coefficients calculated from the recession curve analysis. The average ratio of the August low flows between Meyers Creek (control) and each of the four treatment streams for the pretreatment period (2004–2005) was calculated with estimates of August low flows determined using recession coefficients. The difference in the ratio of August low flows for the control and treatment streams was compared to the average pretreatment ratio for each year. The difference in the ratio for each year was multiplied by the August low flow for the treatment stream to provide the change in runoff in mm attributed to forest harvest. The average, high, and low values of the change in streamflow for the nonfish-bearing streams was calculated with the average, high, and low values of the recession coefficients developed from the correlation method. The high and low values represent the range of recession coefficients calculated from the measured streamflow values.

Results

Recession Curves for the NFH and SFH

The MRCs developed with the correlation method resulted in recession constants of 0.82 and 0.85 for the NFH and SFH and their associated nonfish-bearing streams, respectively. When the data

Table 1. Daily recession coefficients calculated with master recession curves for August for the North Fork Hinkle Creek (NFH) (control watershed), South Fork Hinkle Creek (SFH) (harvested watershed), and their associated nonfish-bearing streams.

Method	NFH ratio of 7-day change in streamflow	NFH recession coefficient (k daily)	SFH ratio of 7-day change in streamflow	SFH recession coefficient (k daily)
Correlation method (NFH, SFH, and headwaters)	0.82	0.968	0.85	0.974
Correlation method (only NFH and SFH)	0.82	0.967	0.87	0.976
Correlation method low range (only NFH and SFH)	0.79	0.962	0.80	0.964
Correlation method high range (only NFH and SFH)	0.91	0.985	0.93	0.988
Matching strip method (only NFH and SFH)	n/a	0.979	n/a	0.964

from the headwater streams were removed from the calculations, the recession constants were similar; 0.82 and 0.87 for the NFH and SFH, respectively (Table 1; Figures 2A and 2B). The recession coefficients for the NFH and SFH and their associated nonfish-bearing streams expressed as daily recession coefficients (k) are 0.968 and 0.974 for the NFH and SFH, respectively.

The results from the matching strip method provided validation of the results from the correlation method. The master recession curves developed with the matching strip method resulted in daily recession coefficients (k) of 0.964 and 0.979 for the NFH and SFH, respectively (Table 1; Figures 3A and 3B). The values of the recession coefficients (k) for the NFH and SFH determined with the correlation and matching strip methods were within 1 to 2% of each other.

August streamflow was estimated for NFH and SFH using the recession coefficients fit by the correlation method. The estimated August streamflow was used to predict the measured August streamflow. The relationship between the estimated and measured values of August streamflow was statistically significant. The 95%-confidence interval of the slope of the relationship was 0.73 to 1.09 (P-value < 0.0001; adj. $r^2 = 0.89$)(Figure 4). A relationship with the slope of 1.0, representing a 1:1 line, indicates an exact fit. The August streamflow estimated with the recession coefficients were on average 6% higher than the observed August streamflow; average slope of the relationship between estimated and measured August streamflow was 0.94.

The Impacts of Forest Harvest on Summer Low Flow

The average August streamflow for the three preharvest years, 2003 to 2005, for the SFH and NFH were 6.8 mm and 4.2 mm, respectively (Table 2). The average August streamflow for the 3 years after the first harvest, 2006 to 2008, for the SFH and NFH, were 8.4 mm and 3.3 mm, respectively. For that time, the average August streamflow for SFH increased by an average of 1.9 mm/year (45%) compared to the preharvest relationship. The average August streamflow for the SFH increased by 4.5 mm (106%) in 2009, the first summer after the second harvest, and 2.0 mm (47%) in 2010 (Figure 5).

The streamflow in August for Clay, Beebe, and Fenton had increases that averaged 1.3 to 1.5 mm in the 2 years (2006 and 2007) after harvest (Figure 6). This is an average increase in August streamflow of 76 to 161% for the three nonfish-bearing streams in the first 2 years following harvest. Russell Creek had a 4.4 mm increase (158%) for 1 year postharvest (2006). The high and low values that represent the range in the estimated increases were from 1 to over 4 mm depending on year and stream (Figure 6).

The results for the estimated streamflow in August 2010 were mixed compared to preharvest values. In 2010, the estimated streamflow in Russell and Beebe Creeks decreased 0.5 and 0.2 mm, respectively, compared to preharvest streamflow. For Clay Creek there was a slight increase in estimated streamflow for August streamflow in 2010 compared to the preharvest mean. However, the 2010 value was within the range of the two preharvest streamflow

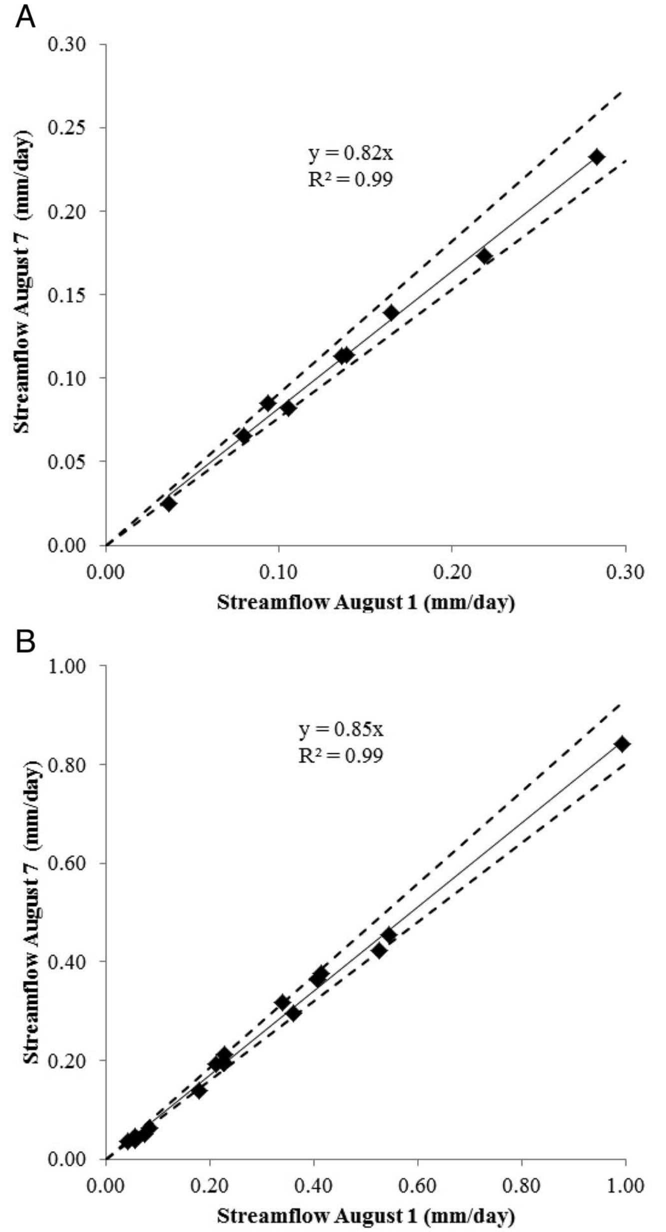

Figure 2. MRC using the correlation method for (A) North Fork Hinkle Creek and associated nonfish-bearing streams and (B) South Fork Hinkle Creek and associated nonfish-bearing streams for 7-day changes in discharge in August. Dashed lines represent the high and low range of correlation constants.

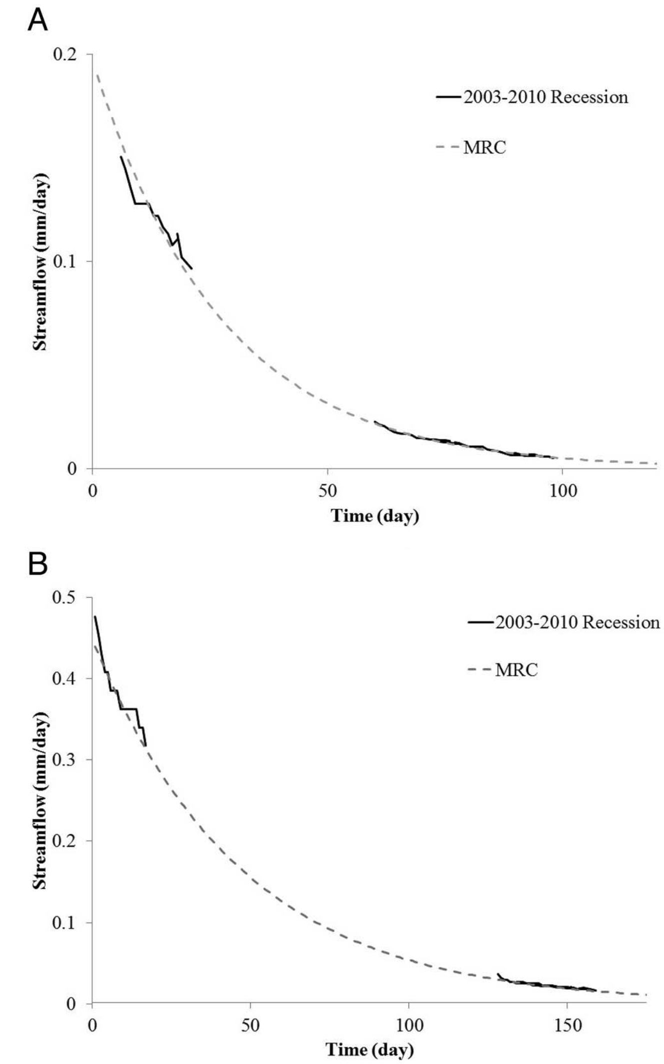

Figure 3. MRCs based on the matching strip method for August baseflow of (A) North Fork Hinkle Creek and (B) South Fork Hinkle Creek. Black lines indicate recession limb of measured streamflow for August, dashed line indicates master recession curve fit to measured streamflow.

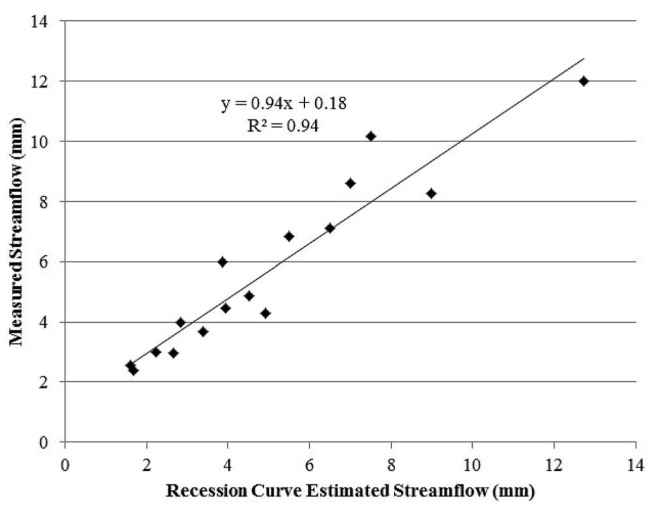

Figure 4. Relationship between measured August streamflow and recession curve estimated streamflow for North Fork Hinkle Creek and South Fork Hinkle Creek (2003–2010).

Table 2. August unit area streamflow in mm measured for the North Fork Hinkle Creek (NFH) (control watershed) and South Fork Hinkle Creek (SFH) (harvested watershed) for 2003 through 2010.

Year	NFH (mm)	SFH (mm)
2003	2.6	6.0
2004	5.4	7.2
2005	4.4	7.1
Preharvest average	4.1	6.8
2006	3.0	8.3
2007	3.0	6.8
2008	4.0	10.2
Postfirst harvest average	3.3	8.4
2009	2.4	8.6
2010	4.9	12.7
Postsecond harvest average	3.7	10.7

estimates which suggests no discernible change for the 2010 streamflow. The estimated streamflow for Fenton Creek remained above the preharvest mean streamflow by 0.4 mm (32%) in 2010.

Discussion

Trend in August Streamflow after Forest Harvest

The estimate of August streamflow for the nonfish-bearing streams showed little or no increase by 2010, except for Fenton Creek (Figure 6). The range of the estimated August streamflow increase for Fenton Creek in 2010 was 0.37 to 0.42 mm. Without measurements of August streamflow for the nonfish-bearing streams in 2008 and 2009, the year that the August streamflows returned to preharvest levels cannot be determined. However, the increased streamflow in August at the SFH in 2008, prior to the second harvest, indicates that streamflow increases were present for at least 3 years after timber harvest.

The observation that August streamflow in the nonfish-bearing streams became indistinguishable from preharvest streamflow within 5 years is consistent with other studies. Increased summer low flows after forest harvest in the Caspar Creek Watershed Study also returned to preharvest levels within 5 years (Keppeler and Ziemer 1990). In the H.J. Andrews Experimental Forest, a 100%-clearcut of Watershed 1 had increased August streamflow for 5 years following forest harvest (Hicks et al. 1991).

In the Caspar Creek Paired Watershed Study, regrowth of the forest was hypothesized to be the reason for the return of summer low flows to preharvest levels (Keppeler and Ziemer, 1990). In Hinkle Creek, the same explanation is hypothesized regarding summer low flows in the nonfish-bearing streams, namely that primary succession and the regrowth of the forest used the water attributed to increased summer low flows. Herbicides were applied to the harvest units in HCPWS that were adjacent to the nonfish-bearing streams to reduce vegetative competition with the planted seedlings. An increase in August streamflow in Fenton Creek was still apparent 5 years after timber harvest. For the other three nonfish-bearing streams, August streamflows in 2010 were indistinguishable from preharvest flows. For Fenton Creek, the harvest unit comprised 74% of the watershed area and for the other three nonfish-bearing streams, the percent of the watershed area harvested ranged from 12 to 34%. For Fenton Creek there was a marked and prolonged increase in summer low flows, which indicates that the combination of the area harvested and the use of herbicides delayed the return of transpiration rates to preharvest levels. With the smaller percent area impacted, it is reasonable to expect a smaller and less robust response from the other watersheds.

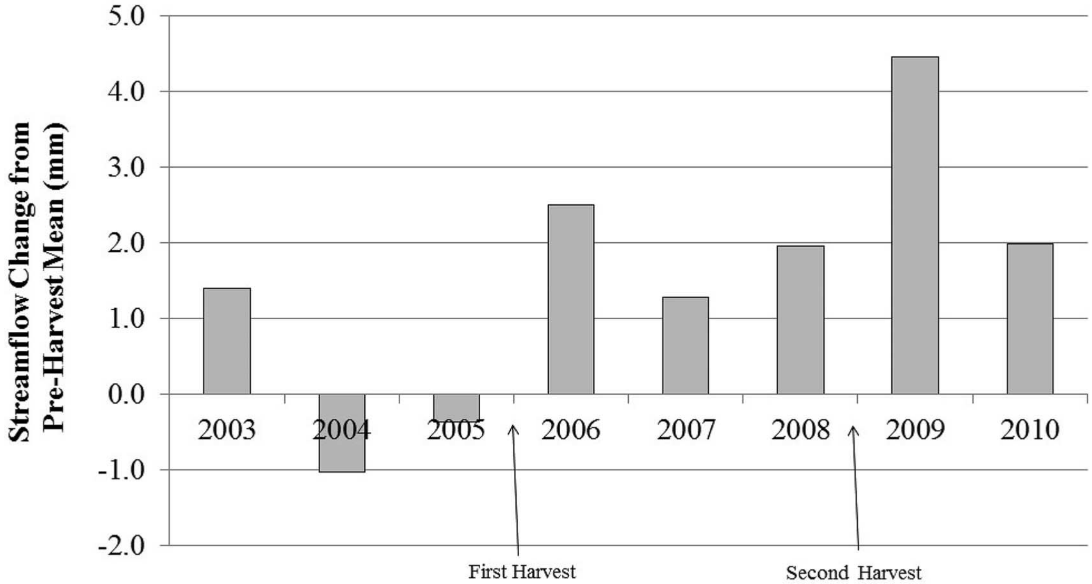

Figure 5. Change in August streamflow for the South Fork Hinkle Creek 2003–2010. First forest harvest occurred in winter of 2005–2006; second forest harvest in winter of 2008–2009.

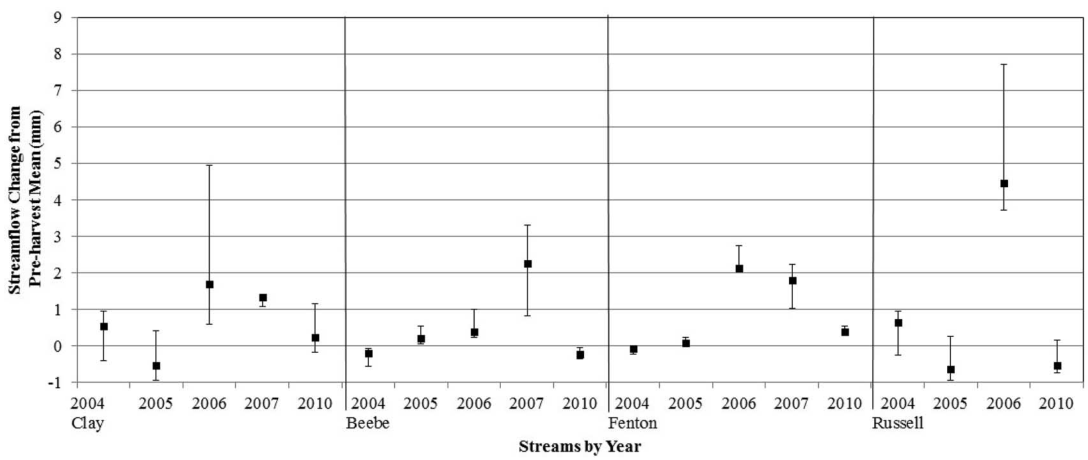

Figure 6. Change in August streamflow compared to mean preharvest streamflow (2004–2005) for four headwater streams of Hinkle Creek. Square represents streamflow estimated from mean recession coefficient by the correlation method; error bars represent the range of streamflow estimates from the high and low range of recession coefficients by the correlation method.

The August streamflow for the SFH was, on average, 1.9 mm (45%) higher in the 3 years after the first harvest (2006–2008). August streamflow for the SFH more than doubled to 4.5 mm (106%) after the second harvest in 2009; which doubled the watershed area harvested. In 2010, the second year after the second harvest, the increase in August streamflow for the SFH was 2.0 mm (47%), a reduction from the 2009 streamflow increase. This decrease may be partly explained by the return of August streamflow in the nonfish-bearing streams to preharvest conditions. When a linear extrapolation of the reduction in streamflow from 2007 to 2010 is made for the nonfish-bearing streams, the change in streamflow by year is on average 24% (e.g., 2009–2010). The harvest in the nonfish-bearing streams represented half of the harvested area in the watershed; 24% of the 2009 streamflow increase in SFH (106%) represents about half of the reduction in streamflow from 2009 to 2010. The remaining percentage loss could be due to natural variability in the response of the August streamflow for NFH and SFH as seen in the preharvest years of 2003–2005.

Use of Recession Curve Estimated Streamflow

The USGS streamflow measurements at the NFH and SFH provided high-quality streamflow data to fit recession curves to the baseflow portions of the hydrographs. The recession curve method accurately estimated streamflow for August for the NFH and the SFH (Figure 4). The 95%-confidence interval of the slope of regression line between the estimated streamflow calculated with the recession curves and the observed streamflow encompassed the l:1 line.

In the HCPWS nonfish-bearing streams, the instantaneous discharges for August streamflow were less than the minimum discharge measurable by the Montana flumes used for winter streamflow measurement. Thus, independent measurements of discharge were used to synthesize August streamflow with recession coefficients from a MRC. There were between one and three individual streamflow measurements for each stream during each summer. Given the low number of streamflow measurements, the error associated with estimated streamflow from recession curve analysis could be high, even the range of estimates due to the range of recession coefficients used were from 1 to 4 mm depending on year and stream (see Figure 6).

The observed increase in August streamflow for the SFH determined with the USGS streamflow data supports the hypothesis that a similar response should occur in the streams nested within the SFH and adjacent or below the harvest units. In fact, a larger increase would be expected in streams directly adjacent to the harvest units. Downstream of the harvest units the increase in streamflow due to forest harvest should be lower due to mixing with streamflow from unharvested portions of the watershed. This was the case for the estimates of August streamflow for the headwater streams compared to the same post harvest time period in the SFH (2006–2007). The estimated increase in August streamflow, for streams directly adjacent or below the harvest units, was greater than the 45% increase for the SFH.

The need to study the impact of timber harvest on summer low flows came up only after the HCPWS was already established. If the impact of timber harvest on summer low flows is a key objective of research, then the use of a recession curve analysis technique would not be a preferred method of analysis. A more precise direct measurement of summer streamflow should be used. However, the situation might arise, such as this one, where a recession curve analysis might be needed to estimate summer low flows for streams nested within gauged streams. If that is the case, it is very important to make many instantaneous streamflow measurements throughout the summer low-flow period to fit the recession curve.

Because of the low number of August streamflow measurements, there was no choice but to use a single "master recession" response. Multiple measurements of summer streamflow at a variety of scales throughout the catchment, which in our case were not available, would have improved the accuracy of the estimates. During several of the summers, only one streamflow measurement was taken for the headwater streams. Yet, even with all the uncertainty associated with use of the recession curve, the trends in streamflow values estimated are consistent with other studies on the impact of timber harvest on summer low flows (Keppeler and Ziemer 1990, Hicks et al. 1991, Stednick 2008).

Low-Flow Increases and Stream Temperature

Many headwater streams, such as Hinkle Creek, are fed by subsurface hillslope water or groundwater. In temperate climates, groundwater has been shown to moderate seasonal fluctuations of surface water temperature (Poole and Berman 2001, Ward 1985). Groundwater maintains cooler water temperatures during summer and decreases stream cooling during winter (Markle and Schincariol 2007). As the water travels down the stream network, the interaction of groundwater on streamflow and temperature varies. The role of groundwater on water temperature generally decreases down a stream network as surface water accumulates. However, variations in stream recharge temperatures, groundwater influx (gaining reaches), or losses of stream water (losing reaches) are influential on a stream's heat budget and aquatic habitat at many scales (e.g., Sinokrot et al. 1995, Meisner et al. 1988).

Otis (2007) quantified groundwater flux in a study of low-flow hydraulics on the nonfish-bearing streams of Hinkle Creek. Using a simple advection mixing model of groundwater inputs and temperature with upstream surface water and temperature, Otis (2007) was able to estimate the 2-hour maximum stream temperature in the downstream reach. The predicted increase in August low flow following forest harvest and subsequent moderation, and in one case a decline in the maximum daily stream temperature, suggests the hypothesis that increased groundwater inputs influence stream temperature in Hinkle Creek. More research is suggested on the groundwater increase and subsequent stream temperature response associated with the Hinkle Creek forest harvest.

Conclusion

August streamflow for the SFH increased by an average of 1.9 mm/year (45%) for the 3 years following clearcut harvest of 14% of the 1,084 ha SFH watershed. August streamflow increased by 4.5 mm (106%) and 2.0 mm (47%) the first and second summers, respectively, following a second harvest of an additional 12% of the SFH watershed (26% total for both first and second harvest entries). MRCs were used to estimate August streamflows for the nonfish-bearing streams, where continuous streamflow measurements were not available. The timing of the increase in streamflow directly following forest harvest and corresponding results from the SFH and nonfish bearing streams indicates the increase in August streamflow was likely the result of timber harvest. This estimated increase in August streamflow persisted until 2010, 5 years after the timber harvest. These results are consistent with conclusions from other low flow studies which suggest that the trends and magnitude of these estimated August streamflows are reasonable. While direct measurement of streamflow is preferred, results from this study indicate that recession curve analysis can be an effective tool for estimating summer low flows from ungauged streams.

Endnote

1. Specifications accessed Apr. 18, 2012; www.tracomfrp.com/montana.htm.

Literature Cited

Andreassian, V. 2004. Waters and forests: from historical controversy to scientific debate. *J. Hydrol.* 291(1–27).

Bergström, S. 1976. Development and application of a conceptual runoff model for Scandinavian catchments. PhD thesis, Lund University, Lund, Sweden. *SMHI Reports RHO* No. 7, Norrköping.

Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby, and T.D. Hofstra. 1987. Stream temperature and aquatic habitat: Fisheries and forestry interactions. P. 191–232 in *Streamside Management: Forestry and Fisheries Interactions*, Salo, E.O., and T.W. Cundy (eds.). University of Washington, Institute of Forest Resources Contribution No. 57.

Bosch, J.M., and J.D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *J. Hydrol.* 55:3–23.

Bransom, M. 1996. Geohydrologic conditions on a steep forested slope: modeling transient piezometric response to precipitation. PhD dissertation, Oregon State University, Corvallis, OR. 179 p.

Brown, G.W., and J.T. Krygier. 1970. Effects of clear-cutting on stream temperature. *Water Resour. Res.* 6(4): 1133–1139.

Brutsaert, W., and J.L. Nieber. 1977. Regionalized drought flow hydrographs from a mature glaciated plateau. *Water Resour. Res.* 13:637–643.

Fedora, M.A., and R.L. Beschta. 1989. Storm runoff simulation using an antecedent precipitation index (API) model. *J. Hydrol.* 112(1–2):121–133.

Hall, F.R. 1968. Base flow recessions–A review. *Water Resour. Res.* 4(5):973–983.

Harr, R.D., and J.T. Krygier. 1972. Clearcut logging and low flows in Oregon coastal watersheds. Oregon State University, School of Forestry, Research Note No. 54. 3 p.

Hewlett, J.D., and A.R. Hibbert. 1963. Moisture and energy considerations within a sloping soil mass during drainage. *J. Geophys. Res.* 64:1081–1087.

Hicks, B.J., R.L. Beschta, and R.D. Harr. 1991. Long-term changes in streamflow following logging in western Oregon and associated fisheries implications. *Water Resour. Bull.* 27(2): 219–226.

Ice, G.G. 2008. Stream temperature and dissolved oxygen. P. 37–54 in *Hydrological and Biological Responses to Forest Practices*, Stednick, J.D. (ed.). Springer, New York.

Johnson, S.L., and J.A. Jones. 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. *Can. J. Fish. Aquat. Sci.* 57(Suppl. 2):30–39.

KEPPELER, E.T., AND R.R. ZIEMER. 1990. Logging effects on streamflow: water yield and summer low flows at Caspar Creek in northwestern California. *Water Resour. Res.* 26(7): 1669–1679.

KIBLER, K. 2007. The influence of contemporary forest harvesting on summer stream temperatures in headwater streams of Hinkle Creek, Oregon. M.S. thesis, Oregon State University, Corvallis, OR. 98 p.

LANGBEIN, W.E. 1938. Some channel storage studies and their application to the determination of infiltration. *EOS Trans. Am. Geophys. Union*. 19:435–447.

LEVNO, A., AND J. ROTHACHER. 1967. Increases in maximum stream temperatures after logging in old-growth Douglas-fir watersheds. USDA Pacific Northwest Forest and Range Experiment Station Research Note, Report No. PNW-85. 12 p.

LEVNO, A., AND J. ROTHACHER. 1969. Increases in maximum stream temperatures after slash burning in a small experimental watershed. USDA Pacific Northwest Forest and Range Experiment Station Research Note PNW-110. 7 p.

MARKLE, J.M., AND R.A. SCHINCARIOL. 2007. Thermal plume transport from sand and gravel pits–potential thermal impacts on cool water streams. *J. Hydrol.* 338:174–195.

MARTINEC, J. 1975. Snowmelt-runoff model for streamflow forecasts, *Nord. Hydrol.* 6(3): 145–154.

MEISNER, J.D., J.S. ROSENFELD, AND H.A. REGIER. 1988. The role of groundwater in the impact of climate warming on stream salmonines. *Fisheries* 13(3):2–8.

MOORE, D. 1997. Storage-outflow modeling of streamflow recessions, with application to a shallow-soil forested catchment. *J. Hydrol.* 198:260–270.

MOORE, R.D., D.L. SPITTLEHOUSE, AND A. STORY. 2005. Riparian microclimate and stream temperature response to forest harvesting: A review. *J. Am. Water Resour. Assoc.* 41(4):813–834.

NATIONAL RESOURCES CONSERVATION SERVICE (NRCS). 1994. *Soil survey of Douglas County Area, Oregon.* National Cooperative Soil Survey Publication, USDA. 935 p. Available online at soils.usda.gov/survey/online_surveys/oregon/; last accessed Jan. 5, 2010.

NATHAN, R.J., AND T.A. MCMAHON. 1990. Evaluation of automated techniques for base flow and recession analysis. *Water Resour. Res.* 26(7):1465–1473.

OREGON DEPARTMENT OF FORESTRY. 2007. Oregon Forest Practices Ace Water Protection Rules: Riparian Management areas and Protection Measures for Significant Wetlands. Oregon Administrative Records Chapter 629, Division 635 and 645, Oregon Department of Forestry, Salem, Oregon.

OTIS, T. 2007. Processes that influence the downstream propagation of heat in streams below clearcut harvest units: Hinkle Creek paired watershed study. M.S. thesis, Oregon State University, Corvallis, OR. 54 p.

POOLE, G.C., AND C.H. BERMAN. 2001. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. *Environ. Manage. (N.Y.)* 27(6):787–802.

RANTZ, S.E. 1982. Measurement and computation of streamflow: Vol. 1. Measurement of stage and discharge. US Geological Survey Water-Supply Paper No. 2175. 313 p.

REES, H.G., M.G.R. HOLMES, A.R. YOUNG, AND S.R. KANSAKAR. 2004. Recession-based hydrological models for estimating low flows in ungauged catchments in the Himalayas. *Hydrol. Earth Syst. Sci.* 8(5):891–902.

ROTHACHER, J. 1970. Increases in water yield following clearcut logging in the Pacific Northwest. *Water Resour. Res.* 6(2):653–658.

SNYDER, F.F. 1939. A Concept of Runoff-Phenomena. *Eos Trans. Am. Geophys. Union* 20:725–738.

SINOKROT, B.A., H.G. STEFAN, J.H. MCCORMICK, AND J.G. EATON. 1995. Modeling of climate change effects on stream temperatures and fish habitats below dams and near groundwater inputs. *Clim. Change* 3:181–200.

STEDNICK, J. 2008. Effects of timber harvesting on streamflow in the Alsea Watershed Study. P. 19–36 in *Hydrological and Biological Responses to Forest Practices*, Stednick, J.D. (ed.). Springer, New York.

TALLAKSEN, L.M. 1995. A review of baseflow recession analysis. *J. Hydrol.* 165:349–370.

TOEBES, C., AND D.D. STRANG. 1964. On recession curves, 1—recession equations. *J. Hydrol.* 3(2):2–15.

TROCH, P.A., P. DE TROCH, AND W. BRUTSAERT. 1993. Effective water table depth to describe initial conditions prior to storm rainfall in humid regions. *Water Resour. Res.* 29(2):427–434.

UNITED STATES GEOLOGIC SURVEY (USGS). 2010. Surface water daily statistics. Available online at waterdata.usgs.gov/nwis/sw; last accessed Nov. 1, 2010.

WARD, J.V. 1985. Thermal characteristics of running water. *Hydrobiol.* 125:31–46.

WELLS, R.E., A.S. JAYKO, A.R. NIEM, G. BLACK, T. WILEY, E. BALDWIN, K.M. MOLENAAR, K.L. WHEELER, C.B. DUROSS, AND R.W. GIVLER. 2000. Geologic Map and Database of the Roseburg 30 x 60 Minute Quadrangle, Douglas and Coos Counties, Oregon. M. P. US Geological Survey, CA.

ZECHARIAS, Y.B., AND W. BRUTSAERT. 1988. Recession characteristics of groundwater outflow and base flow from mountainous watersheds. *Water Resour. Res.* 24(10):1651–1658.

ZILLGENS, B., B. MERZ, R. KIRNBAUER, AND N. TILCH. 2007. Analysis of the runoff response of an alpine catchment at different spatial scales. *Hydrol. Earth Syst. Sci.* 11:1441–1454.