# 2. The Geology of Puget Lowland Rivers

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**Abstract**

Regional and local geologic conditions encompass many of the influences that watersheds impose on their channels: watershed size, water and sediment delivery to channels, the geometry of channels, and the responsiveness of a stream or river to change. Restoration or rehabilitation projects that do not consider the limitations and opportunities posed by the geologic setting are likely to fail, because the newly created features will not be maintained by the geologic conditions and geomorphic processes active in particular locales. The framework of the Puget Lowland has been established by a long history of tectonic and depositional processes, but the major features that control stream and watershed processes are primarily the result of the last ice-sheet advance, culminating about 16,000 years ago, coupled with more localized postglacial modification of the landscape. The effects of geologic history and geologic deposits are expressed across a range of spatial scales, which in turn result in varying biological conditions in different parts of the river network and varying responses to watershed disturbance. As a result of these geologic differences, not all streams have the same level of biological activity, and so not all stream restoration efforts should strive for the same goals and objectives. Even the best of human intentions are likely to fall short of their goals if the tools of geology are not used to recognize those conditions that can limit the success of rehabilitation.

## Introduction

Stream and river channels are commonly described as "products of their watersheds," but this platitude does not convey the tremendous range of spatial and temporal scales over which a watershed influences channel form and channel processes. Regional and local geologic conditions, although rarely described with their fluvial consequences in mind, encompass many of those influences that watersheds impose on their channels: runoff patterns, sediment sources, channel gradient, hydraulic roughness, valley form, watershed size, and the responsiveness of a stream or river to change. The geologic setting of watersheds, and of individual stream reaches, will determine what types of channel morphology and habitat features occurred under natural conditions, and thus what restoration or rehabilitation objectives are appropriate and achievable. Conversely, rehabilitation projects that do not consider the limitations and opportunities posed by the geologic setting are doomed to failure—instream structures will be undermined by channel migration, imported gravel will be buried by the watershed contribution of mobile sediment, and the form of reconstructed channels will not be maintained by the geomorphic processes active in particular locales.

Yet the influence of geology on rivers and streams is not always straightforward. As a fluvial system evolves it becomes an agent of geologic change itself, modifying the same landscape that once determined its behavior. Escarpments are incised by gullies and streams; lowlands are filled with alluvium; and the topographic form of the landscape imposed by tectonic, volcanic, and glacial activity becomes modified by patterns of fluvial erosion and deposition along the drainage network.

The Puget Lowland (Figure 1) shows the interplay of recent fluvial activity superimposed on a much longer history of tectonic, volcanic, and glacial action. It now contains one of North America's premier sheltered waterways, Puget Sound, most of the major population centers of the Pacific Northwest, and once-abundant runs of Pacific salmon. Its counterparts to the north and south, the Georgia Depression and the Willamette Lowland, share many of the same elements of geologic history and fluvial activity. This discussion, although focused on the Puget Lowland, is therefore relevant throughout the humid western region of the Pacific Northwest.

## Overview of Puget Lowland geology

### *Tectonic Setting and Bedrock Framework*

The rocks and unconsolidated deposits of Washington (Figure 2a) record more than 100 million years of earth history. Knowledge of this history has been gained from over a century of careful study, and the story is still unfolding as a result of continued geologic research. The foundation of this landscape is incompletely displayed by rocks now exposed in the North Cascades along the eastern boundary of the Puget Lowland. They record a history of oceans, volcanic island arcs, and subduction zones, mostly of Mesozoic age (the geologic period 220 to 65 million years ago—Ma) but including some late Paleozoic components (in western Washington, as old as 275 Ma) (Frizzell et al. 1987; Tabor and Haugerud 1999; Tabor et al. 2001) (Figure 2b).

The original deposits of these now-metamorphosed Paleozoic and Mesozoic rocks of the Cascade Range are quite varied, suggesting that they formed in widely separated environments and probably far from ancestral North America. (The closest bona-fide "old" North American rocks crop out near Spokane.) These old Cascade deposits were brought together by late Mesozoic plate convergence at the western edge of North America (via subduction) and subsequent translation along the continental margin (via strike-slip fault motion), reflecting the persistence of tectonic activity in the Pacific Northwest at the leading edge of the North American continent.

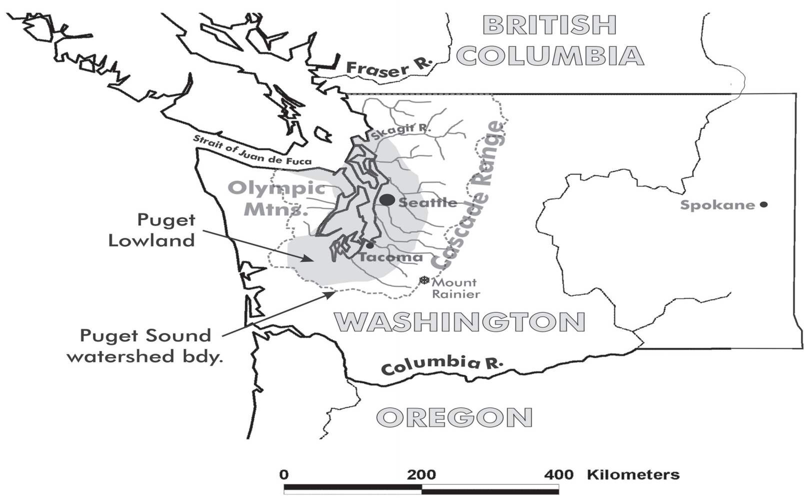


Figure 1. Index map of the Puget Lowland region.

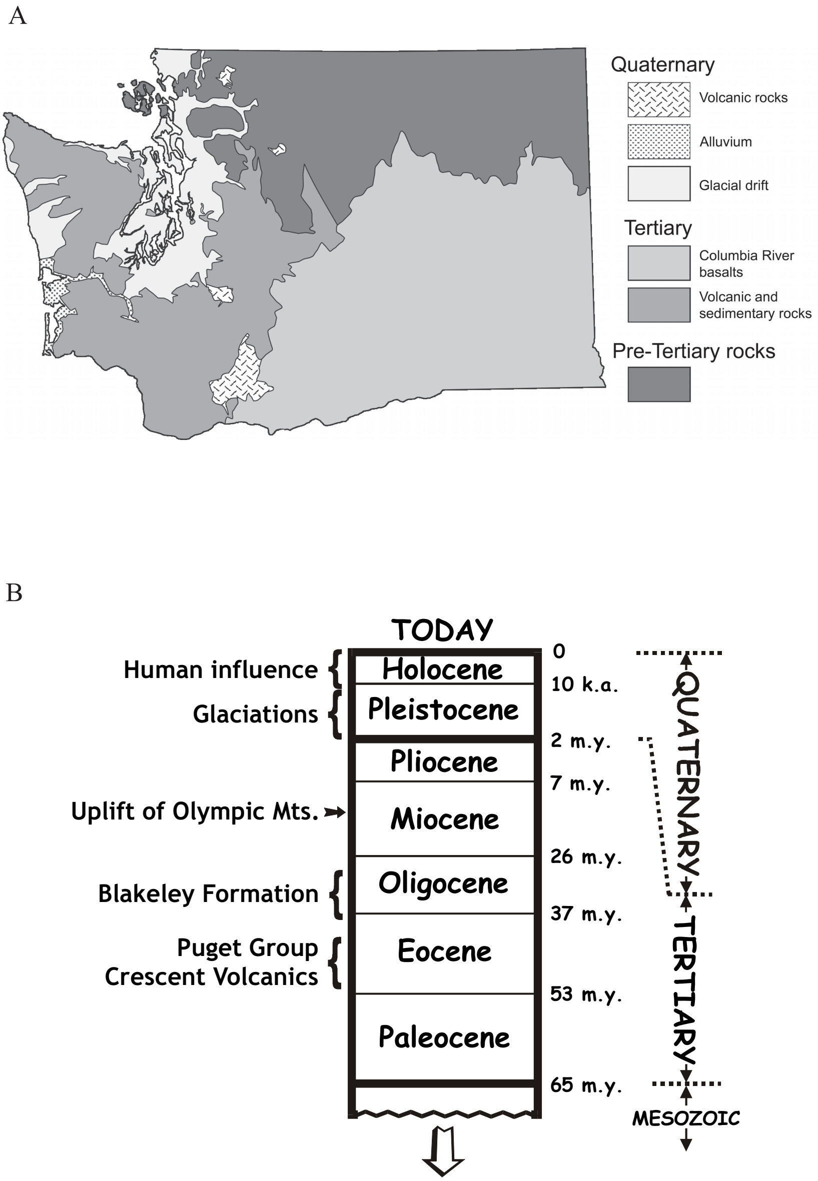


Figure 2. (A) Simplified geologic map of Washington State. (B) Time scale of geologic deposits and events for the Puget Lowland.

Middle and late Eocene (ca. 50 to 42 Ma) sandstone and volcanic rocks overlie these older rocks. During this time, large rivers flowed across an extensive (and subsiding) coastal plain that lay west of the modern Cascade Range and east of the modern Olympic Mountains (and probably east of Puget Sound as well) (Figure 3). This ancient river system produced the rocks of the Puget Group, whose relatively good resistance to erosion is responsible for the prominence of the Newcastle Hills in the central Puget Lowland, and whose abundant plant debris resulted in coal deposits that helped shape the nineteenth century economy and history of the region. Under the rigors of fluvial transport, however, these rocks tend to break down rather quickly, which is why the gravels of modern Puget Lowland rivers and streams overwhelmingly consist of glacially transported sediment derived from more resistant rock bodies farther north.

Subsequent reorganization of tectonic plates in the northeastern Pacific Ocean resulted in renewed plate convergence, subduction, and volcanism


Figure 3. Eocene physiography of the Pacific Northwest (modified from Christiansen and Yeats, 1992).

along the Cascade arc in earliest Oligocene time (about 35 Ma), followed by sedimentary deposition of the Blakeley Formation sandstone across the central Puget Lowland on what is now Seattle and Bainbridge Island. The modern-day form of the Cascade Range is not a direct descendant of this interval of tectonic and volcanic activity—the modern mountain range was uplifted less than 6 Ma (Cheney 1997), but it expresses a similar style of tectonic activity that has been episodically active over the last several tens of million years. Especially in southernmost Washington and in Oregon, the Cascade arc continues to be active, and volcanoes of the arc dominate the landscape (e.g., Mount Baker, Mount Rainier, and Mount Hood). They produce dramatic topographic relief but contribute only relatively weak and easily degraded gravel clasts to downstream rivers.

The Olympic Mountains, most completely described by Tabor and Cady (1978), form the western boundary of the Puget Lowland. They are part of a topographic high built by compression and shortening above the Cascadia subduction zone, driven by the convergence of the North American and Pacific plates. A horseshoe of high peaks along the southern, eastern, and northern part of the range (including Mt. Washington, The Brothers, Mt. Constance, and Mt. Angeles) is underlain by mostly submarine basalt of the Crescent Volcanics, erupted 55 to 50 Ma during rifting of the seafloor at the western edge of the continental margin. These rocks form the abrupt western boundary of the Puget Lowland as seen from the central part of the lowland.

In the core of the Olympic Mountains, enclosed by this horseshoe, lightly metamorphosed deep-water sandstone and shale underlie Mt. Anderson, Mt. Olympus, and the low country farther west. These sediments were largely derived from North America and are younger than (and were transported across) the Crescent Volcanics on their way to deeper water. They were finally deposited on the continental slope above the slowly deforming seafloor and then subducted east and beneath the same terrain across which they had just been transported. Radiometric dating and stratigraphic relationships suggest that uplift of the Olympic Mountains, which eventually raised these ocean-bottom rocks to their modern elevation by some 2 or 3 km, was underway by about 14 Ma (see Brandon et al. 1998, and references therein).

Why is the Olympic Mountains segment of the Pacific-North American subduction zone so much higher than segments to the north and south? The distribution of deep earthquakes indicates that beneath and east of the Olympics, where the trend of the continental margin changes from north to northwest, there is an arch in the subducted oceanic plate. Some geologists have suggested that this arch causes the greater uplift of the Olympics. Or perhaps the Olympics are higher because subduction forces more sediment beneath this part of the continental margin, a plausible consequence of the nearby outfalls of the Fraser and Columbia rivers. If this alternative proves to be correct, fluvial and landscape-forming processes are in fact interacting at a scale beyond any suggested in this chapter.

## ***Glaciations***

### *Quaternary History*

Although the evolution of the tectonic and bedrock framework of the Puget Lowland continues to the present day, most of these influences had been established by the beginning of the Quaternary period, that segment of geologic time defined as the last 2 million years of Earth history. During this period, oscillations in the earth's orbit around the sun have caused alternate warming and cooling episodes that have given rise to an extensive record of continental-scale glaciations. At least six invasions of glacial ice into the Puget Lowland have left a discontinuous record of Pleistocene glacial and interglacial intervals (Blunt et al. 1987). Originating in the mountains of British Columbia, this ice was part of the Cordilleran ice sheet of northwestern North America. During each successive glaciation, ice advanced into the lowland as a broad tongue first called the *Puget lobe* by Bretz (1913). All but the most recent of these advances are older than can be accurately dated with the $^{14}C$ technique, and so their detailed history is somewhat indeterminate.

This most recent ice-sheet advance into western Washington (Figure 4) was named the Vashon stade of the Fraser glaciation by Armstrong et al. (1965) (a *glaciation* is a climatic period of extensive glacial advance and retreat; a *stade* is a period of secondary glacial advance and retreat within a glaciation). Ice occupied the Puget Lowland about 18–15,000 calendar years ago; at its maximum, Seattle was buried by at least 900 m (3000 ft) of ice (Booth 1987; Porter and Swanson 1998). Most Puget Lowland topography is a direct product of, or at least shows a strong imprint from, this period of ice-sheet occupation. By comparison, recent geologic processes such as stream and wave erosion, landsliding, tectonic deformation, and volcanic eruptions have subsequently modified this topography only slightly.

### *Glacial Deposits*

The spatial extent (and the rates) of sedimentation during glacial times was widespread and voluminous. Nonglacial periods (which include the present day), in contrast, have experienced active deposition primarily in river valleys and at the base of steep slopes. Thus the modern landscape is underlain primarily by glacial sediments. The thickness of these deposits varies greatly, but across much of the Puget Lowland it exceeds several hundred meters, and locally the deposits extend over a kilometer below modern sea level where they rest upon an irregular bedrock surface. They are thus of critical importance in understanding the interaction of modern rivers and streams with their watersheds.

Most, although not all, of the glacial deposits exposed at the ground surface in the Puget Lowland are products of the advance and retreat of the Puget lobe during the Vashon stade. These sediments (Figure 5), collectively named Vashon Drift (*drift* refers to any deposit of glacial origin, whether deposited by ice or water), are divided into several units: *advance deposits*—lacustrine silt and clay deposited into proglacial lakes, followed by well-sorted sand and gravel ("outwash") carried by streams flowing from the ice sheet as it spread south; *till*—unsorted sand, gravel, silt and clay deposited beneath the ice sheet; *ice-contact* and *ice-marginal deposits*—comprising sorted and unsorted debris deposited adjacent to, or in some cases on top of, the ice sheet; and *recessional deposits*—well-sorted sand and gravel deposited by streams draining from the ice as the ice-front receded, as well as silt and clay deposited

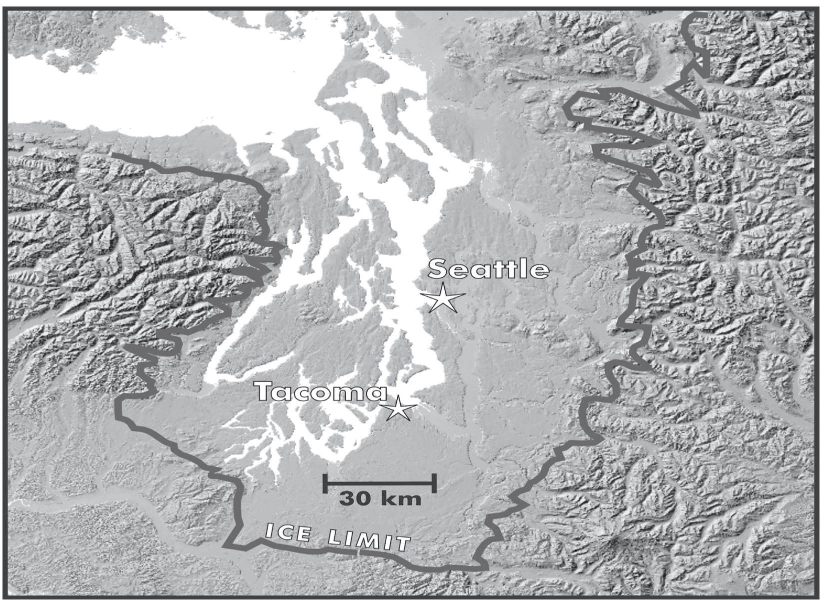


Figure 4. Ice limit of the Puget lobe during the most recent ice-sheet advance, the Vashon stade (redrawn from Thorson 1980 and Booth 1987).

in lakes dammed by the receding ice. In the central and northern Puget Sound, extensive deposits of *glaciomarine drift*—nonsorted sediment deposited off the front or the base of the ice sheet into marine waters—are also found.

These glacial deposits have a wide range of physical properties. From the perspective of hydrologic processes and stream-channel response, two of these properties—permeability and consolidation—are particularly important. Outwash deposits (both advance and recessional) compose the vast majority of permeable sediments found across the Lowland. They permit rapid infiltration and groundwater movement, they lack cohesion and thus are susceptible to fluvial erosion, and they supply abundant bedload-sized sediment to rivers and streams. Lacustrine deposits and till are the most widespread low-permeability materials, providing the dominant controls on groundwater flow and determining whether, and where, infiltrating groundwater will reach deeper aquifers. On sloping terrain, the superposition of highly permeable outwash over low-permeability lacustrine sediments determines the location of hillside seeps and springs; it gives rise to the geologic setting most closely associated with landsliding and other forms of mass-wasting (Tubbs 1974), which in turn provides the dominant source of sediment delivered to lowland rivers and streams (Reid and Dunne 1996). At shallower depths, a similar geologic setting is commonly found where permeable Holocene soils overlay the uppermost unweathered Pleistocene deposit, commonly till (and, locally, bedrock).

In contrast to permeability, consolidation is associated not with depositional environment but with stratigraphic position. Those sediments overrun

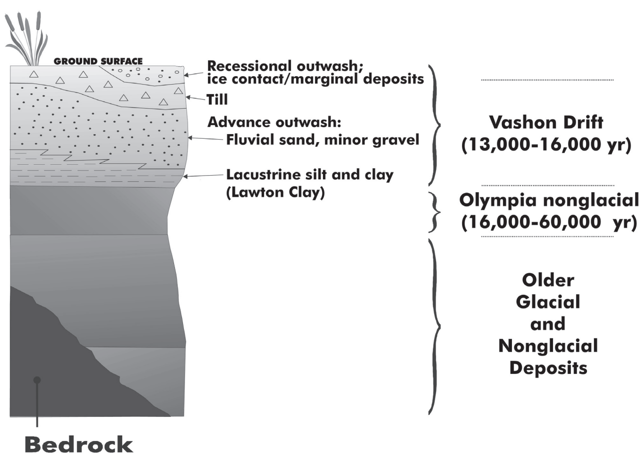


Figure 5. Stratigraphy of Vashon and pre-Vashon glacial and nonglacial deposits of the Puget Lowland.

by one (or more) ice-sheet advance display measurable overconsolidation and relatively high density (Olmstead 1969; Laprade 1982), important physical properties for determining erosion susceptibility and stream-channel morphology. Even noncohesive outwash, if dense and overconsolidated beneath Vashon till, will stand in dry near-vertical faces for many years or decades; cohesive overconsolidated deposits, such as till, may resist even active stream-channel erosion.

Pre-Vashon strata, both glacial and nonglacial, are consistently overconsolidated, but because they are exposed only sporadically across the Puget Lowland, they exert relatively little direct influence on rivers and streams. Where present at depth, they do have a variety of effects on groundwater flow and channel morphology because of their widely varying physical and hydrologic properties, a consequence of their equally varied origins in the multiple glacial and nonglacial periods preceding the Vashon stade (Troost 1999). They also display great variety in their geometry: buried river channels can provide groundwater conduits deep below the surface; lowland lake deposits may provide an effective barrier to groundwater flow but extend laterally only as far as the pre-Vashon lake in which they formed. Where modern stream channels flow over slopes that expose these strata, knickpoints can develop on the more resistant, typically fine-grained layers, imposing steps in the longitudinal profile of the channel that may persist for decades or longer.

In the mountains adjacent to the Puget Lowland, bedrock is the predominant geologic influence on channel morphology, but the valleys are commonly floored with a mosaic of stream deposits, talus, landslide debris, colluvium, and till. These deposits in large part date from an early, pre-Vashon stade of the Fraser glaciation named the "Evans Creek," but some deposits may have been formed in part during minor alpine glacial re-advances during the late Holocene (i.e., in post-glacial time). In the lower reaches of many of these same alpine valleys, valley-bottom deposits are overlain by fine sand, silt, and clay deposited by *upvalley*-flowing streams and in lakes dammed by the ice sheet that occupied the Lowland, beyond the valley mouths, during the Vashon stade.

### *Postglacial Processes and Deposits*

Rivers, landslides, waves, and volcanic mudflows have continued to modify the Puget Lowland landscape and to create deposits younger than those of the last glacial advance. Although not influential at the same scale as continental glaciations, these processes and their resulting products are locally significant. The sediments are uniformly unconsolidated but permeabilities vary widely, reflecting the variety of depositional process and parent materials.

The most dramatic of these processes has been the Osceola mudflow near the town of Enumclaw, deposited after the catastrophic collapse of the northeast side of Mount Rainier about 5,700 years ago. Subsequent erosion and redeposition of the abundant post-Osceola supply of volcanic debris eventually filled the previously marine Green/Duwamish River valley (Dragovich et al. 1994) from about the present city of Auburn north to Seattle's Elliott Bay.

Humans have also modified the Earth's surface in many parts of the Puget Lowland in postglacial time. Some of these modifications have had profound consequences for the region's rivers and streams, either by direct modification of the channels themselves or by alteration of the hydrologic and sedimentological regimes of their watersheds. As separate topics in their own right, these issues are left for discussion in other chapters.

### *Distribution of Deposits in the Puget Lowland*

Although a great variety of Quaternary deposits is found throughout the Puget Lowland, the characteristics of glacial and postglacial erosion and deposition have given rise to broadly predictable patterns of geologic materials across the modern landscape. In plan view, the landscape is mostly mantled by *till*, the compact heterogeneous deposit laid down most recently at the base of the Vashon-age ice sheet. Locally the till is thin or absent, revealing the underlying deposits, most commonly the sandy *Vashon advance outwash* (but locally some older and generally less permeable sediments as well). Extensive advance outwash deposits are also exposed in the walls of channels cut through the till, most commonly during ice-sheet retreat when voluminous meltwater discharges off of the ice sheet combined with alpine rivers draining the Cascade Range and Olympic Mountains.

Glaciomarine drift is also broadly exposed but its geographic extent is more limited, a consequence of the late-glacial history of the Lowland. This deposit, a product of subaqueous melting of the terminus of an ice sheet or the bottom of a floating ice shelf, is common but only in areas that were below sea level during ice retreat. Although global sea level (termed *eustatic* sea level) continued to rise following deglaciation of the Lowland, the earth's crust in the Puget Lowland also rose after deglaciation (Thorson 1989) in response to the weight lost by melting hundreds to thousands of meters of ice (termed *isostatic rebound*), just as it had depressed several thousand years earlier when the ice first advanced. The initial depression (and so also the subsequent uplift) was greater to the north than to the south because the ice was thicker to the north. At about the latitude of Seattle, isostatic rebound equaled eustatic sea-level rise. Thus marine deposits dating from the first opening of Puget Sound to marine waters after deglaciation are common only in the northern Puget Lowland and are not recognized south of Seattle (Pessl et al. 1989; Yount et al. 1993).

In contrast to the distribution of these deposits across broad areas of the Lowland, the distribution of the recessional outwash deposits is more narrowly focused. As the ice sheet retreated from its maximum position, meltwater drained into the axis of the Lowland but could not follow what would become its modern drainage path north and west out the Strait of Juan de Fuca, because the strait was still filled with many hundreds or even thousands of meters of ice. Instead, meltwater was diverted south along the margins of the retreating ice sheet, coalescing into ever-broader rivers. Channels and locally broad plains of *Vashon recessional outwash* now form much of the landscape in these ice-marginal locales and recessional river valleys. These landforms can be traced downstream to their glacial-age spillway out of the Puget Lowland, south through the valley of Black Lake near Olympia and then along the valley of the modern Chehalis River west to the Pacific Ocean. The distribution of extensive postglacial deposits is even more restricted, with river valleys the most common depositional sites and those draining the active Cascade volcanoes displaying a particularly voluminous legacy of Holocene mudflows.

The vertical distribution of sediments is also broadly predictable. Vashon till is laterally extensive but commonly just 1 or 2 meters thick. Below it, Vashon advance outwash provides the bulk of the modern landscape lying above sea level, with thickness of many tens of meters common. The top of the advance outwash is relatively flat, notwithstanding abundant superimposed channels and elongated hills; it records the level of the vast braided-river outwash plain formed during the advance of the Cordilleran ice sheet into the Puget Lowland (Booth 1994). Beneath the advance outwash, deposits are less commonly exposed and more variable in origin and in character. In the Seattle area, early Vashon-age lake deposits (the Lawton Clay) are common and can be found up to elevations of about 60 m; farther south, these sediments are almost entirely absent. Even older glacial and nonglacial deposits are present at low elevations throughout the region, particularly on Whidbey Island (Pessl et al. 1989) and in the Seattle-Tacoma metropolitan area (Troost 1999).

### *Holocene Changes in Base Level*

Rapid changes in both sea level and the ground surface following the retreat of the last ice sheet affected not only the present-day exposure of glaciomarine deposits but also the base level of the major rivers and streams of the Puget Lowland that flow into the Sound. Marine waters reentered the newly scoured and deglaciated Sound as soon as ice-sheet retreat reopened the Strait of Juan de Fuca and Admiralty Inlet, but this was followed almost immediately by isostatic rebound, which ranged from negligible near Olympia to about 200 m in the northern Puget Lowland (Thorson 1989). After this relatively abrupt change in local base levels, global sea-level rise from the melting of ice sheets world-wide continued for about 7,000 years, accounting for approximately 90 m of sea level rise that slowed dramatically only about 5,000 years ago. At this time, global sea level was within 5 m of its present altitude (Matthews 1990).

In the last 5,000 years, global sea level has not been entirely static but its continued rise was nearly complete by 2,000 years ago (Clague and Bobrowsky 1990). If this pattern of global late-Holocene rates are broadly applicable to the Puget Lowland, they should be reflected in a gradual aggradation in the lower reaches of rivers and progressive upstream deposition of deltaic and estuarian sediments more rapid than explainable by the sediment load of the rivers alone. Although tectonic-driven changes in land-surface elevation undoubtedly complicated this simple picture (Eronen et al. 1987), well-dated aggrading shoreline features on West Point, a constructional beach spit extending into Puget Sound from Seattle, confirm the existence of the analogous process in the marine environment (Troost and Stein 1995).

Late-Holocene sea-level rise has been sufficiently slow, however, that other processes are likely to have overwhelmed its manifestation in many other geologic settings. Slow upstream aggradation in estuaries and river mouths was surely obliterated in those valleys where volcanic mudflows have occurred during the Holocene. Of the Cascade Mountain drainages entering the Puget Lowland, only the Snohomish River has been unaffected by such events.

Tectonic movement can also impose abrupt vertical changes in relative base level, of which the Seattle fault is the most prominent source (Figure 6). During an earthquake 1100 years ago (Bucknam et al. 1992), the south side of the fault rose 7 m and the north side dropped at least 1.5 m in the center of the Lowland. The magnitude of the vertical offset is unknown to the east and west of Puget Sound, as are the exact number of events and total vertical offset that may have accumulated from earlier earthquakes during the Holocene. The fault's importance to the base level of several major river systems is undisputed, however, because it passes just upstream of the mouth of the Duwamish River, between the inlet and outlet of Lake Sammamish, and below the bedrock-controlled falls of the Snoqualmie River.

## Influence of Geology on Channel Conditions and Responses—the Effects of Scale

Geologic conditions affect many aspects of watershed and fluvial processes; deposits compose the landscape itself, and so their effects are pervasive. One way to organize these effects is to group them by spatial scale, which in western Washington also corresponds to the geologic process(es) that have

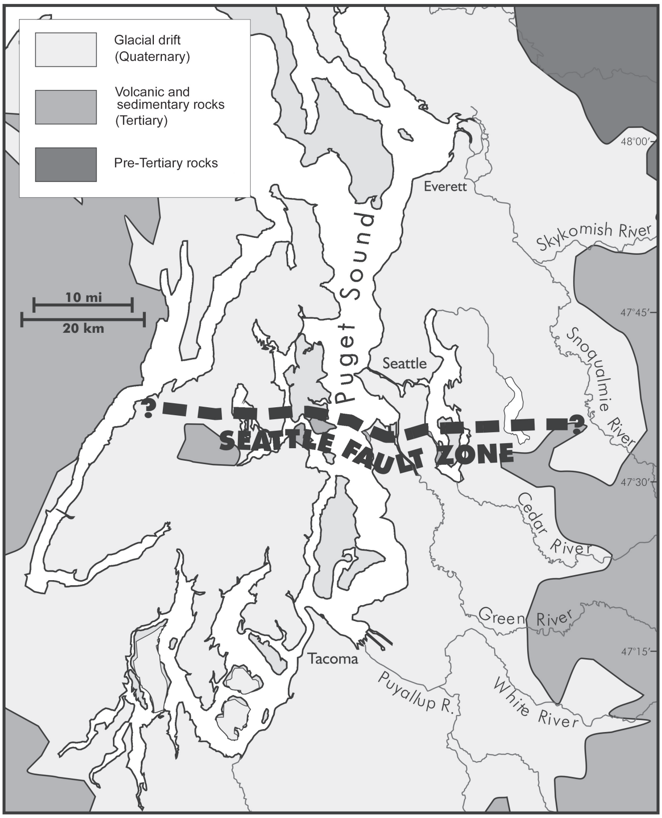


Figure 6. Location of the Seattle fault zone relative to the major rivers of the Puget Lowland. During the last great earthquake 1100 years ago on this fault, the south side rose as much as 7 m in the center of the Lowland; the north side subsided about 1 m.

given rise to them (Figure 7). From a fluvial and hydrologic perspective, these scales correspond to conditions relevant to the broad distribution of rivers and watersheds across the Puget Lowland, to the specific location and character of those watercourses as they traverse the lowland, and to the processes active on a single hillside that deliver water and sediment to the channel below. Geologically, these scales correspond to the tectonic framework of the Lowland, the glacial deposition and scour of the last continental ice sheet that occupied this region, and the resulting deposits (and their history of Holocene weathering) that form the modern ground surface. These divisions are in part arbitrary, but they help our identification of the conditions of greatest relevance to particular settings.

### *Large Scale (10s–100s of km)—The Imposition of Watershed Topography*

The Puget Lowland owes its existence to many tens of millions of years of tectonic activity at the western edge of the North American continent, which in turn has driven both the creation of rocks and their subsequent uplift to form the lateral boundaries of this distinctive topographic region (element "1" of Figure 7). These bordering mountains have imposed a typical maxi-

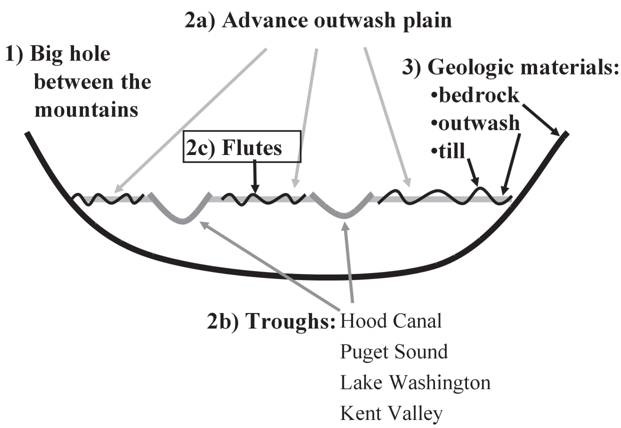


Figure 7. Major topographic scales of the Puget Lowland, expressed in a simplified west-to-east cross section. The "big hole," advance outwash plain, and troughs are at the scale of topography imposed on Lowland watersheds; the flutes provide a finer scale of topographic control on the location of rivers and streams; and the geologic materials of hillslope deposits determine the fate of runoff and groundwater flow.

mum size of approximately 4000 km$^2$ on the main rivers of the Cascade Range (such as the White, Green, Cedar, Snohomish, and Stillaguamish) and their east-flowing counterparts from the Olympic Mountains as they reach Puget Sound. They also form a largely (but not entirely) effective barrier to other rivers that might otherwise have entered this region from a much larger drainage area. Only the Skagit River, with headwaters east of the axis of the Cascade Range, and the Columbia River, with sufficient power from a much greater watershed to erode a path through the actively uparching Cascade Range in late Tertiary time, have breached these mountainous barriers (the Skagit River watershed is about twice the size of its next-largest Cascade drainage; the Columbia River watershed is over 100 times larger). This geologic setting also ensures that the major rivers will follow a relatively uniform downstream progression: rocky alpine headwaters, precipitous decline into confined mountain valleys, and emergence into broad low-gradient lowland valleys where the channels themselves are walled by unconsolidated fluvial sediments.

### *Medium Scale (1s–10s of km)—The Influence of Ice-Sheet Glaciation*

This spatial scale is represented by the overall topographic pattern within the Puget Lowland itself—namely, a moderately dissected but still quite recognizable plateau, extending almost 100 km east-west from the Cascade Range to the Olympic Mountains and even farther north and south from beyond the Canadian border to the city of Olympia and beyond (element "2a" of Figure 7). The discontinuities in that plateau are of two kinds: bedrock prominences, notably the San Juan Islands and the hills that stretch west-to-east across the Puget Lowland immediately south of the Seattle fault (Green and Gold mountains, and the Newcastle Hills); and the marine (and once-marine) channels of Puget Sound (element "2b" of Figure 7). These channels are of nearly the same dimension as the upland plateau itself: narrow, but extending longitudinally as much as 150 km within Washington and several times that distance up past the eastern shore of Vancouver Island, scoured by overriding ice and subglacial meltwater. The plateau is also superimposed with smaller streamlined hills and valleys (element "2c" of Figure 7). Many of these glacial-age valleys continue to guide the modern flow of not only small streams but also the major lowland rivers, particularly as those rivers emerge from the Cascade rangefront. In combination, these influences establish the downstream progression of channel gradient, valley morphology, and sediment-delivery processes that primarily determine channel form and function (see Chapter 3).

*Puget Lowland River Valleys*

The major landscape-altering geologic processes of the Puget Lowland, glaciations and (to a lesser but still noteworthy extent) volcanic activity, have both contributed to the character of the modern drainage network. Invasions of the continental ice sheet created the predominant north-south grain of the topography which now guides the flow of nearly every major river in the southern lowland, imposed on their eastward (Olympic) or westward (Cascade) flow out of the mountains.

Through-going north-south valleys are common near the lateral boundaries of the lowland and particularly along the Cascade rangefront northeast and southeast of Seattle. Numerous subglacial and proglacial valleys provided passageways for voluminous meltwater discharges between the Skykomish, Snoqualmie, Cedar, and Green river valleys and their associated tributaries. Although now perched far above the modern drainage network, these relict river valleys are still evident along much of the Cascade front (Booth and Hallet 1993).

The interplay of glacial and volcanic activity is also evident in river-basin morphology, well-exemplified in nearly every channel with a Holocene volcano in its watershed. One of the best examples is found between the Stillaguamish and Skagit watersheds, where the Sauk River traverses an anomalous south-to-north valley of substantially greater width than that immediately upstream of Darrington. Its neighbor to the immediate south and west, the North Fork Stillaguamish River, also occupies a downstream valley dramatically (and abruptly) broader than its immediate upstream counterpart (Figure 8). These relationships owe their existence to the glacial and postglacial history of the region, initiated by glacial drainage of the upper Skagit River south along what is today the valley of the lower Sauk River by virtue of subglacial drainage pathways (Beechie et al. 2001; Tabor et al. 2001). All of the upper Skagit River, Suiattle River, and Sauk River drained out the valley of the North Fork Stillaguamish River during late-glacial time, diverted first by the ice sheet itself and later by a plug of Vashon-age sediment that temporarily blocked the Skagit River valley downstream of its modern confluence with the Sauk. The valley of the North Fork Stillaguamish River shows the effects of an extensive history of such drainage, with a broad valley carved through bedrock walls now several kilometers apart. The modern North Fork Stillaguamish River itself, however, is clearly an “underfit” channel, occupying a valley previously excavated by a larger river.

The agent of postglacial diversion of the Sauk and Suiattle rivers was volcanic eruptions from Glacier Peak (Vance 1957; Beget 1982). Lahars and lahar-derived fluvial sediment choke the mouth of the Suiattle River and

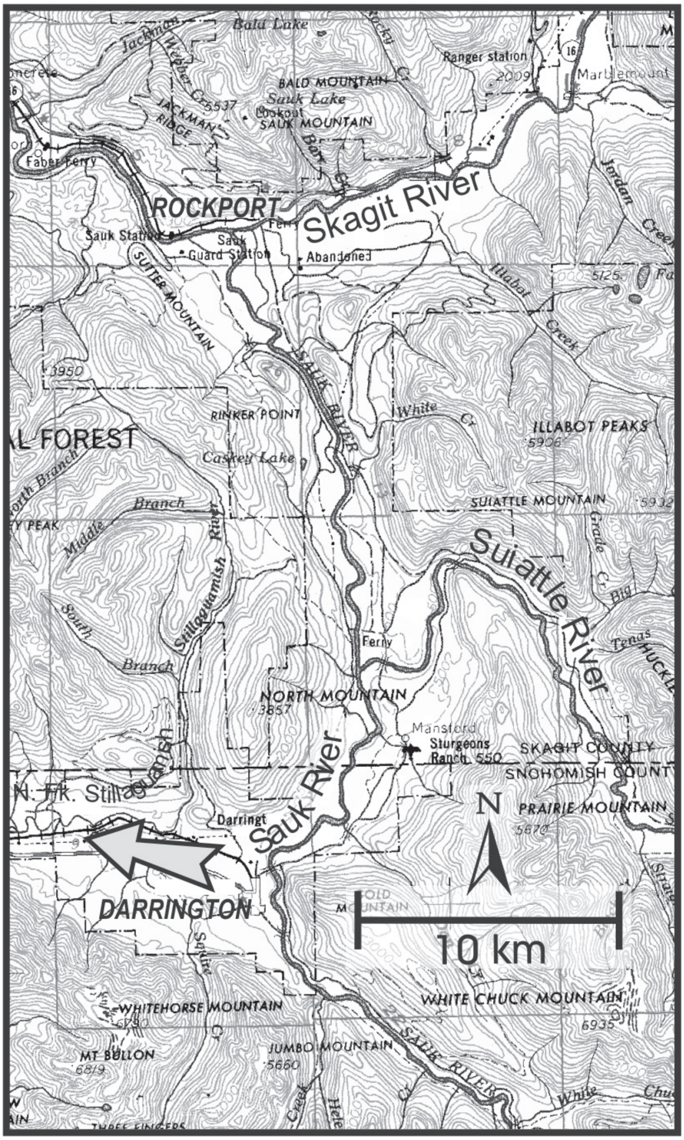


Figure 8. Topography of the lower Sauk River area, where volcanic and glacial modifications to the landscape have diverted major river channels in the Holocene and late Pleistocene Valley (base map from USGS Darrington and Rockport 7.5' quadrangles).

form the drainage divide at Darrington, and they fill much of the lower North Fork Stillaguamish valley. Drainage of the Sauk River is thus a function of local deposition of sediment where the valley widens at Darrington, with the local alluvial-fan topography determining whether the Sauk River will flow west towards the Stillaguamish or north towards the Skagit. The North Fork Stillaguamish River and the lower Sauk River have nearly identical gradients, suggesting that the Sauk established the gradient in both valleys by successive occupations during the Holocene.

The Suiattle River is similarly influenced by laharic deposition at its mouth, but its flow direction is constrained by the Sauk River. In late glacial time, the Sauk would have flowed south, but as the ice receded it would have reversed to flow north into the Skagit. Because of this reversal of drainage, the Suiattle River experienced a base-level change from perhaps 150 m altitude at Darrington (to the south) to 60 m altitude at Rockport (to the north). In response to this lower base level, and thus significantly steeper gradient, the Suiattle has incised as much as 50 m in its lower valley. The highest laharic surface recognized at the mouth of the Suiattle River is at 160 m elevation, barely sufficient to exceed the present valley divide at Darrington, over 10 km distant. As a result, the river is unlikely to drain down the North Fork Stillaguamish River again, even if the Sauk River was so diverted and a new lahar filled the Suiattle River. Westward diversion of the Sauk River thus is quite plausible in a future major eruption of Glacier Peak; southward diversion of the Suiattle River, however, is likely to require another glaciation.

### *Channeled and Elongated Topography of the Puget Lowland*

Many of the watersheds that originate wholly within the Puget Lowland comprise three distinctive geologic and topographic zones—the upland plateau; a steep sideslope; and a base level defined by a lake, major river, or Puget Sound. In contrast to the monotonic decline not only in elevation but also in topographic gradient typical of the major riverine watersheds that begin at the Cascade or Olympic crest, the three watershed “zones” of the Lowland do not display any simple relationship between drainage area, gradient, and substrate. The upper headwaters are *not* always steepest, and the steepest areas are *not* always underlain by the most resistant sediment (or bedrock).

The headwater zones of these lowland watersheds lie on the upland plateau and are underlain by glacial sediment, primarily Vashon till with a thin (or absent) mantle of recessional outwash. The topography in these areas is one of elongated hills and troughs in the down-glacier direction, with gentle slopes and an overall relief of less than 30 m in most areas. This is the surface of the glacially overridden Vashon-age advance-outwash plain, described above. Low-gradient areas or closed depressions that developed beneath the ice sheet have now been partly or completely filled in by lakes, wetlands, or isolated patches of glacial outwash, deposited as the ice was retreating from the region during deglaciation (Figure 9).

As these headwater streams drain off the upland plateau, they flow either *parallel* to the ice-flow direction (generally to the north or south) down a gently to moderately sloping surface, or *across* the ice-flow direction (generally to the east or west) and over a more steeply descending slope. These steeper east-west slopes constitute the second topographic "zone," a result of subglacial scour followed by postglacial erosion. They flank the major subglacial or recessional drainage channels of the Vashon ice sheet, which have captured and are now occupied by the major rivers (*e.g.*, the Snoqualmie and the Cedar), by major lakes (Sammamish and Washington), or by Puget Sound itself.

In this zone, channel erosion has commonly exposed outwash sand and minor gravel derived from the advancing ice sheet overlying silt and clay of the early-glacial lake beds, defining a modern geologic environment characterized by both severe erosion and severe landsliding. In par-

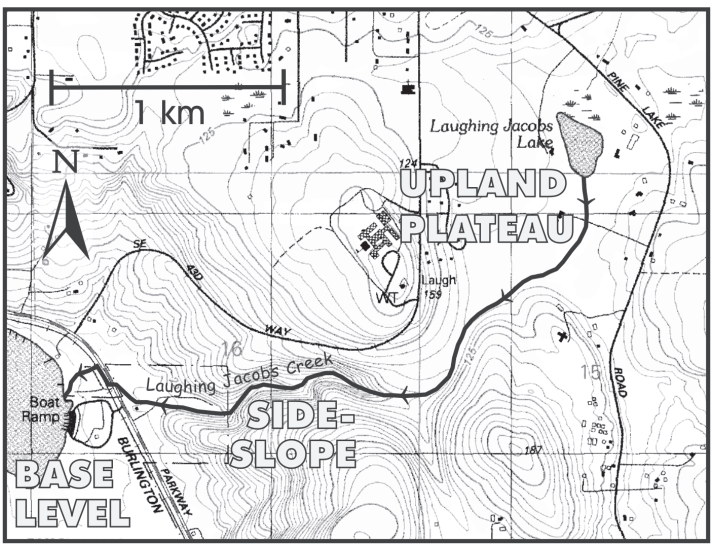


Figure 9. Example of the topography of typical lowland streams, where low-gradient headwaters drop steeply over the sideslope of the upland plateau to a base level set by a major river, Puget Sound, or (in this case) a lowland lake (base map from USGS Issaquah 7.5' quadrangle).

ticular, the advance outwash deposit contains mainly sand and relatively little gravel; thus stream-channel incision, leading to the catastrophic loss of channel grade, can proceed quite rapidly, particularly where new upland development has disrupted the hydrologic regime and culvert outfalls have created new discharge points (Booth 1990). Where gravel is more abundant, the rate of channel downcutting is somewhat less, but the net results appear to be qualitatively equivalent. Landslide susceptibility is enhanced by the perching of groundwater at the top of the older, less permeable deposits marked by the surface appearance of seeps and springs. Increased pore pressures above this boundary reduce the strength of the overlying material and increase the likelihood of mass movement.

The third topographic zone of typical Puget Lowland watersheds lies at the base of the upland plateaus, where channels approach their modern base level. A final type of modern stream channel is common here, flowing in a broad, flat-bottomed valley whose size and gradient has been inherited from glacial activity. The present stream is thus underfit, its valley carved by much more voluminous meltwater either beneath the ice sheet or by subaerial rivers during ice-sheet retreat. As a result of this legacy, the modern channel is incapable of moving all of the sediment delivered to it by the tributary streams, and the valley as a whole is a site for very long-term storage of eroded upland sediment. Olalla Valley on the Kitsap Peninsula (Figure 10) is an excellent example.

Where the stream first transitions from the steeper sideslopes to the valley bottom, much of the sediment load of the channel is deposited as an *alluvial fan*. These features, ubiquitous lobate landforms wherever channels abruptly lose gradient and thus sediment-transport capability, are formed during the lateral migration of sediment-laden discharges. They are poor choices for land development, because they can be made safe for human habitation only by anchoring the location of the channel, exacerbating instream sediment accumulation, and the channels themselves will rapidly bury instream structures and most habitat modifications that obstruct sediment passage in any way. Alluvial fans built by small streams may cover only a few hectares; larger ones may occupy one or more square kilometers and are associated with zones of rapid channel migration and avulsion. Although these landforms are most clearly expressed by relatively small channels undergoing abrupt changes in gradient, many of the same geomorphic processes occur at a larger scale in the mainstem rivers of the Olympic Mountains and the Cascade Range as they emerge from the mountain front into the Puget Lowland. Here, the imposed topography also establishes a change in gradient that results in zones of enhanced sediment deposition and rapid channel migration. Although a “hazard” from the perspective of human occupation of the nearby floodplain,

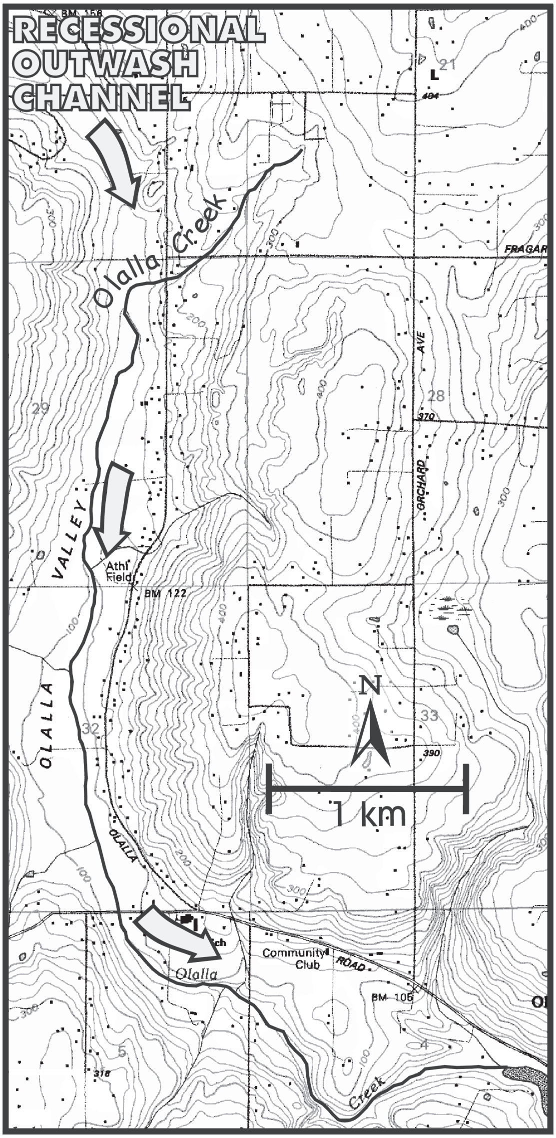


Figure 10. Example of an under-fit modern stream, occupying the late-glacial recessional outwash channel of Olalla Valley (base map from USGS Olalla 7.5' quadrangle).

these processes are also responsible for creating some of the most productive side-channel fish habitat in these river systems.

### *Channel Types and Channel Classification*

Geomorphologists and biologists have been organizing and categorizing the many types of stream channels for about a century. In the mountain-to-lowland forested watersheds of the Pacific Northwest, the classification of Montgomery and Buffington (1997) explicitly characterizes the dominant geomorphic processes found in a typical downstream progression: steep headwater catchments, underlain by bedrock, to larger and more gently sloping watershed areas in broad alluvial valleys. This sequence is a product of watershed geology, as is its counterpart in the central Puget Lowland where headwater reaches can be quite flat and steeper reaches located only farther downstream. Sediment-delivery processes, channel-roughness elements, and incision susceptibility are thus very different in lowland channels than in nearby mountainous channels, and all depend on the geologic controls over watershed processes (see Chapter 3).

## ***Small Scale (Hillslopes and Channel Reaches)— The Influence of Geologic Deposits***

This spatial scale reflects the conditions specific to a hillside or a valley segment, where the hydrologic response of a watershed and the local behavior of a channel are first determined. The range of possible conditions is as broad as the variety of deposits across the Puget Lowland, and the possible extent of channel responses is equally varied.

### *Hillslope Hydrology—Runoff and Infiltration*

When rain and meltwater reach the surface of the ground, they encounter a filter that is of great importance in determining the path by which hillslope runoff will reach a stream channel. The paths taken by water, be they over or under the ground surface, determine many of the physical characteristics of a landscape, the generation of runoff, and the response of stream channels to the climatic regime and to watershed land uses. These factors, in turn, will determine the frequency and magnitude of high flows and channel erosion and deposition, the level of summer base flows, the hillslope processes that deliver sediment to stream channels, and ultimately the suitability of the channel for biota. Stream restoration cannot proceed without knowing the hydrologic regime of a channel, both now and in the future; in a region where forestry and urbanization continue to alter watershed land cover, the hydrologic regime of a channel is a direct product of the hydrologic processes on the hillslopes.

The most common, and most important, analytical task in characterizing hillslope hydrology is normally to "partition" the precipitation amongst runoff, evapotranspiration, infiltration, and groundwater recharge. The overriding determinants of this process are the vegetation and the character of the ground surface and soil layer (Chapter 11), which in turn depends in large measure on the properties of the underlying geologic deposit. The relative magnitudes of runoff and infiltration will determine which process(es) of storm runoff will occur (Dunne and Leopold 1978):

- *Horton overland flow* (surface runoff over unsaturated ground where the rainfall intensity exceeds infiltration capacity),
- *subsurface stormflow* (shallow groundwater flow in direct response to rainfall),
- *return flow* (shallow groundwater that reemerges to flow over the ground surface because of saturated subsurface conditions), and
- *direct precipitation onto saturated areas*.

The last two processes are also known together as *saturation overland flow* (Figure 11).

In *undisturbed* watersheds of the Puget Lowland and across the Pacific Northwest, the underlying geology probably has only a secondary control on these storm runoff processes. In the 15,000 years since deglaciation, weather-

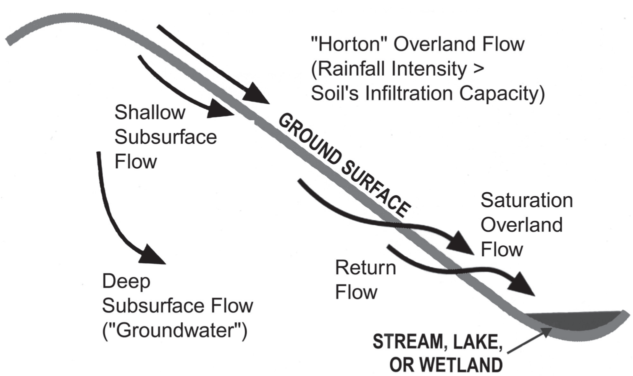


Figure 11. Schematic diagram of flow paths on a hillslope.

ing and biological activity have developed soils that are typically 1–2 m thick over even the most impervious of geologic deposits (or bedrock). These soils have infiltration capacities that are several orders of magnitude greater than their parent material (Snyder et al. 1973) and that greatly exceed typical rainfall intensities. Thus subsurface flow typically will be the dominant runoff process, almost independent of geologic substrate, during all but the largest storms.

Subsurface geology, however, becomes far more critical where natural erosion or human disturbance has thinned, compacted, or stripped the surficial soil. The permeability of the underlying geologic materials across the Puget Lowland varies by more than four orders of magnitude (Olmstead 1969). Typical rainfall intensities will readily exceed the infiltration capacity of the most widespread of these geologic materials, glacial till and bedrock, wherever they are exposed and unweathered. In such areas, delivery of water and sediment can be altered from that of a subsurface flow regime to a Horton overland flow regime, with attendant changes to peak discharges, sediment delivery, and water chemistry.

In contrast, where deep permeable deposits such as glacial outwash are present, erosion of the overlying soil is unlikely to impose substantial hydrologic changes. Yet if urban development covers these areas of once-permeable substrate with pavement, tremendous relative increases in discharges can result (see Chapter 11). Ironically, this geologic setting should also be the easiest to use the intrinsic permeability of the underlying deposit to minimize the increases in runoff delivered to downstream channels, through the infiltration of stormwater. Current stormwater management practices have been slow to recognize these geologic differences at the scale of an individual hillside and thus to take advantage of their opportunities for reducing downstream impacts.

### *Sources of Bed Material and Roughness*

Most of the geologic deposits of the Puget Lowland have been transported to their present-day position by either glacial ice or by voluminous meltwater-fed rivers. They comprise a wide range of grain sizes, from clay- and silt-sized particles to boulders, and so their erosion can deliver a wide range of particle sizes to stream and river channels. At a watershed scale, this allows fluvial adjustment of bed-material sizes in response to changing discharge or sediment loads (Chapter 3). At a site scale, it will determine the susceptibility for channel erosion and incision, the character of the channel morphology, and the suitability of a reach for benthic organisms and fish.

Two exceptions to the general condition of wide-ranging particle sizes merit note, however. The most important arises downstream of extensive hillslope deposits of Vashon advance outwash, exposed beneath the Vashon till as the layers of a cake are exposed beneath its frosting. Although the advance outwash is commonly described as being "increasingly gravelly near the top of the deposit" (e.g., Mullineaux et al. 1965), the volumetric contribution of gravel to this deposit is quite small—it is, overwhelmingly, medium-grained sand throughout the Lowland, fluvially deposited many kilometers in front of the advancing ice sheet (Booth 1994). Where channels are floored by this deposit, channel roughness must be derived from gravel delivered (and subsequently winnowed) from the overlying till, or from large woody debris (Booth 1990). The former is not abundant, and the latter, although historically abundant and quite sufficient to maintain channel stability, is prone to human-induced loss (Montgomery et al. 1995; Booth et al. 1997).

The other common geologic deposits that lack coarse sediment are the lacustrine silts and clays that were also deposited in front of the advancing ice sheet (but at greater distances than the advance outwash). Sporadic "dropstones," gravel clasts rafted out into the proglacial lake within icebergs and subsequently released by melting into the silt and clay of the lake-bottom sediments, compose much less than one percent of this deposit. The remaining sediment is cohesive, sometimes weathering or eroding into gravel-sized fragments, which persist only briefly under the hardships of fluvial transport. Where unfractured, however, the resistance of this deposit to fluvial erosion is many times greater than that of the sandy advance outwash.

### *Susceptibility to Channel Expansion and Incision*

Stream-channel expansion is a natural part of drainage-basin evolution, but its modern importance in the Puget Lowland is a direct consequence of human activity, particularly watershed urbanization. Channel incision is a particularly damaging response to increased discharge because it eliminates instream habitat, isolates the channel from its floodplain and so further increases in-channel flood flows, and releases tremendous quantities of sediment into the downstream channel network. Nearly every watershed subject to urban development responds to the increases in runoff by some degree of channel expansion, but not all suffer from dramatic incision.

Many of the simple physical parameters of a stream or of the watershed, such as slope or imperviousness, show no obvious value in predicting the magnitude of channel change in response to watershed development (Booth and Henshaw 2001). The role of geologic materials, however, shows a consistent relationship with incision susceptibility and magnitude. Incision generally requires relatively steep topographic gradients where human structures (such as culverts or weirs) do not provide local grade control that would limit vertical adjustments of the channel bed. In these settings, a clear difference is observed between cohesive silt-clay substrates, which generally permit only low rates of channel adjustment, and granular hillslope deposits (normally medium sand, most commonly of the Vashon advance outwash), which offer very little resistance to downcutting once the channel's pre-disturbance source of channel roughness (normally large woody debris) is physically removed or undermined by increased discharges.

## Consequences of the Geologic Influences on Watersheds and Channels

Spatial variations in geologic conditions result in profound differences not only in the physical but also in the biological conditions of stream channels. Although aquatic biota depend on many factors (Karr and Chu 1999) of which only a subset are influenced by watershed geology, that influence is pivotal through the imposition of channel gradient and in-channel conditions. Channel gradient is largely determined by position on the landscape, which in the relatively young landscape of the Puget Lowland is determined almost entirely by its geologic history. Salmonids and other fish species exhibit preferred gradients for different life stages; the regional geology thus establishes broad but identifiable zones where the various life histories will be found (e.g., Montgomery et al. 1999). In-channel conditions, also critical to the life histories of many species, are a direct product of geologic conditions and fluvial processes. Watershed sediment sources will partly determine the bed texture of the stream and determine if certain preferred sediment sizes, notably gravel, are available in sufficient quantities. Certain deposits, notably Vashon till and Vashon recessional outwash, have these sediment sizes in abundance; other deposits are almost entirely lacking in gravel. The presence of a hyporheic zone around the channel and the upwelling of groundwater into the channel are both products of valley morphology, floodplain sediments, and subsurface stratigraphy. If our knowledge of these processes is ever to improve, it will require integration of the geologic framework of a channel network with the hydrologic conditions of the surrounding landscape.

The varying temporal history of geologic processes, notably the history of drainage-network development and disturbance, is also important to any understanding of biological conditions. Ice-sheet glaciation of the Puget Lowland has provided ice-free conditions for only the last 15,000 years, a legacy that is abundantly displayed in the genetic stocks of native fish (see Chapter 5).

Because of these diverse physical and biological influences on watershed processes and conditions, aspects of the regional and local geology must be understood for stream restoration or rehabilitation to be successful. Some of these geologic aspects are obvious and readily determined—measuring channel gradient, for example, needs no specialized geologic information—but others, such as the delivery of sediment, the likely long-term disturbance history, or the flux of groundwater into and out of the channel, can be evaluated only with knowledge of geologic materials, history, and processes. Predicting the response of a stream to human manipulation demands conceptual models of water and sediment delivery to the fluvial system, and of the physical framework through which those fluxes occur. The geologic setting of a river or stream also imposes intrinsic natural constraints on what can be accomplished through human intervention.

Whether evaluated or not, these geologic conditions have *always* imposed constraints on the nature of channel networks, and on the biological productivity of their rivers and streams. Not all streams have the same level of biological activity, and so not all stream restoration efforts should strive for the same goals and objectives. If the tools of geology are not used to recognize those conditions that can limit the success of rehabilitation, even the best of human intentions are likely to fall short of goals and to waste resources in the process. Furthermore, other opportunities may be passed unrecognized, even where stream and watershed conditions hold the promise of a favorable response. We cannot afford such ignorance.

## Acknowledgments

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