Spatial and Temporal Runoff Response to Snowmelt, and the Influence of Geomorphology in a Headwater Catchment, Central Eastern Cascades, Washington.

By

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Title: Spatial and Temporal Runoff Response to Snowmelt, and the Influence of Geomorphology in a Headwater Catchment, Central Eastern Cascades, Washington.

Abstract Approved:

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Jeffrey J. McDonnell

This report presents a nested gauging study of streamflow variability from three sub-catchments (150-200 ha in area) of the Burns Creek catchment (565 ha) in the Entiat Experimental Forest of central Washington State. We test and reject the hypothesis that headwater catchments of this size are composed of physically and chemically homogenous sub-catchments with regard to the volume and timing of runoff generation. Our methods included sub-catchment distributed accounting of precipitation and snowmelt, nested gauging of flow, and electrical conductance measurement (EC) for water years 2005 and 2006. Our results showed that temporal and spatial contributions to streamflow varied widely among the sub-catchments. Over 50% of annual precipitation accumulated within the headwaters of the catchment, yet the highest elevation sub-catchment dominated streamflow only during the immediate melt season. Baseflow was otherwise maintained by discharge from the lowest elevation sub-catchment. Flow and EC data suggested groundwater dominated streamflow response to rainfall and snowmelt. Over 90% of stormflow in each of the monitored sub-catchments was comprised of pre-event water using the standard two-component hydrograph separation method. Annual runoff ratios and pre-event water contributions to streamflow increased with increasing basin area. Runoff ratios from the three sub-catchments and the headwater catchment as a whole were more uniform over the much wetter 2006 water year.

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1.0 Introduction

Paired-catchment comparisons and single-catchment studies have been cornerstones of hydrological research since the 1960s (Beven, 2006). Advances in our understanding of the water balance, sediment budgets, and hydrologic response to controlled treatments can all be attributed to methods of measuring catchment discharge at a point (Jones, 2000). However, studies in recent years have indicated that the dominant runoff processes vary widely in space *below* the headwater catchment scale, as defined by a single gauging station (McDonnell, 2003, McGlynn et al., 2004). The significance of streamflow heterogeneity below the headwater catchment scale is poorly understood and rarely considered in determining the appropriateness of a single chosen gauge location. It is critical to identify the extent to which sub-catchment processes act independently and in concert to produce the integrated runoff response ultimately recorded at the catchment outlet.

Field strategies that identify the variety of sub-catchment behaviors at work in headwater catchments are also needed to test theoretical concepts like the Representative Elementary Watershed (Reggiani et al., 1999, Sivapalan et al., 2003) and the Deterministic Length Scale (Seyfried and Wilcox, 1995). It is logical to begin these endeavors with research on spatial and temporal interactions between sub-catchment runoff generation processes (Seyfried and Wilcox, 1995). Existing experimental and paired catchments with a history of hydrologic research provide a logical starting point for this research.

This paper examines within-catchment flow characteristics and tracer components from nested gauges at the Burns Creek headwater catchment in central Washington State,

USA. We test the null hypothesis that a headwater catchment defined by a single gauge is composed of sub-catchments with physically and chemically homogenous traits. Our overall objective is to develop physical characterizations of several sub-catchments, and relate these to the sequencing of runoff generation in time and space over two water years.

Few studies have used longitudinal gauging to associate seasonal runoff patterns with elements of geomorphic variability below the headwater catchment scale (Huff et al., 1982, Kobayashi et al., 1999, Portman, 2003). We identify the source, timing and quantity of runoff from each sub-catchment, and relate these to the overall water balance and runoff response of the headwater catchment. This work attempts to identify sub-catchment units that are more disposed to the capture and storage of water, and those with more efficient flow routing and yield. The nested delineation of sub-catchment responses offers insight into the synthesis of heterogeneous runoff mechanisms into a signal captured at the catchment outlet.

2.0 Study Site: The Entiat Experimental Catchments

2.1 Location and context

The experimental catchments of the Entiat Experimental Forest (EEF) are situated approximately 70 km northwest of Wenatchee, WA, in the 440 km^2 Entiat River basin, itself a tributary of the Columbia River (Figure 1). The EEF consists of three headwater catchments: Fox (474 ha), Burns (565 ha), and McCree (513 ha) (Figure 1). The catchments were first instrumented in 1959 to study the effects of forest harvest on

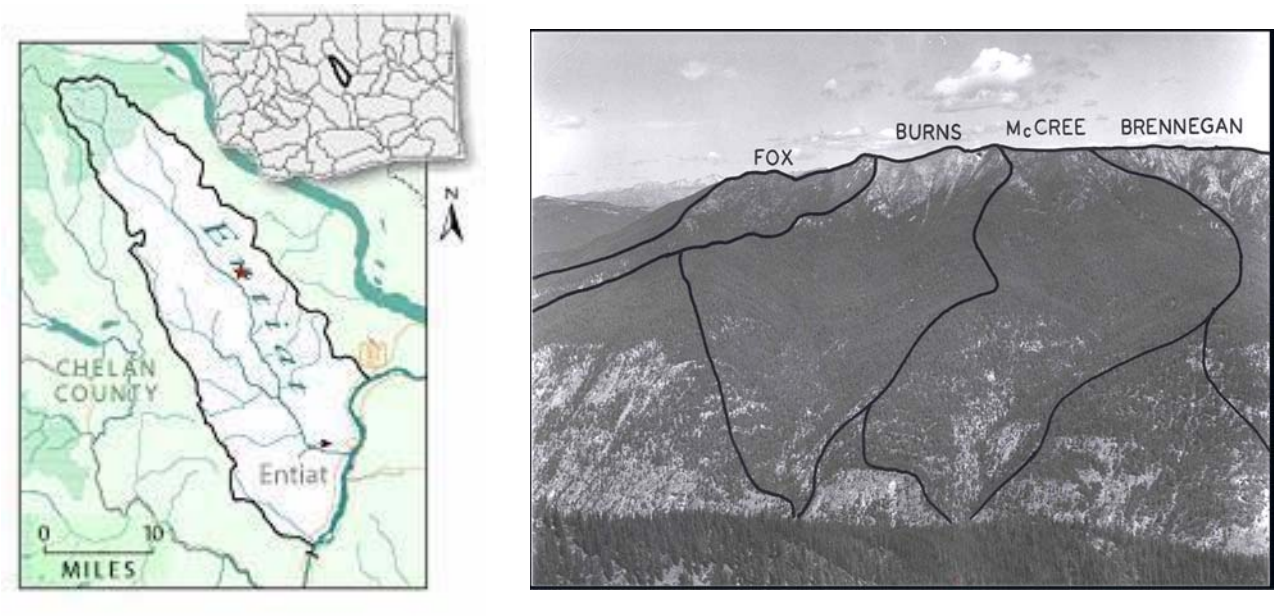

Figure 1: The Entiat River basin with Burns Creek catchment denoted by star (left). The Burns Creek catchment and neighboring catchments of the Entiat Experimental Forest, prior to the 1970 wildfire (right).

streamflow timing, quality and quantity from dry-climate forests of the east-Cascades (Helvey et al., 1976).

After a calibration period of ten years, all three catchments were burned severely by wildfire in August of 1970. The focus of study was shifted to monitor the effects of the fire, with additive treatments of salvage logging and aerial seeding of grass for erosion control in the Burns and McCree catchments (Tiedemann and Klock, 1973). Sediment export, peak flows and base flows from all three catchments were markedly increased after the fire. Observed increases in discharge were attributed to decreased soil moisture deficits in the absence of evapotranspiration (Helvey, 1980). Debris flows in 1972 destroyed the v-notch weirs in Fox and McCree catchments. Despite the replacement of those weirs with Parshall flumes, official hydrologic monitoring of all three catchments ceased from 1977-2003. A summary of hydrologic conclusions from work in the EEF was presented by Helvey (1980).

The Burns Creek catchment received the most extensive experimental treatment following the fire, with roads constructed, trees salvage-logged, and grass seed aerially applied as an erosion control method (Tiedemann and Klock, 1973). McCree Creek was similarly treated, while Fox Creek was left as a control. Burns Creek has been the primary focus of re-instrumentation in the EEF beginning in 2003 because of the survival of the original weir, the continuity of data before and after wildfire, and generally good access to the catchment.

2.2 The Burns Creek catchment

The Burns Creek headwater catchment is the largest EEF catchment at 565 hectares. Elevation ranges from 800 m at the weir to 2,200 m, with a median of 1,400 m. The weir itself is positioned 300 m above the floor of the Entiat River Valley along the margin of a lateral moraine. Catchment slope aspects are 30% western, 20% southern, 30% southeastern, and 20% southwestern. Hillslope gradients within the gauged catchment generally range from 40% to 60%, but frequently exceed 100% adjacent to the stream channel. The gradient of the stream channel itself averages 24%. (More details about the catchment are provided in Table 1 on page 17.)

Exposed bedrock, deep, coarse-grained soils, and high relief influence flow routing and water storage in the Burns catchment. The drainage density of the catchment was reported as 1.29 km/km^2 by Helvey et al. (1976). A more accurate estimate of this figure, taking into account 4,400 m of perennial channel only, may be 0.76 km/km^2. An estimated 2,200 m of bedrock and talus-filled channel above 1,600 m elevation flows only during snowmelt. Summer baseflow is maintained by a number of

perennial springs. These are common in the catchment at every elevation, and many of them issue from fractured rock at grade with the stream channel. Others are located high on side slopes, forcing abrupt transitions between arid upland soils and moist riparian potholes.

2.2.1 Geology, geomorphology and soils

The dominant bedrock of the Burns catchment is Eocene series biotite-granite and granodiorite, with intrusions of fractured rhyolite (Tabor et al., 1987). Bedrock exposures are common at high elevations in Burns Creek, with Frog Rock as a particularly prominent example (Figure 2, left). The bedding plane of these features consistently strikes northeast-southwest and dips northwest at approximately 65°. Bedrock exposures lower in the catchment also exhibit this orientation, most notably along road cuts and at a series of waterfalls 200 m upstream from the weir.

Extensive glaciation occurred in the Entiat River basin during the Peshastin and Leavenworth stages of the late Pleistocene epoch (10-20,000 years ago). Glaciers 80 km in length left lateral moraines 750 meters above the river valley, and terminal moraines near Potato Creek and the town of Ardenvoir, 24 km down-valley from the EEF (Long, 1951). Evidence of glaciation in the Burns Creek catchment can be observed in several places. Broad deposits of glacial till and debris flow outwash along Burns Creek indicate an upper bound of glacial activity above the road-stream crossing at elevations of 1,220-1,280 m. Below the road-stream crossing, scoured, canyon-like geomorphology is typified by abrupt slope shifts, shallow depth to bedrock at drainage divides and bedrock

Figure 2: Frog Rock and a mid-slope spring that initiates flow in Burns Creek tributary, 2005 (left). Vegetation is regenerating pine in the foreground and ceanothus at higher elevations. Depth of view in the left photo is approximately 1 km. The Burns Creek catchment soon after the 1970 wildfire, with main access road and incised geomorphology in the foreground (right). Frog Rock is visible along the catchment boundary on the upper left.

stream reaches with multiple waterfalls and poorly developed riparian areas (Figure 2, right). Glaciofluvial deposits at lower elevations of the Burns catchment have been weathered and largely obscured by ashfall and colluvial erosion (Helvey et al., 1976).

Soils in the Burns catchment are residual, granite-derived, coarse sandy loams, inter-bedded with blankets of pumice and ash from eruptions of Glacier Peak and Mt. Mazama (Helvey et al., 1976, Tabor et al., 1987). Drainage rates are moderate to excessive (2-6 cm/hr, and 13-25 cm/hr respectively), owing to the high percentage of pumice incorporated into surface horizons (McColley, 1976). Most of the catchment consists of mildly dissected side-slope morphology, with very long slope lengths before convergence.

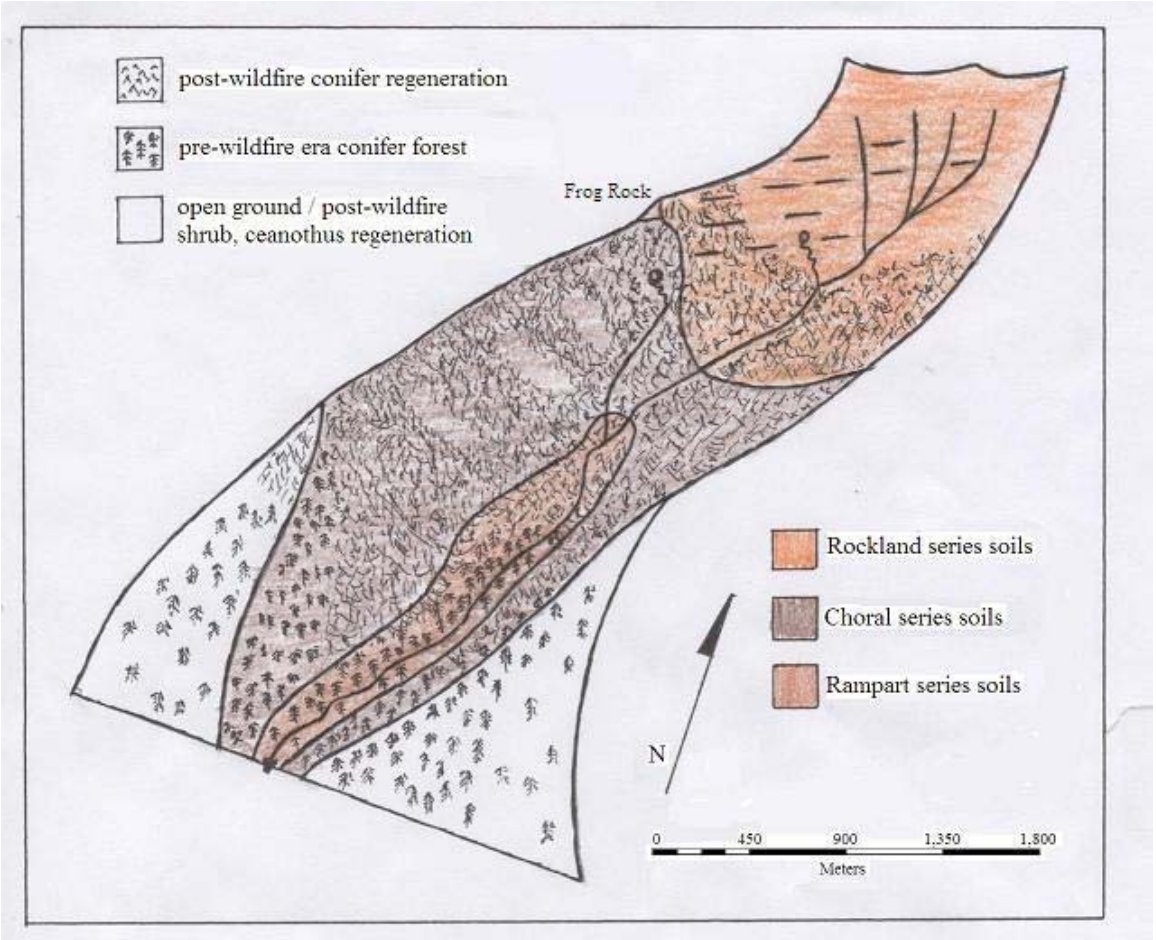

Figure 3: Soils and vegetation of the Burns Creek headwater catchment (adapted from McColley, 1976 and 2003 aerial photographs).

Choral, Rampart, and Rockland series soils are described by Helvey et al. (1976). Choral soils (Figure 3) are prevalent at mid elevations, with depths of three meters. Mid-elevation soils are also characterized by till and bedrock parent material, with high transmissivity at the soil-till interface, and high soil water storage potential (McColley, 1976). The highest elevations of the Burns catchment feature abundant rock outcrops and Rockland soils, estimated to be less than two meters thick (Figure 3). These profiles form from parent material in place and drain rapidly with comparatively low soil storage capacity. Rampart soils occupy steeply incised slopes above the stream channel in the

lower catchment. They are the least developed soils, but are also deep, owing to colluviation and pumice deposition. These soils form over glacial till in low slope positions, with high drainage and susceptibility to slipping (McColley, 1976).

2.2.2 Climate and vegetation

Catchments east of the Cascade Crest experience a pronounced rain shadow effect, warmer summer temperatures, colder winter temperatures and less seasonal cloud cover than catchments west of the Crest. Precipitation in the EEF catchments averages only 60 cm/yr at 900 m elevation (Helvey et al., 1976). As much as 70% of the yearly precipitation in the EEF catchments falls as snow. Seasonal snowpack begins to accumulate as early as October, but elevations below 900 m may alternately receive snow or rain in winter months.

The vegetation of the Burns catchment is well-adapted to moisture deficits during the growing season. Ponderosa pine, Douglas-fir, and lodgepole pine exchange dominance along elevation and aspect gradients in response to water deficits. Ponderosa pine is particularly well-adapted to low elevations of the catchment, where soils range in depth, but are uniformly arid. The range of Douglas-fir is restricted, occurring between 1,500-2,000 m of elevation where moisture is adequate and slopes are protected from extreme weather. Lodgepole pine is most prevalent above 2,000 m. Ceanothus, bitterbrush, and grass species occur at all elevations, and are currently the dominant species above 1,700 m elevation, where trees have colonized slowly since the 1970 wildfire (Helvey et al., 1976). A contingent of pre-wildfire-era mixed ponderosa pine,

Douglas-fir and western redcedar forest remains in low elevation, protected portions of the catchment (Figure 3).

Aside from these tree and shrub species, which occupy nearly 90% of the total catchment area, riparian vegetation is a key indicator of concentrated moisture in the catchment. Willow and ash are extremely competitive with conifers where moisture is abundant, and consequently, springs, seeps, and areas of upslope moisture concentration are surrounded by patches of these species (Figure 2). Similarly, when flow originating from a spring is re-absorbed into the soil, there may be a visible transition of willow and ash to dry scrub and tree species longitudinally down slope.

3.0 Methods

3.1 Sub-catchment delineation

Prior to 2003, the only stream gauging structure in the Burns Creek catchment was a 120° v-notch weir. This structure had been un-monitored for approximately 25 years after the 1970 wildfire and weir-destroying debris flows in the neighboring EEF catchments. The Burns creek weir and Fox and McCree Creek flumes were re-instrumented in 2003.

Longitudinal sampling for flow increases and anomalous electrical conductance (EC) of water was conducted upstream of the Burns Creek weir on consecutive days in April 2004. Dilution gauging was used as a means of identifying hydrologic contributions in remote portions of the headwater catchment. “Slug” dilution methods were adapted to measure reach discharge using a YSI 550 handheld probe and table salt as a tracer (Hudson and Fraser, 2002, Moore, 2005). Flow gains were associated with the

occurrence of springs in the catchment, but these sources were often diffuse and difficult to quantify with the dilution gauging approach. The most significant flow-gaining reach of Burns Creek bracketed the junction of Burns Creek and its tributary (Figure 4). Significant differences in baseline EC and flow per unit area between the upper and lower portions of the Burns catchment appeared to result from the influence of the tributary northwest of the main channel. This prompted the division of the Burns Creek catchment into 'headwaters', 'canyon' and 'tributary' sub-catchments for investigation of within-catchment seasonal flow contributions (Figure 4). This division emphasized the geomorphic variability between the three sub-catchments, and was intended to capture the temporal variability of snowmelt and groundwater contributions to flow over the course of the year.

3.2 Discharge gauging

Parshall flumes and/or stage monitoring devices were installed at four locations in April and May of 2004 (Figure 4, left). Three-inch (7.6 cm) Parshall flumes were installed in Burns Creek above and below the tributary junction. A Tru-Track, Inc. (model WT-HR 64K) capacitance rod was placed at a culvert above the mouth of the tributary, and a one-inch (2.5 cm) Parshall flume was placed beneath the spring at the head of the tributary. In autumn of 2005, Forest Service personnel installed one six-inch (15.2 cm) Parshall flume upstream, and one nine-inch (22.9 cm) Parshall flume downstream of the 7.6 cm flumes installed in 2004 (Figure 4, right). These larger flumes proved critical for accommodating the peakflows of the 2006 melt season after both of the 7.6 cm flumes were breached.

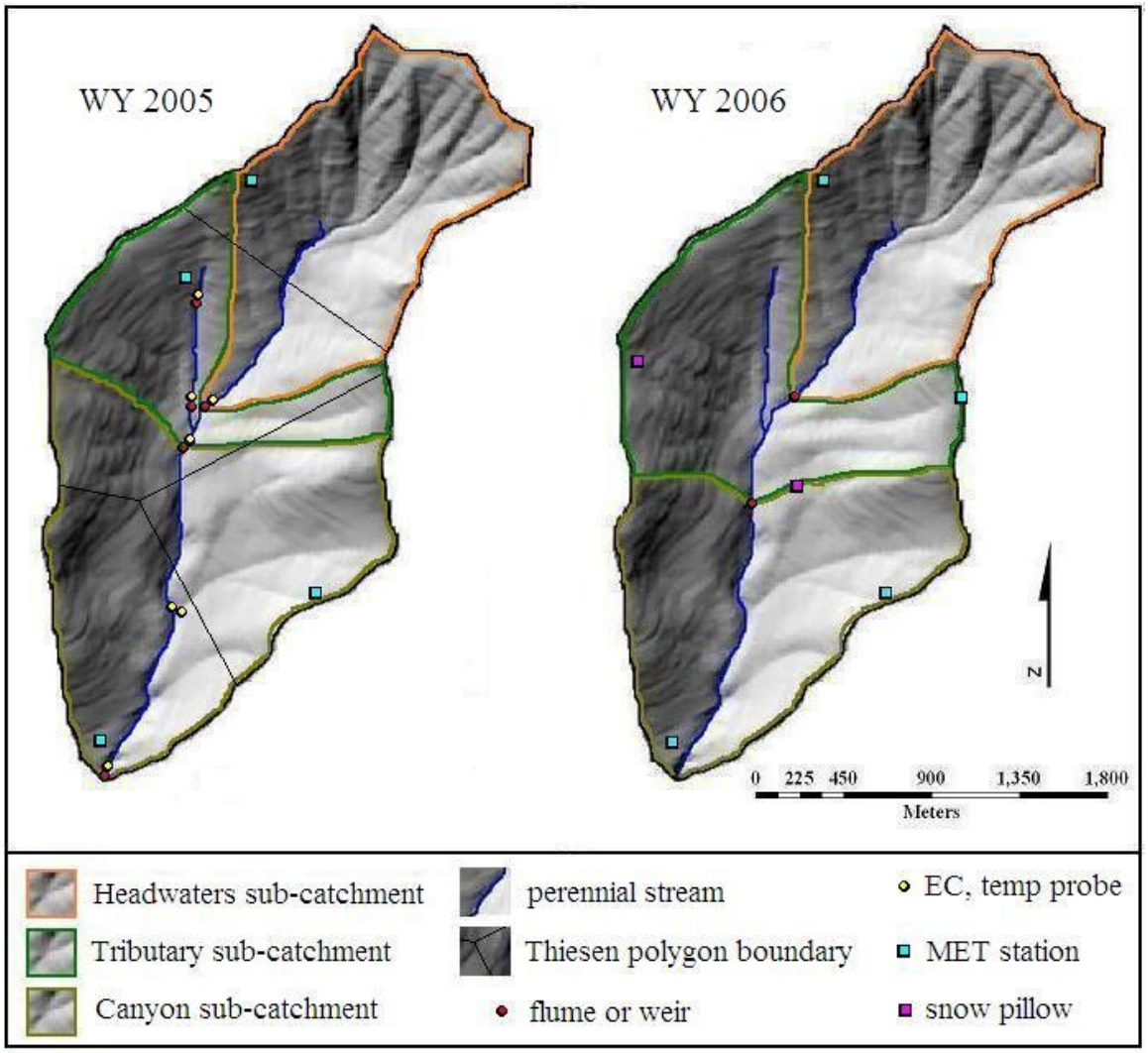

Figure 4: Sub-catchments and instrument configuration within the Burns Creek catchment. Thiessen polygons were used for WY 2005 only. Only MET and snow pillow stations used for energy balance and WAR variable calculation are shown for WY 2006. Flumes and EC gauges installed in WY 2005 were used both years, but are shown once for simplicity. HOBO stream temperature probes (densely deployed) are not shown.

Stage height was recorded from April 2004 to August 2006 with a combination of sensors: Global, Inc. pressure transducers (measuring stage +/- 0.31 mm (0.01 ft)), HOBO, Inc. sealed barometric pressure transducers (measuring pressure +/- 0.001 kPa), Tru-Track, Inc. capacitance rods (measuring stage +/- 1.0 mm) and Aqua Rods (measuring stage +/- 1.0 mm) were all used at some point. Stage was converted to L/s

and mm/day discharge using ISCO, Inc. in-channel flow measurement discharge tables (Grant, 1995) for the Parshall flumes, and Manning's equation for flow through a culvert measured with the capacitance rod.

Runoff contributions (area-adjusted discharge) from the sub-catchments of Burns Creek for the 2005 and 2006 water years were calculated from combinations of nested flume and weir data. Runoff from the canyon sub-catchment was determined by subtracting flow at the lower 7.6 cm Parshall flume from flow at the Burns Creek weir. Runoff from the headwaters sub-catchment was measured directly by the upper 7.6 cm Parshall flume. Runoff from the tributary sub-catchment was determined by subtracting flow at the upper flume from flow at the lower flume. Tributary runoff was corroborated using discharge measured at the culvert. Lastly, runoff from the tributary spring was determined directly from discharge through the 2.5 cm Parshall flume. Runoff for the melt season of 2006 was calculated similarly, but relied on data from the large-diameter flumes, and was adjusted for the relevant changes in drainage area (Figure 4, right).

Stage data records at the Burns Creek weir and at the lower 7.6 cm Parshall flume required no major adjustments during the study period. Most of the other stage sensors, however, recorded some periods of erroneous data. The entire discharge record from November 2004 until the beginning of melt in April 2005 at the upper Parshall flume (headwaters sub-catchment) was reconstructed from data collected at the lower flume due to equipment malfunction. This was accomplished using separate linear regression equations for baseflow and melt periods after reliable data had been collected at both flumes over the course of water year 2006. Other flow data corrections were necessary

due to clogging of the 2.5 cm flume, short-term spikes, and the eventual washing out of the two 7.6 cm Parshall flumes in April 2006.

3.3 Precipitation gauging

Meteorological (MET) stations were installed at 850 m, 1,130 m, and 1,700 m elevations in May of 2004, and snow pillow sites were installed at 1,220 m and 1,580 m elevations in October of 2004. MET stations equipped with HOBO, Inc. sensors recorded air temperature (+/- .1°C), humidity (+/- .1%), precipitation (+/- .254 mm), wind velocity (+/- .1 m/s), and in some cases, wind direction (+/- 1° azimuth) and net solar radiation (Li-Cor sensor, +/- .01 w/m^2), at fifteen or thirty minute intervals. Snow pillow sites equipped with HOBO and Schavetiz sensors recorded air temperature (+/- .1°C), total precipitation (+/- .254 mm), snow water equivalence (+/- .1 mm) and snow depth (+/- 1 mm) at 60 minute intervals. MET station data were used in this study to monitor general weather patterns, measure precipitation amounts, and determine whether precipitation fell as rain or snow based on air temperature and dew points.

Rainfall data collected at each MET station were distributed with the standard Thiessen polygon method (Dingman, 2002) (Figure 4, left). Elevation banding of precipitation was considered, but there was poor correlation between the elevation of the gauges and the amount of precipitation observed at MET sites. Data from an additional tipping bucket at the tributary source was unreliable for the spring of 2005 due to clogging with tree pollen. Data from that instrument was removed from the analysis.

Precipitation data for the 2006 water year was augmented with sub-catchment-distributed daily water available for runoff (WAR) from a spatially distributed energy

balance snowmelt model (Mazurkiewicz 2006). These modeled data quantified the depth equivalent of snowmelt water added to the catchment each day, and regionalized snow ablation data from the snow pillow sites and climate data from four MET stations (one in McCree Creek catchment) (Figure 4, right). The regionalized data were especially useful for accounting of precipitation-runoff relations in snow-dominated WY 2006. Tipping bucket data were compared with the modeled data in 2006, but were not used for data analysis because of severe under-catch of precipitation during the winter.

3.4 Environmental tracers

Stream temperature and EC were monitored as naturally occurring, economical tracers for purposes of hydrograph separation. Seven Campbell Scientific EC/temperature probes (+/- .001 mS/cm^3, +/- .1°C) and 25+ HOBO submersible temperature probes (+/- .1°C) were installed along the main stream and tributary, and at selected springs (Figure 4). Sensors recorded data at fifteen minute (Campbell) or thirty minute (HOBO) intervals to capture the range of signal variability, diurnal and seasonal fluctuation, and to indicate threshold behaviors triggered by rain or snowmelt events.

The hydrograph separation method of Sklash and Farvolden (1979), involving the division of stream water chemical or isotopic signals into pre-event and event water components, was used as an indication of sub-catchment flow source contributions:

$$CtQt = CpQp + CeQe \qquad (1)$$

where Qt was stream discharge, Qp was volume of pre-event water, Qe was volume of event water, and Ct, Cp, and Ce were specific conductivities of stream, pre-event and event waters. The fractional contribution of pre-event water was computed assuming that

baseflow and precipitation EC were significantly different, and each remained constant throughout the duration of the storm. Prior to each storm, background EC levels were low and fairly constant, and it was assumed that the pre-event EC signal of the stream was equal to groundwater or soil water inputs. Rainfall EC was assumed to be 0.000 mS/cm^3 for all storms. The hydrograph separation was ceased once EC had returned to pre-event levels. In some cases, this was necessary to prevent "baseflow" from exceeding total streamflow due to the effect of elevated EC signals at the tail end of storms.

4.0 Results

4.1 Geomorphic delineation of sub-catchments

Figure 5 shows the orientation of the headwaters, tributary, and canyon sub-catchments and geomorphic characteristics of the Burns catchment mapped during longitudinal sampling in 2004. Slopes in the headwaters sub-catchment ranged from 35-60% near the stream channel, but exceeded 200% on bedrock outcrops and in areas sculpted by mass wasting (Table 1, Figure 5, A) Perennial streamflow was initially thought to originate beneath accumulated debris and colluvial deposits at the base of the uppermost bedrock headwalls (Figure 5, B). Closer inspection revealed that summer low-flows were generated largely by two springs on east-facing side slopes, 50 meters uphill from the main channel (Figure 5, C). A number of other bedrock associated springs at grade with the stream contributed flow from west-facing aspects (Figure 5, D). Geomorphic influences to the headwaters sub-catchment also included shallow soils, laterally intrusive bedrock at high elevations(Figure 5, I), and braided stream channels on

top of glaciofluvial and debris slide deposits (Figure 5, E). The headwaters portion of the catchment had the highest drainage density of the three sub-catchments (Table 1), but at least half of the drainages were above the influence of perennial springs and were dry during times of the year that the area could be accessed (Figure 5, A, B).

Slope gradients of the tributary sub-catchment were about 50% on average (Figure 5, F). The tributary channel was less than one meter wide and was incised up to one meter into fine-grained alluvial sediments. The channel clearly did not experience the magnitude of high flows associated with channel shaping events in the headwaters or

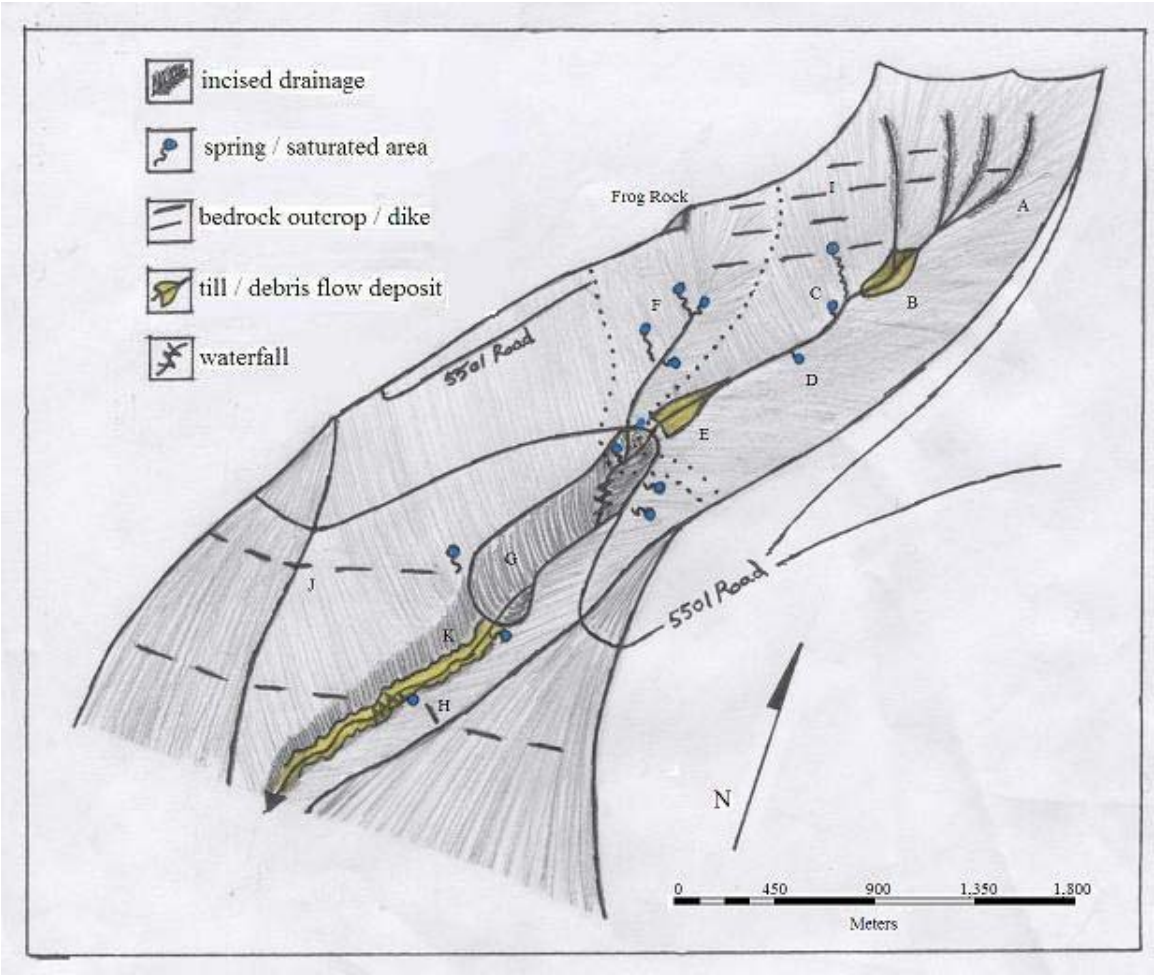

Figure 5: Geomorphic rendering of the Burns Creek headwater catchment, EEF, WA.

Table 1: Geographic characteristics of the Burns Creek sub-catchments.

	Canyon sub-catchment		Tributary sub-catchment		Headwaters sub-catchment		Burns Creek whole-catchment	
	WY 2005	WY 2006	WY 2005	WY 2006	perennial	ephemeral	perennial	ephemeral
Area (ha)	294	242	105	157	184	184	583	583
Channel length (m)	1,610	1,510	1,440	1,540	1,370	3,600	4,420	6,650
Drainage density (km/km2)	0.55	0.62	1.37	0.98	0.74	1.96	0.76	1.14
Channel elevation range (m)	800 to 1210	800 to 1135	1210 to 1460	1135 to 1460	1250 to 1610	1610 to 2000	800 to 1610	800 to 2000
Average channel gradient (%)	25	22	17	21	26	108	24	24
Hillslope aspect	30% W 20% SW 50% ESE		35% W 20% S 45% ESE		40% W 40% S 20% SW		30% W 23% S 20% SW 27% ESE	
Drainage area elevation range (m)	800 to 1650		1210 to 1780	1135 to 1780	1280 to 2175		800 to 2175	
Avg. distance, ridge to channel (m)	720		700		880	400	750	600
Avg. elevation, ridge to channel (m)	350		280		470	335	370	320
Average hillslope gradient (%)	49		50		64	64	50	50

canyon sub-catchments. Side slope colluviation appeared to be the dominant geomorphic process occurring in the sub-catchment, including reaches partially buried by logging slash from the 1970's, and segments where streamflow was subsurface, but where flow was still audible. Flow in the tributary originated from springs on east-facing slopes (Figure 5, F). The riparian corridor was more developed in the tributary sub-catchment than elsewhere in the catchment, but an abrupt boundary was usually present between riparian and upland characteristics. The drainage density of the sub-catchment was high (Table 1), but there was comparatively little fluctuation in stream stage or discharge from the tributary during any period of field observation.

The canyon sub-catchment of Burns Creek featured high gradient reaches with minimal riparian corridor development (Figure 5, K). Slopes intersecting this portion of the stream were up to a kilometer in length and ranged in elevation from 820 to 1,650 meters. Side slope gradients were 49% on average, but steepened to 100% or more near the active channel. The coarse texture and relatively poor cohesion of soils in the canyon

left slopes prone to constant geomorphic adjustment of angle of repose and profile depth. In one place, a recent slide scarp adjacent to the stream exposed subsoil consisting of two meters of continuous pumice (Figure 5, G). The horizon, though well consolidated, was largely un-weathered and crumbly to the touch. Active channel drainage density of the canyon sub-catchment was only .55 km/km^2. Visible flow contributions to the channel were limited to bedrock-associated springs at grade with the stream. These appeared to drain topographically defined regions of west-facing slopes only (Figure 5, H).

4.2 Water year 2005

4.2.1 Precipitation accumulation

The beginning of water year 2005 followed a summer of average precipitation in the Entiat and Chelan River basins (NRCS, 2006). A series of low-precipitation, warm-temperature storms over the winter resulted in 235 mm of cumulative precipitation recorded by tipping buckets in the Burns catchment as of May 15, 2005 (Figure 6). Burns Creek total precipitation for WY 2005 was 311 mm – only 54% of the long-term annual average of 580 mm from 1962-1970 (Helvey et al., 1976). Neither snow pillow site in the Burns catchment recorded useful data, and there was very little snow observed below 1,800 meters elevation during a field visit in February, 2005.

Snow depth and snow water equivalent (SWE) recorded 13 km northwest of the EEF at Pope Ridge SNOTEL site were only 30% of average for the 2005 winter (Figure 7). Cumulative precipitation measured at Pope Ridge was 635 mm - 66% of the long-term average (NRCS, 2006). 2005 was the lowest snow year on record in the Oregon and Washington Cascades since 1941 (Andalkar, 2006).

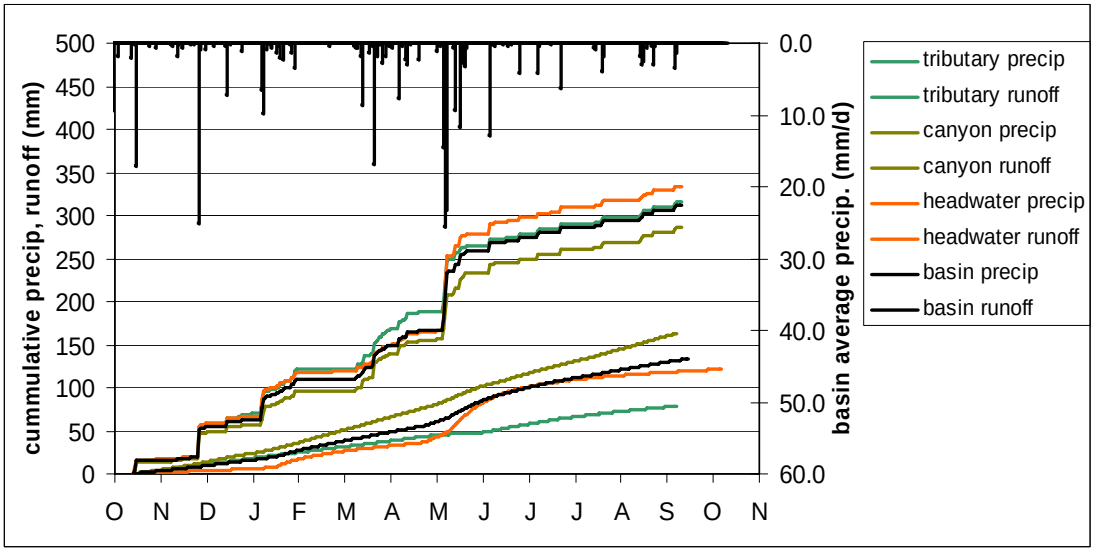

Figure 6: Water year 2005 cumulative precipitation and runoff, Burns Creek, WA.

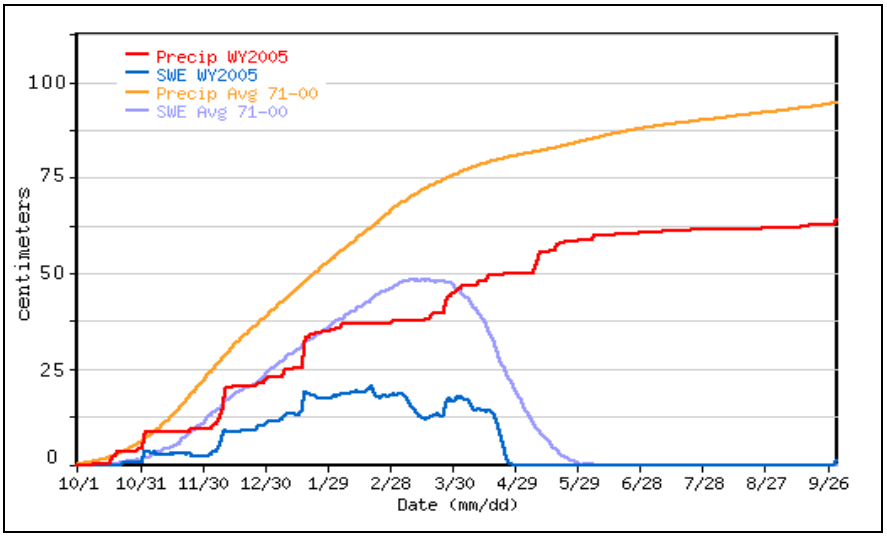

Figure 7: Water year 2006 cumulative precipitation and SWE at Pope Ridge, WA SNOTEL site (NRCS, 2006).

4.2.2 Sub-catchment responses to seasonal events

Two melt events were observed during the 2005 water year. The first of these occurred in mid January after a 15 day period of -10° C temperatures and snow accumulation (Figure 8). Air temperatures rose abruptly to approximately 10° C coincident with a rain event on January 17. The hydrograph at the weir and both main-

stem flumes reacted to the storm within the hour. Gauges then showed a flow recession from the storm followed seven days later by a much larger hydrograph rise indicative of snow melt. Catchment-wide runoff increased 0.15 mm/day for 4 days due to the January 17 rain storm. In comparison, catchment-wide runoff increased by 0.20 mm/day for 14 days due to the January 24 melt event, and baseflow was subsequently elevated by 0.15 mm/day for the duration of the winter.

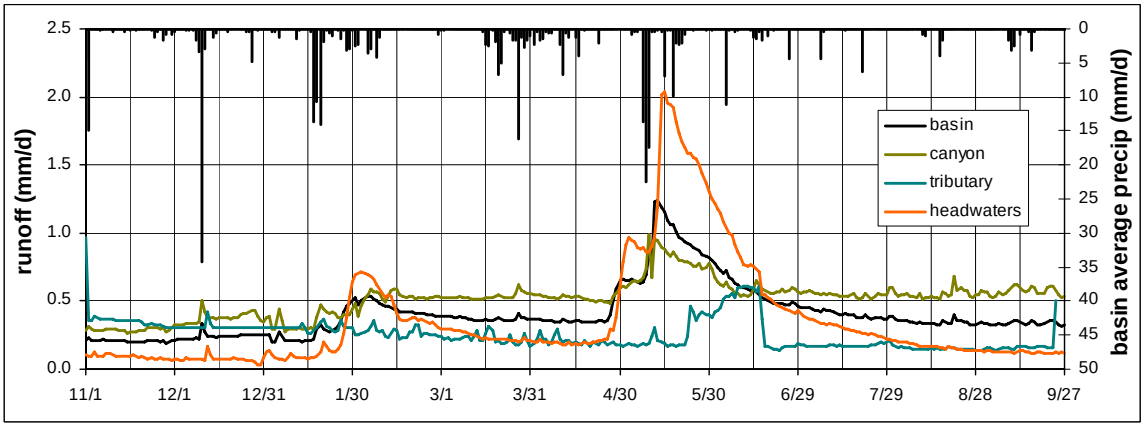

Figure 8: WY2005 precipitation and area-adjusted discharge from Burns Creek sub-catchments.

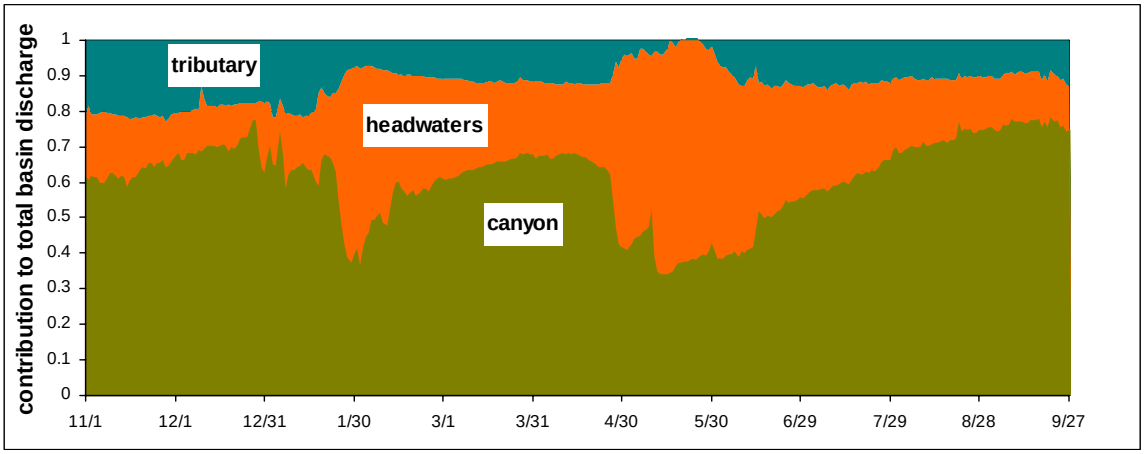

Figure 9: WY2005 sub-catchment contributions to daily-averaged discharge measured at Burns Creek weir (discharge not adjusted for sub-catchment area).

Each monitored sub-catchment reacted differently to the melt event beginning January 24. The headwaters sub-catchment reacted most strongly (Figure 8), with an immediate eight-fold increase in runoff, possibly due to significant snow water equivalent mobilized from near channel storage. The headwaters dominated flow contributions to the catchment from February 1-10 before a clear recession over the rest of the month (Figure 8). Baseflow from the headwaters sub-catchment remained at double the pre-melt rate through late April, 2005. The canyon sub-catchment hydrograph reacted less abruptly to the January melt event, reaching a maximum runoff condition on February 7 (Figure 8). This elevated hydrograph did not recede, and also remained at twice its pre-event baseflow through the end of April. Lastly, the Burns Creek tributary sub-catchment responded similarly to other catchments to the January 17 rain event, but was far less responsive to the melt event beginning seven days later. Flow in the tributary actually dropped steadily from February to late April, with periodic fluctuations from unknown causes.

From March 16 to April 15, 2005, the catchment reverted to colder conditions, and snowpack accumulated from major, late season storms blanketing much of the Cascade Range (Andalkar, 2006). Beginning on April 16, daytime highs moved steadily upward, reaching a maximum of 22°C on April 27. Over this eleven day period, temperatures did not fall below freezing, even at Frog Rock (elev. 1,700 m), and snow that was in the catchment became isothermal. The patterns of sub-catchment melt response described in January were repeated during the main melt period over the first two weeks of May (Figure 8). The headwater sub-catchment again responded quickly and peaked above 2 mm runoff per day. The canyon sub-catchment again increased in

Table 2: Rainfall-runoff characteristics of Burns Creek sub-catchments, WY 2005.

Total Precip Recorded from Nov. 1, 2004 to Sep. 30, 2005 and average daily precip.

whole basin	headwaters	trib spring	whole trib	canyon
311 mm	334 mm	343 mm	315 mm	286 mm
.93 mm/d	1.00 mm/d	1.03 mm/d	.94 mm/d	.86 mm/d

Total Runoff Recorded from Nov. 1, 2004 to Sep. 30, 2005 and average daily runoff

whole basin	headwaters	trib spring	whole trib	canyon
134 mm	121 mm	82 mm	79 mm	163 mm
.40 mm/d	.34 mm/d	.25 mm/d	.24 mm/d	.49 mm/d

Rainfall-runoff efficiency

whole basin	headwaters	trib spring	whole trib	canyon
44%	34%	24%	26%	57%

flow more gradually, and peaked with lower discharge per unit area. The tributary again produced a subdued hydrograph response, but it *did* respond promptly to a storm on May 9-11. The tributary sub-catchment hydrograph in Figure 8, which appeared to show a delayed peak response to snowmelt was partly caused by a response to the melt event and partly caused by debris in the flume. Precise dates for when the obstruction affected data could not be identified. The obstruction was removed on June 17, 2005.

The hydrograph recessions shown in Figure 8 also highlight differences between the three sub-catchments. There was clear evidence that the melt runoff response was dominated by the headwaters sub-catchment on the rising limb. However, the abrupt recession of the headwaters sub-catchment hydrograph to a post-melt level nearly as low as the pre-melt baseflow suggested a shortage of dynamic storage potential in the uppermost sub-catchment of the Burns Creek catchment. In contrast, the canyon sub-catchment did not respond as dramatically to the spring melt, but clearly sustained the baseflow condition of the catchment as a whole. Both rising and falling limbs of the

hydrograph for the canyon sub-catchment were consistent with deep-flowpath routing and a large potential storage reservoir. Low contributions from the tributary sub-catchment at all times of the year were also consistent with deep flowpath drainage from the sub-catchment or with un-requited storage deficits from previous summers.

Heterogeneity among sub-catchment contributions to discharge measured at the Burns Creek weir is evident in Figure 9. The headwaters sub-catchment clearly dominated discharge contributions during snowmelt events, whereas the canyon sub-catchment dominated discharge contributions to all non-peak periods of the year. Additionally, the tributary sub-catchment discharged nearly as much late summer baseflow as the headwater sub-catchment, even though the headwaters sub-catchment was twice the size.

Sub-catchment runoff ratios (defined as area-adjusted total annual discharge divided by total annual precipitation) are shown in Table 2. Disparities were especially evident between the canyon and headwaters sub-catchments. The headwaters sub-catchment accumulated 20% more precipitation per unit area over the course of WY 2005, had greater drainage density, shallower soils and exposed bedrock aspects, but the canyon sub-catchment ultimately produced 35% more annual runoff. Conversely, the tributary sub-catchment accumulated nearly the same depth of precipitation as the headwaters sub-catchment per unit area, but released 30% less annual runoff than the headwaters sub-catchment, and 50% less annual runoff than the canyon sub-catchment. Data recorded at the “tributary spring,” where flow in the tributary first appeared, indicated that overall annual runoff gauged at that point was consistent with flow from the tributary sub-catchment as a whole.

4.3 Water year 2006

4.3.1 Precipitation accumulation

The winter of 2006 provided a stark contrast to WY2005. Snowpack began to accumulate in the Burns Creek catchment and throughout the Cascades in late October. Frontal storms continued through January and February of 2006, ultimately depositing up

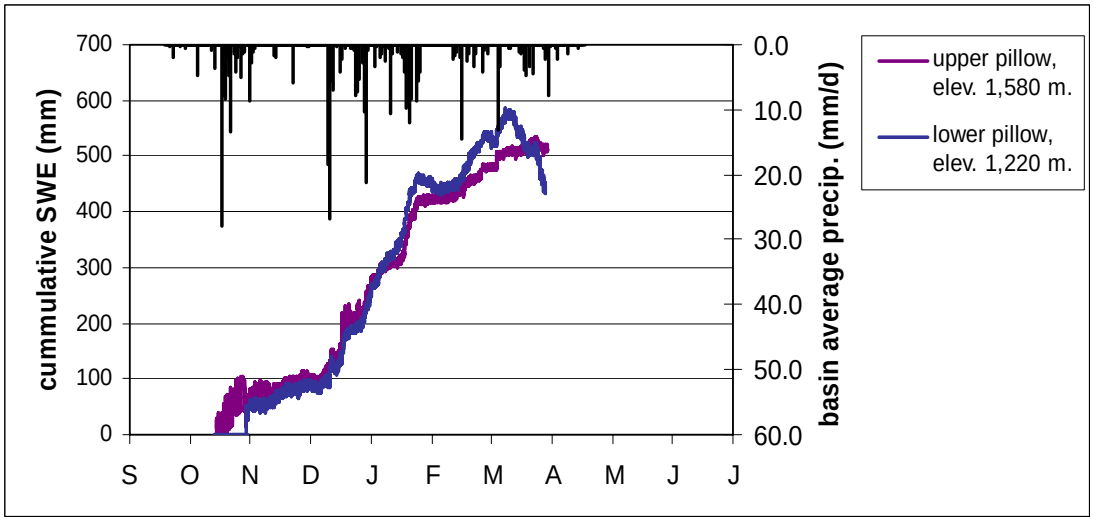

Figure 10: Water year 2006 precipitation events and SWE accumulation, Burns Creek, WA.

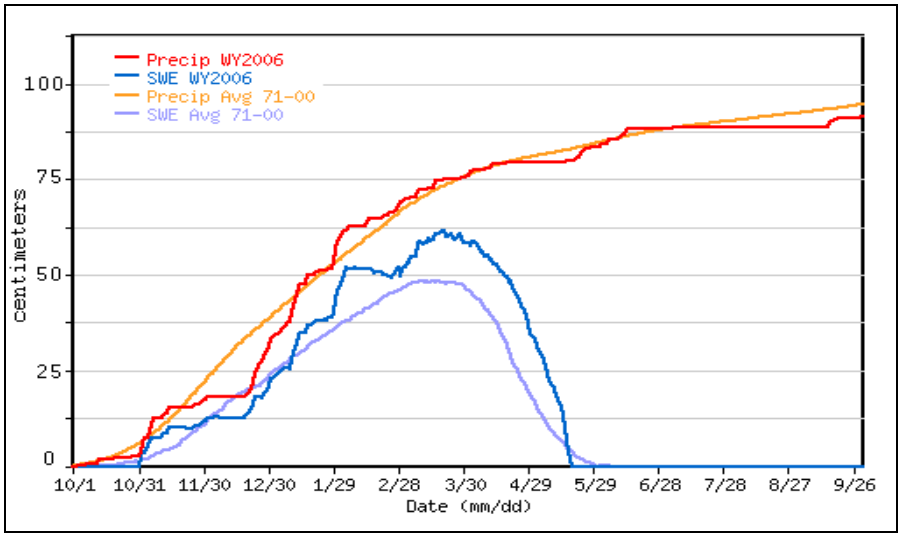

Figure 11: Water year 2006 cumulative precipitation and SWE at Pope Ridge, WA SNOTEL site (NRCS, 2006).

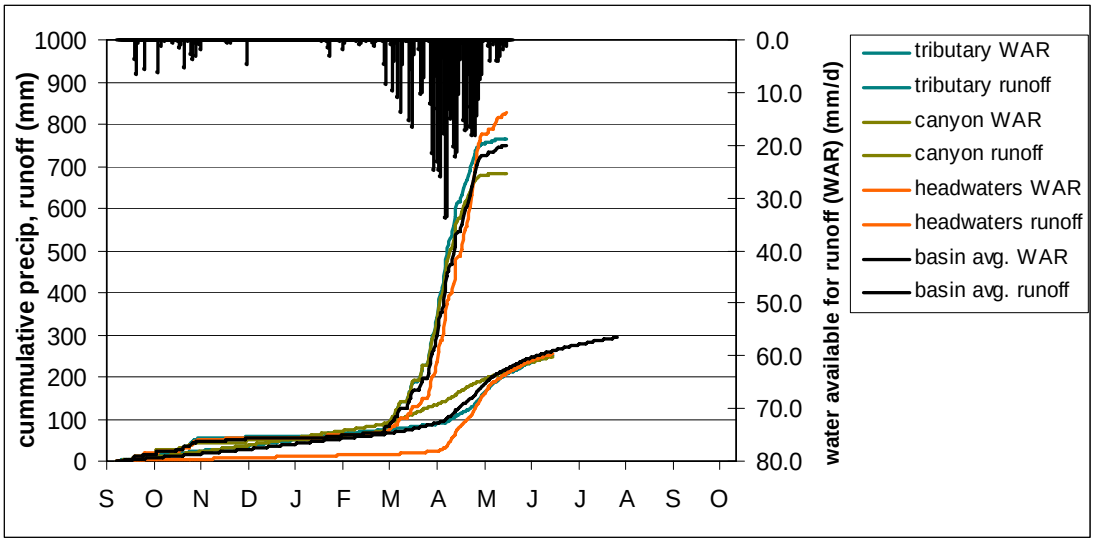

Figure 12: Water year 2006 cumulative water available for runoff (WAR) and sub-catchment runoff, Burns Creek, WA.

to 580 mm of SWE on snow pillows in the Burns Creek catchment by late March (Figure 10). SWE measured at the Pope Ridge SNOTEL site was 627 mm, 110% of the thirty year average for the site (Figure 11). Overall annual precipitation at Pope Ridge in WY 2006 was approximately 930 mm, equal to the long term average (NRCS, 2006).

An analysis of catchment runoff response to snowmelt in WY 2006 could not be accomplished sufficiently using the precipitation data from tipping buckets or snow pillows alone. Instead, our analysis of WY 2006 incorporated distributed water available for runoff (WAR) output from the energy balance snowmelt model of Mazurkiewicz (2006). Unlike those data presented in Figure 10, the WAR calculation accounted for precipitation that may have fallen as rain, but was frozen in the snowpack and released later during the spring melt (Figure 12). Thus, some of the precipitation events shown in the hyetograph in Figure 10 were captured by the model and released as WAR later in the spring in Figure 12. Catchment-averaged total precipitation in the Burns Creek catchment over WY 2006 was 750 mm using the modeling approach and the WAR

output (Mazurkiewicz, 2006). This amount equated to 130% of the average annual precipitation measured in Burns Creek from 1962-1970 (Helvey, 1980). It should be noted that the 1962-1970 average was based on fixed-elevation bulk precipitation gauges whereas the model took into account the full range of elevation and aspect in the catchment. SNOTEL records, estimating the 2006 snowpack as 110% of average, were based on a 30-year average and are likely to be the most reliable estimate.

4.3.2 Sub-catchment responses to seasonal events

Water year 2006 was characterized by an extended period of baseflow and relative dormancy of the Burns sub-catchments followed by snowpack ablation proceeding from low elevations to the headwaters. Three stages of melt runoff were visible in hydrographs of the 2006 melt period, in response to increasing WAR (blue hyetograph, Figure 13). From March 5 to April 14, snowpack ripening in the low reaches of the catchment generated runoff that was limited to the canyon sub-catchment. Even without significant contributions of flow from the tributary and headwaters sub-catchments, this period of melt reduced the overall SWE in the Burns Creek catchment by 25%. Whole-catchment runoff increased at about half the rate of the canyon sub-catchment, reflecting the still-frozen condition of SWE at higher elevations.

Meltwater generated from the headwaters and tributary sub-catchments became evident on April 20th, signaling a second stage of 2006 melt. Similar to the melt response of 2005, the headwaters sub-catchment hydrograph rose abruptly, indicating a rapid generation of snowmelt routed to perennial and ephemeral channels. The headwaters

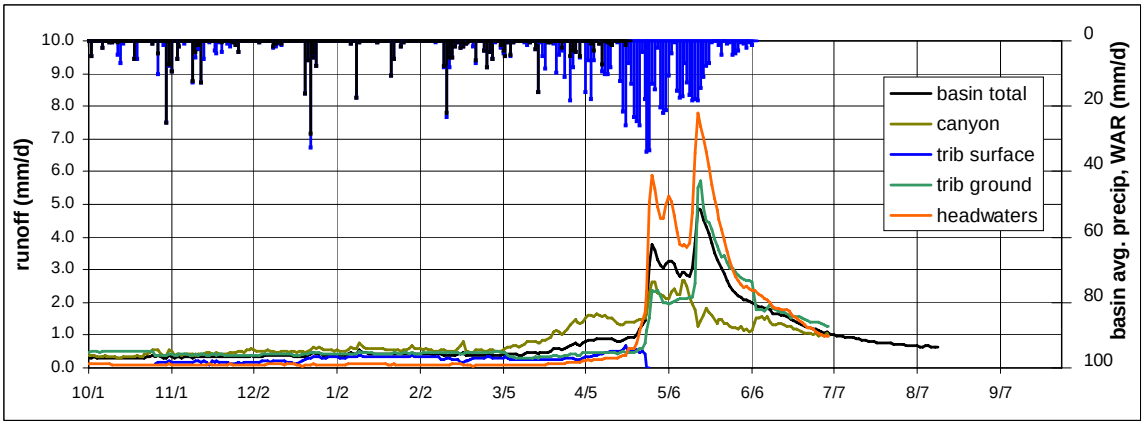

Figure 13: WY2006 precipitation and area-adjusted discharge from Burns Creek sub-catchments.

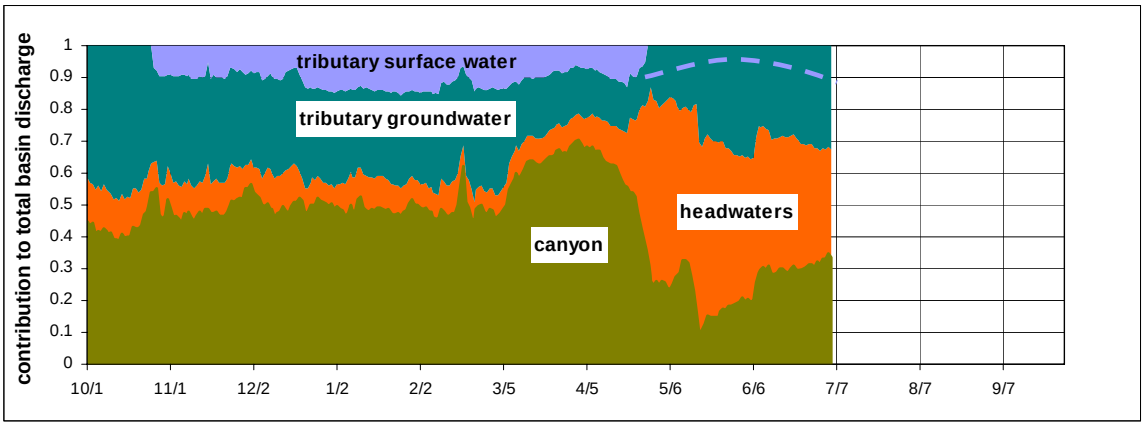

Figure 14: WY2006 sub-catchment contributions to daily-averaged discharge measured at Burns Creek weir (discharge not adjusted for sub-catchment area).

sub-catchment achieved a maximum runoff rate of 6 mm/d during this period, while the canyon sub-catchment reached a lesser maximum of 2.5 mm/d and then receded slowly over the rest of the season.

The installation of additional flumes in autumn of 2005 enabled the differentiation of surface and groundwater flow for the tributary sub-catchment in WY 2006 (Figure 4, page 11). "Tributary surface water" was calculated identically to tributary flow in 2005, using data collected at 7.6 cm flumes near the junction of the tributary and Burns Creek.

Table 3: Rainfall-runoff characteristics of Burns Creek sub-catchments, WY 2006.

Total Water Available for Runoff (WAR) from Oct. 1, 2005 to Jun 5, 2006 and avg. daily WAR

whole basin	headwaters	trib spring	tributary (ground)	canyon
750 mm	826 mm	~765 mm	765 mm	684 mm
3.02 mm/d	3.33 mm/d	3.08 mm/d	3.08 mm/d	2.76 mm/d

Total Runoff Recorded from Oct. 1, 2005 to Jul. 5 or Aug 15, 2006 and average daily runoff

whole basin	headwaters	trib spring	tributary ground	canyon
294 mm	254 mm	46 mm	253 mm	248 mm
.92 mm/d	.91 mm/d	.21 mm/d	.91 mm/d	.89 mm/d

WAR - runoff efficiency

whole basin	headwaters	trib spring (Oct.-Apr. only)	whole trib	canyon
30%	27%	7%	29%	32%

"Tributary groundwater" consisted of water entering Burns Creek between the 7.6 cm flume and the new, 15.2 cm flume approximately 100 m downstream. The reach incorporated by the placement of the new flume increased the tributary sub-catchment area by 52 ha (50%) in WY 2006 (Figure 4, right), but augmented annual runoff calculations there by 120%. The "groundwater" component of flow was thus named because there was no point-source contribution that readily explained the volume of flow added over this reach. After the breaching of both 7.6 cm flumes in April, 2006, surface and ground water contributions could no longer be differentiated. The dotted line drawn in Figure 14 represents a conservative trajectory for the surface water contribution over the 2006 snowmelt period. Field observations and additional data from a culvert stage recorder also indicated that tributary flow was only slightly elevated during snowmelt.

The tributary sub-catchment groundwater contribution peaked gradually, and was the least reactive component of flow during the second stage of melt. This muted peak may have resulted from a lag in runoff reaching the channel through groundwater

flowpaths. In the third stage of melt, beginning on May 13, the headwaters sub-catchment, tributary sub-catchment groundwater contribution, and Burns Creek catchment as a whole reached their maximum runoff equivalents. These patterns likely signified the maximum expansion of surface and subsurface drainage networks in the upper two sub-catchments, while the slow decline of the canyon sub-catchment hydrograph appeared to confirm snowpack ablation and the recession of a subsurface drainage network from lower elevation slopes.

In 2006, total discharge from the Burns Creek catchment was more evenly divided among the three sub-catchments on a per area basis despite great differences in the shape and timing of the melt hydrographs (Table 3). Each of the sub-catchments and the Burns catchment as a whole had similar runoff-ratios following the large 2006 spring snow melt, even after accounting for variable depths of precipitation accumulation. An exception was the spring at the source of the tributary, for which data was unavailable after the malfunctioning of a stage recorder at the beginning of April. A particular difference in sub-catchment behavior between WY 2005 and WY 2006 was that the recession of the hydrographs from all three sub-catchments appeared to converge on the catchment-averaged condition (Figure 13).

4.4 Electrical conductance as an environmental tracer

4.4.1 Seasonal patterns of EC fluctuation

Continuous monitoring of electrical conductance (EC) was an important supplement to nested gauging of the Burns Creek sub-catchments. Daily-averaged runoff at the Burns Creek weir, daily precipitation and WAR, and daily-averaged EC at probes

in the basin are shown in Figures 15 through 18. The scales of the figures have been adjusted to show seasonal fluctuations of EC in response to snowmelt (Figures 16 and 18) and details of the variability among probes over shorter time periods and in response to precipitation events (Figures 15 and17).

Three key things were observed at coarse resolution: 1) signals recorded by all EC probes apart from the weir were annually consistent, 2) a threshold response of EC enrichment was apparent at the weir following the peak and recession of snowmelt in the catchment, and 3) background EC concentrations were higher at springs and at progressively lower elevation channel positions. A high degree of short-term signal variability and lagged responses to some melt events were observed at finer resolution.

EC data representing the headwaters sub-catchment alone and the headwaters and tributary sub-catchments combined were from probes located about 100 meters apart. As a result, the signals were well matched, with EC at the lower probe enriched slightly by the influence of (surface) water from the tributary sub-catchment (Figure 15). EC at both stations spiked briefly after the rain-event of January 17-23, 2005, followed by a sustained depression as flow contributions from the sub-catchments were elevated by the snowmelt event beginning on January 24. The two signals converged from February to mid-May of 2005, as the volume of flow from the headwaters sub-catchment overwhelmed that of the tributary. The signals were depressed only slightly further in response to the primary melt period in May, indicating little change in the proportional contributions of meltwater and groundwater during that time. The signals separated again in late May, with tributary sub-catchment water resuming the enrichment of the headwater sub-catchment contribution.

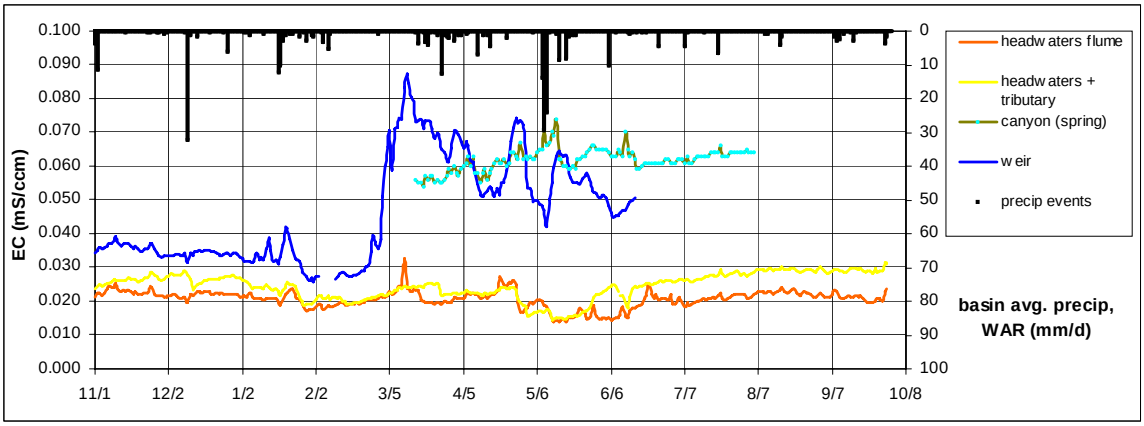

Figure 15: Fine-resolution EC patterns for four locations in the Burns Creek catchment, WY 2005.

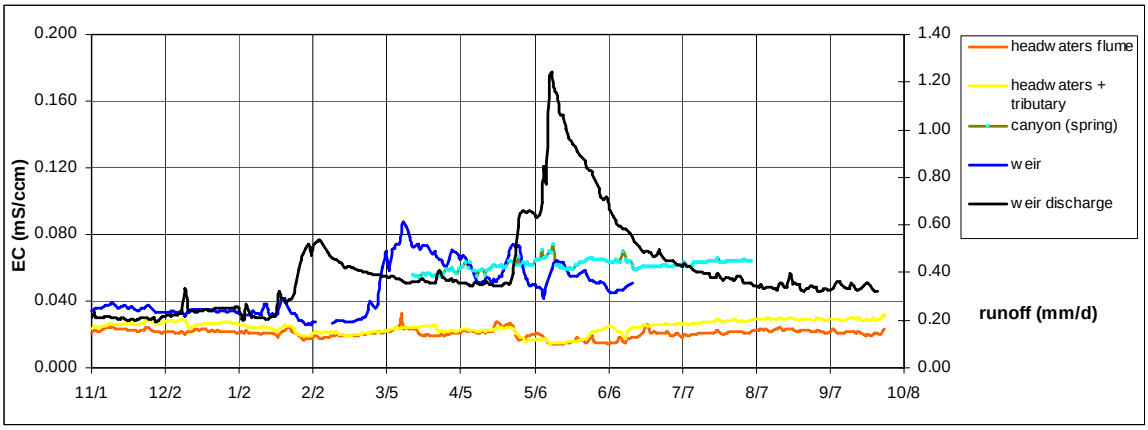

Figure 16: Coarse-resolution EC patterns for four locations in the Burns Creek catchment, WY 2005.

A disparity between EC recorded at the weir and elsewhere in the catchment can be recognized at both coarse and fine resolution (Figures 15 and 16). Weir EC spiked briefly at the onset of melt in January 2005, in unison with the signals from the upper two sub-catchments (Figure 15). This was followed, however, by a much more prominent four week depression and then a dramatic enrichment of EC during the February-May melt recession. During the enriched period, weir EC appeared to shift from a concentration similar to the upper two sub-catchments to one more similar to spring

water in the canyon sub-catchment (Figure 15). The weir signal oscillated twice more coinciding with two rain events and the primary melt event in May, but the pattern did not appear directly related to the events. Regrettably, data for the remainder of the summer at this probe were lost or corrupted, so the behavior of the weir EC signal after the recession of the primary melt hydrograph could not be observed.

More frequent visits to the Burns catchment in WY 2006 resulted in more complete coverage of EC in the sub-catchments. Colder weather and deep snowpack over the winter also increased the likelihood that results would differ from WY 2005. The black and blue hyetographs in Figure 17 show the offset of melt-induced WAR (blue) compared to precipitation events (black), many of which were not "released" by the accounting of the energy balance model. Correspondingly, EC was not acutely sensitive to precipitation events even at fine resolution (Figure 17), but EC signals were depressed slightly once WAR generation began in March, 2006.

Overall, sub-catchment EC levels stayed relatively constant again over the course of WY 2006. EC levels continued to be elevated at springs and at progressively lower channel elevations. EC at the highest probe, where tributary flow originated at a spring, was approximately equal to the average EC of flow in Burns Creek through the canyon sub-catchment (Figure 17). EC recorded at the canyon sub-catchment spring was the first signal to decline after a precipitation event on February 12-18, 2006. This decline continued over the next month as snowpack ripened at low elevations. EC at the tributary spring also started to decline during this period, coinciding with an *increase* of EC at the junction of Burns Creek and the tributary (Figure 17). This indicated an increase of flow within the tributary sub-catchment that proceeded the generation of melt

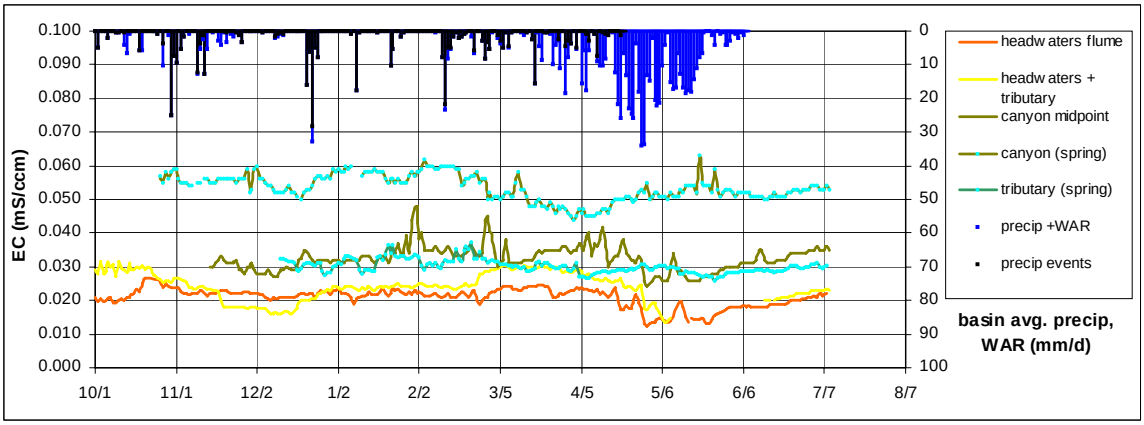

Figure 17: Fine-resolution EC patterns for four locations in the Burns Creek catchment, WY 2006.

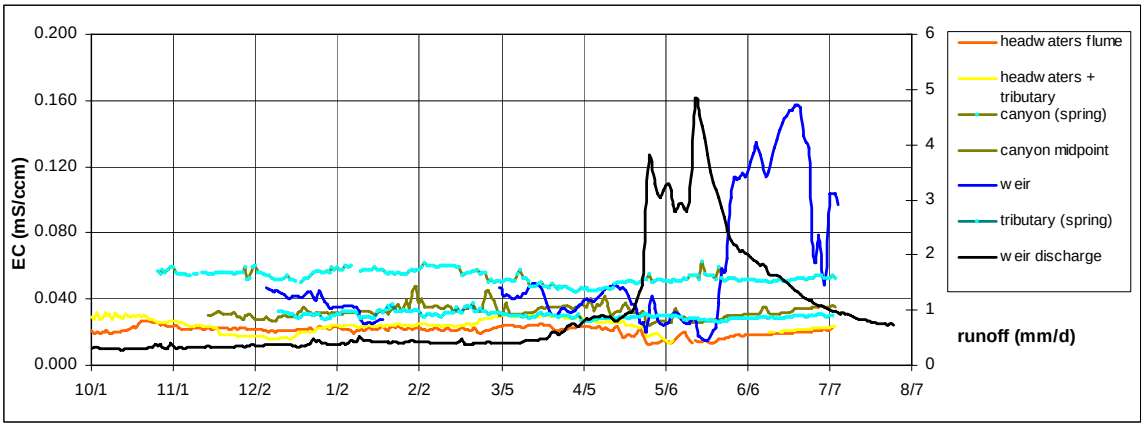

Figure 18: Coarse-resolution EC patterns for four locations in the Burns Creek catchment, WY 2006.

from the headwaters sub-catchment. The remaining probes in the catchment recorded EC depression beginning on April 13, coinciding with increased WAR generation. However, these signals were not depressed any further than during the WY 2005 melt, and EC enrichment at the two springs actually rebounded during this period.

EC signals at the weir continued to defy interpretation through WY 2006. For much of the year, the signal oscillated between EC concentrations recorded at the upper two sub-catchments and at the canyon sub-catchment spring, with average values most

closely resembling those of the nearest probe (canyon midpoint, Figure 18). Depression of EC at the weir appeared to be influenced primarily by the increase of WAR, but the concentrations were quite erratic in comparison to any other part of the catchment. A threshold response in EC concentration was again observed during the recession of the snowmelt hydrograph, but EC enrichment at the weir doubled the increase of 2005, which rendered the canyon sub-catchment spring inadequate for consideration as an "end-member" (Figure 18). In addition, the pulse of enriched EC displayed a double peak, mirroring the peaks of the hydrograph itself, and a precipitous decline. These patterns lagged the rising limb of the hydrograph by four weeks, just as the threshold EC pattern lagged the rise of the hydrograph in March of 2005.

4.4.2 Storm hydrograph separation

Storms occurring on December 9-11, 2004, January 17-23 and May 8-10, 2005 brought 32.2 mm, 26.9 mm, and 18.7 mm of precipitation to the catchment respectively (Figure 19 A-F). These were the largest storms of the year measured by tipping buckets, and the only three storms to cause distinct hydrograph peaks prior to the onset of snow melt in WY 2005. Hydrograph separations were performed for main-stem flumes and Burns Creek weir for these storms, using EC as a semi-conservative tracer.

Prior to the December storm (Figure 19 A,B) only 20 mm of precipitation had fallen on the Burns Creek catchment since October, 2004, far less than necessary to satisfy storage deficits. The 32 mm that fell during the storm failed to cause more than slight deflections of EC recorded at any point in the catchment. All EC probes responded similarly to the December, 2004 storm. Between 92% and 98% of storm-period stream

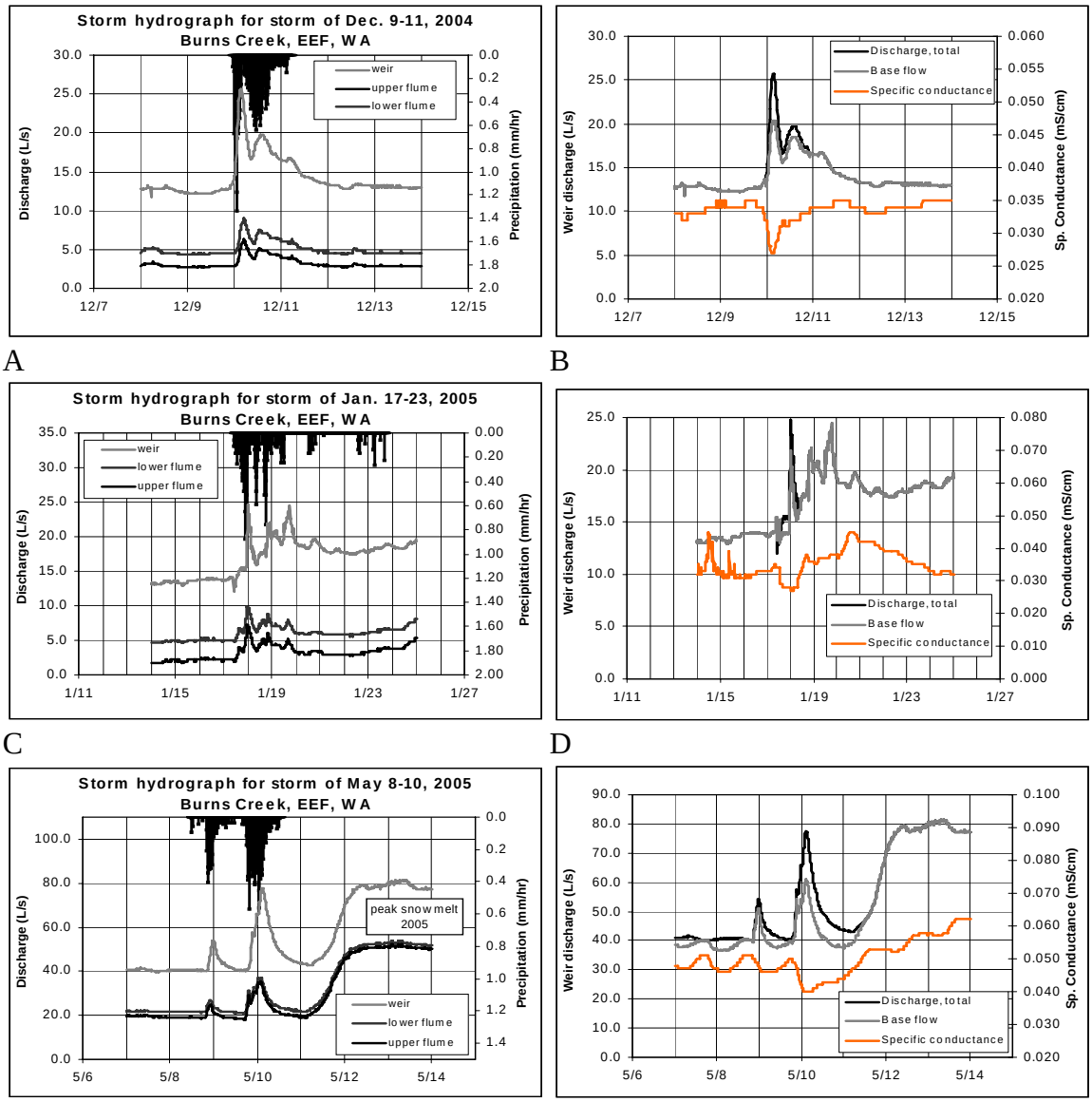

Figure 19, A-F: Hydrograph storm separations for three storms in the Burns Creek catchment, using electrical conductance as a tracer, WY 2005. Only separations for stormflow at the catchment-outlet weir are shown.

flow was pre-event water. For the gauge that registered only 92% pre-event water, the baseflow separation had been allowed to continue beyond the immediate influence of the storm. Had the separation been ceased, the pre-event component to streamflow at this gauge would have been calculated as 98.4%.

Table 4: Runoff ratios and event water contributions to stormflow for three storms in the Burns Creek catchment.

Burns Creek storm of Dec. 9-11, 2004

	Total Precip	Total Runoff	Pre-event water (baseflow)	Event water (rain)
Upper flume	32.2 mm	.45 mm (1.4%)	98.2%	1.8%
Lower flume	32.2 mm	.47 mm (1.5%)	92.0%	8.0%
Weir	32.2 mm	.73 mm (2.3%)	98.0%	2.0%

Burns Creek storm of Jan. 17-23, 2005

	Total Precip	Total Runoff	Pre-event water (baseflow)	Event water (rain)
Upper flume	26.9 mm	.80 mm (3.0%)	97.2%	2.8%
Lower flume	26.9 mm	.96 mm (3.6%)	98.1%	1.9%
Weir	26.9 mm	1.49 mm (5.5%)	99.4%	0.6%

Burns Creek storm of May 8-10, 2005

	Total Precip	Total Runoff	Pre-event water (baseflow)	Event water (rain)
Upper flume	18.7 mm	2.55 mm (13.6%)	82.0%	18.0%
Lower flume	18.7 mm	1.93 mm (10.3%)	87.7%	12.3%
Weir	18.7 mm	2.09 mm (11.2%)	95.0%	5.0%

The storm of January 17-23, 2005 delivered 27 mm of precipitation, and also resulted in very slight event water contributions (Table 4). Results were nearly identical to those of the previous series of separations, except that there was an apparent flushing of high-conductivity water at each station after rainfall ceased (Figure 19 C,D). Pre-event water again composed 97-99% of runoff. The January storm had the additional distinction of being a “pineapple express” on a path from the Pacific south (Andalkar, 2006). With the storm came significantly warmer air temperatures and high relative humidity. After a seven day lag time, stream stage at all flumes in the catchment experienced dramatic increases in runoff. This apparent temperature and latent heat-induced ripening of the snowpack produced a runoff response at all gauges that dwarfed

the effect of either of the two small storms, and increased baseflows over the next three months (Figure 8).

In the case of both the December 9-11, 2004 and January 17-23, 2005 storms, the Burns catchment runoff ratio (ratio of total storm-generated runoff in mm to total rainwater falling in mm) increased at progressively lower channel positions. 1.4%, 1.3%, and 2.3% of runoff per unit area was generated by the December storm, and 3.0%, 3.6%, 5.5% by the January storm (Table 4). The general increase in runoff ratio through time at each point also suggested a general wetting up of near stream soils and a greater efficiency in translation of rainfall to runoff as the winter progressed.

The last storm for which hydrograph separation was possible occurred midway through the primary melt event on May 8-10, 2005 (Figures 19 E,F). For the May storm, pre-event EC values appeared to fluctuate with a diurnal pattern, and this may have affected the separation technique. This storm added only 18.7 mm of rain to the catchment, but the runoff response was immediate and substantial compared with other storms. While earlier storms elicited runoff ratios of 1.4 – 5.5%, this storm produced runoff ratios of 11.2-13.6%. Hydrograph peaks caused by this storm were nearly equivalent to the peak of snow melt runoff occurring several days later.

In contrast to earlier storms, the May, 2005 storm occurred while the catchment was at its wettest condition of the year, and even areas distant from the stream channel may have contributed to the quickflow response through subsurface flow paths. Additionally, because snow was already melting in the catchment, some of the runoff attributed to the storm was likely to have been melt water rather than rain. Pre-event water composed 82% of the hydrograph response in the headwaters sub-catchment, 88%

in the tributary catchment and 95% at the catchment outlet. These numbers support a snowmelt influence in our calculations of the new water fraction, but they also suggest that the lower reaches of the stream were more groundwater dependent than the upper reaches during this hydrologically crucial part of the year. The hydrograph separations in May more clearly illustrated the increasing proportion of groundwater with decreasing elevation than did the hydrograph separations of December and January.

5.0 Discussion

The results presented here, incorporating physical and chemical measures of flow variability below the headwater catchment scale, challenge the hypothesis that headwater catchments are composed of physically and chemically homogenous sub-catchments with regard to the volume and timing of runoff generation. Our work followed the incremental gauging approach advocated by McDonnell and Vache (2004), and showed divisions between direct and indirect sub-catchment contributions to streamflow over the study period. These results were consistent with recent studies by Onda et al. (2001) and Uchida et al. (2005), who have documented linkages between streamflow generation and the activation of deep-seated flowpaths.

Nested gauging of the Burns Creek catchment detected temporal and chemical differences in runoff disposition from the headwaters, tributary and canyon sub-catchments, and indicated variable capacities for storage and discharge. Most significantly, sub-catchment runoff ratios and ratios of pre-event water to event water were found to increase with increasing drainage area. These findings were similar to Brown et al. (1999), but contradicted Shanley et al. (2002). Pre-event water contributions

to precipitation- and snowmelt-induced streamflow were exceptionally high in all cases. Progressively larger precipitation and snowmelt events decreased the variability of the runoff ratio among the three sub-catchments and the headwater catchment as a whole. However, progressively larger events did not significantly decrease ratios of pre-event water contributing to streamflow. Each of these findings pointed to groundwater-oriented flow controls at the headwater catchment scale. A range of lag times, threshold behaviors, and flow smoothing characteristics was also observed that suggested a continuum between surface (direct) and subsurface (indirect) flowpaths.

More than half of the total precipitation entering the Burns catchment over the study period fell into the topographically defined headwaters sub-catchment. Most of that precipitation fell as snow, and remained frozen until the spring. Snowmelt runoff from the headwaters sub-catchment was characterized by temporally and spatially direct contributions, aided by high drainage density at upper elevations, relatively shallow soils, and a portion of the sub-catchment made up of exposed bedrock. The abrupt peak and recession of the annual snowmelt hydrograph did not appear to be sensitive to storage deficits within the headwaters sub-catchment, and seemed to have been influenced most strongly by variable source area fluctuation and the expansion of the near-surface drainage network.

In contrast, EC gauged at the outlet of the headwaters sub-catchment indicated that both storm and melt-induced high flows consisted overwhelmingly of pre-event water. Annual runoff ratios from the headwaters sub-catchment were approximately equal in 2005 and 2006 (34% and 27% respectively), despite a 250% increase in annual precipitation delivered to the sub-catchment in 2006. Baseflow from the sub-catchment

was limited to only 10% of the total runoff of either year. The consistency of the runoff ratio suggested that the dynamic storage capacity of this sub-catchment was actually quite large, while the low ratio of baseflow to snowmelt runoff suggested also that water stored in the sub-catchment was isolated from the stream except during high flows.

After new Parshall flumes were installed in autumn of 2005 upstream and downstream of existing flumes, a significant groundwater contribution to streamflow was detected below the junction of Burns Creek and its tributary. This groundwater component was quantified independently of tributary surface water, but the general event-insensitivity of flow stage in the tributary sub-catchment led us to consider that the groundwater may have originated in the tributary sub-catchment and bypassed our original flumes through deeper flowpaths. When hydrograph separations were performed for combined flow from the headwaters and tributary sub-catchments, pre-event water made up an even more significant fraction of stormflow and melt water responses.

The response of the groundwater contribution to snowmelt in 2006 was consistent with longer flowpath routing to the channel and a range in potential recharge elevation. The onset of the response was synchronous with other melt induced contributions, but the double peaked pattern exhibited by the headwaters sub-catchment was muted in the groundwater hydrograph. The flattened initial peak of the groundwater hydrograph was similar to the pattern of the canyon sub-catchment, and appeared to show a lagged runoff response as storage deficits were filled over a period of two to three weeks. This was followed by an abrupt hydrograph response similar to the pattern of the headwaters sub-catchment, and consistent with the well known transmissivity-feedback mechanism (Rodhe, 1981, Kendall et al., 1999).

Threshold responses in EC concentration at the weir following the onset of melt each spring further supported the theory of groundwater mobilization, but in a notably different way that at the individual sub-catchment scales. During both years of this study, an initial melt pulse prompted a dilution of catchment EC on the rising limb of the hydrograph, followed three to five weeks later by substantially elevated EC recorded at the weir. If high EC can be assumed to be a proxy for increased flowpath length or residence time of water (Kobayashi et al., 1999, Wolock et al., 1997), the data recorded at the weir suggest that flow on the recession limb of the snowmelt hydrograph may, on average, originate from flowpaths deeper than those emerging at low elevation springs. Higher EC concentrations in 2006 further suggested that the volume of groundwater mobilized in the channel above the weir was proportional to the magnitude of annual precipitation and melt. The data recorded at the weir illustrated a flushing pattern unique to that gauge and not easily explainable. This evidence perhaps most refuted the hypothesis that headwater catchment properties could be adequately deduced from a single gauging station at the catchment outlet.

We interpreted the pattern of increasing groundwater contributions with increasing catchment area as a result of water contributions from underlying geomorphic reservoirs. The advanced degree of down-cutting observed in the canyon sub-catchment relative to the condition of the upper two sub-catchments was circumstantial evidence of this (Figure 2). The stream reach accountable for the 2006 groundwater component of gauged flow marked a transition from relatively mildly sloped, coarse-substrate lined channel conditions above the tributary junction to deeply incised, bedrock channel conditions through the canyon sub-catchment (Figure 5). This geomorphic boundary

appeared as a head scarp or nickpoint of the canyon, left as a remnant of glaciation of the greater Entiat River basin. Streamflow gains appeared to be a consequence of both the abrupt steepening of the stream gradient and the scouring of sediments which may have otherwise damped the pulsed release of groundwater into lower elevation reaches.

6.0 Conclusion

In this study, observations of sub-catchment precipitation and snowmelt runoff responses were highly conditioned by the scale of internal geomorphic characteristics. We rejected our original null hypothesis, that a headwater catchment is composed of physically and chemically homogenous sub-catchments. Flow and chemistry in our gauged sub-catchments were affected by the interactions of geomorphology and climate at a scale below that of the Burns Creek headwater catchment as a whole. The Burns catchment was a sum of its parts insomuch as it was inclusive of both surface and sub-surface runoff processes, but the disaggregation of sub-catchments was not well correlated with sub-catchment area. Our specific conclusions from this study were:

1) Annual runoff ratios increased with increasing catchment area for each of the monitored sub-catchments.

2) Only six storms produced measurable runoff responses from the sub-catchments of Burns Creek for the 2005 and 2006 water years. Of these, only three produced meaningful deflections of EC for hydrograph separation at multiple gauge locations. These events represented less than one percent of the total flow recorded over the study period. The annual snowmelt period generated far more runoff than rain events, and represented about 60 percent of flow in 2005 and 80 percent of flow in 2006.

3) Runoff ratios for storm events were exceptionally small (5-10%), while runoff ratios for snowmelt events were much higher (25-30%).

4) Pre-event water contributions to storm and snowmelt runoff were exceptionally high, suggesting that even when hydrologic connections were made between hill slopes and the channel, most water entering the stream was near-stream groundwater. Low drainage density in all but one sub-catchment seemed to support the notion of a large reservoir of stored water.

5) Variability among sub-catchment runoff ratios was less when catchment precipitation was slightly above the long-term average in WY 2006, than in the comparatively dry WY 2005. This suggested spatial heterogeneity in the dynamic storage function of each of the sub-catchments.

6) Pre-event water contributions to streamflow over the course of the year increased in a down-valley direction. A higher percentage of groundwater in stormflow at the Burns Creek weir than in the monitored sub-catchments suggested deep groundwater movement from areas of high elevation recharge to areas of low elevation discharge to the stream.

Future research using stable isotope tracers (more suited to a low-background-EC environment) should be attempted at this site to more accurately quantify streamflow gains and water residence time in the Burns Creek catchment. The structural and relic glacial geology of the catchment as they relate to topographic controls on deep flowpaths should also be interpreted. These steps will likely be valuable for testing correlations between the orientation of geomorphic features and the distribution of runoff processes in the neighboring headwater catchments of the Entiat Experimental Forest and throughout the Entiat River Basin.

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