A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon

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[1] In ungauged basins, predicting streamflows is a major challenge for hydrologists and water managers, with approaches needed to systematically generalize hydrometric properties from limited stream gauge data. Here we illustrate how a geologic/geomorphic framework can provide a basis for describing summer base flow and recession behavior at multiple scales for tributaries of the Willamette River in Oregon. We classified the basin into High Cascade and Western Cascade provinces based on the age of the underlying volcanic bedrock. Using long-term U.S. Geological Survey stream gauge records, we show that summer streamflow volumes, recession characteristics, and timing of response to winter recharge are all linearly related to the percent of High Cascade geology in the contributing area. This analysis illustrates how geology exerts a dominant control on flow regimes in this region and suggests that a geological framework provides a useful basis for interpreting and extrapolating hydrologic behavior. *INDEX TERMS:* 1860 Hydrology: Runoff and streamflow; 1824 Hydrology: Geomorphology (1625); 1884 Hydrology: Water supply; *KEYWORDS:* geologic framework, low flow, Oregon Cascades, recession analysis

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1. Introduction

[2] Predicting streamflows in ungauged catchments is emerging as a major scientific and societal challenge, prompting the International Association of Hydrological Sciences (IAHS) to declare the years 2003–2012 as the IAHS Decade on Predictions in Ungauged Basins (PUB). Providing information on distributed streamflow is often limited by the availability and spatial distribution of long term streamflow records. Within the United States, stream gauge networks are often sparse in large tracts of undeveloped land and wilderness areas. The western slopes of the Cascade Mountains in Oregon are such a region. Here the sharply seasonal Mediterranean climate results in high winter precipitation and an extended summer drought, and translates into a streamflow pattern of high winter peaks and very low summer flows. There is, however, considerable spatial variability in the degree to which streamflow reflects the seasonal precipitation pattern, with some streams having muted winter peaks and sustained high summer base flows [*Grant*, 1997]. Climate alone cannot explain this behavior. Moreover, the existing streamflow network does not adequately capture this variability, in large part because the importance of the spatial structure of streamflow production in this region has not been recognized until now.

[3] In this paper, we characterize flow regimes of western Oregon based on a geological framework. Conceptually, our approach follows *Winter* [2001], who advocates hydrologic comparison based on geologic-geomorphic landscape attributes. We examine streamflow regimes in the westward draining tributaries of the Willamette River system and systematically relate spatial differences in streamflow to differences in geology and geomorphology within the region. In particular we characterize flow regimes with respect to a broad geologic partitioning of the Cascade Mountains into the older, deeply dissected Western Cascades and the younger, relatively undissected High Cascades [*Sherrod and Smith*, 2000; *Walker and MacLeod*, 1991]. The lateral contiguity of two lithologically similar but geomorphically and age-distinct geological terranes provides a unique opportunity to examine geological control of hydrologic regimes at the landscape scale.

[4] Using data compiled from long-term streamflow records for both High Cascade and Western Cascade streams, we examine a population of streamflow volumes, hydrograph recession curves, and other time series measures. We also examine the extent to which flow regimes of the larger tributaries of the Willamette and main stem Willamette reflect this underlying geological framework. We focus on summer base flow responses because these flows most dramatically highlight differences between the two geologic provinces, and have significant ramifications for water resource management and the ecology of the region.

2. Background

2.1. Regional Setting

[5] The western slopes of Oregon's Cascade Mountains are drained by large westward flowing rivers that are

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tributaries to the northward flowing Willamette River. Within the Cascades, these large rivers generally flow perpendicular to the strike of two distinct geologic provinces: the Western and High Cascades (Figure 1). In both provinces 80% of the precipitation falls during the winter months. Most of this precipitation falls as snow above 1500 m and as rain below 400 m, with a mix of rain and snow at intermediate elevations. By virtue of their higher elevations, the High Cascades are more snow-dominated than the Western Cascades, although the highest elevations of the Western Cascades typically retain snowpacks until late into the spring, similar to the High Cascades. Winter storms for both regions result from broad frontal systems; convective systems and thunderstorms are generally limited to summer months and though locally intense represent a very small fraction of the annual water budget.

[6] The Western Cascades are dominated by deeply weathered, layered, basaltic and andesite lavas and volcaniclastic flows of mostly Miocene age. The steep, highly dissected landscape of the Western Cascades ranges in elevation from 400 to 1800 m and reflects significant erosion by fluvial, glacial, and mass movement processes. The region is typically well-drained, with soils 1–3 m in depth of moderate to high surface hydraulic conductivities grading vertically to shallow subsurface confining layers of clay, saprolite and unweathered bedrock of generally low permeability. Drainage densities are high, averaging 3 km/km^2, further reflecting an efficient well-organized drainage system [*Wemple et al.*, 1996].

[7] The High Cascades form a broad volcanic platform, fault-bounded in places to the west and east, and represent a much younger geological terrane. Higher in elevation but lower in relief than the Western Cascades, the High Cascades primarily reflect recent constructional volcanism rather than erosional forms. Rock type is dominated by low gradient basaltic and andesitic lava flows, cinders, pumice, and volcanic ash, mostly from shield volcanoes, cones, and vents of Plio-Pleistocene age or younger. Blocky aa-type basalt flows are often visible at the surface in areas of the High Cascades. The young age of the surficial deposits results in poor soil development. Surface and subsurface hydraulic conductivities in young volcanic deposits are exceptionally high due to highly porous and permeable volcanic layers. Many areas of the High Cascades appear to lack surface drainage systems, and drainage density in the High Cascade province is significantly lower than in the Western Cascade province, averaging 1–2 km/km^2 [*Grant*, 1997]. Several High Cascade streams are headed by large, voluminous springs, indicating the existence of extensive, well-developed subsurface drainage systems.

2.2. Previous Research on Cascade Mountain Hydrology

[8] The earliest work on the hydrology of the Cascades is probably that of *Stearns* [1929], who documented the importance of spring flow from deep volcanic aquifers as contributing to the base flow of the McKenzie River. Most of the hydrologic research since then, including virtually all studies of the impacts of forest management on streamflow, has focused on Western Cascade systems and has demonstrated the importance of shallow, rapid subsurface flow as a factor contributing to high peak flows and flow variability [*Rothacher*, 1965, 1970, 1973; *Harr*, 1976a, 1976b, 1986; *Harr et al.*, 1975, 1982; *Jones and Grant*, 1996].

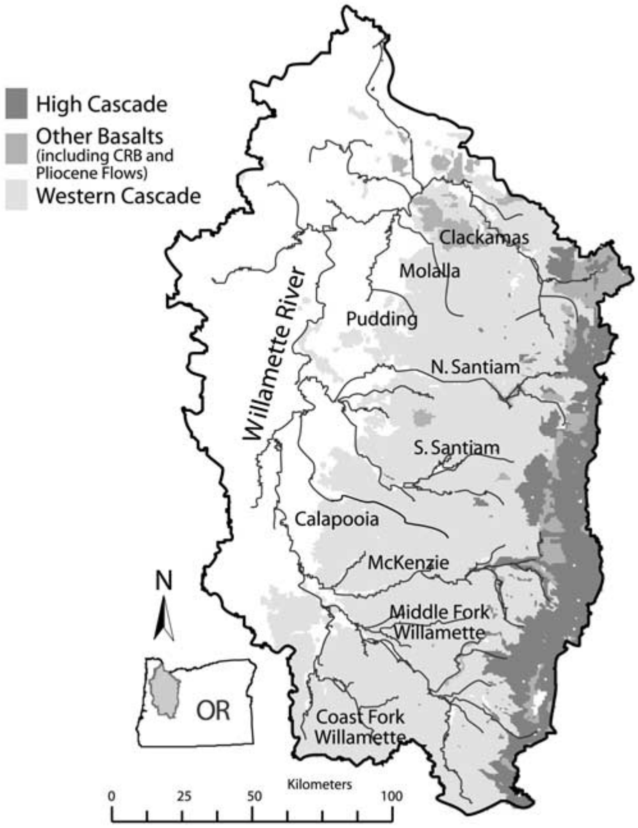

Figure 1. Willamette River Basin, Oregon, showing approximate location of High and Western Cascade geologic divide. Gray scale represents percent High Cascade geology in contributing area of east-west trending subbasins.

[9] High Cascade streams, in contrast, have received much less attention. Virtually all hydrologic research has focused on characterizing High Cascade snowmelt and spring-dominated streams on the eastern slopes of the range [*Manga*, 1996, 1997, 1999; *Gannett et al.*, 2003]. Although they share a broadly similar geology, there are important differences between the eastern and western slopes of the Cascades particularly with respect to the amount of annual precipitation (westside ~2000 to 3800 mm; eastside ~750–1650 mm [*Taylor and Hannan*, 1999]).

3. Methods

3.1. Geological Classification

[10] For the purposes of this study we classified rock units as High Cascade or Western Cascade based on rock type and age, using a 1:500,000 scale geologic map of Oregon [*Walker and MacLeod*, 1991] (Figure 1). Volcanic rocks greater than 8 Myr old were classified as Western Cascade, volcanic rocks younger than 2 Myr old were classified as High Cascade, and rocks between 2 and 8 Myr old were classified in one or the other category based on topographic position (i.e., ridge-capping basalts) or geography (i.e., proximity to High Cascade vents or

Table 1. Watersheds

Basin and Watershed	USGS Gauge Number	Drainage Area, mi^2	Elevation, feet	Percent High Cascade	Period of Record	Mean August, mm/month	Mean Annual, mm/year	Slope b	Intercept a	R2	RMSE	n
Middle Fork Willamette												
Fall	14150300	118	844	0%	1963.09.01–1999.09.30	11.23	1210.21	1.39	−3.40	0.78	0.93	3341
Hills	14144900	52.7	1631	9%	1958.10.01–1981.10.01	17.96	1433.72	1.53	−3.90	0.74	0.88	3211
Salmon	14146500	117	1462	52%	1986.10.01–1994.06.13	36.89	2150.63	2.04	−5.56	0.70	0.89	1892
Salt	14146000	113	1246	63%	1933.10.01–1951.09.30	30.68	1130.31	2.02	−5.33	0.64	0.95	3175
McKenzie												
Gate	14163000	47.6	764	0%	1966.10.01–1990.09.30	17.23	1103.92	1.46	−3.78	0.78	0.87	3313
Blue (at Tidbits)	14161100	45.8	1387	3%	1963.09.01–1999.09.30	13.60	2130.37	1.38	−3.50	0.80	0.90	3251
Blue	14161000	11.5	1960	3%	1947.10.01–1955.09.30	19.54	1700.99	1.20	−3.31	0.75	0.87	1950
Lookout	14161500	24.1	1377	16%	1963.09.01–1999.09.30	17.76	1689.55	1.42	−3.81	0.79	0.87	3226
Springfield[a]	14164000	1066	554	40%	1911.05.01–1915.03.31	56.15	2829.25	2.06	−5.89	0.61	0.85	2008
Coburg[a]	14165500	1337	392	46%	1944.10.01–1972.09.30	49.57	2678.66	2.18	−6.20	0.73	0.89	3268
Walterville[a]	14163900	1081	600	58%	1989.10.01–1999.09.30	32.94	1850.81	1.87	−4.89	0.52	1.36	2292
Leaburg[a]	14163150	1030	710	61%	1989.10.01–1999.09.30	30.28	1787.63	1.88	−4.82	0.54	1.32	2396
Vida[a]	14162500	930	856	68%	1924.10.01–1999.09.30	71.32	1750.04	2.44	−6.87	0.69	0.93	3080
S.F. McKenzie (above Cougar)	14159200	160	1710	68%	1957.10.01–1987.09.30	44.44	1191.64	2.30	−6.32	0.71	0.94	3320
Horse	14159100	149	1426	83%	1962.10.01–1969.09.30	59.63	1532.56	2.73	−7.59	0.60	0.89	1649
Mckenzie Bridge[a]	14159000	348	1419	88%	1910.10.01–1994.09.30	101.40	2084.72	3.02	−9.28	0.53	0.83	2458
Clear[a]	14158500	92.4	3015	95%	1937.10.01–1999.09.30	96.59	2853.57	2.10	−7.23	0.60	0.76	3421
Belknap[a]	14158700	146	2602	95%	1957.10.01–1962.09.30	93.17	1485.27	3.16	−9.85	0.63	0.74	1220
South Santiam												
Quartzville	14185900	99.2	1050	3%	1965.08.10–1999.09.30	43.39	1837.78	1.38	−3.47	0.80	0.93	3321
North Santiam												
L.N. Santiam	14182500	112	655	5%	1931.10.01–1999.09.30	16.59	2003.09	1.37	−3.42	0.81	0.90	3268
E. Humbug	14178700	7.32	2050	0%	1978.08.01–1994.07.10	15.01	1316.71	1.49	−3.81	0.82	0.86	3346
Breitenbush	14179000	108	1574	46%	1932.06.01–1987.10.01	46.27	2350.72	1.82	−5.06	0.72	0.91	3313
Santiam	14178000	216	1591	78%	1928.10.01–1999.09.30	64.57	1877.80	2.24	−6.51	0.67	0.90	3215
Clackamas												
Clackamas	14208000	136	2040	82%	1920.04.01–1970.09.30	56.13	1989.92	2.69	−7.46	0.67	0.90	3105
Fish	14209700	45.2	940	3%	1963.09.01–1999.09.30	12.34	1697.19	1.46	−3.54	0.84	0.82	2368
Oak	14208500	54	3140	85%	1915.10.01–1928.09.30	79.97	2091.87	2.30	−7.20	0.47	0.86	2264
Roaring	14209600	42.4	1040	30%	1966.01.28–1968.09.30	41.91	1370.95	1.74	−4.83	0.61	0.94	622

[a]Gauge on main stem.

volcanic centers, location with respect to north-south bounding faults).

3.2. Correspondence Between Geology and Streamflow Volumes

[11] Streamflow records for 22 headwater (third to fifth order) streams from the Western Cascade and High Cascade provinces in the Willamette drainage basin were obtained from the USGS gauge network (Table 1). Historically the USGS has maintained a much denser network of gauges in the Western as opposed to High Cascade region, primarily to predict flood discharges and inflows to reservoirs. All available USGS streamflow sites that contain significant High Cascade contributing area were included in this study, while Western Cascade sites spanning a range of drainage areas were randomly selected to represent this geologic province. With the exception of Oak Grove Fork (site 14208500), no dams or diversions are located above these sites. On Oak Grove Fork, the small storage facility at Timothy Lake is primarily operated as run-of-river and does not significantly affect streamflows. To explore higher-order stream response that integrates both High Cascade and Western Cascade contributing areas, we also included records from 6 USGS gauges located along the main stem of the McKenzie. For each of the available gauges standard long-term low flow statistics, including mean August and mean annual flow, were computed and compared with the proportion of High Cascade geology in the contributing area. These measures were used to describe differences in the magnitude of total and summer flow within the region.

3.3. Recession Analysis

[12] *Brutsaert and Niebert* [1977] developed a method for estimating soil and geomorphic parameters from low flow analysis based on analytical solutions to the Boussinesq equation. The Boussinesq equation describes flow, Q, from an unconfined, horizontal aquifer; Brutsaert and Niebert related parameters a and b in the recession equation (1) to geomorphic and soil characteristics of the aquifer:

$$\frac{dQ}{dt} = -aQ^b \quad (1)$$

Formal recession analysis [*Brutsaert and Niebert*, 1977; *Brutsaert and Lopez*, 1998] requires both that the watershed be reasonably conceptualized as a single unconfined aquifer; and the characteristic response time of the aquifer be less than the period over which significant recharge does not occur. However, *Manga* [1999] found that for an eastside Cascade spring system, aquifer response time was longer than the period without significant recharge. In spite of negligible High Cascade summer precipitation, the period without significant recharge is shorter than might be expected because significant snowmelt recharge typically continues into the summer months. Further, exploratory analysis of recession behavior, as discussed below, suggests

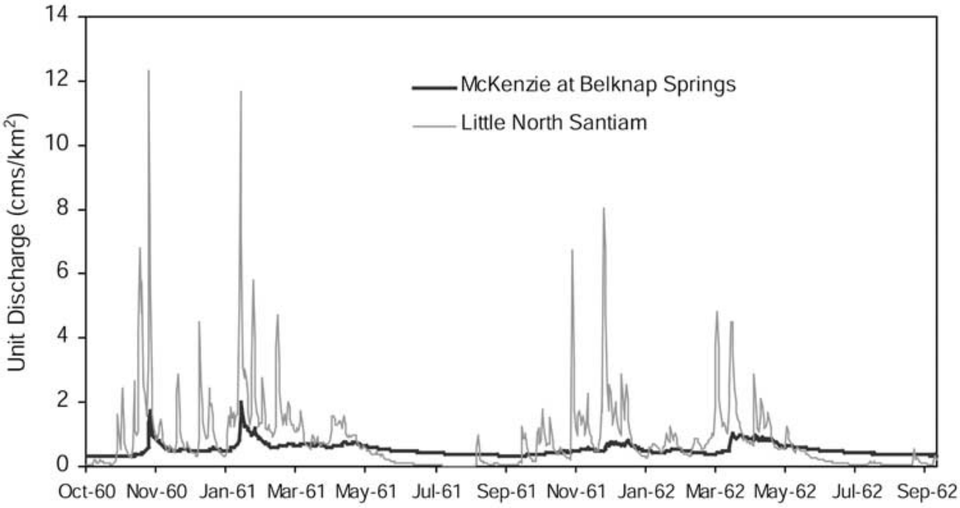

Figure 2. Daily streamflow hydrographs, normalized by drainage area, for a predominantly High Cascade (McKenzie at Belknap) and Western Cascade (Little North Santiam) rivers.

that High Cascades catchments may be better conceptualized as a system of two aquifers (surface and deeper groundwater) rather than as a single aquifer.

[13] Although prerequisite conditions for formal recession analysis were not met in this case, exploratory analysis of the relationship between log(dQ) and log(Q) provides insight into system behavior and may indicate fundamental differences in controlling processes. In particular, changes in the log(dQ) versus log(Q) relationship over the distribution of flows may indicate differences in dominant streamflow generation processes – both between different catchments and for different streamflow periods in the same catchment.

[14] If long term (multiple year) historical streamflow records are used to compute a mean slope of the log(dQ)/log(Q) relationship, this slope reflects the interaction among the time-distribution of recharge, the characteristic response time of the system, and aquifer hydraulic characteristics. Since seasonal patterns of precipitation are relatively similar across the High/Western Cascade region cross-basin differences in average recession behavior (i.e., slope of the logdQ/Q relationship) represent the combined effects of differences in snowmelt-driven recharge and watershed drainage properties. The maximum recession rate for a given streamflow, as described by the upper envelope of the log(dQ)/logQ relationship, should indicate the response of the system with the least impact from previous recharge events. These values should approach the catchment response where time without significant recharge is longer than the characteristic response time of the system. The slope of this envelope curve should therefore approach the recession behavior due primarily to underlying aquifer characteristics.

[15] Hydrograph recessions for each site were extracted from historical streamflow records, with a recession period defined as any period following a recharge event (defined as a decrease in daily 3-day averaged streamflow). Log(dQ/dt) versus log(Q) relationships for all recession periods were plotted and fit to a linear least squares regression model for each site. A first-order difference was used to approximate dQ. The resulting slope and intercept (b and a, respectively, in equation (1)) for all sites was then plotted against proportion of High Cascade geology to examine the extent to which geology defines mean basin recession characteristics.

3.4. Cross-Correlation Analysis

[16] We evaluated the difference in timing of response to winter recharge events between the Western and High Cascades. Visual analysis of High Cascade stream hydrographs suggested a delayed and muted response to winter recharge events relative to Western Cascade systems (Figure 2). Quantification of this delay thus provides another metric to assess how differences in snowmelt and geology define hydrologic response between the two systems. *Manga* [1999], following *Padilla and Pulido-Bosch* [1995], used cross-correlation between spring discharge and discharge from a neighboring surface water-dominated stream to estimate the time lag associated with the spring system. In Manga's study, discharge from the surface water-dominated system was used as a proxy for recharge. Although we did not have neighboring streams with contrasting subsurface and surface hydrology, in this study we estimated the average delay associated with High Cascade systems relative to Western Cascade systems using a similar approach.

[17] Five pairs of low-order High Cascade and Western Cascade streams were selected based on (1) high proportion of either High or Western Cascade geology in contributing area, (2) availability of overlapping time periods for streamflow records, and (3) spatial proximity. Cross correlation between the High Cascade and Western Cascade streams, and autocorrelation for the Western Cascades stream, were computed for each pair using methods described by *Box and Jenkins* [1976]. The average lag between the Western and High Cascade streams was estimated as the shift (in days) of the center of mass of the cross correlation function relative to the autocorrelation function. The center of mass was computed over the range of lags with a positive temporal correlation.

[18] To examine time lag response in higher-order streams incorporating both High Cascade and Western

Cascade influences in their drainage area, this analysis was repeated for the 6 sites along the main stem McKenzie. In this case, an arbitrary Western Cascade stream (Lookout Creek) was selected as the reference stream, and relative delays were determined for each of the 6 sites. The relationship between this delay and percent High Cascade contributing area was then determined.

4. Results

[19] Unit area hydrographs for High Cascade and Western Cascade streams with similar drainage areas reveal the contrasting hydrologic regimes of the two regions (Figure 2). The High Cascade hydrograph (McKenzie River at Belknap) depicts much more uniform flows with muted winter peaks, slower rates of recession, and higher summer base flows that remain nearly constant throughout the summer dry season. Winter flows are only 3–4 times higher than summer flows. In contrast, the Western Cascade stream (Little North Santiam at Mehama) exhibits a much flashier and more variable hydrograph, with winter peak flows that are several orders of magnitude greater than summer base flows.

4.1. Correspondence Between Geology and Streamflow Volumes

[20] Historical averages of low flow volumes show a strong relationship with geology for both low- and higher-order streams. Low-order streams that are predominately sourced in the High Cascades maintain 4–5 times the summer streamflow volumes (per unit drainage area) relative to those primarily sourced in the Western Cascades (Table 1 and Figure 3). Further, when streams draining areas with both High Cascade and Western Cascade rocks are examined, the log-transformed mean August streamflow, normalized by drainage area, shows a near-linear relationship ($R^2 = 0.76$; least squares linear regression is significant at 1% level) with the proportion of High Cascade geology in the contributing area (Figure 3). Mean annual flow, on the other hand, shows no significant relationship with geology which is not surprising given similarities in total annual precipitation over the two regions.

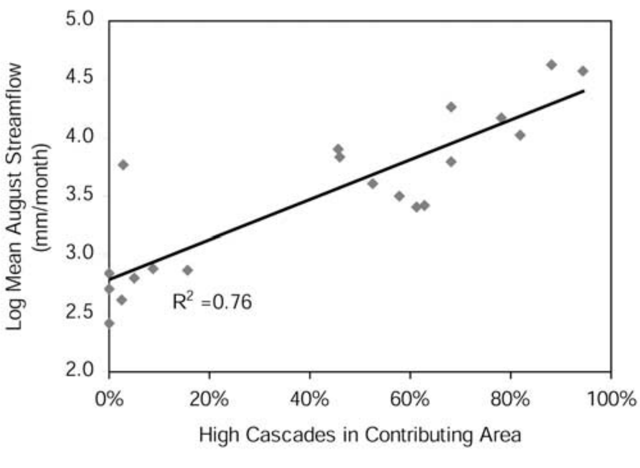

Figure 3. Relationship between mean August streamflow and percent High Cascade geology in contributing area for low-order streams.

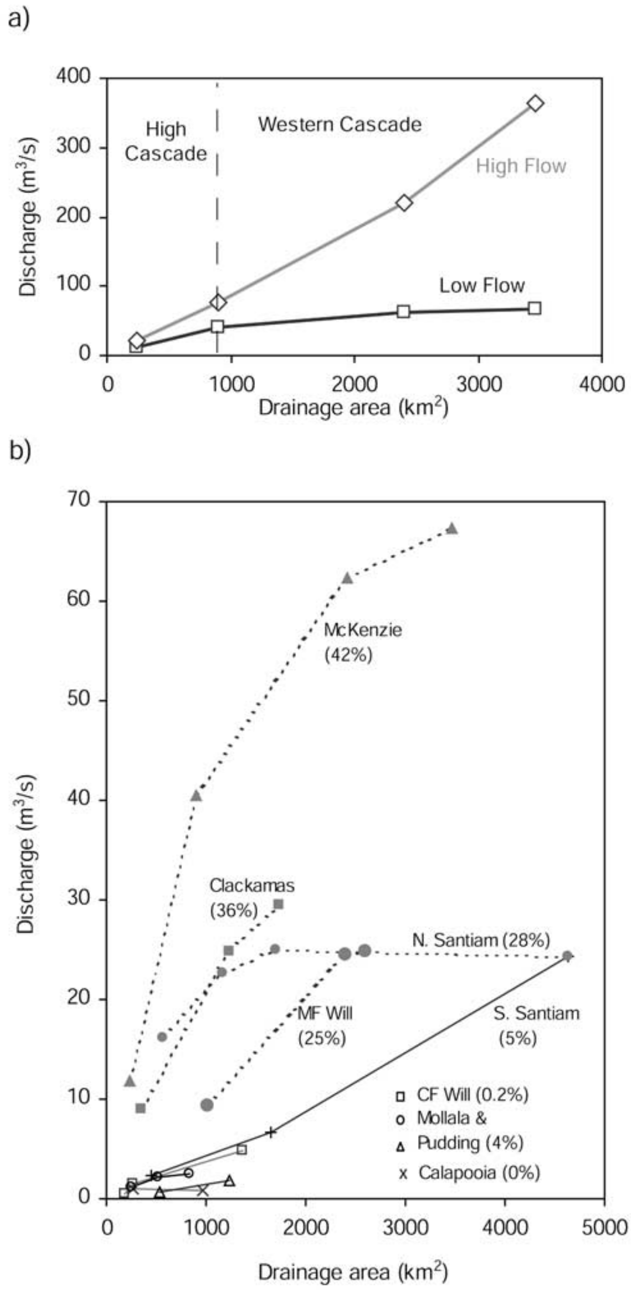

Figure 4. Discharge-drainage area relations showing impact of High Cascade contributions for (a) gauges along the McKenzie River at high (1 March 1950) and low (1 September 1950) flow and (b) east-west trending subbasins of the Willamette at low flow (1 September 1950). Percentages of High Cascade basin area shown in parentheses.

[21] Larger streams such as the McKenzie amass an increasing proportion of Western Cascade geology with longitudinal distance downstream, resulting in a nonlinear discharge-drainage area relationship (Figure 4a). During the summer, most of the water in the McKenzie is sourced from the High Cascades, producing a convex upward trend. During the winter wet season, on the other hand, most streamflow is derived from the surface and shallow subsurface runoff system in the Western Cascades, producing a

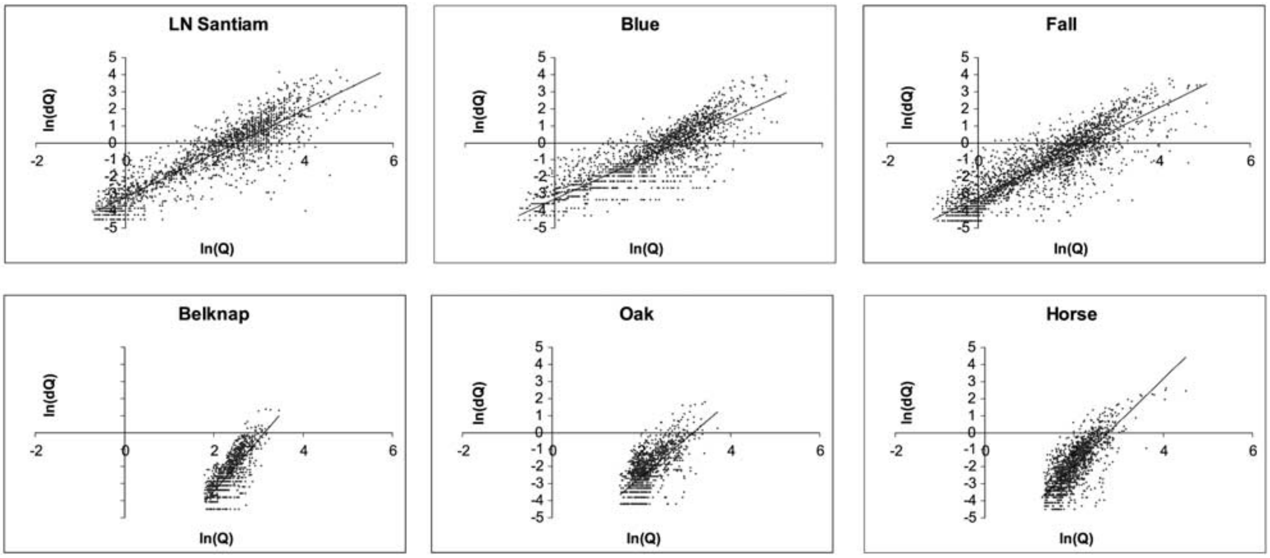

Figure 5. Log(dQ) versus Log(Q) relationships for three predominantly Western Cascade (LN Santiam, Blue, and Fall) and three predominately High Cascade (Belknap, Oak, and Horse) streams.

concave upward relationship between drainage area and discharge. The shape of the discharge versus drainage area curve is quite diagnostic for the proportion of basin area classified as High Cascade for other westward flowing Willamette basins as well (Figure 4b). Basins with a high proportion of High Cascade geology show a characteristic convex upward trend (i.e., McKenzie), with the inflection denoting the boundary between the High and Western Cascade provinces. Basins sourced entirely within the Western Cascades (i.e., S. Santiam), on the other hand, display a linear increase of discharge with drainage area.

4.2. Recession Analysis

[22] The two provinces also differ in characteristic recession behavior, as revealed by the relationship between log(dQ) and log(Q) and the associated linear regression models across the continuum of High and Western Cascade streams. Both stream types maintain a reasonably log-log linear relationship between flow and recession rate, although High Cascade streams appear to have a curvilinear upper envelope, suggesting that the rate of change of flow decreases at higher flows (Figure 5).

[23] These recession characteristics suggest that High Cascade streams more closely resemble the flow behavior of Western Cascade streams at particularly high flows, as indicated by the reduced slope of the log (dQ) versus log (Q) relationship. This pattern of response is consistent with an interpretation of the High Cascade system as comprised of a deep aquifer that dominates the low flow end of the curve, with some shallower subsurface flow paths that become active at higher flows, while Western Cascade response almost entirely reflects the dominance of shallow subsurface flow paths. Intercepts also differ between Western and High Cascade streams with higher intercepts (less negative) associated with the Western Cascades. A higher intercept in the log(dQ) versus log(Q) relationship indicates more rapid recession and thus a more efficient drainage system. Steeper hillslopes and higher drainage densities contribute to this efficiency. In contrast, the many spring-fed High Cascade streams tend to have very flat recessions at the low flow end, hence lower intercepts.

[24] *Brutsaert and Niebert* [1977] argue that the Boussinesq equation will produce a slope of 3 in the log(dQ)/log(Q) relationship for short-time solutions, and 1.5 for longer time solutions. Thus the log(dQ)/log(Q) behavior of

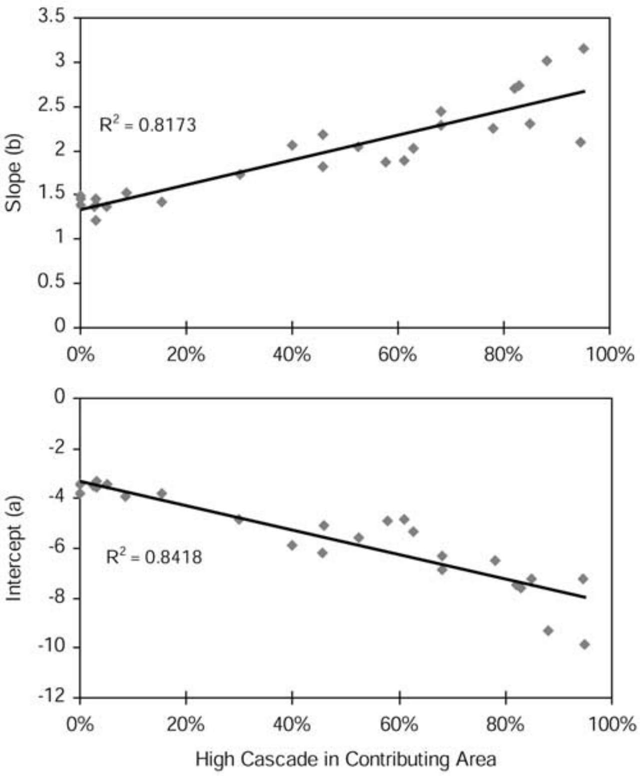

Figure 6. Average slope b and intercept a of log(dQ)/log(Q) relationship with percent High Cascade contributing area.

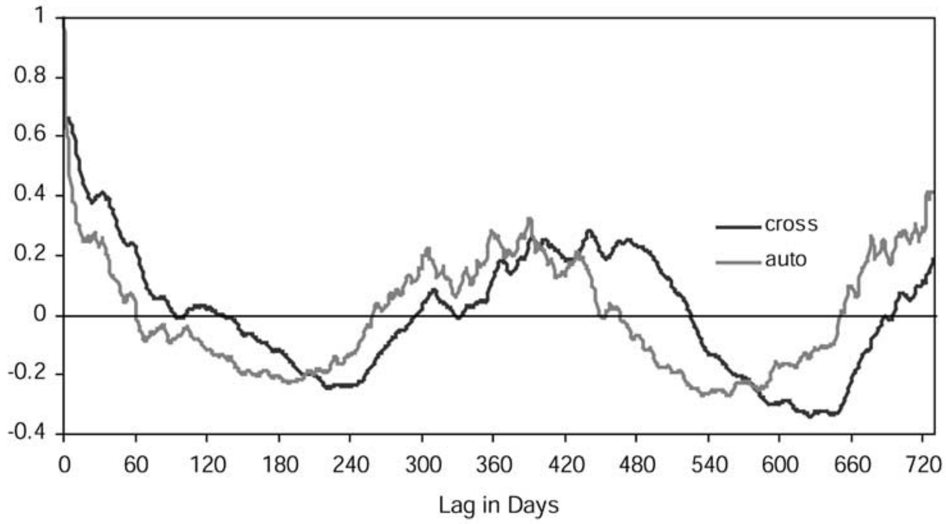

Figure 7. Cross-correlation functions for McKenzie at Clear Lake (High Cascade) against Blue River (Western Cascade); showing shift in days relative to autocorrelation function for Blue River.

systems that respond more quickly (i.e., steep, shallow subsurface aquifers) will generally reflect a slope of 1.5 corresponding to the longer time solution. Mean slope values for High Cascade dominated streams range between 2–3, while slopes for Western Cascade streams are closer to 1.5. High Cascade systems therefore suggest response characteristics of an aquifer that remains close to fully saturated while the mean slope of the Western Cascade streams reflect conditions that are less than fully saturated. At very high flows, slopes of the High Cascade relationship tend to reduce; suggesting the transition to a different (shallow subsurface) flow system with much shorter timescales.

[25] We emphasize that in addition to geologic controls on rock permeability and aquifer characteristics, recession behavior of High Cascade system may result from the greater prevalence of seasonal snowmelt as opposed to rain and rain-on-snow as the primary sources of recharge in the often lower elevation Western Cascades. However, parameters estimated for relatively high elevation Western Cascade streams, such as East Humbug, still fall within the range expected for Western Cascade streams (Table 1). This suggests that geology is the dominant factor controlling Western and High Cascade streamflow distinctions.

[26] Further evidence of the extent of geological control is implied by the mean responses of the log(dQ)/log(Q) relationship across a population of streams with varying proportions of High/Western geology and elevations (Figure 6). The strong linear relationship between recession characteristics (slope and intercept) and percent High Cascade geology, regardless of elevation, suggests that properties related to the geology exert first-order controls on recession behavior.

4.3. Cross-Correlation Analysis

[27] Consistent with the slower rates of recession associated with High Cascade systems, the timing of response to winter recharge is delayed for High Cascade systems. This delay is evident in the comparison between the cross-correlation function (between High and Western Cascade streams) and the autocorrelation function associated with the Western Cascade streams. Figure 7 provides an illustrative example; other pairs behave similarly.

[28] When delay is quantified as the difference in center of mass between the cross and autocorrelation function, the response of High Cascade streams is delayed, on average, 30 days relative to Western Cascade streams (Table 2). These values are significantly shorter than the 47–137 day time delay estimated by *Manga* [1999] in a similar analysis that compared runoff and spring-dominated streams on the eastern side of the Cascades. The difference may lie in the steeper topography, hence assumed hydraulic gradients, on the westside of the Cascade crest, resulting in more rapid response. At larger scales, for a series of streams along the McKenzie, relative to a reference Western Cascade stream (Lookout Creek), delay increases linearly as proportion of High Cascades increases (Figure 8).

5. Discussion

[29] Using a geologic framework as a basis for hydrograph analysis provides a broad scale characterization of flow regimes at multiple scales along the western side of the Oregon Cascades. By classifying the region into High Cascade and Western Cascade geologic provinces, two end-member hydrologic behaviors emerge that differ in terms of magnitudes of summer low flows, recession dynamics and the timing of seasonal response to winter recharge. High Cascade end-members show total annual

Table 2. High Versus Western Lag Time

Western	High	Lag, days
East Humbug	Breitenbush	6
L. N. Santiam	N. Santiam	25
Lookout	SF McKenzie	14
Molalla	Clackamas	34
Fall Creek	Salmon Creek	22

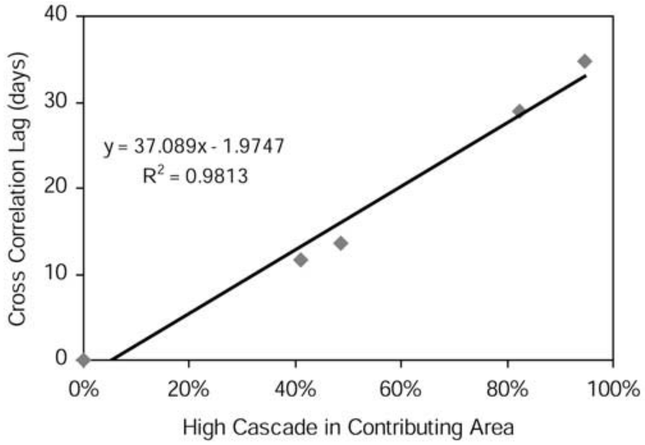

Figure 8. Estimation of lag (difference between auto and cross correlation function) between Lookout Creek (Western Cascade) and streams along the McKenzie with varying proportions of High Cascade contributing area.

flows comparable to Western Cascade end-members but 4 to 5 times higher summer low flows, when normalized by drainage area. High Cascade end-members also show slower recession rates and evidence of two-phase recession behavior that includes a relatively fast response to winter storm events, but is dominated by slower and deeper groundwater flow. Finally, High Cascade streams reflect a 30–40 day delay in the timing of response to winter recharge.

[30] In streams that include both geologic types in their contributing area, there is a surprisingly consistent and predictable relationship between the relative proportion of High Cascade and Western Cascade geologies and key aspects of hydrologic response. Total summer monthly streamflow volumes, slope and intercept of master recession curves, and relative delay of response to winter recharge are all linearly related to the percent of High Cascade geology in the contributing area. These results give us some confidence that useful quantitative estimates of low flow hydrographs can be extrapolated from gauged to ungauged catchments in this area, using a geologic framework as the basis for extrapolation. One caveat is that these values represent historical long term averages, and there may be variation in these relationships under different climatic conditions, i.e., between wet and dry years.

[31] The above analysis suggests two distinctive hydrologic mechanisms that control base flow response in this region. The geologic partitioning into High Cascade and Western Cascade to some extent combines the effects of elevation-driven differences in rain- versus snow-dominated precipitation, and geologic controls on drainage efficiency. The linear response of both timing and magnitude of flow regime to percent High versus Western Cascade geology, regardless of mean basin elevation, suggests that geology has a strong direct (i.e., via flow path, hydraulic gradient and conductivity) control on the response. The observed streamflow behavior is consistent with an interpretation of the Western Cascades as dominated by a well-developed flow network of shallow subsurface flow paths, along steep gradients with high lateral conductivities. High Cascade behavior is consistent with a deeper groundwater system with some rapidly drained shallow subsurface flow paths accessed during high flow periods. Field surveys showing the importance of large springs as primary sources for many High Cascade streams support this interpretation [*Stearns*, 1929; *Ingebritsen et al.*, 1992; *Manga*, 1996, 1997, 1999; *Grant and Tague*, 2002]. Further research using isotopic tracers and other techniques is needed to better resolve these flow path distinctions as well as the relative importance of snowmelt as a key control.

6. Conclusion

[32] Geology and geomorphology are often the dominant controls on flow regimes through their direct effect on hydrologic pathways, storage properties, and relief, and indirectly through their effect on meteorologic forcing. Analysis of summer streamflow regimes in the Oregon Cascades suggests a geological framework provides a useful basis for interpreting and extrapolating hydrologic regimes in this region. Although the mountainous volcanic landscapes of the western slopes of the Cascades have many distinctive attributes that lend themselves well to this kind of analysis, we maintain that the degree to which geology affects streamflow in this region is not unique. This paper provides an illustrative example that suggests that progress toward resolving the problem of predicting streamflows in ungauged basins can be made by explicitly structuring the analysis of streamflow using geo-hydrologic landscape types: broad regional areas defined by similarity in the physical and hydraulic properties of underlying rocks, history of landscape evolution, and key processes mediating flow. Results from this example suggest that a major task within the Predictions in Ungauged Basins initiative may be to identify these geo-hydrologic landscape types and develop a multiprong analysis to evaluate their relationships with flow regimes.

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