7 A Geomorphic Basis for Interpreting the Hydrologic Behavior of Large River Basins

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Many of the processes controlling runoff at both small and large scales are linked to the underlying geomorphology of a region. The westward-flowing tributaries of the Willamette River in western Oregon flow perpendicular to regional geologic trends, affording the opportunity to examine effects of geomorphology on streamflow. The interaction of geologic substrate, topography, and climate determines the overall surface water discharge regime, including the shape and timing of the annual hydrograph. Drainage density, reflecting the hydraulic transmissivity of the underlying rocks, influences the efficiency of the channel network to transmit water during individual storm events. An understanding of the physical and biological responses of watersheds to human modifications, including reservoir and forest management, requires appreciation of the broader geomorphic framework in which such changes occur.

INTRODUCTION

For much of its history, the hydrologic sciences have concentrated on relatively modest space and time scales. During this century, much hydrologic research has focused on plot, field, or small watershed studies, and addressed problems of water input, throughput, storage, and consequences for physical and biological processes that could be measured over time scales of minutes to seasons to years. Despite the fact that human activities, including reservoir management, irrigation, shifting land use, and urbanization were modifying flow regimes of rivers and landscapes at unprecedented rates, scant research examined these impacts and their consequences over spatial scales of large watersheds and regions, or timescales of decades to centuries. The result has been that our ability to transform river systems has far outdistanced our ability to understand the implications of those transformations.

The past two decades, however, have witnessed a dramatic increase in the scales and objectives of hydrologic science. Driven by concerns of impending global climate change, loss of biodiversity, fragmentation of river systems (i.e., Dynesius and Nilsson, 1994), and deteriorating water quality (i.e., Smith et al., 1987), hydrologists are beginning to examine the behavior of river systems at regional, continental, and even global spatial scales, and to consider the effects of environmental changes well into the next century. The difficulty of interpreting cause-and-effect relations increases markedly as the temporal and spatial scales of inquiry expand, however, because the hiearchy of controlling processes shifts with scale, and opportunity for experimentation and direct observation commonly diminish with increasing scale. Processes that strongly influence streamflow generation at the scale of small- to moderate-sized catchments, e.g., subsurface flow and channel routing, all but disappear at the scale of larger catchments, where they are replaced by other processes, such as regionally and topographically controlled precipitation patterns. Understanding controlling processes at appropriate scales has become a fundamental challenge to hydrologists (National Research Council, 1991).

Many of the processes controlling runoff at both small and large scales are linked to the underlying geomorphology of a region. This chapter examines how geomorphology controls runoff generation processes in watersheds with drainage areas of 10^2 to 10^4 km^2. Using examples from the Willamette River Basin in western Oregon, I consider how the flow regime of channels is determined by the interaction of climate and intrinsic geomorphic controls. Finally, I discuss the utility of this geomorphic perspective for evaluating human modifications of the fluvial system.

STUDY AREA

The area of the Willamette River Basin is more than 11,000 km^2 and includes several large tributary river systems draining the central Oregon Cascades: the Clackamas, N. Santiam, S. Santiam, McKenzie, and Middle Fork Willamette Rivers (Figure 1). Within the Willamette River Basin, sharp contrasts in climate, geology, and topography are expressed along an east-west transect (Figure 1). These zonations are also reflected in the soils and vegetation type and productivity. Major tributaries of the Willamette, including the McKenzie, Santiam, and Clackamas Rivers, generally flow westward; the upper reaches of the McKenzie and Santiam trend north-south, however, as they follow the western margin of the fault-bounded High Cascade province (Sherrod and Smith, 1989). Because of their orientation orthogonal to major topographic and geologic trends, the rivers cross three biogeoclimatic zones: (1) the High Cascades, with elevations >1200 m where most precipitation falls as snow, is underlain by glacial deposits and <2 million year (MY) old, porous, volcanic rocks; (2) the Western Cascades, with elevations of 400 to 1200 m where precipitation falls as rain and snow, is underlain by 3.5 to 25 MY old, deeply weathered but relatively impervious, volcanic rocks; and (3) the Cascade foothills and Willamette Valley, with elevations of less than 400 m where most precipitation falls as rain, is underlain by alluvium and > 25 MY old sedimentary and volcanic rocks (Figure 1). Portions of the High and Western Cascades basins have been modified since 1950 by timber harvest, roads, and dams; the Willamette Valley has been extensively modified since the middle of the last century by agriculture and urbanization. Timber harvest and road construction have affected little of the high-elevation zone, which includes extensive federal wilderness, but up to 25% of mid-elevation public forestlands and 100% of some low-elevation private lands have been harvested. Large dams have been constructed on Willamette River tributaries mostly below 200 to 400 m. Each of the five large river systems has historical gaging records dating back to the early part of this century from up to 20 nested subbasins, each ranging from 1 to 5000 km^2.

GEOMORPHIC CONTROLS ON HYDROLOGY AT THE PROVINCIAL SCALE

Geomorphology, including both geomorphic processes and landforms, exerts both direct and indirect controls on the pattern, timing, and volume of runoff generated within a basin (Figure 2). At the scale of physiographic provinces, the natural (i.e., uninfluenced by human activities) flow regime is determined by two factors: (1) the broad-scale interaction between geology and climate establishes the overall pattern of runoff at the annual scale (i.e., amount, seasonality) and (2) drainage network structure and longitudinal organization of the river determines the timing and rate of runoff for individual storm events.

Effects of Climate, Topography, and Geology

The regional climate determines the overall volume, seasonality, form (i.e., rain vs. snow), and areal distribution of precipitation. Geology strongly influences the topography and landforms of a region and determines the moisture holding and transmissivity properties of the soil and regolith; these properties also interact with climate to determine the distribution of vegetation. The interaction of climate and geology, as mediated by topography, soils, and vegetation, determines the distribution and intensity of precipitation by elevation, the precipitation state (i.e., rain, snow), the potential for

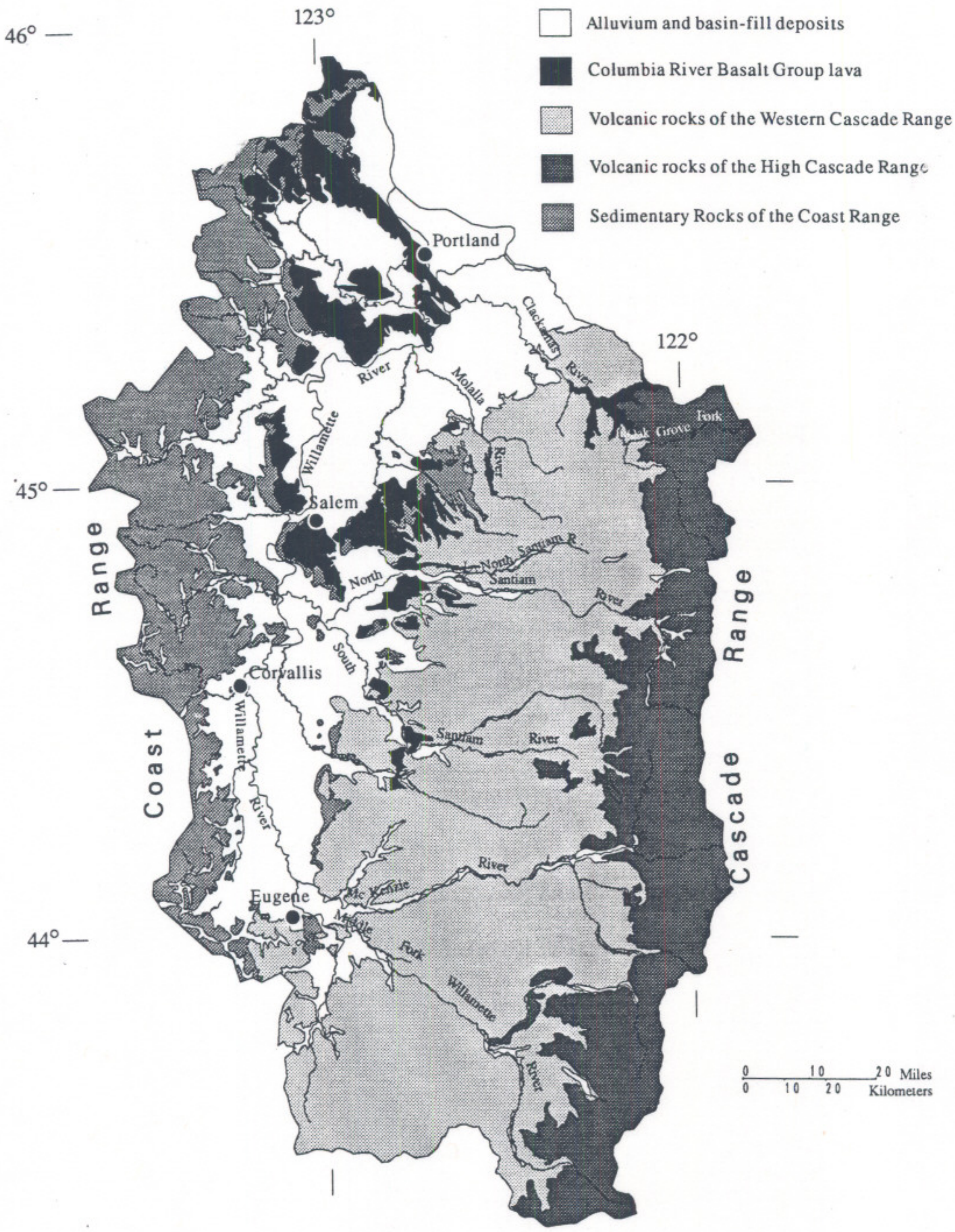

FIGURE 1. Location map showing geology, topography, and trends of major rivers, Willamette River system, Oregon.

storage on the landscape or in the soil mantle, the loss of moisture through evapotranspiration, and the rate that precipitation is transformed into runoff.

The broad geographic setting, as defined by climate, geology, soils, topography, and vegetation, therefore strongly influences riverine systems over ecologically relevant time scales (Schumm and Lichty, 1965). Because all of these factors operate simultaneously in most rivers, we have a poor understanding of how they interact to affect hydrologic behavior and stream and riparian zone

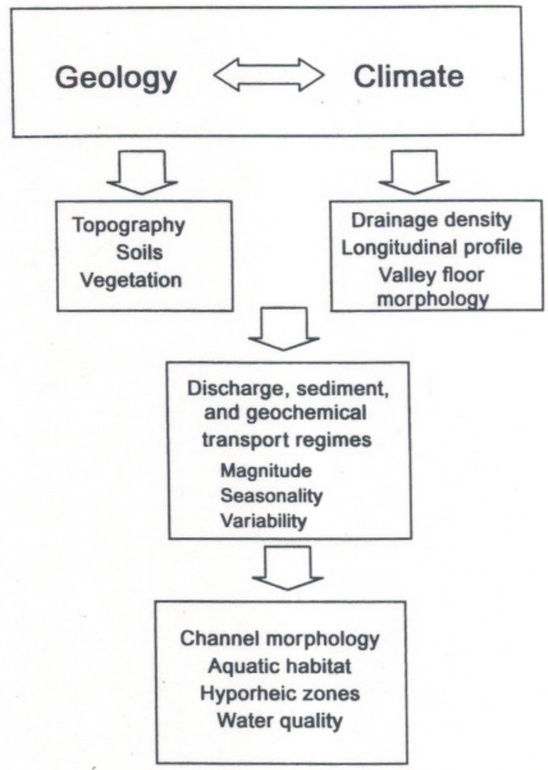

FIGURE 2. Conceptual model of effects of geomorphology on hydrology and other watershed processes.

conditions. At the provincial scale, however, their separate influences on the resultant hydrograph can be disentangled.

This can be observed in a comparison of mean monthly discharges for five unregulated streams draining watersheds with different geologic and topographic conditions in the upper Willamette Basin, using streamflow data from Moffat et al. (1990), and geological mapping and characterization by Ingebritsen et al. (1991) (Table 1; Figure 3). The five watersheds all have approximately the same drainage area, ranging from 250 to 500 km^2. Two distinct patterns of annual runoff are observed: the Little North Santiam, Molalla, and South Santiam Rivers all have sharp increases in runoff in the late fall with peak runoff during the winter months, a long period of declining runoff

TABLE 1
Topographic and Geologic Characteristics of Five Watersheds Shown in Figure 1

Watershed	USGS station No.	Drainage area (km^2)	Elevation (m)	Geology
Little North Santiam	14182500	290	805	17–25 ma andesite
Molalla River	14198500	250	887	7–17 ma andesite
South Santiam River	14185000	450	875	17–25 ma andesite
Oak Grove Fork	14209000	330	1140	<7 ma andesite
Clackamas River	14209500	500	1088	7–17 ma andesite

Data from Ingebritsen, S. E., Sherrod, D. R., and Mariner, R. H., *J. Geophys. Res.*, 97, 4599, 1991.

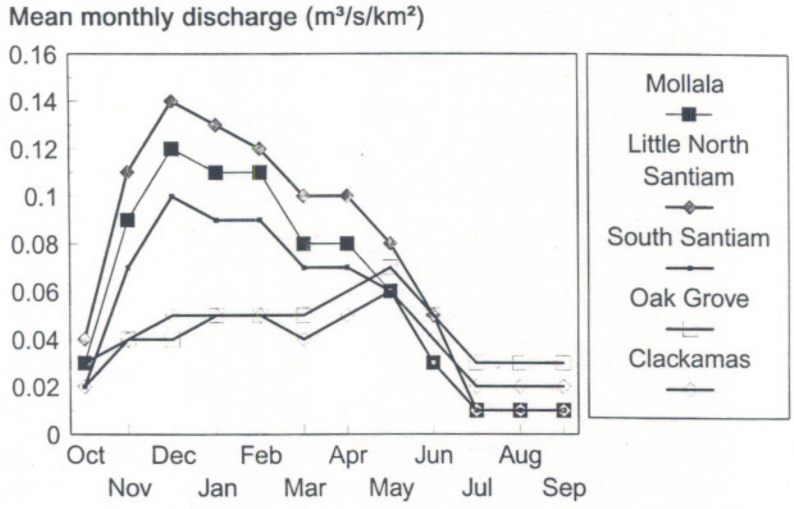

FIGURE 3. Mean monthly unit discharges for Western and High Cascade basins listed in Table 1. (Data from Moffat et al., 1990.)

during the spring, and constant low flows during the summer. The upper Clackamas and Oak Grove Fork of the Clackamas, on the other hand, have much less variable annual hydrographs with much less pronounced rises during the fall and winter months, late spring peak flows, and more sustained, higher low flows during the summer months. During the winter peak flow months, mean monthly flows for the Clackamas streams are half of the mean monthly flows for the other streams on a unit area basis; conversely, average summer low flows in the Clackamas streams are more than twice as high (Figure 3).

These differences can be explained by the interaction among climatic, topographic, and geologic factors. The Little North Santiam, Molalla, and South Santiam drainages are at lower elevations (Table 1), and tend to accumulate less snow during the winter than the two Clackamas streams. At elevations lower than 1200 m, winter storms are often a mix of both rain and snow, and peak flows occur from rapid melting of snowpacks during warm rainstorms from November to March (Harr, 1981). In contrast, most winter precipitation is snow at elevations higher than 1200 m, and peak flows occur during the spring snowmelt. With mean elevations ranging from 805 to 887 m, the three lower elevation watersheds have a greater proportion of their area subject to rain-on-snow melting and produce higher winter peaks than the two higher elevations, Clackamas watersheds that peak in the spring (Figure 3). The geology also contributes to this pattern in that the two higher elevation watersheds are underlain by younger, more porous volcanic rocks (i.e., thick piles of aa lava flows), which act as geologic reservoirs, storing groundwater during the melt season and releasing it slowly during the low flow summer months. The importance of this effect is readily observed in a comparision of flow duration curves for the five watersheds for mean daily discharges during August (Figure 4). The two Clackamas basins have significantly higher mean daily discharges than the other three watersheds.

Effects of Drainage Network Structure

Hydrologic regimes of large river basins also reflect the underlying architecture of the drainage basins themselves. The areal distribution of streams determines the rate at which water accumulates with distance downstream and the overall efficiency of the landscape for transforming precipitation and groundwater into streamflow. One measure of the drainage network structure is the drainage density, or total length of streams per unit area (km/km^2). The drainage density has been shown in other studies to reflect the hydraulic transmissivity of the underlying rocks (Carlston, 1963). Where

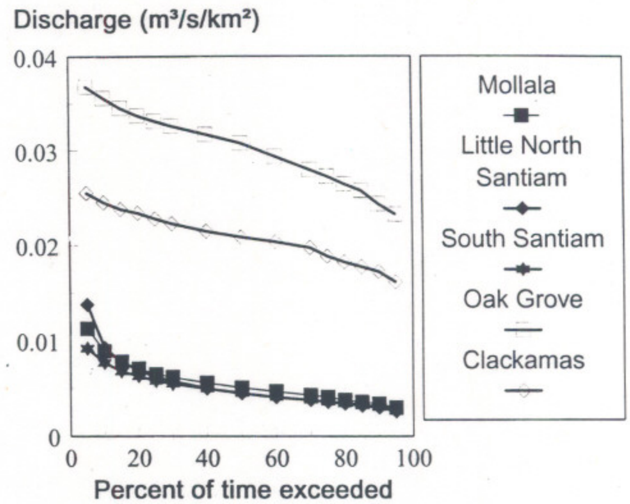

FIGURE 4. Flow frequency curves for mean daily flows during August for Western and High Cascade Basins listed in Table 1. (Data from Moffat et al., 1990).

rocks are highly permeable, transmissivity is high and a greater proportion of total precipitation is transmitted as groundwater. Conversely, where rocks are impermeable and transmissivity low, a greater proportion of incoming precipitation cannot infiltrate and must take a surface-water path downslope. Through geologic time, this greater proportion of surface-water flow develops discrete channel networks and higher drainage densities. Areas with highly permeable rocks should therefore support lower drainage densities than areas with less permeable rocks.

This is borne out in a comparison of drainage densities between the High and Western Cascades (Figure 5). The young, porous volcanic rocks of the High Cascade Province have very high hydraulic permeabilities and support a poorly integrated trellis to dendritic network of surface streams. Measured drainage densities from a random sampling of 1:24,000 U.S. Geological Survey ranged from 1.14 to 2.85 km/km^2, averaging 1.73 (FEMAT, 1993). In contrast, streams draining the older, less permeable rocks of the Western Cascade have well-developed dendritic drainage patterns and drainage densities ranging from 1.49 to 7.15 km/km^2, averaging 4.10.

Because the stream network is less dense and well integrated in the High Cascades, peak discharges tend to be less per unit area than in the Western Cascades for the same frequency of flow. A comparison of the rate of increasing discharge with drainage area for the 5% exceedance probability flow (Q_5) for 9 High and 44 Western Cascade Basin shows that unit discharges of this frequency are approximately 43% higher for the same drainage area in the Western Cascades (Figure 6). Assuming a zero-intercept, the corresponding empirical equations for the Q_5 flows (measured in m^3/s) as a function of drainage area (DA) in km^2 are

$$\text{Western Cascades:} \quad Q_5 = 0.13 \text{ DA} \quad (R^2 = 0.94, n = 44) \tag{1}$$

$$\text{High Cascades:} \quad Q_5 = 0.09 \text{ DA} \quad (R^2 = 0.98, n = 9) \tag{2}$$

Since the large trunk streams, such as the McKenzie or Santiam, drain the High Cascade province before entering the Western Cascade Province, the rate at which they accumulate discharge with distance might be expected to increase with distance downstream. Hence a curve of drainage area vs. discharge should be concave upward. This can be seen in the drainage area — discharge relation for the unregulated 5% exceedance probability flow for the McKenzie River (Figure 7). The McKenzie turns west out of the High Cascade Province at a drainage area of approximately 1000 km^2 and enters the Western Cascades (Figure 1). The upward concavity of this relation

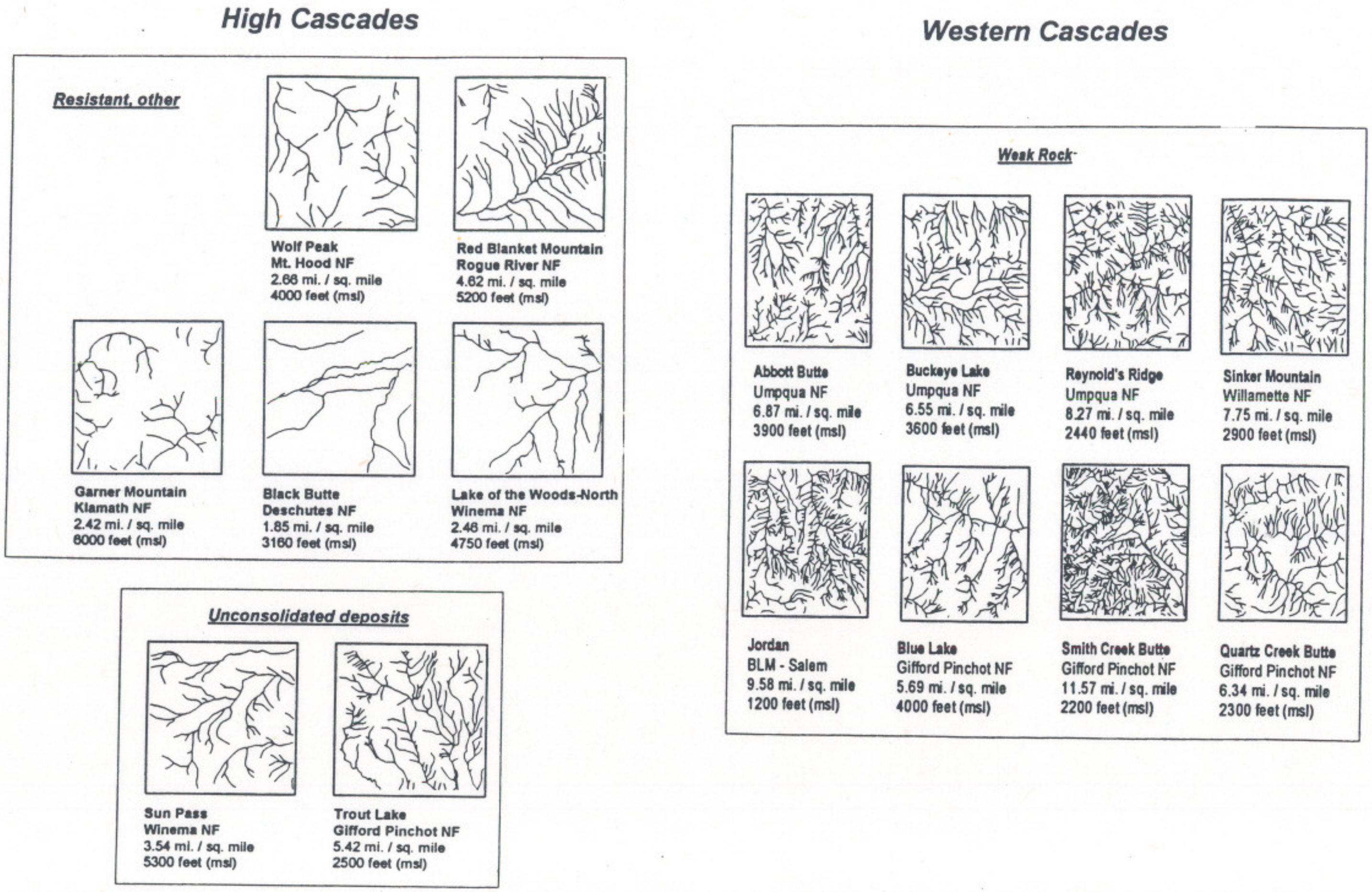

FIGURE 5. Examples of contrasting drainage densities and patterns in the High and Western Cascades. (After Forest Ecosystem Management Assessment Team, U.S. Dept. of Interior, 1993.)

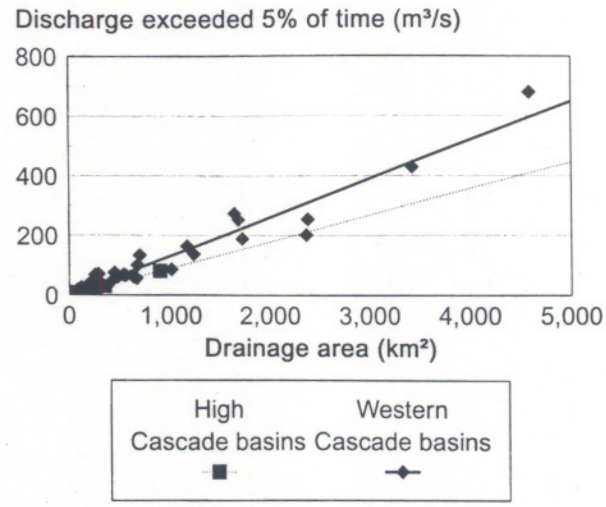

FIGURE 6. Relation between Q_5 (discharge exceeded 5% of time) based on mean daily flows and drainage area for selected Western and High Cascade Basins.

demonstrates the distinct nonlinearity between discharge and drainage area as province boundaries are crossed. The opposite trend is apparent in the low flow data (Figure 7). Although the data are limited, the downward inflection at a drainage area of 1000 km^2 shows that contribution to low flow is higher for the High Cascades relative to the Western Cascade portions of the landscape.

EFFECTS OF HUMAN ACTIVITIES ON HYDROLOGY

Human activities affect streamflow in this region in several ways. Direct human manipulation of flow regimes through dam regulation is a primary mechanism for altering the magnitude, frequency, and timing of runoff. These flow modifications occur at discrete locations (dam sites) and are well characterized by comparison of flow frequency relations before and after dam construction. A more subtle mechanism is land-use activities distributed throughout a watershed that alter flow regimes through various processes. These activities are not uniformly distributed through the landscape, and data on the extent of streamflow alteration due to land use is usually limited or absent. Forest

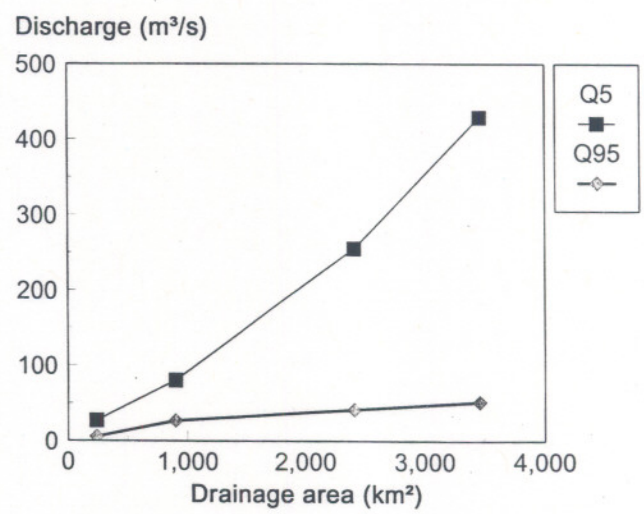

FIGURE 7. Relation between Q_5 and Q_{95} and drainage area for the McKenzie River watershed.

cutting and roads are the dominant land-use activity in the region considered here. This next section considers how the effects of both dam regulation and forest harvest activities may vary in relation to large-scale geomorphic controls.

Reservoir Management

Major flood control reservoirs were constructed on many of the tributaries of the Willamette River system from 1940 to 1970. Most of these reservoirs were located in the Western Cascades, although several small projects on the McKenzie (i.e., Carmen Smith, Trailbridge Dams) are located in the High Cascade Province. These reservoirs are primarily used for flood control during the winter and low flow augmentation of the Willamette during the summer, with hydroelectric power generated throughout the year at some sites. The common regulating schedule for the flood control reservoirs is to begin drawdown during the summer and early fall and continue until November when lowest pool volume is reached. The reservoirs then store flood flows during the winter months and are refilled during the spring to achieve full pool volume by early summer.

The effect of these flow alterations is to reduce the highest winter peaks and increase summer base flows. A comparison of flow frequency curves for the McKenzie River at Vida, which is located below three large dams, reveals that post-dam low flows increased by 47%, as indexed by the 95% exceedance probability discharge (Figure 8). High flows, as indexed by the 5% exceedance probability discharge, also increased slightly (8%) following dam construction. The major effect on peak flows, however, was to reduce the size of the annual instantaneous peak flows by 44%, from an average of 895 m^3/s between 1925 and 1962 to 504 m^3/s between 1968 and 1992 (Figure 9) (Minear, 1994). Overall, post-dam flows are less variable than pre-dam flows (Figure 8). Analysis of climate records during this period indicates that climate variability was not a factor in these changes (Minear, 1994).

From a regional perspective, the effect of dam regulation is to impose a more High Cascade type of flow regime on regulated Western Cascade streams. This is true both in terms of the hydrology and temperature regimes. Release of cold water from thermally stratified reservoirs mimics the contribution of cold water from groundwater sources in the High Cascades. The geomorphic and ecological consequences of propagating a colder and more uniform flow regime further downstream are not well understood. Potential consequences might include an extension of channel geometries and sediment sizes characteristic of High Cascade streams further downstream as channels adjust their dimensions. Reduced high flows and consequent reductions in transport of coarse sediment and large woody debris below dams might be expected to result in more stable

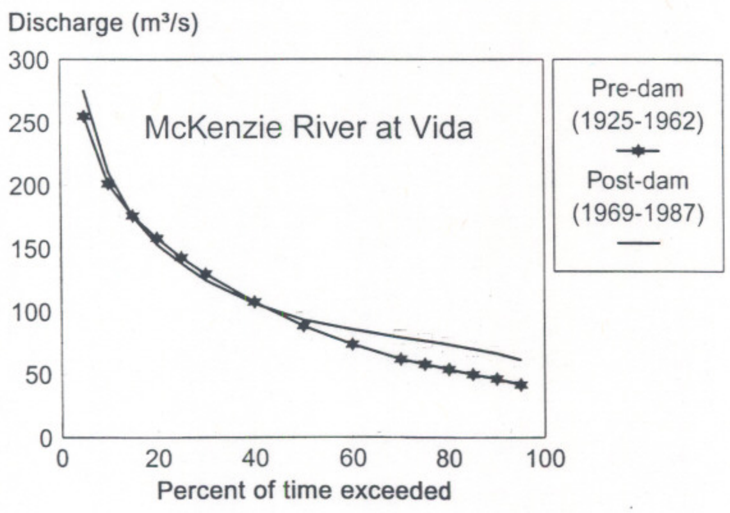

FIGURE 8. Pre- and post-dam flow frequencies based on mean, daily discharges. McKenzie River at Vida, OR (USGS gauge number 14162500). (Data from Moffat et al., 1990).

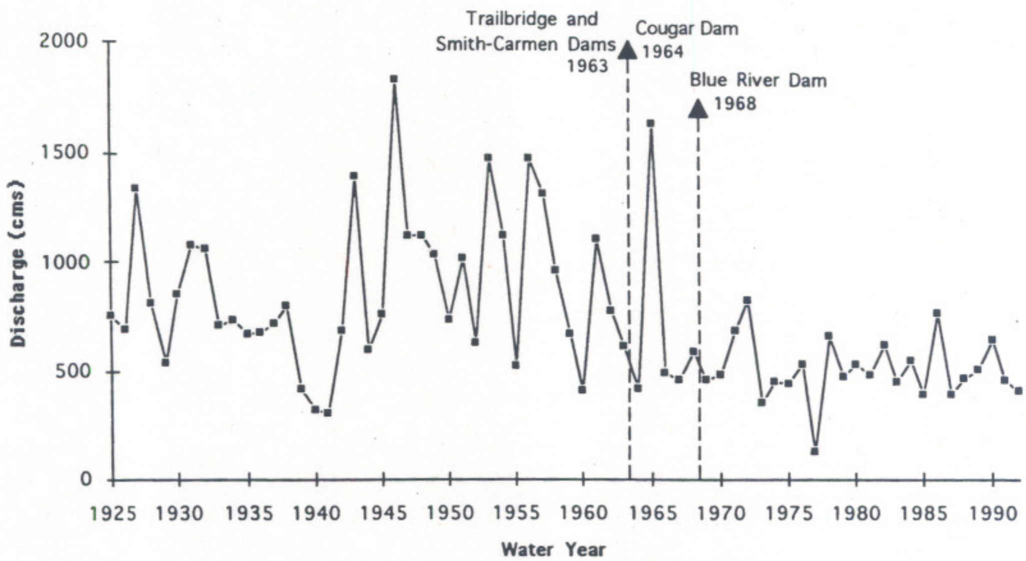

FIGURE 9. Maximum annual instantaneous peak discharges, McKenzie River at Vida, OR, 1925–1992 showing timing of upstream dam construction. (From Minear, P. J., M.S. thesis, Dept. of Fisheries and Wildlife, Oregon State University, 1994, 173.)

riparian surfaces and vegetation, and a similar downstream extension of aquatic diversity representative of the High Cascades. The latter effect may be most pronounced for aquatic invertebrates, which are highly sensitive to thermal regulation. Potential downstream changes in aquatic biota are complicated by the physical barriers to migration posed by the dams and reservoirs themselves in the fluvial system.

Effects of Forest Harvest Activities

The effects of forestry activities on streamflow have been hotly debated in this region, due in part to the equivocal results of more than 30 years of research into this question. Recent studies from more than 40 years of streamflow records in small and large basins with different levels of harvest activities have demonstrated that clearcutting and road construction can increase peak flows from 20 to 50% for small- to moderate-sized storms (less than a 2-year return period) (Jones and Grant, 1996). While the small watersheds examined (<1 km^2) were exclusively located in the Western Cascades, the larger basin pairs (up to 630 km^2) straddled both the Western and High Cascade Provinces. Much of the High Cascade Province is managed as wilderness where no logging is allowed, however, most of the cutting is concentrated in Western Cascade portions of the larger watersheds, and the observed changes in peak flows can only be applied with confidence there.

One reason for the sometimes contradictory results of research into effects of forest management on streamflow (e.g., Ziemer, 1981; Wright et al., 1990) is differences in the larger geomorphic context in which these studies occur. The response to forest cutting and road construction is likely to be different in watersheds whose hydrologic regimes are dominated by rain vs. rain-on-snow processes (Wright et al., 1990; McDonald et al., 1991). Differences in hydraulic transmissivity of the substrate and drainage density will also play a role. For example, a major mechanism proposed by Jones and Grant (1996) to explain the increases in peak flows observed in the Western Cascades was the extension and integration of the drainage network due to impervious forest roads and associated ditches. The effect of the road network potentially increased the drainage density by as much as 40%, thereby increasing the efficiency by which water moved downslope (Wemple, 1994; Wemple et al., in press). These density increases were measured for Western Cascade basins where the unaltered drainage density for the winter high-flow stream network was 3.0 km/km^2 (Wemple, 1994). If the same absolute increases in density after roading occurred in the High Cascades, where natural densities are half as high (1.5 km/km^2), the corresponding drainage density after roading would be approximately 2.59 km/km^2 or an increase of 73%. On the other hand, the gentler slopes and greater infiltration rates in the High Cascades might be expected to decrease the efficiency of roads in capturing subsurface flow, thereby offsetting the effect of roads.

Although speculative, these comments underscore the importance of understanding the regional coupling between geomorphology and hydrology in interpreting effects of human modifications to the landscape. At a minimum they suggest the need for extreme caution in applying results of studies conducted within one physiographic province to other areas.

CONCLUSIONS

These examples demonstrate that the large-scale geologic and topographic setting strongly controls important properties of hydrographs. Depending on the intrinsic hydrologic properties of geologic provinces, drainage density, and orientation of streams relative to province boundaries, the rate of change of discharge with drainage area may be either linear or nonlinear. Furthermore, this rate may vary with discharge and season. The consequences of these results for interpreting stream geomorphology and ecology, particularly the effects of human activities on streams are not well understood. Recognizing the importance of geomorphic controls on streamflow is the first step toward placing human alterations to hydrology in their proper context.

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RIVER QUALITY

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